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THE COLOR OF THE OCEAN

Sponsored By
EARTH SURVEY OFFICE
ELECTRONICS RESEARCH CENTER
NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION
CAMBRIDGE, MASSACHUSETTS

Held At
WOODS HOLE OCEANOGRAPHIC INSTITUTION
WOODS HOLE, MASSACHUSETTS

THE COLOR OF THE OCEAN

Report of the Conference

on August 5-6, 1969

Sponsored by

Earth Survey Office
Electronics Research Center
National Aeronautics and Space Administration
Cambridge, Massachusetts

Held at the

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

Compiled by

William I. Thompson, III

Earth Survey Office
Electronics Research Center

THE COLOR OF THE OCEAN

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August 5-6, 1969
Woods Hole, Massachusetts

Participants

Raymond Alfaya
Science Engineering Research Group
Long Island University
P.O. Box 400
Greenvale, N. Y. 11548

Roswell Austin
Visibility Laboratory
Scripps Institution of Oceanography
San Diego, Calif. 92152

Maurice Blackburn
Scripps Institution of Oceanography
La Jolla, Calif. 92037

Myron Block
Block Engineering, Inc.
19 Blackstone St.
Cambridge, Mass. 02109

George L. Clarke
Harvard Biological Laboratory
18 Divinity Ave.
Cambridge, Mass. 02138

Alfred Conrod
Experimental Astronomy Laboratory
Massachusetts Institute of Technology
265 Massachusetts Ave.
Cambridge, Mass. 02139

Kirby Drennan
U.S. Fish & Wildlife
239 Frederick St.
Pascagoula, Miss. 39567

Gifford C. Ewing
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

Frank Hebard
Bureau of Commercial Fisheries
75 Virginia Beach Dr.
Miami, Fla. 33149

Rudolph Hollman
Dept. of Meteorology and Oceanography
New York University
Bronx, N. Y. 10468

George Huebner
Dept. of Oceanography
Texas A & M. University
College Station, Tex. 77843

N. G. Jerlov
Dept. of Physical Oceanography
University of Copenhagen
Denmark

Mahlon G. Kelly
Dept. of Biology
New York University
University Heights, N. Y. 10453

Glenn Larson
Electronics Research Center
National Aeronautics and Space Admin.
575 Technology Square
Cambridge, Mass. 02139

Leonard N. Liebermann
Dept. of Physics
University of California, San Diego
La Jolla, Calif. 92038

Carl Lorenzen
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

Paul Maughan
Bureau of Commercial Fisheries
C Between 18th & 19th NW
Washington, D. C. 20001

William J. Merrell, Jr.
Dept. of Oceanography
Texas A & M University
College Station, Tex. 77843

Michael Miller
Electronics Research Center
National Aeronautics and Space Admin.
575 Technology Square
Cambridge, Mass. 02139

Richard C. Ramsey
TRW Systems
One Space Park
Redondo Beach, Calif. 90278

Donald Ross
Philco-Ford Corp., WDL Division
3825 Fabian Way
Palo Alto, Calif. 94303

Peter M. Saunders
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

John D. Sherman III
Spacecraft Oceanography Project Office
Naval Oceanographic Office
Washington, D. C. 20390

Raymond C. Smith
Visibility Laboratory
Scripps Institution of Oceanography
San Diego, Calif. 92152

Robert Spiers
Langley Research Center
National Aeronautics and Space Admin.
Hampton, Va. 23365

Joachim Stephan
Battelle Institute
505 King Ave.
Columbus, Ohio 43201

Robert E. Stevenson
Bureau of Commercial Fisheries
Galveston, Texas 77550

Martin J. Swetnick
National Aeronautics and Space Admin.
Office of Space Applications
Washington, D. C. 20546

O. Lyle Tiffany
Aerospace Systems Divisio-
Bendix Corporation
3300 Plymouth Rd.
Ann Arbor, Michigan 48105

John Tyler
Visibility Laboratory
Scripps Institution of Oceanography
San Diego, Calif. 92152

Morris Weinberg
Block Engineering, Inc.
19 Blackstone St.
Cambridge, Mass. 02109

Peter G. White
Electronic Systems Dept.
TRW Systems
One Space Park
Redondo Beach, Calif. 90278

Charles Yentsch
Nova University
College Ave.
Ft. Lauderdale, Fla. 33314

FOREWORD

In our invitation to the conference, "The Color of the Ocean," which was held in Woods Hole, Massachusetts, on the 5th and 6th of August, 1969, we described the topics to be considered as follows:

1. Upwelling radiance of the ocean with special reference to color. Applications to physical oceanography and to biological problems, including primary productivity, fisheries, pollution, currents, bottom studies, etc.
2. The physical basis of upward radiance, scattering and absorption in the sea.
3. Instrumentation, data reduction and interpretation.

We explained that our eventual goal was to use spectrophotometry and photography as an aid in aerial and satellite reconnaissance of the ocean to locate distinct water masses and areas of high biological productivity.

This report presents the remarks and presentations given at the conference as well as papers and thoughts contributed by the participants after the meeting.

George L. Clarke
Professor of Biology, Harvard University
Associate in Marine Biology,
Woods Hole Oceanographic Institution

Gifford C. Ewing
Senior Scientist
Woods Hole Oceanographic Institution

SUMMARY CONCLUSION

Recognizing that a series of earth resources technology satellites will be orbited in the early 1970's, this conference recommends that the quantitative measurement of the color of the oceans should be one of the prime objectives of one or more of the on-board remote detection systems.

We believe that such measurements, in addition to differentiating between water masses, will assist in the assessment of oceanic biological productivity, bottom topography and related hazards to navigation, coastal ecology of the bottom biota, and certain kinds of water pollution. Such an assessment is essential to management of oceanic resources on a national and world-wide basis.

It is recommended that:

1. The satellite color measurement system meet the following resolution specifications:

1 mile spatially
100 angstrom spectrally
10 days temporally

The required sensitivity will vary over fairly wide limits, being lowest over coastal areas and highest over the high seas. Color contrasts to be found over the open ocean are exceedingly small and are further degraded by atmospheric transmission. Although further investigation will be needed to specify the required sensitivity with certainty, present indications are that this is physically attainable and can be achieved in the next few years by reasonable advancement of the art. More detailed recommendations of specifications are presented in the conference review publication.

