Chapter 17
Some Reflections on Thirty-Five Years of Ocean Color Remote Sensing

Howard R. Gordon

17.1 Some Historical Milestones

In the first 15 or so years of my 35-year involvement in ocean color remote sensing, I was fortunate to have witnessed and participated in much of the early development of this enterprise. In this paper I relate those that had a significant impact on the subject and on my own work, and try to describe the historical setting in which they took place. These were very exciting and sometimes trying times for the members of the CZCS Experiment Team. I hope I can convey some of that excitement and frustration, and along the way, a few details about the subject.

My ocean color initiation was in the early 1970s when I started investigating radiative transfer in natural waters with Otis Brown (then a graduate student), when I supervised the Ph. D dissertation of George Maul on the application of LANDSAT-1 imagery to optical oceanography, and when I tried (and failed) to make in-situ optical measurements in support of an aircraft experiment by Fabian Poulson (ERIM) to try to remotely measure bathymetry. The latter failure showed me the difficulty of validation exercises in support of remote sensing. Although ocean optics has a considerable history, I shall describe only the events that occurred during, or had an influence on, my own involvement with ocean color remote sensing. A more complete history of events leading up to the Coastal Zone Color Scanner's (CZCS) approval for flight by NASA is given by Austin (1992), and a comprehensive history of ocean color remote sensing is presently being prepared by Jim Acker.

My first contact with ocean optics was in late 1967, when I moved to the University of Miami. Most of what I learned about the subject in my first 2 years there came from Jerlov's book *Optical Oceanography* (1968) and from Jerzy Dera, who visited from the fall of 1967 to the summer of 1968. Reading *Optical Oceanography* now, one realizes that ocean color was barely on the horizon at that time.

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Probably the most important event in establishing the potential of ocean color observations, and leading directly to CZCS, was the work of Clarke et al. (1970). They used a spectroradiometer mounted on an airplane to measure the radiance backscattered from the water, and the intervening atmosphere, off Georges Bank at an altitude of 305 m. Contemporaneous measurements of the chlorophyll *a* concentration were made in the surface waters along the airplane's flight track. The results provided a clear indication that the modification to the spectrum of upwelling radiance by chlorophyll variations, over the range 0.1–3.0 mg/m^3, could be observed at aircraft altitudes. The authors also pointed out that backscattering from the atmosphere between the sensor and the surface added light that seriously degraded the quality of the spectra. Referring to such "air light," they stated at the close of their paper: "If such interference can be eliminated or identified and allowed for, spectroscopic procedures from aircraft (and perhaps from satellites) will be of great value in the rapid investigation of oceanic conditions, including conditions important for biological productivity."

This work initiated several studies in which aircraft measurements of color were combined with surface radiometry, further demonstrating the potential of ocean color remote sensing, and resulting in the approval of the CZCS in 1973. Although the experiments did confirm the serious degrading effect on the apparent color of the water by the intervening atmosphere on aircraft spectra, insufficient data were collected for development of analysis algorithms. The development of such algorithms became the first task of the CZCS Experiment Team.

17.2 The CZCS Nimbus Experiment Team (NET)

The CZCS Nimbus Experiment Team (NET) was formed in mid-1975 based on competitive proposals for membership. Its primary responsibility in the prelaunch era was to develop algorithms for the processing of CZCS imagery. The team membership is provided in Table 17.1.

There were essentially three areas that needed to be addressed. The first was various questions concerning the sensor, which was actually being built at the time.

Table 17.1 CZCS nimbus experiment team (NET) membership

Member	Affiliation
W. Hovis (Leader)	NASA/GSFC
F. Anderson	NRIO, Capetown, South Africa
R.W. Austin	SIO, Visibility Laboratory
E.T. Baker	NOAA/PMEL
D.K. Clark	NOAA/NESS
S.Z. El-Sayed	Texas A&M University
H.R. Gordon	University of Miami
B. Sturm	JRC Ispra, Italy
R.C. Wrigley	NASA/Ames
C.S. Yentsch	Bigelow laboratory for ocean sciences

These issues were addressed by Warren Hovis, the NET leader (Sensor Scientist). The second was the development of an atmospheric correction algorithm (removal of the "air light" described by Clarke et al., 1970). The group charged with this consisted of Austin, Gordon, J.L. Mueller, Sturm, and W.H. Wilson. The third was the development of in-water algorithms. This group consisted of Anderson, Austin, Baker, Clark, El-Sayed, R.C. Smith, Wrigley, and Yentsch. Mueller, Smith, and Wilson were not NET members, but nevertheless directly participated in NET activities and made important contributions to the NET's algorithm development effort. It should be emphasized again that, at the time of the NET's formation, there were no algorithms available for processing the incoming data.

17.2.1 Bio-Optical Algorithms

The main thrust of the in-water algorithm group was to try to acquire as much data as possible, in a large variety of waters, relating the water-leaving spectral radiance, $L_w(\lambda)$, or the upwelling spectral radiance (propagating toward the zenith) just beneath the water surface, $L_u(\lambda)$, to the concentration of chlorophyll *a*, the total mass of suspended material, or Total Suspended Matter (TSM), the concentration of some detrital materials (e.g., phaeophytin *a*), etc. The NET's data collection began after its formation and continued through 1979.

The first time I ever saw anything resembling a bio-optical algorithm was at a NET meeting in Miami in December 1977. At that time Ray Smith presented preliminary data that convinced me that one might be able to discern perhaps 5–6 levels of chlorophyll *a* based on measurement of $L_w(\lambda)$. Prior to that, I had felt that the CZCS would be more useful in estimating sediment concentrations in coastal areas than in estimating chlorophyll *a*. From then on, I was a believer.

As part of the NET's efforts, there were two significant cruises prior to launch and three post-launch cruises. The data from both pre- and post-launch cruises were pooled for the final algorithm. Figure 17.1 provides the station locations of the NET cruises organized by Dennis Clark as chief scientist. Clearly the focus of algorithm development by the NET was the waters off the coast of the United States.

