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Abstract

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission is based on the scientific heritage of the Coastal Zone Color Scanner (CZCS), a proof-of-concept instrument carried on the National Aeronautics and Space Administration (NASA) NIMBUS-7 environmental satellite for the purpose of measuring upwelling radiance from the ocean surface. The CZCS mission provided the first observations of ocean color from space, and over the mission lifetime of 1978–1986, allowed oceanographers an initial opportunity to observe the variable patterns of global biological productivity. One of the key elements of the CZCS mission was the formation of the CZCS NIMBUS Experiment Team (NET), a group of optical physicists and biological oceanographers. The CZCS NET was designated to validate the accuracy of the CZCS radiometric measurements and to connect the instrument's measurements to standard measures of oceanic biological productivity and optical seawater clarity. In the period following the cessation of CZCS observations, some of the insight and experience gained by the CZCS NET activity has dissipated as several proposed follow-on sensors failed to achieve active status. The SeaWiFS mission will be the first dedicated orbital successor to CZCS; it in turn precedes observations by the Moderate Resolution Imaging Spectroradiometer (MODIS) of the Earth Observing System (EOS). Since the CZCS NET experience is an important model for SeaWiFS and MODIS surface truth efforts, this document is intended to provide a comprehensive review of the validation of oceanographic data for the first orbital ocean color sensor mission. This document also summarizes the history of the CZCS NET activities. The references listed in the Bibliography are a listing of published scientific research which relied upon the CZCS NET algorithms, or research which was conducted on the basis of CZCS mission elements.

1. INTRODUCTION

The Coastal Zone Color Scanner (CZCS) was launched on board the NIMBUS-7 environmental satellite on 24 October 1978. The CZCS was considered a *proof-of-concept* mission, and was only operated on a limited basis, nominally two hours per day, due to the power budget for the other NIMBUS-7 instruments. The CZCS data was subsequently reprocessed by Goddard Space Flight Center (GSFC) and the University of Miami, as described in Feldman et al. (1989). Algorithms for the calculation of total pigment concentration and the diffuse attenuation coefficient K for light at a wavelength of 490 nm, $K(490)$, were created for CZCS remotely sensed data. These algorithms were based on data collected during a series of pre- and post-launch ocean optical survey cruises conducted by members of the CZCS NIMBUS Experiment Team (NET).

The CZCS was a scanning radiometer with five spectral bands at 443, 520, 550, 670, and 750 nm in the visible and near-infrared (IR) range, and a sixth thermal IR band at 10.5–12.5 μm. The NIMBUS-7 orbit was placed at a height of 955 km, giving the CZCS a ground resolution of 825×825 m. The CZCS was equipped with a 20° tilt capability, in 2° increments, to minimize the effects of sun glint. The CZCS operated from 1978–86, producing approximately 250,000 minutes of data (about 125,000 two-minute scenes) for oceanographic research. Each scene contained 970 scan lines.

The CZCS NET data set, collected in both Case 1 (clear, low productivity) and Case 2 (turbid, high productivity, coastal) waters (Morel and Prieur 1977), forms the primary data set for the CZCS pigment algorithm to which improved algorithms for the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission will initially be compared. In order to provide an accessible resource for this baseline data set, the SeaWiFS Project initiated a compilation of the CZCS NET ocean optical surveys to serve as both a guideline for the SeaWiFS algorithm development process and a review of the CZCS in-water calibration and validation effort.

Despite continual use of the CZCS NET data in the years following the launch of NIMBUS-7, no single, comprehensive overview of CZCS NET research activities has been compiled. Due to the importance of this data set, it is clearly advantageous to the SeaWiFS Project, as well as subsequent satellite missions carrying ocean color sensors planned by the United States and other countries, to compile a single document for archive and reference. The National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) program plans a mission (called EOS-Color) similar to SeaWiFS in the late 1990s, and plans several deployments of the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS will be carried on the EOS multi-instrument orbital platforms with morning and afternoon equatorial crossing times, designated as the EOS-AM and -PM platforms. The Japanese National Space Development Agency (NASDA) Advanced Earth Observation Satellite (ADEOS) will carry the Ocean Color Temperature Sensor (OCTS). The Medium Resolution Imaging Spectrometer (MERIS) is designated for a late 1990s European Space Agency (ESA) mission. Given the manifest of approved or projected ocean color missions, compilation of the CZCS NET effort is both timely and useful.

1.1 The CZCS NET Program

1.1.1 Membership

The scientists who participated in the CZCS NET team program are shown in Table 1. The name of each scientist is followed by his affiliation during the CZCS NET activity and current affiliation or status (if known).

1.2 CZCS NET Areas of Responsibility

The following presents a concise summary of the designated responsibilities of each member of the original CZCS NET, along with a supporting description of activities the member carried out during his CZCS NET tenure.

Frank Anderson
South African Representative to the CZCS NET

Anderson and his colleagues conducted their research in South African waters concerning ocean optics and fisheries applications of CZCS data.

Roswell Austin
Diffuse Attenuation Coefficient

Austin employed data from several cruise stations to develop the robust $K(490)$ algorithm used by the CZCS NET. Austin and Petzold (1981) describes the $K(490)$ algorithm and methods used in the beam attenuation measurements.

Edward Baker
In Situ Concentrations

Baker's measurements of *in situ* concentrations of total, inorganic, and organic particulate matter during the pre- and post-launch cruise program aided the development of CZCS algorithms for both pigment concentration and water clarity.

Dennis Clark
Global Case 1 Water Phytopigment Concentration Algorithm

In conjunction with several other CZCS NET members, Clark conducted pre- and post-launch validation cruises. He selected bio-optical data from cruise stations for the development of a functional relationship between spectral absorption and pigment concentration. The location of the cruise stations, the general methodology for bio-optical measurements made by the CZCS NET, and the CZCS pigment algorithm are described in Clark (1981). He was also responsible for level-2 products.

Sayed El-Sayed
Post-launch Investigations of Pigment Concentrations

El-Sayed coordinated one of two prelaunch cruises for the investigation of ocean optical properties aboard the R/V *Gyre*. The Texas A&M group conducted research in conjunction with the CZCS mission in several oceanic regions during the course of CZCS operation, particularly in the Southern Ocean and the Mediterranean Basin investigating pigment concentrations. He also acted as the liaison between the CZCS NET and data system personnel, and contractors at GSFC during the development of the level-2 product algorithm and its validation.

Warren Hovis
CZCS NET Chairman

Prior to the CZCS mission, Hovis conducted airborne ocean observations that supported the CZCS mission concept. During the prelaunch phase he coordinated the development of initial algorithms and acted as liaison to the NIMBUS-G mission planning. Following launch, his activities included the scheduling of CZCS operations, instrument calibration, facilitating the production of data products, team coordination, level-1 products, and the monitoring of instrument function.

Howard Gordon
Atmospheric Correction Algorithms and Surface Truth Measurements

Gordon's description of the CZCS atmospheric correction algorithm has been published in several works. *Ocean Colour: Theory and Applications in a Decade of CZCS Experience* (Barale and Schlittenhardt 1992) has a chapter devoted to the subject. The primary function of CZCS NET cruises was to provide measurements of water-leaving radiance that could be compared to atmospherically corrected values measured by the CZCS. These measurements allowed determination of the best method for correcting ocean radiances for light scattering induced by the intervening atmosphere and aerosols. Gordon et al. (1980 and 1983a) provide good overviews of the atmospheric correction method.

During the post-launch cruises, Gordon and his associates conducted measurements of the backscattering coefficient, for correlation with pigment concentration, and made preliminary measurements of aerosol optical thickness.

James Mueller
Data Production and Instrument Calibration

Mueller's CZCS NET activities included improvements to CZCS data processing, monitoring of instrument operation and sensitivity degradation, scheduling of observations, and instrument calibration. Mueller acted as the NIMBUS-7 Applications Scientist for Oceanography during his CZCS NET tenure at GSFC.

Table 1. Institutional affiliations of the NET during the period of the CZCS NET activity and at present.

Name	*Affiliation as NET Member*	*Present Affiliation*
Warren Hovis	GSFC and NOAA/NESS[1]	Ret., Bradenton, Florida
Dennis Clark	NOAA/NESS	NOAA/NESDIS[2]
Frank Anderson	Nat'l. Research Inst. for Oceanology, S. Africa	Ret., Cape Town, S. Africa
Roswell Austin	SIO[3] Visibility Laboratory	CHORS/SDSU[4]
Howard Gordon	University of Miami, Miami, FL	Same
James Mueller	GSFC	CHORS/SDSU
Sayed Z. El-Sayed	Texas A&M University	same
Boris Sturm	*Commissione delle Comunita Europee* JRC[5]	Same
Robert Wrigley	NASA Ames Research Center	Same
Charles Yentsch	Bigelow Laboratory for Ocean Sciences	Same
John Apel	NOAA/PMEL[6], Seattle, WA	JHU-APL[7]
Edward Baker	NOAA/PMEL, Seattle, WA	Same
Wayne Esaias[8]	GSFC	GSFC
Charles McClain[8]	GSFC	GSFC

1. National Oceanic and Atmospheric Administration/National Environmental Satellite Service
2. National Environmental Satellite Data Information Service
3. Scripps Institution of Oceanography
4. Center for Hydro-Optics and Remote Sensing/San Diego State University
5. Joint Research Centre, Ispra, Italy
6. Pacific Marine Environmental Laboratory
7. Johns Hopkins University Applied Physics Laboratory
8. Voted associate NET members during the latter stages of the CZCS operational lifetime.

Boris Sturm

European Representative to the CZCS NET

Sturm reported on, and conducted research in, European waters during the CZCS mission. Sturm also reviewed the production of level-2 scenes for European waters, and was responsible for atmospheric correction methods.

Robert Wrigley

Airborne Program Supporting CZCS

Wrigley and his colleagues conducted airborne ocean color surveys during the CZCS mission period, notably in regions along the Pacific coast of the US and in Monterey Bay. In addition, he was responsible for oceanic and lacustrine color measurements, and data analysis.

Charles Yentsch

Relationship of Optical Properties

Yentsch participated in the sea truth program, and made initial applications of the CZCS data to several aspects of ocean biological productivity. He worked on the relationship of optical properties to biological production rates, level-2 products, and oceanographic applications.

2. CHRONOLOGY OF EVENTS

The primary source of information on the activities of the CZCS NET is the minutes of team meetings held prior to the launch of NIMBUS-7 and during the operational lifetime of CZCS. Secondary sources include cruise data reports and published scientific journal articles.

Many of the scientific issues facing the CZCS NET were dealt with over the course of several meetings. This chronology provides an overview of how ocean color remote sensing from an orbital sensor developed into a significant tool for oceanographic research. The initial skepticism of the oceanographic research community toward CZCS evolved into a recognition of both the usefulness of ocean color data and the necessity for a dedicated orbital ocean color mission (for which SeaWiFS was designed).

In this summary, terminology in use at the time, such as *sea truth* for data validation, and *sun glitter* for sun glint, is used for consistency and clarity.