2. A substantial "ground truth" program of measurement must be instituted promptly which is primarily aimed at the understanding of the causes and interpretation of ocean color, and how this is degraded by atmospheric scattering and by surface, waves, foam and glitter. This must be so planned that meaningful correlations will come from the data acquired during the experimental orbital missions.

SUPPLEMENTAL REFERENCES

Oceanography from Space. Ed. by G. C. Ewing. Proc. of Conf. on The Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories, Woods Hole, Mass., 24-28 Aug. 1964.

Oceans from Space. Ed. by P. C. Badgley, L. Miloy and L. Childs. Proc. of Symposium on Status of Knowledge, Critical Research Needs, and Potential Research Facilities Relating to the Study of the Oceans from Space, Houston, Tex., Gulf Pub. Co., 1969.

Bailey, J. S. and P. G. White, (1969), Remote sensing of ocean color, *Advances in Instrumentation*, Vol. 24, Pt. 3, NASA Accession Number A70-18592.

Raymond Alfaya
Science Engineering Research Group
Long Island University
Greenvale, New York

This group is engaged in remote sensing research, in the area of multispectral color aerial photography. They have developed their own four-lens multispectral aerial camera which simultaneously exposes four spatially identical black and white negatives through different optical filters. Using a specially designed additive color viewer, a corresponding set of four black and white positives are combined, by superposed projection, to produce an additive color display. Because this technique permits precise, independent control of the many individual variables in photography and viewing, it can distinguish subtle differences in the spectral reflectance of land and water masses, which are far too small to be detected by conventional color films. The group has also developed radiometric instrumentation and techniques for measuring reflectance spectra of ground and water target objects, to obtain the ground truth which is required for proper support of quantitative multispectral photography.

Roswell Austin
Visibility Laboratory
Scripps Institution of Oceanography

Professional interests have been in the optical properties of the atmospheric and oceanic environments and their measurement. Main current interests are in the study of the visibility of submerged objects as seen from above, the assessment of sea state by the determination of the fractional area of the sea surface covered by white water, and the determination and subsequent removal of atmospheric transmission effects in the remote optical sensing of properties of the ocean surface.

SOME OBSERVATIONS ON WATER COLOR ON THE CONTINENTAL SHELF

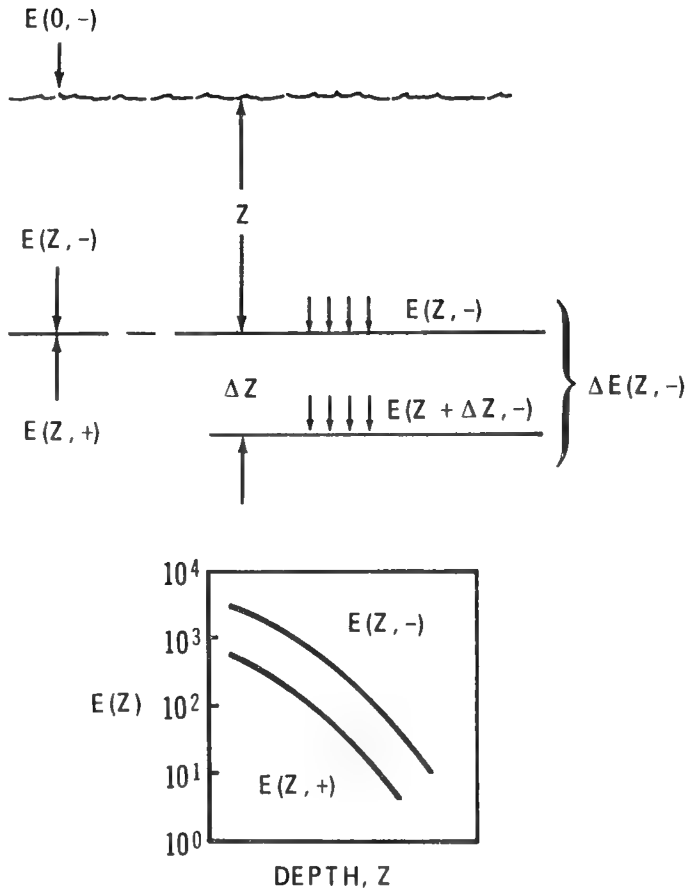
R. W. Austin

NOTE: The original presentation relied heavily upon colored photographs obtained from Gemini and Apollo space missions and by the author from surface vessels. The following is considerably modified and abbreviated as it is not feasible to use color printing in these proceedings.

The author had the opportunity to make observations and measurements from a surface vessel along the very extensive continental shelf bordering the eastern coast of Asia from the Yellow Sea to the South China Sea. Subjective determinations were made of water color and physical measurements were made of the attenuation of the natural (diffuse) light field in the water and of the reflectance of the water (ratio of the upwelling to the downwelling illuminances). Information was obtained at over 50 locations.

Space photographs show marked local variations in water color, and presumably other optical properties, over small horizontal distances in the areas seaward from the mouths of rivers for many miles. Some of these rivers carry large quantities of silts having strong colorations. The measurements made from the surface vessel many miles from the coast confirmed the existence of many areas having higher than usual water reflectance values and concomitant high values of attenuation.

The diffuse attenuation coefficient, K, was plotted against the water reflectance, $R_{U/D}$ and a definite correlation was obtained between the two properties with the clearer (low attenuation coefficient) waters having generally low reflectance values and the turbid waters (high attenuation coefficient) generally showed higher reflectances. Figure 1 shows the defining relationships for K and $R_{U/D}$. Figure 2 shows the relationship between the two properties and, additionally, shows that a correlation existed between these two parameters and the water color as subjectively determined by two observers.



$$\Delta E(Z,-) = E(Z + \Delta Z,-) - E(Z,-) \qquad (1$$

$$dE(Z,-) = -K\,E(Z,-)\,dZ \qquad (2$$

$$K = -\frac{1}{E(Z,-)}\,\frac{dE(Z,-)}{dZ} = -\frac{d(\ln E(Z,-))}{dZ} \qquad (3$$

$$E(Z_2,-) = E(Z_1,-)\,e^{-K(Z_2 - Z_1)} \qquad (4$$

$$E(Z\ ,-) = E(O,-)\,e^{-KZ} \qquad (5$$

$$R_{U/D} = \frac{E(Z,+)}{E(Z,-)} \qquad (6$$

Figure 1.

