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SYSTEM CONCEPT FOR WIDE-FIELD-OF-VIEW OBSERVATIONS OF OCEAN PHENOMENA FROM SPACE

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SYSTEM CONCEPT FOR WIDE-FIELD-OF-VIEW OBSERVATIONS OF OCEAN PHENOMENA FROM SPACE

REPORT OF THE JOINT EOSAT/NASA
SeaWiFS WORKING GROUP

AUGUST 1987

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SUMMARY

Satellite-acquired ocean-color and sea-surface-temperature data are powerful tools for understanding biological and physical processes in the ocean on a global scale. From 1978 to 1986, the Coastal Zone Color Scanner (CZCS) aboard the Nimbus-7 satellite provided the first ocean-color data. During this period researchers demonstrated that these data can be used to determine the abundance of ocean biota. As a result, many commercial, operational, and research applications were developed that take advantage of the direct relationship of the ocean's color to its phytoplankton content.

Also, data from the long-wavelength infrared bands of the Advanced Very-High Resolution Radiometer (AVHRR) aboard the NOAA series of satellites have proven useful in developing global maps of sea-surface temperature. Used jointly, these data have given new insights into the role of the oceans in our biosphere as well as providing economic benefits to several major industries.

This work demonstrates the need for an operational spaceborne sensor that would provide data on ocean color and sea-surface temperature simultaneously. Since the CZCS has become nonoperational, this need has become acute. Recognizing the importance of satisfying this need and the opportunity for incorporating such a sensor on the Landsat-6 spacecraft, NASA, Headquarters and EOSAT convened a SeaWiFS[1] Working Group in early 1987 to:

- *Discuss and document commercial, operational, and research applications for wide-field-of-view ocean-color imagery from the Landsat-6 satellite,*
- *Define users' requirements for sensor performance and for data products and dissemination, and to*
- *Determine the feasibility of meeting the users' requirements with respect to sensor design, accommodation of the sensor on the Landsat-6 satellite, data collection and distribution, and necessary spacecraft and ground-station interfaces.*

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1 Sea-viewing, Wide-Field-of-View Sensor

The Working Group was organized into three panels, representing commercial and operational users of oceanographic data, research users, and those responsible for implementing the system.

The Need for Ocean-Color Data

The Commercial and Operational Users' Panel identified two principal user groups. The first comprises the 36,000 - 37,000 ocean-going vessels engaged worldwide in fishing and marine transportation and U.S. Navy vessels. The second, smaller user group comprises the value-added and offshore oil and gas exploration and development industries.

Ships at sea need the ocean-color data to:

- *Locate fish populations, thereby improving catch efficiency, and to*
- *Optimize ship routes, thereby reducing costs.*

Oil and gas exploration and development industries need the data to:

- *Provide an accurate and detailed understanding of the oceanographic environment for offshore platform design, reducing the risks attendant to underdesign,*
- *Determine "weather windows" when offshore operations, such as shipping supplies, pipelaying, and platform installation, can be conducted most safely and efficiently, and to*
- *Provide timely information on strong current jets and eddies, since these can cause a loss of drilling time due to increased loads on the drilling riser.*

The value-added industry needs ocean-color data to support all of the above applications in providing interpreted data products to its clients.

The Research Panel documented a number of important research goals that could be reached only through continued availability of ocean-color data. These goals are to:

- *Specify quantitatively the ocean's role in the global carbon cycle and other major biogeochemical cycles,*
- *Determine the magnitude and variability of annual primary production by marine phytoplankton on a global scale,*
- *Understand the fate of fluvial nutrients and their possible effect on carbon budgets,*
- *Elucidate the coupling mechanism between upwelling and large-scale patterns in ocean basins,*
- *Answer questions concerning the large-scale distribution and timing of spring blooms in the global ocean,*
- *Acquire a better understanding of the processes associated with mixing along the edge of eddies, coastal currents, western boundary currents, etc., and to*
- *Acquire global data on marine optical properties.*

Supporting Research Requirements

Several types of supporting research were defined by the users' panels to fully implement the applications defined by the commercial and operational users and to realize research goals. The following objectives of some ongoing projects from the Navy's Research Program represent the type of research required to support future commercial and operational applications:

- *Develop general water-mass classification by coupling satellite-derived bio-optical data with sea-surface temperature data.*
- *Study the biota using ocean-color properties.*
- *Develop thermodynamic ocean models, including the absorption of solar heat by the oceans. (The absorption in the near-surface layer and the dissipation of this heat are partially controlled by the diffuse attenuation coefficient, k, of the water, measurable from SeaWiFS data.)*
- *Examine ways of using data on integrated aerosol distribution, which would be obtainable from SeaWiFS data.*

Three initiatives are proposed in the mission-support science plan for achieving oceanographic-research goals:

- *A sequence of cooperative international studies using high-resolution ocean-color observations of an ocean basin to address stratified sampling issues*
- *An expanded effort to improve bio-optical relationships for the SeaWiFS band set and to develop and verify a physiologically based algorithm for productivity estimates*
- *A global collection of SeaWiFS observations and production of composite moderate-resolution maps of pigments and primary productivity.*

User Requirements and Performance Goals

Although the users' panels readily agreed on most requirements and sensor performance goals, three issues were debated at some length: revisit interval, number and location of the spectral bands, and data-dissemination requirements.

The revisit-interval issue centered on assessing the value of data acquired at scan angles larger than about 30° to the two user communities since, currently, atmospheric effects make quantitative interpretation of these data infeasible. The research users, whose interests lie in quantitative interpretation, were satisfied with the first SeaWiFS design that had a ±45° scan angle, providing every-other-day global coverage at the equator. However, the commercial and operational users demonstrated the great value of qualitative interpretation of imagery at scan angles greater than 45° for their uses and the need for daily revisits to the same scene location. Since the effect on sensor design was slight, it was agreed that the baseline design would have a ±58° scan angle in order to provide a daily revisit interval.

The baseline SeaWiFS spectral bands and radiometric performance requirements given in Table A-1 represent a consensus that balances the needs of both commercial and operational and research data users. Other important operating characteristics of the sensor are also presented in the table.

With respect to the data dissemination issue, most commercial and operational users need to receive data once a day within 24 hours or less of the time of acquisition, and major user groups require daily, real-time reception. For example, the commercial fishing fleet needs to receive the data in near real time with relatively inexpensive equipment that is small in size, implying reception by a nondirectional antenna. Potential naval use would require daily, real-time reception in a format compatible with their systems (e.g., the Tactical Environmental Support System (TESS) and/or the AN/SMQ-11 receiver-recorder sets). A number of applications envisioned by the value-added industry

Table A-1. SeaWiFS Baseline Spectral Regions and Performance Goals

Parameter		Goal	
Band	Bandwidth	Minimum Signal-to-Noise Ratio[1]	Minimum Noise-Equivalent Temperature Difference
1	433 - 453 nm	510	
2	490 - 510 nm	500	
3	555 - 575 nm	350	
4	655 - 675 nm	285	
5	745 - 785 nm[2]	280	
6	843 - 887 nm	280	
7	10.5 - 11.5 μm		0.29K (300K)
8	11.5 - 12.5 μm		0.29K (300K)

Spatial Resolution:	1.13 km, inherent sensor resolution [Local area coverage (LAC)] 4.5 km, synthesized on board [Global area coverage (GAC)]
Polarization Sensitivity:	≤ 2% (worst case)
Dynamic Range:	10 bits quantization (gain adjustable on board)
Bright Target Recovery:	10 samples or less
Scan Plane Tilt:	± 20°
Orbit:	705 km, circular, polar, sun-synchronous
Equatorial Crossing Time:	10:30 a.m. (acceptable between 10:30 a.m. and 1:30 p.m.)

[1] H. R. Gordon 1987: personal communication. The signal-to-noise values must be met at all sun angles.
[2] Blocked from 760 to 770 nm.

will also require daily access to the stored data that is downlinked to the EOSAT ground-processing facility within 24 hours of their acquisition.

Researchers will use the data downlinked to the EOSAT ground-processing facility after it is transferred to the NASA/GSFC facility. Occasionally, quick-look data products for selected areas will be required within 12 hours of collection for positioning research vessels. However, for the most part, research needs will be satisfied if the raw data are available within 7 days of acquisition and other data products are available within 8 to 10 days of collection.

Implementation of Requirements

The purpose of the Implementation Panel was to translate the mission objectives of the commercial, operational, and research users into a workable system concept that would provide the data required to meet the users' needs. The work of this panel supported the other panels by defining the technical tradeoffs among the performance parameters and by identifying the practical consequences of various options in terms of cost and complexity. Thus, the Implementation Panel established a feasibility envelope for the Working Group, leading to a system concept that was not only useful from the users' perspective, but also technically and economically realizable.

Sensor Design Concept

The baseline SeaWiFS design, meeting all desired sensor requirements, is shown in Figure A-1.

The sensor concept is based on low-cost, low-risk technology and results in a lightweight and compact instrument. In the proposed design, the telescope rotates 360° about a pivot axis to scan the scene, thereby avoiding the use of a scan mirror and its associated polarization effects. Specular sun reflection is avoided by tilting the telescope in the plane perpendicular to the scan plane (i.e., along track) to one of three positions: +20°, 0°,

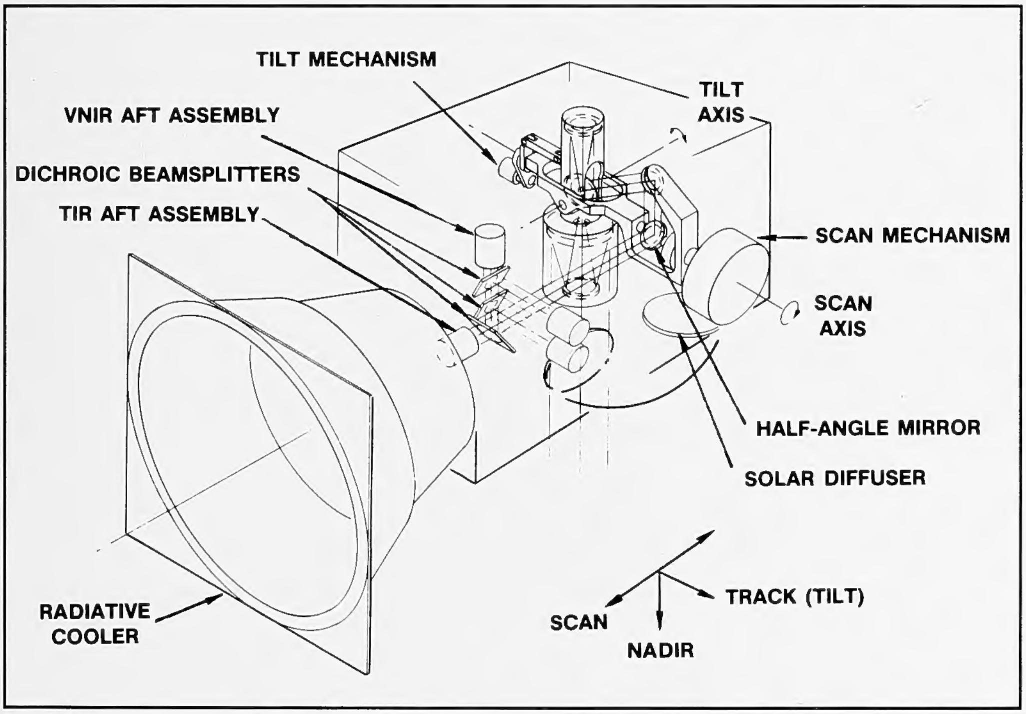


Figure A-1. Baseline SeaWiFS design.

or -20°. The continuous 360° scan allows reference sources to be viewed during the non-scene-viewing part of the scan, as well as allowing a deep space view for a zero reference just before the scan begins. There is also a solar diffuser that can be inserted into the field of view of the sensor for calibration against the input solar radiance.

Expected Sensor Performance

Estimates of three key performance parameters were made: radiometric performance, modulation transfer function (MTF), and polarization sensitivity. The expected radiometric performance, shown in Table A-2, meets the performance goals established by the user groups.

The MTF was calculated at the Nyquist angular frequency of 0.313 cy/mrad. The results indicate that the VNIR MTF will be 0.36 in the scan direction and 0.57 in the track direction; TIR MTF will be 0.34 and 0.53 in the scan and track directions, respectively. These values correlate well with the nominal rule for sensor design that the MTF should equal or exceed 0.3 at the Nyquist frequency; again, there is performance margin relative to the user requirements.

For the SeaWiFS, the polarization sensitivity depends on the scan angle, since the major contributor is the half-angle mirror. Figure A-2 shows the estimated polarization sensitivity of the SeaWiFS as a function of scan angle at a wavelength of 443 nm and that it always remains within the 2% desired limit. Moreover, the 443 nm data represent the worst case; polarization effects are smaller in all other bands.

Table A-2. SeaWiFS Estimated Radiometric Performance

Band	Saturation Radiance[1] (nW/cm^2-sr-μm)	Signal Radiance[1] (nW/cm^2-sr-μm)	Signal-to-Noise Ratio	Noise-Equivalent Temperature Difference[2] (K)
1	12.0	10.3	692	
2	9.0	7.5	703	
3	7.5	5.2	610	
4	3.8	2.8	507	
5	2.7	2.0	552	
6	1.9	1.4	589	
7				0.29
8				0.29

[1] H. R. Gordon 1987: personal communication.
[2] At 300K.

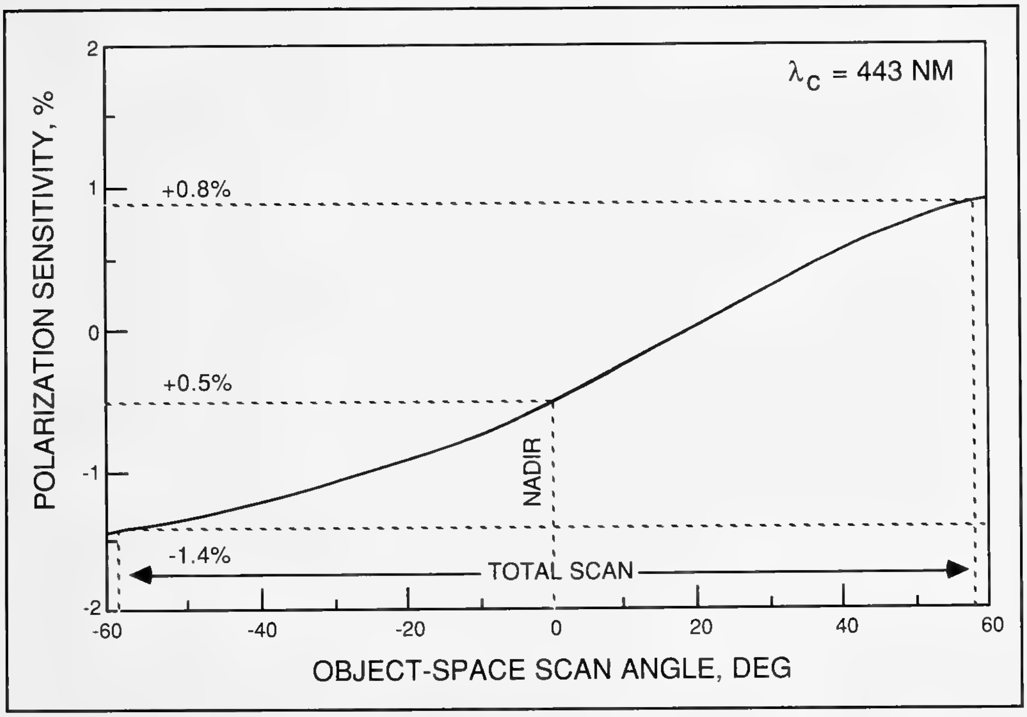


Figure A-2. SeaWiFS estimated polarization sensitivity.

Spacecraft and Ground Segment

The current spacecraft configuration into which the SeaWiFS sensor would be integrated, differs from the original Landsat-6 spacecraft configuration due to programmatic changes and changes in the launch vehicle. The spacecraft concept is derived from a DMSP/TIROS-type system, but it has been extended to meet the EOSAT mission's needs. The projected SeaWiFS subsystem weight of 153 pounds is well within the 360 pounds available for growth in the proposed spacecraft. Hence, the spacecraft can support the SeaWiFS mission and may also be able to satisfy an EOSAT goal of adding a third, spare wideband recorder for the Enhanced Thematic Mapper (ETM) data.

One of the key spacecraft limitations encountered in accommodating both the SeaWiFS mission and ETM mission on Landsat-6 lies in the power subsystem. These power constraints, which will affect mission operations (particularly with respect to nighttime operations) are currently being examined in a System Integration Study, sponsored by EOSAT. Some compromises in the ETM and SeaWiFS tasking profiles may be necessary to accommodate the SeaWiFS. However, if the required compromises are unacceptable, expansion of spacecraft power resources will be addressed.

SeaWiFS data will be acquired for, nominally, 40 minutes per orbit. Current plans and power budgets call for daylight-only imaging, but nighttime imagery might be acquired occasionally for experimental purposes. During imaging, SeaWiFS data will be transmitted in real time and recorded on on-board tape recorders. By combining the spacecraft-support resources for the SeaWiFS and ETM sensors and extending the capacity of the command/telemetry tape recorders, the eight orbits of data storage required for data collection outside the reception range of the EOSAT ground station can be acquired, and all stored data can be downlinked to a single facility.

On-Board Data Processing

The sensor's data stream will be formatted and the spacecraft's time code and ephemeris data incorporated into the format prior to recording or transmitting data. The attitude of the spacecraft (pitch, roll and yaw) will be reported with a within-limits flag.

Data Downlinks

Three downlinks are currently planned for SeaWiFS data. One would be a stored-data downlink that would provide the global area coverage and local area coverage data to the EOSAT ground receiving facility. These data would be downlinked directly on the X-band.

Another downlink would convey real-time, high-resolution LAC data at a frequency compatible with currently operating high-resolution picture transmission (HRPT) receiving stations and planned naval AN/SMQ-11 stations (L-band or S-band). The baseline direct-downlink data format is similar to the TIROS-N HRPT frame format. It provides the proper synchronization blocks for the hardware while still transmitting all of the required data at an effective data rate of 665 kbps.

The third downlink would convey real-time, low-resolution GAC data to subscribers on a UHF frequency. These data would be transmitted at 56 kbps, allowing some subscribers (e.g., moderately sized ships at sea that cannot mount large, tracking, dish antennas) to use relatively inexpensive, commercially available receivers and fixed receiving antennas.

The data for real-time transmission will be provided on a subscription basis. They will be encrypted by the SeaWiFS Data Formatter to protect their commercial value; decoding keys will be furnished to subscribers in a manner similar to those furnished to subscribers of television services. No tape-recorded data will be available on either real-time downlink.

The Implementation Panel recognized that reception of high-resolution LAC data is also desired by users restricted to unsophisticated receiving stations. However, transmitting high-resolution data to a fixed antenna would require much greater power in the spacecraft transmitter than is available on the currently envisioned Landsat spacecraft. Adding the required power would not only be costly, but also might exceed the weight limitations of the spacecraft. One potential solution to this problem would be to process the 1.13-km recorded data immediately upon receipt by the ground-receiving site, redistributing the data products via radio facsimile or telecommunications links.

The desire of some users to have near-real-time access to a global data set presents a greater problem, since the current data-handling plans for the tape-recorded global data set do not allow real-time access. However, a study is being undertaken to determine the feasibility and cost of rerouting the X-band, downlinked global data set via communication links to the processing facilities of commercial and operational users.

Data Products For Research Users

The following data products will be produced at NASA/GSFC within 8 to 10 days of data acquisition:

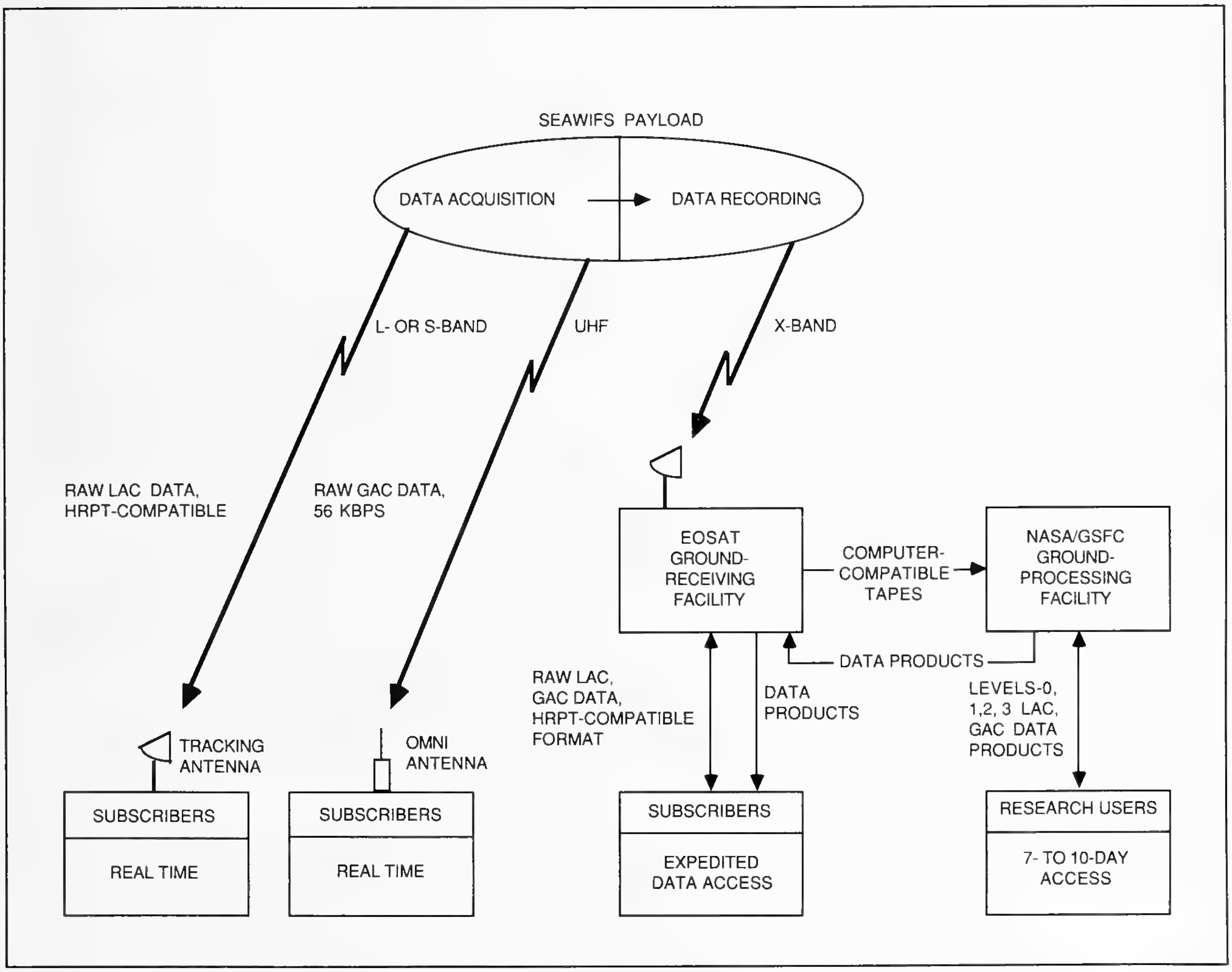
- *The Level-1 data product will contain the total radiances for visible and near-infrared bands and brightness temperatures for thermal bands.*
- *The Level-2 product is a product derived from Level-1 data containing chlorophyll-a, other pigments, water-leaving radiances, and sea-surface temperature.*
- *Level 3 is a daily mosaic product for nine Level-2 products on an 18-km grid with statistics including the number of pixels, number of days, and sums of squares for each grid element. Weekly composites will be made of the geophysical data.*

Browse images will be available, consisting of images of all data products recorded on video disks.

NASA/GFSC will provide data products to its principal investigators, Announcement-of-Opportunity Investigators, and other national and international research users through its archival and distribution system. EOSAT will acquire copies of the data products for its archive to serve all commercial and operational users.

Figure A-3 summarizes the baseline SeaWiFS data acquisition and dissemination plans.

Figure A-3. Baseline SeaWiFS data acquisition and dissemination plans.



FOREWORD

Global and mesoscale oceanographic applications and coastal-zone studies require ocean-color imagery and sea-surface temperature measurements from satellite-borne instruments. Measuring and mapping chlorophyll concentrations, sediments, and temperature are of particular interest. These data provide a measure of the spatial and temporal variability of phytoplankton biomass, sediment concentration, and ocean currents. In addition to this research that promises to provide an enhanced understanding of basic physical and biological processes in the biosphere, these data also constitute the basis for many commercial and operational applications of significant importance to several industries and to the U.S. Navy.