2.1 NET Activities in 1975

2.1.1 Field Activities

In 1975, the first CZCS NET algorithm development cruise was conducted from 26 October–3 November. The research area was the Southern California Bight where seven bio-optical stations were occupied. CZCS NET participants on this cruise were R. Austin and C. Yentsch. The data from this cruise is used in the CZCS pigment algorithm data set (Clark 1981).

2.2 NET Activities in 1976

2.2.1 CZCS NET Meetings

In 1976, four CZCS NET meetings were held—the first through fourth—in what became a series of 25 such meetings held during the course of the CZCS mission.

2.2.1.1 First Meeting

The first meeting of the CZCS NET took place 15–16 January 1976 at GSFC. Design and work on the instrument at Ball Brothers was described, including some calibration components. W. Hovis was selected by the team as the CZCS NET Leader. The ground facility for CZCS and NIMBUS-7 was described. Questions concerned *certification* of data, ship scheduling, calibration, and oceanographic usage of the data. The meeting minutes include an initial description of the CZCS concept, and aircraft observations with an ocean color imager which supported the mission concept.

2.2.1.2 Second Meeting

The second CZCS NET meeting was also held at GSFC, on 19–20 February 1976. W. Hovis described an airborne optical scanning radiometer, called the Ocean Color Scanner (OCS), designed to be deployed on the NASA U-2 aircraft. He also noted that a scanning radiometer was slated to fly on SEASAT-A. The team entered a discussion of engineering, power budgets, and berthing on NIMBUS-G. A report from R. Austin and D. Clark included discussion of surface truth and a NIMBUS Observation Processing System (NOPS) review. The report also described the October 1975 experiment off the coast of Southern California with OCS overflights of surface vessels. A report from S. El-Sayed covered similar topics.

H. Gordon commented on modeling and removal of atmospheric effects, and on the need for measurements of upwelling irradiance. These comments may be considered the genesis of the CZCS atmospheric correction algorithm.

C. Yentsch discussed surface truth requirements, and the Surface Truth Subcommittee, consisting of R. Harris, D. Clark, R. Austin, F. Newth, S. El-Sayed, and C. Yentsch, was named. R. Wrigley reported on pre- and post-launch investigations and ground, i.e., surface truth, requirements. Wrigley also provided a review of NOPS.

CZCS NET members were given several Task Assignments at this meeting:

1) surface truth measurements (Surface-Truth Subcommittee);
2) optical modeling (H. Gordon and R. Austin);
3) aircraft program (F. Newth, R. Wrigley, D. Clark, and W. Hovis);
4) algorithm development and data processing (CZCS NET);
5) ancillary data (W. Hovis and D. Clark);
6) outside coordination of measurements (R. Austin, W. Hovis, and F. Newth for Europe);
7) user-community contact (D. Clark and S. El-Sayed);
8) output products (D. Clark);
9) data distribution and archive (W. Hovis); and
10) investigations and data utilization (W. Hovis).

A discussion of the budget allocations for pre- and postlaunch investigations was undertaken during the meeting. The Surface Truth Subcommittee convened and submitted a strawman proposal for *minimal* sea truth measurements. One notable point was the stipulation that irradiance measurements were to be made for the four CZCS spectral bands. The initial suite of minimal sea truth measurements were:

- Optical—upwelling irradiance, downwelling irradiance, Alpha (beam transmission), path radiance and atmospheric transmittance, Secchi depth, Munsell color;
- Biochemical—chlorophyll, seston mass, species composition, Gelbstoff fluorescence; and
- Physical—temperature (three methods—PRT-5, towed thermistor, and bucket), and salinity.

W. Hovis was given the task of identifying a standard instrumentation package for ship deployment.

2.2.1.3 Third and Fourth Meetings

The third meeting of the CZCS NET was scheduled to take place at the Ball Brothers plant where the CZCS was fabricated on 24–25 May 1976. An agenda for this meeting is found as an appendix to the second meeting, but no other record is available.

The fourth meeting of the CZCS NET was held 27–29 September 1976 in Brussels, Belgium, at the Commission of the European Communities. The meeting was held in conjunction with a meeting of the European Association of Scientists in Environmental Pollution (EURASEP).

W. Hovis discussed ocean color research and described the CZCS instrument and data products. C. Yentsch discussed light interaction with suspended and dissolved matter in the water column, and S. El-Sayed described remote sensing ground truth and estimation of primary productivity. H. Gordon discussed radiative transfer modeling with respect to the ocean and atmosphere. R. Austin outlined ocean color measurement problems and provided preliminary results from the Southern California experiment for D. Clark, who could not attend. R. Wrigley presented data from spectrometric measurements of western lakes. CZCS data flow and output products were also described. B. Sturm provided a detailed description of European activities planned in support of NIMBUS-G. The CZCS NET members agreed that a prelaunch cruise combined with an OCS overflight was "absolutely necessary," and planned the cruise for the R/V *Gyre* in September–October 1977 (see below).

2.3 NET Activities in 1977

2.3.1 CZCS NET Meetings

In 1976, four CZCS NET meetings were held. The fifth through seventh meetings are summarized herein. The minutes for the eighth meeting were not available.

The fifth CZCS NET meeting was held in La Jolla, California, 13–14 January 1977. Great Lakes research with the OCS and real-time communication during OCS operations was described. The planned Monterey experiment (May 1977) was outlined by W. Barnes. The *Gyre* cruise was rescheduled to mid-October 1977 to reduce the hurricane threat. The South African contingent described a redefined effort emphasizing fisheries applications, with a change in CZCS NET membership. C. Yentsch discussed sea-truth methods. W. Hovis discussed the design and construction of a four-channel underwater photometer, which was first discussed at the third CZCS NET meeting (Section 2.2.1.3). The team toured the Scripps Optical Laboratory and heard presentations by D. Kiefer and W. Wilson. The team also considered ground station capability, cloud cover, data distribution, and data archiving. The CZCS algorithm development team was assembled at this meeting, and a long list of action items was generated.

The minutes of the sixth CZCS NET meeting of 4 April 1977 held at GSFC, contain a discussion of items relevant to the algorithm development effort. Four new algorithms not in the original plan are stated in these minutes as required. A request was made by the data system developers for a preliminary algorithm form. It was agreed that a two-step delivery would be made, with preliminary algorithms of several types to be provided by 9–10 June 1977, and final algorithms due 1 March 1978. H. Gordon was tasked with providing possible algorithm forms for deriving chlorophyll and sediment from CZCS radiance measurements. Specification of CZCS targets was also requested.

At the 9 June 1977 meeting (though entitled in the minutes as the *Second CZCS Algorithm Development Team Meeting,* this meeting was the seventh CZCS NET meeting in numerical sequence), W. Wilson presented equation forms for atmospheric correction of sediment and chlorophyll. Revisions of these forms were specified to be due January–February 1978. An examination of the possible regional and seasonal variability of constants in the algorithm equation was requested. J. Mueller evaluated preprocessing techniques. It was determined that atmospheric correction "dramatically" increased processing time; therefore, the first CZCS processing plan from the Image Processing Division (IPD) would not have atmospheric correction. The CZCS NET was tasked with determining constants for the chlorophyll and sediment algorithms, and to assess the regional variability of these constants.

As was previously stated, the minutes for the eighth CZCS NET meeting were not available.

2.3.2 Field Activities

A prelaunch algorithm development cruise was conducted on the R/V *Gyre* in the Gulf of Mexico during October, under the auspices of Texas A&M University. S. El-Sayed participated, and was aided by C. Trees. Ten stations were visited on this cruise, which took place from 8–27 October. Data from these 10 stations are included in the CZCS pigment algorithm data set (Clark 1981).

The NOAA R/V *Researcher* conducted a prelaunch cruise in the Gulf of Mexico simultaneously with the *Gyre,* occupying nine oceanographic stations at the same time as the *Gyre.* R. Austin, on board the *Researcher,* conducted measurements of spectral downwelling irradiance, upwelling radiance, attenuation and scattering properties.

A measurement at Mill Creek site in the Chesapeake Bay was made in August 1977. This data point is cited in Hovis et al. (1980) and Clark (1981).

2.3.3 Miscellaneous Activities

An article entitled "Remote Sensing of Ocean Color," (Hovis and Leung 1977), was published in the March–April 1977 issue of *Optical Engineering*. The article described some theoretical constraints on remote sensing of ocean color from space, and also contained observations made with the OCS from a U-2 aircraft at 19.8 km altitude.

A NIMBUS-G meeting entitled, "Third Data Handling Meeting," was held 3–4 November 1977 at GSFC. W. Hovis discussed CZCS coverage plans, and CZCS supporting research, including planned sea truth measurements to be conducted on board the *Researcher* and *Gyre.*

2.4 NET Activities in 1978

Only one meeting was held in this year—the ninth CZCS NET meeting.

2.4.1 CZCS NET Meeting

PMEL, in Seattle, Washington, was the site of the ninth CZCS NET meeting on 8–9 August 1978. W. Hovis discussed the NIMBUS-G launch scheduler. B. Ramsey, NOAA, was assigned to be the full-time CZCS coordinator and scheduler. Funds for the *Researcher* extended post-launch cruise were discussed. Anomalies with the thermal band were described from the prelaunch instrument review.

F. Anderson reported on planned 1978–79 South African cruises. R. Wrigley displayed airborne ocean color imagery taken over the Gulf of Mexico. His attachment describes OCS overflights in the Gulf of Mexico in October 1977 over the *Gyre* and *Researcher,* with simultaneous measurements performed by D. Clark and R. Austin on the *Researcher.*

H. Gordon, with the assistance of A. Morel, reported on the deliberations of the Water Color Working Group colloquium of the Inter-Union Commission on Radio Meteorology (IUCRM) and also provided a preliminary draft of the atmospheric correction algorithm. The NOPS discussion included a description of cloud and land masks.

The CZCS NET recommended changing the term *chlorophyll* in the product list to *Pigment,* and *sediment* to *Diffuse Absorption Coefficient-K*.

A report on the prelaunch Gulf of Mexico expedition was sought with particular urgency, with inputs to W.

Hovis due by the end of September, before the launch of NIMBUS-G. Plans for future validation cruises were discussed.

2.4.2 Field Activities

The most prominent activity was the first post-launch CZCS NET cruise, on which D. Clark and H. Gordon were participants. The cruise took place in the Gulf of Mexico on the R/V *Athena* from 1–14 November 1978. A report on this cruise appears in Gordon et al. 1980. A more detailed description appears in Section 3.1. Data from the 10 stations occupied on this cruise comprise part of the CZCS pigment algorithm data set (Clark 1981).

The *Gyre* also conducted a post-launch cruise under chief scientist S. El-Sayed from 8–20 November 1978 in the Gulf of Mexico.

2.5 NET Activities in 1979

2.5.1 CZCS NET Meetings

At the 10th CZCS NET meeting, conducted on 7–8 January 1979 at GSFC, W. Hovis reported that roughly 118 minutes of the 120 minute CZCS allocation were being used. Degradation was already apparent in the CZCS and other instruments on board NIMBUS-7.

