Initial Analysis of OSTA-1 Ocean Color Experiment Imagery

Abstract. *Ocean images were obtained at three widely separated locations on the earth as part of NASA's ocean color experiment. Digital computer enhancement and band-ratioing techniques were applied to radiometrically corrected spectral data to emphasize patterns of chlorophyll distribution and, in one case, of bottom topography. The chlorophyll pattern in the Yellow Sea between China and Korea was evident in a scene produced from shuttle orbit 24. The effects of the discharge from the Yangtze and other rivers were also observed. Two scenes from orbits 30 and 32 revealed the movement of patches of plankton in the Gulf of Cádiz. Geometric corrections of these images permitted ocean current velocities in the vicinity to be deduced. The variability in water depth over the Grand Bahama Bank was estimated by using the blue-green channel of the instrument. The very clear water conditions in the area caused bottom-reflected sunlight to produce a sensor signal that was inversely related to the depth of the water.*

The ocean color experiment (OCE) was designed to map ocean features with an eight-channel scanning radiometer installed on the second orbital flight test of the space shuttle Columbia. The operational principle of this instrument relied on a process whose feasibility has been recognized for some time (*1*). For instance, in 1972 NASA began high-altitude aircraft sensor investigations known as the U-2 ocean color scanner program (*2*). Then, in October 1978 the coastal zone color scanner (CZCS) was launched on Nimbus-7 to make periodic observations of ocean color, primarily in coastal areas (*3*). The concept of a shuttle-borne scanner originated as a result of these developments.

The primary goal of the OCE was to detect phytoplanktonic algae on a global basis and to determine the chlorophyll pigment concentrations. To implement the scientific objectives, a team of scientific investigators was formed [H. H. Kim, N. E. Huang, R. S. Fraser, C. R. McClain, and L. R. Blaine from Goddard Space Flight Center and H. van der Piepen from Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt (DFVLR)].

The OCE was to focus mainly on deepwater areas, in contrast to the objectives of the CZCS. This was to avoid the complicated spectral characteristics of coastal waters, which are induced by the influence of coastal marine constituents introduced by continental sources. The relations between the radiometric spectra and water content are not well understood.

The OCE was also to address particular problems of the radiometry of the ocean-atmosphere system. The investigators realized that the ocean's albedo is small compared to that of most land surfaces. For instance, less than 10 percent of the blue spectral radiance is returned to the atmosphere by oceanic scattering. Thus, most of the light received by the sensor in space would never have interacted with the subsurface water mass but would only have interacted with the molecular and particulate components of the atmosphere and the ocean surface. Therefore the experiment was to study the aerosols, sea state, and other parameters that mask the perceived subsurface oceanic radiance.

The scanner used for the shuttle experiment was originally built as an aircraft instrument at Goddard Space Flight Center and was modified to meet the shuttle payload specifications. By late 1979 development of the scanner's hardware was completed, and the device was mounted on the shuttle payload pallet by the spring of 1980. The allocation and characteristics of the eight spectral channels are summarized in Table 1. The signal-to-noise ratio was superior to that of the original aircraft instrument. The geometric and optical design gave the scanner a swath of 506 km and an instantaneous field of view (IFOV) at nadir of about 1 km^2 at orbiter altitude. With this IFOV and a scan frequency of 4 revolutions per second, the scanner undersampled by a factor of 50 percent. This permitted a data-recording rate that met the quota allotted to the OCE for storage on a recorder in the orbiter's cabin.

The general plan of the OCE was to collect 120 minutes of data during the orbiter's passes over selected test sites. The sites chosen were known from previous experiments to be likely to produce interesting chlorophyll distribution patterns—produced, in some cases, by mesoscale anomalous flow patterns in the regions.