Most of these sites would be considered to be Case 1 waters (Morel and Prieur, 1977; Gordon and Morel, 1983); however, some Case 2 waters were observed (off the Mississippi Delta and off the Chesapeake Bay). The oligotrophic waters of the Sargasso Sea were included in the data set as well. The principal measurements on the pre- and post-launch cruises were the spectral water-leaving radiance (made with an in-water spectral radiometer designed at the SIO Visibility Laboratory) and the concentrations of chlorophyll *a* and phaeophytin *a* measured fluorometrically (Clark, 1981).

Figure 17.2 provides examples of the spectra obtained and the final "blue-green" algorithm for estimation of the pigment concentration (*C*, the sum of the concentrations of chlorophyll *a* and phaeophytin *a*). In the final analysis, the data from Clark's cruises suggested that, in Case 1 waters, given measurements of $L_w(\lambda)$, it

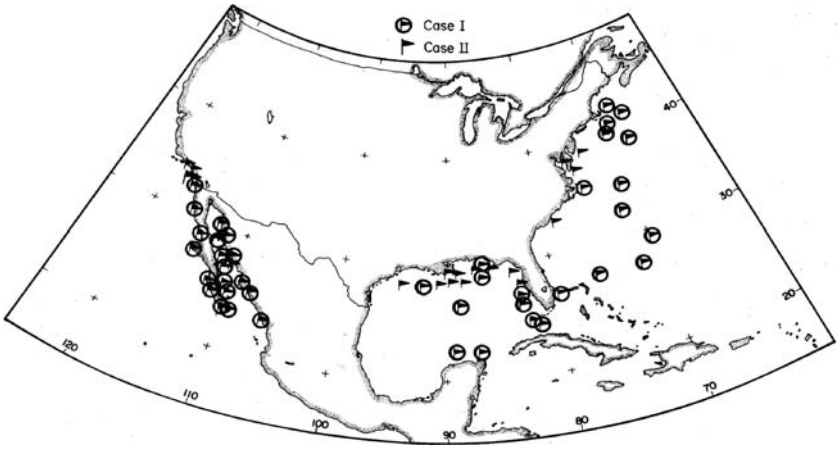

Fig. 17.1 Location of stations used in the development and the validation of CZCS imagery. From Gordon et al. (1983)

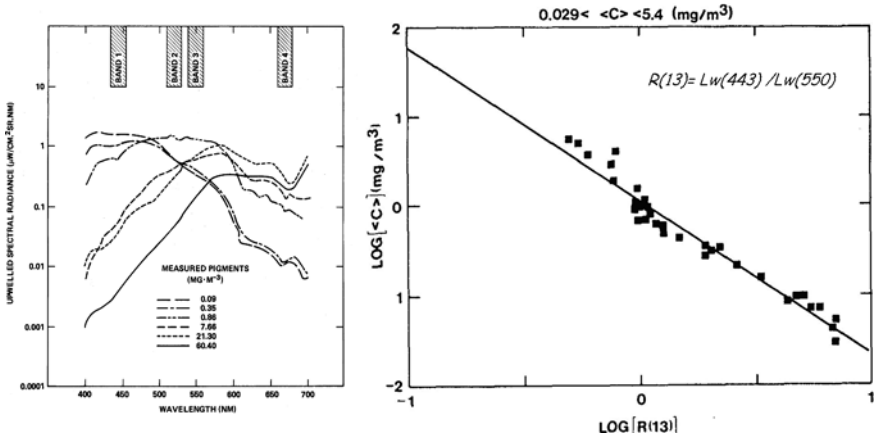

Fig. 17.2 *Left*: examples of water-leaving radiance spectra for several pigment concentrations. From Hovis et al. (1980). Reprinted with permission from the AAAS. *Right*: the *blue-green* algorithm used to retrieve the pigment concentration. From Gordon et al. (1983)

should be possible to retrieve C with an uncertainty of about 30% over the range $0.029 \leq C \leq 5.4$ mg/m^3. This was far better than I had thought possible.

17.2.2 Atmospheric Correction

My earliest thoughts about atmospheric correction (about 1976) were derived on the basis of solving the radiative transfer equation in the simplest of cases (single scattering). In this approximation the radiance (L_t) reaching the sensor can be decomposed into atmospheric components due to Rayleigh scattering (L_r), aerosol

scattering (L_a) and a component due to the water-leaving radiance (L_w) transmitted (t) to the top of the atmosphere:

$$L_t(\lambda_i) = L_r(\lambda_i) + L_a(\lambda_i) + t(\lambda_i)L_w(\lambda_i), \tag{17.1}$$

where λ_i is the wavelength of the ith spectral band. I had discovered that the single scattering formula for the radiance L_r compared very favorably to the full multiple scattering result as long as the limit of small Rayleigh optical thickness (τ_r) was adopted, i.e., $\exp(-\tau_r) \approx (1 - \tau_r)$. The resulting formula is

$$L_r(\lambda_i) = \frac{\tau_r(\lambda_i)F_0(\lambda_i)p_r(\theta_v,\varphi_v;\theta_0,\varphi_0;\lambda_i)}{4\pi \cos\theta_v}, \tag{17.2}$$

where $F_0(\lambda_i)$ is the extraterrestrial solar irradiance at λ_i,

$$p_r(\theta_v,\varphi_v;\theta_0,\varphi_0;\lambda_i) = P_r(\Theta_-,\lambda_i) + [r(\theta_v) + r(\theta_0)]\,P_r(\Theta_+,\lambda_i),$$