R. Austin, S. El-Sayed, C. Yentsch, and others discussed the Gulf of Mexico post-launch cruise. Cloud cover was a significant problem. The next planned cruise was in the Gulf of California region on the R/V *Velero IV* and R/V *New Horizon*. Cloud cover was expected to be minimal from January–March. A radiance profiler for measurements of upwelling radiance and downwelling irradiance in five bands was being constructed and expected to be available for the California mission.

C. Yentsch described plans for the Northeast Coast mission, covering Nova Scotia to the Chesapeake Bay.

NOPS data processing was reported to be very slow—one hour for each two-minute CZCS scene. Algorithm improvements were expected to reduce the processing time, but hands-on cloud screening by W. Hovis was currently very useful. Data requests were still being handled without difficulty. Emphasis on ocean pollution monitoring was recommended in the event more CZCS power became available.

There were two attachments to the report. One described computing methods for derived products, and the other concerned activities of EURASEP.

The CZCS NET members met for the 11th official meeting at the Scripps Institution of Oceanography, La Jolla, California, on 14–15 November 1979. In his instrument status update, W. Hovis reported on the degradation of radiation cooler efficiency. Calibration had changed precipitously by two counts in all bands.

Data processing delays substantially affected the validation effort. The identification of "high" and "super" priority scenes for validation purposes was stressed.

Image processing and improvements to image processing methods were discussed. The undetermined causes of grey-scale banding were topics of discussion both prior to and after the meeting. Efforts to complete software to compute CZCS derived products were also described.

Attendees watched a live overpass of NIMBUS-7 in the Scripps Visibility Laboratory's recently completed image processing facility. B. Sturm reported on delays in the EURASEP program and on a study that took place 8–9 November 1979 at the mouth of the Tiber River in the Mediterranean Sea.

C. Yentsch reported that the CZCS experiment had already demonstrated that the primary factor determining ocean color was biological productivity. He noted that ocean color sensing should become a significant element of the NASA oceanographic program, as ocean color remote sensing could allow estimates of global ocean productivity. In this regard, W. Hovis noted that NASA had requested him to lead the algorithm development effort of the National Oceanic Survey.

2.5.2 Field Activities

Two algorithm development cruises took place in 1979. The first, in the Gulf of California and the Pacific Ocean, took place on 4–26 March on the *Velero IV*, and occupied 20 stations from which data were used in the CZCS pigment algorithm. The second, aboard the R/V *Athena,* occupied 15 stations along the eastern continental United States and in the Sargasso Sea, including one station designated "Nowhere." According to the ship's cruise track, "Nowhere" is located approximately 31° N and 72° W in the western Atlantic. Data from the 15 stations is used in the CZCS pigment algorithm (Clark 1981).

S. El-Sayed participated in a cruise on the R/V *Islas Orcadas*, in the Scotia Sea and southwestern Atlantic Ocean, from 22 February–9 April 1979.

2.6 NET Activities in 1980

2.6.1 CZCS NET Meetings

The two primary objectives of the 12th CZCS NET meeting, held at GSFC on 23–24 January 1980, were a review of CZCS quick-look images, and the identification of the areas for which complete processing was desired. A decision on CZCS Radiation and Temperature Tape (CRTT) production, in view of J. Mueller's findings, was also slated for discussion.

W. Hovis noted that the CZCS thermal channel had stopped producing useful data in November 1979, probably due to cooler failure. Banding in the images, primarily due to film transport speed, had been considerably reduced. Other causes included errors in satellite attitude measurements. Pseudo-contouring was judged to be overcome by processing errors and was abandoned.

Scheduling over validation areas and missions was discussed, and F. Anderson described upcoming work in South African coastal waters, which would be extended by S. El-Sayed into the Antarctic Ocean. C. Yentsch described the potential usefulness of spectral band ratios, particularly with regard to chlorophyll absorption. R. Austin presented imagery which showed large variations in euphotic zone particulate content due to transient variability in offshore currents.

J. Mueller described the problems inherent in the use of *stair-case,* i.e., electronic degradation, information used in CZCS calibration. Meetings on this subject led to the recommendation to use "raw" radiance values in CRTT production. Delays were expected in the IPD production schedule due to this and other changes. Calibration information was to be added to the header on reprocessed CRTTs.

The CZCS NET and visitors examined numerous quick-look images to determine scenes of interest.

2.6.2 Miscellaneous Activities

J. Mueller provided memoranda for the period of time before and after the 12th CZCS NET meeting, concerning changes to the CZCS data processing and calibration methodology.

The initial problem consisted of random banding seen in initial CRTT runs. The culprit bug was variation in the CZCS active calibration, which varied by 1–2 digital counts. Scaling to the table had the effect of amplifying the effect to 4–8 digital counts in the actual data. Initially, the scan was recalibrated every 16 lines.

The first fix was to use only the initial voltage staircase and test lamp value for each scene. Shifts in voltage and lamp output would still occur between scenes. The NET agreed to use prelaunch coefficients applied to raw CZCS output counts, based on the belief that the detectors would be more stable than the active reference sources. This new processing scheme involved several changes to the way the calibration data was documented on the data records.

While the changes were being implemented, interim scenes were produced for use in the algorithm validation program. The new processing scheme was developed so that CZCS data could be reliably archived.

In addition, Mueller's correspondence from this period described the calibration of CZCS channel 6, which required a separate algorithm. It can be noted that this correspondence reflected the difficulty and complexity of implementing these changes to the data processing system during active mission operations. This early CZCS experience indicates the utility of providing a great deal of flexibility in both data processing software and calibration methods for current and future sensors. Such built-in flexibility will allow such systems to adapt to unanticipated bugs in the hardware and software interface while not causing extensive data processing delays.

2.6.3 Algorithm Development Meeting

The 25 April 1980 algorithm development meeting at GSFC included some of the CZCS NET members. The meeting featured a discussion of schemes developed to decrease scene processing time. Orbit numbers 130, 296, and 1,330 were designated for the derived products validation effort.

H. Gordon provided an assessment of grey-scale range for the output product derived from data collected on these orbits. A memo in the minutes described the work of R. Austin and T. Petzold on the diffuse attenuation coefficient $K(490)$ algorithm, including data discrimination for the initial algorithm.

2.6.4 CZCS NET Meeting

The CZCS NET, hosted by A. Morel, convened the 13th meeting overseas on 21–22 May 1980 at the *Laboratorie Physique et Chemie Marines,* Villefranche, France. The sensor status report from W. Hovis involved the thermal channel, which was operational, but was likely to be affected by increasing temperature during the summer. Hovis reported that 131 validation scenes had been processed.

The data processing system status was presented to the CZCS NET, with considerable discussion of the calibration method. Requests for data tapes with regional data were solicited.

H. Gordon gave a summary of algorithm development, noting several improvements to the running time. Effects from satellite tilt geometry were to require reprocessing. He provided a table of grey-scale level assignments.

R. Smith described chlorophyll concentrations and features in the California Bight, and F. Anderson reported on South African research activities. B. Sturm reported on JRC activities, including their cloud-masking technique and calculation methods. B. Sørensen, of EURASEP, reported on validation studies, aerial surveys with an instrument similar to the NASA OCS, and the need for regional European algorithms. NASA-ESA connections for CZCS quick-look data were described. S. El-Sayed reported on Texas A&M validation of data from the Gulf of Mexico cruise.

J. Mueller reported on the production of validation scenes. D. Clark, J. Mueller, and W. Hovis were appointed to oversee the release of CZCS data to the archive.

The 14th CZCS NET meeting returned to GSFC on 18–19 September 1980. R. Austin reviewed activities of the Scripps group and presented results from the R/V *Oceanographer* trans-Pacific cruise. Further work on the diffuse attenuation coefficient, $K(490)$, algorithm was presented. R. Wrigley provided an analysis of central Pacific data and a report on a fisheries related cruise. S. El-Sayed reported on the February–March Gulf of Mexico cruise, and W. Wilson reported on the nearly completed status of atmospheric algorithms.

2.6.5 Field Activities

The Texas A&M group conducted two simultaneous cruises, one in the Gulf of Mexico from 25 February through 27 March, and the second aboard the *S.A. Agulhas* in the Southern Ocean, between Africa and Antarctica.

2.7 NET Activities in 1981

2.7.1 CZCS NET Meeting

The 15th CZCS NET meeting, 13–14 January 1981, held at the Naval Postgraduate School, Monterey, California, featured several different items. C. Yentsch reported on possible research applications of CZCS data. H. Gordon described a correction factor for level-2 products. R. Austin presented Scripps Visibility Laboratory research on spectral irradiance curves and work in the Pacific. B. Sturm described algorithm correction methods, and D. Clark described how the CZCS system would be *tuned* to surface radiance and pigment measurements. C. Yentsch also discussed methods for algorithm corrections from *in situ* sampling, and sun glint avoidance protocols. J. Mueller discussed corrections to the chlorophyll algorithm and suggested that 20% of observing time be devoted to open ocean coverage. S. El-Sayed described Texas A&M activities.

2.7.2 Algorithm Development Meeting

During the 25 March 1981 algorithm development meeting held at GSFC, H. Gordon discussed two primary topics: 1) possible different algorithms for each target area, and 2) compatibility with the European ocean color program. J. Mueller suggested assessing how many scenes were contaminated with sun glitter, and how much data loss this might entail. Removal of contaminated scenes and screening methods were presented.

2.7.3 CZCS NET Meetings

After the March algorithm development meeting, two additional CZCS NET meetings were held during 1981—the 16th and 17th in the series.

2.7.3.1 16th Meeting

The 16th CZCS NET meeting of 19–20 May 1981, at GSFC, began with the sensor status report given again by W. Hovis. His report only mentioned degradation of calibration lamp 1 and the non-recovery of the thermal band to an acceptable operating temperature. Data processing and delivery were discussed.

The development of the level-2 product was reviewed, and the approved level-2 film products were approved for archive. Open ocean coverage plans were reviewed, with emphasis on coverage of "approved" ship support deployments.

D. Clark reported on the level-2 algorithms, with the recommendation that a single algorithm be chosen, allowing calculation of derived products. The manuscript *Phytoplankton Pigment Algorithms for the NIMBUS-7 CZCS* (Clark 1981) was attached to this set of minutes. The manuscript located the cruise stations in the Gulf of Mexico, western Atlantic, and California and Mexican coastal waters, from which data for algorithm development was obtained, and also described the measurement methods used during the sea truth cruises (see Section 4.1).

H. Gordon reported on further progress with the atmospheric correction algorithm. He recommended holding the processing of gain 1 validation scenes until further investigation had been completed with the orbit 3,226 scene. F. Anderson evaluated the *Gordon algorithm* with data taken from South African coastal waters.

J. Mueller provided an analysis of sun glint contamination, with findings and recommendations. The primary recommendation was to cease processing any scenes below a 17° sun angle. The CZCS NET recommended not processing scenes at 10° latitude or less. Mueller also presented a draft proposal to publish CZCS oceanographic data maps.

C. Yentsch reported on work being done in the Georges Bank region and attached a research manuscript to the minutes which related light attenuation to phytoplankton chlorophyll estimates. S. El-Sayed reported on activities in the Antarctic Ocean and Eastern Mediterranean, with two manuscripts on plankton productivity in the eastern Mediterranean Sea.