To augment the OCE results, the plan

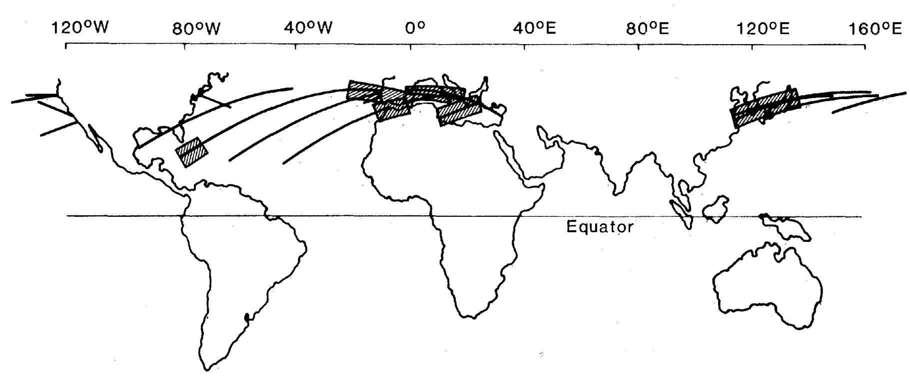

Fig. 1. Ground tracks of the space shuttle where OCE data were acquired, 12 to 14 November 1981. The areal coverage of clear ocean view data that were of sufficient quality to process is shown by the hatched areas.

Table 1. Allocation and characteristics of the eight spectral channels of the OCE sensor.

Spectral channel	Wavelength (nm)	Spectral bandwidth (nm)	Signal-to-noise ratio	Peak spectral radiance (mW/cm^2-μm-sr)	Spectral region	Purpose
1	485.9	23	1200:1	53.7	Blue	Chlorophyll absorption (maximum), atmospheric Rayleigh scattering
2	518.4	23	1400:1	37.8		Chlorophyll hinge point
3	552.6	23	1200:1	26.8	Green	Chlorophyll absorption (minimum)
4	584.5	23	1000:1	21.0		Backscattering (water and atmosphere)
5	620.6	23	800:1	16.3		Backscattering (water and atmosphere)
6	655.1	23	800:1	13.4	Red	Nonfluorescence band
7	685.1	23	680:1	11.6		Chlorophyll fluorescence at 685 nm
8	786.6	23	550:1	7.5	Near-infrared	Atmospheric backscattering (Mie)

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Table 2. Time segments of the OCE data in which clear views of the ocean are represented.

Orbit	Time segment* (day:hour:min:sec)	Geographic location
24	318:01:32:00 to 318:01:42:15	Yellow Sea, Sea of Japan, Pacific Ocean
29	318:09:00:00 to 318:09:04:00	Gulf of Libya, Greece (partially cloud-covered)
30	318:10:28:00 to 318:10:36:15	Portuguese coast, Mediterranean Sea
31	318:12:08:00 to 318:12:15:00	Spanish coast to Italy (partially cloud-covered)
32	318:13:23:00 to 318:13:26:00	Great Bahama Bank
32	318:13:39:00 to 318:13:42:15	Strait of Gibraltar

*Greenwich mean time.

included establishment of several in situ data collection projects. These involved collection of ocean samples, ground-based observations of atmospheric transmissivity, and correlative aircraft flights. The predesignated test sites were off the coast of Portugal (participating experimenters: A. G. Fiuza, University of Lisbon, Portugal; H. van der Piepen, DFVLR, West Germany; and M. Viollier, University of Lille, France), warm core eddy rings in the northwest Atlantic (P. Wiebe, Woods Hole Institute of Oceanography), the South Atlantic Bight (J. A. Yoder and L. P. Atkinson, Skidaway Institute of Oceanography), off the coast of Costa Rica (V. Klemas, University of Delaware), and frontal zones of the Kuroshio Current near Honshu (M. Takahashi, University of Tsukuba, Japan).

The OCE acquired 118 minutes of data during the orbiter's 3-day flight, which began on 12 November 1981 and terminated on 14 November 1981, after 54.25 hours. The ground tracks where OCE data collection took place are shown in Fig. 1. Many of the data acquisition areas had not been designated in the original plan. The deviations from the original flight plans were caused by the following operational difficulties:

1) The actual launch of the orbiter on 12 November was delayed by 3 hours from the originally planned 0700 hours Eastern Standard Time (EST). This delay caused significant changes in the solar zenith angles at the target sites when the orbiter passed. Alternative orbital passes, mostly in ascending orbital portions, had to be selected to get proper solar zenith angles.