$P_r(\Theta,\lambda_i)$ is the Rayleigh scattering phase function for scattering through an angle Θ, $r(\theta)$ is the Fresnel reflectance of the sea surface for light incident at an angle θ, and

$$\cos\Theta_\pm = \pm\cos\theta_v\cos\theta_0 - \sin\theta_v\sin\theta_0\cos(\phi_v - \phi_0),$$

with θ_0 and θ_v, respectively, the angle between a vector directed from the sea surface to the sun and the sensor, and ϕ_0 and ϕ_v, the corresponding azimuth angles of the two vectors. The phase function for Rayleigh scattering is

$$P_r(\Theta) = \frac{3}{4}\left(1 + \cos^2\Theta\right).$$

I felt this observation was very important, because it provided an analytical expression for L_r, significantly reducing the computation time required for its determination. More important, using the same approximation, it seemed clear that the aerosol contribution should be given by a similar formula with the terms having the subscript "r" being replaced by terms having the subscript "a" for aerosol (and p_r replaced by $\omega_a p_a$, where ω_a is the aerosol single scattering albedo – scattering coefficient ÷ extinction coefficient). Thus, the spectral variation of L_a should follow the spectral variation of $\omega_a\tau_a p_a$, i.e.,

$$S(\lambda_i,\lambda_j) \equiv \frac{L_a(\lambda_i)}{L_a(\lambda_j)} = \frac{F_0(\lambda_i)}{F_0(\lambda_j)}\frac{\omega_a(\lambda_i)\tau_a(\lambda_i)p_a(\lambda_i)}{\omega_a(\lambda_j)\tau_a(\lambda_j)p_a(\lambda_j)} \equiv \frac{F_0(\lambda_i)}{F_0(\lambda_j)}\varepsilon(\lambda_i,\lambda_j). \tag{17.3}$$

This relationship gave me the idea for an atmospheric correction algorithm. Assuming that the aerosol size distribution could be described by a power law in particle diameter (in accordance with models at that time), the phase function should be almost independent of wavelength and $\tau_a(\lambda_i) \propto (\lambda_i)^{-\alpha}$, where α is called the Ångström exponent and typically, $0 \le \alpha \le 2$. Furthermore, when the aerosol is non-absorbing ($\omega_a = 1$),

$$\varepsilon(\lambda_i,\lambda_j) = \left(\frac{\lambda_j}{\lambda_i}\right)^{\alpha}. \tag{17.4}$$

Under these conditions, if we knew L_a at a single wavelength (and knew α) we could determine L_a at all other wavelengths. Knowing that $L_w(\lambda_{\mathrm{Red}})$ in the red is often negligible compared to the blue and the green (Fig. 17.2),

$$L_a(\lambda_{\mathrm{Red}}) = L_t(\lambda_{\mathrm{Red}}) - L_r(\lambda_{\mathrm{Red}}), \text{ and } L_a(\lambda_i) = \frac{F_0(\lambda_i)}{F_0(\lambda_{\mathrm{Red}})}\left(\frac{\lambda_{\mathrm{Red}}}{\lambda_i}\right)^{\alpha} L_a(\lambda_{\mathrm{Red}}), \tag{17.5}$$

essentially reducing the atmospheric correction problem to determining a single parameter: α.

To test these ideas, in particular the formula for $\varepsilon(\lambda_i,\lambda_i)$, Equation (17.4), we attempted to use the Ocean Color Scanner (OCS, a CZCS simulator built by NASA/GSFC and designed to fly on a U-2 aircraft) based at NASA Lewis Research Center under the direction of Jack Saltzman. Data of $L_t(\lambda_i)$ were obtained by Jack on a flight of altitude $\sim$ 15 km over the Gulf of Mexico south of the Mississippi delta coincident with a CZCS NET prelaunch algorithm development cruise. I used the data and Equation (17.1) to form

$$L_a(\lambda_i) = L_t(\lambda_i) - L_r(\lambda_i) - t(\lambda_i)L_w(\lambda_i), \tag{17.6}$$

expecting the resulting spectral variation to be $L_a(\lambda_i) \sim F_0(\lambda_i) \times (\lambda_i)^{-\alpha}$, verifying that we were on the right track. Indeed, the spectral variation did follow the expected relationship, but with $\alpha = 8$: completely impossible! Recall that for the Rayleigh component $L_r(\lambda_i) \propto F_0(\lambda_i) \times (\lambda_i)^{-4}$, and the variation of the aerosol scattering must be a weaker function of wavelength than molecular scattering. Thus, the results made no sense whatsoever. I told Jack the results and he said he would get back to me in a few days. Later he called and said I should take the measured $L_t(443)$ and multiply it by 0.7, with corrections of a similar magnitude for the other spectral bands. Thus, Jack believed the OCS calibration was in error by as much as 30%. With errors of this magnitude, I saw no sense in trying to use the OCS to show that our formulas were reasonable approximations to reality. That was the last time I tried to use aircraft data to validate our atmospheric correction ideas, and there was *no* prelaunch test of the algorithms or even their underlying assumptions.

17.3 IUCRM Colloquium: "Passive Radiometry of the Ocean"

During this same time period (1976–1978), I had tested these ideas using simulated data derived from multiple scattering solutions to the radiative transfer problem in the ocean-atmosphere system (Gordon, 1978). They seemed to hold up well, so Dennis Clark and I decided to combine his proposed algorithm (Clark, 1981) for estimating the water's pigment concentration from radiance ratios, e.g.,

$L_w(443)/L_w(550)$, with my atmospheric correction ideas to try to estimate the accuracy with which C could be estimated. This work led to three important conclusions, if the assumptions underlying the correction algorithm were correct. First, knowledge of the value of the parameter α is much more important than the actual aerosol concentration, i.e., given knowledge of α the error in C is only a weak function of the aerosol optical thickness. Second, for low values of C, e.g., ≤ 0.2 mg/m^3, accurate values can be retrieved as long as α is not overestimated. Third, as C increases, the accuracy with which α must be known also increases; however, accuracies in C considerably better than $\pm(1/4)\log_{10}(C)$, for $C \leq 1.0$ mg/m^3 are possible with only a coarse estimate of α. This work was reported at the IUCRM Colloquium on "Passive Radiometry of the Ocean" at the Institute of Ocean Sciences, Patricia Bay near Victoria, BC, Canada from June 14 to 21, 1978 (Gordon and Clark, 1980).