R. Austin reported on the Fisheries Demonstration Project, which utilized a rapid data processing scheme from direct transmission of CZCS data. He noted problems regarding drops in channel radiances.

B. Sørensen reported on further EURASEP activities. B. Sturm reported on JRC European algorithm development research, noting that the NASA algorithm was useful in the Mediterranean yet underestimated chlorophyll in the North Sea (see section 6.1).

2.7.3.2 17th Meeting

The 17th CZCS NET meeting took place at Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, Maine, on 9–10 September 1981. W. Hovis reported on the critical issue of apparent sensor degradation. S. El-Sayed reported on the cruise series in the Mediterranean, and provided a draft of a paper by C. Trees and El-Sayed on the level-2 Gelbstoff parameter. D. Clark described the status of the level-2 processing effort. R. Austin also discussed sensor degradation and described fast data processing. R. Wrigley reported on research in the deep ocean and off the Monterey peninsula. C. Yentsch described both the East Coast and Gulf of Mexico programs and led a discussion of a CZCS follow-on mission. H. Gordon presented a paper on the clear water radiance atmospheric correction method, co-authored by D. Clark.

2.7.4 Field Activities

The Texas A&M group conducted another cruise on the *S.A. Agulhas*, in the Southern Ocean, from 10 February–20 March 1981. The Texas A&M group also conducted a cruise off the coast of Israel in July, the first of a five-cruise effort off the Israeli coast in the Mediterranean. (The exact dates for all five cruises are not available—the effort continued through February 1983.) The first of four cruises off the Egyptian coast by the Texas A&M group took place in December 1981.

2.8 NET Activities in 1982

2.8.1 CZCS NET Meetings

The 18th CZCS NET meeting was held 26–27 January 1982, at GSFC, and opened with a review of several items by W. Hovis, including: the status of open ocean level-1 processing, quick-look products, quality control on level-2 products, and an appeal to the CZCS NET to cosign a memo for continued advocacy of open ocean coverage. He pointed out that the final issue was relevant to the issue of a CZCS follow-on sensor. C. Yentsch reported on level-2 processing and the choice of selected scenes with considerable oceanographic interest. H. Gordon discussed both in-water algorithms and atmospheric corrections, as well as an evaluation of gain settings.

R. Austin discussed calibration issues and CZCS applications programs. S. El-Sayed provided a summary of the level-2 algorithm development for review by the team (see below). B. Sturm discussed JRC activities in 1981, and presented measurements of chlorophyll and total suspended matter in the northern Adriatic Sea. F. Anderson discussed research performed by the South African group in Lambert's Bay on the southwest coast of South Africa, and J. Mueller described the assembly of *Global Productivity* charts.

The CZCS NET assembled in College Station, Texas, for the 19th meeting on 11–12 May 1982. C. Yentsch discussed investigations of warm and cold core rings. H. Gordon reported correction factors for sensor drift. R. Austin described activities by the Scripps group on the coast of California and studies encompassing aerosols, fisheries, and sensor degradation and calibration. F. Anderson reported on further research in South African waters.

J. Mueller advocated CZCS usage during the upcoming Optical Dynamics Experiment (ODEX) for aerosol studies. B. Sturm reported on European activities, including research in African waters and in the English Channel. The Open Ocean Project, use of the CZCS over oligotrophic waters, was under consideration by the NIMBUS Project due to tape recorder utilization needs.

At the 20th meeting, held at the University of Rhode Island on 28–29 July 1982, W. Hovis discussed the status of the CZCS atlas and the assignments to the CZCS NET for regional coverage and data. A paper by D. Kiefer and B. Mitchell on light levels and productivity was presented to the team. C. Yentsch discussed studies of Georges Bank productivity and provided seven relevant papers to the minutes. R. Austin reported on the cruise of the R/V *Bartlett*, which addressed water clarity and light attenuation. H. Gordon discussed aerosols and warm core rings.

2.8.2 Reports

In the report from the Department of Oceanography at Texas A&M on CZCS NET activities, S. El-Sayed described his assignment at GSFC for the purpose of supervising the Clear Water Radiance (CWR) procedure. El-Sayed acted as the liaison between the CZCS NET scientists and GSFC data processing personnel and associated contractors. He helped develop an automated CWR processing scheme and processed 115 validation scenes using a combination of manual and automated methods. Gain settings affected this process, so El-Sayed processed gain 1 scenes, with D. Clark and H. Gordon collaborating on gain 2 scene processing.

S. El-Sayed also assisted in the following five areas:

1) a collaboration with R. Austin which assessed sensor degradation,
2) updated CZCS Derived Product Algorithm specifications,
3) assisted the analysis of "no data found" cancellations of special requests,
4) applied various CZCS image enhancement techniques, and
5) assisted W. Hovis in the selection of CZCS scenes for coverage of the BIOMASS oceanographic experiment.

He noted that there was a clear need for the continuing presence of optical or biological oceanographers to interact with the CZCS data processing environment at GSFC. This recommendation predates the establishment of the Ocean Optics Group and the SeaWiFS Project at GSFC.

2.8.3 Field Activities

The second Egyptian coast cruise by the Texas A&M group took place in April 1982. The final two Egyptian coast cruises conducted by the Texas A&M group took place in August and November of 1982.

2.9 NET activities in 1983

2.9.1 CZCS NET Meetings

Two CZCS NET meetings were held during 1983, the minutes of which each had various papers and manuscripts attached to them. The papers that were published appear in the following summaries with their dates of publication.

2.9.1.1 21st Meeting

The 21st NET meeting was held at the NASA Ames Research Center, in California, on 19–20 January 1983. The report prepared by W. Hovis covered the reduced power available on NIMBUS-7 due to solar cell degradation and the requirements of other instruments. Level-1 and level-2 production rates were also described. He also reported that work on the CZCS atlas was continuing. The CZCS NET was instructed to continue submitting level-2 product requests with a production target of 500 scenes produced in 1983.

The effects of El Chichón aerosols were discussed. Although the products from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellites were substantially affected, the CZCS atmospheric correction algorithm capably handled atmospheric perturbations produced by the volcanic aerosols.

R. Austin presented the results of work on water clarity and the global K atlas. F. Yap of Computer Sciences Corporation (CSC) reported on geolocation grids for CZCS imagery.

Manuscripts attached to the minutes of this meeting included:

a) Sturm, Viollier, Wrigley, and Klooster on turbid coastal waters;

b) El-Sayed, Ichiye, and Trees on Gulf of Mexico imagery in the Ocean Color Atlas; and

c) Trees et al. (1985) on errors in the standard fluorometric chlorophyll/pigment method.

Three manuscripts addressing CZCS applications were also attached to the minutes:

- Traganza et al. (1983);
- Traganza and Conrad; and
- Traganza, Nestor, and McDonald.

The latter two papers were produced at the U.S. Naval Postgraduate School, in Monterey, California.

2.9.1.2 22nd Meeting

The U.S. Naval Academy hosted the 22nd meeting on 29 July 1983. The sensor status report by W. Hovis continued to highlight the diminishing power availability on the NIMBUS spacecraft.

The CZCS Atlas was moving toward a mid-1984 publication date. H. Gordon presented an analysis comparing the current CZCS sensor degradation algorithm, adopted in July 1982, and his updated version. D. Clark presented results supporting Gordon, with dramatic errors up to a factor of 10 in some scenes. Implementation of the new algorithm was discussed.

C. Yentsch and R. Austin presented results from their activities. The CZCS NET went on record with a recommendation for a minimum of one annual validation exercise and also endorsed the concept of a microfilm *browse* product of CZCS scenes.

Numerous research manuscripts were attached to this report, including:

1) Gordon et al. (1983b) on the reduction of CZCS radiometric sensitivity;

2) Austin and McGlamery (1983);

3) Trees et al. (1985) on errors in the standard chlorophyll and pigment fluorometric determination;

4) Yentsch (1983) on the remote sensing of biological substances;

5) Gordon et al. (1983a) on Middle Atlantic Bight phytoplankton pigment concentrations derived from CZCS data and compared to surface measuremnts;

6) Caraux and Austin (1983) on seasonal chlorophyll frontal boundaries observed by the CZCS instrument;

7) a list of South African publications;

8) Walters and Neethling (undated) on total suspended solids derived from CZCS data along the South African coast;

9) Walters (1983) on the South African CZCS algorithm; and

10) Traganza et al. (1983) on nutrient mapping with satellite remote sensing.

2.10 NET activities in 1984

2.10.1 Meetings Held

The minutes of an algorithm development meeting, held 22 February 1984 at GSFC, were attached to the minutes of the 22nd CZCS NET meeting. A report from the contractor discussed the implementation of the CWR procedure, instrument degradation corrections, and the derived products user's guide. A succinct description of the CWR procedure was shown and was compared to H. Gordon's results. The CZCS NET was then tasked with providing GSFC with copies of all validation reports that compared CZCS derived products with surface truth measurements, and also any other sea surface data taken coincedent with CZCS coverage.

A letter from W. Esaias, Ocean Productivity Program Manager at NASA Headquarters (HQ), discussed concerns related to the accuracy of CZCS derived products, instrument sensitivity, and the "quasi-operational" use of CZCS data. Esaias noted the success of CZCS in demonstrating the potential of satellite ocean color data.

The 23rd CZCS NET meeting was held at Bigelow Laboratories, in Boothbay Harbor, Maine, on 22 August 1984. No minutes are available for this meeting; the only record available for this meeting is a list of attendees.

2.11 NET Activities in 1985

2.11.1 Final CZCS NET Meeting

GSFC hosted the 24th, and final meeting on 8–9 May 1985. W. Hovis reported a degraded operations capability of the CZCS, the primary difficulty being non-recognition of *on* commands to the instrument. Production of derived products, level-1 microfilm, the Derived Products User's Guide, the CZCS Atlas, and the NESDIS archive were all covered in reports. The CZCS Atlas was close to printing. J. Sissala was overseeing the Open Ocean coverage effort. W. Esaias reported on the Global CZCS Ocean Basin Chlorophyll Data Set using level-2 processing with software from the University of Miami. Continuation of the diffuse attenuation coefficient $K(490)$ measurement was recommended.

C. Yentsch discussed warm core ring studies and other ocean processes studies. R. Austin discussed continuing CZCS sensitivity decay studies. B. Sturm reported on research and calibration efforts in the Adriatic Sea. R. Wrigley discussed testing of the ER-2 instrument and comparison to the CZCS. D. Clark reported on the NOAA level-2 processing effort and plans for ocean color instruments on NOAA platforms.

The CZCS NET requested redefinition of their role in the calibration and validation of level-2 and level-3 products and a plan for level-2 validation.

W. Esaias and C. McClain were voted in as associate CZCS NET members at the conclusion of this meeting.

3. SEA TRUTH PROGRAM

Tables 2–6 give a review of the cruise stations occupied during the pre- and post-launch CZCS NET validation cruises. Marine optical data from the listed cruise stations were used in the CZCS Case 1 water pigment algorithm, as described in Clark (1981). Figure 1 shows all the stations occupied during the CZCS NET at-sea data validation program. Figures 2–6 display maps of the bio-optical stations occupied during each of the pre- and post-launch cruises.