2) Relatively low sun angles in the month of November in the Northern Hemisphere substantially limited the number of chlorophyll target areas that could be selected.

3) Because of spacecraft malfunctions, the shuttle's mission time was shortened by 2 days.

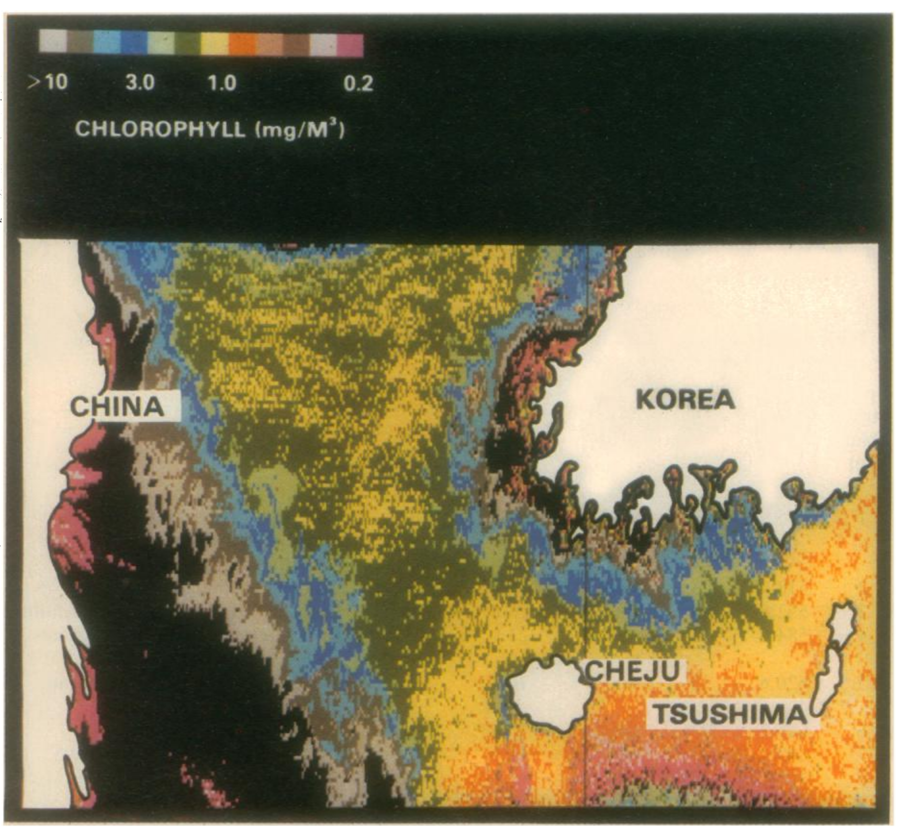
4) During the mission, two large storm systems covered both the east and west coasts of the United States. The South Atlantic Bight, which extends from Cape Canaveral to Cape Hatteras, was one of the OCE's important predesignated test sites. Thus, a relatively low percentage of cloud-free scenes resulted in about 20 to 30 minutes of useful data out of the total 2 hours.

In spite of these difficulties, the device acquired enough data to meet its basic objectives by demonstrating the ability to map chlorophyll concentration and identify ocean circulation features.

Excellent ocean scenes from some of the unplanned areas became available from the mission. Segments of the OCE data in which clear views of the ocean are represented are listed in Table 2. In addition to these data, coordinated data obtained with a similar instrument on low-flying aircraft piloted by a West German team and shipboard measurements of oceanic parameters from the Portuguese coast are available for 10 to 14 November 1981.

It will require some time to process, analyze, and correlate the OCE observations with the ground truth and aircraft data. However, initial assessments of the OCE data are given below.

