Remote Sensing of Ocean Color and it's Potential Uses To Address Chesapeake Bay Management Issues

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Cover Image: The cover image is a SeaWifs True Color image of Chesapeake Bay taken 12 April 1998 courtesy of NASA Goddard Space Center, Greenbelt MD

Executive Summary

The purpose of this report is two-fold. The first objective is to provide a brief overview of the science behind the remote sensing of ocean color data and two of its derived products: chlorophyll *a* and Kd490. The second objective is to identify potential applications of available ocean color data to address Chesapeake Bay Program (CBP) information needs (e.g., habitat assessment, water quality criteria attainment). It is hoped this report will stimulate discussion in the Bay management community on the potential uses of frequent, high resolution, readily available remote sensing information about Chesapeake Bay habitat quality and quantity.

The Chesapeake 2000 Agreement reiterates many directives from earlier agreements, and creates additional directives, that require monitoring and data analysis (Chesapeake Executive Council, 2000). A number of these directives could be cost-effectively accomplished with the use of ocean color data. In fact, the need for frequent, high resolution monitoring data is becoming increasingly apparent in ongoing CBP restoration efforts. The Program currently obtains water quality data from a network of over 100 fixed stations and several transects in the Bay mainstem and major tributaries. While these field data have provided reliable status and trend information, they may not be able to provide adequate spatial and temporal detail about exceedances of the new water quality criteria for the Bay. Remote sensing data could significantly enhance the frequency and resolution of chlorophyll monitoring in open water habitats and water clarity monitoring in areas adjacent to near-shore habitats. It is now technically feasible to combine ocean color remote sensing data with field data and produce high-resolution maps of habitat suitability with modeling protocols. High-resolution maps of habitat suitability facilitate better restoration targeting and more accurate ecosystem assessments for fisheries management purposes.

Recent advances in remote sensing technology are making satellite and aircraft images of the Chesapeake Bay surface easy to obtain and utilize. Satellite images are available as frequently as every 3-4 days and are provided free to most users whereas shipboard data are collected every two weeks or monthly and are a direct cost to CBP partners. The intensities of different wavelengths (colors) captured in the images can be rapidly and inexpensively processed with readily available software tools to generate chlorophyll *a* and light attenuation (K490) products for individual pixels. The imagery currently has pixels that represent an area as small as 1 square kilometer, and a grid of pixels derived from the satellite images can cover large sections of the Bay surface to within 1 kilometer of the shoreline. The error associated with image-derived, average chlorophyll *a* values for the Bay mainstem appears to be about 2% - 34%, depending on season and turbidity of the water (Robinson 2000, Table 7). While not negligible, these error rates may be smaller than the error associated with values generated by the CBP 3-D Interpolator from fixed station data alone (Perry 2002). If both shipboard and remote sensing approaches were employed to monitor open water habitats, the merged data sets could provide the spatial and temporal coverage needed to ascertain chlorophyll criteria attainment. Remote sensing data would significantly enhance the current monitoring program's ability to track ecosystem responses to management actions (nutrient and sediment reductions), and greatly improve the information used by various CBP modeling and analysis efforts.

Possible pilot studies are introduced in this report that would address specific C2K directives. The CBPO Data Center is developing the computing resources and staff with expertise to use and interpret ocean color data. The pilot projects would test and refine these nascent abilities of the CBPO Data Center to utilize ocean color remote sensing data, and demonstrate the capabilities of this readily available, cost-effective source of monitoring information. The report makes four recommendations, which are summarized below. While some of these recommendations extend beyond the confines of ocean color data, they do address information needs of the Chesapeake Bay Program that will arise in the next 5 to 10 years.

RECOMMENDATION: *Start using the available remote sensing data products as soon as possible to explore its potential for answer Bay Program management questions.* CBP currently is not using satellite remote sensing imagery for water quality or habitat resource assessment, areas in need of spatially and temporally intensive data. Apart from the SAV aerial survey, the Bay Program does not apply the available aircraft imagery data that has been collected to track Chesapeake ecosystem responses to management actions. The information requirements of some CBP activities, including confirmation of criteria attainment, may require spatial data that is best generated by satellite or aircraft imagery.

Furthermore, many species-specific habitat evaluations require spatially and temporally dense data. These are applications for which remote sensing images are ideal suited. Three pilot studies to evaluate the utility of available ocean color products in addressing specific CBP information needs are suggested in the report. They are:

- Chlorophyll and Turbidity in Waters Adjacent to SAV Beds (to screen for habitat requirements failure)
- Comparison of Statistical Confidence in Interpolated and Remotely Sensed Surface Chlorophyll Data (to obtain error estimates for chlorophyll data from different monitoring sources)
- Monitoring Program Enhancement (to determine if inclusion of remotely sensed data improves CBP status and trend analyses and eutrophication model calibrations for several water quality parameters)

RECOMMENDATION: *Develop a core remote sensing team.* If the potential of remote sensing imagery is to be realized, a core team of trained analysts needs to be developed. This team would be composed of individuals from both the CBPO Data Center and the remote sensing community at large. Ideally, these individuals would be given well-defined assignments (i.e., specific questions to answer through analyses of remote sensing data) that address specific information needs of the CBP. Individuals located at the Bay program office will need appropriate computer (hardware, software, computer maintenance) and technical support from the remote sensing community. All team members will need Bay Program management support.

RECOMMENDATION: *Establish an in-house collection or access to ready to use remote sensing ocean color images and data products for rapid application to Bay Program management questions.* Data from the aircraft-based remote sensing project in Chesapeake Bay are currently available through the NOAA Chesapeake Bay Program Office and Maryland Sea Grant Program web sites. Satellite-derived ocean color data products are readily available from NASA. If remote-sensing data is deemed useful in addressing time-sensitive CBP issues such as water quality criteria attainment and habitat targeting, plans should be made to establish the routine acquisition and analysis the SeaWIFS, MODIS and other remotely sensed data products for the Chesapeake Bay region.

RECOMMENDATION: *There is currently no demonstrated need for "real time" data sets. However, if the proposed pilot projects demonstrate ocean color imagery to be a useful management tool, then avenues for obtaining this data should be explored.* Currently, the Chesapeake Bay Program Partner agencies perform most of their environmental management in a retrospective manner. Under this scenario there is little benefit to be gained from the acquisition of real time remote sensing products. Near real time data does provide the potential to aid in harmful algae bloom detection, but this is not currently a focus of CBP monitoring efforts. If the proposed pilot project yield useful management tools, it might be productive to re-examine the acquisition and avenues for obtaining and using real time data in the future.

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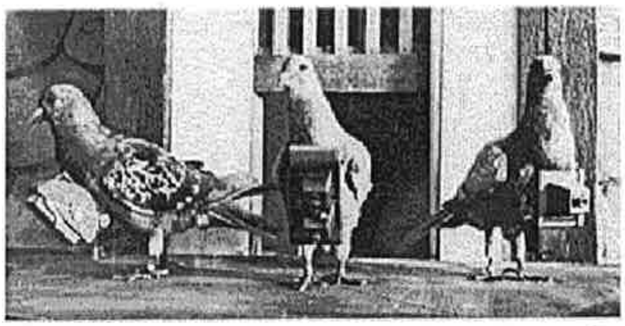
Introduction

There are a variety of definitions for the term "remote sensing." The broadest definition identifies remote sensing as the collection of information about an object without being in physical contact with the object. (Earth Observatory 2002) Using this definition, a wide range of tools including moored buoys, drifting drones, towed body arrays, aerial based sensors (satellites and aircraft mounted instruments), and even pigeons (Figure 1) can all be considered remote sensors of the estuarine environment.



Europe's remote sensing Pigeon Fleet of the late 1800s.

Figure 1. An Early Estuary Remote Sensing Program. Photo courtesy of Florida Department of Natural Resources.