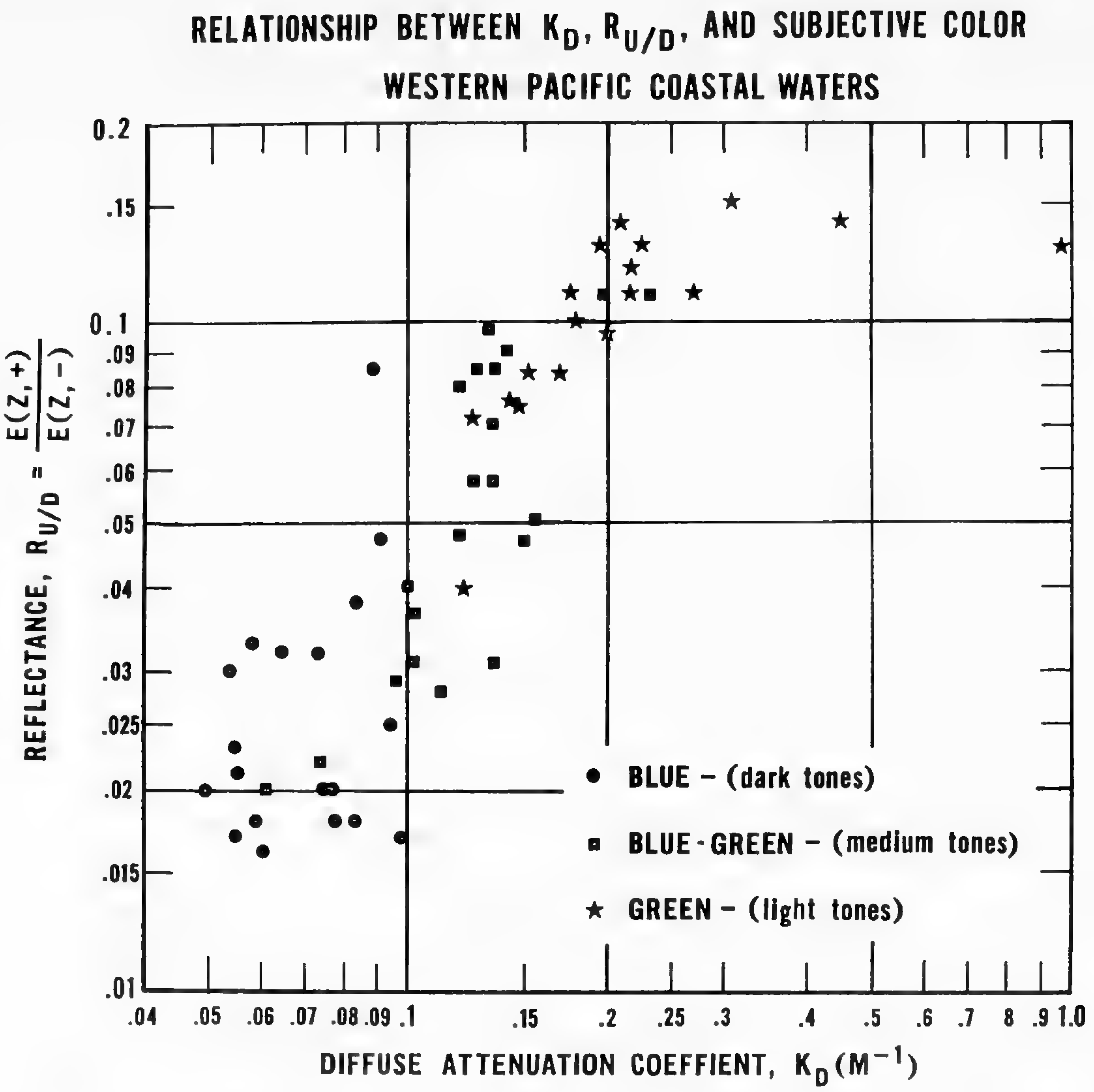

RELATIONSHIP BETWEEN K_D, $R_{U/D}$, AND SUBJECTIVE COLOR
WESTERN PACIFIC COASTAL WATERS
REFLECTANCE, $R_{U/D} = \frac{E(Z,+)}{E(Z,-)}$
0.2
.15
0.1
.09
.08
.07
.06
.05
.04
.03
.025
.02
.015
.01
.04
.05
.06
.07
.08
.09
.1
.15
.2
.25
.3
.4
.5
.6
.7
8
.9
1.0
DIFFUSE ATTENUATION COEFFIENT, $K_D(M^{-1})$
● BLUE – (dark tones)
▪ BLUE-GREEN – (medium tones)
★ GREEN – (light tones)

Figure 2.

Maurice Blackburn
Scripps Tuna Oceanography Research Program,
Institute of Marine Resources,
Scripps Institution of Oceanography,
University of California, San Diego
La Jolla, California 92037

My work is oriented to fishery oceanography. It involves the study of relations between pelagic fishes, their food supply, and the standing stock of chlorophyll. Examples are given in the abstract of my presentation, entitled "Applications to Fishery Oceanography".

Applications to fishery oceanography

What is the use of surface chlorophyll measurements in specifying and understanding the distribution of surface fish? I propose to answer this question by giving the results of some of my own recent studies.

During the years 1964-1966 I made a detailed study of the ecology of two species of tropical tuna along the west coast of Baja California, where these species occur from about June to December in each year. The results are in press in the Fishery Bulletin of the U.S. Fish and Wildlife Service. The following four figures show the main results. Each figure shows: the surface isotherm at 20° C., below which temperature these tunas rarely occur; the area of maximum standing stock of surface chlorophyll a; the area of maximum standing stock of the pelagic crab Pleuroncodes planipes, which in this area is the principal consumer of phytoplankton and the principal species that the tuna eat; and the areas in which tuna were caught by the fishermen.

Figure 1 shows the situation off western Baja California at an early stage in the tuna season, such as July, or August in a cold year. The seasonal upwelling regime has begun to decay, whereby some waters have surface temperatures at or over 20° C., and tropical tunas can enter the area. Tongues of upwelled water protrude offshore from the coastal upwelling centers. They are rich in chlorophyll and herbivorous crabs, but too cold for tropical tunas (< 20° C.) except at the edges. On the other hand the warmer waters, where the temperatures are suitable for the tunas, are relatively poor in chlorophyll and tuna food. The tunas, therefore, are found at the boundary between the warm blue biologically poor water and the cool green biologically rich water, and not elsewhere.

Figure 2 shows the same area at a later stage, such as August in a warm year, when the tongues of upwelled water have become much warmer although they are still richer in chlorophyll and herbivores than any other waters. Tunas are now found in the middle of the tongues as well as along the edges, exploiting the richest areas of forage without any restriction imposed by unsuitable surface temperature. They are not found in the equally warm areas where biological material is scarce, however.