3.1 Post-launch Deployments

Segments of the R/V *Athena* cruise were described and analyzed in Gordon et al. 1980. This paper highlighted comparisons of along-track pigment measurements with CZCS imagery. The along-track pigment measurements made from 13–14 November (Dry Tortugas to Tampa Bay) were compared to pigments estimated from the CZCS image (orbit 296) of the Gulf of Mexico, Florida Straits, and Atlantic Ocean. The NIMBUS-7 overpass occurred while the ship occupied Station 10, due west of Tampa Bay. In addition to the along-track measurements, the measured pigment concentration at Station 10 was compared to two estimates taken from the CZCS scene, based on different choices for the clear water atmospheric correction algorithm.

4. RESEARCH METHODS

4.1 Published Descriptions

The following sections are excerpts from publications written by CZCS NET members. The excerpts describe the methods used for optical and biological measurements used in the development of the CZCS atmospheric correction and the CZCS pigment algorithm. Other descriptions of methods can be found in related publications. These excerpts are published here verbatim except for editorial comments, contained within brackets, [ ], included for clarity. The full citations of the following are included in both the Bibliography and the References section of this document.

4.1.1 Gordon et al. (1980)

"Upwelled radiance measurements were made with a submersible scanning spectral radiometer with a 2° FOV [field-of-view] and a 5-nm spectral resolution. Values of C [pigment] which ranged from 0.07 to 77 mg m^{-3}, were measured by means of the fluorometric technique (7)." [The symbol (7) refers to the Yentsch and Menzel (1963) paper cited by Gordon.]

4.1.2 Gordon et al. (1983a)

"The upwelled spectral radiance measurements were made at 5 nm increments with a submergible radiometer covering a 400–700 nm spectral range. The spectral resolution of the instrument was 4 nm."

4.1.3 Clark (1981)

"The actual optical measurements which were carried out on a typical pre- and post-launch bio-optical station are depicted schematically in Figure 2, in which the spectral radiometer denoted by SR 1 measures the downwelling spectral irradiance E_d (λ,z) at depth z, while SR 2 measures the upwelling spectral radiance L_u (λ,z) at depth z and SR 3, mounted on the deck of the ship, measures the downwelling sky and sun spectral irradiance E_{sun} (λ,z) when SR 1 and SR 2 are at depth z to compensate for variations in the incident irradiance. Usually, measurements are obtained at three depths. Profiles of C [pigment], total seston, and the beam attenuation coefficient are also obtained at each station." [Actual calculations for $K_L(\lambda)$, $L_u(\lambda,0)$ and $L_W(\lambda)$ to derive $L_W(443)$, $L_W(520)$, $L_W(550)$, and $L_W(670)$ are given in the text.]

4.1.4 Austin (1980)

"The primary optical surface-truth measurements for the remote sensing of ocean color are the upwelling (nadir)

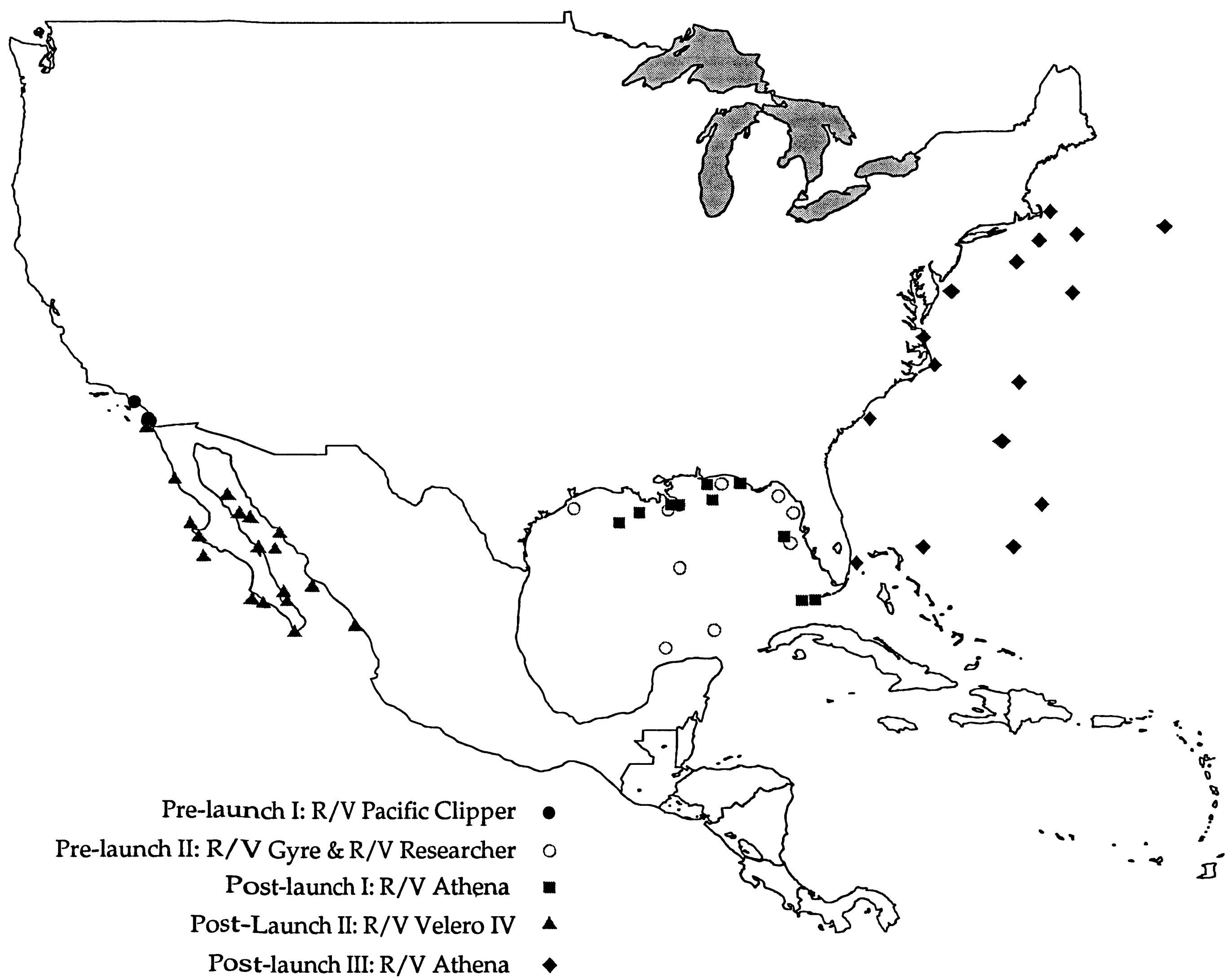

Fig. 1. Oceanographic stations occupied during the CZCS NET at-sea data validation (*sea truth*) program. Both pre- and post-launch stations are shown.

Table 2. Prelaunch cruise I took place aboard the R/V *Pacific Clipper*. The actual research dates were 26 October–3 November 1975, in the Southern California Bight. The CZCS NET participants in this cruise were R. Austin and C. Yentsch. Fig. 2 maps the cruise stations.

Station No.	*Station Name*	*Coordinates Longitude (West)/Latitude (North)*	*Occupation Date and Time [GMT]*
1	Pacific Beach	117°17.2, 32°48.1	10/26/75, 2258
6	Mission Bay	117°24.1, 32°46.6	10/28/75, 2050
7A	La Jolla	117°25.0, 32°46.9	10/29/75, 1904
7B	La Jolla	117°24.0, 32°45.9	10/29/75, 2115
15A	Del Mar	117°22.8, 32°55.8	11/01/75, 2030
15B	Del Mar	117°22.8, 32°55.8	11/01/75, 2350
17	San Pedro	118°06.6, 33°39.5	11/03/75, 2020

Table 3. Prelaunch cruise II took place aboard the R/V *Gyre*. The actual research dates were 10–25 October 1977, in the Gulf of Mexico. The CZCS NET participants in this cruise were S. El-Sayed, D. Clark, E. Baker, and H. Gordon. C. Trees also performed ocean optics research on this cruise. The R/V *Researcher* joined the *Gyre* at the Tampa South Station, and accompanied the *Gyre* to the Campeche East Station. R. Austin of the CZCS NET participated on board the *Researcher*. Fig. 3 maps the cruise stations.

Station No.	*Station Name*	*Coordinates Longitude (West)/Latitude (North)*	*Occupation Date and Time [GMT]*
1	Galveston	94°44.7, 28°49.5	10/10/77, 1428
2	Tampa South	83°20.0, 27°11.6	10/14/77, 1746
3	Tampa North	83°12.0, 28°39.0	10/15/77, 1702
4	Apalachee Bay	83°58.0, 29°26.0	10/16/77, 1855
5	DeSoto Canyon	86°48.0, 30°00.2	10/17/77, 1946
6	Mississippi Delta	89°39.0, 28°46.2	10/19/77, 1650
7	Mississippi South	89°01.9, 28°59.2	10/21/77, 1815
8	Mid-Gulf	89°00.0, 25°59.5	10/22/77, 1817
9	Campeche East	87°10.0, 22°54.8	10/24/77, 1931
10	Campeche West	89°47.2, 22°01.6	10/25/77, 1555

Table 4. Post-launch cruise I was on the R/V *Athena*. The actual research dates were 1–14 November 1978, in the Gulf of Mexico. The CZCS NET participants in this cruise were D. Clark, H. Gordon, and E. Baker. Other ocean optics researchers included: W. Broenkow, A. Strong, R. Stumpf, R. Comeyne, E. King, J. Kapsch, R. Hill, S. Roman, D. Kiefer, and J. Soohoo. Fig. 4 maps the cruise stations.

Station No.	*Station Name*	*Coordinates Longitude (West)/Latitude (North)*	*Occupation Date and Time [GMT]*
1	Panama City	85°52.4, 30°01.0	11/01/78, 1643
2	Mobile	87°32.0, 29°57.0	11/02/78, 1750
3	Mississippi S. Pass	89°02.0, 29°00.0	11/03/78, 1745
4	Louisiana W.	92°17.0, 28°09.5	11/04/78, 1855
5	DeSoto Canyon	87°15.2, 29°15.0	11/05/78, 2032
6	Mississippi SW Pass	89°29.5, 29°00.0	11/09/78, 1803
7	Louisiana Ship Shoal	91°11.0, 28°38.0	11/10/78, 1815
8	Key West	82°03.0, 24°26.0	11/12/78, 1720
9	Dry Tortugas	82°44.0, 24°23.0	11/13/78, 1739
10	Tampa Bay	83°39.0, 27°30.0	11/14/78, 1731

Table 5. Post-launch cruise II took place on board the R/V *Velero IV*. The actual research dates were 4–26 March 1979, in the Gulf of California. CZCS NET participants in this cruise were D. Clark, E. Baker, and other unidentified members of the team. The ocean optics research was performed by B. Mitchell. Fig. 5 maps the cruise stations.