For the purposes of this report, remote sensing will be defined using a more stringent NASA definition. *Remote sensing is the measurement and analysis of electromagnetic radiation reflected from, transmitted through, or absorbed and scattered by the atmosphere, the hydrosphere and by material at or near the land surface, for the purpose of understanding and managing the Earth's resources and environment (*Earth Observatory 2002*).* Under this definition of remote sensing, measurements are made predominantly by aircraft and satellites. For the purposes of this report, the authors further confine the scope of remote sensing to the measurement of Ocean Color and data products that can be derived from those measurements. The report first provides a brief overview of the science behind remote sensing of ocean color and its derived data products (e.g. chlorophyll *a*, K490). The current potential sources of ocean color data for Chesapeake Bay include an aircraft based program and two satellite based programs, Sea-Viewing Wide Field-of-View Sensor (SeaWIFS) and Moderate Resolution Imaging Spectroradiometer (MODIS). Potential uses of ocean color information in addressing some Chesapeake Bay Program issues are then presented and discussed.

General Background

Data Acquisition and Products

Ocean color is created when visible light from the sun illuminates the ocean surface. The available light is subject to several optical effects including reflection and absorption. In the ocean, suspended particulate matter, dissolved organic material, phytoplankton, and the water itself selectively absorb and/or scatter some wavelengths of light while allowing the transmission of others. Light that is radiated back from the ocean surface has been altered as a result of these optical interactions. This returning radiance or water leaving radiance can be measured, and the quantitatively related to various constituents in the water column that interact with light. (SeaWIFS Readme 2000, Kirk 1994)

Whether satellite or aircraft mounted, a photometer/or radiometer is the primary instrument for measuring ocean color (Kirk 1994). While each ocean color instrument varies in the details of how data are collected, data collection occurs following these general steps. The photometer measures radiance intensity at specific wavelength bands. The measured radiance values at various wavelengths are recorded for an area of the ground as a pixel. The radiance value for a pixel represents an estimate of average radiance value of light at a given wavelength over the pixel's area of the ocean or earth surface. A typical radiometer will collect data as it passes over the earth's surface, at which point the data are either stored for later processing or transmitted directly to a receiving facility for processing. Data collected and immediately sent to a receiving facility is referred to as real-time data. After collection, data has variety algorithms and corrections applied as part of multi-step processing to derive a final radiance values. Radiance values are geo-referenced and a variety of additional ocean color products such as chlorophll A and K490 (a light attenuation product) may be calculated (For additional potential ocean color products see Appendix C, Esaias etal 1997, SEAWIFS 2000). Subsequent data processing involves projecting data into map coordinates and analysis of imagery (For additional details on the processing of imagery see Appendix A).

Data Distribution

Today much of the satellite data collected by the US government is collected as a collaborative effort between NASA, other government agencies, and/or private corporations. The collaborative nature of these information collection programs has resulted in some cost recovery for certain types of imagery. NASA serves as the primary holder of much of the available ocean color data as well as large archives of past and current data from a variety of other satellites and space programs. As part of its Earth Observing System (EOS) NASA's established a network of DAACs, or Distributed Active Archive Centers, at each of its major facilities to provide data to the scientific/technical community and public. Each DAAC serves as a repository for a specific science discipline (Table 1). NASA currently has eight data centers spread through out the country connected via Internet. The centers serve data through a variety of mechanisms including FTP and hard media requests. Much of the available data is distributed without cost. The centers also provide a variety of data user support services.

DATA CENTER	DATA SPECIALTY
Alaska Synthetic Aperture Radar Facility, Fairbanks, Alaska	National Snow and Ice Data Center Snow and ice, cryosphere, and climate. SAR Sea Ice and Polar Processes Imagery
EROS, Earth Observing Data Center, Sioux Falls, South Dakota	Land process data, land surface temperature, evapotranspiration, and land cover
Goddard Space Flight Center, Greenbelt, Maryland	Upper atmosphere chemistry, atmospheric dynamics, global biosphere, hydrology, ocean color and geophysics
Langley Research Center, Hampton, Virginia	Radiation budget, clouds, aerosols, surface radiation, land processes, and tropospheric chemistry
Jet Propulsion Laboratory- Pasadena, California	Ocean Circulation and Air Sea Interactions
Global Hydrology Resource Center, Huntsville, Alabama	Hydrologic Cycle and Lighting
National Snow And Ice Data Center, Boulder, Colorado	Snow, Ice, Cystophere and Climate
Oakridge National Laboratories, Oakridge, Tennessee	Biogeochemical Dynamics

Table 1. List of NASA Data Centers and their area of data expertise. Note the highlighted data centers are those holding data of potential value to the Chesapeake Bay Program.

The Distributed Active Archive Center (DAAC) of the Goddard Space Center in Greenbelt, Maryland, is the primary NASA repository for ocean color data. SeaWIFS, MODIS, CZCS and a variety of other ocean color imagery are made available through Goddard's web site (http://daac.gsfc.nasa.gov/) and related sites (e.g., http://simbios.gsfc.nasa.gov/, http://seabass.gsfc.nasa.gov/dataordering.html). NASA places strong emphasis on quality assurance of data. Imagery from the various satellite missions is routinely reprocessed as instrument adjustments are made and algorithms for data processing are improved. Even data from retired satellites are periodically reprocessed with new protocols to improve the data products. NASA also provides a variety of user support products and services.

Sources of Ocean Color Imagery

The following section identifies the most viable sources of ocean color information currently available for Chesapeake Bay Program applications, in chronological order based on instrument launch date. All of these sources provide high-resolution data that could be used to evaluate living resources habitat quality or water quality criteria attainment. Prior to the SeaWIFS program, satellite-based instruments were not targeted for use in areas such as the Bay. Therefore, the data record of ocean color imagery for Chesapeake Bay begins with an aircraft-based remote sensing program in 1989.

Aircraft-Based Ocean Color Imagery

Chesapeake Bay Chlorophyll Remote Sensing Project The National Oceanographic and Atmospheric Administration (NOAA) in conjunction with NASA began funding a University of Maryland remote sensing program in 1989 with the goal of obtaining ocean color measurements from aircraft and determining the spatial and temporal variability of Chesapeake Bay chlorophyll a. An underlying need for improving the resolution of chlorophyll patterns was to "detect changes in phytoplankton biomass in response to nutrient reductions in the Bay mandated as part of the clean up of the estuary." Aircraft measurements are made at low altitudes (150 meters) along a set of flight tracks that crisscross the Bay, and then interpolated to create complete images of Bay chlorophyll patterns. From 1990 to 1995, data were generated using the Ocean Data Acquisition System (ODAS). The ODAS instrument consisting of multiple radiometers recording water-leaving radiance in the blue-green region of the visible spectrum, at 460 nm, 490 nm, and 520 nm. In 1996, the SeaWIFS Aircraft Simulator (SAS II) was used in parallel with the ODAS instrument. SAS II contains sensors at 7 wavebands, including the 6 visible bands also recorded by the sea-viewing wide field-of-view sensor (SeaWIFS) satellite ocean color instrument. The additional bands of SAS II allowed for improved recoveries of chlorophyll in highly turbid conditions or at the extremely high concentrations that accompany algal blooms. Overflights were attempted once per week between April and October from 1989 to 2001. Coverage was extended into the Patuxent and Choptank rivers in 1999. Radiances at the various instrument bands and chlorophyll values calculated using a custom algorithm for the Bay are available along the aircraft flight tracks (Harding 2000, NOAA CBP 2001). Interpolated *.gif images of the data are also available at http://noaa.chesapeakebay.net/odas_sas.html or http://www.cbrsp.org/.