The first satellite-borne ocean-color sensor was the Coastal Zone Color Scanner (CZCS), which was launched aboard the Nimbus-7 satellite in October 1978 and operated successfully until the summer of 1986. The purpose of this instrument was to establish the feasibility of determining chlorophyll concentrations from space by measuring ocean color. A mathematical relationship between the CZCS estimates of algal pigments and in-situ plankton chlorophyll measurements was first established in 1980, and validation experiments are continuing to extend the accuracy and utility of this relationship. CZCS data were also found to be useful in defining ocean fronts, current patterns, and coastal sediment transport. The knowledge of these phenomena, in conjunction with sea-surface temperature measurements, was clearly shown to have economic significance for fisheries through the NASA Fisheries Demonstration Program.

These successes led to formation of a Science Working Group, chartered by NASA, with members representing the academic oceanographic community, Goddard Space Flight Center (GSFC), and other agencies. The group recommended that NASA build and fly an advanced Ocean Color Imager (OCI) to meet requirements for ocean chlorophyll data. The group's report, "Marine Resources Experiment Program," outlining the justification and necessary performance specifications was published in December 1982.

In 1986 NOAA suggested that a government-industry partnership be formed to provide ocean-color data. In response, EOSAT initiated efforts to survey the market and to define user requirements and studies on sensor design and spacecraft accommodation of the sensor. In addition, NASA initiated "Phase A" studies to define ground-segment and data-processing requirements. Recognizing the mutual benefits accruing from the joint collaboration of NASA and EOSAT, demonstrated by the Thermal Infrared Working Group (Putnam 1986), the Sea-viewing Wide-Field Sensor (SeaWiFS) Working Group was organized. The overall purpose of the EOSAT/NASA SeaWiFS Working Group was to define the specifications for a feasible and cost-effective SeaWiFS system, including spacecraft and ground segments.

The SeaWiFS Working Group convened in a 2-day session at EOSAT headquarters in Lanham, Maryland, February 11 and 12, 1987. The workshop was attended by about 70 persons from government, academia, and industry. The charter of the Working Group was to:

- *Demonstrate the technical capability of achieving the OCI/MAREX mission objectives through flying a wide-field-of-view sensor in addition to the Thematic Mapper on board the Landsat-6 spacecraft, and*
- *Define on-board and ground data-processing systems with the capability of acquiring, processing, distributing, and archiving SeaWiFS data within the time and data-format constraints of the commercial, operational, and research user communities.*

The Working Group was organized into three panels, representing the interests of commercial and operational users of oceanographic data, oceanographic research, and those responsible for implementing the system. The panels met simultaneously and convened each day in a plenary session to exchange information on progress made and emerging recommendations. The Research Panel focused on defining the scientific purposes that could be served by remotely sensed ocean-color imagery and temperature measurements and the system parameters that would be required to acquire these data. The Commercial and Operational Users' Panel summarized the public- and private-sector applications for these data and the data processing and dissemination system that would be required for commercial and operational use. The Implementation Panel explored sensor-concept definition, spacecraft integration, data handling, downlinks and formats, and data processing and distribution scenarios that were feasible for implementation to satisfy the requirements of the potential users of the data. The recommendations of the panels were integrated and summarized during a second meeting of the Working Group on 8 April 1987. This report contains the findings of the two meetings.

The SeaWiFS Working Group effort builds on the success of the prior Thermal-Infrared Working Group and represents an ongoing process of joint government and industry program evaluation to ensure development of significant new remote-sensing initiatives with commercial and scientific research applications.

CONTENTS

1

HISTORICAL PERSPECTIVE

The Coastal Zone Color Scanner (CZCS) was the first instrument to acquire ocean-color data from space. It was one of eight experiments on NASA's Nimbus-7 satellite, which was launched in 1978.[1] The CZCS was designed only to verify "proof of concept," and the instrument had a design lifetime of about 1 year. However, the CZCS provided high-quality imagery from October 1978 until the summer of 1986 when the instrument stopped sending data. Table 1 summarizes the characteristics of the CZCS system. Since the CZCS is the only instrument of its kind, its loss is of major consequence to those interested in research, commercial, and operational applications for ocean-color data.

Table 1. Major Parameters and Characteristics of the CZCS

Band	Center	Width	Phenomenon
1	443 nm	20 nm	Chlorophyll
2	520 nm	20 nm	Reference
3	550 nm	20 nm	Gelbstoffe, sediments
4	670 nm	20 nm	Chlorophyll
5	750 nm	100 nm	Surface vegetation
6	11.5 µm	2.0 µm	Surface temperature

Orbital Altitude:	955 km
Inclination:	99.2°
Period:	104.15 min.
Ascending Node:	11:52 a.m. (Local mean solar time)
IFOV:	VNIR, 0.865 x 0.865 mrad TIR, 0.927 x 0.88 mrad
Footprint:	VNIR, 0.826 x 0.826 km TIR, 0.885 x 0.840 km
Scan Angle:	± 39.4°
Swath Width:	1600 km
Scan Plane Tilt:	± 20° along track
Digitization:	8 bits
Repeat Coverage:	6 days
Revisit Interval:	2 days
Data Rate:	800 kbps average 3.5 Mbps, maximum

[1] The Nimbus Program consisted of seven different research satellites that surveyed the atmosphere of the Earth, mapped land and water characteristics, and observed weather and climate patterns. Advanced operational satellites now in use for weather and land observations include instruments and systems based on Nimbus designs. During its orbit the AVHRR instrument observes a given point on the surface of the Earth twice during each 24-hour period, once in daylight and once in darkness.

The incentive to acquire ocean-color imagery from a satellite platform developed in the 1960s when aircraft and shipboard studies demonstrated it would be possible to use satellite-acquired data to measure the spectra of sunlight reflected from ocean waters. The radiance reflected from the ocean in the visible wavelength region (400-700 nm) is related to the concentration of chlorophyll and other plant pigments present, since chlorophyll is a green pigment and the color of the water changes from blue to green as the concentration of chlorophyll increases. If the concentration of chlorophyll is known, the amount of phytoplankton in ocean waters can be calculated. Thus, satellite-acquired ocean-color data constitute a powerful tool for determining the abundance of ocean biota on a global scale. As discussed in the following sections, many applications have been developed that take advantage of this simple concept relating the color of the ocean to the amount of phytoplankton it contains.

The CZCS measured the radiance reflected from the sea's surface in the visible and near-infrared (VNIR) region and in the thermal-infrared (TIR) region. The information from the visible wavelengths was used to calculate chlorophyll concentration, whereas sea-surface temperature was calculated from the information acquired from the TIR band. Data from the near-infrared band (750 nm) was used to correct the data acquired in the visible bands for the effects of the atmosphere.

The amount of radiance reflected from the ocean is very small compared to the atmospheric radiance arriving at the sensor due to Raleigh scattering. Since the atmospheric radiance constitutes as much as 90% of the apparent ocean-color signal, it is necessary to correct radiance measured by the satellite for the effects of the atmosphere. Successful development of accurate atmospheric-correction algorithms was a crucial step in making CZCS data useful in quantitative oceanographic studies, and one of the important conclusions drawn from the CZCS experience was that the utility of atmospheric-correction algorithms is a key consideration in the design of any ocean-color sensor.

From a scientific perspective, acquisition of ocean-color data from space in the early 1990s is a high-priority goal that has been recognized in reports of the National Research Council of the National Academy of Sciences. For example, satellite-acquired ocean-color measurements are key to the success of the Global Ocean Flux Study (GOFS), a major component of the National Science Foundation's Geosciences Initiative. In addition to the U.S. scientific community, scientists from Europe, Japan, and from many other countries are also interested in participating in GOFS, and an international Joint GOFS program for the 1990s will soon be formalized under the auspices of the International Council of Scientific Unions. The scientific uses of ocean-color data will be enhanced if the next mission is concurrent with NASA and European Space Agency (ESA) altimeter (TOPEX, ERS-1) and scatterometer (NSCAT, ERS-1) missions, scheduled for the early 1990s.[2] These satellite-borne instruments will measure global ocean winds and currents, and this information will help explain global patterns in the distribution of phytoplankton determined from satellite-acquired ocean-color measurements.

Commercial and operational users of ocean-color data also are intensely interested in a follow-on mission to the CZCS. During the period when CZCS data was available, a focused effort was mounted by NASA (JPL) and NOAA to develop

[2] TOPEX is the Topography Experiment satellite, ERS-1 is the ESA's first Earth Remote Sensing satellite, which will carry an Active Microwave Instrument (AMI) and an Along-Track Scanning Radiometer (ATSR), and NSCAT is the scatterometer scheduled to fly on the Naval Research Oceanographic Satellite System (NROSS)

applications of commercial and operational use. For example, an experimental demonstration program, the Fisheries Demonstration Program, was conducted on the U.S. West Coast to assess the utility of environmental charts tailored for commercial fishing operations. This program, initiated in 1981, continued until cessation of CZCS data and showed the value of ocean-color data in increasing catch efficiency. Based on the success of this program, the value-added industry is still using sea-surface temperature data from the Advanced Very-High Resolution Radiometer (AVHRR) to support U.S. and Japanese fishing fleets. As discussed in some detail in the following sections, these data are of importance to several other user groups in the private and public sectors, including the marine-transportation industry, offshore oil exploration and production industry, and the U.S. Navy, which has an ongoing research program to develop applications for ocean-color data.

2

COMMERCIAL AND OPERATIONAL USERS' PANEL REPORT

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Background

The diverse interests of commercial and operational users of remotely sensed ocean data include commercial fishing, marine transportation, ocean mining, offshore oil and gas exploration and extraction, hydrology, marine ecology, naval operations, and value-added products, such as "fisheries-aids" charts. Satellite-acquired data on ocean phenomena from the experimental Coastal Zone Color Scanner (CZCS) and the operational Advanced Very High Resolution Radiometer (AVHRR) have provided the basis for developing a number of important applications serving these interests. For example, the fishing industry has used data on sea-surface temperature, surface currents, and ocean color to improve catch efficiency, enhancing profitability.

The marine-transportation industry uses remotely sensed ocean data primarily for ship routing. Ship-routing firms provide a route advisory to vessels being serviced prior to sailing *via* Telex and then update this advisory by satellite communications or marine radio every few days during the voyage. The goal of these services is to optimize the transit of a vessel, thus minimizing total cost. These costs include fuel, damage to equipment and cargo on board, crew injuries, delays due to adverse weather, and operating costs. Potential savings can be viewed in the light of the fact that between 600 to 800 larger vessels of the merchant fleet, occupied primarily in open-ocean trade, are *en route* each day. According to a recent unpublished study of approximately 25 voyages between the west coast of the United States and Japan from November to March, an average savings of over 20 hours per voyage were attributed to the use of ship-routing services. An improvement in the accuracy of weather prediction and the location of ocean currents and eddies would increase these savings.

The marine-transportation industry and the U.S. Navy also use ocean-current analyses and routine weather-chart analyses and prognoses for information on currents and visibility. These data products are disseminated either directly *via* government services or are routed to users by weather-forecasting services. At this time, information on ocean currents is provided about twice a week, while visibility data can be obtained as often as four times daily. SeaWiFS data will provide a finer definition of ocean currents, resulting in the ability to take full advantage of favorable circulation patterns for oceanic transit. SeaWiFS data will also provide information on horizontal atmospheric visibility.

The oil and gas industry constructs offshore platforms for mining hydrocarbons, and the current state of technology supports production in water depths greater than 1000 feet. These exploration and production operations, particularly in the Gulf of Mexico, are costly and often very sensitive to environmental conditions. In these deeper drilling areas and off the edges of the continental shelf, an accurate and detailed understanding of the oceanographic environment is required for platform design. For example, underestimating the potential force of the wind, waves, and currents in a drilling location may result in underdesigning a structure with attendant risks. Conducting offshore operations, such as shipping supplies, pipelaying, and platform installation, also requires a thorough knowledge of the ocean environment to determine "weather windows" when these operations can be conducted most safely and efficiently.

The total drag force (a dominating constraint for steel-jacket structures used in the Gulf of Mexico) on a platform member is a function of the square of the total water particle velocity. For many ranges of water depths, particularly seaward of the continental shelf break, and for certain types of structures, water particle motion from both orbital wave motion and ambient currents must be considered. For offshore structures in regions where eddy events are possible, an eddy force contribution must also be considered as well as storm-generated effects.

Timely information on transient mesoscale circulation features with maximum surface velocities in the 100 to 150 cm/sec range (e.g., the Gulf of Mexico Loop Current and eddies) is required, since they can cause a loss of drilling time due to increased loads on the drilling riser. Eddy monitoring is also required to schedule other operations, such as rig movement, remotely operated vehicle activities, and supply-vessel operations.

Many potential users of satellite-acquired data are not equipped to receive these data and many do not possess the resources or technical ability to analyze and prepare the data products required to utilize the information. This has led to formation of a loosely organized, but growing, value-added industry that provides the data products to some members of the industries described above. For the most part, these emerging entrepreneurs have small, poorly capitalized firms, and the cost of acquiring SeaWiFS data by them is a concern.

In the public sector, the National Marine Fisheries Service (NMFS) has been using ocean-color and sea-surface temperature data in operational and research applications. Operational applications include identifying fronts, river plumes, upwelling, and other areas of high productivity for guiding research-vessel sampling, for providing timely reports to local fishermen of potentially favorable zones, and in predicting potentially lethal conditions for certain species, such as zones of oxygen depletion and pollution. Research applications include monitoring long-term changes in the environment and their effects on fisheries recruitment, pollution effects on both standing stock and recruitment, niche or habitat studies for specific fish stocks, and flow visualization for monitoring larval transport conditions in coastal waters for estuarine-dependent offshore spawning species. Other research interests include determining the migration patterns of highly mobile species such as tuna, billfish, and marine mammals, improving fishery conservation and management techniques, and improving resource assessments.

The U.S. Navy has not yet documented operational requirements for the ocean-color data that will be acquired by the SeaWiFS sensor. As a result, its current interest is in using SeaWiFS data in research programs to develop techniques and algorithms for deriving usable geophysical parameters for which the Navy has identified requirements. However, it is clear these data can be used to enhance the detail and timeliness of the oceanographic information currently used by the Navy and to supplement the meteorological data currently being received and used for fleet support. In this regard, the location of ocean features, such as fronts, eddies, and warm- and cold-core rings, is of prime interest. Their position and distribution is needed on a global basis in near real time.

Sea-surface temperature measurements from the AVHRR sensor are currently being used by the Navy for frontal detection and as inputs into numerical models; SeaWiFS data will be an additional source of information for these applications. As described later in this section, in many instances ocean-color imagery has given a better indication of circulation patterns than the sea-surface temperature measurements acquired by the AVHRR.

Other naval interests include the spatial and temporal distribution of atmospheric aerosols, water optical properties, water mass identification, prediction of bioluminescence, coastal characteristics and processes, and chlorophyll pigment concentrations. Naval ship and operational centers will need near-real-time coverage of these quantities once the Navy's research programs have demonstrated their utility.

There is also an interest on the part of the Navy in assessing the variability of these parameters in the oceans in the form of a digital atlas. The data now in the digital atlas are based on data acquired by the CZCS. Hence, when the SeaWiFS sensor becomes operational, these data will enable this investigation to be completed.

Commercial Applications

Fishing Industry

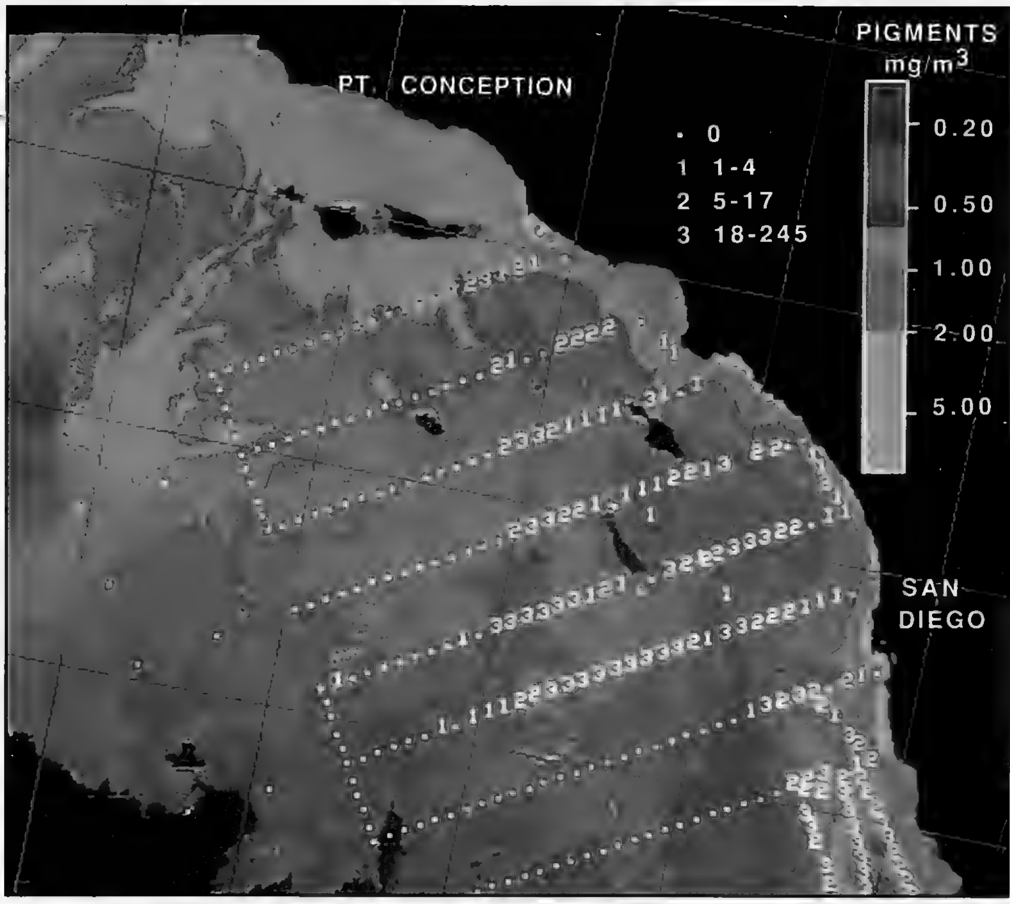
As indicated above, sea-surface temperature and ocean-color data have been successfully utilized in increasing the efficiency of the fishing industry, and commercial fishermen on the U.S. West Coast are currently paying for satellite-acquired data products. The potential commercial value of SeaWiFS to the fishing industry has been demonstrated with respect to the anchovy fishing fleet. Anchovy fishing occupies a sizeable portion of the West Coast fleet, and approximately 25 million pounds of anchovy are caught each year off the coast of Southern California.

The northern extent of anchovy spawning areas in the California bight and the offshore extent of spawning north of Santa Catalina Island are limited by cold, upwelling waters flowing from the north. These cold-water boundaries are easily identified in thermal-infrared CZCS imagery. The southern limit of anchovy spawning can be defined using ocean-color measurements, since there is a direct correlation between chlorophyll concentration and spawning activity. Figure 1 demonstrates this correlation. In this figure, warm colors (yellow, orange, and red) depict high chlorophyll concentrations, and cool colors (green, aqua, and blue) depict lower concentrations of chlorophyll. The numbers overlaid on the image represent the number of anchovy eggs collected over a 20-day experimental survey.

Another example of the use of ocean-color imagery by the fishing industry can be drawn from the experience of shrimp fisheries in the Gulf of Mexico. As indicated in Figure 2, shrimp cannot live in areas where the concentration of oxygen in the bottom waters is low. Oxygen depletion often occurs when huge numbers of microscopic plants and other living matter die and sink to the bottom where decomposition takes place, depleting the water of most or all of the oxygen. The amount of chlorophyll in the water is related to the biomass of the microscopic organisms and, hence, is an indicator of potential locations of oxygen-deficient waters.

Figure 3 is an image from the CZCS showing the chlorophyll pigment concentration in the water off the Gulf Coast. The warm colors in this image (yellow, orange, and red) represent areas of high chlorophyll pigment concentration, and the cool colors (green, aqua, and blue) represent areas of lower chlorophyll concentration. Figure 4 shows a prediction of potential areas of oxygen-deficient waters, derived by combining the pigment-concentration data of Figure 3 with sea-surface temperature measurements.

Figure 1. Anchovy spawning limits defined by ocean color measurements. (Fiedler 1983)



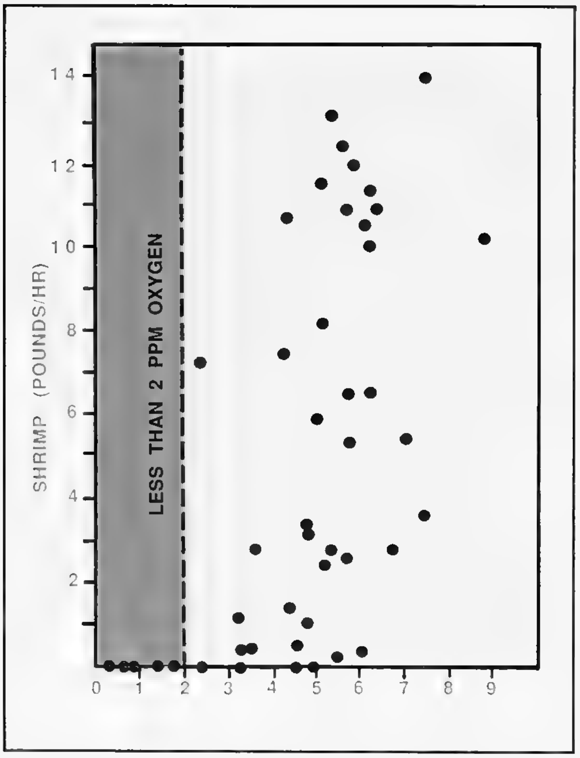


Figure 2. Relationship between bottom oxygen content and shrimp catch. (Leming and Stuntz 1984)

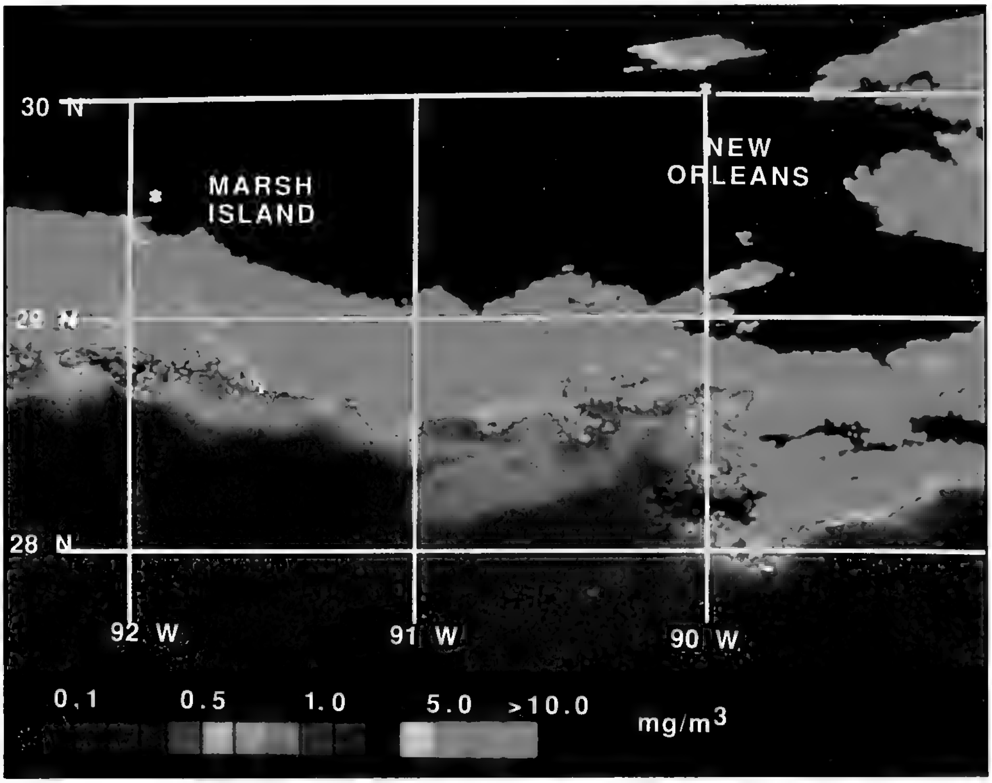


Figure 3. CZCS imagery showing the chlorophyll pigment concentration in the water off the Gulf Coast. (Leming and Stuntz 1984)

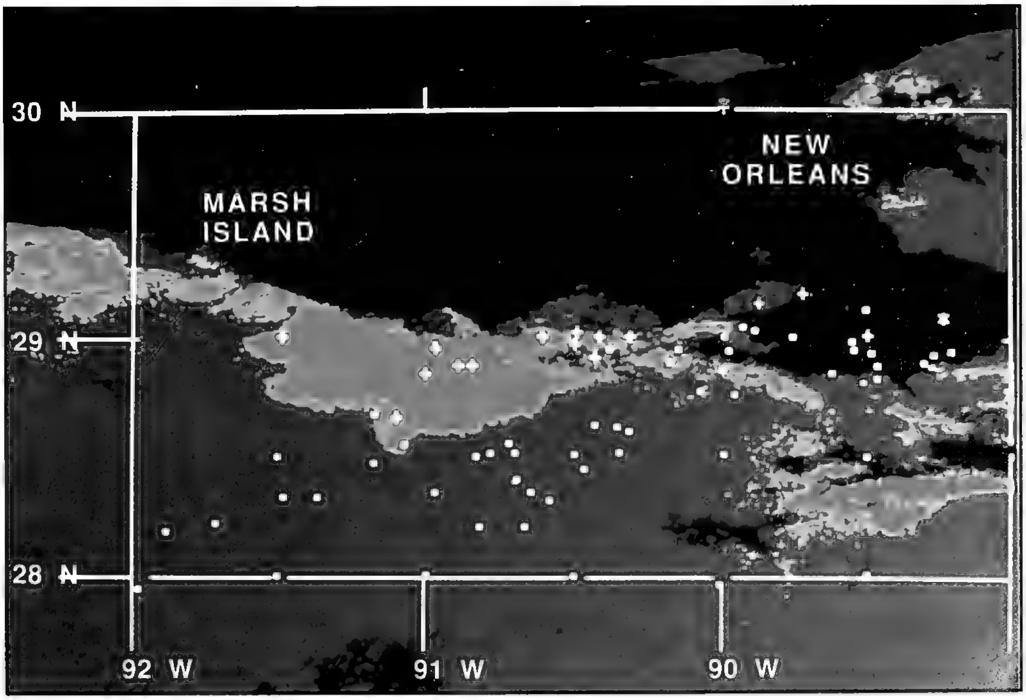


Figure 4. Correlation between high chlorophyll concentrations, sea-surface temperature, and waters with low oxygen content. (Leming and Stuntz 1984)

In Figure 4, the white crosses show the location of research vessels where the concentration of oxygen in the bottom water was found to be less than 2.5 mg/l; dots indicate areas where the concentration of oxygen was greater than 2.5 mg/l. This experiment, conducted by the NMFS (Leming and Stuntz 1984), demonstrates the utility of using ocean-color information to aid the shrimp fishing industry, which is valued at nearly $500 million annually.