Chlorophyll analysis. Figure 2 is a false-color image of the Yellow Sea



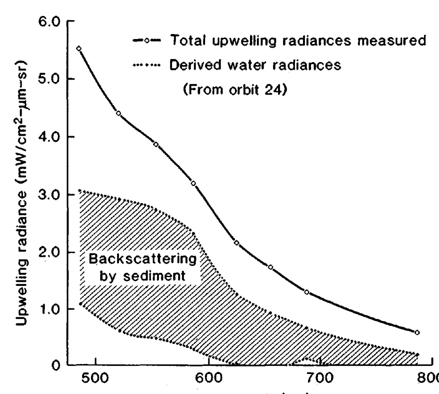


Fig. 2 (left). Map of chlorophyll pigments in the Yellow Sea on 13 November 1981 (STS-2 orbit 24). This false-color image shows the distribution patterns of chlorophyll pigment bearing phytoplankton. The color scale gives the quantity of pigments associated with each color in the figure. Fig. 3 (right). Spectral curves for two selected areas of the scene in Fig. 2, showing total upwelling radiance of the Yangtze river plume as perceived by the scanner (solid line) and the derived water radiance of the plume (upper dotted line). For comparison, derived water radiance for open ocean water just east of Cheju Island is shown by the lower dotted line.

showing the chlorophyll distribution of the area on 13 November 1981. The data were taken as the orbiter emerged from mainland China and headed toward Japan during its 24th orbit. The image was created by ratioing the difference of data from bands 1 and 3 to their sum after atmospheric obscuration effects were calculated and subtracted by using band 8 (near-infrared) data. Chlorophyll features are digitally enhanced. Scaling of the pigment concentration was done by using the following empirical relation, which defines a correlation between the shipboard measurement of concentration, C, and the derived water radiance products, R:

$$C = 17.5 \exp(-5.44R)$$

where

$$R = \frac{I^w(486 \text{ nm}) - I^w(552 \text{ nm})}{I^w(486 \text{ nm}) + I^w(552 \text{ nm})}$$

The $I^w(\lambda)$ is the ocean spectral radiance obtained after applying a correction to eliminate atmospheric radiance. Table 3 lists all the radiance components of an OCE data set in Fig. 2. This particular set was taken from an area just east of Cheju Island. Quantitative estimates of surface chlorophyll require that the contributions of backscattered radiation from the atmosphere (last column in Table 3) and the sea surface (column 7) be removed from the total upwelling radiance (column 2).

In OCE radiative analysis, an atmospheric radiative transfer computation method commonly known as Dave Code was used (*4*). An effective albedo of the lower boundary is determined for each pixel by using total upwelling radiance measured by the scanner (column 3 in Table 3). Certain reasonable assumptions are needed to construct an appropriate atmospheric model. The primary assumption is that the particle sizes of the aerosols are distributed according to the Jungean size distribution with a Jungean parameter of 3.0. This model gave upwelling radiance values of 0.22 for Rayleigh sky conditions and 0.56 mW/cm^2-μm-sr for a columnar aerosol content of 2.77×10^8. The measured OCE radiance of the 786 nm was 0.37 (Table 3), from which a particle content of 1.55×10^8 was interpolated from the model and used as input to the calculations for other channels.

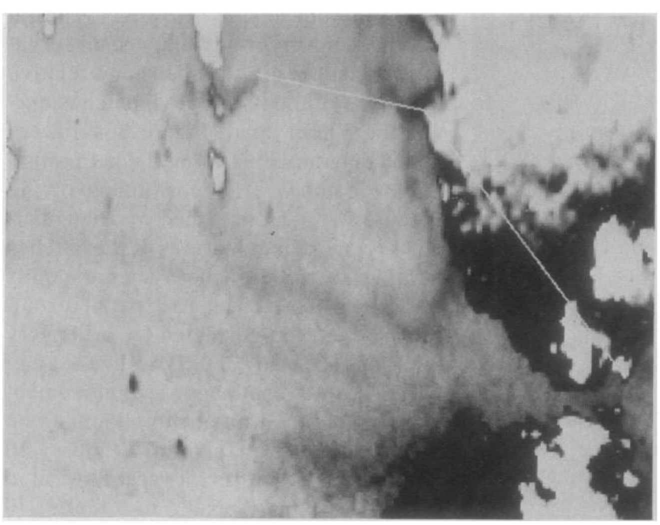
For image processing, such computation processes can be performed for each picture element, on a pixel-by-pixel basis, to construct an entire ocean image corrected for atmospheric effects. However, such measures would require a considerable amount of computer processing time. An alternative method, that of taking a proportionality constant between the atmospheric channel and other visible channels, has been discussed (*2*).