Satellite-Based Imagery Sources

SEAWIFS The Sea-Viewing Wide Field-of-View Sensor (SeaWIFS) was launched on the OrbView-2 satellite platform in August of 1997. The SeaWIFS scanner has 8 channels, and produces imagery at a LAC spatial resolution of 1 square kilometer. Operation of the SeaWIFS instrument is expected to continue through 2003. NASA produces four standard 4-km GAC products from SeaWIFS imagery and provides 1-km LAC data for the Bay region (Appendix C, or SEAWIFS 2000). http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/index.html

MODIS The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the TERRA (EOS AM-1) satellite was launched in December 1999 and the AQUA satellite launched in May 2002. The MODIS scanner has 36 channels, which produces data of spatial resolutions from 250 to 1000 meters, depending on the channel. Based on the anticipated design life of the MODIS instrument, imagery will be obtainable through at least 2008. The MODIS instrument produces 45 standard data products, 36 of which are ocean color related (see Appendix C or Esaias etal. 1997 for a complete details). http://modis-ocean.gsfc.nasa.gov

Data Usage Issues

It is not the intent here to go in to extensive detail about all the potential data limitations and caveats associated with the use of remotely sensed data, but we do wish to address some specific questions which have been put forward by members of the CBP community.

Q) Where geographically is remotely sensed ocean color data best used?

A) Aircraft-based remote sensing data can provide coverage of most of the Bay's surfaces to within a short distance of shore. The aircraft has instruments that capture information at high resolutions and makes measurements at low elevations, which eliminates most atmospheric influence. Satellite-derived data is best used for open waters more than 1km away from shore, with relatively low suspended sediments. These limitations are caused by pixel loss due to land masking and cloud cover, interference from other water constituents, and other technical issues. See Sea WIFS and MODIS data documentation for details (http://daac.gsfc.nasa.gov/).

Q) How often can we get images of the bay?

A) Due to local atmospheric conditions (cloudy/smoggy days) a complete picture of the Bay is not obtained on every pass of a satellite-based ocean color instrument. The SeaWIFS instrument averages 5 - 9 unobscured images of the Bay per month, or 60 – 108 images per year. This is significantly more frequent than what can be done with the current ground surveys. Additionally, skies over the lower bay have more clear days; thus there is more imagery available for that region. The aircraft surveys have previously been conducting 20-30 complete coverage flights of the Bay per year.

Q) How do the aircraft-based and satellite-based images compare with spatially intensive ground monitoring?

A) Aircraft-based chlorophyll data are similar to the spatially intensive ground monitoring (horizontal *in vivo* fluorescence and Dataflow) chlorophyll data in that both types of data are collected along transects, over extended time periods. The NOAA funded aerial survey consists of 45 transects crisscrossing the Bay, over the course of a 10-hour day. Chlorophyll values for water areas not covered by over-flight tracks are determined by interpolating between the aircraft tracks. Similarly, the spatially intensive measurements made by the CBP monitoring programs are collected over an even long time span, sometimes more than five days. The data are grouped and analyzed as a single event, or "cruise," and interpolating between stations/transects generates images of surface chlorophyll for the Entire Bay. In both approaches, interpolation error and diel/tidal/weather-related changes can become large sources of variance in the information. Satellite-based ocean color images, on the other hand, are generated on a single instrument pass. The satellite carrying the SeaWIFS sensor orbits the earth every 90 minutes. The SeaWIFS sensor field of view is approximately 2,800 km (~1740 miles) in width, and the satellite photographs the entire Chesapeake Bay in less than a minute.

Q) What is the accuracy and precision of the chlorophyll measurements derived from remote sensing data?

A) At this time, the authors have been unable to compile error estimates for chlorophyll data for individual pixel readings obtained from the various ocean color instruments. An original performance goal for the SeaWIFS instrument was to produce water-leaving radiances with an uncertainty of 5% in clear-water regions and chlorophyll *a* concentrations within +/-35% over the range of 0.05-50 mg m^{-3} (Hooker and McClain 2000). The numerous SeaWIFS Post Launch documents demonstrate a high correlation (R^2 values) between remotely sensed and *in situ* chlorophyll (http://seawifs.gsfc.nasa.gov/SEAWIFS/TECH_REPORTS/). Table 3 below compares estimates of the *average* chlorophyll concentration for the Chesapeake Bay mainstem, between the Patuxent River and the Bay mouth, derived from SeaWIFS's third processing of raw ocean color data and from *in situ* measurements for three time periods. The high standard deviations in both data sets reflect the naturally high variability in surface chlorophyll *a* concentrations. The smaller standard errors of the SeaWIFS data indicate the SeaWIFS estimates for this Bay region are more precise. The SeaWIFS averages were consistently higher (+2% - +34%) than the *in situ* averages, putting into question the relative accuracy of the field and remotely sensed estimates. The difference, however, could reflect the higher resolution of the SeaWIFS data and its ability to detect patches of high chlorophyll concentrations rather than a calculation bias. Available journal articles pertaining to the University of Maryland aircraft survey's algorithm development suggest that use of seasonally specific algorithms improve accuracy (e.g., Harding *et al.* 1995). The determination of accuracy or lack of accuracy in remotely sensed data will ultimately decide if the Bay Program should use these data for management purposes.

Table 2. Average chlorophyll *a* (micrograms per liter) in the Chesapeake Bay mainstem, between the Patuxtent River and the mouth of the bay, derived from *in situ* measurements and SeaWIFS third processings of the raw remote sensing data. The standard deviation (σ), number of observations (n), and standard error, $\sigma/\sqrt{n}$, as % of the mean (SE) are given. (Source: Table 7 in Robinson *et al.* 2000).

	In Situ				SeaWIFS Third Processing			
Date	Mean	σ	n	SE	Mean	σ	n	SE
11-19 April 1998	11.93	11.31	91	±9.94%	16.01	7.96	1960	±1.12%
4-12 August 1998	10.83	10.61	89	±10.38%	11.06	3.71	1810	±0.79%
19-23 October 1998	7.43	4.08	67	±6.71%	7.96	2.97	2133	±0.81%

Q) The MODIS instruments seem to have a lot of products. Other than chlorophyll, are there any of interest to CBP?

A) MODIS instruments have a large number of new ocean color products, which may be of great value to the Bay Program in the future. These instruments have chlorophyll products derived with several new algorithms. New fluorescence products, which may be less subject to interference by organic matter and sediment in the water, will also be available to estimate chlorophyll concentrations and primary productivity. Several other products measure accessory plant pigments (e.g., Phycobilirubens) and may be useful in the detection of harmful alga blooms. (See Appendix B in Esaias *et al.* 1997, and http://daac.gsfc.nasa.gov/MODIS/products.shtml for more details).

Q) Is remote sensing data really free?

A) Data sets from the aircraft-based survey efforts are readily available in-house at the Chesapeake Bay Program Data Center. The SeaWIFS sensor is on a commercial satellite and the owner of the satellite has a 15 days exclusive use period after data collection, after which the data are made available for free to authorized scientific users. Data used for "non-scientific" applications must be purchased (SeaWIFS 2002). The Chesapeake Bay Program should not assume all of its potential applications of SeaWIFS imagery would be considered "scientific," and should apply to NASA for authorization to use SeaWIFS images for each potential project. Data sets from the MODIS instruments do not have the usage restrictions that SeaWIFS does. They are freely available to any registered user (MODIS 2002)

Potential Applications of Ocean Color Imagery to Chesapeake Bay Issues

There are an ever-increasing number of research papers being published that use ocean color for assessment of environmental conditions and ecological processes. The SeaWIFS program currently reports having over 1900 registered imagery users. While ocean color imagery in scales useful for estuary work is a relatively new data source, the gap between development of ocean color imagery applications and their use in routine monitoring and assessment is closing. For example, both the Massachusetts Water Resource Authority and Florida Department of Environmental Protection have incorporated remote sensing into their routine monitoring programs, and both programs currently use remote sensing to provide oceanographic data on a regional scale for surface temperature and chlorophyll monitoring. Both programs prominently feature SeaWIFS imagery on their web pages with image interpretations, and use chlorophyll imagery to track the temporal and spatial extents of plankton blooms.

