Nimbus-7 Coastal Zone Color Scanner: System Description and Initial Imagery

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Reports

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Abstract. *The Coastal Zone Color Scanner (CZCS) on Nimbus-7, launched in October 1978, is the only sensor in orbit that is specifically designed to study living marine resources. The initial imagery confirms that CZCS data can be processed to a level that reveals subtle variations in the concentration of phytoplankton pigments. This development has potential applications for the study of large-scale patchiness in phytoplankton distributions, the evolution of spring blooms, water mass boundaries, and mesoscale circulation patterns.*

The possibility of using remote sensing of ocean water color (*1*) to determine the water content has been recognized for many years and was given new impetus by the work of Clarke *et al.* (*2*). This work, together with reports by Yentsch (*3*), led the National Aeronautics and Space Administration (NASA) in 1972 to begin aircraft investigations to determine whether ocean color could be measured usefully from spacecraft, whether ocean color could be detected through the scattering atmosphere, and whether other interfering effects, such as the direct specular reflectance of the sun (glint) from the water surface, could be avoided or corrected for (*4*). The results of these efforts were reported by Hovis *et al.* (*5*), Arvesen *et al.* (*6*), and Mueller (*7*). The results were sufficiently encouraging that in 1973 NASA agreed to fly an ocean color sensor, to be called the Coastal Zone Color Scanner (CZCS), on Nimbus-G, which was scheduled for launch in 1978.

The physical processes of absorption and scattering relate the upwelling radiance just beneath the sea surface to the constituents of the water (*8*). Except for waters in close proximity to coastlines and the confluences of rivers and the sea, biological constituents play a dominant role in these processes (*9*). The most important constituent appears to be phytoplankton, microscopic plant organisms that photosynthesize and constitute the bottom link in the ocean food chain. These plankton contain chlorophyll *a* (the dominant photosynthetic pigment), which absorbs strongly in the blue and red regions of the visible spectrum. Hence, increasing concentrations of phytoplankton (chlorophyll *a*) have the effect of changing the color of water to green hues from the deep blue of its pure state. This effect can be clearly seen in Fig. 1, which compares measurements by one of us (D.K.C.) of the upwelled spectral radiance just beneath the sea surface for various concentrations of chlorophyll *a* plus phaeopigments *a*. Figure 1 also shows the locations of the CZCS spectral bands in the visible region and illustrates the rationale for their selection. The bands centered at 443 and 670 nm are located in spectral regions of high chlorophyll *a* absorption, that is, at wavelengths where upwelled radiance variations are strongly dependent on chlorophyll concentrations. The two bands at 520 and 550 nm are located at wavelengths where upwelled radiance variations with chlorophyll concentrations are small, near the so-called "hinge point" (*10*).

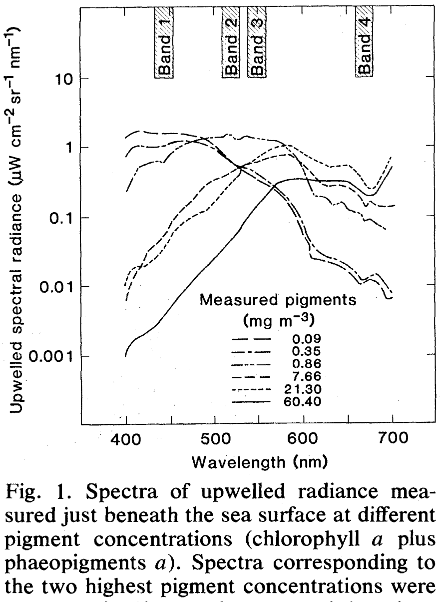

Fig. 1. Spectra of upwelled radiance measured just beneath the sea surface at different pigment concentrations (chlorophyll *a* plus phaeopigments *a*). Spectra corresponding to the two highest pigment concentrations were measured in Chesapeake Bay, and the others were measured in the Gulf of Mexico. The hatched areas represent the positions of CZCS spectral bands 1 through 4.

The effect of chlorophyll absorption on upwelled radiance is most striking in the blue band (443 nm), where a change in upwelled radiance of more than two orders of magnitude is seen over the range of chlorophyll concentrations measured (Fig. 1). This sensitivity at 443 nm is very useful when one is trying to discriminate between water masses of high and low chlorophyll content and, perhaps more important, between water masses of very low, but different, chlorophyll *a* concentrations.