These atmospheric effects correction algorithms were repeatedly tested with high-altitude U-2 aircraft data obtained during the 1979–1981 oceanographic field studies of Gulf Stream frontal eddies. The aircraft experiments helped us to refine the correction algorithms and also provided us with an empirical relation correlating the shipboard measurements of chlorophyll concentration with the derived radiance ratios.

The quantitative assessment of chlorophyll is valid only for open ocean waters.

Table 3. Radiance components of OCE data set, orbit 24 (location, 33°15′N and 126°40′E; Greenwich mean time, 318:01:34:00; solar zenith angle, 56°; azimuthal angle, 70°).

OCE band	Measured radiance (mW/cm^2-μm-sr)	Effective albedo (%)	Downwelling fluxes (mW/cm^2-μm)			Upwelling radiance (mW/cm^2-μm-sr)			
			Total	Sun	Diffused	Fresnel	Total	Water	Atmospheric
1	3.92	3.4	96.3	70.3	26.0	0.08	1.04	0.96	2.88
2	2.75	2.15	92.4	70.6	21.7	0.069	0.63	0.561	2.12
3	2.00	1.7	89.0	71.2	17.7	0.057	0.48	0.423	1.52
4	1.49	0.95	90.2	72.9	17.2	0.049	0.27	0.221	1.22
5	1.00	0	81.5	67.8	13.7	0.041	0.041	0	0.96
6	0.88	0	82.6	69.9	12.7	0.036	0.036	0	0.88
7	0.69	0.35	78.4	67.3	11.1	0.031	0.07	0.04	0.62
8	0.37	0	65.2	57.5	7.7	0.004	0.004	0	0.366



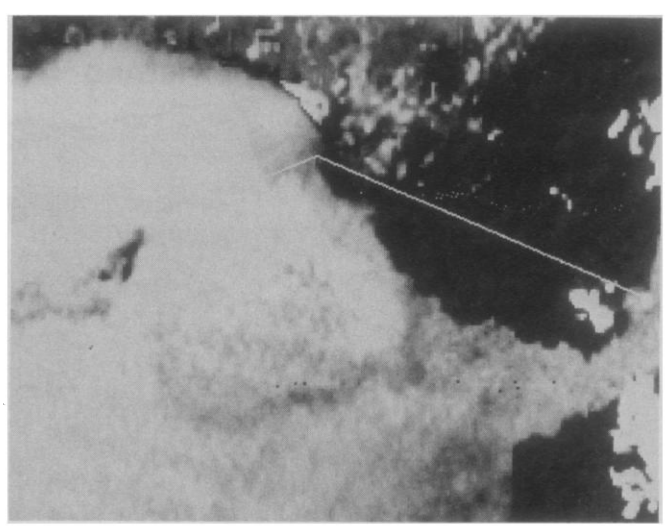


Fig. 4 (left). Chlorophyll image of the Gulf of Cádiz on 14 November 1981 (STS-2 orbit 30). The elongated dark feature (center) stretches from the entrance to the Strait of Gibraltar to the southern Spanish shore. Fig. 5 (right). An OCE image taken 3 hours later during orbit 32, showing the same chlorophyll features as in Fig. 4. Careful measurements of the salient features reveal motion of the chlorophyll patches.

The total upwelling spectral radiance of open ocean water versus that of coastal water can be seen in the same scene. Figure 3 illustrates upwelling spectral radiances for a clear water case, from a point just east of Cheju Island, and for a turbid water case, from a pixel in the middle of the Yangtze River plume (shaded area in Fig. 2). The upwelling spectra for the river plume show considerable enhancement in the regions of bands 3 to 8, indicating that the plume contains a significant amount of sediment particles and perhaps a high chlorophyll concentration. Knowledge of radiative transfer in the turbid area is still not sufficiently complete to provide reliable chlorphyll data for this zone. In any event, the absence of strong shelf circulation in the area causes remarkable plume patterns in the discharge from the Yangtze.