Despite a history of investing in aircraft remote sensing, CBP partners have not fully utilized the available remote sensing data to monitor Bay ecosystem responses to nutrient reductions. A 1999 report reviewed the Chesapeake Bay chlorophyll monitoring efforts, including the NOAA/NASA sponsored aircraft-based monitoring program (Haas 1999). The report, entitled "Application and Integration of New Technology for the Chesapeake Bay Monitoring Program Development and Evaluation of CBOS, In vivo Fluorescence and Remote Sensing Data," advocated using remote sensing data for the detection of phytoplankton bloom frequency. The CBP subsequently did not implement the report's recommendations to utilize available ocean color resources, and has not incorporated the data into CBP routine monitoring and data analyses.

CBP Information Needs

Remote sensing of ocean color can provide high resolution data to address water quality and living resources habitat directives of the Chesapeake Bay 2000 (C2K) Agreement. Water quality assessments are prominent activities under the C2K Agreement's Water Quality goal to "achieve and maintain the water quality necessary to support the aquatic living resources of the Bay and its tributaries and to protect human health" (USEPA 2000b). The CBP partners have committed to improving open water areas by correcting nutrient- and sediment-related problems sufficiently to remove the Chesapeake Bay mainstem and the tidal portions of its tributaries from the Clean Water Acts list of impaired waters. Water clarity (light attenuation) and chlorophyll *a* are two of the three water quality parameters that will be used to determine if the Bay can be "delisted." Criteria are being developed that, if attained, will facilitate the restoration of healthy aquatic biological communities in Chesapeake Bay.

Monitoring information is needed to verify that criteria attainment is sufficiently improving habitat quality in Chesapeake Bay, and the restoration of healthy biological communities is possible. The CBP partners committed in the C2K Agreement to develop and implement multi-species fisheries management plans and ecosystem-based goals for targeted species and certain aquatic habitats (SAV beds, oyster reefs, fish passages). These plans and goals would be ill timed or even futile if water quality improvements were not having their intended effect on habitat quality. Actual habitat quality evaluations will determine if implemented nutrient and sediment reductions are meeting specific living resources habitat requirements as well as the CBP water quality criteria. These evaluations will allow managers to better gauge the ability of the recovering Chesapeake ecosystem to withstand fishing pressure and other anthropogenic impacts.

High-resolution data to support these CBP information needs can be provided by ocean color remote sensing. The CBPO Data Center is in the process of establishing the necessary computer infrastructure (computer hardware and software) and staff with expertise to use and interpret a variety of remotely sensed data. In this section, potential pilot studies are introduced which address specific CBP information needs. These pilot projects would test and refine the nascent abilities of the CBPO Data Center to utilize ocean color data, and would demonstrate the capabilities of this readily available source of existing monitoring information. It is hoped the suggested Chesapeake Bay applications of ocean color remote sensing will stimulate discussion in the Bay management community on the potential uses of frequent, high resolution, readily available remote sensing information.

Proposed Pilot Studies

Chlorophyll and Turbidity in Waters Adjacent to SAV Beds

One potential application for ocean color data (both chlorophyll and turbidity products) is determining species-specific habitat suitability and targeting restoration sites. It is technically feasible to use remote sensing data with available Habitat Suitability Model protocols to produce maps that identify and quantify suitable habitat for living resources. Habitat Suitability Models (HSM) generate their maps based on established species habitat requirements and gridded, high-resolution environmental data. These models have become heavily used in the assessment of habitat for finfish and commercially valuable invertebrates, but can also be used for non-commercial or lower trophic level species with clearly defined habitat requirements (Brown et.al. 2000). Many of the Bay's ecologically valuable aquatic species have habitat requirements for chlorophyll and turbidity. Previous efforts to identify and assess their habitat conditions have been hindered by the scarcity of chlorophyll and turbidity data in or near the geographic areas of interest. Both satellite and aircraft based imagery can provide some of the needed high-resolution data.

The Chesapeake Bay Program places great emphasis on the restoration and protection of SAV (USEPA 1992, USEPA 2000b). The program supported efforts to determine SAV habitat requirements in 1992 and 2000. These habitat requirements identify the minimal water quality conditions needed to promote the growth of SAV. The SAV habitat requirements were intended not only for the area of the SAV bed but also for adjacent areas that influences the bed. The original 1992 habitat requirements established thresholds for light attenuation, total suspended solids (TSS), chlorophyll, dissolved organic nitrogen (DIN), and dissolved organic phosphorous (DIP) during critical SAV growing periods for the Bay's various salinity regimes (USEPA 1992).

Evaluation of chlorophyll and turbidity levels near beds of submersed aquatic vegetation (SAV) would make a good test case for the use of remote sensing imagery in Chesapeake Bay. In 2001, NASA approved an application submitted by the Living Resources Data Manager to use SeaWIFS data for this purpose. K490 is a standard SeaWIFS product that quantifies light attenuation in surface waters. The potential use of K490 as an indicator of turbidity has been proposed in the literature (Joint and Groom 2000, Woodruff *et al.* 1999). The intent of this project is to use satellite-derived measurements of K490 (as a surrogate for Secchi depth) and chlorophyll to identify where and how often waters adjacent to nearshore habitats meet the SAV water clarity requirements during the critical SAV growing periods.

Comparison of Statistical Confidence in Interpolated and Remotely Sensed Surface Chlorophyll Data

The Chesapeake Bay Program currently uses fixed-station ship samples and the 3D Interpolator Model (http://www.chesapeakebay.net/cims/interpolator.htm) to generate chlorophyll estimates for the Bay's surface plane and 3D view (extrapolating to 238,669 cells). Ocean color remote sensing data could greatly enhance the spatial and temporal resolution of chlorophyll information in Chesapeake Bay if the accuracy and precision of remotely sensed chlorophyll estimates are equal to or better than that of interpolated chlorophyll estimates. The accuracy and precision of remote sensing chlorophyll estimates depends in part on the algorithms used to translate water leaving radiance. These algorithms may overestimate chlorophyll *a* in turbid coastal waters (e.g., Harding *et al.* 1995, Robinson *et al.* 2000). For example, in a comparison of matched 1998 data from the Chesapeake Bay mainstem below 38.5° N latitude, the average surface chlorophyll concentration derived from SeaWIFS pixels (third reprocessing) was between 2% and 34% higher than the overall average derived from *in situ* chlorophyll measurements (Table 3). However, the standard deviation and standard error around each average was consistently smaller in the remote sensing data.

A pilot study to compare error estimates for various sources of Chesapeake Bay surface chlorophyll data would help to determine if remote sensing data can be used to address CBP issues such as chlorophyll criteria attainment, a regulatory process requiring a high level of statistical confidence in the data. Specifically, the comparisons would determine for individual Bay segments whether ocean color remote sensing provides more accurate and precise estimates of surface chlorophyll than estimates interpolated from ship data. An initial analysis by Perry (2002) found surface chlorophyll error estimates in Interpolator model cells approached 29% as interpolator distance from a fixed station increased from 1 to 10 km. The pilot study could compare on a cell-by-cell basis the surface chlorophyll values obtained from a) ocean color remote sensing data, b) *in vivo* fluorescence transect data using the 3D Interpolator and c) fixed station data using the 3D Interpolator. Segment-based error estimates for surface chlorophyll could then be generated for data from each of the three data sources.

Given their high spatial resolution, remotely sensed data may also improve estimates of the total chlorophyll mass in the Bay. Chlorophyll mass is currently calculated from interpolated ship data alone and used as a response indicator of nutrient loads (http://noaa.chesapeakebay.net/data/interp1.htm). The pilot study could be expanded to compare estimates of total chlorophyll mass generated with ship data alone and with ship and ocean color data combined. The two types of data can be merged using the CBP 3D Interpolator Model. Surface cell estimates would be derived directly from remotely sensed pixel values, and subsurface estimates would be derived with interpolation from the combined remotely sensed surface data and the ship data depth profiles.