The CZCS was built by the Ball Brothers Research Corporation to NASA specifications, summarized in Table 1. The instrument is a spatially imaging multispectral scanner, with a geometric instantaneous field of view of 865 μrad for a nadir field of view of 825 m from a spacecraft altitude of 955 km. All six spectral bands are precisely coregistered and internally calibrated. The swath width of the CZCS is slightly more than 1600 km.

The designers recognized that a large fraction of the signal sensed would be sunlight backscattered from the atmosphere, with variable polarization, and so the CZCS was built with less than 2 percent polarization sensitivity. For the avoidance of sun glint, the sensor has a provision for tilt that allows it to scan up to 20° from nadir ahead of or behind the spacecraft. Both the sensor tilt and the gains of spectral bands 1 through 4 are adjusted according to solar elevation at the scene under study.

One can obtain a feeling for the sensitivity of the CZCS through comparison with the Landsat-1 multispectral scanner (MSS). The MSS band 5 (600 to 700 nm) had a saturation radiance of 20 mW cm^{-2} sr^{-1} μm^{-1}, and the data were digitized on board at 6-bit quantization. The CZCS band 4 (670 nm) has a saturation radiance of 1.34 mW cm^{-2} sr^{-1} μm^{-1} (at gain 3, which would be used at Landsat sun angles) and is 8-bit digitized on board. The resulting radiometric sensitivity of the CZCS is greater by a factor of 60 than that of the MSS.

Like Landsat, Nimbus-7 contains three onboard tape recorders. With these, it is possible to acquire imagery for areas out of range of the receiving stations.

Nimbus-G was renamed Nimbus-7 after its successful launch on 23 October 1978. The first five CZCS bands were

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turned on 5 days later. Band 6, the thermal infrared (sea-surface temperature) channel, was turned on 21 days after launch. After a short engineering check period, data collection was begun on a routine basis, with a limit of 2 hours of collection time per day.

In order to supply scientific guidance to the CZCS program and to carry out data validation, NASA formed a Nimbus Experiment Team (NET) for each Nimbus-G sensor. The NET for CZCS (*11*) met first in January 1976 and has been working since then to prepare for the flight of CZCS and to develop the necessary data-processing algorithms. In particular, a number of pre- and postlaunch experiments were planned and carried out. 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. The first results of one of these postlaunch investigations are given in (*12*).

The initial imagery from the CZCS appears to be of excellent quality. Figure 2, taken from orbit 130 of Nimbus-7 on 2 November 1978, is a false-color image of the Gulf of Mexico extending from Florida west to approximately 94°W. Figure 2 is the result of a photographic combination of bands 1, 3, and 4 of the CZCS. No attempt has been made to remove the atmospheric contribution from the signal at this level of processing. As a result, considerable structure due to aerosols over the Gulf of Mexico dominates the image off the west coast of Florida and south of the coasts of Louisiana, Alabama, and Mississippi. This high spatial variability of aerosols demonstrates that any scheme for removing the contribution of aerosols cannot rely on direct extrapolation from one location in the scene to another. The approach of the NET has been to utilize an algorithm (*12, 13*) that will calculate the aerosol contribution and remove it on a picture element by picture element basis throughout the entire image.

Figure 3 is derived from the same CZCS data as Fig. 2. In this case, however, the atmospheric contribution has been removed, and an algorithm (*13, 14*) for computing the pigment concentration based on the ratio of band 1 to band 3 has been applied. Areas characterized by low concentrations of chlorophyll are shaded blue, and areas of high concentration are shaded red. Because the band 1 radiance effectively goes to zero at high chlorophyll concentrations, this ratio can only yield faithful pigment maps at low concentrations. Areas for which the Fig. 3 pigment map is not correct are shaded reddish-brown (concentrations

Table 1. Characteristics of the CZCS.

Band number	Wavelength (nm)	Gain	Saturation radiance (mW cm^{-2} sr^{-1} μm^{-1})	Measured signal/noise
1	433 to 453	3	5.41	158/1
		2	7.64	
		1	9.23	
		0	11.46	
2	510 to 530	3	3.50	200/1
		2	5.10	
		1	6.20	
		0	7.64	
3	540 to 560	3	2.86	176/1
		2	4.14	
		1	5.10	
		0	6.21	
4	660 to 680	3	1.34	118/1
		2	1.91	
		1	2.32	
		0	2.88	
5	700 to 800		23.9	350/1
6	10,500 to 12,500			0.22 K*

*Noise equivalent temperature difference at 270 K.