Another example of using ocean-color imagery to locate fish species is shown in Figure 5, also in the Gulf of Mexico. Here, large concentrations of butterfish were found by NMFS research vessels in April 1985 in the region of the temperature and chlorophyll front (Leming and Herron 1986). As discussed in greater detail below, these fronts can only be detected in summer and fall through use of ocean-color imagery at these latitudes, partially because of the low temperature differentials in the ocean's surface and partially because the high humidity makes atmospheric correction impossible. Hence, a SeaWiFS-type sensor will increase temporal coverage for the Gulf of Mexico by at least 25 to 35%.

The prior three examples are drawn from experiments conducted with CZCS imagery. However, the albacore fishing industry used similar imagery to increase its catch during the period of time when this imagery was available. More tuna is consumed in the United States than any other type of seafood – over a billion cans annually – and albacore is the most valuable species of tuna. This species migrates to waters off the coast of North America during the summer and fall months, and commercially valuable aggregations of albacore are found in the warm, blue waters near ocean-temperature and ocean-color boundaries on the seaward edge of coastal water masses.

For several years during the operation of the CZCS, the imagery was processed in real time to derive ocean-color boundary charts. The charts were distributed to fishermen at sea by facsimile, and color photographs of the images were also distributed by overnight mail to Sea Grant Marine Advisors and to fishing ports. Figure 6 is an example of a CZCS image that has been processed to delineate ocean color boundaries. The boundaries between water masses are accentuated

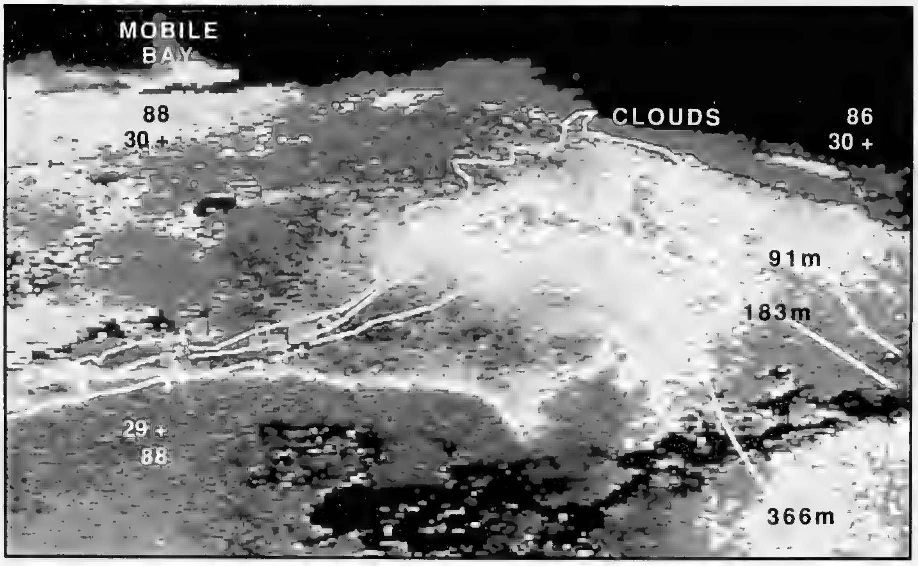


Figure 5. Butterfish catches are correlated with high chlorophyll concentration and temperature fronts. (Leming and Herron 1986)

by false color enhancement. The greener coastal waters are represented by red, orange, and gold. The bluer, oceanic waters are colored blue and aqua. Circles overlaid on the image show the location and size of albacore catch for a 6-day period in 1981, demonstrating that most of the albacore were caught along the seaward side of the ocean-color boundaries. These products were used, not only by commercial albacore fishermen, but also by commercial swordfish and salmon fishermen in Southern California. The availability of real-time data from SeaWiFS will greatly enhance the ability of these industries to improve their cost-effectiveness.

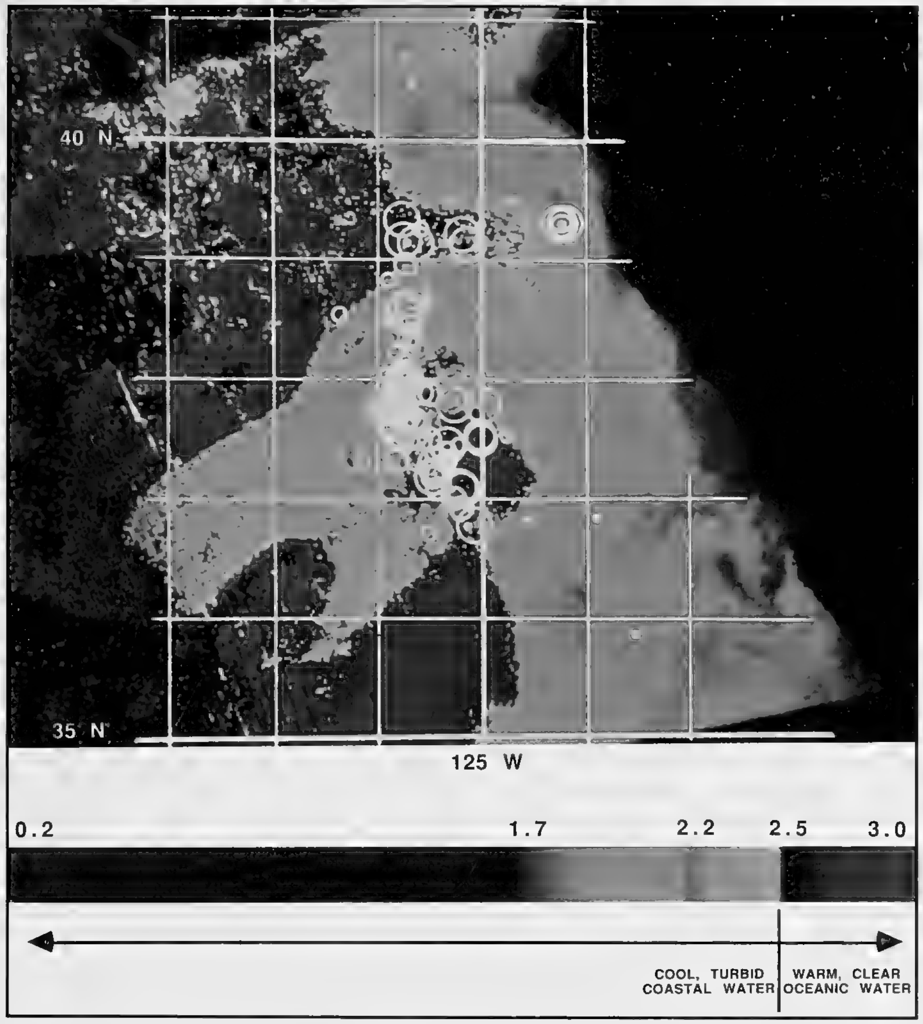
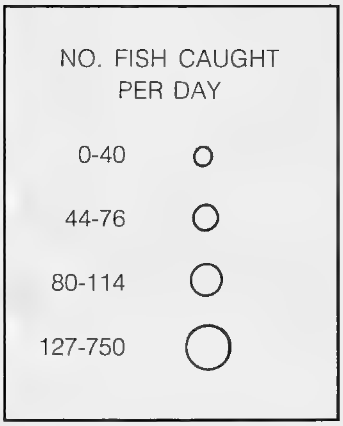


Figure 6. CZCS imagery, processed using computer enhanced false color to identify water color structure. Commercial fish catch data are depicted on the image. (Montgomery et al. 1986)



Ocean-color imagery also has potential commercial applications in the recreational sportfishing industry. For instance, most large gamefish, such as sailfish and marlin, are nearly always found in the blue water typical of open-ocean conditions. An operational map of distance and heading to the nearest blue water from selected sportfishing ports or marinas would be an attractive commercial value-added data product. Figure 7 is an example of such a map of the northern Gulf of Mexico derived from CZCS data. Alternatively, the availability of SeaWiFS data at a central site would also be extremely valuable to the sportfishing industry in reducing the time and fuel now spent searching for blue water.

Offshore Oil and Gas Exploration and Production

AVHRR sea-surface temperature data currently are major sources of the information used in preparing eddy forecasts for offshore oil exploration and production (Haustein and Vastano 1987). Temporal changes in eddy size and position and current frontal locations are used to produce routine summaries of their positions, surface-flow directions, and estimates of their probability, duration, and magnitude. Figure 8 shows a typical summary.

However, the utility of thermal-infrared sea-surface temperature measurements deteriorates seriously from the summer through fall in the Gulf of Mexico and in many other regions at latitudes between 30° South and 30° North (e.g., the equatorial Atlantic and Pacific Oceans and the Indian Ocean). First of all, during these months surface conditions are relatively isothermal as a result of strong solar heating of the surface layer, with temperature ranges in the narrow band from about 29 to 31°C. Secondly, humid atmospheric conditions cause a severe attenuation of some regions of the thermal-infrared signature. The limitations due to surface heating are greatest when the surface is calm and solar intensity is high. In some instances the ocean's features are masked, significantly diminishing the usefulness of the data.

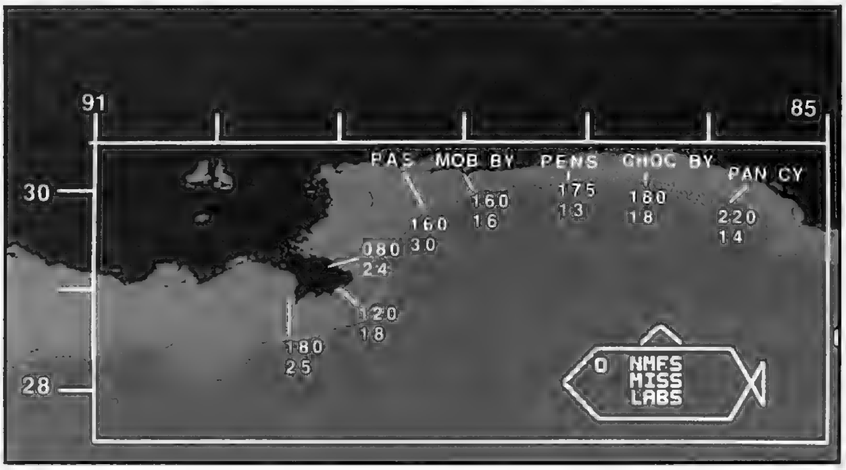
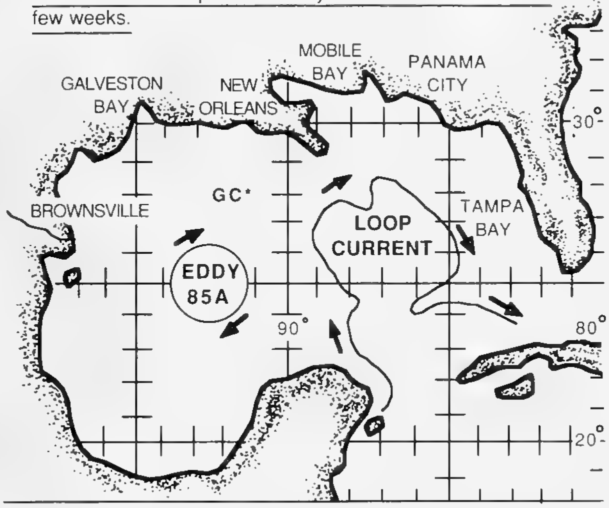


Figure 7. Distance in nautical miles and heading in degrees (from true North) from selected ports to the nearest blue water in the northern Gulf of Mexico on 9 May 1982. (Courtesy of T. Leming.)

GULF OF MEXICO EDDY MONITORING FOR OFFSHORE OPERATIONS

VALID DATES: 11/6-13/85

IMPORTANT OBSERVATIONS: Narrowing of Loop Current neck indicative of potential eddy detachment in the next few weeks.



ARROWS INDICATE DIRECTION OF FLOW

DRILLING AND PLATFORM SITES: G C = GREEN CANYON

SYNOPSIS OF FEATURES

EDDY ID	CENTER LAT	CENTER LONG	MOTION TO SPEED	MAXIMUM SURFACE VELOCITY
85A	25.3	92.8	W 2.5 n.mi./day	1 to 2 knots

DRILLING AND PLATFORM SITES

SITE	EDDY POTENTIAL START DURATION	MAX EXPECTED SURFACE VELOCITY
GC	None at this time	Less than 1 knot

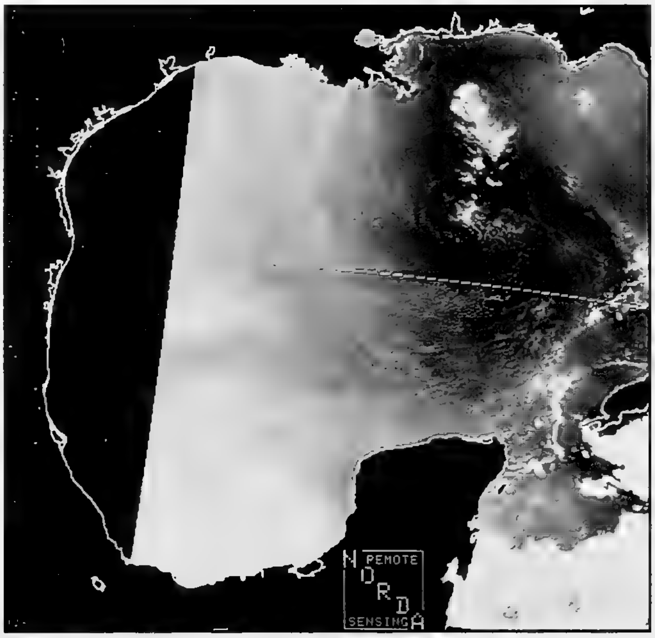
Figure 8. Typical summary of eddy and current-jet locations used by the offshore oil exploration and production industry. (Courtesy J. Haustein)

An example of thermal-infrared imagery under these conditions is given in Figure 9. In this TIROS channel-4 (11 μm) image, only the northern boundary of the Loop Current can be observed in the northeastern Gulf. In contrast, Figure 10 shows the CZCS imagery taken on the same day.[3] In this figure, regions with high chlorophyll concentrations are denoted by the lightest colors and those with low concentrations by darker colors. Clouds are shown in black. Many ocean features are clearly observable in this imagery. For instance, the continuous boundary of the Loop Current can be seen as it enters through the Yucatan Channel and meanders to its eastern extent. Two eddies can be observed in the western Gulf, and, within the shelf waters off Louisiana, Mississippi, Alabama, and Florida, the mixing patterns of these waters can be identified as significant fronts.

It should be noted that the imagery in Figure 10 has been processed to the end of the swath in the western Gulf. Although these data cannot be subjected to quantitative analysis, the ocean's features clearly can be seen at the outward extent of the CZCS's 40° scan, documenting that useful data can be obtained from CZCS imagery at scan angles greater than 30° from nadir. Despite the fact that a scan angle of 58° will be required to provide daily coverage from the Landsat-6 orbital altitude, the value of having daily coverage is enormous, even if some of the data can only be interpreted qualitatively.

[3]This image was processed to eliminate the atmospheric component using a Principal Component technique (Holyer and LaViolette 1984), although similar results can be obtained using the more typical Gordon subtraction atmospheric removal technique.

Figure 9. TIROS thermal-infrared imagery of the Gulf of Mexico, 20 June 1979. (Courtesy of R. Arnone)



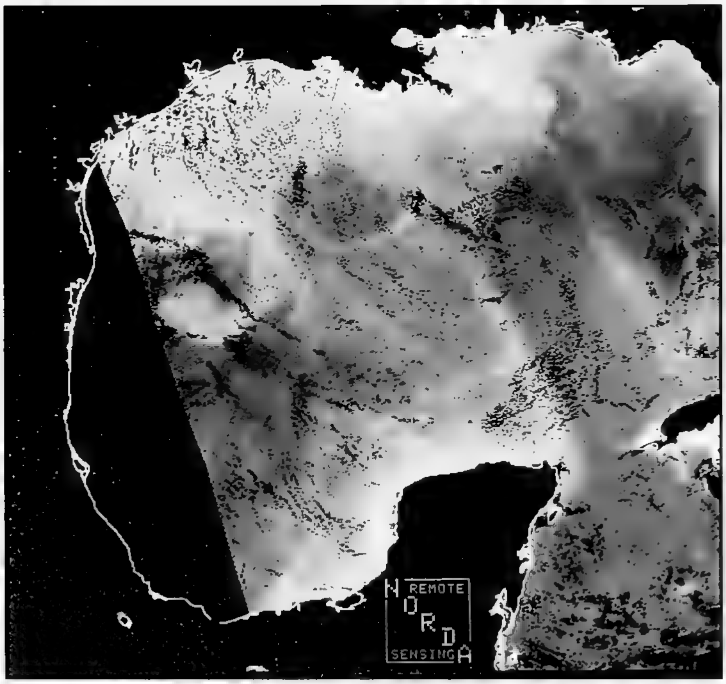


Figure 10. CZCS imagery of the Gulf of Mexico, 20 June 1979. (Courtesy of R. Arnone)

Operational Applications

Navigation and Ship Routing

As indicated earlier, the location of eddies, fronts, and currents is important for maritime and naval applications. The importance of ocean-color imagery to these uses is demonstrated in. Figures 11 and 12, both taken 12 May 1986, separated in time by 14 hours. The thermal image from the AVHRR shown in Figure 11 indicates there is a warm spot in the center of the image below Majorca, Spain (represented by dark gray shades). During this period, ship and aircraft surveys registered calm sea conditions and high solar heating. The upper 1 meter of the water was reported to be as much as 3°C warmer than the lower layers. Hence, in interpreting this image, consideration must be given to the fact that surface heating may mask the actual circulation patterns.

In the imagery of Figure 12 there is no evidence of biological distribution patterns below Majorca usually associated with warm water surrounded by colder water. Since the radiance leaving the water emanates from a depth of approximately one attenuation coefficient (typically 4 to 20m, depending on turbidity), the imagery represents the circulation patterns below the heated surface of the ocean. Since the ground-truth data indicates high solar heating that may mask the actual circulation patterns, it can be concluded that the general circulation patterns of the ocean are better represented by biological distribution patterns than by surface thermal patterns under certain conditions.

Hydrology

The utility of satellite-acquired imagery in monitoring floods was also demonstrated using CZCS data. For example, Figure 13 is imagery acquired by the CZCS of the Parana River Valley in Argentina. The flooded area extends 700 km from the confluence of the Rio Parana to the Rio de la Plata near Buenos Aires and ranges from 20 to 70 km in width. While data from stream gauges can often provide warning of impending flood conditions, they do not provide information on the extent of flooding, which may be of critical importance to rescue or relief operations.

Surveying, Monitoring, and Managing of Inland and Coastal Fisheries

Compared to conventional ground-sampling techniques, remotely sensed data from inland and coastal fishing areas are more cost-effective for gathering data, if the data are received in a timely fashion or in near real time. This is especially true in sparsely populated, developing countries where communications are poor and environmental data are not available. Welcomme (1985) has enumerated the surveying and monitoring functions that can be accomplished using satellite imagery. A brief summary of those functions that can only be accomplished using data acquired by a SeaWiFS-type sensor is presented below.

The potential fishery output of rivers has been found to be directly related to the flooded area of the river, i.e., catches in flood-plain rivers in a particular year are correlated with the flood intensity of the previous year (Welcomme 1985). Welcomme also found that macrophytes tend to tie up nutrients for longer periods than phytoplankton. Data from a sensor like SeaWiFS can be used to measure macrophyte growth, phytoplankton growth, and the extent of the drawdown of water bodies. The seasonal turnover and even upwelling can also be efficiently monitored.

The same kinds of information can be acquired on coastal waters where circulation patterns are better defined, due to the increased flows and often higher color-to-temperature contrasts between various water masses. These areas are often large and remotely located and, therefore, best assessed through use of satellite-acquired data.

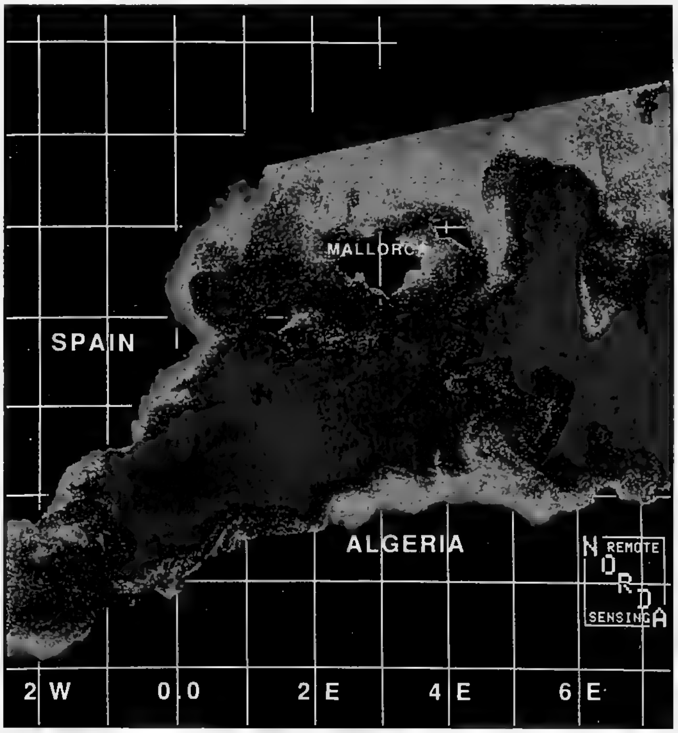


Figure 11. Thermal-infrared Imagery of the Mediterranean, 12 May 1986. Pigments concentration ratio 443:550 nm. (Courtesy of R. Arnone)

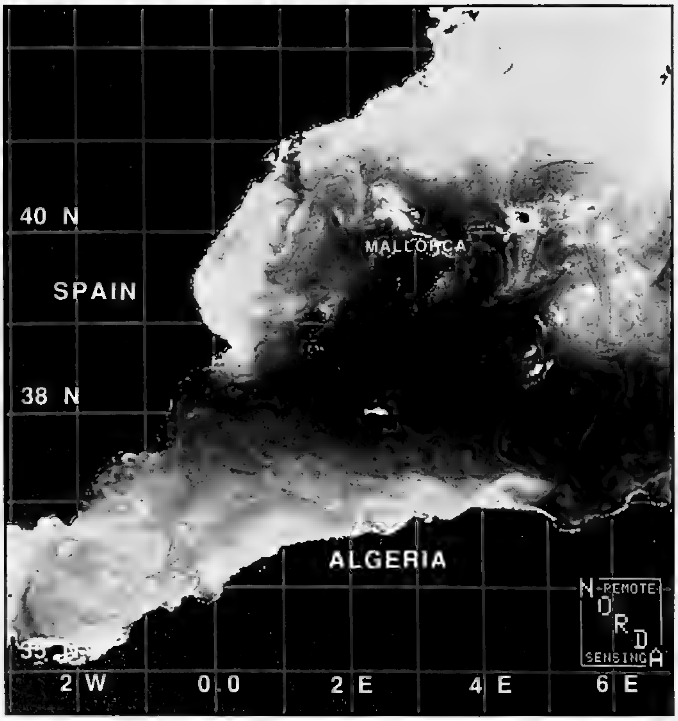


Figure 12. CZCS imagery of the Mediterranean, 12 May 1986. (Courtesy of R. Arnone)

Figure 13. Flood monitoring based on CZCS imagery. (Courtesy of Organization of American States and Satellite Hydrology, Inc.)