The IUCRM Colloquium was the precursor to "Oceanography from Space" Venice 1980. More important, it also provided one of the first opportunities for those interested in water color to exchange ideas. Most at the meeting understood that the CZCS was not optimally designed for ocean color. At the "Working Group on Water Color" session at the end of the meeting, several proposals were made concerning the specifications of a dedicated ocean color instrument (a CZCS follow-on sensor) with due respect for the requirements of atmospheric correction and of the absorption and scattering properties of water constituents. These are summarized in Table II in Morel and Gordon (1980).

With the exception of the "low priority" bands at 610 and 640 nm and the absence of a band near 670 nm, the specifications closely resemble the final configurations of SeaWIFS and MODIS. In addition, the Working Group also recommended that a program be established to assess the "spatial and temporal variation of the phytoplankton pigment concentration on a global scale. This Global Assessment of Phytoplankton Pigments (GAPP) would consist of utilizing the CZCS to prepare monthly or bi-monthly worldwide maps of the pigment concentration and hence provide an estimate of the total phytoplanktonic biomass of the world oceans as well as the spatial and temporal variation of the primary productivity" (Morel and Gordon, 1980). Thus, even before launch, when many considered CZCS to be a boondoggle being carried out by lunatics, those knowledgeable in oceanic optics could see important improvements that could be made in the system, and important applications of the ocean color data.

17.4 CZCS Launch, Initial Imagery and Validation Cruises

CZCS was launched in October 1978, and the first image I saw was from Orbit 116 (November 1, 1978). Because there was a history of space-borne instruments failing soon after launch, every effort was made to try to validate the CZCS data and the algorithms as soon after launch as possible. Thus, the NET organized two cruises in the Gulf of Mexico to commence as soon as imagery was available. R. Austin and C. Yentsch organized a cruise aboard the NOAA Vessel Researcher, with Team members R. Austin, C. Yentsch and S. El-Sayed participating. Dennis Clark

chartered the Athena II, a 165 ft decommissioned patrol boat, from the Vietnam War, that was capable of speeds as high as 40 kt. The participating NET members on the Athena II were E. Baker, D. Clark and myself. Dennis' idea was to perform a hydrographic station at local noon, simultaneous with the satellite overpass. Measurements of upwelling spectral radiance, downwelling spectral irradiance, beam attenuation coefficient, phytoplankton pigments, TSM, particle size distribution, Secchi depth, and atmospheric transmittance were carried out at each station. I measured the backscattering coefficients of water samples in the blue (436 nm) and green (546 nm) with a light scattering photometer, and made hand-held atmospheric transmittance measurements with a Volz-like sun photometer.

The speed of the Athena II enabled us to proceed to the nadir point of the next day's satellite overpass with plenty of time to prepare for the station. With a ship proceeding at normal speeds ($\sim$10 kt) the best one could hope to accomplish would be to have the next day's station located near the edge of the scan, where atmospheric correction would be significantly more difficult because of the longer path through the atmosphere. During that cruise we made several stations in which the weather was sufficiently clear that excellent simultaneous CZCS imagery was obtained. In the next 8 months Dennis Clark organized two more cruises (Gulf of California and Middle Atlantic Bight) in support of the CZCS validation (and algorithm development). To underscore the difficulty of validating an ocean color sensor, one should note that of the 55 stations made underneath the CZCS, only 9 were usable for validation because of cloud contamination and the proximity of land.

At the time of launch, the proposed algorithms had yet to be implemented on the CZCS Processing System at GSFC. Processing a CZCS scene at that time (1979) was an enormous task, as the large mainframe computers were excruciatingly slow even by standards that would be set within the next 5 years. Under pressure to finish the validation, we had to scrounge computer time wherever we could find it. Dennis Clark, Jim Mueller, and I (assisted by Dave Ball of Computer Sciences Corporation, who worked with Jim) found an available computer coupled to an image display device at the AOIPS (Atmospheric and Oceanic Image Processing System) facility at GSFC. The computer was a PDP 1155 (minicomputer), and we were allowed to use it from time to time between the hours of about 6 PM–6 AM. The room was very cold and I always brought a hood from my parka to keep warm while processing the data.

I had developed a program that could take the ephemeris for the orbit and compute the Rayleigh scattering component for each pixel along a scan line. I did this computation using a UNIVAC 1106 mainframe computer for two overpasses coincident with our surface measurements, and stored the results on tape. I could also take the latitude and longitude along ship tracks and determine the line and pixel numbers along the track. We then took 512×512 pixel subscenes of CZCS images and applied the atmospheric correction algorithm (assuming $\varepsilon(\lambda_i,\lambda_i) = 1$) to the imagery to derive an estimate for $L_w(\lambda_i)$. This processing took several seconds per scan line. The monitor displayed the original $L_t(\lambda_i)$, which was then replaced by $L_w(\lambda_i)$ as each scan line was completed. The first image processed was from Orbit 130 (Fig. 17.3) near the Mississippi Delta.