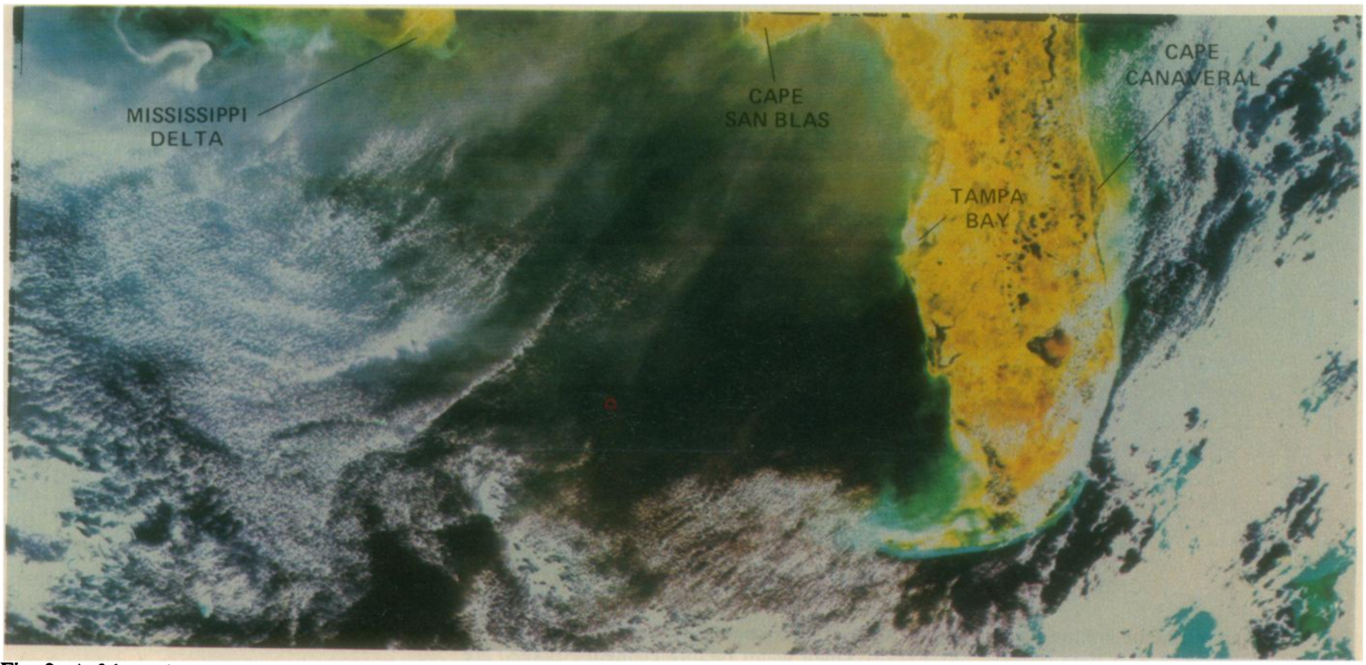

Fig. 2. A false-color CZCS image of the Gulf of Mexico from Nimbus-7 orbit 130. Highly variable haze obscures the patterns of ocean color, which emerge after application of an aerosol correction algorithm (see Fig. 3).

above 1.0 mg m^{-3}). For such areas a pigment algorithm based on other CZCS channels is appropriate (*12, 14*). The spatial structure in the phytoplankton distribution throughout the Gulf of Mexico is impressive, especially in view of the fact that the pigment concentration is less than 0.1 mg m^{-3} throughout much of the Gulf. Virtually none of this structure could be discerned before the application of the aerosol correction algorithm (compare Fig. 2).

Land and clouds were preserved in Fig. 3 by the use of a mask derived from band 5. Band 5 of the CZCS is so insensitive to the level of ocean and atmospheric aerosol radiance that a simple threshold effectively discriminates open water areas from clouds and land. The pigment algorithm was not applied to picture elements thus flagged as clouds or land. Instead, an arbitrary combination of data from bands 1, 2, and 3, which produces false colors similar to our natural color perceptions, was applied to these picture elements with the results shown. The color coding scale for pigment concentration was then selected to avoid confusion with land.

Data from the Nimbus-7 CZCS will be processed to two levels at the NASA Goddard Space Flight Center. The first level of processing will convert the digital counts from the spacecraft to measured radiances in the first five bands and equivalent blackbody temperature for band 6. These data will be archived and made available in two forms through the Environmental Data Information Service (EDIS) of the National Oceanic and Atmospheric Administration (NOAA). One form will be a black-and-white photograph showing a 2-minute segment of CZCS data for each of the six bands. Bands 1 through 5 will be enhanced somewhat by removal of the Rayleigh-scattering component of the signal as calculated for the center of the image. Band 6 will be shown as equivalent blackbody temperature.