Seafood, such as shrimp, oysters, crabs, and clams, are often cultured and harvested in the coastal ecosystem, and fish-related aquaculture activities are also increasing in these areas. Data from the SeaWiFS sensor will be valuable in monitoring and managing these resources. For example, the opening and closing of shrimp grounds has traditionally been related to catch information in conjunction with water temperature and suspended sediment data. The SeaWiFS sensor system will also provide excellent seasonal water quality information that can be used to locate the best sites for new aquaculture facilities.

Supporting Research Issues

Except for the value-added industry, most potential users of processed data are not trained in its use or interpretation. For example, experience gained while distributing CZCS data to the fisheries industry showed that substantial user support is required before the information is put to its appropriate use and, hence, considered to be of value by the user. Commercial users need to be able to test the potential of applications of interest to them, including the compatibility of the system with existing software and hardware processing packages. Potential applications using SeaWiFS data should be demonstrated far enough in advance of data availability that commercialization can commence immediately after launch.

Hence, a study should be undertaken by the research community to establish the utility of SeaWiFS-type data, based on AVHRR and historical CZCS data, for specific commercial applications. Tutorial sessions with members of associations representing potential users and user workshops are likely to lead to an improved perception of the value of the data and increased use of it.

The following examples of ongoing research in support of operational uses of SeaWiFS data are drawn from the Navy's research program. However, much of this research is applicable to other users.

In a research program funded by the Office of Naval Research (ONR), general water-mass classification is being developed by coupling satellite-derived bio-optical data with sea-surface temperature data. Since the information content in the visible bands and in the thermal-infrared bands is different, combining these data reveals improved methods of viewing the ocean surface and, therefore, of classifying ocean waters. At this time this is a basic research program and, hence, does not describe an operational requirement of the Navy. However, SeaWiFS would be an ideal sensor for this work since the visible and infrared data will be coregistered.

Basic research at ONR is also being directed toward assessing the biota using ocean-color properties. This research reflects the Navy's interest in ambient noise from marine life and in bioluminescence. The occurrence of specific phytoplankton pigments and their concentration are related to data acquired on ocean color, and research is being directed toward determining a mechanism for isolating the phytoplankton groups responsible for bioluminescence from the spectral signature. Frontal locations can also be correlated with the probability of the presence of marine life. Hence, data from the SeaWiFS sensor could be applied to this research and, if the research were successful, an operational Navy requirement might result.

Thermodynamic ocean models are being developed for naval programs that require a knowledge of the absorption of solar heat by the ocean. The absorption in the near-surface layer and the dissipation of this heat are partially controlled by the diffuse attenuation coefficient, k, of the water. That is, the depth to which solar heat penetrates into the water column is inversely related to the water's attenuation coefficient. The extent of this effect has not been determined, since the horizontal and temporal scales of variation in water types are not known. However, preliminary studies have shown the effect of water type on resulting circulation and mixed-layer depth prediction calculations (Martin 1985). SeaWiFS data will be used as an input into the Navy's thermodynamic model, although basic research will be required to determine how these data can be interpreted.

The distribution of aerosols in the atmosphere, as defined by the 670 and 750 nm bands of the CZCS, is of significant importance to the research of the Navy's meteorological community, since there is a strong naval requirement for surface horizontal atmospheric visibility. The Naval Environmental Prediction and Research Facility (NEPRF) is examining ways of using data on integrated aerosol distribution for naval needs. Although basic research will be required to define the specific application, SeaWiFS will provide improved data for meeting this requirement.

The Navy also needs to establish a temporal and spatial optical property (diffuse attenuation coefficient) data base, which can be used to establish scales of variability and to develop models that predict their distribution (Esaias et al. 1986). These data can only be acquired from a satellite platform with a sensor like the proposed SeaWiFS.

3

RESEARCH USERS' PANEL REPORT

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Background

Photosynthesis by land and ocean plants converts carbon dioxide into plant tissue and is one of the most important natural processes that removes carbon dioxide from the atmosphere and oceans. Marine phytoplankton are responsible for at least 30% of the total global photosynthesis, and recent studies suggest that phytoplankton photosynthesis may be underestimated by a factor of two. Phytoplankton photosynthesis is a key process in controlling the biogeochemical cycles of carbon, nitrogen, phosphorus, sulfur, and oxygen. These elements play major roles in controlling the global environment, and understanding their cycles is a major goal of the emerging field of Earth System Science.

Phytoplankton contain chlorophyll and other pigments that capture sunlight, which provides the energy required for the photosynthetic process. Chlorophyll is a green pigment, and the color of water changes from blue to green as the concentration of phytoplankton and, hence, chlorophyll increases. As a result, phytoplankton concentration and, thus, the photosynthetic potential of ocean waters can be estimated in most of the global ocean by measuring ocean color. As discussed in Section 1, the possibility of measuring the photosynthetic potential of the sea from a satellite-borne sensor led to a "proof-of-concept" mission, the Coastal Zone Color Scanner (CZCS) on the Nimbus-7 satellite.

Once oceanographers verified the chlorophyll distribution patterns revealed by CZCS imagery, the use of the imagery revolutionized biological oceanography. For the first time, oceanographers could obtain measurements of a biological property over large areas of the ocean. The concentration of phytoplankton varies greatly in space and time because the growth medium, water, is in constant, three-dimensional motion. Until CZCS imagery was available, biological oceanographers were generally restricted to studying relatively small-scale phenomena, since ships cannot cover enough area in a sufficiently short period of time to synoptically sample at ocean-basin or global scales. In the future, oceanographers will be able to use SeaWiFS imagery to solve large-scale problems, such as the role of phytoplankton production in the global carbon cycle. It is possible to consider such ambitious goals for the future partly because of the successful integration of CZCS imagery into studies of relatively small-scale systems.

The remainder of this section consists of a brief review of some of the scientific uses of CZCS imagery, a description of how SeaWiFS imagery will be used in the early 1990s, and a discussion of scientific research requirements for the SeaWiFS system.

Studies of Small-scale Processes

Small-scale ocean features, i.e., features encompassing less than about 10,000 km^2 of ocean area, generally form and dissipate within relatively short periods of time (days to weeks). The predominant use of CZCS imagery has been in conducting studies of small-scale features in the ocean because, until recently, small-scale features were of greatest interest to biological and chemical oceanographers. The dimensions of these features are clearly visible in satellite imagery. In contrast, mapping small-scale features from oceanographic research vessels is difficult, if not impossible, because the features change faster than the ships can map them. Small-scale studies will continue to be an important application for satellite-acquired ocean-color imagery, since the results of such studies are the building blocks upon which programs to study large-scale processes are built.

River Plumes

Riverine and estuarine plumes contain relatively high concentrations of suspended organic and inorganic material that are highly reflective in the visible spectrum. This high reflectance is easily observed by satellite-borne color scanners, such as the CZCS. An issue currently being debated is the fate of fluvial nutrients and their possible effect on carbon budgets. Simply stated, "Do the nitrates and phosphates produced from agricultural and urban sources and injected via freshwater discharge into the coastal zone result in a significant enhancement in primary production?" To answer this question requires an understanding of the sedimentation and circulation processes that control the exchange of material across the continental shelf. Ocean-color imagery is beginning to provide answers to such questions by providing time-series imagery of plume formation and dissipation on continental shelves and insight into other processes that affect the rate at which river and ocean water intermix.

Coastal Upwelling

Vertical movement, or upwelling, of deep, cold, nutrient-rich water is an important process in the marine ecosystem. Upwelling areas tend to be highly productive and are often the site of important fisheries, such as the anchovy fishery off the Peruvian coast. Upwelling is largely caused by wind stress and may occur in the coastal ocean and deep sea. Winds favorable for upwelling are episodic, varying on time scales of 3 to 5 days and on length scales from a few tens to several hundreds of kilometers. In freshly upwelled waters, phytoplankton grow faster than zooplankton can consume them, and, as a result, a large fraction of the phytoplankton may sink to the bottom. Thus, sites of wind-driven upwelling are important in understanding the ocean's role in the global carbon cycle.

Studies of wind-driven upwelling systems off the U.S. West Coast revealed that their extreme variability is difficult to resolve using traditional ship sampling. Hence, satellite imagery is a necessary tool for resolving upwelling dynamics and, perhaps more importantly, for determining the large-scale effect of these systems. For instance, CZCS and AVHRR imagery showed for the first time that plumes of upwelled, productive waters extend hundreds of kilometers seaward off the U.S. West Coast, as illustrated in

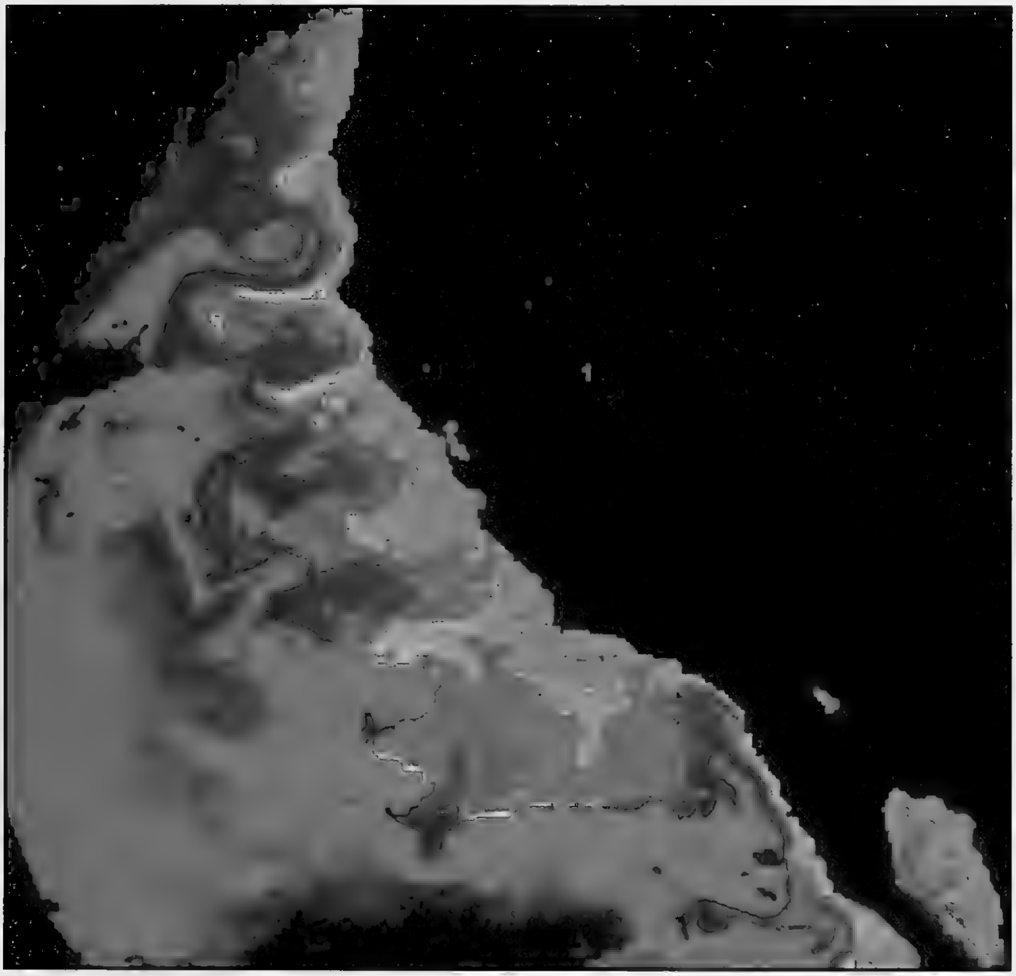


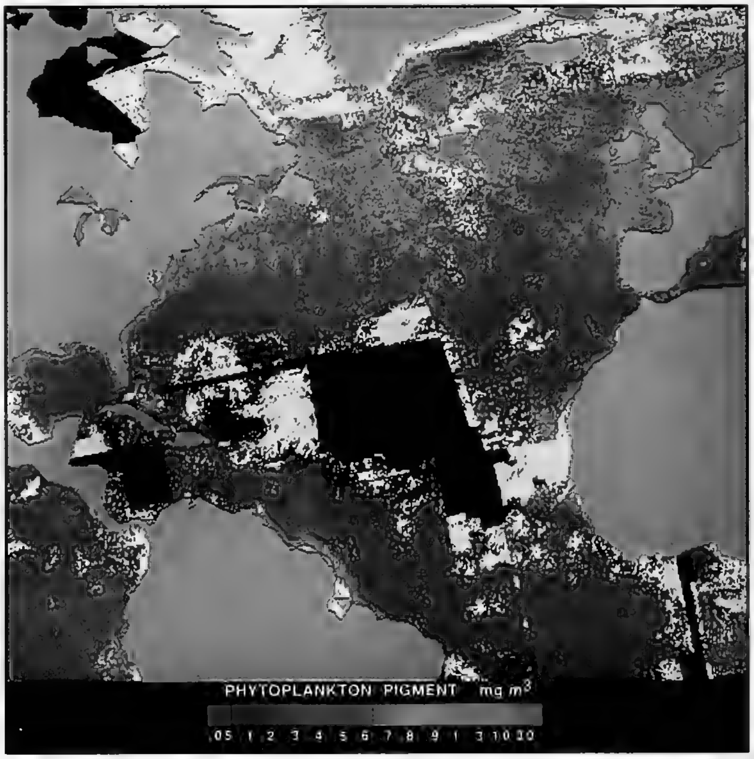
Figure 14. Plumes of chlorophyll-rich waters extend many kilometers off the U.S. West Coast. (Courtesy of M. Abbott)

Figure 14. A time series of imagery extending over many years will be required to quantitatively determine the coupling between upwelling and large-scale patterns in ocean basins.

Seasonal Phytoplankton Blooms

During the vertical mixing process in winter, deep waters rich in plant nutrients are mixed with near-surface waters that are depleted of nutrients. The net effect is fertilization of the upper layers of the ocean and stimulation of rapid phytoplankton growth as the daily sunlight increases in the spring. This period of rapid growth and accumulation of phytoplankton biomass in the mixed layer is called a "spring phytoplankton bloom" and is illustrated in Figure 15. The spring bloom is one of the major events in the sea and is a time when the flux of dissolved carbon dioxide into phytoplankton biomass is very rapid. Thus, spring blooms in the global ocean may play an important role in the global carbon cycle. Satellite ocean-color measurements provide the only means of answering questions concerning the large-scale distribution and timing of spring blooms in the global ocean.

Figure 15. Spring bloom in the North Atlantic. (Courtesy of G. Feldman and W. Esaias)



Western Boundary Currents and Eddies

Eddies and other physical processes associated with the large horizontal shears in the Gulf Stream and other major ocean currents give rise to significant lateral mixing and cross-frontal entrainment. The resulting exchange of physical, chemical, and biological properties often results in a large modification of the local environment causing noticeable changes in the distribution of animals and plants at or near the frontal interface. Fishermen routinely make use of such conditions to locate commercially exploitable quantities of fish that tend to congregate along oceanic fronts in search of prey.

The variety of ocean eddies and the different environments in which they are found are the basis for a great diversity in physical and biological effects. For instance, eddy systems observed off the U.S. West Coast draw plumes of cold, pigment-rich coastal waters offshore. This process is an important mechanism for enriching offshore waters with plankton and nutrients. Gulf Stream eddies off the U.S. East Coast north of Cape Hatteras, NC, constitute an important mechanism for exchanging chemical and biological properties between coastal and offshore waters. CZCS imagery, such as shown in Figure 16, and AVHRR observations provided the first synoptic view of Gulf Stream eddies and showed how eddies are formed, how long they last, and where they go during their lifetime.

It is clear the processes associated with mixing along the edge of eddies, coastal currents, western boundary currents, etc., are not only quite complex, but also that they vary greatly from one region and oceanographic feature to the next. Given their importance in the mixing of oceanographic parameters (salinity, temperature, biological populations, etc.), a better understanding of this variability is critical to gaining a better understanding of the distribution of oceanographic parameters in general.

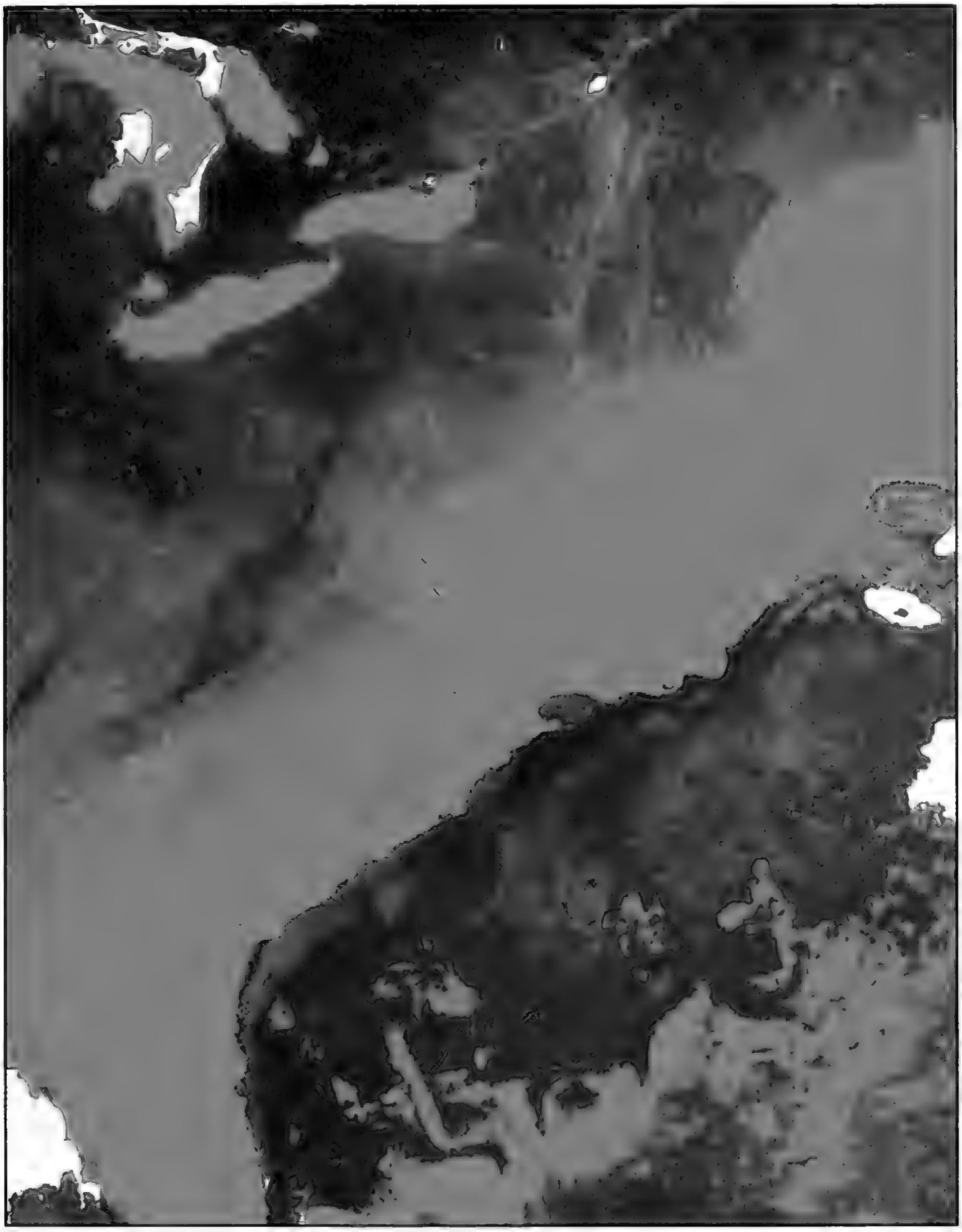
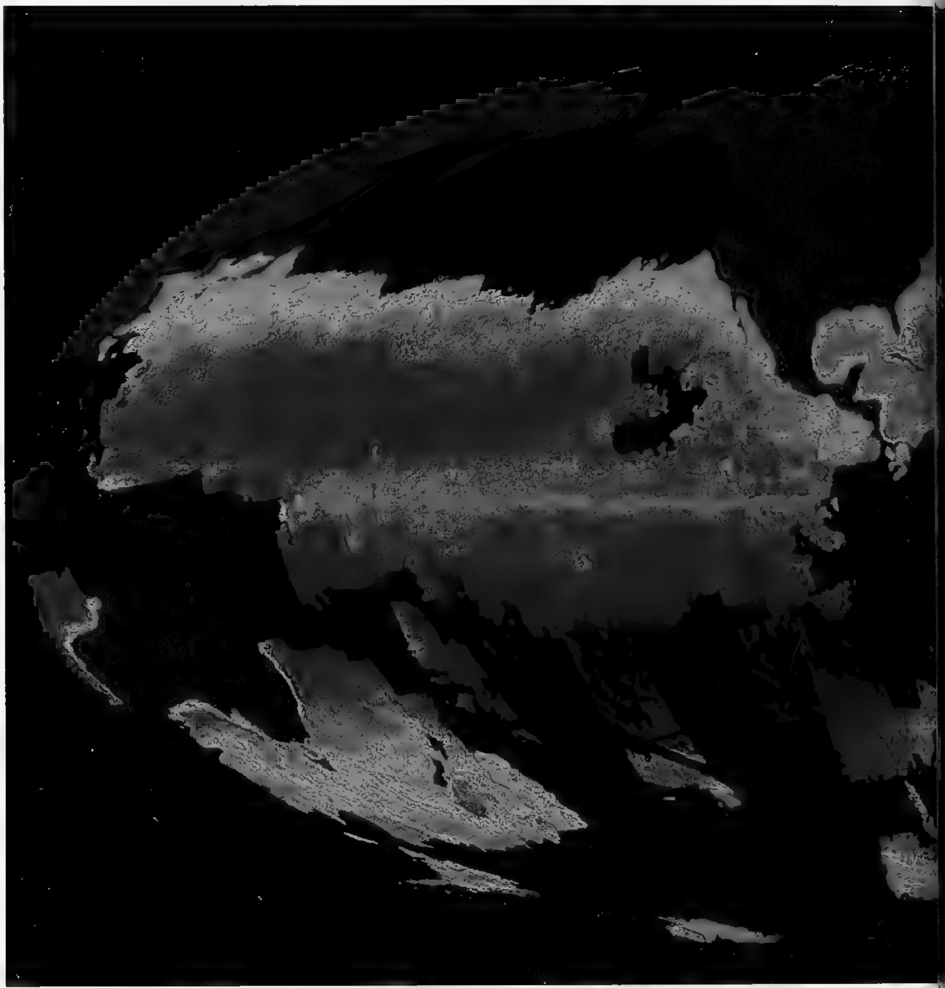


Figure 16. Chlorophyll-rich continental shelf waters off the U.S. East Coast contrasted with less productive offshore water. A Gulf Stream ring is forming in the right center of the image. (Courtesy of O. Brown and R. Evans)



Mixed-Layer Optical Properties

Recent studies of mixed-layer dynamics have shown that it is essential to characterize the optical properties of the upper water column. The absorption of solar radiation and its variation with depth can greatly affect the vertical stability of the water column, and variations in pigment concentration are largely responsible for variations in optical properties in most of the world's oceans. The stability of the water column has a major effect on primary production by controlling nutrient supply and the effective solar radiance captured by the phytoplankton. Vertical mixing also affects sea-surface temperature and, hence, may influence the air-sea interaction and the climate. The availability of global data on marine optical properties, combined with global sea-surface temperature and wind measurements, will improve our understanding of the complex interaction between physical and biological properties in the upper ocean.