Monitoring Program Enhancement

Remote sensing data have the potential to significantly enhance routine monitoring of primary productivity, suspended solids, and dissolved and particulate organic matter as well as chlorophyll a and light attenuation. All of these parameters are currently monitored by CBP at fixed stations in open water habitats of Chesapeake Bay. Federal, state, and academic partners work extensively with these monitoring data to document status, trends, and responses to management actions. Additional, high-resolution data from remote sensing sources would improve the monitoring program's ability to detect, locate, and measure water quality responses to management actions. Some of the parameters above are also state variables in the Chesapeake Bay 3D Water Quality and ECOSYM/ECOPATH models, each important CBP tools used to investigate and forecast Bay water quality and ecosystem responses to management actions. Monitored values of these parameters are used to calibrate the model.

The SeaWIFS and/or MODIS instruments currently have products or evaluation products that estimate all the parameters above. A pilot study to determine if including the remote sensing data would significantly and cost-effectively enhance CBP monitoring programs is suggested. The study would a) review the comparability of shipboard data and ocean color remote sensing measurements of turbidity, suspended solids, primary production, dissolved and particulate organic matter, and b) examine the influence of adding remote sensing data on status and trend analysis results. NASA science teams and others in the remote sensing community have done similar comparison studies for other shipboard data sets. What is needed is a demonstration project focused on Chesapeake Bay Program data analysis requirements.

Program Start-up Costs and Requirements

A frequent criticism of remote sensing imagery is that data are expensive to buy, highly trained individuals are required to process and interpret the imagery, and expensive computer resources are needed to support the effort. These criticisms are not entirely true when dealing with satellite ocean color imagery. One of NASA's goals has been to make satellite ocean color imagery easy and affordable to use. In particular, the NASA SeaWIFS project has supported the development of free image processing software and subsidized user education to promote and expand the use of ocean color imagery in the scientific community. The actual imagery generated by the SeaWIFS instrument is free for scientific users and MODIS instrument is free for all users. Data from the NOAA sponsored aircraft remote sensing project in Chesapeake Bay are similarly available.

The bulk of the costs for users of ocean color data at the Chesapeake Bay Program will be incurred in personnel, personnel training and the hardware and software for image processing and utilization. Start-up costs, however, are probably within the scope of many Chesapeake resource agencies or institutions. For example, training and equipping the Living Resources Data Manager at the CBPO Data Center totaled about $8560. An itemized cost description is given in Appendix B.

General Recommendations

While some of these recommendations extend beyond the confines of ocean color data, they do address pressing data needs of the Chesapeake Bay Program that will arise in the next 5 to 10 years.

RECOMMENDATION: *Start using the available remote sensing data products as soon as possible to explore its potential for answering Chesapeake Bay management questions.* Three pilot studies are suggested in the report. These pilot studies should be conducted to evaluate the utility of the available ocean color products in addressing specific CBP information needs. CBP currently does not use satellite imagery of ocean color in a significant way. Apart from the SAV aerial survey, the Bay Program does not apply the currently available aircraft or satellite imagery to track Chesapeake ecosystem responses to management actions. Arguments that remote sensing image resolution is not perfect, the data are not close enough to shore, or the confidence intervals around the data values are not as good as ground monitoring data are loosing ground in the face of technological improvements. The data requirements of some CBP activities, including assessment of criteria attainment, may require spatial data that can only be generated by satellite or aircraft imagery. Furthermore, many species-specific habitat evaluations require spatially and temporally dense data. These are applications for which remote sensing images are ideal suited. The imagery holdings at Goddard Space Flight Center for ocean color, the Jet Propulsion Laboratory for ocean circulation, and the EROS Earth Observing Data Center for land data will become increasingly valuable. The Chesapeake Bay Program Data Center should establish working relationships with at least the three mentioned data centers for routine data product acquisition.

RECOMMENDATION: *Develop a core remote sensing team.* If the potential of remote sensing imagery is to be realized, a core team of analysts needs to be developed. The team should consist of individuals with expertise in different areas of remote sensing: Ocean Color, Land Cover, and Ocean Processes. The team would be composed of individuals from both the CBPO Data Center and the remote sensing community at large. These individuals located at the CBPO Data Center should coordinate with the existing GIS and database teams. They should not be dedicated exclusively to remote sensing data acquisition and processing, but also participate in the analysis and interpretation of the imagery and the integration of imagery-based information with ongoing monitoring and analysis efforts. Team members at the Data Center will need appropriate computer (hardware, software, computer maintenance) support. Ideally, the entire remote sensing team would be given well-defined assignments (i.e., specific questions to answer through the analyses of remote sensing data) that address carefully identified data needs of the CBP while receiving consistent Program management support.

RECOMMENDATION: *Establish an in-house collection or access to ready to use remote sensing ocean color images and data products for rapid application to Bay Program management questions.* Data from the aircraft-based remote sensing project in Chesapeake Bay are currently available through the NOAA Chesapeake Bay Program Office and Maryland Sea Grant Web sites. Satellite-derived ocean color data products are readily available through the NASA DAAC system. Currently at the CBP Data Center acquisition of SeaWIFS imagery is in progress as part of the SAV related pilot project. Plans should be made soon to acquire the SeaWIFS and MODIS data products for Chesapeake Bay if satellite remote sensing data are deemed useful in addressing time-sensitive CBP issues such as water quality criteria attainment and additional habitat assessment. These data are becoming relatively inexpensive for and end-user to obtain, but require time to download, process, and analyze. SeaWIFS is a good starting point from which to build an in-house data archive of Chesapeake Bay chlorophyll and turbidity imagery. The MODIS instrument will also be producing turbidity, chlorophyll, sea surface temperature and the cadre of other data layers that the fisheries modeling and habitat targeting efforts may need in the next 5-10 years.

RECOMMENDATION: *There is currently no demonstrated need for "real time" data sets. However if the proposed pilot projects demonstrate ocean color imagery to be a useful management tool, then avenues for obtaining this data should be explored.* Currently the Chesapeake Bay Program Partner agencies perform most of their environmental management in a retrospective manner. Thus there is currently little benefit to be gained from the acquisition of real time remote sensing products ocean color or otherwise. Near real time data does provide the potential to aid in harmful algae bloom detection and other rapid response applications, however this is not currently a focus of CBP monitoring efforts. The CBP Data Center and many of the active program partners lack the computer and staff resources to support this type of data acquisition. More importantly, the Bay Program does not currently have in place a mechanism to use real time information in its deliberations and actions. However if the proposed pilot project yield useful management tools, it might be productive to re-examine the acquisition and avenues for obtaining and using real time data in the future.

Appendix A: Detail Technical Background

Data Acquisition

Ocean color is created when visible light from the sun illuminates the ocean surface. The available light is subject to several optical effects including reflection and absorption. In the ocean, suspended particulate matter, dissolved organic material, phytoplankton, and the water itself selectively absorb and/or scatter some wavelengths of light while allowing the transmission of others. Light that is radiated back from the ocean surface has been altered as a result of these optical interactions. This returning radiance or water leaving radiance can be measured, and the quantitatively related to various constituents in the water column that interact with light. (SeaWIFS Readme 2000, Kirk 1994)

Whether satellite or aircraft mounted, a photometer/or radiometer is the primary instrument for measuring ocean color (Kirk 1994). While each ocean color instrument varies in the details of how data are collected, data collection occurs following these general steps. The photometer measures radiance intensity at specific wavelength bands. The measured radiance values at various wavelengths are recorded as pixels. The radiance value for a pixel represents an estimate of average radiance value of light at a given wavelength over an area of the ocean or earth surface. A typical radiometer will collect data as it passes over the earth's surface, at which point the data are either stored for later processing or transmitted directly to a receiving facility for processing. Data collected and immediately sent to a receiving facility is referred to as real-time data.