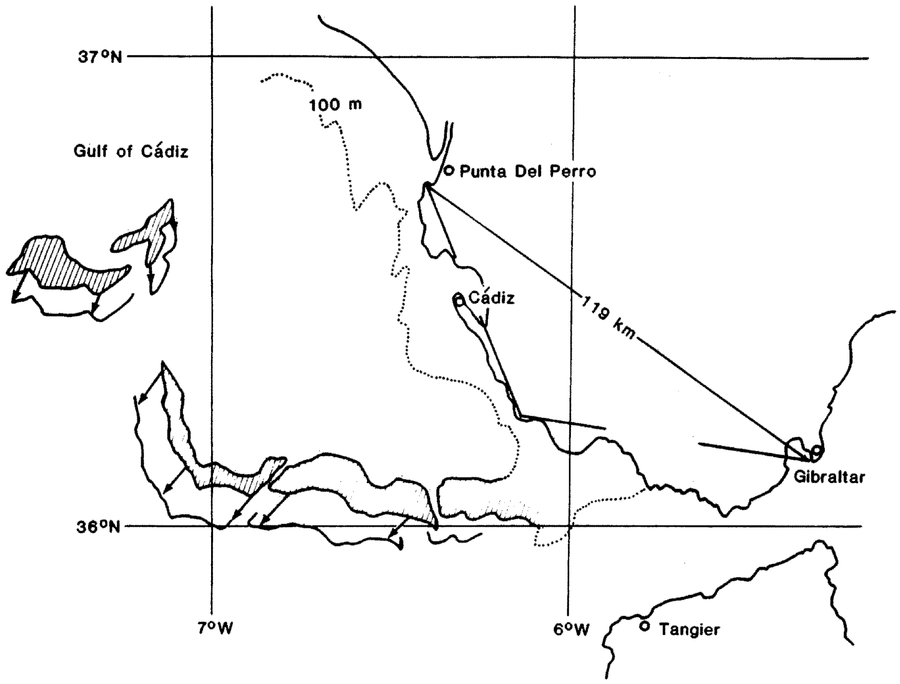


Fig. 6. Relative motion of chlorophyll patches, given in exaggerated vectors. The presence of a clockwise circulation in the Gulf of Cádiz on 13 November 1981 is suggested by the directional patterns of drift.