Later still, as in September (Figure 3), tongues of upwelled water can no longer be recognized by their surface temperature, but they can still be recognized by their relatively high content of surface chlorophyll and herbivores. Tunas are found in these food-rich areas, and not elsewhere, although surface temperatures are suitable (> 20° C.) everywhere.

Figure 4 shows the situation late in the tuna season (November), when all signs of upwelling have disappeared; thermal and biological conditions are rather uniform and suitable for tunas over large areas, and tuna occurrences are scattered through these areas. Later still, temperatures become unfavorably low throughout the whole area, and the tunas retreat to the tropics.

In Figures 1 and 2 the areas of low temperature (< 20° C.) and high chlorophyll were broadly congruent, so that distribution of tuna food and tunas could perhaps have been specified from data on temperature only; but in Figures 3 and 4 these distributions could not have been specified from temperature data, although they could have been specified from chlorophyll data.

These studies supported a hypothesis, for which there was previous evidence as well, that two main ocean properties determine the distribution of tuna (and possibly other pelagic fish) at any particular time: namely temperature, which sets limits of total range, and food supply, which determines the patchy distribution within the range limits. They also showed that surface chlorophyll is distributed like the tunas' supply off Baja California, and could therefore be used to specify areas in which tunas would be expected to occur (provided temperatures were suitable).

One might expect less close relationships between distributions of surface chlorophyll and tuna food in other areas, where tunas are known to eat a greater variety of species, many of which are not herbivores. Nevertheless I have data, from cruises made at different seasons over a large area of the eastern tropical Pacific on EASTROPAC expeditions, which show that surface chlorophyll may be a good estimator of tuna forage, even in those situations. Figures 5 and 6, for opposite seasons, show the distribution of the standing stock of animals that skipjack tuna eat, in two different ways: as actually observed, and as estimated from a regression on surface chlorophyll measured at the same time and place. The agreement is at least fair: with more data and more understanding, it could probably be much improved.

These remarks give an idea of what it may be possible to accomplish with a large and regular coverage of sea surface chlorophyll, such as might be obtained from aircraft or a satellite — namely, the ability to specify at short notice the areas of maximum concentration of food of tunas, and thus of the tunas themselves, and possibly the same for other kinds of pelagic fish. It may be more efficient to estimate the fish-food distributions from chlorophyll distributions, than to measure them directly. In many situations, data on surface temperature would be required as well.

Legends for M. Blackburn's Figures

Fig. 1. Distribution of tropical tuna and environmental properties off Baja California: the situation early in the tuna season, when tongues of biologically rich upwelled waters are too cold for the tunas except at the edges.

Fig. 2. Distribution of tropical tuna and environmental properties off Baja California: the situation later in the tuna season, when tongues of biologically rich upwelled waters are warm enough for tunas to penetrate.

Fig. 3. Distribution of tropical tuna and environmental properties off Baja California: a later situation, like Fig. 2 except that the tongue of biologically rich upwelled water is not shown by the temperature.

Fig. 4. Distribution of tropical tuna and environmental properties off Baja California: the situation late in the tuna season when no signs of upwelling remain.

Fig. 5. Skipjack tuna forage on EASTROPAC Expedition, August-September 1967, in ml./1,000 m^3: (Above) as observed in net hauls; (Below) as estimated from a regression on surface chlorophyll.

Fig. 6. Skipjack tuna forage on EASTROPAC Expedition, February-March 1968, in ml./1,000 m^3: (Above) as observed in net hauls; (Below) as estimated from a regression on surface chlorophyll.