Data Processing

While it is not necessary to understand all the technical details of how satellite data are processed, it is important to have a general understanding of the general data processing steps. The NASA Earth Observing System (EOS) has developed a classification system for remote sensing data products based on the degree of processing applied to the data (Table A1). First, instrument telemetry is transformed into raw radiance values and any corrections for instrument calibration are applied (Level 1). Next, atmospheric corrections are applied to the radiance values, the data are geo-referenced, and geophysical data products are calculated. At this point, radiance values can then be converted into useful parameters such as chlorophyll (Level2). Subsequent processing involves projecting data into map coordinates (Level 3) before the data can finally be analyzed. The final level of data products are composited images or evalutations of lower level data products (Level 4) (ECSInfo 2002).

Level 0	Data at this level is raw instrument telemetry at full resolution.	
Level 1	Data at this level comes in two varieties.	
	Level 1A	Data consists of raw radiance measured at the satellite, and also includes calibration and navigational data along with selected instrument and spacecraft telemetry.
	Level 1B	Level 1A data that has been processed to sensor units. Many satellites do not distinguish between levels 1A and 1B.
Level 2	Data at this level are derived from the processing of Level 1 data. All the Geophysical variables at the same resolution as in the Level 1 set. Data has instrument calibrations and atmospheric corrections applied, and the data may have additional algorithms applied to generate estimated data values.	
Level 3	Data processing involves projecting level two data products into a map projection for further analysis.	
Level 4	The data derived at this level are products and images derived from analysis of imagery (i.e., - multi-day composite images, modeled data).	

Table A1. EOS Standard Data Level Classifications for Remote Sensing Data. (The Earth Observatory,2002b)

An important concept in processing and using of remote sensing data is the concept of resolution. The term resolution, as it is used here, refers to the size of the pixels as they relate to area on the face of the earth and the manner in which data are collected. For example, if a pixel has a 1-kilometer resolution, each pixel represents a 1-kilometer area on the ground/water surface. Ocean color data from a given instrument may be processed to several levels of resolution. Two commonly used imagery resolutions are Local Area Coverage (LAC) and Global Area Coverage (GAC) resolutions (Earth Observatory 2002).

The initial data collected by an instrument has the highest, or finest, resolution and is referred to as LAC data. Data resolution may be reduced as part of data processing by sub-sampling or averaging. Reduced resolution data is referred to as GAC data. With some ocean color instruments, data reduction to GAC occurs immediately after the radiance measurements are collected; with others it is part of a later processing step. For example, the SeaWIFS instrument samples at a 1 km resolution but subsamples its LAC data to create global coverage data sets with 4 km resolution (SeaWIFS Readme File 2000).

Processing ocean color data involves the application of numerous algorithms and mathematical relationships in order to address a variety of issues, including instrument calibration, satellite navigation, geolocation of measurements and atmospheric correction of radiance values. Extensive detail about these various corrections is not needed to understand how meaningful data products can be generated from raw radiance measurements. However, a general understanding of the process for deriving chlorophyll *a* and light attenuation products from raw measurements is helpful because the Chesapeake Bay, like other turbid coastal areas, presents special challenges (Ruddick *et al.* 2000, Woodruff *et al.* 1999, Joint and Groom 2000, Hu *et al.* 2000, Chuannmin *et al.* 2000).

When a satellite based instrument at the top of the earth's atmosphere measures radiance, the signal at any wavelength can be broken down into three major components: signal due to atmospheric interaction, signal due to sea surface interaction and signal due water leaving radiance (Equation A1).

Total Radiance = Radiance attributed to Atmospheric Interaction
+ Radiance attributed to Sea Surface Interaction
+ Water Leaving Radiance

Equation A1. A Generalized Equation for total radiance measured by a remote sensor at the top of the atmosphere (Kirk 1994).

Users of ocean color data are most interested in the signal due to water leaving radiance. Atmospheric interference and sea surface interaction make up the largest portion of the total radiance signal (Kirk 1994). Therefore, a major step in data processing is removing the 80% or more of the total radiance signal attributable to atmospheric and sea surface interactions. This removal process is referred to as atmospheric correction of data (Gordon *et al.* 1983, Siegel *et al.* 2000). The remaining radiance signal is attributed to water leaving radiance.

After water leaving radiances are derived, they can then be converted into products such as chlorophyll estimates using a variety of algorithms. Water leaving radiances are the product of the interactions of light with the water as well as light with constituents in the water column (Kirk 1994, SeaWIFS 2000). Constituents that most influence absorption and scattering of light are dissolved organic material (also referred to as Gelbstoffe), suspended material other than phytoplankton (sediment and detritus), and phytoplankton (Kirk 1994, Parsons *et al.* 1984). Water bodies are divided into two classes - Case 1 and Case 2 - based on which constituents influence their color the most (Figure A1).

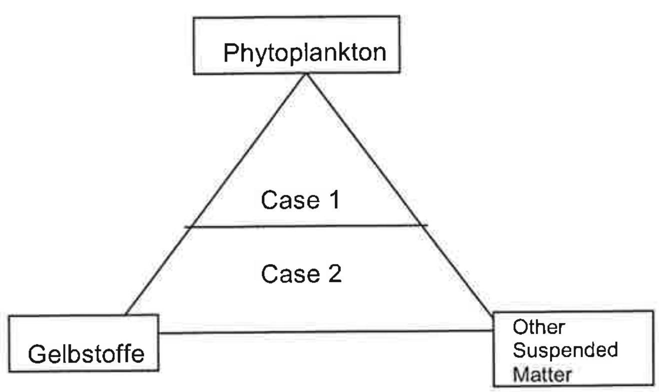


Figure A1. The Case Triangle. Each apex represents a major component controlling the color of natural waters.

Case 1 describes clear oceanic waters where most of the optical influence is due to phytoplankton and its by-products (e.g., cellular decay compounds). Case 2 waters are those where optical properties are dominated by or significantly influenced by constituents other than plankton. Coastal areas like the Chesapeake Bay are considered Case 2 waters because of their relatively high concentrations of dissolved organic matter and inorganic sediments.

The concept of Case 1 and 2 becomes important when interpreting water-leaving radiances. Each of these individual components (water, plankton, Gelbstoff and miscellanous suspended material) in natural waters has their own light absorption spectra. While there is overlap of spectra among constituents, characteristics of the individual spectra can be employed to determine the concentration of a given component in seawater. For example, phytoplankton-specific chlorophyll has its strongest absorption signatures at 400-515 nm and 515-600 nm (Parsons *et al.* 1984). Based on this optical characteristic of plankton, algorithms to estimate chlorophyll based on radiance measurements at these wavelength bands were established (Gordon *et al.* 1983, Hooker *et al.* 1993). The initial algorithms perform well in Case 1 waters but over estimate chlorophyll *a* in Case 2 waters where Gelbstoffe and other particulate materials also absorb light significantly at these wavelengths. Later ocean color instruments began to measure radiances for a larger number of narrow wavelength bands, allowing data processing algorithms to be refined for specific parameter as well as atmospheric correction (Esaias *et.al.* 1997). The additional bands have improved data accuracy in Case 2 waters. Still, the unique regional mixes of phytoplankton, organics and sediments in estuarine and near shore waters have made it difficult is to use a universal set of algorithms to estimate chlorophyll *a* concentrations. Thus, an active area of research has been the development or refinement of algorithms and special data processing protocols for chlorophyll *a* and other parameters for specific near shore and estuarine environments (see, for example, Harding *et al. 1995,* Woodruff *et al.* 1999).