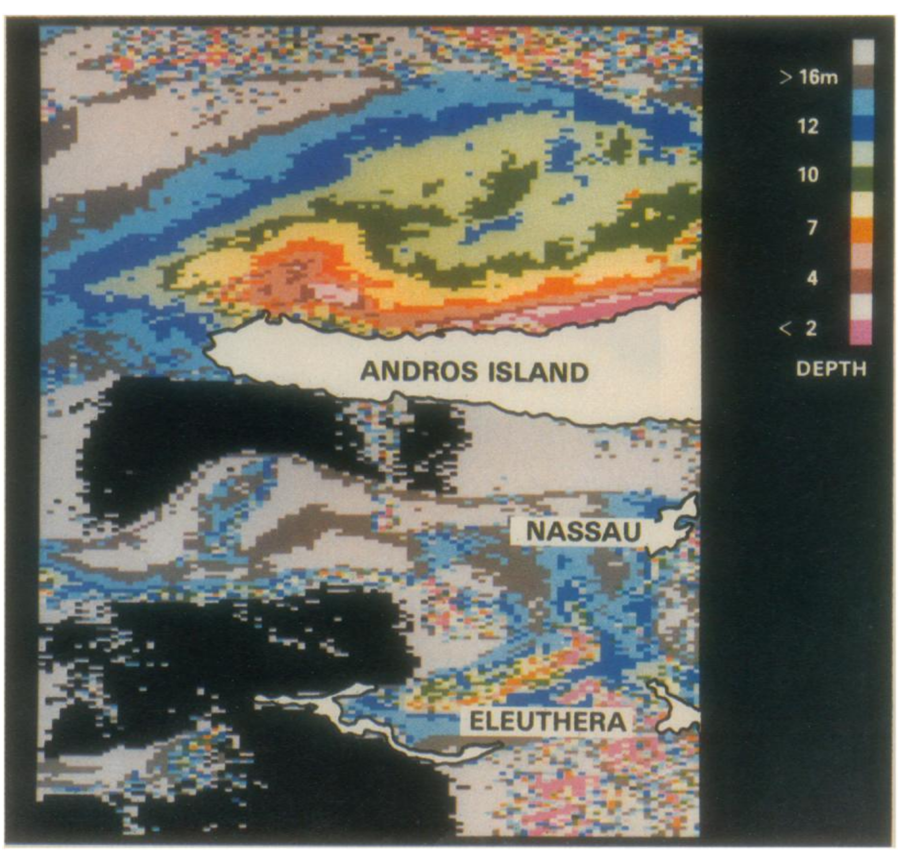


Fig. 7. False-color image of the Great Bahama Bank and its vicinity at 0825 hours (EST) on 14 November 1981 (orbit 32). Ocean depth is indicated by the color bar.

Remote measurement of current velocity. Legeckis in 1979 (*5*) reported that high-resolution thermal infrared data from polar orbiting satellites can be used to track water features in currents. One example is the time variation in the flow of the Gulf Stream between Florida and Cape Hatteras. Similarly, visible color imagery of the ocean offers another means of assessing current patterns. The spatial resolution of visible imagery is better than that of thermal imagery, and the measurement of current velocity based on the chlorophyll drift patterns is more precise and directly related to water mass transport phenomena.

An opportunity to demonstrate the possibility of using color images to measure ocean circulation occurred when the shuttle passed over the Strait of Gibraltar twice on the same day. As shown in Figs. 4 and 5, similar chlorophyll contour images of the Gulf of Cádiz were taken on orbits 30 and 32 as the orbiter passed over the area at 1032 and 1400 hours (Greenwich Mean Time) on 14 November 1981. In these images, areas of high chlorophyll concentration are represented by darker shades. An elongated chlorophyll feature appears to stretch from the Strait of Gibraltar to the middle of the Gulf of Cádiz and then curls north toward the southern Spanish shore in both images. However, careful geometric corrections allowed observation of changes in the shape and relative positions of the chlorophyll patches during the 3-hour span. Figure 6 is a schematic diagram illustrating the net motion of the patches. The positioning of the feature was accomplished by triangulating several salient features of the patches relative to three onshore anchor points near the water's edge. The spatial resolution of the ratio-corrected OCE imagery provides accuracy of 0.5 km. Image analysis showed southeastward movement away from the Strait of Gibraltar at a rate of 5.5 km (11 pixels) in 3 hours, 10 minutes and southwestward flow at a rate of 2.0 km (4 pixels) in 3 hours, 10 minutes along the shallow coastal lines. The net motion constitutes an anticyclonic circulation in the Gulf of Cádiz.

Ultimately, the compatibility of the OCE data analysis with sea truth will have to be tested when buoy measurements and wind field data for 14 November 1981 become available. However, historical current measurements show a strong surface current in the upper 100 m near the entrance to the strait. This current flows into the Mediterranean along the coasts of North Africa and Spain. Also, a relatively saline Mediterranean undercurrent flows out from the strait at below 100 m and surfaces some distance into the Atlantic.

Bathymetry. The Great Bahama Bank forms a semicircular shoal whose depth ranges from few meters to tens of meters. Gradients in depth occur at the northern edges, known as the Tongue of the Ocean. This topographic feature is surrounded with seawater of low oxygenation. Thus, the area is characterized by a scarcity of planktonic marine life. These conditions make the area highly suitable for visual observation of the underwater topography. The blue-green components of visible light, in the absence of chlorophyll pigment, penetrate deep into the water and reflect from the bottom. Data obtained at 0824 hours (EST) during orbit 32, in the vicinity of Nassau and Andros Island, were processed to depict underwater topographic features of the Great Bahama Bank (Fig. 7). The enhanced false-color image is based on the upwelling radiance of the band at 518 nm. The return signal is related inversely to the depth of the water. Upwelling spectral radiances taken from a shallow zone and from a deepwater zone represented in Fig. 7 are shown in Fig. 8. The dotted lines (subsurface radiance) are corrected for the atmospheric effects; hatched areas represent bottom reflection signals.