Flow Visualization

An often-overlooked contribution of satellite-acquired imagery of ocean color or temperature fields to oceanographic research lies in the opportunity it offers to visualize flow fields. It is difficult to quantify such a contribution, but often the insight gained by examining a satellite image gives rise to new discoveries. For example, entrainment of streamers around a large warm-core eddy can be observed in the CZCS imagery

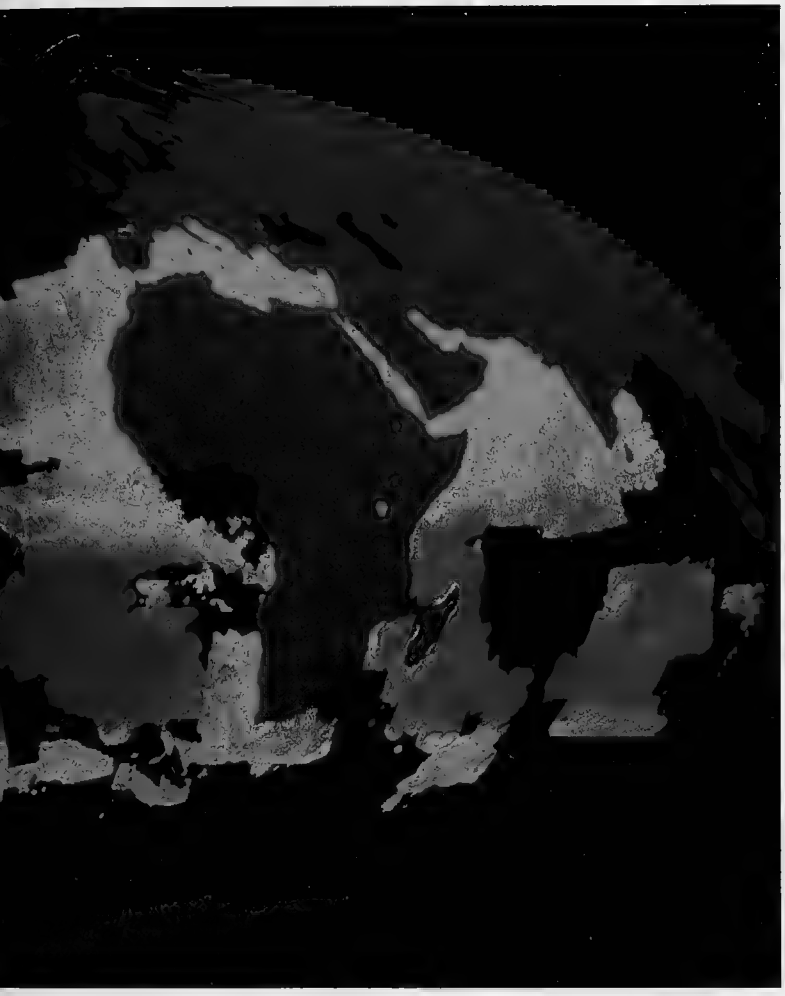


Figure 17. A composite CZCS image showing the distribution of chlorophyll in the global oceans during December, 1981. High concentrations (over 4 µg/l) of chlorophyll (phytoplankton) are indicated by orange and red, whereas low concentrations (less than 0.5 µg/l) are indicated by blue. (Courtesy of GSFC and the Univ. of Miami)

of the Gulf Stream. This process was unknown until CZCS imagery was available. Statistical techniques are currently under development that can be applied to satellite thermal and color data to better quantify ocean flow fields. Concurrent and coregistered AVHRR and CZCS imagery can also be used to study and statistically describe mixing between two different water masses.

Studies of Global-Scale Processes

The recent widespread distribution of CZCS imagery in the oceanographic community has stimulated ambitious plans for oceanographic studies in the 1990s. For example, scientists in the United States and abroad are planning the Global Ocean Flux Study (GOFS) to better quantify the ocean's role in the global carbon cycle and other major biogeochemical cycles. Ocean-color measurements are required to implement the scientific strategy of GOFS and other programs whose goals include the study of primary production on a global scale. Acquisition of data on ocean color is the key to the success of these studies, because these data are the only global measure of ocean biota that can be obtained within a relatively short period of time (days). Figure 17 is an example of the global images that can be obtained from satellite ocean-color measurements.

The Global Carbon Cycle

Over the last few decades, our knowledge of the Earth's oceans, atmosphere, continents, and ice cover has increased dramatically. The interaction and balance among these elements of the biosphere are being increasingly appreciated, as is their influence on man and human society. Most change in the global system is natural, due to such causes as volcanic activity and changes in the Earth-to-Sun distance, but evidence is accumulating that human activity also plays a major role in aspects of global ecology that directly affect the Earth as a unique home for life.

The steady increase in the carbon dioxide content of the atmosphere associated with the burning of fossil fuels is a well-documented example, but the cycles of other biogenic gases, such as nitrous oxide, methane, and carbon monoxide are also affected by anthropogenic activity. These gases also contribute to the heating of our atmosphere through their property of absorbing infrared radiation (i.e., the "greenhouse effect"). With respect to carbon dioxide, at the present rate of increase of about 1.5 ppm per year, the concentration of carbon dioxide in the atmosphere is expected to double relative to pre-Industrial-Age levels sometime in the next century. The other biogenic gases mentioned above are also increasing in the atmosphere and contributing to the greenhouse effect. Thus, some atmospheric models predict a gradual warming of the Earth's climate with as-yet-unknown consequences.

The pathways and rates of removal of carbon dioxide from the atmosphere have not been definitively established, but it is known that about 50% of the carbon dioxide released from burning fossil fuels has accumulated in the atmosphere, and most of the remainder is in the ocean. To provide quantitative answers to questions concerning the ocean's role in the global carbon cycle and to predict the fate of anthropogenically derived carbon dioxide that reaches the ocean, observations and models must focus on key aspects of the ocean's biogeochemistry.

The Role of Phytoplankton in the Global Carbon Cycle

The role of ocean biota in the global carbon cycle is understood qualitatively. Marine phytoplankton carry out photosynthesis, converting inorganic carbon dissolved in the water to organic particles and dissolved organic materials. This process is known as primary production. The rate of primary production varies by as much as a factor of ten from ocean region to ocean region, and, thus, some parts of the ocean are referred to as being more productive than others. Much of the organic carbon produced from photosynthesis is eaten and recycled back to inorganic carbon in the surface waters by animals and bacteria. The residual organic matter, along with associated inorganic skeletal components, such as calcite, aragonite, and opal, settle out of the surface waters. A small fraction of this flux is ultimately buried in the sediments and potentially represents an important mechanism for removing carbon from the global cycle.

Ocean Productivity Measurements on a Global Scale

The magnitude and variability of annual primary production by marine phytoplankton is poorly specified on a global scale, largely due to the high degree of spatial and temporal variability in the distribution of phytoplankton in the sea. As noted previously, phytoplankton primary production accounts for at least 30% of the total annual global photosynthesis, but this percentage is not known with the level of accuracy required to accurately model the role of phytoplankton in the global carbon cycle. Recent studies suggest that phytoplankton photosynthesis may be underestimated by a factor of two; this uncertainty partially accounts for the difficulties encountered when attempting global-scale analyses using traditional oceanographic sampling methods.

Only through satellite remote sensing of ocean color can information on marine primary production be obtained on a global scale, given that significant changes occur over short periods of time (days to weeks) and over small distances (10 to 100 km). In much the same way that meteorologists use satellite data as input to models that predict the weather, oceanographers will input satellite-acquired measurements of ocean chlorophyll into computer simulation models to improve predictions of the state of ocean ecosystems and their effects on the biogeochemical cycles of carbon, nitrogen, phosphorus, sulfur, and oxygen. In both cases, satellite data provide global coverage that is impractical to obtain in any other manner. Thus, satellite-acquired ocean-color imagery is essential to the development and verification of accurate models that quantify the role of ocean biota in the major biogeochemical cycles – the key to understanding the global ecosystem.

The acquisition of global ocean chlorophyll measurements from the CZCS instrument was an important first step that moved the field of oceanography toward a new global perspective on the couplings between atmosphere and ocean and the special role of phytoplankton primary production in biogeochemical cycles. The acquisition of SeaWiFS global data is essential if this new approach in oceanography is to develop and mature.

Mission Support Science

Scaling up from the present focus on small-scale studies of phytoplankton biomass (chlorophyll) distributions to the goal of providing global estimates of primary production in the 1990s will require ocean-color and sea-surface temperature data on a global scale. It will also require conducting the experiments necessary to understand the relationship of small-scale to basin-scale distributions. This subsection briefly outlines a science plan for making the transition from small scale to ocean-basin and global scales.

Three initiatives are proposed in the mission-support science plan for SeaWiFS. The first is a sequence of cooperative international studies using high-resolution ocean-color observations of an ocean basin to address stratified sampling issues. The second is an expanded effort to improve bio-optical relationships for the SeaWiFS band set and to develop and verify a physiologically based algorithm for productivity estimates. The third is to collect SeaWiFS observations globally and to composite them into moderate-resolution maps of pigment and primary productivity.

Ocean Basin Study

A detailed study of one ocean basin using SeaWiFS imagery and mooring and ship data is essential to bridge the gap from current applications of CZCS imagery to ocean-basin scales. Physical processes, for the most part, control phytoplankton distribution and productivity, and, generally, physical processes at small scales are dominated by local wind-forcing and eddy-scale features. At the ocean-basin scale, global oceanic and atmospheric circulation patterns predominate, but eddies and local wind forcing significantly modify the overall pattern. The biological consequences of basin-scale physical processes have not been studied.

The GOFS and other international programs planned for the early 1990s will collect much of the essential data required to study ocean basin-scale primary productivity. What is needed is a focused effort, in collaboration with these programs, to process both the high- and low-resolution SeaWiFS data for the North Atlantic, or another appropriate ocean basin, simultaneously with *in-situ* optical and biological measurements. This kind of multiplatform study would be an essential first step toward the goal of obtaining global-scale productivity estimates.

Bio-Optical Modeling

Spatial variability in primary production is currently being investigated by means of satellite sensors. On the other hand, low-frequency (months to years) temporal variability at a given location is best investigated from moored arrays, which can provide continuous long-term data at a single location and as a function of depth in the water column. Vertical strings of bio-optical sensors, deployed strategically in the major ocean provinces, are required to provide the complementary surface information necessary to fully exploit the scientific return from the SeaWiFS satellite data. Unattended buoy systems would provide the long-term bio-optical data from various ocean provinces and would be used (1) to investigate both the long-term and vertical-distribution behavior of bio-optical algorithms, thus increasing the accuracy of those models, linking the dissolved and suspended biological material to the subsequent optical properties, (2) as a platform for the direct long-term determination of the vertical distributions of pigment biomass, primary production, and ocean carbon flux, and (3) as a component of the multiplatform stratified sampling strategies for optimizing remotely sensed estimates of pigment biomass, primary production, and carbon flux.

Validation of the SeaWiFS data product will require at least one dedicated cruise of at least 30 days in addition to a "calibration" cruise shortly after launch. Similar cruises during the operation of the sensor will confirm its on-going performance and stability. The cruises should be devoted to measuring pigment concentration continuously along the ship's course as well as upwelling spectral irradiance, downwelling spectral irradiance, pigment concentration, etc., at positions within the field of view of the sensor. This data will also provide a basis for developing better bio-optical algorithms.

Remote sensing of ocean color with the four CZCS visible channels is well understood. It is based on firm physical principles of radiative transfer and environmental optics as well as on a considerable body of experimental data linking biological constituents in ocean waters with their corresponding optical properties. Additional spectral bands are proposed for SeaWiFS that should greatly improve the accuracy of chlorophyll estimates, particularly in areas with high chlorophyll concentrations and with suspended sediments or dissolved organic matter (Case-2 waters). There is also significant room for improvement in the algorithms used for estimating primary production from ocean-color imagery. In particular, a robust and general algorithm for the purpose of handling imagery from various regions and over long time periods is needed, such as would be required in order to make basin-wide productivity estimates from color imagery. Recently, several biological optical models that could fill this need have been proposed. A systematic effort is required to evaluate, test, and refine these models using sample data from a wide variety of ocean environments. The objective is to develop a generally agreed-upon algorithm by the time SeaWiFS is operational, so that we may proceed to produce global ocean productivity maps in support of GOFS and other studies planned for the early 1990s.

To achieve the accuracy in pigment-concentration estimates associated with the CZCS, the existing CZCS atmospheric-correction algorithm can be directly adapted to SeaWiFS data. The bands at 665, 765 and 865 nm, discussed in Section 4, where the ocean approximates a blackbody, will be used to determine the aerosol radiance and its spectral variation. However, some studies will be necessary to establish the most accurate method of extrapolating the spectral variation in these bands into the visible region.

To take advantage of the 10-bit sensitivity of the SeaWiFS sensor, compared to the 8-bit sensitivity of the CZCS, a more careful analysis of atmospheric correction will be required. The assumption that Rayleigh and aerosol contributions to the radiance at the sensor can be separated will not be valid at the full 10-bit resolution of the sensor, and a more complex algorithm will be needed. Development of such algorithms has been underway for 4 to 5 years, their feasibility has been demonstrated, and they will be in place by launch. These improved algorithms should enable correction of atmospheric effects almost to the 58.25° edge of scan of the baseline SeaWiFS instrument.

Global Compositing of Chlorophyll and Productivity

As indicated in Section 5, part of the data processing planned for SeaWiFS data is to produce global maps of phytoplankton chlorophyll. Before these products can be incorporated into GOFS and other studies, the users must understand the limitations of large-scale composite imagery. Thus, a project will be required to provide a firm assessment of large-scale sampling statistics and to perform initial comparisons with high-level (binned and averaged) correlative data sets.

4
SYNTHESIS OF REQUIREMENTS

The issues surrounding the questions of what spectral bands and other sensor characteristics would best serve the users' needs and whether the desired characteristics could be implemented within acceptable cost and risk constraints were discussed at length in all of the panel sessions at the initial workshop meeting. Considerable discussion also focused on defining the required revisit interval and data-processing, downlink, data-format, and dissemination requirements. The plenary sessions served to expose the positions of the panel members and to focus attention on the salient characteristics desired. Much of the second workshop meeting was devoted to working out viable compromises among the positions represented. This section presents the views expressed and the agreements reached.

Sensor Requirements

The point of departure for developing sensor requirements for the SeaWiFS was the sensor parameters and performance of the CZCS, summarized in Section 1. The characteristics relevant to formulation of requirements for the SeaWiFs are repeated below:

Spectral Bands			
Band	**Center**	**Width**	**Phenomenon**
1	443 nm	20 nm	Chlorophyll
2	520 nm	20 nm	Reference
3	550 nm	20 nm	Gelbstoffe, sediments
4	670 nm	20 nm	Chlorophyll
5	750 nm	100 nm	Surface vegetation
6	11.5 µm	2.0 µm	Surface temperature
Scan Plane Tilt: ±20° along track			
Digitization: 8 bits			

Spectral Band Selection

The CZCS demonstrated the feasibility of determining ocean chlorophyll concentrations and diffuse attenuation coefficients from multispectral, visible, satellite-acquired observations. The goal of the SeaWiFS Working Group's band-selection process was to recommend a baseline set of bands that would be capable of providing the data required to resolve chlorophyll concentrations to within 50 percent over a range of concentrations from 0.05 μg/l in the open ocean to 10.0 μg/l in outer continental shelf areas. This is a major goal for a follow-on ocean-color sensor to the CZCS (JOI 1984, 1985).

Visible and Near-Infrared Bands

The topic of spectral band selection for SeaWiFS was introduced by the instrument design experts by proposing the following baseline band centers in the visible and near-infrared regions: 443, 500, 565, and 765 nm. The band at 443 nm is near the absorption maximum of chlorophyll at 435 nm, but its location minimizes interference from a Fraunhoffer absorption line (G) that occurs near 435 nm. The 500 nm band is between the maximum and minimum regions of pigment absorption, so it can be used to estimate pigment concentration when the concentration is so large that useful signals cannot be derived from measurements at the absorption peak. The 565 nm band is near the absorption minimum of phytoplankton pigments, and the 765 nm band is in the near-infrared region where water can be considered black, enabling use of data from these bands in atmospheric-correction algorithms.

Since the instrument designers indicated that two bands could be added in the visible/near-infrared (VNIR) rather easily with only a minor increase in cost, in the ensuing discussion several other bands were suggested. For example, a band centered at 665 nm was requested for atmospheric correction instead of the CZCS band at 670 nm to avoid the strong overlap of the 670 nm band with the *in-vivo* sunlight-induced fluorescence feature of chlorophyll, centered at 685 nm. Although the SeaWiFS band center would be 5 nm lower than the CZCS band center, it would still permit existing CZCS algorithms for atmospheric correction to be used. This was considered essential, since time will be required to determine the optimum techniques for using the new 765 nm band for estimating aerosol radiance, and because it is important to have direct comparisons between historical CZCS data and SeaWiFS data to provide continuity in the study of long-term trends in marine productivity. After the atmospheric-correction algorithms for the 765 nm band have been validated, the 665 nm band will be useful in developing new algorithms for estimating pigment concentration (Clark 1981) and in assisting in the effort to extrapolate Angstrom exponents from the near-infrared region to the visible.

As a result of these discussions, both panels agreed that the following five VNIR bands should be included in SeaWiFS as a minimum set: 443 ±10 nm, 500 ±10 nm, 565 ±10 nm, 665 ±10 nm, and 765 ±20 nm. Data from these bands would be used for the purposes identified in Table 2.

After agreement on adding a band at 665 nm was reached, the possibility of adding a sixth band was explored. It was felt that this opportunity should be exploited to improve accuracy and the number of optical properties of the ocean that could be derived in the presence of multiple constituents. The spectral position of this band was debated at length, using as a guideline that the position of the selected band should not have a significant influence on the cost or complexity of the instrument.

Table 2. Recommended Visible and Near-Infrared Bands (Minimum) for the Baseline SeaWiFS Instrument.

Band	Wave-length (nm)	Phenomenon	Use
1	443	Chlorophyll Absorption	Used with the 565 nm band for determining color boundaries, chlorophyll concentration, and diffuse attenuation coefficient (k).
2	500	Pigment Absorption	Used with the 565 nm band for mapping color and chlorophyll concentration in coastal waters.
3	565	Sediment/ Hinge Point	Used as a hinge point for determining chlorophyll, pigments, water optical properties (k), and measuring suspended sediments.
4	665	Atmospheric Aerosols	Used to correct above bands for atmospheric effects. This band is not the best for aerosols since total radiance at the sensor is not zero in coastal waters, but it is compatible with CZCS processing techniques.
5	765	Atmospheric Aerosols	Used to correct first three bands for the atmosphere. Better than 665 nm, if the sensitivity of the band is set to monitor aerosols and not land/water boundaries.
NOTE: The band centered at 765 nm actually consists of two bands, 745 to 759 nm and 770 to 785 nm, illuminating a single detector, but blocked to avoid interference by oxygen absorption near 765 nm.			

405 nm Band. A number of panel members suggested including a band at 405 nm for the primary purpose of observing the strong blue absorption by gelbstoffe.[4] Since the maximum absorption by chlorophyll is near 435 nm and gelbstoffe absorption increases almost exponentially with decreasing wavelength in this region, proceeding to lower wavelengths accentuates the difference between gelbstoffe and chlorophyll concentrations. It is impossible to determine when gelbstoffe absorption is affecting pigment-concentration estimates with band-ratio techniques using the CZCS suite of bands. A 405 nm band would provide this information, at least at low pigment concentrations where reflectance at 405 nm is still measurable.

However, good atmospheric correction for this band will be critical for use of the data and will be very difficult to achieve. In addition, detector performance in this region is poor, and the sensor's signal-to-noise ratio (SNR) performance is likely to be significantly lower in this band than in other bands. Also, polarization sensitivity would be worst in this band. For these reasons, the concensus of the panels was to select a different region for the sixth band.

[4] It is important to note that gelbstoffe (yellow substance or blue absorbing matter) is not synonomous with what is commonly referred to in the literature as dissolved organic matter (DOM). Gelbstoffe is a variable, generally small, component of the total DOM that is strongly absorbing in the violet and blue and is comprised, classically, of highly stable humic and fulvic acids from terrestrial plant decomposition found in rivers and swamps. On occasion, decomposing phytoplankton blooms also produce optically similar compounds. The DOM released extracellularly from plankton (considered by some to be a major pathway of carbon cycling in the ocean) generally shows little absorbance in the visible. Hence, the 405 nm band cannot be used to estimate DOM.

490 and 520 Bands. Moving the 500 nm band to 490 nm and including a 520 nm band was suggested since these bands would permit multiband spectral-curvature algorithms and related second-derivative algorithms to be applied to derive chlorophyll pigment concentrations in coastal (Case-2) waters. These types of algorithms, and, in particular, one using a combination of 460, 490, and 520 nm bands, discovered empirically by Grew (1981), have been shown to be relatively insensitive to the effects of nonchlorophyll absorption and scattering. Comparisons of the results obtained from applying curvature algorithms to remotely sensed data with similar results obtained from laser-stimulated chlorophyll fluorescence data routinely yield correlation coefficients greater than 0.9 (Hoge and Swift 1986). Hoge and Swift's analysis also showed that although the CZCS band set precluded application of the Grew relationship, a combination of 443, 490, and 520 nm bands was equally effective.

Another reason presented for including a 520 nm band was that its use would benefit from the CZCS heritage and, like the 665 nm band, would permit better comparisons to be made between CZCS and SeaWiFS observations. This could be especially important in waters with high pigment concentrations, where the values from nearly 8 years of CZCS observation have been derived using a 520/550 nm band ratio. Unless this heritage is available, it will be extremely difficult to assess the validity of any long-term trends observed between CZCS and SeaWiFS data if their derivations differ. Where this is likely to be most troublesome is in detecting changes in community structure based on pigment groups, since the 520 and 500 nm bands lie near the peak of the complex, multicomponent accessory pigment absorbance region. Changes in accessory pigment composition and concentration are common when the phytoplankton community's structure changes in response to nutrient stress, eutrophication, or other environmental changes. The proposed change from 550 to 565 nm will also affect this comparison, but to a lesser degree, since these two wavelengths are both near the minimum of chlorophyll pigment absorption.

The combination of 443, 490, and 520 nm was considered, but was found to be infeasible from an instrument-design point of view. This is because the dichroic beamsplitters used to reflect the shorter wavelengths and to pass the longer wavelengths do not have the ability to precisely cleave the spectrum. To avoid polarization effects near adjoining spectral regions of band pairs, there must be a minimum of 20 nm between the upper wavelength of one band and the lower wavelength of the adjacent band (in this case 500 nm and 510 nm).[5] The concensus was that the 443, 500, and 565 nm bands of the baseline selection would accomplish the same purposes as the 443, 490, and 520 nm set.

565 and 570 nm Bands. Inclusion of a band at 570 nm in conjunction with the band at 565 nm was discussed because of the recent work of Hoge and Swift (submitted to *Applied Optics*). In this work they obtained extremely strong relationships between their laser-stimulated fluorescence concentration and results obtained from using a 566/571 nm band ratio on data from Case-2 waters. Correlation coefficients obtained using this band ratio exceeded those obtained using 443/550 nm and 520/550 nm band ratios when applied to data taken in four flight experiments. The choice of two closely spaced bands is attractive in that it lessens the need for highly accurate Angstrom exponent extrapolations. It also minimizes errors due to strong vertical inhomogeneity, since the penetration depth for the two wavelengths is so similar. The narrow separation of these bands would be possible in the SeaWiFS design, in contrast to the CZCS, OCI, or MODIS sensors, since individual detector filters are used for the detectors in band pairs.

However, selection of 570 nm as the location of the additional band was rejected in favor of the substantial advantages to be gained in the accuracy of atmospheric-correction algorithms through inclusion of a band at 865 nm.

[5] Upper wavelength of the 490 nm band = 490 + 10 = 500 nm. Lower wavelength of the 520 nm band = 520 - 10 nm = 510 nm.