Appendix B: Description of Project Startup Cost

Computer Software and Hardware Costs

SEADAS The primary software for the processing of ocean color imagery is SEADAS, designed by NASA. SEADAS is a comprehensive image analysis package for the processing, display, analysis, and quality control of all SeaWIFS data products and ancillary meteorological and ozone data. SEADAS also has incorporated in it the capabilities for viewing and partial processing of CZCS, ADEOS / OCTS and MOS data. SEADAS currently supports only the display of MODIS Ocean Products as well as AVHRR SST files. SEADAS will convert the processed imagery in to a limited number of images (Postscript, GIF, and TIFF) and data (ASCII, HDF SD and binary flat file) output formats. SEADAS is distributed at no cost to the user. The software requirements to run SEADAS are as follows:

Operating Systems:	SGI: IRIX 6.3 or 6.5, SUN: Solaris 2.6 or 2.7, PC: Red Hat LINUX 6.0, 6.2, 7.0, or 7.1
Optional Software:	IDL 5.3 or IDL 5.4
Optional Compiler:	C, FORTRAN (required if desire to compile from scratch
Software Libraries:	HDF 4.1r1 (included in SEADAS)

The processing and use of ocean color is done primarily on the UNIX operating system platforms due to a wide array of technical computing issues. The computer hardware specifications for running SEADAS are very flexible and affordable since LINUX implementations of SEADAS are being supported. (LINUX is a PC based UNIX implementation). A PC based LINUX system capable of running the required software and the NOAA CBPO office purchased process and store imagery in December of 2001 for approximately $4000.00. (Dell Precision 330, Pentium 4, 1.4 GHz Processor, 511 MB RAM)

IDL (Interactive Data Language) IDL is the parent application in which SEADAS is written. SEADAS comes with a runtime IDL license and does not require a full IDL license to run the application. However to an IDL license is required to run SEADAS in the batch mode. Batch mode is used for serial processing of a large number of images. It is also a convenient tool for imagery manipulation and analysis after SEADAS processing. IDL can also be used to manipulate a variety of imagery formats other than those used for ocean color. An IDL license for the LINUX OS, is currently priced at $1895.00 (plus $100.00 for a software documentation set). The NOAA CBPO office purchased a single license in December of 2001. IDL licenses under other implementations of UNIX are significantly more expensive. (Please consult www.ResearchSystems.com for more details).

REDHAT Processing Ocean color data is a computing application still firmly rooted in the world of the UNIX computer operating system. The LINUX version of SEADAS has enabled the processing and use of imagery to occur on cheaper readily available personal computer hardware. Current retail price for version 7.1 of REDHAT LINUX is $59.95.

ACCESSORY SOFTWARE There are a few additional pieces of software one needs in order to acquire and use remote sensing data above and beyond SEADAS and IDL. Most of the additional software is available at low or no cost. In particular one will need a web browser such as Netscape, an FTP Client, EMAIL client, text editor, C compiler and simple graphics utilities. Most of these base utilities are bundled with UNIX operating system distributions.

HARDWARE The recommended hardware platform requirements for running the basic image processing software are as follows:

Hardware Platform:	SGI O2, SUN UltraSPARC workstations or PC
Computer Memory:	192MB (regular user), 384 (HRPT user)
Hard Disk Space:	9 GB -The actual SEADAS installation requires about 330 MB without demo files and 950 MB with demo files. The embedded IDL runtime

	feature will require an additional 130-MB. A large amount of disk space is suggested for storing data.
Tape Drive:	4 MM (DAT) or 8 mm Exabyte (for data from DAAC)
Display:	19" Console or X-terminal with 20-MB memory, 1280x1024 resolution, 8-bit, 256 colors

Personnel Training Costs

BASIC TRAINING Obtaining the basic training to use remote sensing data is costly. There are a variety of ways to obtain ocean color training; most of their programs have a large number of academic prerequisites. The month long "Introduction to Remote Sensing" course taken by the Living Resources Data Manager in 2000 had a listed tuition of $4,000 without travel and selected lodging expenses. (NOTE: Tuition costs were decreased to $2500 after academic scholarships were awarded). This six-credit college course covered the science of ocean color and the basics of SEADAS data processing and IDL programming. This course had been developed in conjunction with the NASA SEAWIFS program. Several remote sensing courses are offered at the University of Maryland, however they do not specifically focus on ocean color. Courses at UMD cost approximately $1400 per three-credit course. Additional programming training from RSI, the manufacturer of the IDL software, costs $1500 a week per course. It is undetermined at this time what, additional training may be required.

Total Estimated Start-up Costs

The total cost of starting an ocean color effort at the CBPO office to-date is shown in Table 4. Overall, ocean color is an inexpensive area in which to start working in remotely sensed imagery. While in the future there may be additional costs including the purchasing of more network or hard drive storage space for imagery and training, much of the initial cost to start an ocean color program at the Chesapeake Bay Office has already been expended to date.

Table B1. Start-up costs expended by the CBPO Data Center to develop the capability to obtain, process and use ocean color data to date.

ITEM	COST
SEADAS	FREE
REDHAT	$59.95
IDL	$1895.00
PC	$4000.00
TRAINING	$3000.00
Grand Total	**$8559.95**

Note: personel salary for the analyst to work on the ocean color data and the computer support for the UNIX system is not included because remote sensing work is being done by current staff as part of their existing duties.

Appendix C: Technical Overview of Potentially Valuable Satellite Based Ocean Color Instruments.

Satellite Description: SEAWIFS

SeaWIFS was launched August 1, 1997 by a Pegasus XL launch vehicle. Data acquisition commenced on September 4, 1997. SeaWIFS acquires approximately 15 pole-to-pole orbital swaths of data per day, and approximately 90% of the ocean surface are scanned every two days. SeaWIFS has seven standard data products: Normalized water-leaving radiance at 412, 443, 490,510, 555, and 670 NM; Chlorophyll a concentration; K (490); Angstrom coefficient, 510-865 NM; Epsilon of aerosol correction at 765 and 865 NM; and Aerosol optical thickness at 865 NM.

Nominal orbit parameters for the OrbView-2 satellite:

Orbit	Sun synchronous
Nominal altitude	705 km
Equator Crossing	Noon +/ 20 min., descending node
Inclination	98 deg 12 min
Orbital Period	98.9 min

Nominal operating parameters for SeaWIFS:
(LAC stands for Local Area Coverage; GAC stands for Global Area Coverage)

Scan Width	58.3 deg (LAC); 45.0 deg (GAC)
Scan Coverage	2,800 km (LAC); 1,500 km (GAC)
Pixels along Scan	1,285 (LAC); 248 (GAC)
Nadir Resolution	1.13 km (LAC); 4.5 km (GAC)
Scan Period	0.167 seconds
Tilt	-20, 0, +20 deg
Digitization	10 bits

Nominal radiometric parameters for SeaWIFS:

Band	Center Wavelength (NM)	Primary Use
1	412 (violet)	Dissolved organic matter (incl. Gelbstoffe)
2	443 (blue)	Chlorophyll absorption
3	490 (blue-green)	Pigment absorption (Case 2), K(490)
4	510 (blue-green)	Chlorophyll absorption
5	555 (green)	Pigments, optical properties, sediments
6	670 (red)	Atmospheric correction (CZCS heritage)
7	765 (near IR)	Atmospheric correction, aerosol radiance
8	865 (near IR)	Atmospheric correction, aerosol radiance

Bands 1-6 have 20 NM bandwidth; bands 7 and 8 have 40 NM bandwidth.

Notes: Gelbstoffe (German for "yellow substance") describes amorphous, high molecular weight organic matter with a somewhat polymeric nature. It absorbs strongly in the blue region of the spectrum.

The term "Case 1" (and also "Case 2") refers to a water "type" defined by optical characteristics. Case 1 water is clear, open-ocean water, and Case 2 is generally coastal, higher productivity, turbid water.

K (490) is the diffuse attenuation coefficient at 490 NM, a measure of optical clarity.

SeaWIFS Ocean Parameters

The following are the SeaWIFS ocean parameters. The data products are available for these parameters.