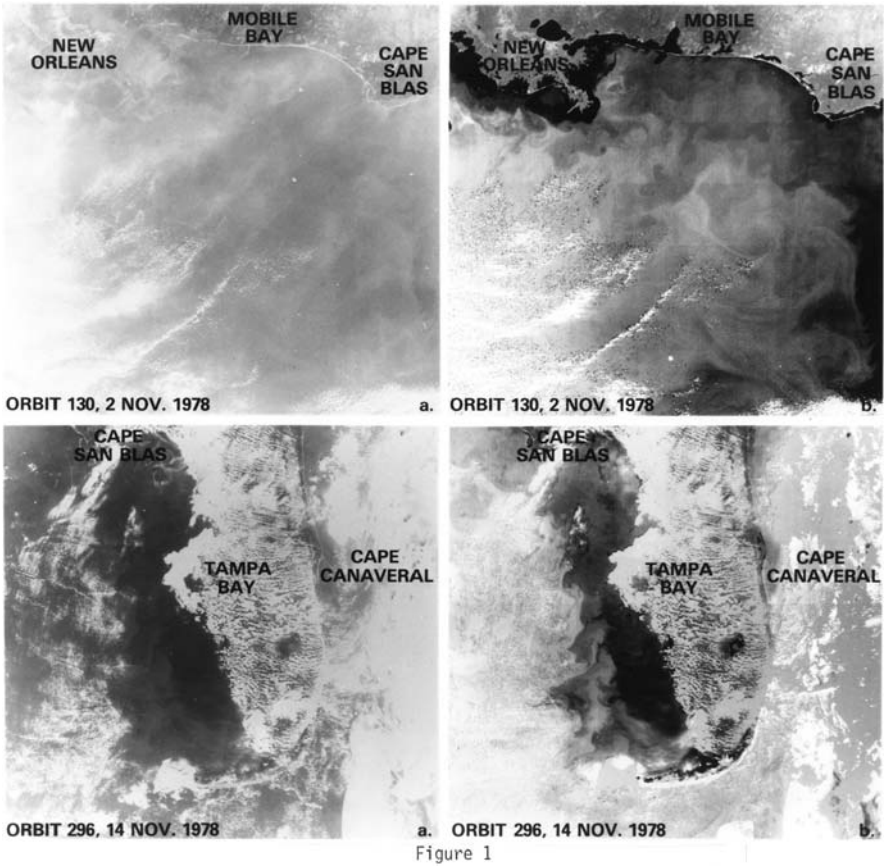

Fig. 17.3 Images of $L_t(443)$ (*left*) and $L_w(443)$ (*right*) for Orbits 130 (*top*) and 296 (*bottom*) over the Gulf of Mexico. From Gordon et al. (1980). Reprinted with permission of AAAS

This was a particularly hazy day, and as the computer was carrying out the correction, it appeared on the monitor that a veil was slowly being removed from the image. We were amazed at the clarity of the L_w image, which as can be seen, showed variability at a wide range of spatial scales, and strongly suggested that the biological activity was being driven by (or at least closely coupled to) the physical motion of the water. We applied the in-water algorithms to the retrieved $L_w(\lambda_i)$ to derive the pigment concentration. The resulting concentration for Orbit 296 off Tampa, FL is shown in Fig. 17.4, and the derived pigment concentration along the track is given in Fig. 17.5.

It was fortuitous that the ship track went through a particularly intense bloom (apparently caused by nutrient sources in the Everglades) off Fort Myers, FL. This in fact was a total accident. We did not know the bloom was there (no "real-time" color imagery to guide the ship), and expected the ship to traverse a track straight from the station near Key West to Tampa. However, the ship's crew wanted to watch

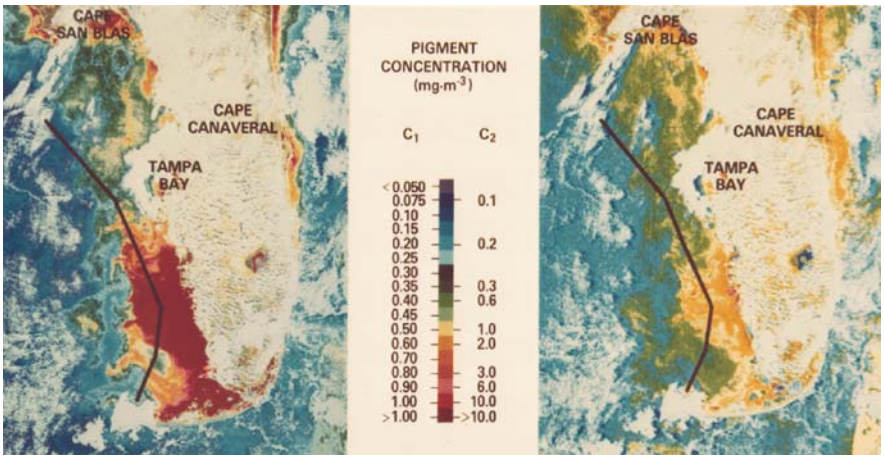

Fig. 17.4 Phytoplankton pigments for Orbit 296 processed with the two different algorithms: *Left* is using $R(13) = L_w(443)/L_w(550)$ and *right* is using $R(23) = L_w(520)/L_w(550)$. The *dark line* is the ship track of the Athena II. From Gordon et al. (1980). Reprinted with permission of AAAS

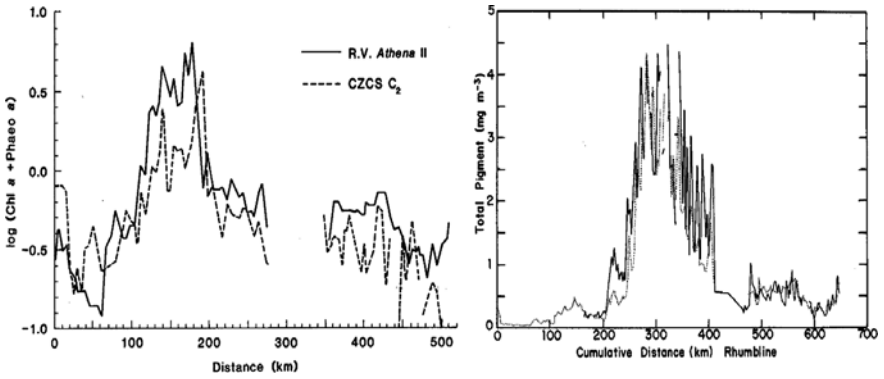

Fig. 17.5 *Left*: The retrieved pigment concentration using $R(23)$ along the track line in Fig. 17.4 (CZCS C_2) compared with that measured by the Athena II. From Gordon et al. (1980). Reprinted with permission of AAAS. *Right*: The same track line processed using the $R(13)$ algorithm 3 years later. From Gordon and Morel (1983)

Monday Night Football on television, and had to alter the course to take the ship close to Fort Myers in order to get good reception (Raiders 34, Bengals 21). This bloom provided an excellent test of the algorithm as is shown in Fig. 17.5 on the left comparing the surface-measured and CZCS-estimated pigment concentrations. This work constituted the initial validation of CZCS data and the processing algorithms. The rapid improvement of CZCS retrievals with time is underscored by the right panel in Fig. 17.5, which shows the same track line processed 3 years later with improved algorithms and improved calibration. Note that the scale on the y-axis is no longer logarithmic as it was in the first analysis of the data.