865 nm Band for Atmospheric-Correction Algorithms. In the currently used atmospheric-correction algorithms, it is necessary to assume that the ratio of aerosol radiance at two wavelengths is independent of position (except over waters where the chlorophyll concentration is less than 0.25 µg/l). However, spatial variations in the type of aerosol will induce spatial variations in the aerosol radiance ratio. If there were a band at 865 nm (where there will be virtually no radiance at the sensor) in addition to the band at 765 nm, variations in the aerosol radiance ratio could be detected by checking for spatial variations in the aerosol radiance ratios from the 665 and 765 nm bands and from the 665 and 865 nm bands. The addition of the 865 nm band would also improve atmospheric correction in coastal waters where the total radiance at the sensor from the 665 nm band is not zero.

Since atmospheric correction is so vital to the accuracy of pigment-concentration estimates, this band was selected as the sixth VNIR band for the SeaWiFS instrument.

Bands in the Mid- and Long-Wavelength Infrared

To remain within cost and weight constraints, the SeaWiFS design can support only two bands in the mid- or long-wavelength regions. Since pairs of bands in either region are required for sea-surface temperature algorithms, the discussion focused on a pair of bands in the 3.5 to 4.0 µm region or a pair of bands in the 10.5 to 12.5 µm region. A pair of bands in the long-wavelength region would provide continuity with the substantial use of AVHRR data from this region, separately and in conjunction with CZCS data, and would provide these data from the same platform. On the other hand, a pair of bands in the mid-wavelength region would provide a capability for determining sea-surface temperatures between ±30° latitudes where the long-wavelength data is inadequate and would improve the accuracy of the measurements since transmission in this region is greater than in the long-wavelength infrared. The panel members supporting the mid-wavelength position assume that AVHRR data will continue to be made available for measurements in the 10.5 to 12.5 µm region. Additional rationale for both locations is presented below.

The Commercial and Operational Users Panel recommended the long-wavelength bands based on their need to make continued use of the algorithms now used to interpret the data from the NOAA AVHRR sensors. The Research Panel members pointed out that AVHRR-derived estimates of sea-surface temperature in conjunction with CZCS-derived estimates of pigment concentration have been useful in several studies of mesoscale processes (e.g., Brown et al. 1985 and Abbott and Zion 1985). However, since the CZCS and AVHRR measurements are not simultaneous, constraints are imposed on certain studies due to the movement of clouds and other ocean features between the satellites' overpasses. Also, scientists must access two separate data archives. Since sea-surface temperature can be used as an indicator of physical processes, simultaneous measurements might improve estimates of productivity. Finally, simultaneously acquired information on sea-surface temperature and the diffuse attenuation coefficient (closely related to the pigment concentration) may be useful in studying mixed-layer dynamics and surface-transport mechanisms.

The Research Panel members recognized the value of acquiring sea-surface temperature data in the tropical latitudes, but pointed out that, to obtain precise estimates, these measurements would have to be made in the nighttime segment of each orbit. This is because daylight-segment sea-surface data in the mid-wavelength region would need to be corrected for the atmospheric backscatter of the solar mid-infrared by aerosols, and this correction would be difficult to achieve. Furthermore, the instrument would always be undergoing a tilt change somewhere in these latitudes, so daytime sea-surface temperature measurements would be sporadic at the latitudes where the capability was desired.

Since, as discussed in Section 5, the Landsat-6 nighttime power capacity is limited and nighttime data would be separated by 12 hours from data acquired in the visible regions, the Research Panel also favored locating the infrared bands in the 10.5 to 12.5 μm region, preserving the continuity with prior AVHRR-based work. As a result, the baseline SeaWiFS instrument design contains the split long-wavelength band set.

Band Selection Summary

The spectral regions and band characteristics agreed upon for the baseline SeaWiFS instrument are summarized in Table 3. The SNR performance goals for the VNIR bands are chosen so that the error induced by the noise on the signal approximately equals the error inherent in the atmospheric correction algorithms. These values represent minimum acceptable performance. The noise-equivalent temperature differences (NEΔTs) of Table 3 are sufficient to determine sea-surface temperatures in cloud-free areas to a few tenths of a Kelvin. An accuracy of 0.1K is the anticipated requirement for the 1990s; however, the resulting NEΔT requirement of a few hundredths of a Kelvin would exceed the capability of the SeaWiFS instrument. Considering that the NEΔT performance of the CZCS at 300K was 0.29K, the goal for the SeaWiFS was taken as a NEΔT of less than 0.29K at 300K.

Spatial Resolution

As discussed in Section 5, the Landsat orbital altitude of 705 km, in conjunction with the decision to use the AVHRR High-Resolution Picture Transmission (HRPT) data format of six frames per second, fixes the sensor's spatial resolution at 1.13 km at nadir. Both panels agreed that this resolution would be adequate for their local-area

Table 3. SeaWiFS Baseline Spectral Regions and Performance Goals

Band	Spectral Region	Spectral Range	Expected Signal	
			Radiance (mW/cm^2-sr-μm)[1]	Minimum SNR/NEΔT[1]
1	Visible	433-453 nm	10.3	510
2	Visible	490-510 nm	7.5	500
3	Visible	555-575 nm	5.2	350
4	Visible	655-675 nm	2.8	285
5	Near IR	745-785 nm[2]	2.0	280
6	Near IR	843-887 nm	1.4	280
7	IR	10.5-11.5 μm	--	0.29K[3]
8	IR	11.5-12.5 μm	--	0.29K[3]

[1] H. R. Gordon 1987: personal communication. The SNR values must be met at all sun angles.
[2] Notched between 760 and 770 to minimize interference from the oxygen absorption band.
[3] At 300K.

coverage uses, but also requested that the data be aggregated on board to provide global-area coverage at approximately 4.5 km resolution. The rationale for these requirements can be summarized as follows.

The distribution of chlorophyll in the ocean is patchy on all scales down to less than a kilometer. To adequately map the variation in phytoplankton concentration in high-concentration shelf areas (a major goal of the first of the MAR-EX studies), a sensor must be able to resolve about a kilometer of the ocean. This small footprint size also allows measurements to be made close to the shore, permitting resolution of local outwelling and upwelling zones, which tend to be near-shore phenomena. The high data rate that will result from such a spatial resolution may be reduced somewhat for wide-area studies of open-ocean phytoplankton concentration, where statistical rather than process experiments are of more interest. For the latter case, a 4.5-km resolution is acceptable. Therefore, a system is required that generates, stores, and transmits both resolutions of data. This type of data-processing system is analogous to the NOAA/AVHRR system, which has been used as a basis for defining the proposed SeaWiFS data products.

The conversion of the higher resolution (1.13 km) data to a global (4.5 km) data set should take place in the on-board data processing system prior to recording or transmitting the data. The algorithm for this conversion will be determined at a later date; however, the consensus was that averaging the 16 1.13-km pixels is not desirable and that selecting the output of a single cloud-free pixel to represent a 4.5-km area would be a better solution.

Radiometric Accuracy and Relative Precision

The scientific and operational utility of an ocean-color imaging system depends completely on the ability to measure radiance at the instrument's aperture with sufficient accuracy and resolution to separate and remove from each measurement the contributions from the atmosphere and, thus, to infer the amount of water-leaving radiance within, essentially, the limits in accuracy of the atmospheric-correction models. On this basis, a radiometric accuracy of approximately 5% is required in each band, and the relative precision between individual measurements within each band must be much less than 1%. The emphasis in the expression of these requirements is on the importance of relative precision between measurements in a given image or band and between images on different days when a given position on the surface is viewed at different scan and solar angles.

On small spatial scales, pixel-to-pixel variations in aerosol radiance are typically of the same order of magnitude as variations in the amount of water-leaving radiance. Under hazy conditions, the fluctuation in the amplitudes of aerosol radiance may be 4 to 10 times larger than the variations in water-leaving radiance associated with ocean fronts of similar spatial scales. As a result, the algorithms used to remove the aerosol effects require precision between bands to within 1%. Even limited atmospheric correction algorithms, sufficient to locate front and eddy boundaries, require removal of these atmospheric effects, and all quantitative applications require good radiometric accuracy and extremely good relative precision.

Polarization sensitivity and the constancy of the solid-angle field of view of the radiometer are two major factors affecting relative radiometric precision.

Polarization Sensitivity

Polarization sensitivity is defined as the ratio of the difference between maximum and minimum output to the sum of the maximum and minimum output obtained when the plane of incoming linearly polarized radiation is rotated through 180°.

Normally, a radiometer is calibrated using unpolarized input radiance. Under these circumstances, if the radiometer's response is polarization sensitive (usually because of internal reflecting surfaces), its calibration is valid only for scenes characterized by unpolarized radiance. However, in the ocean-atmosphere system, the largest signal contributor (and largest signal variation) is Rayleigh scattering radiance, which is very strongly polarized. Moreover, the polarization varies greatly across the range of relevant scan angles. Since the instrument's error due to polarization sensitivity may also vary with scan angle, the problem is compounded. These errors would be very difficult to correct, even using completely polarized radiative-transfer models. While the problem might be possible to solve at a satisfactory level of accuracy, the expense and uncertainty are far greater than would be the case with an instrument designed with a low polarization sensitivity. The CZCS specification was 2%, and this level of polarization sensitivity was deemed satisfactory.

Solid Angle Resolution of IFOVs

If a radiometer were designed with an optics train that varied the solid angle subtense of the instrument's field of view, e.g., to correct for footprint distortion, that variation could lead to a loss of relative precision in the cross-scan direction or between tilt configurations. If the instrument's optical configuration is modified to vary the angular IFOV for any reason, then the calibration of each distinct angular resolution configuration becomes essentially independent. Aside from the complexity inherent in calibrating such a system, the loss of relative precision would cause the errors in achievable atmospheric corrections to reach totally unacceptable levels for any quantitative use of the data. In addition to these untenable results, a variable-resolution design would be extremely difficult to monitor for degradation of the overall radiometric sensitivity.

These effects can be avoided only if the instrument is designed in such a way that the product of the detector's solid angle and the area of the final optics aperture (or the area of the detector and the final optics solid angle) are constant for all instrument fields of view.

Dynamic Range

Both panels emphasized that the dynamic range of the SeaWiFS instrument must be such that subtle variations in reflectance and temperature in open-ocean scenes of interest can be detected as well as major variations in scenes with high entropy, such as coastal waters. Within a fixed number of available quantizing bits these two requirements might conflict. Therefore, on-board adjustment of dynamic range is desirable. Possible solutions include programmable gain changes and nonlinear encoding. Careful consideration must also be given to the quantization of the points of the on-board calibration curve (i.e., from space and on-board calibration target(s)). It is anticipated that 10 bits of digitization should provide sufficient range for detection of the radiance from typical open-ocean scenes. However, additional studies should be conducted to firmly establish the required range and to determine whether gain changes, additional bits, and/or nonlinear digitization are desirable. Adjustable gain could also be used to enhance the signal at the reduced light levels occurring near the twilight portion of the orbit and to reduce the signal when employing the diffuser plate for in-flight instrument calibration.

Bright Target Saturation

The CZCS instrument experienced saturation-induced errors immediately after scanning over bright clouds or land. Following saturation, the data became unusable for distances up to 100 km, depending on the brightness of the clouds and their spatial extent. The SeaWiFS design should incorporate protective circuitry to minimize or, if possible, eliminate this type of instrument artifact.

Locational Accuracy

The location of data from all pixels in latitude-longitude coordinates is important for quantitative, scientific use of ocean-color imagery. In order to make these data useful, scientists must be able to utilize observations from many passes to generate time series and to do statistical analyses. This implies that the locational accuracy of data from different passes must be sufficiently precise to allow compositing. For these purposes, an absolute navigational accuracy of 1 km for high-resolution data and 5 km for low-resolution global data are required.

Maximum Scan Angle and Revisit Interval

The topic of revisit interval engendered much discussion during the workshop. In fact, having a daily revisit interval emerged as the *sine qua non* for most commercial and operational users. The baseline SeaWiFS instrument design presented during the initial workshop had a ±45° scan angle, resulting in a scan swath of 1500 km and a 2-day revisit interval. This design was selected based on the understanding that data from scan angles greater than about ±30° could not be interpreted quantitatively. However, as demonstrated in Section 2, commercial and operational users find great qualitative value in imagery acquired at scan angles in excess of 40°. With the Landsat-6 orbit, a scan angle of ±58.3° would be required to provide a daily revisit interval (2800 km swath), and this angle can be accommodated in the instrument design without difficulty. (This scan angle will give complete coverage at the equator with increasing overlap at higher and lower latitudes.) The positions of both panels on this issue and its resolution are presented below.

Commercial and Operational Users' Requirements for a Daily Revisit Interval

A daily revisit cycle was strongly recommended by commercial and operational users since the temporal variability of ocean-color and temperature features are of prime interest to them. A knowledge of the daily changes in these features is critical in understanding water-mass movements and in observing the movements of ocean-circulation features. For example, the movements of waves along the north wall of the Gulf Stream change significantly within a 1-day period. In addition, navigating ship movements for research station locations, positioning frontal boundaries for naval operations, and locating fish populations all require a daily revisit interval.

This revisit-interval requirement is based on experience. Usually cloud cover hampers routine coverage of areas of interest. With a revisit interval of every other day, if clouds hamper the image for 1 day (as is often the case in tropical or subtropical regions during summer and in polar regions during winter), then no imagery is obtained for a period of 4 days. This is not adequate, since many ocean frontal boundaries are moving too rapidly to be able to infer the temporal variability from data that differs by 4 days. Experience has also shown that the image-processing technique of "movie looping" successive images for flow visualization requires at least one image a day in frontal regions in order for the human eye to interpolate or see and understand the motions of the ocean features. Circulation patterns are readily discernable in movie loops using twice-daily AVHRR images. Once-daily images provide poor, but usable, results; however, circulation patterns are not recognizable with every-other-day coverage.

An important and attractive use of the SeaWiFS data will be in gaining an understanding of the temporal variability of the ocean surface. If the data are undersampled in time so that the daily scales, or bidaily scales, of variability are not obtained, the utility of the sensor for any type of near-real-time commercial or operational application would be greatly limited.

Research Users' Requirements for Revisit Interval

Research requirements for world-wide chlorophyll observations dictate global measurements at least once every 3 or 4 days. However, because imagery is lost due to cloud cover and sun glint, this requirement results in a need for global coverage on a 1- or 2-day cycle.

Currently, algorithms for correcting ocean-color data for the effects of atmospheric degradation are viable to a scan angle of approximately

30°, and qualitative observations of color features are possible at larger angles, depending on atmospheric conditions. In a like manner, the accuracy of sea-surface temperature measurements decreases as the amount of water-vapor absorption increases due to slant path viewing. Therefore, the scientific community was satisfied with 2-day coverage (45° scan). However, since the commercial and operational users needed daily coverage and since providing daily revisit would not interfere with use of the data for research purposes, the Research Panel agreed that daily coverage should be a baseline SeaWiFS requirement.

Scan Plane Tilt

Over the oceans, the data from a nadir view is contaminated by specular reflections from the oceans' surface (sun glint). In order to minimize this effect, the field of view must be pointable on command along track to 20° on either side of nadir, in addition to nadir (0°). Rapid slewing along track is desirable to minimize the loss of data.

Calibration

The research users expressed the absolute radiometric calibration accuracy goals for the SeaWiFS instrument as follows: When the instrument receives radiance levels from zero to the maximum level at its entrance aperture from a traceable (National Bureau of Standards) source, the output will be convertible to a value that is within 2% of the maximum radiance from the source for all reflectance bands. The desire for a lunar view to monitor the instrument's stability was also expressed.

For the thermal-emittance bands, a calibrated blackbody "standard" source should be used. The measurements in the thermal-emittance bands should give values that are within 1% of the maximum radiance from the source value, which should range from zero to the maximum level. Thermal calibration requires a minimum of two points, with three being desirable. A deep-space view serves as a zero-radiance reference, and two blackbodies, emitting at appropriate temperatures in the thermal range of the sensor, provide the other two points. It is recommended that every effort be made to include two blackbody sources in SeaWiFS.

System Requirements

Data Processing, Downlinks and Formats, and Dissemination

Commercial and Operational Users' Requirements

The spatial resolution, revisit interval, and access time recommended by the Commercial and Operational Users' Panel is summarized in Table 4. These requirements are based on the panel members' knowledge of the data products delivered from the CZCS and the AVHRR.

The Navy has established the Navy and Marine Corps Specific Data Requirements for Atmospheric-Environmental Data Measurements from Satellites. Recently an *ad hoc* committee of the Navy Space Oceanography Science Working Group reevaluated this list to recommend new scientific research and development programs and projects that should be carried out over the next decade in order to ensure proper utilization of forthcoming satellite resources by the Navy (Mitchell 1987). Of these requirements, those that might be addressed by the SeaWiFS sensor or next-generation instruments are included in Table 4.

As indicated in Table 4, most commercial and operational users need to receive data once a day within 24 hours or less of the time of acquisition, and some applications require daily, real-time reception. Two major user groups for commercial and operational applications can be identified, and the data downlinks required differ for each.

The first and largest group consists of merchant, fishing, and naval fleets who require a direct, daily downlink of data on local conditions. Currently, the worldwide merchant fleet comprises over 25,400 ships over 1000 gross tons, and there are 11,800 oceangoing fishing vessels. On the order of 400 naval vessels are types that would be useful to equip for reception of these data. The second user group represents the

Table 4. Commercial and Operational Users' Recommended Spatial Resolution, Revisit Interval and Data Access Time.

Discipline and Application	Resolution (Nominal at Nadir) (km)	Satellite Revisit Interval (hr)	Data Access Time (hr)
Fishing Industry			
Fish Location	1	48	24 max
Currents	1 and 4	48	24 max
Visibility	1 and 4	24 max	ASAP
Fisheries Research			
Development of Applications	1 and 4	48	24
Monitoring Larval Transport	1 and 4	48	24
Habitat Studies	1 and 4	48	N/A
Monitoring Unusual Environmental Events	1	48	24 max
Pollution Detection/Monitoring	1	48	24 max
Research and Development	1 and 4	48	24 max
Offshore Oil and Gas Industry			
Currents	1	48	24 max
Fronts/Eddies	1	48	24 max
Ice-Edge Location	1 and 4	48	24 max
Sediment	1 and 4	48	12-24
Pollution Detection/Monitoring	1 and 4	24 max	12 max
Research and Development	1 and 4	48	N/A
Marine Transportation Industry*			
Currents	1 and 4	24 max	24 max
Fronts/Eddies	1	24 max	12-24
Ice-Edge Location	1	24 max	12-24
Visibility	1 and 4	24 max	12-24
U.S. Navy**			
Sea Ice Cover	25	24	12
Sea-Surface Temperature	10/25	12/72	3/12
Turbidity (Differential Attenuation Coefficient)	0.5/25	3/12	0.25/3
Bioluminescence	5	24/72	6/12
Ocean Color (Chlorophyll)	1	24/72	6/12
Atmospheric Visibility (Aerosols)***	10	1	0.25
Littoral Sediment Transport***	10m	3/12	0.5/3
Shallow Water Bathymetry***	10/300m	1/3	0.25/24

* To improve centralized ship routing, SeaWiFS data covering all areas where these services are provided will be required. Daily global data at a resolution of 4.5 km will satisfy this requirement. Data of this resolution will enable routing services to improve their strategic advisories to take advantage of ocean currents and eddies. However, vessels at sea will require higher resolution data in real time to tactically position their vessels to take full advantage of these currents.

** If there are two parameters in the columns, the first is for a 4200 x 4200 km coverage, and the second is for global coverage.

*** In conjunction with other sensors.

value-added industry, some elements of the offshore oil and gas industry, and the Navy who would use a central-processing facility to preprocess global data prior to distribution.

The market comprising the commercial maritime fleet, for the most part, can be captured only if the data can be acquired daily in near real time, the price of the receiving equipment is modest, and its size relatively small. This implies direct reception by a nondirectional antenna. However, the value of such data to these users is great enough to justify a monthly subscription fee of $1000 to $2000. If all of these conditions cannot be met, there will be much less interest in the data on the part of these users.

Regarding reception by naval ships, the potential exists for SeaWiFS data to be received by existing naval systems that are capable of handling environmental data from satellites. Although these systems are not designed to handle SeaWiFS-type data or products derived from this sensor, it is important to consider that these systems represent a naval asset that can and will utilize SeaWiFS data, if the Navy's requirements for ocean-color and sea-surface data can be satisfied.

The attractiveness of SeaWiFS data to the Navy will be judged partially on the degree of compatibility in reception and data format with their existing systems. In this context, the Tactical Environmental Support System (TESS) is a major Navy system that might be a candidate for processing SeaWiFS data. The system's specifications have been documented by the Space and Naval Warfare Systems Command (1986). Also, by 1990 the Navy will have installed meteorological data receiver-recorder sets (AN/SMQ-11) on ships and at regional sites. For naval use, it is important for the SeaWiFS data to be available in a real-time direct-readout mode as well as being receivable (compatible frequency and format) by the AN/SMQ-11.

The second user group requires a stored-data downlink, since members of this group serve customers whose platforms are located throughout the world or implement operational applications whose regions of interest are worldwide. For most of these potential users it will be logistically and economically infeasible to establish and maintain receiving facilities at one or more locations. Hence, direct access to the data base in a central facility is needed. These users also require daily data acquisition and access to the data within 24 hours of its collection.

The need for data in near real time, documented in Table 4, is perhaps the most stringent commercial- and operational-user requirement. Since most users will be unable to supply their own satellite receiving station, central ground stations for users to access data is desired. User access to sequentially stored local area coverage (LAC) and global area coverage (GAC) data (i.e., last 48 hours of data) for review is useful in some applications, including forecasting models.[6] A real-time browse capability with the ability to capture some of the data is also needed.

Although digital and analog imagery are potential real- or near-real-time SeaWiFS data products, the commercial and operational user is most interested in receiving full-resolution, 10-bit, digital data, including ephemeris and calibration data. Data products in a digital format will permit the user to preprocess the data, correcting for atmospheric effects, prior to use. It appears there is very little demand for lesser quality analog data products.

6 For the SeaWiFS, LAC data will be at a spatial resolution of 1.13 km, GAC data will be at a spatial resolution of 4.5 km.

Research Users' Requirements

Satisfactory data processing and delivery is of the highest priority to the success of the SeaWiFS mission. Data processing and delivery for research users should meet the following requirements:

- *Global coverage at 4.5 km resolution with a 2-day revisit cycle*
- *Quick-look data products for selected areas within 12 hours of collection for near-real-time use in positioning of research vessels*
- *Level-1 imagery available in 7 days. Level-2 imagery for both high- and low-resolution data, available to the user within 10 days of observation.*[7]

Crossing Time

Landsats 1 through 5 have been maintained in a sun-synchronous, 705-km orbit with a 9:30 a.m. equatorial crossing time, principally because the main function of their sensors is to observe land masses. However, the observation of ocean color depends critically on having sunlight penetrate into the water where it is absorbed and backscattered into the sensor. For this reason, ideally, observations should be as near noon (solar zenith = 0°) as possible, but the research community agrees that there will be adequate water penetration by sunlight and that viable atmospheric correction will be possible if the equatorial crossing time is no earlier than 10:30 a.m. and no later than 1:30 p.m. This implies that the Landsat-6 crossing time be moved from its current 9:30 a.m. baseline to at least 10:30 a.m.[8]

Duty Cycle

The SeaWiFS instrument is designed to provide world coverage of the ocean basins, and many commercial, operational, and research applications will require data from the Mediterranean Sea, Central Atlantic, Pacific, and Indian oceans and regions in the Arctic and Antarctic. Selected regions will probably be routinely covered according to schedule while other regions will be viewed on an *ad hoc* basis. A 100% duty cycle would be ideal, since sea-surface temperature data could be acquired during nighttime, giving a swath of visible and infrared imagery during the day and a swath of infrared data at night. However, it is recognized that satellite power restrictions may not permit a full duty cycle. The capability of the satellite in this regard is discussed in Section 5.

Mission Life

In order to conduct the *in-situ* field work necessary to exploit the research value of ocean-color observations from space, experiments must be staged in a variety of seasons and conditions. Logistically, the spacecraft mission must last at least 3 years to encompass typical events, e.g., the occurrence of the El Niño phenomenon. In addition, even the coarsest values for ranges in interannual productivity are not known for most ocean areas. Hence, a minimum of 3 years is necessary to identify its scale of variability. The nominal lifetime of Landsat-6 is 5 years, and this extension in time is highly desirable. In this regard, the instrument's calibration must be constant or identifiable during the mission to allow valid comparisons of ocean values observed at different times.