Station No.	*Station Name*	*Coordinates Longitude (West)/Latitude (North)*	*Occupation Date and Time [GMT]*
1	San Christobal Bay	114°40.2, 27°28.0	3/04/79, 1926
2	Lazaro	112°10.0, 24°25.0	3/05/79, 2329
3	Cabo Falso	109°58.8, 22°51.0	3/06/79, 1955
4	San Jose Island	110°32.9, 24°51.0	3/07/79, 1855
5	Punta Pulpito	111°27.2, 26°32.0	3/08/79, 1745
6	Isla Tiburon	112°16.0, 28°24.0	3/09/79, 1810
7	Angel de la Guardia	113°20.0, 29°25.0	3/10/79, 1856
8	Bahia Guaymas	110°46.0, 27°42.6	3/11/79, 1937
9	Isla San Ignacio	109°02.0, 25°09.2	3/12/79, 2045
10	Mazatlan	106°38.5, 23°08.5	3/15/79, 1954
11	Isla Macapule	109°03.1, 25°04.7	3/16/79, 1938
12	Punta Concepcion	111°52.1, 26°59.6	3/17/79, 1941
13	San Lorenzo	112°45.0, 28°34.0	3/18/79, 1945
14	Mid-Gulf	111°01.5, 26°57.5	3/19/79, 2240
15	La Paz Bay	110°23.0, 24°24.5	3/20/79, 1840
17	Punta Tosca	111°38.5, 24°16.8	3/22/79, 1932
18	Isla Cedros	115°07.5, 28°06.5	3/24/79, 1937
19	Cabo San Quintin	115°58.8, 30°11.8	3/25/79, 2112
20	Isla Los Coronados	117°29.4, 32°32.9	3/26/79, 2022

Table 6. Post-launch cruise III took place on the R/V *Athena*. The actual research dates were from 31 May–23 June 1979 in the Northwest Atlantic Ocean and Sargasso Sea. The CZCS NET participants in this cruise were D. Clark, H. Gordon, and E. Baker. Fig. 6 maps the cruise stations.

Station No.	*Station Name*	*Coordinates Longitude (West)/Latitude (North)*	*Occupation Date and Time [GMT]*
1	Cape Romain	78°52.8, 32°58.5	5/31/79, 2050
2	Chesapeake Entrance	75°53.4, 36°34.2	6/01/79, 1713
3	Gulf Stream Eddy	71°12.5, 34°34.9	6/04/79, 2034
4	North Wall	68°14.6, 38°26.4	6/09/79, 1800
5	Nantucket Shoals	70°04.9, 40°38.3	6/10/79, 1724
6	Cape Cod	69°28.0, 41°48.0	6/13/79, 1600
7	Georges Bank	68°01.0, 40°52.7	6/14/79, 1548
8	Warm Eddy	71°18.9, 39°44.5	6/15/79, 1606
9	Delaware Bay Entr.	74°27.0, 38°32.0	6/16/79, 1600
10	Cape Hatteras	75°16.0, 35°22.0	6/18/79, 1750
11	Nowhere	72°03.9, 31°56.0	6/19/79, 1800
12	Bermuda Triangle	69°58.0, 28°59.0	6/20/79, 1739
13	Sargasso Sea	71°30.0, 27°00.0	6/21/79, 1619
14	Western Sargasso	75°55.4, 27°00.0	6/22/79, 1704
15	Gulf Stream	79°40.6, 26°13.1	6/23/79, 1758

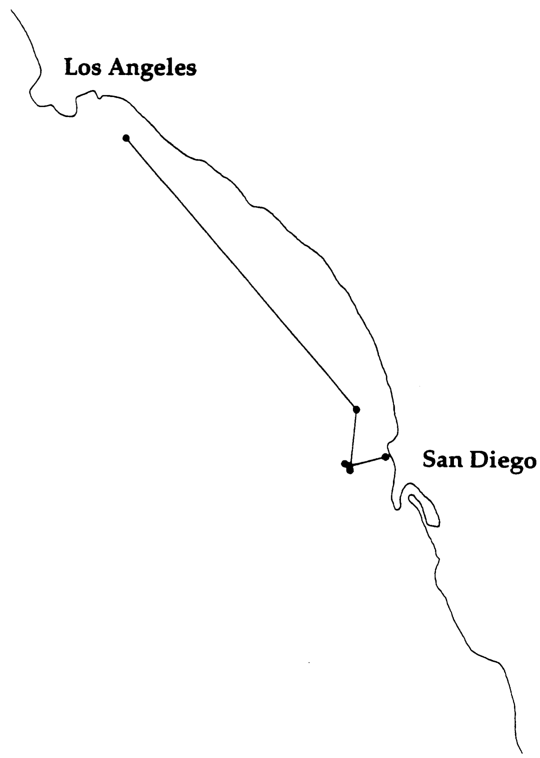

Fig. 2. Map of the bio-optical stations occupied by the R/V *Pacific Clipper* during the first CZCS NET prelaunch cruise.

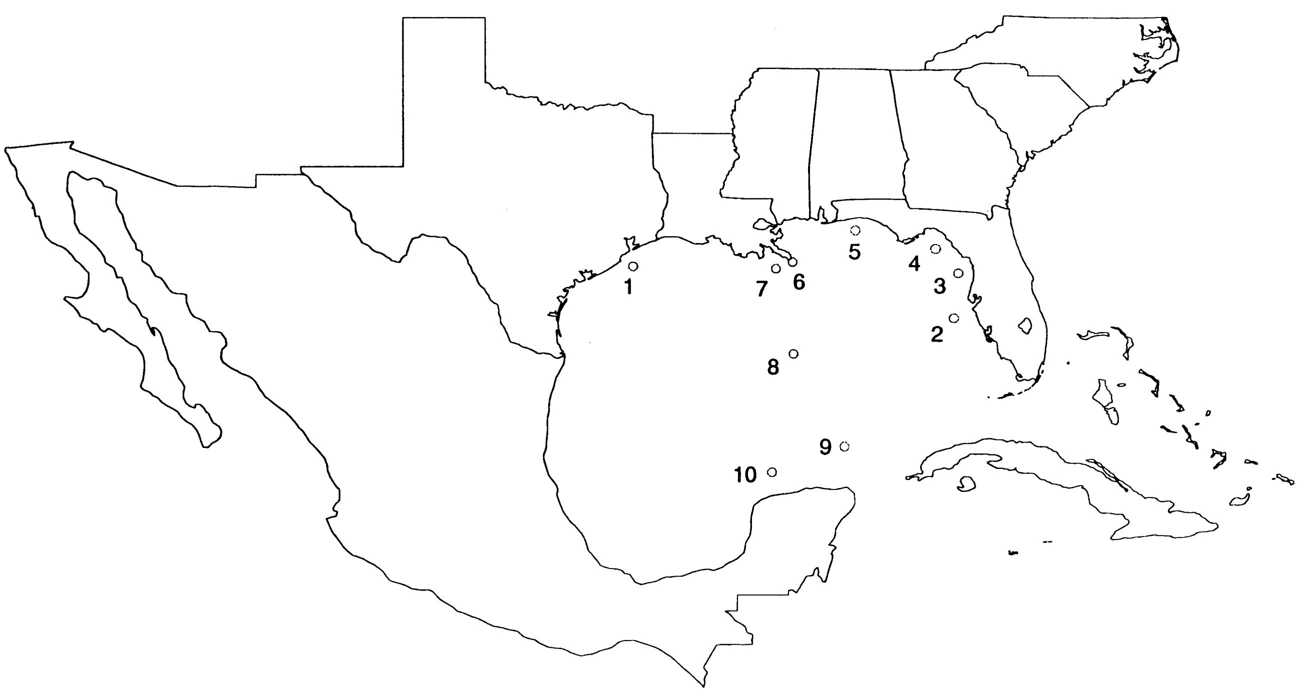

Fig. 3. Map of the bio-optical stations occupied by the R/V *Gyre* and R/V *Researcher* during the second CZCS NET prelaunch cruise. The *Researcher* met the *Gyre* at Station 2, the Tampa South Station, and the two ships worked in tandem at the remaining oceanographic stations.

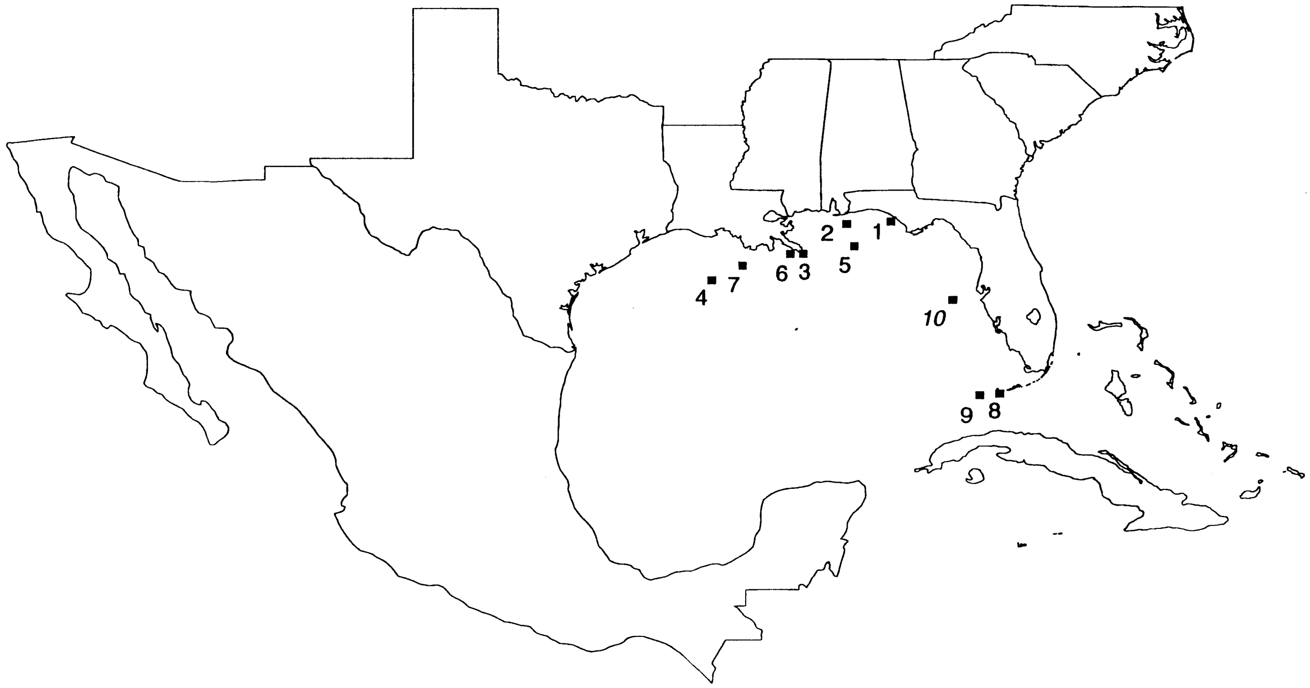

Fig. 4. Map of the bio-optical stations occupied by the R/V *Athena* during the first CZCS NET post-launch cruise. Station 10 was occupied at the time of a CZCS (on board the NIMBUS-7 satellite) overflight. A comparison of the at-sea data obtained at Station 10 with the CZCS data is found in Gordon et al. (1980).

spectral radiance L_u; the upwelling spectral irradiance, E_u; and the downwelling spectral irradiance, E_d; all as function of depth z." (Austin then describes other properties which may be derived.)