At that time it was clear that there were three problems that needed to be addressed before significant progress could be made in ocean color studies. First, we needed a method of estimating the value of $\varepsilon(\lambda_i,\lambda_j)$ for a given pixel. Second, we had no way to judge the quality of the sensor calibration, as it was determined prior to launch. Third, there were only enough NASA computational resources available to process a small number of CZCS scenes.

It seemed to me that it was reasonable to expect that $\varepsilon(\lambda_i,\lambda_j)$ would be almost independent of position within an image. My reasoning was based on the fact that for a given aerosol type (i.e., a given size frequency distribution and a given particle refractive index) $\varepsilon(\lambda_i,\lambda_j)$ can depend on the viewing direction only through differences in the shape (the variation of $P(\Theta)$ with Θ) of the aerosol scattering phase function with wavelength. Since these differences are assumed to be small, if the aerosol type is the same throughout an image, although the aerosol concentration may vary, $\varepsilon(\lambda_i,\lambda_j)$ should be constant.

I decided to test this hypothesis by looking at the variation of the apparent value of $\varepsilon(\lambda_i,\lambda_j)$ along a line on the image in Fig. 17.3 from Orbit 130. This is what I wanted to test earlier with the OCS. We had measured $L_w(\lambda_i)$ at many locations within the Gulf of Mexico and found that as long as extreme coastal areas were avoided, $L_w(\lambda_i)$ had relatively stable values of $\sim$0.31 and 0.22 mW/cm^2μmSr, respectively, at 520 and 550 nm. In addition, $L_w(670)$ was found to be close to zero. Thus, given $L_t(\lambda_i)$ and computing $L_r(\lambda_i)$, we could use $L_w(\lambda_i)$ to compute L_a at 520, 550, and 670 nm as given in Equation (17.6).

The computation could not be done accurately at 443 nm because $L_w(443)$ depends strongly on the pigment concentration, which as the figures above show, is highly variable in the Gulf, especially near the coast. We selected a track starting from Choctawhatchee Bay, FL (the large bay approximately midway between Mobile Bay and Cape San Blas on the image) due south, running for approximately 400 km. The graph on the left in Fig. 17.6 provides the radiances $L_t(\lambda) - L_r(\lambda)$, along the track. As $L_t(670) - L_r(670) = L_a(670)$, and L_a is proportional to the

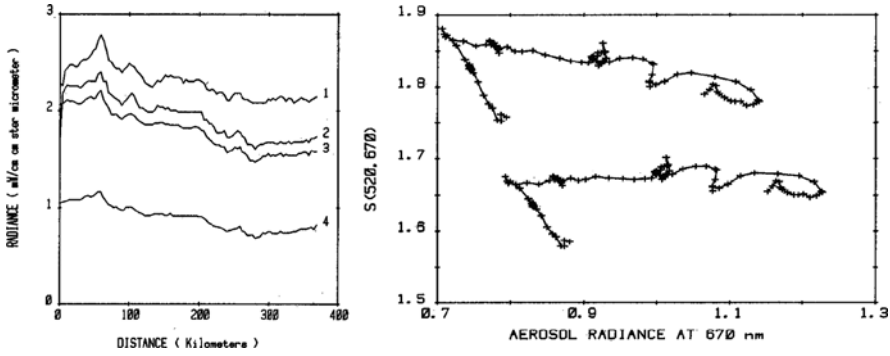

Fig. 17.6 *Left*: $L_t(\lambda) - L_r(\lambda)$, for the four CZCS bands, from Orbit 130 along a track from Choctawhatchee Bay, FL due south, running for approximately 400 km. *Right*: $S(520,670)$ along the same track before (*upper*), and after (*lower*), $F_0(670)$ adjustment as described in the text. From Gordon (1981)

aerosol optical thickness, the figure suggests that the aerosol concentration varies by a factor of 1.5 along the track. Using Equation (17.3) to form $S(\lambda_i,\lambda_j)$, the graph on the right in Fig. 17.6 (upper curve) shows the resulting variation of S(520,670) along the track as a function of the aerosol radiance (concentration).

The result seems to show that S(520,670) varies with aerosol concentration; however, there are two items in this estimate that carry significant uncertainties: the values of $F_0(\lambda_i)$ and the sensor calibration leading to the values of $L_t(\lambda_i)$. Error in either of these could lead to significant variations in S(520,670) with aerosol concentration (Equations (17.2) and (17.6)). As an example, I decreased the value of F_0(670) by about 6% and this simple change led to the lower curves in Fig. 17.6 (right), i.e., rendered S(520,670) nearly constant along the track. This exercise, which was the subject of my paper at Oceans from Space, Venice 1980 (Gordon, 1981), convinced me (1) that it was probably reasonable to assume the S (and ε) is independent of aerosol concentration, and (2) that the sensor calibration (relative to whatever version of the extraterrestrial solar irradiance is being used) is of paramount importance, and we needed to address the CZCS calibration.

At approximately the same time, at the urging of Charlie Yentsch and Ros Austin, the NET agreed to devote a significant portion of the 2 h/day that CZCS operated to acquiring a global data set. Although the computer resources to analyze such a data set did not exist at the time, they would in a few years. This turned out to be an key decision and the results demonstrated the importance of ocean color to global marine ecology.