Requirements Summary

Table 5 summarizes the goals for the SeaWiFS system set forth by the SeaWiFS Working Group.

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[7] Level-1 imagery is raw data in a reformatted structure with calibration and navigation information within the header. Level-2 imagery is geophysical data, not gridded nor resampled.

[8] This accords with the recommendations of the Geology and Evapotranspiration/Botany panels of the Thermal Infrared Working Group (Putnam 1986) that the equatorial crossing time of Landsat-6 be as close as possible to noon without excessive loss of imagery due to cloud cover, i.e., about 10:30 a.m.

Table 5. Users' Baseline Goals for the SeaWiFS System.

<table>
<tr><th>Parameter</th><th>Goal</th></tr>
<tr><td>Spectral Bands</td><td>
<table>
<tr><th>Band</th><th>Bandwidth</th><th>Minimum SNR/NEΔT</th></tr>
<tr><td>1</td><td>433 - 453 nm</td><td>510</td></tr>
<tr><td>2</td><td>490 - 510 nm</td><td>500</td></tr>
<tr><td>3</td><td>555 - 575 nm</td><td>350</td></tr>
<tr><td>4</td><td>655 - 675 nm</td><td>285</td></tr>
<tr><td>5</td><td>745 - 785 nm[1]</td><td>280</td></tr>
<tr><td>6</td><td>843 - 887 nm</td><td>280</td></tr>
<tr><td>7</td><td>10.5 - 11.5 μm</td><td>0.29K (at 300K)</td></tr>
<tr><td>8</td><td>11.5 - 12.5 μm</td><td>0.29K (at 300K)</td></tr>
</table>
</td></tr>
<tr><td>Spatial Resolution</td><td>1.13 km</td></tr>
<tr><td>Radiometric Accuracy:</td><td>5%, each band</td></tr>
<tr><td>Relative Precision</td><td>≤ 1%</td></tr>
<tr><td>Between-Band Precision</td><td>≤ 1%</td></tr>
<tr><td>Polarization Sensitivity</td><td>≤ 2% (worst case)</td></tr>
<tr><td>Dynamic Range</td><td>10 bits quantization (gain adjustable on board)</td></tr>
<tr><td>Bright Target Recovery</td><td>10 samples or less</td></tr>
<tr><td>Locational Accuracy</td><td>1 km absolute, high-resolution data; 5 km absolute, low-resolution data</td></tr>
<tr><td>Scan Plane Tilt</td><td>± 20°</td></tr>
<tr><td>Revisit Interval</td><td>1 day</td></tr>
<tr><td>Repeat Coverage</td><td>16 days</td></tr>
<tr><td>VNIR Absolute Radiometric Calibration</td><td>Within 2% of maximum radiance from source (traceable to NBS standards) when receiving radiation from zero to the maximum level.</td></tr>
<tr><td>TIR Absolute Radiometric Calibration</td><td>Within 1% of maximum radiance from each of two blackbody sources when receiving radiation from zero to the maximum level, a space view serving as a zero-radiance reference.</td></tr>
<tr><td>Data Access</td><td>Direct reception of local area coverage in near real time and direct access to global data base within 24 hours of collection.</td></tr>
<tr><td>Data Product Delivery</td><td>Seven days, Level-1 imagery, 10 days, Level-2 high- and low-resolution imagery.</td></tr>
<tr><td>Crossing Time</td><td>10:30 a.m. (between 10:30 a.m. and 1:30 p.m., acceptable).</td></tr>
<tr><td>Mission Life</td><td>Three years or more.</td></tr>
</table>

[1] Blocked from 760 - 770 nm

5
IMPLEMENTATION PANEL REPORT

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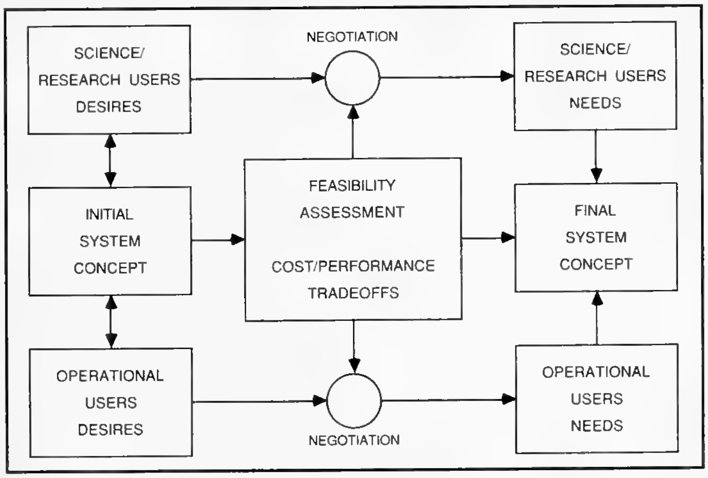
Implementation Panel Charter and Objectives

The purpose of the Implementation Panel was to translate the mission objectives of the commercial, operational, and research users into a workable system concept that would provide the data required to meet the users' needs. The work of this panel supported the other panels by defining the technical tradeoffs among the performance parameters (e.g., radiometric sensitivity versus spectral bandwidth) and by identifying the practical consequences of various options in terms of cost and complexity. Thus, the Implementation Panel established a feasibility envelope for the Working Group, leading to a system concept that was not only useful from the users' perspective, but also technically and economically realizable.

In essence, the role of the Implementation Panel was to pass the desires of the two user panels through the dual filters of physical and fiscal reality to arrive at a practical system concept meeting their needs. This process is illustrated in Figure 18, and the panel's charter is summarized below.

Figure 18. Interactive process leads to a workable system concept.



Implementation Panel Charter

- *Develop a complete system concept meeting user requirements.*
- *Establish system feasibility.*
- *Negotiate with user groups to arrive at a baseline system concept.*
- *Quantify the performance of the baseline system.*

The end-to-end definition of a spaceborne remote sensing system encompasses a wide variety of topics including:

- *Sensor Definition - What type of instrument is required to perform these missions, and what are its specific design and performance characteristics?*
- *Spacecraft Integration - How will this sensor be accommodated on the spacecraft in terms of its mass, power, and viewing requirements?*
- *On-board Data Handling - How will the data stream from the instrument be processed and stored on the spacecraft?*
- *Data Downlink Formatting - How will the sensor's data be formatted, and what are the specifics of the radio frequency channels for data transmission?*
- *Ground Reception and Processing - How and where will the downlinked data be received and processed?*
- *Data Product Definition - What are the specific end products to be derived from the data stream, and how will they be formatted?*
- *Data Access and Distribution - How and how soon after reception can the data be accessed and how and in what form will the data products be distributed?*
- *Algorithm Development - What software tools are required to produce useful output data products from the raw data? Who will develop these tools, and how will these tools be made available to users?*

These and other issues were addressed by the Implementation Panel during the working sessions in February and April 1987. The results are discussed in some detail in the balance of this section.

Sensor Definition

Design Tradeoffs

Usually a sensor concept is developed by performing tradeoffs among instrument performance characteristics, e.g., spatial, spectral, temporal, and radiometric resolution. However, in evolving the SeaWiFS design concept, many of the degrees of freedom normally available have already been constrained by spacecraft and data-format considerations. In addition, the high level of performance required of the sensor restricts the remaining design options.

First of all, the resources of the Landsat-6 spacecraft must be assumed to be principally dedicated to supporting the Enhanced Thematic Mapper (ETM) mission. Hence, the SeaWiFS instrument must be lightweight and require little power. Also, the current launch schedule for Landsat-6 (4th quarter of 1990) limits the SeaWiFS sensor design and fabrication efforts to an activity of about 20 to 24 months. This latter constraint leads to the requirement for an uncomplicated, proven-technology concept. Secondly, to minimize ground station requirements for users of SeaWiFS data, the SeaWiFS data product should be compatible with the AVHRR High-Resolution Picture Transmission (HRPT) format, for which there are many existing ground stations.

Since HRPT is formatted into six frames of data per second, the best choice of line rate for SeaWiFS is equal to this frame rate. At an orbital altitude of 705 km, this immediately defines the sensor ground sampling distance (GSD). That is, the satellite's orbital velocity moves it 1.13 km over the ground in 1/6 second; therefore, successive scan lines will be 1.13 km apart on the ground at nadir. Since data-processing requirements are eased when data are sampled in a square grid (equal angular sample spacing along the scan and the track directions), the sample spacing along track is also taken to be 1.13 km at nadir. This results in a nominal square instantaneous field of view (IFOV) of 1.6 mrad.

The requirement for a proven-technology approach leads to a choice of moderately sized detectors, particularly for the thermal-infrared (TIR) region. Existing instruments, such as the VAS/VISSR, and detectors developed for several Santa Barbara Research Center IR&D programs use long-wavelength infrared (LWIR) HgCdTe detectors in sizes ranging from 100 to 125 μm. Hence, the initial detector size selected was 100 μm. However, in optimizing the optics and mechanical-packaging design, a 20% increase in the nominal detector size was required, resulting in 122 μm detectors. This fixes the optical focal length at 7.64 cm (for an IFOV of 1.6 mrad).

The very low reflectivity of the ocean creates a requirement for high signal-to-noise performance in the visible and near-infrared (VNIR) region that drives the design towards concepts that use either long dwell times or time-delay integration (TDI). The only practical method for realizing long dwell times is to reduce the required scan rate by using more than one detector per band along the track direction. For example, if there are two detectors along track rather than one, then the required scan rate for contiguous scan swaths would be three scans per second instead of the six scans per second required for one detector. Since the scan rate is halved, the detector dwell time and, therefore, the available signal integration time, is doubled. Unfortunately, the very wide scan angles of the SeaWiFS instrument cause severe bowtie distortion when multiple detectors are used along track, i.e., the off-axis angle and the Earth's curvature cause the spacings between sample centers along track to become larger and larger on the ground as the scan angle increases. This effect is shown in Figure 19. In order to avoid this geometric distortion, the SeaWiFS design was constrained to using a single detector along track.

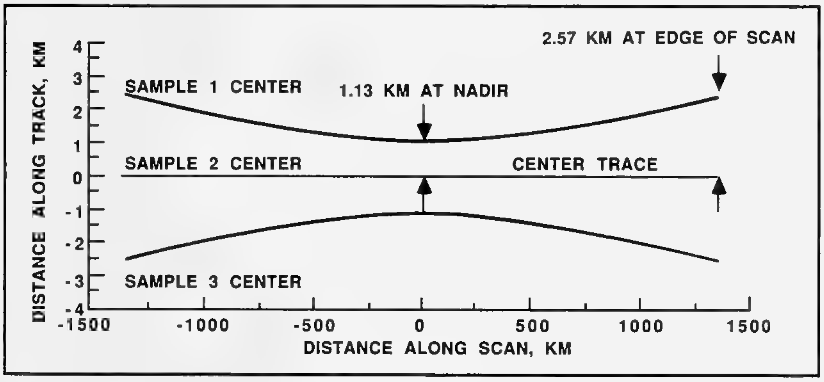


Figure 19. Bowtie distortion from more than one detector per band along track and wide scan angle.

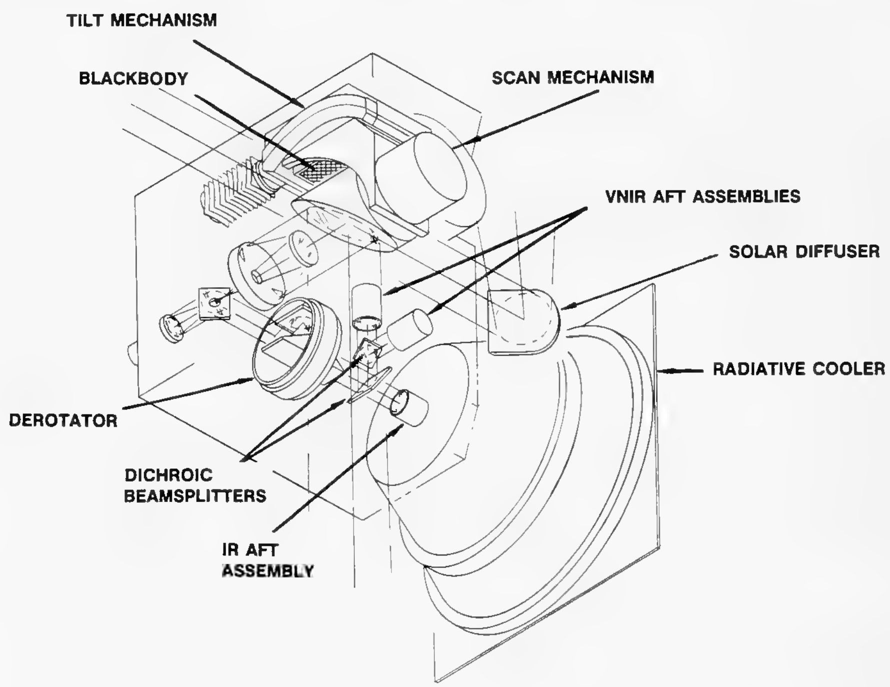


Figure 20. Initial SeaWiFS design.

This constraint left TDI as the primary technique for increasing the signal-to-noise ratio (SNR) performance of the VNIR bands. Initial performance estimates lead to a requirement for five detectors in TDI along scan, thereby providing a square-root-of-five improvement in SNR. Since sensor complexity (and cost and risk) increase rapidly with the number of detectors in TDI in the TIR region, those bands had to be limited to one detector per band.

Based on these parameters, summarized in Table 6, several different sensor configurations were evaluated. The initial design concept, developed as an input to the SeaWiFS Working Group, utilized a continuously rotating scanner (90 degree fold), followed by an afocal telescope and an image derotator, as shown in Figure 20. This design was compact, lightweight, high in performance, and low in risk (i.e., low in complexity). However, a polarization analysis showed that the design had a polarization sensitivity on the order of 5%, principally due to the large angles of incidence of the k-mirror derotator. Since, as discussed in Section 4, low polarization sensitivity is one of the key requirements of SeaWiFS, an alternate concept was pursued. The alternate concept entailed a design with as few reflections as possible, kept as close to normal incidence as possible. The resulting concept is described below.

Table 6. Initial SeaWiFS Design Parameters

Parameter	Value	Units
Scan Rate	6	lines per second
GSD	1.13	km
IFOV	1.6	mrad
Detector Size	122	µm
Optics Focal Length	7.64	cm
Number of Detectors	1	per TIR band
	5	per VNIR band, TDI along scan

Baseline SeaWiFS Design

In the proposed baseline SeaWiFS design concept, shown in Figure 21, the telescope rotates 360° about a pivot axis to scan the scene, thereby avoiding the use of a scan mirror and its associated polarization effects. Also, the fold mirrors used to direct the scene energy out of the telescope are located so as to minimize angles of incidence, and the half-angle mirror is placed in the plane perpendicular to the fold mirrors. This allows the polarization introduced by the half-angle mirror to be partially balanced by the fold mirrors' contributions. The resulting polarization sensitivity is less than 1.4%, well within the SeaWiFS requirement of 2%.

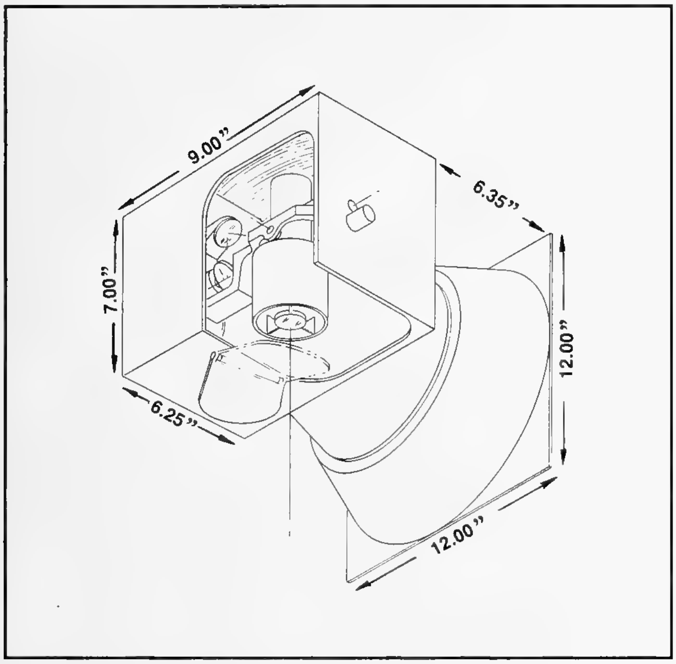


Figure 21. Baseline SeaWiFS design.

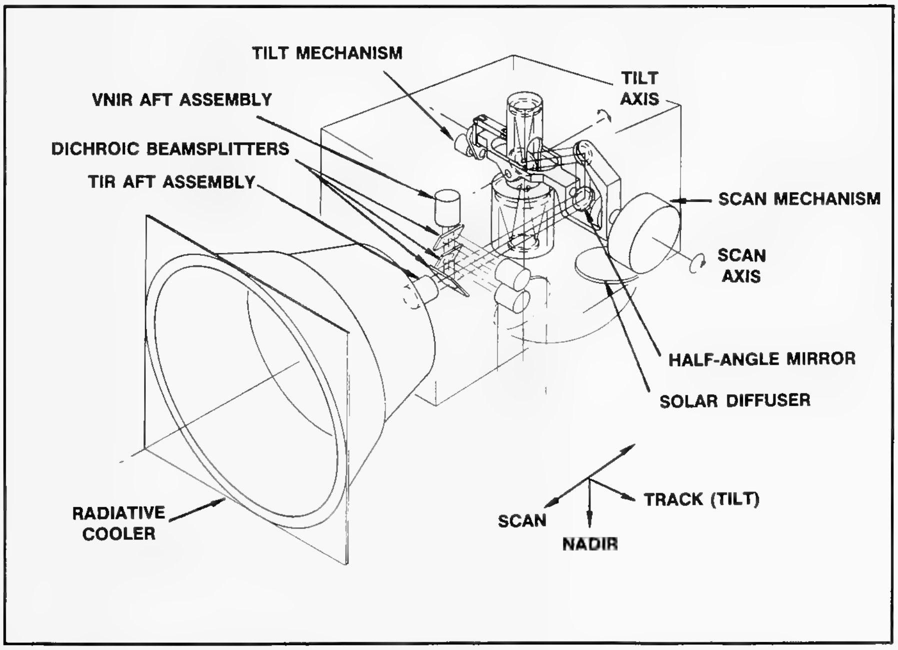
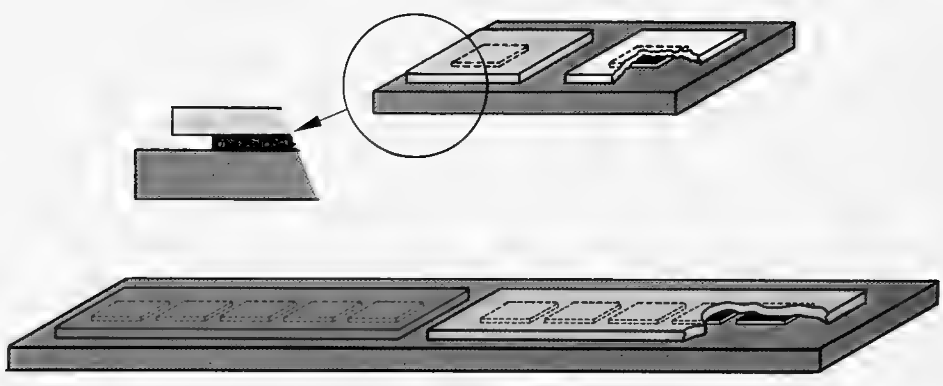


Figure 22. SeaWiFS focal-plane assembly layouts.



Specular sun reflection is avoided by tilting the telescope in the plane perpendicular to the scan plane (i.e., along track) to one of three positions: +20°, 0°, or -20°. The continuous 360° scan allows reference sources to be viewed during the nonactive, or non-scene-viewing, part of the scan, as well as allowing a deep-space view for a zero reference just before the scan begins[9] There is also a solar diffuser that can be inserted into the field of view of the sensor for calibration against the input solar radiance. This concept has an active scan of 58.3°, providing a scan length of 2800 km (i.e., daily global coverage).

After the scene energy leaves the 3X afocal telescope and fold mirrors, it is spectrally separated into four beams. All separations are performed by dichroic beamsplitters to provide co-registration of the beams on the ground . The first dichroic splits the TIR (3 to 13 μm) from the VNIR (0.4 to 1.0 μm). The TIR travels straight through and is focused onto the detectors in the TIR aft assembly (consisting of focusing optics and two detectors).

As mentioned above, one TIR detector per band minimizes the complexity of the instrument and allows a very simple radiative cooler to be used. The cooler envisioned, a standard product manufactured by Arthur D. Little Corp., provides a detector operating temperature of about 110K. The TIR detectors are discrete photoconductive HgCdTe elements. These detectors and the layout of their spectral filters are shown in Figure 22. The design of the aft assembly enables either two LWIR bands (e.g., 10.5 to 11.5 μm and 11.5 to 12.5 μm), two mid-wavelength infrared bands (e.g., 3.5 to 3.75 μm and 3.75 to 4.0 μm), or even one band from each region (e.g., 3.5 to 4.0 μm and 10.5 to 12.5 μm) to be accommodated. However, in accordance with the users' agreement discussed in Section 4, the baseline design consists of the two LWIR bands.

The VNIR light reflected from the first dichroic is spectrally separated by the second dichroic into a short-wavelength VNIR beam and a beam containing the two longest wavelength VNIR

[9]The 360° scan would also permit calibration from a lunar view. However, provision of regular lunar radiance calibration would require maneuvering the spacecraft. If deemed necessary, the occasions when a full moon happens to be within the field of view of the sensor could be calculated, and the sensor could be activated at these times.

bands. Assuming the baseline spectral bands agreed upon by the users' panels and shown in Table 7, this split would occur between 675 nm and 745 nm (i.e., between bands 4 and 5). The VNIR bands are paired so that a minimum of dichroic splits and VNIR aft assemblies are needed; this requires two sets of five VNIR detectors (for TDI in each band) per aft assembly. Since this array of detectors extends along the scan direction, the field of view required of the optical system is 1.0° (11 IFOVs, as shown in the detector layout in Figure 22). The remaining spectral split occurs between 510 nm and 555 nm (between bands 2 and 3). In each of the three VNIR aft assemblies, two VNIR bands are focused and detected. The VNIR detectors are photodiode/preamplifier hybrids.

Since the hardware synchronization of the existing HRPT ground stations is fixed at 6 frames per second and 11,090 10-bit words per frame, the data frame structure shown in Table 8 was selected. This format provides the proper synchronization blocks for the hardware, while still transmitting all of the required data, and yields an effective data rate of 665 kbps.

Sensor Performance

Three key performance parameters were examined: radiometric performance, modulation transfer function (MTF), and polarization sensitivity. For the radiometric performance estimates, the VNIR SNR was calculated, and the results are given in Table 9. For these SNRs, the sensor gain was chosen so that each band saturated at a radiance equivalent to the radiance from a turbid atmosphere with maximum water-leaving radiances. The signal radiances are typical of the maximum radiances expected at a 45° scan angle. As shown, the SeaWiFS performance exceeds the goals in all six VNIR bands. In addition, since the sensor has a selectable gain (one of four values) prior to quantization, performance can be tailored to various expected signal levels.

In the TIR region, the noise-equivalent temperature difference (NEΔT) for a 300K scene was calculated, and Table 10 shows these results for various spectral-band pairs. These values are all well within the performance goal of 0.29K at 300K set forth in Section 4.

The MTF was calculated at the Nyquist angular frequency of 0.313 cy/mrad. The results indicate that the VNIR MTF will be 0.36 in the scan direction and 0.57 in the track direction; TIR MTF will be 0.34 and 0.53 in the scan and track directions, respectively. These values correlate well with the nominal rule for sensor design that the MTF should equal or exceed 0.3 at the Nyquist frequency.

Table 7. SeaWiFS Baseline Spectral Bands

Band	Band Center	Band Width	Purpose
1	443 nm	20 nm	Low chlorophyll
2	500 nm	20 nm	Other pigments
3	565 nm	20 nm	Baseline chlorophyll
4	665 nm	20 nm	Subsurface scattering
5*	765 nm	40 nm	Atmospheric correction
6	865 nm	44 nm	Atmospheric correction
7	11 µm	1.0 µm	Sea-surface temperature
8	12 µm	1.0 µm	Sea-surface temperature

*Blocked from 759 to 770 nm to minimize interference from the oxygen absorption band.