"The measurements of spectral radiance and irradiance were performed with the Scripps submersible radiometer. This instrument was described by Tyler and Smith (1970); however it has since been modified in a variety of ways to improve its stability, to allow its calibration to be readily checked in the field and facilitate operation and data reduction. Briefly, the instrument consists of a dual Ebert-Fastie monochromator with a photomultiplier detector. The spectral range is from 350 to 750 nm and the spectral bandwidth is approximately 5 nm. The stray-light sensitivity of the instrument is extremely low as a result of the dual monochromator design allowing measurements to be made in the red spectral region, far removed from the wavelength of maximum water transmittance, at input irradiances of $5\times10^{-3}\,\mu\mathrm{W\,cm^{-2}\,nm^{-1}}$ or less. The instrument is housed in an underwater pressure case capable of operating at depths down to 100 m. For radiance measurements, the flux is transmitted through a clear plexiglas port and the field of view, as determined by the monochromator and the fore-optics, is approximately $0.4\times6.0^{\circ}$. The irradiance measurements were obtained by covering the clear entrance port with a diffuse cap of special design which provides a cosine angular sensitivity in water (Tyler and Smith 1970).

"A deck sensor continuously monitored the irradiance from the sun and sky and provided the information necessary to correct for changes in the input irradiance at the ocean surface. Data were corrected for the variations occurring in the period of the subsurface measurements by scaling to a reference value obtained with a clear high sun.

"The functions of the underwater unit, such as the selection of wavelength, wavelength interval per step, integration time, system sensitivity, etc., were controlled by the investigator from a deck control and display console. The output data were passed to a data logger which added time, date, station number, and other fixed data, and recorded all information on paper tape. An HP 9825A calculator was interfaced with the data logger, enabling all data to be recorded on magnetic tape cassette and flexible

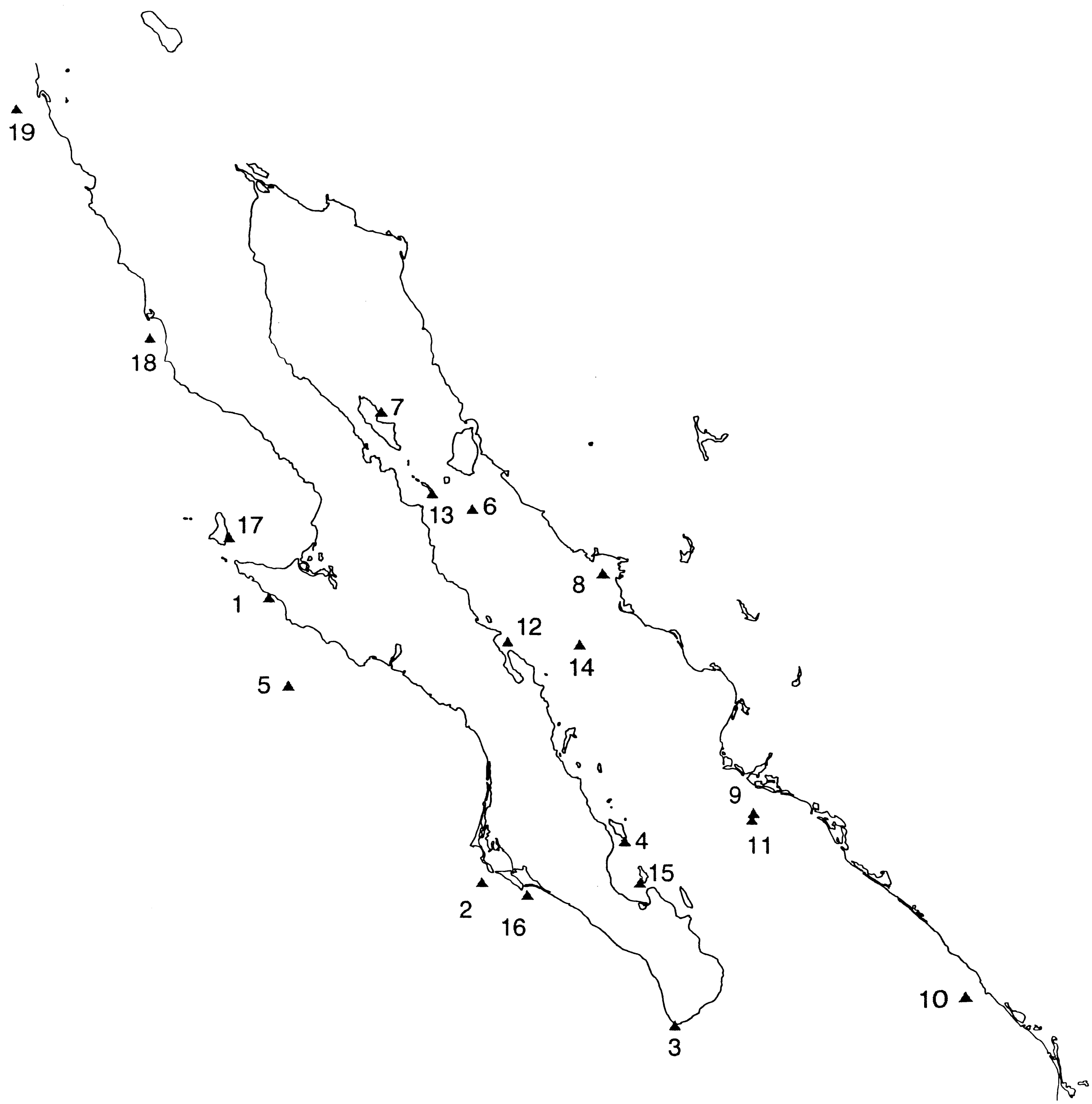

Fig. 5. Map of the bio-optical stations occupied by the R/V *Velero IV* during the second CZCS NET post-launch cruise.

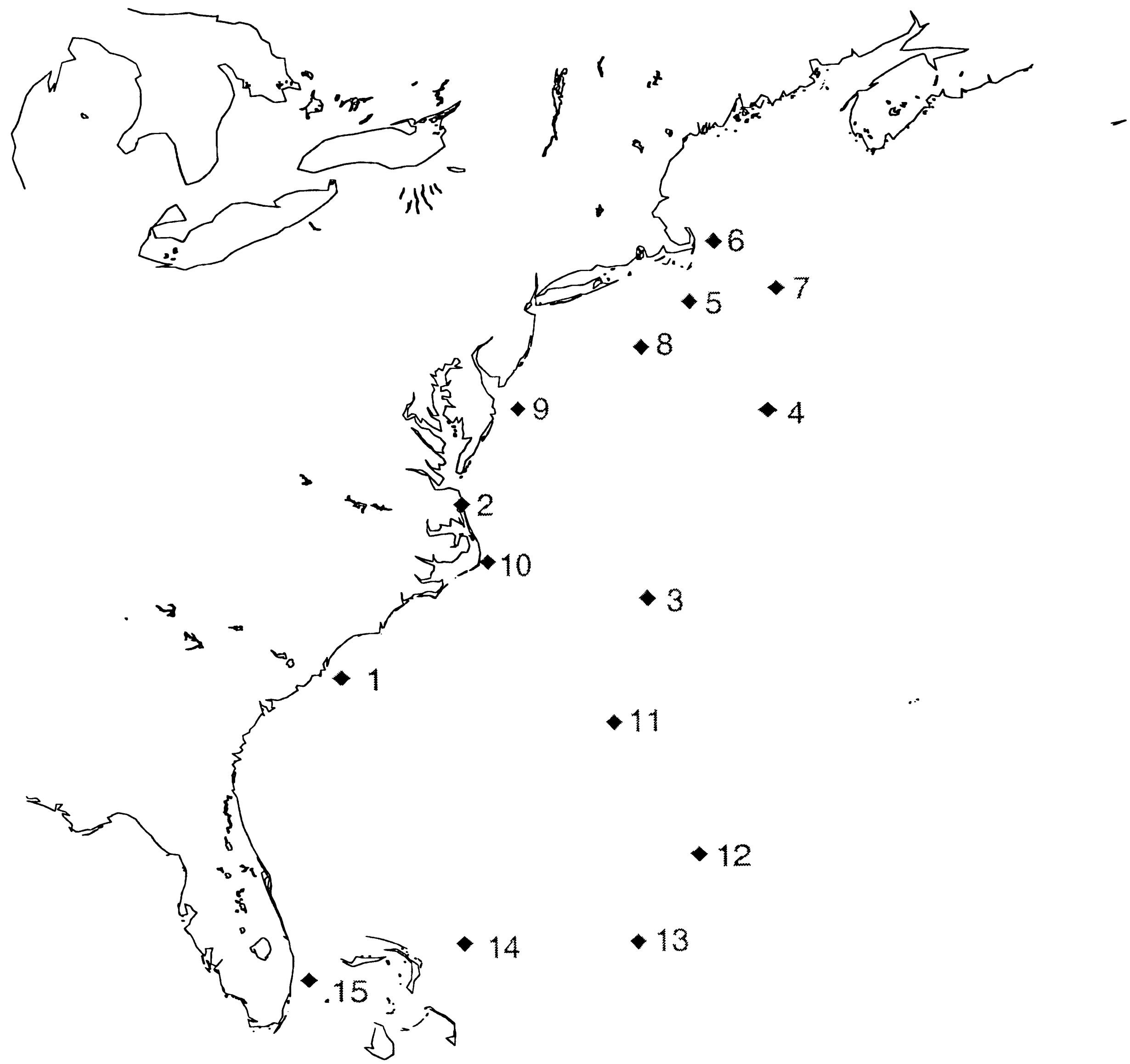

Fig. 6. Map of the bio-optical stations occupied by the R/V *Athena* during the third and final CZCS NET post-launch cruise.

disk for permanent storage and to allow the data to be analyzed, listed, and plotted directly after acquisition for immediate review."

4.1.4.1 Also From Austin (1980)

"Vertical Irradiance Profiles: Vertical profiles of the downwelling irradiance at 518 nm were taken at each station. The data were used to determine the depths for obtaining water samples for productivity studies and to determine the diffuse attenuation coefficient in the water column.

"The irradiance meter consisted of an underwater sensor unit with a spectrally filtered photomultiplier tube and a pressure transducer, a gimballed deck cell to provide corrections for changes in surface irradiance, and a deck control and display console. The instrument computed the logarithm of the ratio of underwater irradiance to surface irradiance, and recorded it against depth on an x-y plotter. The required depths for sampling were obtained directly from the plot and diffuse attenuation coefficients were computed from the slope of the plotted curve."

4.1.4.2 Also From Austin (1980)

"Beam Transmittance and Volume Attenuation Coefficient: Vertical profiles of the beam transmittance of the water provide a rapid means of assessing the vertical structure of the water column. Layers of turbid and clear water are often present in close juxtaposition and their presence, thickness, and location have major implications relative to the depths at which other measurements are to be made and water samples are to be taken, and to the nature of the optical signal which is returned upward to the water surface. Such profiles were made at each station. The instrument used for most of these measurements was the Visibility Laboratory-built ALSCAT (Austin and Petzold 1975). The instrument measures the beam transmittance at any of 10 operator-selectable wavelengths from 400 to 670 nm. In addition, it measures the volume scattering function (VSF) at 0.175, 0.35, and 0.7° from the forward direction. The instrument measures water temperature and pressure together with the above optical properties and plots two of the measured variables against depth." [Derivation equations follow this section.]