In addition to the photographic product, the data from the first level will be available digitally on magnetic computer tape. Each tape will contain three image segments, each consisting of up to 2 minutes of data, stored in chronological order as taken aboard Nimbus-7. The magnetic tape segments will contain the calibrated radiances measured by the CZCS in bands 1 through 5, the equivalent blackbody temperature measured in band 6, the geographic locations of the data elements, and the time at which the data were taken. The calibrated radiance and temperature tapes are being made available so that anyone wishing to process CZCS data using algorithms other than those used by the NET may do so. Therefore, no atmospheric or other corrections will have been applied to these data.

Figure 3 illustrates the second level of analysis that will be applied to the Nimbus-7 CZCS data. After application of atmospheric corrections, the appropriate algorithms will be applied to derive phytoplankton pigment concentrations and the diffuse attenuation coefficient (*15*) from ratios of corrected radiances at the CZCS bands. The accuracy with which these quantities can be extracted from the imagery is discussed in (*12*). The derived data will be archived in the same photographic format as the data from the first level of processing—that is, a black-and-white photograph with six images, each showing a CZCS band covering 700 km along the spacecraft track and 1636 km in swath width. The data from the second level will also be archived on computer-compatible tape. These products will also be available through EDIS.

The imagery we have presented here shows that the Nimbus-7 CZCS allows observation of very subtle variations in water color. The most significant aspect of these color variations is their direct relationship to variations in the concentration of phytoplankton. This living marine resource supports all higher life forms in the sea and is, consequently, critical to man's commercial fishing endeavors. We are confident that, with further observations of water color over large geographical areas, we will be able to improve our understanding of the state of the standing crop of phytoplankton. This new information may, in turn, lead to improved methods for managing and exploiting fisheries. Another potential application of water-color data is the early detection of massive phytoplank-