Table 8. SeaWiFS Baseline Data Frame Format

Block	Size	Content	Use on TIROS/AVHRR
1	6	Synchronization	Synchronization
2	2	Identification	Identification
3	4	Time code	Time code
4	10	Telemetry	Telemetry
5	30	Spare	AVHRR back-scan data
6	50	Spare	AVHRR space-view data
7	1	Synchronization	Synchronization
8	520	Calibration	TIP data
9	127	Spare	Spare/synchronization
10	10,240	Data	Data
11	100	Synchronization	Synchronization

NOTE: Size is in 10-bit words,
calibration = (2 TIR bands) x (10 calibration samples + 100 space samples) + (6 VNIR bands) x (50 space samples), and
data = (8 bands) x (1274 samples per line) + (48 blanks).

Table 9. SeaWiFS Estimated VNIR Radiometric Performance

Band	Saturation Radiance[1] (mW/cm^2-sr-μm)	Signal Radiance[1] (mW/cm^2-sr-μm)	SeaWiFS SNR	SNR Goal[2]
1	12.0	10.28	692	510
2	9.0	7.48	703	500
3	7.5	5.21	610	350
4	3.8	2.85	507	285
5	2.7	1.96	552	280
6	1.9	1.40	589	280

1 H. R. Gordon 1987: personal communication.
2 See Table 3.

Table 10. SeaWiFS Estimated TIR Radiometric Performance

Band (μm)	NEΔT (K)
10.5-11.5	0.20
11.5-12.5	0.23
3.50-3.75	0.29
3.75-4.00	0.18
3.50-4.00	0.12
10.50-12.50	0.11

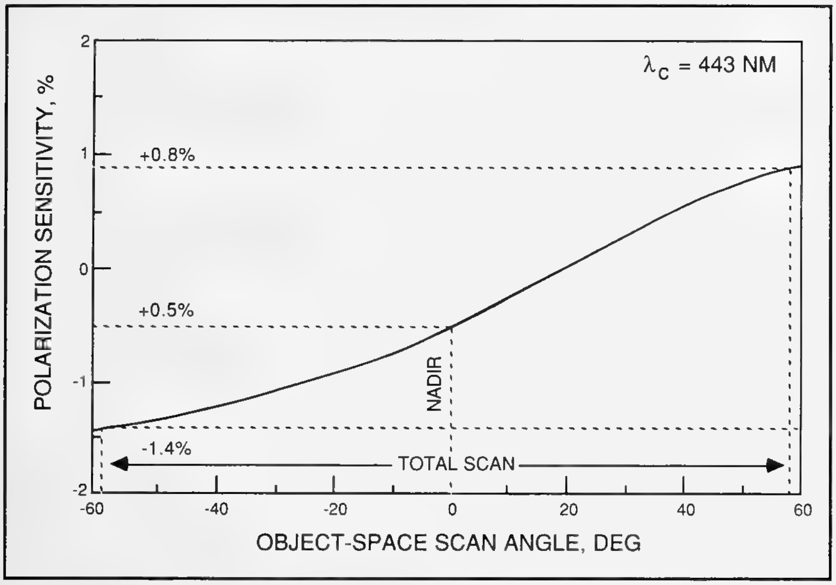


Figure 23. SeaWiFS estimated polarization sensitivity.

The polarization sensitivity depends on the scan angle, since the major contributor is the half-angle mirror. Figure 23 shows the SeaWiFS polarization sensitivity as a function of scan angle for fresh silver at a wavelength of 443 nm.[10] The Thematic Mapper mirrors have measured polarization values very close to fresh silver, so this is a reasonable approximation to use. Also, calculating the polarization sensitivity at 443 nm is a worst case; the values are less at longer VNIR wavelengths. The figure shows that the polarization sensitivity is less than 1.4% and is significantly lower in the region around nadir. This allows those whose applications require even lower polarization sensitivities to still derive useful data from the SeaWiFS by using only the data acquired from near nadir.

Calibration

The high degree of calibration accuracy required for SeaWiFS, described in Section 4, can be met only by using a multistep calibration process since the calibration accuracy and precision called for probably cannot be achieved through preflight ground calibration alone. During ground calibration, a calibration accuracy of 3% will probably be acheivable for all bands. After launch, a data-gathering and calibration analysis program will be required, as suggested in Section 3. Data gathered by ships coincident with SeaWiFS imagery will enable accurate calibration of the radiance measurements, probably to a calibration accuracy of about 1%.

Calibration stability is actually more important than absolute radiometric precision. Because of this, a solar diffuser has been included in the instrument, allowing periodic calibration of SeaWiFS against the known exo-atmospheric solar illumination. Calibration against a lunar view was also requested by the users, since the moon acts as an almost ideal solar diffuser. Unfortunately, to provide this view on demand would require either an attitude adjustment of the spacecraft or the capability to point the instrument. Therefore, the moon will be considered a "target of opportunity," and a lunar calibration will take place only when the moon can be viewed during the space-view interval of the scan cycle.

[10]Assumes 100% polarized input.

Spacecraft Integration

Spacecraft Configuration

The current spacecraft configuration into which the SeaWiFS sensor would be integrated, differs from the original Landsat-6 spacecraft configuration due to programmatic changes and changes in the launch vehicle; the baseline launch vehicle is now expected to be a Titan II. The concept is derived from a DMSP/TIROS-type system, but it has been extended to meet the needs of the EOSAT mission and will change the spacecraft's flight orientation; the Titan II thrust axis (spacecraft long axis) is now the roll axis of the spacecraft and is perpendicular to the local vertical and in the plane of the orbit. Table 11 tabulates the key performance features of this spacecraft.

The design concept utilizes equipment that is currently under NOAA contract for the STS version of the Landsat-6 spacecraft, combined with the latest versions of the DMSP S-15 program hardware.

Table 11. Spacecraft Characteristics, Exclusive of Payload

Capacity:	6000 pounds including the apogee kick motor
Orbit:	Sun synchronous, 98.2° inclination; 705 km altitude
Power:	Solar array: 156 sq ft Batteries: 150 A-hr capacity Sun-oriented array 28V regulated power bus 1310W EOL array power to the load 1140W peak power at night
Attitude:	Star-referenced inertial guidance 0.01° about all axes Magnetic torquers and reaction wheels for attitude control
Propulsion:	Thiokol Star 37 XFP solid motor Hydrazine engines: 100 lbs and 0.5 lb Cold gas control system Hydrazine orbit adjust subsystem
Thermal:	Louvers and heaters combined with thermal blankets
Communications:	X-Band System for the ETM mission data with three transmitters redundantly multiplexed to high-gain steerable antennas, S-Band command, telemetry, and ranging on an omnidirectional antenna
Command Telemetry:	Command and telemetry subsystem derived from the DMSP system of hardware in conjunction with Landsat units where appropriate.

The SeaWiFS subsystem can best be accommodated by the spacecraft system if it is designed to utilize the smallest possible amount of the growth-weight allocation and does not significantly increase the demand for critical power subsystem resources. This goal will be achieved best if the data-processing requirements on the spacecraft and ground segments are integrated. A more detailed System Integration Study is being conducted by EOSAT to better integrate the SeaWiFS and the ETM data requirements and to determine optimal ways of accommodating SeaWiFS on Landsat-6.

Required Modifications to the Landsat-6 Spacecraft for Integration of SeaWiFS

Although the baseline for the SeaWiFS equipment is still being developed at this time, NASA/GSFC has proposed a potential configuration for it. Figure 24 shows the block diagram for this configuration.

It is assumed that the SeaWiFS scan motor will be running continuously. However, the instrument will take data only during the 40 minutes per orbit when useable data can be acquired and will provide recorded data and real-time data transmission. During the instrument's operating phase, the sensor, data formatter, and signal switching unit will be operating, as well as recording units for global area coverage data and one S-Band or UHF transmitter. Other tape recorders will be used for up to 10 minutes during the 40 minutes of data-taking on each orbit to record high-resolution data. After the data are collected, the recorded information will be transmitted to an EOSAT ground receiving station and then relayed to the NASA ground-processing facility. In the recorder playback mode, the signal switching unit, one recorder unit, and one S-band transmitter will be operating. SeaWiFS equipment and their key features are listed in Table 12.

The projected total subsystem weight of 153 pounds is well within the 360 pounds available for growth in the currently proposed spacecraft. Hence, the spacecraft can support the SeaWiFS mission and might also be able to satisfy an EOSAT goal of adding a third, spare wideband recorder weighing 157 pounds.

Figure 24. Block diagram of proposed configuration of the SeaWiFS on the Landsat-6 spacecraft.

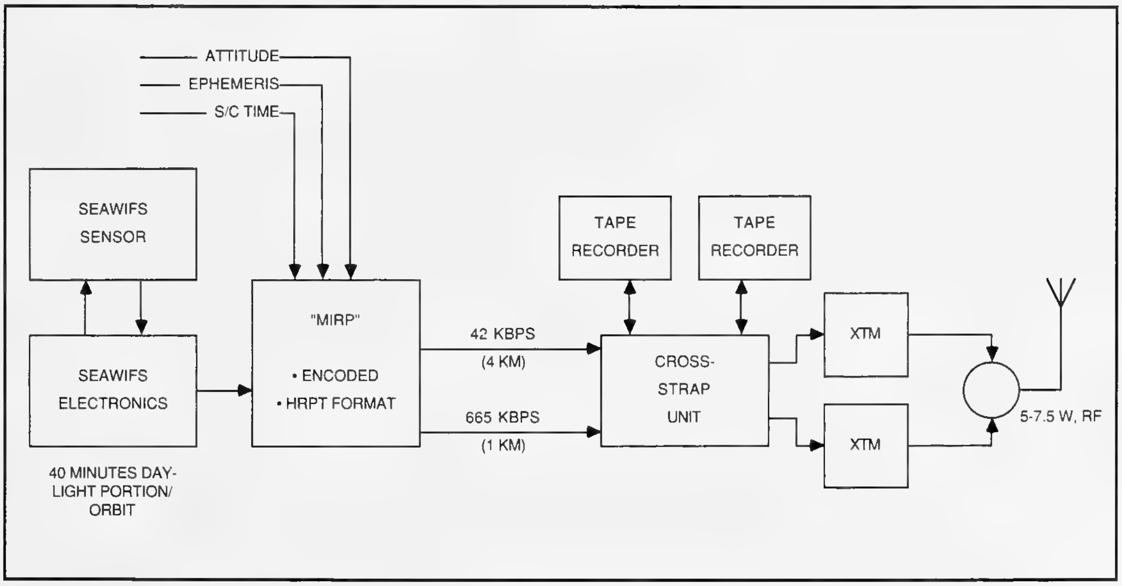


Table 12. Weight and Power Characteristics of the SeaWiFS System

Equipment	Acronym	Weight (lbs)	Power (watts)	Qty	Comments
Sensor	CWS	18	--	1	
Electronics	CWE	7	63	1	Portion of CWS
Heaters	CWH	--	10	1	Motor & heater
Data Formatter	CDF	10	10	1	Preliminary Estimate
Switch Unit	CSU	5	5	1	Preliminary Estimate
Data Recorder	CTR	21.6	15 23	2	Record Playback
XMT S-Band	CTS	6.2	26	2	
Antenna	CAS	1	--	1	
S-Band	CTU	6.2	26	2	
XMT UHF Band	CAU	1	--	1	
Antenna UHF	CHN	5	--	1	
Harness	CHN	5	--	1	
Thermal	CMS	10	--	1	
Brackets	CMS	23	--	1	
Balances					
TOTALS		**153**	**268**		

Data Management

On-Board Data Processing

The sensor's data stream will be formatted and the spacecraft's time code and ephemeris data incorporated into the format prior to recording or transmitting data. The attitude of the spacecraft (pitch, roll and yaw) will be reported with a within-limits flag.

The baseline data format is similar to HRPT, and the high-resolution data from the sensor will nearly fill this format at 665 kbps. The low-resolution data rate is one-fourth the resolution and one-sixteenth the data rate, or 41.6 kbps. The low-resolution data will be reformatted to transmit at 56 kbps so they can be received by commercially available demodulators. The high- and the low-resolution data for real-time transmission will be encrypted by the SeaWiFS Data Formatter to protect their commercial value. Subscribers will be furnished encryption keys.

On-Board Data Storage

The maximum gap in the ability to receive a direct downlink from the satellite at the EOSAT ground station amounts to about eight orbits per day. Since the initially planned tape-recorder capacity would be reached after four orbits, at first a second ground station was premised. However, an alternate configuration that combines the spacecraft support resources for the SeaWiFS and ETM sensors was evaluated, and this configuration, in conjunction with an extension in tape-recorder capacity, obviates the need for a second ground station. In the alternate configuration, a second transport is added to both ETM wideband recorders, i.e., the SeaWiFS and the ETM use identical recording units, and the tape speed is altered to increase its capacity. Not only does this provide maximum redundancy, but storage capacity is provided for SeaWiFS data from an additional four orbits, giving a total storage capacity of eight orbits per day.

Eliminating the need for a second ground station offers two main advantages. First, the spacecraft can employ existing communications equipment for the playback data, reducing the amount of equipment on the spacecraft and requiring less operating power.[11] Second, the global data set would be available at a single location at the EOSAT ground receiving station, and there would be no delays in data access due to shipping from a second, remote facility. The System Integration Study is examining tradeoffs between increased spacecraft tape recorder capacity and the possibility of an additional ground receiving station, including the power required for nighttime data playback.

Data Downlinks

Current plans are for SeaWiFS to have three data downlinks. The first would be a stored-data link that would provide 40 minutes of global area coverage (GAC) and 10 minutes of local area coverage (LAC) to the EOSAT ground receiving facility. These data would be downlinked directly on the X-band. EOSAT will collect these data on some form of computer-compatible media and make them available to NASA for transfer to the NASA/GSFC ground receiving facility.

The second data downlink would convey real-time, high-resolution LAC data, downlinked at 665 kbps, at a frequency compatible with currently operating HRPT receiving stations and planned naval AN/SMQ-11 stations (probably L-band or S-band). The third data link would convey real-time, low-resolution GAC data to subscribers on a UHF frequency. These data would be transmitted at 56 kbps, allowing some subscribers (e.g., moderately sized ships at sea that cannot mount large, trainable, dish antennas) to use relatively inexpensive, commercially available receivers and fixed receiving antennas.

The direct data downlinks will be provided on a subscription basis. No tape-recorded data would be available on either real-time link, and the real-time data will be encrypted to protect their commercial value. A key will probably be used for encryption and each subscriber will be supplied with a suitable key.

The Implementation Panel recognized that reception of high-resolution LAC data is also desired by users restricted to unsophisticated receiving stations. However, transmitting high-resolution data to a fixed antenna would require much greater power in the spacecraft transmitter than is available on the currently envisioned Landsat spacecraft. Adding the required power would not only be costly, but also might exceed the weight limitations of the spacecraft. One potential solution to this problem would be to process the 1.13-km data immediately upon receipt by the ground-receiving site, redistributing the data products via radio facsimile or telecommunications links.

The desire of some operational users to have near-real-time access to a global data set presents a greater problem, since the current data-handling plans for the tape-recorded global data set do not allow real-time access. A study is being undertaken to determine the feasibility of rerouting the X-band, downlinked global data set via communication links to the processing facilities of commercial and operational users. However, this strategy is likely to be quite costly.

Ground-Station Data Processing for Research Users

Global data for research will be acquired from the EOSAT ground station on computer-compatible media and routed to a government ground-processing site. As currently envisioned, NASA will serve as the agent for processing and distributing these data.

[11] It is important to note that one of the key spacecraft limitations encountered in accommodating both the SeaWiFS mission and ETM mission on Landsat-6 lies in the power subsystem. These power constraints will affect mission operations, particularly with respect to nighttime operations. Some compromises in the ETM and SeaWiFS task profiles may be necessary to accommodate the SeaWiFS mission. However, if the required compromises are unacceptable, expansion of spacecraft power resources will be addressed.

The following levels of data processing will be undertaken:

- *Level 0. This is the raw data stream, i.e., what is contained on the ground station's tapes. This data stream will have navigation, predicted ephemeris elements, and attitude and housekeeping data within it.*

- *Level 1. This is Level 0 data in a reformatted structure, reversible to Level 0, with calibration and navigation information within the header. The data product from this level of processing contains the total radiances for visible and near-infrared bands and brightness temperatures for thermal bands. The basic block of data will be determined by the recording period. That is, for 4.5-km data, the basic block of data will be an entire orbit. For 1.13-km data, the smallest block of data will be the minimum recording period. A minimum recording period of 2 minutes is recommended, with a maximum of 12 minutes.*

- *Level 2. This level of data processing represents the geophysical data in satellite swath format, not gridded nor resampled, and not reversible to Level 1 format. The data product is a product derived from Level-1 containing chlorophyll-a, other pigments, water-leaving radiances, and sea-surface temperature.*

- *Level 3. This level of data processing consists of the geophysical data that have been resampled and/or composited - not reversible to Level-1 format. The data products are daily mosaics of nine Level-2 images on an 18-km grid with statistics including the number of pixels, number of days, and sums of squares for each grid element. Weekly composites will be made of the geophysical data.*

Browse images will be available, consisting of all Level-1, -2, and -3 data products recorded on video disks.

NASA will process all recorded high- and low-resolution data to Level-3 data products. The processing capacity has been sized to be twice that of the raw data rate to allow for processing backlog, implementation of improved algorithms, and possible processing of locally recorded HRPT data supplied to NASA.

Archiving and Distribution of Data for Research

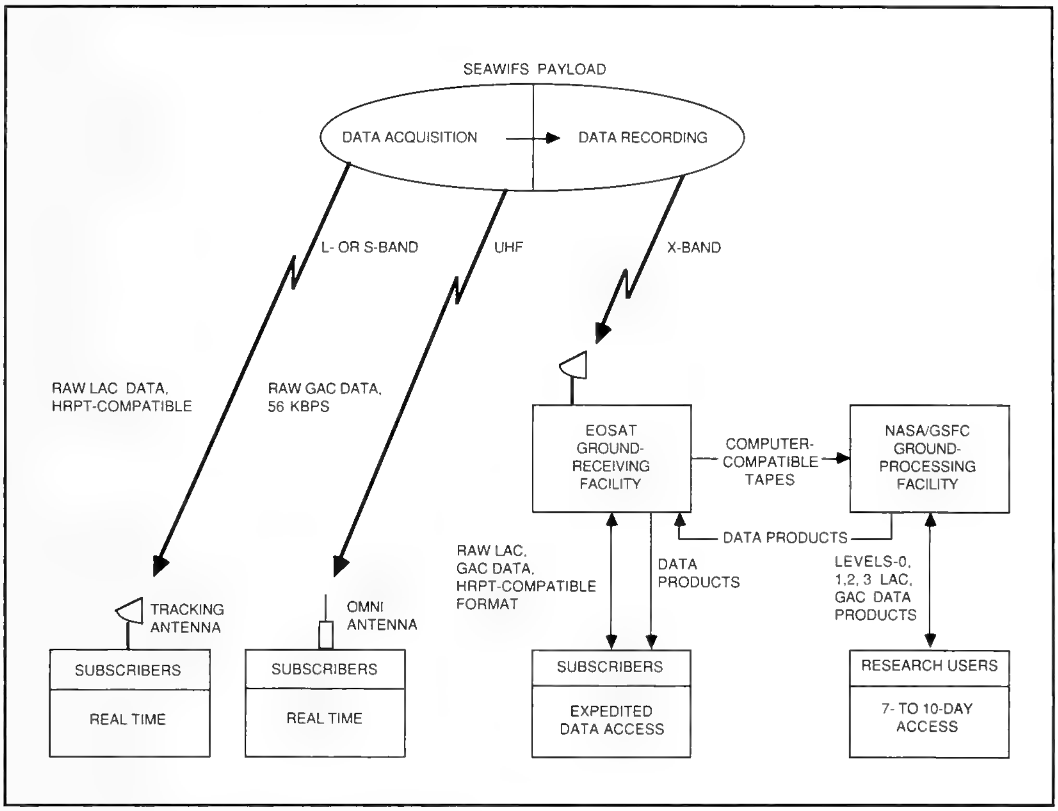
All data products will be archived and distributed through NSSDC/NODS. Three months of Level-1 data products and all Level-3 data products will be accessible on-line at any time. Data will be loaded into the archive at monthly intervals, 1 to 2 months following collection. Catalogue listings and inventory listings for digital and analog data, searchable by time and location via SPAN or other network systems, will be maintained and updated using the processing data base.

NASA/GFSC will provide data products to its principal investigators, Announcement-of-Opportunity Investigators, and other national and international research users through the archival and distribution system described above. NASA will not offer its stored data to commercial or operational users in the private sector nor operational users within the government. EOSAT will acquire copies of the data products for its archive to serve all commercial and operational users.

The system for processing and archiving the research data from SeaWiFS is based on the CZCS global data-processing and archiving effort underway at GSFC in terms of hardware, software, and methodology. Existing algorithms and processing times have been assumed for determining pigment concentration and sea-surface temperature.

Figure 25 summarizes the baseline SeaWiFS data acquisition and dissemination plans.

Figure 25. Baseline SeaWiFS data acquisition and dissemination plans.



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Appendix A

DISCIPLINE – SPECIFIC VOCABULARY AND ACRONYMS

Definitions

Advection

The flow of a current of water (as in the sea); also: transport by such a flow

Anthropogenic

Of, relating to, or resulting from the influence of human beings on nature

Case-1 waters

Waters in which phytoplankton and derivatives dominate in determining optical properties - generally the open ocean

Case-2 waters

Waters in which inorganic and/or organic sediments dominate in determining optical properties - generally coastal waters

Epipelagic

Of, relating to, or constituting the part of the oceanic zone into which enough light penetrates for photosynthesis

Euphotic

Of, relating to, or constituting the upper layers of a body of water into which sufficient light penetrates to permit growth of green plants

Eutrophic

Water rich in dissolved nutrients and often shallow with a seasonal deficiency in dissolved oxygen

Fluvial

Of, relating to, or living in a stream or river

Gelbstoffe

Yellow substance or blue absorbing matter

Gyre

A giant circular oceanic surface current

Insolation

Rate of delivery of direct solar radiation per unit of horizontal surface

Intergrade (v)

To merge gradually, one with another, through a continuous series of intermediate forms

Intergrade (n)

An intermediate form

Macrophytes

Large aquatic plants or seaweeds

Mesoscale

Of, or relating to, a meteorological or oceanographic phenomenon approximately 1 to 100 km in horizontal extent

Mesotrophic

Having a moderate amount of dissolved nutrients

Movie loop

A piece of film whose ends are spliced together so as to project the same material continuously

Oligotrophic

Deficient in nutrients and plant biomass

Phaeophytin-*a*

Degradation product of chlorophyll-*a*

Phytoplankton

Single-cell, drifting algae of the sea and other bodies of water. Most require only carbon dioxide or carbonates as a source of carbon and inorganic nutrients for metabolic synthesis.

Phytoplankton pigments

Any of various photosynthetic pigments of which chlorophyll-*a* and phaeophytin-*a* are usually the dominant components

Plankton

Passively floating or weakly swimming animal and plant life of a body of water

Recruitment

The addition of young to a natural population

Trophic level

One of the hierarchical strata of a food web characterized by organisms that are the same number of steps removed from the primary producers

Troposphere

The portion of the atmosphere below the stratosphere that extends outward about 7 to 10 miles from the Earth's surface and in which temperature generally decreases rapidly with altitude, clouds form, and convection is active

Zooplankton

Animal plankton

Acronyms

APT

Analogue Picture Transmission

AVHRR

Advanced Very High Resolution Radiometer

CZCS

Coastal Zone Color Scanner

ESA

European Space Agency

ETM
Enhanced Thematic Mapper

GAC
Global Area Coverage

GOFS
Global Ocean Flux Study

GSFC
Goddard Space Flight Center

HRPT
High-Resolution Picture Transmission

IFOV
Instantaneous Field of View

LAC
Local Area Coverage

LWIR
Long-wavelength Infrared

MAREX
Marine Resources Experiment

MIRP
Manipulated Information Rate Processor

NASA
National Aeronautics and Space Administration

NEΔT
Noise-Equivalent Temperature Difference

NEPRF
Naval Environmental Prediction and Research Facility

NMFS
National Marine Fisheries Service

OCI
Ocean Color Imager

ONR
Office of Naval Research

SNR
Signal-to-noise ratio

TESS
Tactical Environmental Support System

TIR
Thermal Infrared

VNIR
Visible and Near Infrared

Appendix B

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