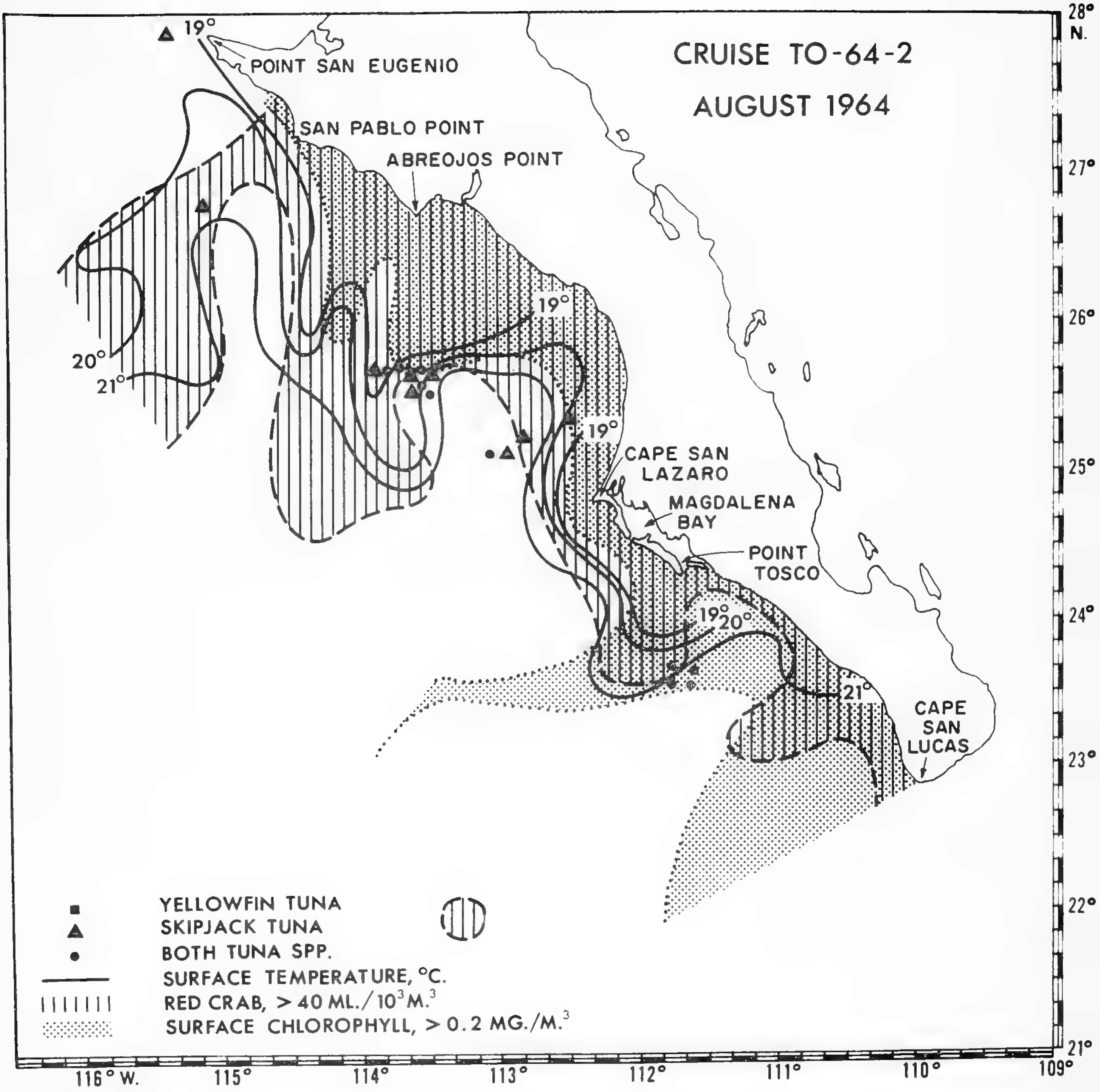

CRUISE TO-64-2
AUGUST 1964
POINT SAN EUGENIO
SAN PABLO POINT
ABREOJOS POINT
CAPE SAN LAZARO
MAGDALENA BAY
POINT TOSCO
CAPE SAN LUCAS
19°
20°
21°
YELLOWFIN TUNA
SKIPJACK TUNA
BOTH TUNA SPP.
SURFACE TEMPERATURE, °C.
RED CRAB, > 40 ML./10³ M.³
SURFACE CHLOROPHYLL, > 0.2 MG./M.³
28° N.
27°
26°
25°
24°
23°
22°
21°
116° W.
115°
114°
113°
112°
111°
110°
109°

Figure 1.

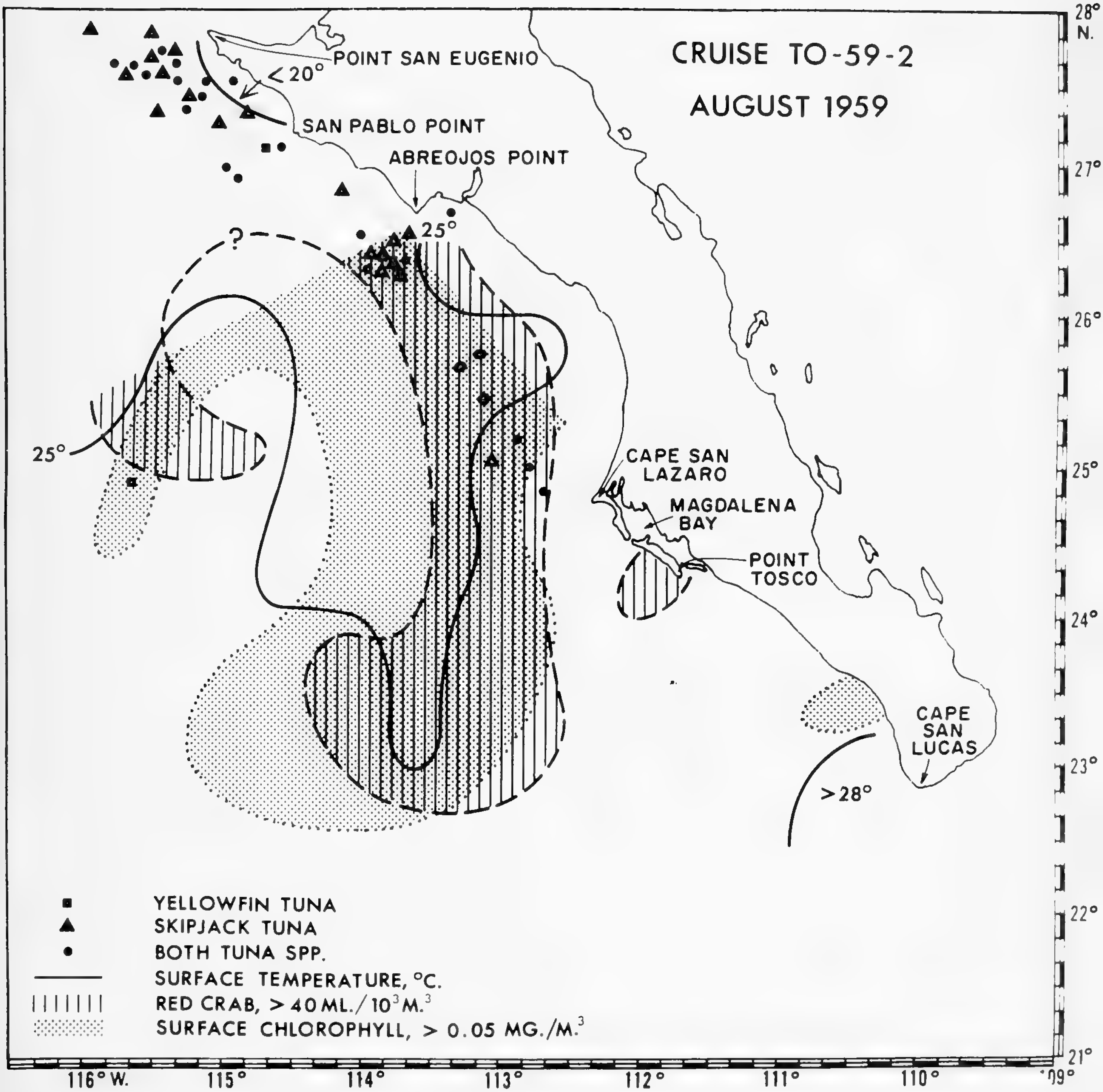

CRUISE TO-59-2
AUGUST 1959
POINT SAN EUGENIO
<20°
SAN PABLO POINT
ABREOJOS POINT
?
25°
25°
CAPE SAN LAZARO
MAGDALENA BAY
POINT TOSCO
CAPE SAN LUCAS
>28°
■ YELLOWFIN TUNA
▲ SKIPJACK TUNA
● BOTH TUNA SPP.
SURFACE TEMPERATURE, °C.
||||||| RED CRAB, > 40 ML./10³M.³
SURFACE CHLOROPHYLL, > 0.05 MG./M.³
116° W.
115°
114°
113°
112°
111°
110°
109°
28° N.
27°
26°
25°
24°
23°
22°
21°

Figure 2.