#	Parameter Name	Units
1	Normalized water-leaving radiance at 412 nm	W/m2/um/sr
2	Normalized water-leaving radiance at 443 nm	W/m2/um/sr
3	Normalized water-leaving radiance at 490 nm	W/m2/um/sr
4	Normalized water-leaving radiance at 510 nm	W/m2/um/sr
5	Normalized water-leaving radiance at 550 nm	W/m2/um/sr
6	Normalized water-leaving radiance at 670 nm	W/m2/um/sr
7	Diffuse Attenuation at 490 nm	1/M
8	Aerosol optical thickness at 865 nm	Non-dimensional
9	Angstrom Coeffcient from 510 to 865 nm	Non-dimensional
10	Epsilon Aersol Correction at 765 and 865 nm	Non-dimensional
11	Chlorophyll-a concentration (OC4)	Mg/M3

Additional Available Parameters of Potential Interest

#	Parameter Name
10	NDVI –Vegetation Index
11	Cloud Depth and cloud fraction
12	Colored dissolved matter/detritus
13	PAR-Photosynethically Active Radiation
12	Aerosol Index

Tables based on following souce

1)

2) Frederick S. Patt , Michael Darzi , James K. Firestone, Brian D. Schieber , Lakshmi V. Kumar , and Douglas A. (11 May 2000) "SeaWiFS-OPERATIONAL ARCHIVE PRODUCT SPECIFICATIONS Version 4.0" SeaWiFS Project, Code 970.2, NASA Goddard Space Flight Center

Satellite Description: MODIS

The MODIS is one of several instruments on board the NASA's Earth Observing System (EOS), Terra which launched on December 18, 1999, and began collecting science data on February 24, 2000. MODIS has a viewing swath width of 2,330 km and views the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands between 0.405 and 14.385 NM, and it acquires data at three spatial resolutions -- 250m, 500m, and 1,000m.

Along with all the data from other instruments on board the Terra spacecraft, MODIS data are transferred to ground stations in White Sands, New Mexico, via the Tracking and Data Relay Satellite System (TDRSS). The data are then sent to the EOS Data and Operations System (EDOS) at the Goddard Space Flight Center. After Level 0 processing at EDOS, the Goddard Space Flight Center Earth Sciences Distributed Active Archive Center (GES DAAC) produces the Level 1A, Level 1B, Geolocations and cloud mask products. Higher-level products are produced by the MODIS Adaptive Processing System (MODAPS), and then are parceled out among three DAACs for distribution. There are 44 standard MODIS data products that scientists are using to study global change. Global products are being produced for 8-day periods at 4.6-km resolution. These products are being used by scientists from a variety of disciplines, including oceanography, biology, and atmospheric science.

Nominal orbit parameters for the Terra satellite:

Orbit	Sun synchronous
Nominal altitude	705 km
Equator Crossing	10:30 a.m. descending node
Inclination	Near-Polar, Circular
Orbital Period	

Nominal operating parameters for MODIS:
(LAC stands for Local Area Coverage; GAC stands for Global Area Coverage)

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, focal (collimated), with intermediate field stop
Size:	1.0 x 1.6 x 1.0 m
Weight:	228.7 kg
Power:	162.5 W (single orbit average)
Data Rate:	10.6 Mbps (peak daytime); 6.1 Mbps (orbital average)
Quantization:	12 bits
Spatial Resolution:	250 m (bands 1-2) 500 m (bands 3-7) 1000 m (bands 8-36)
Design Life:	6 years

Nominal radiometric parameters for MODIS:

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud/Aerosol Boundaries	1	620 – 670	21.8	128
	2	841 – 876	24.7	201
Land/Cloud/Aerosol Properties	3	459 – 479	35.3	243
	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/ Phytoplankton/ Biogeochemistry	8	405 – 420	44.9	880
	9	438 – 448	41.9	838
	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 Water Vapor	17	890 – 920	10.0	167
	18	931 – 941	3.6	57
	19	915 – 965	15.0	250

Nominal radiometric parameters for MODIS continued:

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required NE[delta]T(K)[4]
Surface/Cloud Temperature	20	3.660 - 3.840	0.45(300K)	0.05
	21	3.929 - 3.989	2.38(335K)	2.00
	22	3.929 - 3.989	0.67(300K)	0.07
	23	4.020 - 4.080	0.79(300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	0.25
	25	4.482 - 4.549	0.59(275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16(240K)	0.25
	28	7.175 - 7.475	2.18(250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58(300K)	0.05
Ozone	30	9.580 - 9.880	3.69(250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05
	32	11.770 - 12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25
	34	13.485 - 13.785	3.76(250K)	0.25
	35	13.785 - 14.085	3.11(240K)	0.25
	36	14.085 - 14.385	2.08(220K)	0.35

1 Bands 1 to 19 are in nm; Bands 20 to 36 are in μm
2 Spectral Radiance values are (W/m2 -μm-SR)
3 SNR = Signal-to-noise ratio
4 NE (delta) T = Noise-equivalent temperature difference

MODIS Ocean Parameters

The following are the MODIS ocean parameters. The data products are available for these parameters.

#	Parameter Name	Units
1	Normalized water-leaving radiance at 412 nm	W/m2/um/sr
2	Normalized water-leaving radiance at 443 nm	W/m2/um/sr
3	Normalized water-leaving radiance at 488 nm	W/m2/um/sr
4	Normalized water-leaving radiance at 531 nm	W/m2/um/sr
5	Normalized water-leaving radiance at 551 nm	W/m2/um/sr
6	Normalized water-leaving radiance at 667 nm	W/m2/um/sr
7	Normalized water-leaving radiance at 678 nm	W/m2/um/sr
8	Aerosol optical thickness at 865 nm	non-dimensional
9	Epsilon of aerosol correction at 765 and 865 nm	non-dimensional
10	Aerosol model identification number 1	non-dimensional
11	Aerosol model identification number 2	non-dimensional
12	Epsilon of clear water aerosol correction at 531 and 667 nm	non-dimensional
13	Chlorophyll-a + pheopigment (fluorometric, empirical)	mg/m3
14	Chlorophyll-a concentration (HPLC, empirical)	mg/m3
15	Total pigment concentration (HPLC, empirical)	mg/m3
16	Chlorophyll fluorescence line height	W/m2/um/sr
17	Chlorophyll fluorescence baseline	W/m2/um/sr
18	Chlorophyll fluorescence efficiency	non-dimensional
19	Total suspended matter concentration in ocean	g/m3
20	Pigment concentration in coccolithophore blooms	mg/m3
21	Detached coccolithophore concentration	1/m3
22	Calcite concentration	mgC/m3
23	Diffuse attenuation coefficient at 490 nm	1/m
24	Phycoerythrobilin concentration	1/m
25	Phycourobilin concentration	1/m
26	Chlorophyll-a concentration (SeaWIFS analog – OC3M)	mg/m3
27	Chlorophyll-a concentration (semianalytic)	mg/m3
28	Instantaneous photosynthetically available radiation	Ein/m2/sec
29	Instantaneous absorbed radiation by phytoplankton for fluorescence	Ein/m2/sec
30	Gelbstoffe absorption coefficient at 400 nm	1/m
31	Phytoplankton absorption coefficient at 675 nm	1/m
32	Total absorption coefficient at 412 nm	1/m
33	Total absorption coefficient at 443 nm	1/m
34	Total absorption coefficient at 488 nm	1/m
35	Total absorption coefficient at 531 nm	1/m
36	Total absorption coefficient at 551 nm	1/m

Sea Surface Temperature

#	Parameter Name	Units
D1	Sea surface temperature (daytime), 11 micrometer	degrees Celsius
D2	Sea surface temperature (daytime), 4 micrometer	degrees Celsius
N1	Sea surface temperature (nighttime), 11 micrometer	degrees Celsius
N2	Sea surface temperature (nighttime), 4 micrometer	degrees Celsius

MODIS Ocean Parameters

Ocean Primary Productivity

#	Parameter Name
1	Behrenfeld-Falkowski primary production index (semi-analytical model)
2	Howard-Yoder-Ryan primary production index (semi-analytical model)
P	Ocean carbon primary production (statistical model)
N	New nitrogen production (statistical model)
X	Export carbon production (statistical model)
C	Annual chlorophyll-a concentration (semianalytic)
E	Photosynthetically available radiation
D	Mixed-layer depth

Note these Level 4 model-derived products.

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