Discussion. Because of the orbiter's shortened mission, the OCE netted only a minimum amount of data for clear ocean views. Also, some of the surface experiments that were designed to validate interpretations of OCE observations were not carried out because of the rescheduling of the shuttle launch date. In spite of these difficulties, we believe that the primary objectives of the OCE were achieved. A wide variety of phenomena were observed and analyzed from the color expressions of the ocean.

The OCE demonstrated that, properly treated, ocean colorimetry provides a simple and direct method of remotely sensing the oceans. Until now, oceanographic studies incorporating satellite imagery of visible color have been limited to inferring near-shore and estuarine circulation. In those regimes high reflectivity of suspended material provides a relatively easily identified signature. The method of detecting variations in chlorophyll concentration in spatial and temporal domains promises to provide a new dimension.

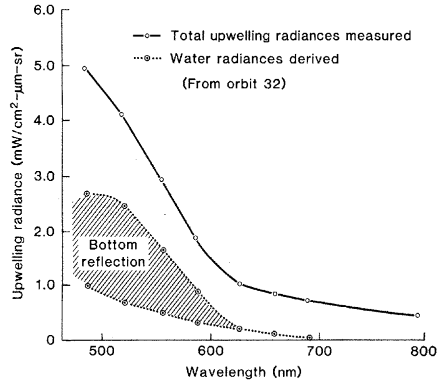


Fig. 8. Spectral curves for two selected areas of the scene in Fig. 7, showing total upwelling radiance from a shallow zone of the Great Bahama Bank as perceived by the sensor (solid line) and the derived water radiance (upper dotted line). The derived water radiance from an area of deep water, the Tongue of the Ocean, is shown by the lower dotted line.

To measure the concentrations of phytoplankton pigments in the ocean, the radiance detected at satellite altitudes needs to be corrected for atmospheric effects. The method devised to remove aerosol effects for the CZCS is a possible alternative (*6*). But in our OCE analysis a sophisticated model was incorporated to account for all the components in absolute radiance (Table 2). The outcome of such a method provides us with a consistent relation between the signal measured and the concentration of the chlorophyll pigments in the open ocean (*7*). However, the spectral curves in Figs. 3 and 8 imply that chlorophyll analyses are still limited to oceanic conditions of hydrospheric homegeneity and clarity.

The method of using chlorophyll concentration as a tracer may be applied to the deduction of oceanic flow patterns in large areas (Fig. 6). Plankton patches are natural drifters and can be tracked by satellites. Thus the color scanner has proved its utility in studies of both ocean circulation and biological processes.

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8. D. Clem and B. Johnson were responsible for the flawless performance of the OCE instrument during the shuttle mission.

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Feature Identification and Location Experiment

Abstract. *The feature identification and location experiment (FILE) senses radiation from the earth in spectral bands centered at 0.65 and 0.85 micrometers and compares ratios of the reflected solar radiation in the two wavelengths to make real-time classification decisions about four primary features: water, vegetation, bare land, and a cloud-snow-ice class. The radiance ratio classification algorithm successfully made automatic data-selection decisions. The classification image obtained on the mission is providing information needed to evaluate the FILE algorithm and system performance.*

The feature identification and location experiment (FILE) (Fig. 1) was flown on the second space shuttle flight to test a technique for real-time autonomous classification of four primary earth features—water; vegetation; bare land; and clouds, snow, and ice. The experiment, based on a simple and easily implemented classification algorithm, is considered a logical step toward providing the advanced technology needed to achieve data selectivity at the sensing stage, thus reducing the data load and delays in the data handling and data dissemination in earth monitoring and data-gathering missions. This classification technique is contributing to the development of advanced cloud detection, pointing, tracking, and navigation technology.

A FILE development instrument was first flown in aircraft, and about 1500 images were obtained in cross-country