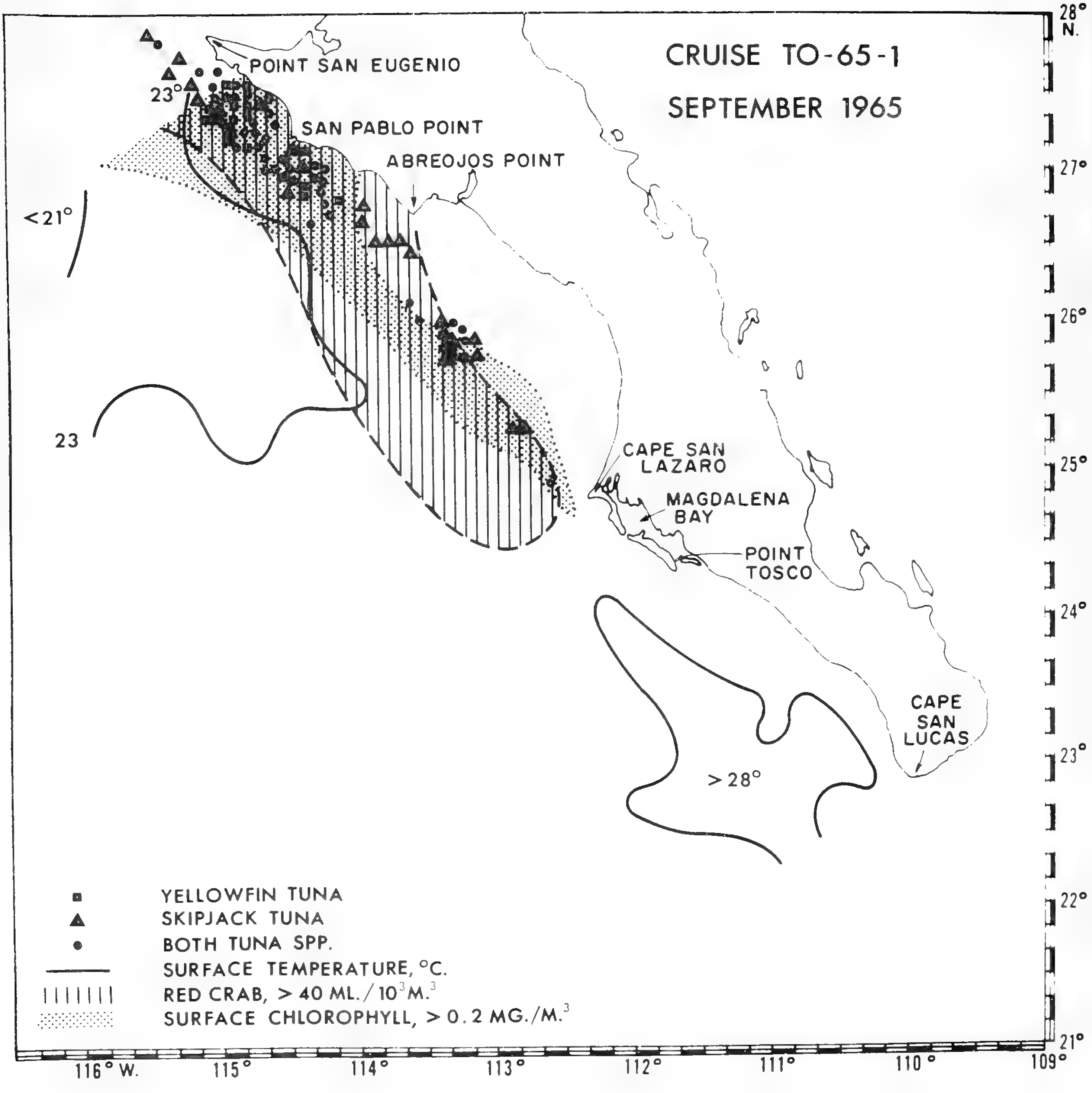

CRUISE TO-65-1
SEPTEMBER 1965
POINT SAN EUGENIO
SAN PABLO POINT
ABREOJOS POINT
CAPE SAN LAZARO
MAGDALENA BAY
POINT TOSCO
CAPE SAN LUCAS
23°
<21°
23
>28°
YELLOWFIN TUNA
SKIPJACK TUNA
BOTH TUNA SPP.
SURFACE TEMPERATURE, °C.
RED CRAB, > 40 ML./10³M.³
SURFACE CHLOROPHYLL, > 0.2 MG./M.³
116° W.
115°
114°
113°
112°
111°
110°
109°
28° N.
27°
26°
25°
24°
23°
22°
21°

Figure 3.