17.5 Calibration

Understanding the calibration (or at least the relative calibration) of CZCS was a difficult problem (and, without several assumptions, impossible). Calibration as used here refers to the conversion from the digital counts (DC) recorded by the sensor to top-of-atmosphere radiance L_t, i.e., $L_t(\lambda_i) = k(\lambda_i) \times DC(\lambda_i)$, where $k(\lambda_i)$ is the "calibration constant." The onboard calibration system did not work well and did not include the entire optical train, so its use was abandoned. The only calibration scheme that seemed possible was what is now referred to as *vicarious calibration*, estimating the sensor radiance based on theoretical considerations and measurements of $L_w(\lambda_i)$ made at the surface, or equivalently, ensuring that the application of the algorithms to (re)calibrated sensor radiances yielded the observed $L_w(\lambda_i)$'s within their expected uncertainties. For CZCS, we had only the measurements of $L_w(\lambda_i)$ carried out on the validation cruises. We made the leap-of-faith assumption that the atmospheric correction algorithm was valid (and L_w(Red) ≈ 0). Thus, combining Equations (17.1), (17.2), (17.3), (17.4) and (17.5), the $L_w(\lambda_i)$'s are given by

$$t(\lambda_i)L_w(\lambda_i) = L_t(\lambda_i) - L_r(\lambda_i) - [L_t(\text{Red}) - L_r(\text{Red})] \times \left[\frac{F_0(\lambda_i)}{F_0(\text{Red})}\right] \varepsilon(\lambda_i,\text{Red}),$$

where $t(\lambda_i)$, the diffuse transmittance, can be computed with good accuracy by simply ignoring aerosols. However, we still needed an independent method of estimating $\varepsilon(\lambda_i,\text{Red})$. This was supplied by what Dennis Clark and I referred to as the "clear water radiance concept." This was based on our observation that when $C \leq 0.25$ mg/m^3, the normalized water leaving radiance, $[L_w(\lambda_i)]_N$, defined through $L_w = [L_w]_N \cos\theta_0 t_0 / a_\oplus^2$, where t_0 is the diffuse transmittance of the solar beam to the sea surface, θ_0 is the solar zenith angle, and $a_\oplus$ is the Earth-Sun distance in astronomical units (the mean $a_\oplus$ over 1 year is unity), at 520 and 550 nm were constant and known, and that at 670 nm was essentially zero (Gordon and Clark, 1981). Thus, if clear water could be located in a scene containing the $L_w(\lambda_i)$ measurements, it would be possible to determine ε(520,Red) and ε(550,Red), and through extrapolation (using a power law) ε(443,Red). Then, assuming $\varepsilon(\lambda_i,\text{Red})$ is independent of position in the image under consideration (a much weaker assumption than assuming a constant aerosol concentration), and assuming the sensor calibration was correct at 670 nm, we could estimate the water-leaving radiance in the other bands. Note the assumptions required to perform this vicarious calibration assessment: (1) the atmospheric correction algorithm is correct; (2) the ε-values are independent of position and their variation with wavelength is given by a power (Ångström's) law; and (3) the calibration of the spectral band at 670 nm is correct. The procedure is then to fractionally change $L_t(\lambda_i)$, i.e., $k(\lambda_i)$ for the fixed $DC(\lambda_i)$, until the measured and retrieved $L_w(\lambda_i)$'s are brought into confluence. Note that the computation of $L_r(\lambda_i)$ requires the extraterrestrial solar irradiance (Equation (17.2)), so any error in this quantity will be interpreted as an error in sensor calibration, i.e., $k(\lambda_i)$, therefore the "calibration" will be dependent on the particular values used for the solar irradiance. With these assumptions, we determined adjustments to the sensor calibration that seemed to work well for imagery from *all* of the validation scenes obtained during June of 1979. Unfortunately, when we used this vicarious calibration and examined data from earlier cruises, we found that the agreement between the measured and retrieved $L_w(\lambda_i)$ values became increasingly poorer as we progressed backward in time. We interpreted this as a decrease in the sensitivity of the instrument with time. This decreasing sensitivity with time was a major problem for the analysis of CZCS data. It was apparently caused by residue accumulating on the scan mirror due to out gassing of the instrument. This made it clear that ensuring the stability of, or carefully monitoring the stability of, future ocean color sensors was paramount. It is interesting to note that most of the validation data that were obtained within a year of launch were also used to adjust the sensor calibration for its variation with time. This is likely the origin of the term "cal-val" in reference to such activities.

17.6 The NOSS Interlude

In the early 1980s, with the success of the CZCS, a proposal was made to include an expanded instrument on a new platform, the National Ocean Satellite System (NOSS). Armed with high quality CZCS imagery, and the IUCRM Water Color

Working Group's recommendations regarding optimal spectral bands, we felt that the proposed ocean color sensor would face little opposition for inclusion on the platform. Little did we know. There was fierce opposition to its inclusion. I recall a presentation to a NASA advisory committee regarding ocean color at which the most prominent member of the committee made the statement: "I know of no respectable biologist that thinks this [ocean color] is important." It is interesting to note that years later Dick Barber referred to CZCS as one of the seven most important developments in marine biology in the last 50 years! After much time was spent trying to get an ocean color instrument on NOSS, the entire NOSS program was canceled; the first of several such failures. However, the time and effort were not wasted.

17.7 Back to CZCS

One of the significant problems processing CZCS imagery was the intense amount of computational resources required. Basically, in 1980 the image processing systems were PDP mini-computers coupled to image display devices. I was fortunate to work with Otis Brown and Bob Evans at the University of Miami, who developed a system for SST image processing. However, one of the biggest breakthroughs for ocean color processing was the development of the VAX computer systems by DEC. These "super-min" computers enabled the processing of CZCS scenes with acceptable computation times, and made processing of the entire CZCS data set a possibility. The Brown-Evans image processing system was ported to the VAX along with all of the CZCS processing algorithms. This processing system was then duplicated on a larger scale at GSFC in a joint project with Wayne Esaias, Chuck McClain and Gene Feldman to process all of the CZCS imagery and demonstrate the full potential of ocean color remote sensing to marine ecology (Esaias et al., 1986).