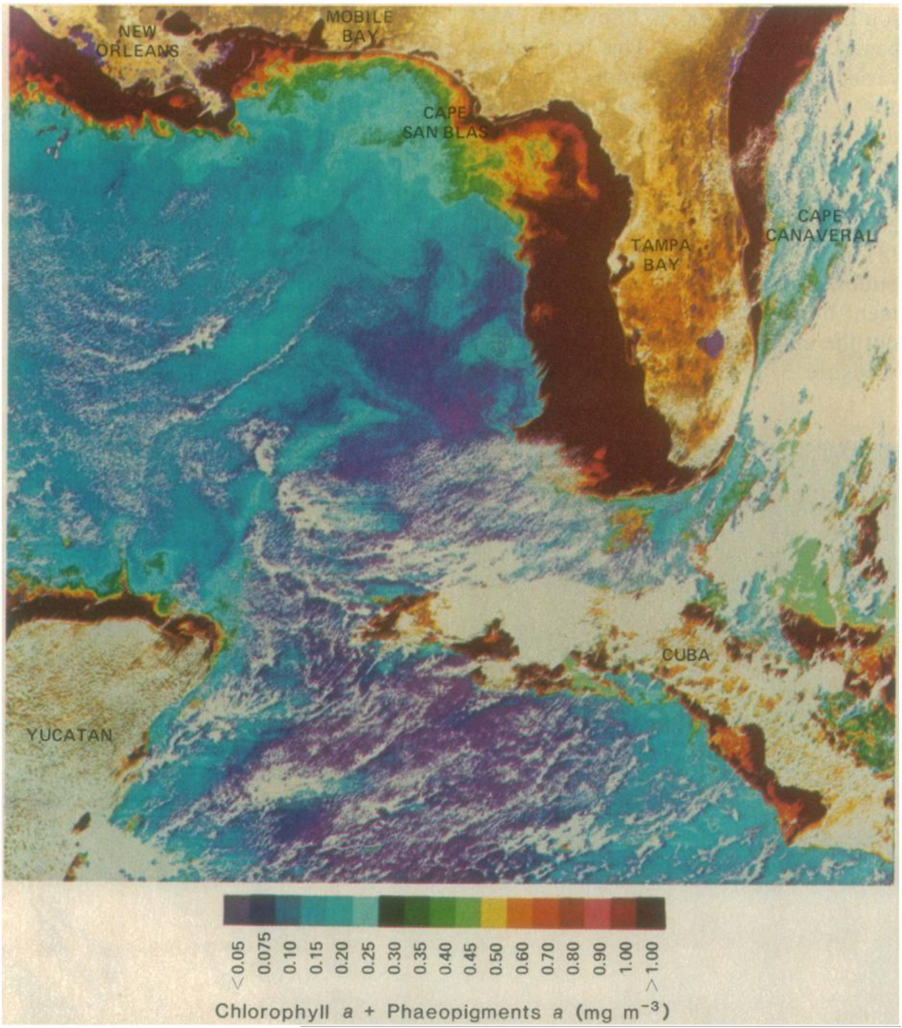

Fig. 3. A map of phytoplankton pigments in the Gulf of Mexico on 2 November 1978 derived from the Nimbus-7 CZCS data of orbit 130 (Fig. 2). Open water picture elements (pixels) are coded according to the color scale to show estimated chlorophyll *a* + phaeopigments *a*. Cloud and land pixels are represented in quasi-natural colors [see text and (*12*) for further details].

ton blooms due to excessive nutrient influxes; if unchecked, such conditions can deplete the oxygen content of the water and result in massive fish kills. The link between ocean color and phytoplankton concentration afforded by the Nimbus-7 CZCS offers an important and exciting new observational tool.

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Phytoplankton Pigments from the Nimbus-7 Coastal Zone Color Scanner: Comparisons with Surface Measurements

Abstract. *The removal of atmospheric effects from Nimbus-7 Coastal Zone Color Scanner (CZCS) images reveals eddy-like ocean turbidity patterns not apparent in the original calibrated images. Comparisons of the phytoplankton pigment concentrations derived from the corrected CZCS radiances with surface measurements agree to within less than 0.5 log* C, *where* C *is the sum of the concentrations of chlorophyll* a *plus phaeopigments* a *(in milligrams per cubic meter).*

The Nimbus-7 Coastal Zone Color Scanner (CZCS) was designed to measure the concentrations of phytoplankton pigments in the ocean (*1*). We report here initial comparisons between CZCS and surface determinations of pigment concentrations in the Gulf of Mexico. The data were collected during our first postlaunch experiment in November 1979.

The signal measured by the CZCS is related to the pigment concentration in the water through the scattering and absorption properties of the phytoplankton (*2*). Phytoplankton contain the photosynthetically active pigment chlorophyll *a* (Chl *a*), which is strongly absorbing near 443 nm. This absorption causes the solar radiation backscattered out of the ocean at 443 nm to decrease rapidly with increasing Chl *a* concentration. The Chl *a* absorption is much weaker at 520 and 550 nm. Therefore, an increase in Chl *a* causes the backscattered radiance to increase at these wavelengths as a result of the scattering associated with the phytoplankton [see figure 1 of (*1*)]. Thus, water that is poor in Chl *a* will appear a deep blue in sunlight, whereas water rich in Chl *a* will appear green.

A detrital pigment of Chl *a*, phaeopigments *a* (Phaeo *a*), possesses almost the same absorption spectrum as Chl *a*, and hence it cannot be separated from Chl *a* with the bands available on the CZCS. Because of this, only the sum of Chl *a* plus Phaeo *a* (henceforth indicated by C) can be estimated with this sensor (*3*). Usually, the Phaeo *a* concentration is lower by a factor of 5 to 10 than the Chl *a* concentration (*4*).

Following earlier investigators (*5, 6*), we relate the pigment concentration to ratios of radiances at various wavelengths λ rather than to absolute radiances. This procedure has the advantage of partially compensating for the influence of other material in the water, such as nonorganic suspensoids, as well as the masking effects of the atmosphere discussed below. The algorithm relating ratios of radiances to C has been developed from measurements of upwelled subsurface spectral radiance L_w^{λ} and the associated pigment profiles from three areas: Southern California, Chesapeake Bay, and the Gulf of Mexico (including the Mississippi discharge region). Upwelled radiance measurements were made with a submersible scanning spectral radiometer with a 2° field of view and a 5-nm spectral resolution. Values of C, which ranged from 0.07 to 77 mg m^{-3}, were measured by means of the fluorometric technique (*7*). A regression analysis of these data (*4*) related C to the radiance ratios $R_1 = L_w^{443}/L_w^{550}$ and $R_2 = L_w^{520}/L_w^{550}$ through

$$\log C_i = \log a + b \log R_i, i = 1 \text{ or } 2 \quad (1)$$

where the coefficients log a and b, along with the coefficient of determination r^2