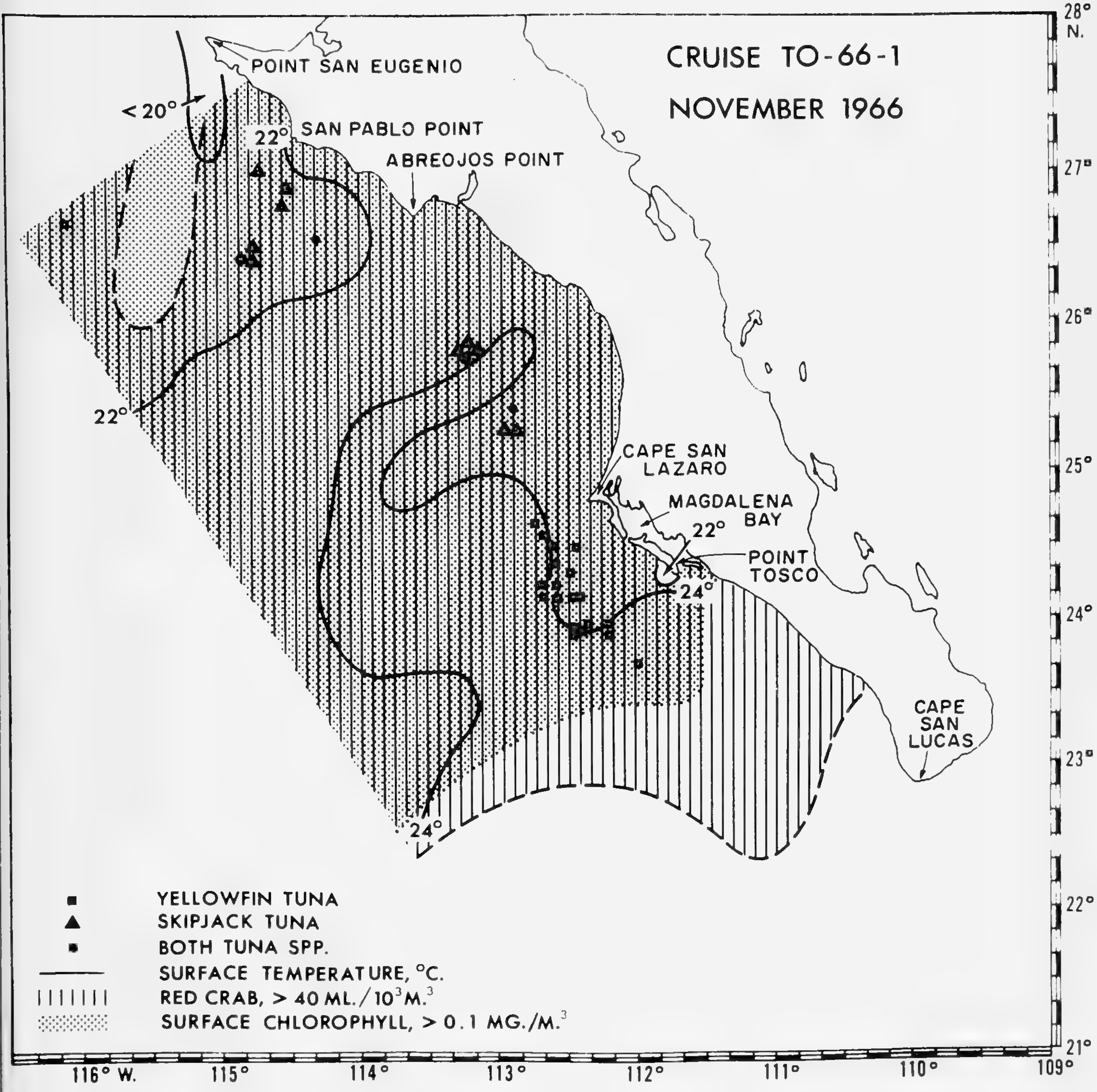

CRUISE TO-66-1
NOVEMBER 1966
POINT SAN EUGENIO
< 20°
22°
SAN PABLO POINT
ABREOJOS POINT
22°
CAPE SAN LAZARO
MAGDALENA BAY
22°
POINT TOSCO
24°
CAPE SAN LUCAS
24°
YELLOWFIN TUNA
SKIPJACK TUNA
BOTH TUNA SPP.
SURFACE TEMPERATURE, °C.
RED CRAB, > 40 ML./10³M.³
SURFACE CHLOROPHYLL, > 0.1 MG./M.³
116° W.
115°
114°
113°
112°
111°
110°
109°
28° N.
27°
26°
25°
24°
23°
22°
21°

Figure 4.