17.8 SeaWiFS and MODIS

Between 1984 and 1988 there was much work devoted to flying an improved ocean color scanner. After several failures, this effort succeeded with the approval of SeaWiFS as a joint project between NASA and EOSAT, a private, for-profit company. The SeaWiFS sensor was designed solely for the purpose of ocean color, with a special emphasis on accurate radiometry. Special features included NIR spectral bands for atmospheric correction, a solar diffuser for on-board calibration, the facility for viewing the moon to monitor the long-term stability of the radiometry, and increased radiometric sensitivity for better resolution of the water-leaving signal. The sensor was designed to operate continuously, which greatly increased the data coverage over CZCS. In addition, in support of SeaWiFS (and later MODIS), a dedicated calibration facility was developed by Dennis Clark (Clark et al., 1997). This

facilitated the vicarious calibration of these sensors over time. SeaWiFS, which is in its 11th year of operation, has been an enormous success.

From the end of CZCS to the approval of SeaWiFS, most of my effort was devoted to enhancements to the atmospheric correction algorithm, with some work on a semi-analytic model of water-leaving radiance (Gordon et al., 1988). We replaced the single scattering computation of $L_r(\lambda_i)$ with a full multiple scattering computation, including polarization (Gordon et al., 1988), and tried to understand the influence of sea surface roughness on atmospheric correction (Gordon and Wang, 1992a, b). We also examined calibration requirements and enhancements and signal-to-noise considerations for future sensors (Gordon, 1987, 1990). During this time André Morel and coworkers examined the influence of the variation of Ozone concentration and the variation of atmospheric pressure on atmospheric correction (André and Morel, 1989) and developed the first atmospheric correction algorithm that truly coupled a model of ocean color to first-order radiative transfer (Equations (17.1), (17.2), (17.3), (17.4), (17.5) and (17.6)) (Bricaud and Morel, 1987). However, even with all of the algorithm enhancements, it became clear that significant improvement in CZCS processing was unlikely simply because of instrument limitations.

With the improved radiometric sensitivity of SeaWiFS (and later MODIS) over that of CZCS, the atmospheric correction was still not up to the task because of the partial neglect of multiple scattering effects, particularly the interaction between aerosol and Rayleigh scattering. Menghua Wang and I set out to try to modify the correction algorithm to include multiple scattering effects. Our idea was (1) to use the basic structure of the algorithm, but to rewrite Equation (17.1) to explicitly include the Rayleigh-aerosol interaction ($L_{ra}(\lambda_i)$), i.e., $L_t(\lambda_i) = L_r(\lambda_i) + L_{ra}(\lambda_i) + L_a(\lambda_i) + t(\lambda_i)L_w(\lambda_i)$, (2) compute $L_t(\lambda_i)$ for various aerosol models and concentrations with $L_w(\lambda_i) = 0$ including all orders of multiple scattering, (3) compute $L_r(\lambda_i)$ as before using a full multiple scattering code, and (4) compute $L_t(\lambda_i) - L_r(\lambda_i) = L_{ra}(\lambda_i) + L_a(\lambda_i)$ as a function of the aerosol optical thickness and model and store the computations for later use in look-up-tables (LUTs). We tested such a scheme using (as before) an aerosol model for which the scattering phase function was independent of wavelength, and then re-evaluated it using more realistic aerosol models. Our final algorithm was still being used in SeaWiFS and MODIS processing into 2009 (Gordon and Wang, 1994).

CZCS, SeaWiFS, and MODIS are the only sensor programs with which I have had direct involvement. Although I have no first-hand knowledge of them, for completeness I mention the other sensors that were flown in the mid to late 1990s. These include OCTS (JAXA) and POLDER (CNES) on ADEOS (JAXA) and MOS (DLR) on IRS-P3 (ISRO).[1]

[1] For information on these sensors, see http://www.ioccg.org/sensors_ioccg.html

17.9 The Future

For classical ocean color remote sensing, i.e., utilizing sensors with a small number of spectral bands, there are still difficulties with atmospheric correction in the presence of absorbing aerosols (Gordon, 1997), which fortunately contaminate only a small fraction of the imagery. The difficulties associated with these aerosols are that (1) they cannot be identified using spectral bands in the NIR, (2) their effect in the visible depends strongly on their vertical distribution, and (3) their perturbation on L_t increases as λ decreases, so their effect is large where phytoplankton absorb light. I believe that dealing with absorbing aerosols for sensors of this type requires using coupled ocean-atmosphere algorithms such as those proposed by Moulin et al. (2001) or Chomko et al. (2003). They are also easily modified to operate in Case 2 waters (Kuchinke et al., 2009).

Beyond the classical instruments lies the promise of sensors with high spectral resolution. It has already been demonstrated that with such sensors separation of the total phytoplankton population into functional groups is possible (Bracher et al., 2008), even *without* what is traditionally though of as "atmospheric correction."

17.10 Some Closing Remarks

There are many people who have contributed to the success of ocean color remote sensing "behind the scenes" with little recognition. Early in the CZCS mission, Jack Sherman and Harold Yates at NOAA/NESS were strong supporters. Bob Kirk saw the SeaWiFS instrument to completion as project manager. Stan Wilson at NASA/HQ wisely instituted a temporary (2-year) rotating position at HQ to oversee ocean color activities and shepherd its development. To those who interrupted their own research to serve in this position: Ken Carder, Wayne Esaias, Curt Davis, Jim Yoder, Frank Muller-Karger, Marlon Lewis, Gregg Mitchell, Robert Frouin, Janet Campbell, John Marra, and Chuck Trees; we all owe a debt of gratitude. The position was finally made permanent and is now filled by Paula Bontempi.

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