4.1.5 Hovis et al. (1980)

"During these experiments, NET investigators made *in-situ* measurements of ocean optical properties, together with measurements of phytoplankton pigments, total suspended particulates, salinity, phytoplankton species, and surface temperature."

4.2 Actual Measurements

Bio-optical data taken at 62 at-sea stations on five research cruises constitutes the CZCS pigment algorithm database. Dates, times, and locations for these stations appear in the listing of pre- and post-launch cruise deployments in the historical section of this document. In addition to spectroradiometer measurements, measurements were made of spectral beam attenuation with a transmissometer, as well as Secchi depth and Munsell color estimates. The pigment fluorescence measurements were aided by fluorometer calibration performed by D. Kiefer, using cultured phytoplankton stocks, for which chlorophyll *a* was determined by the spectrophotometric trichromic method (Strickland and Parsons 1972).

Austin and Petzold (1981) described measurements of the diffuse attenuation coefficient in sea water and the CZCS diffuse attenuation coefficient algorithm.

4.3 Algorithm Synthesis

The CZCS NET assisted the NIMBUS experiment science team in the development and coding of algorithms based on the in-water measurements. Level-1 and level-2 products were based on the algorithms submitted by the CZCS NET to the NIMBUS experiment.

Clark (1981) describes data analysis and development of the mature CZCS phytoplankton pigment algorithm.

5. ATMOSPHERIC CORRECTION

The use of an algorithm to correct water-leaving radiances for the effects of light scattering and aerosol absorption by the intervening atmosphere was an innovative aspect of the CZCS mission. Theoretical considerations and actual measurement techniques for the atmospheric correction algorithm adopted by the CZCS NET are described below, with pertinent references highlighted.

5.1 Methods

Gordon (1978) gives a theoretical description of an atmospheric correction method for a CZCS-type sensor. His method is based on a theoretical treatment of Rayleigh and aerosol scattering of upwelled radiance from the sea surface. An algorithm for this method was initially applied to CZCS data.

An improved method of atmospheric correction is described by Gordon and Clark (1981), which describes the clear-water radiance estimation method. This method was employed for reprocessing of CZCS data and was employed in an analysis of CZCS imagery of the mid-Atlantic Bight (Gordon et al. 1983a).

Gordon and Castaño (1989) describes an atmospheric correction method which incorporates multiple scattering effects.

5.2 Actual Measurements

Gordon (pers. comm.) conducted some measurements of aerosol optical depth during the post-launch cruise phase of the CZCS NET activity. However, the primary measurements used to improve atmospheric correction of CZCS data were actual atmospheric pressure and total ozone fields (Austin 1993).

5.3 Algorithm Synthesis

Atmospheric correction was a keystone of the CZCS mission from its inception. Algorithms based on theoretical consideration of atmospheric light scattering were incorporated in the initial production of CZCS scenes and all subsequent reprocessing programs. Initial processing of CZCS data using atmospheric correction was cumbersome, slow, and limited by computer speed, but improvements in algorithms and computer technology allowed significant improvement in the processing of CZCS data and creation of higher level products. Descriptions of the technical details and software development for both in-water pigment and atmospheric correction algorithms are scarce in the documentation of CZCS NET activities, but may be more readily available in NIMBUS documentation.

One of the most notable successes of the CZCS atmospheric correction algorithm was demonstrated subsequent to the eruption of the El Chichón volcano in 1983. While the aerosols from El Chichón confounded other remote sensing instruments, notably the AVHRR, the CZCS atmospheric correction algorithm compensated for the El Chichón aerosol layer with little or no perturbation to the radiance data.

6. CURRENT STATUS

SeaWiFS relies on the heritage of CZCS for some of the basic fundamentals of marine optics and atmospheric correction methods. A brief overview of evaluation and potential improvements of pigment algorithms and atmospheric correction algorithms is given below.

6.1 In-Water Algorithms

The SeaWiFS Project, using the CZCS NET experience as a guideline, has established rigorous methodologies for the collection of bio-optical oceanographic data, and has sought to improve both the instrumentation and methods used for the calibration of radiometric sensors. It is anticipated that the database of in-water radiometric measurements will be augmented through the conduct of bio-optical research performed in coordination with the SeaWiFS mission.

McClain and Yeh (1994) compared the results obtained by utilizing the bio-optical algorithms of: D. Clark (Muller-Karger et al. 1990); Gordon et al. (1983a); Smith and Wilson (1981); Andersen (1991); and Sturm (1993). The latter two publications describe the *European algorithm*, which was developed for waters near the European continent. In their analysis of two CZCS scenes using each algorithm, McClain and Yeh found similar agreement for all the algorithms except the *European algorithm*, which gave somewhat higher pigment concentrations.

6.2 Atmospheric Correction Algorithms

The existing methods for the atmospheric correction of ocean color data have reached an applicable limit with regard to the processing of CZCS data. The SeaWiFS Project is developing an improved atmospheric correction scheme that is more site-specific, based on aerosol sources, and using the multiple-scattering treatment of Gordon and Castaño (1989).

7. CONCLUSIONS

Despite the fact that the CZCS mission can be viewed retrospectively as a remarkable success, one of the primary lessons of the CZCS NET is the need for a well-integrated team and consistent, continuing examination of the data. The historical record indicates that several known factors, as well as unanticipated events, had to be addressed in order to obtain meaningful analyses of CZCS data, both during the lifetime of the instrument and in subsequent refinements and reprocessing of the data.

S. El-Sayed (pers. comm.) provided several *lessons learned* from his CZCS NET experience. He noted the criticality of team member interaction in the development of the algorithm. The CZCS NET attained a goal that was originally thought to be difficult or impossible to achieve by the broader oceanographic community. A distinct advantage was the selection of NET members with noteworthy expertise in their respective fields.

In addition to vital team member rapport, quality leadership was another key to the success of the CZCS mission. El-Sayed commended Hovis for his outstanding leadership role of the CZCS NET. International cooperation was also necessary for the global CZCS program, as specialists from Europe and South Africa were members of the CZCS NET.

Finally, El-Sayed states "sheer doggedness and persistence" were necessary to overcome obstacles to algorithm development. Although this observation constitutes a fairly fundamental lesson, it seems important to note that in order for CZCS successors to provide scientifically valid oceanographic data, "sheer doggedness and persistence" are likely to be just as vital to the program as state-of-the-art technology.

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Glossary

AM-1 Not an acronym, used to designate the morning platform of EOS
A&M (Texas) Agriculture and Mechanics (University)
ADEOS Advanced Earth Observation Satellite (Japan)
APL Applied Physics Laboratory
AVHRR Advanced Very-High Resolution Radiometer

CHORS Center for Hydro-Optics and Remote Sensing
CRTT CZCS Radiation and Temperature Tape
CSC Computer Sciences Corporation
CWR Clear Water Radiance
CZCS Coastal Zone Color Scanner

EOS Earth Observing System
ESA European Space Agency
EURASEP European Association of Scientists in Environmental Pollution

FOV Field-of-View

GMT Greenwich Mean Time
GSFC Goddard Space Flight Center

HP Hewlett-Packard
HQ Headquarters (NASA)

IPD Image Processing Division
IR Infrared
IUCRM Inter-Union Commission on Radio Meteorology

JHU Johns Hopkins University
JRC Joint Research Centre (Europe)

MERIS Medium Resolution Imaging Spectrometer
MODIS Moderate Resolution Imaging Spectroradiometer

NASA National Aeronautics and Space Administration
NASDA National Space Development Agency (Japan)
NESDIS National Environmental Satellite Data Information Service
NESS National Environmental Satellite Service
NET NIMBUS Experiment Team
NIMBUS Not an acronym, but a series of NASA experimental weather satellites containing a wide variety of atmosphere, ice, and ocean sensors.
NOAA National Oceanic and Atmospheric Administration
NOPS NIMBUS Observation Processing System

OCS Ocean Color Scanner
OCTS Ocean Color Temperature Sensor
ODEX Optical Dynamics Experiment

PM-1 Not an acronym, used to designate the afternoon.
PMEL Pacific Marine Environmental Laboratory

R/V Research Vessel

SDSU San Diego State University
SeaWiFS Sea-viewing Wide Field-of-view Sensor
SIO Scripps Institution of Oceanography

VSF Volume Scattering Function

Symbols

E_d Downwelled spectral irradiance.
$E_d(\lambda, z)$ Downwelled spectral irradiance.
$E_{sun}(\lambda, z)$ Spectral sun irradiance distribution.
E_u Upwelled spectral irradiance.

$K(490)$ Diffuse attenuation coefficient of seawater measured at 490 nm.
$K_L(\lambda)$ Attenuation coefficient upwelled radiance.

$L_u(\lambda, 0)$ Upwelled spectral radiance at the surface.
$L_W(\lambda)$ Water-leaving radiance.
$L_W(443)$ Water-leaving radiance at 443 nm.
$L_W(520)$ Water-leaving radiance at 520 nm.
$L_W(550)$ Water-leaving radiance at 550 nm.
$L_W(670)$ Water-leaving radiance at 670 nm.

x Abscissa.

y Ordinate.

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13. ABSTRACT *(Maximum 200 words)*
The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission is based on the scientific heritage of the Coastal Zone Color Scanner (CZCS), a proof-of-concept instrument carried on the National Aeronautics and Space Administration (NASA) NIMBUS-7 environmental satellite for the purpose of measuring upwelling radiance from the ocean surface. The CZCS mission provided the first observations of ocean color from space, and over the mission lifetime of 1978–1986, allowed oceanographers an initial opportunity to observe the variable patterns of global biological productivity. One of the key elements of the CZCS mission was the formation of the CZCS NIMBUS Experiment Team (NET), a group of optical physicists and biological oceanographers. The CZCS NET was designated to validate the accuracy of the CZCS radiometric measurements and to connect the instrument's measurements to standard measures of oceanic biological productivity and optical seawater clarity. In the period following the cessation of CZCS observations, some of the insight and experience gained by the CZCS NET activity has dissipated as several proposed follow-on sensors failed to achieve active status. The SeaWiFS mission will be the first dedicated orbital successor to CZCS; it in turn precedes observations by the Moderate Resolution Imaging Spectroradiometer (MODIS) of the Earth Observing System (EOS). Since the CZCS NET experience is an important model for SeaWiFS and MODIS surface truth efforts, this document is intended to provide a comprehensive review of the validation of oceanographic data for the first orbital ocean color sensor mission. This document also summarizes the history of the CZCS NET activities. The references listed in the Bibliography are a listing of published scientific research which relied upon the CZCS NET algorithms, or research which was conducted on the basis of CZCS mission elements.

14. SUBJECT TERMS
SeaWiFS, Oceanography, Coastal Zone Color Scanner, CZCS, NIMBUS-7, NIMBUS-7 Experiment Team, CZCS NET

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