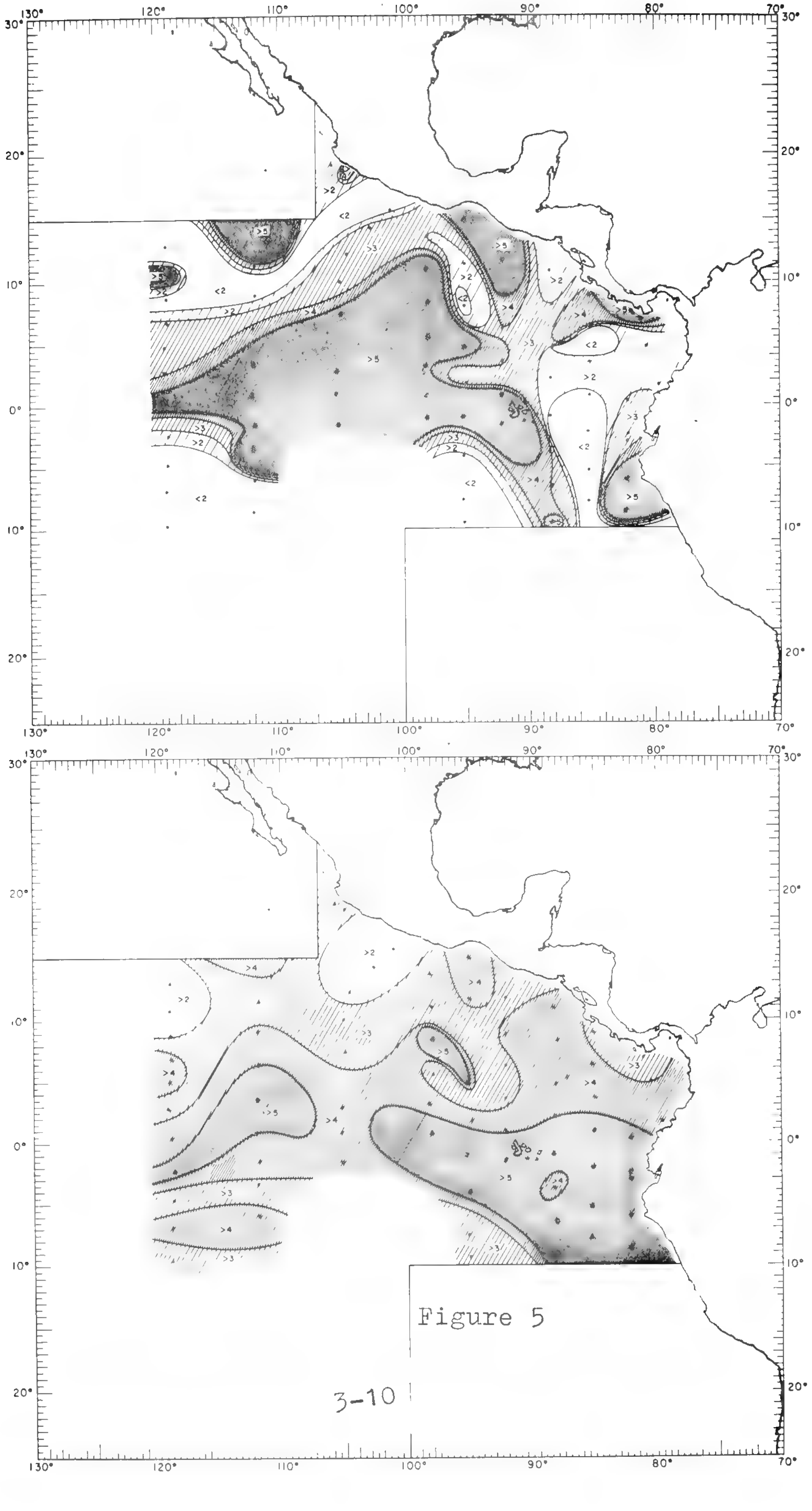


Figure 5

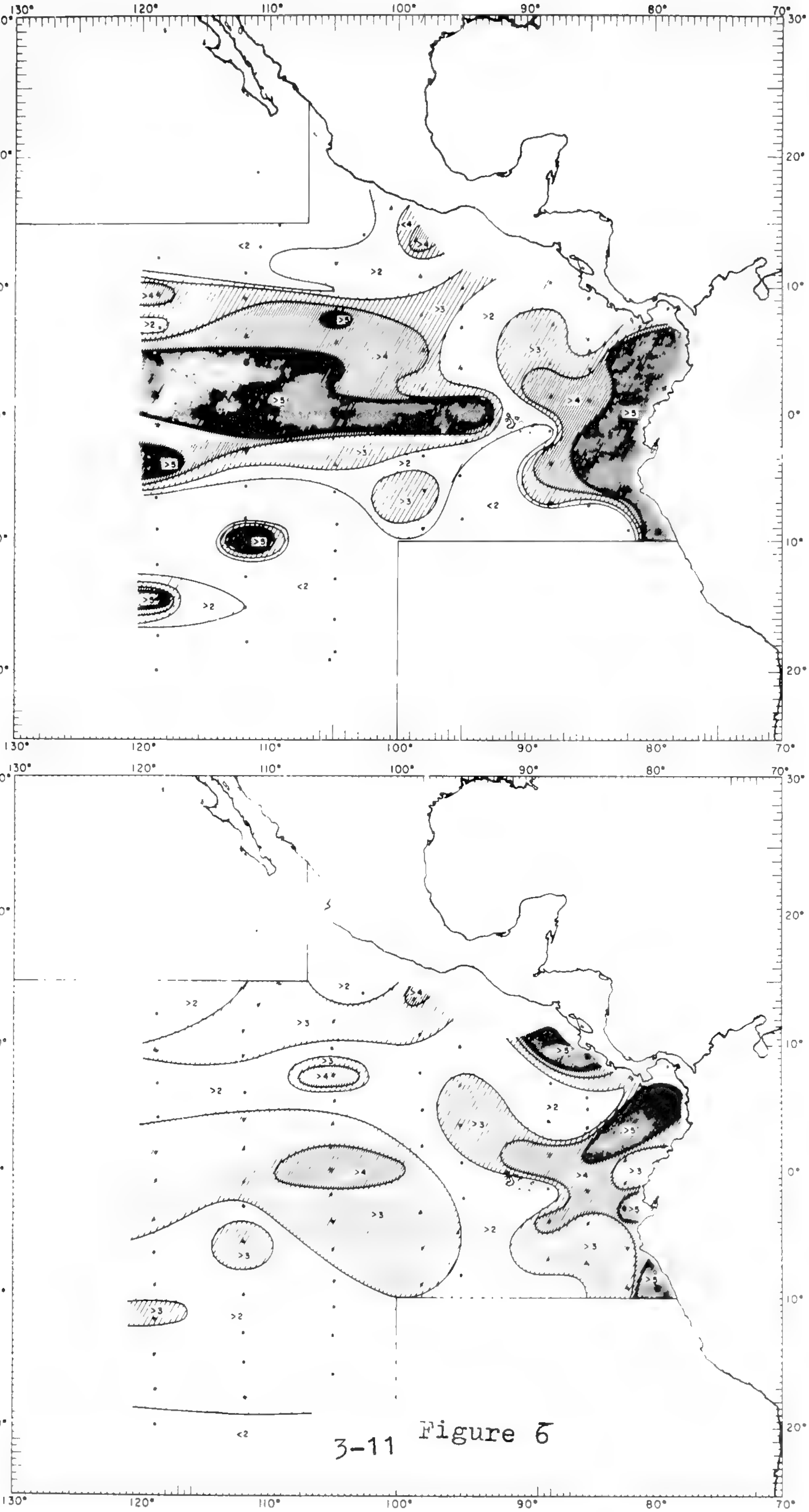


Figure 6

Myron Block
Block Engineering, Inc.
19 Blackstone Street
Cambridge, Mass.

New instrumentation concepts have been developed at Block that can have usefulness for oceanography.

1. Fourier transformation spectroscopy -- 10,000 times improvement over former techniques of spectral measurement.

2. Remote Raman spectroscopy technique -- quantitative high-resolution spectroscopy of gases and liquids. Uses pulsed laser light of certain pulse length, range gates the data, then does spectroscopy on return signal, measures parts/million of chemical composition.

3. Technique to measure daytime fluorescence without seeing the effects of sunlight in same spectral region.

4. Currently we are tying all this into a system called "digilab" -- computerized outputs of all sensors with operator using teletype input. For example, in interferometric spectrometry the system operates by "closed loop" instrumentation, i.e., the system calibrates itself, wavelength scale is plotted, optimization takes place.

We need to know something about depolarization of light in sea water.

George L. Clarke

Associate in Marine Biology, Woods Hole Oceanographic Institution
and Prof. of Biology, Harvard University.

My special interest is in the application of light measurements to the biological problems of the sea. Light in the ocean is derived from the sun, the moon, and the sky, and also from the luminescent discharge of many kinds of marine organisms. The conditions of light in the sea control the growth of the primary plant producers and influence the behavior of many oceanic animals. The absorption, scattering, and spectral distribution of daylight passing through the water are modified by dissolved and particulate matter, both living and non-living. Our present investigations are concerned with measurements from ship and aircraft of the spectrum of light back-scattered from beneath the surface. Changes in the spectra in space and time are under scrutiny as means for delineating water masses, detecting pollution, and evaluating chlorophyll abundance as an index of productivity. A summary of our recent work on this subject is presented in this publication.

Reprinted from Science, 167, (1970)

Reports

Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration

Abstract. *Spectra of sun and skylight backscattered from the sea were obtained from a low-flying aircraft and were compared with measurements of chlorophyll concentration made from shipboard at the same localities and at nearly the same times. Increasing amounts of chlorophyll were found to be associated with a relative decrease in the blue portion of the spectra and an increase in the green. Anomalies in the spectra show that factors other than chlorophyll also affect the water color in some instances; these factors include other biochromes, suspended sediment, surface reflection, polarization, and air light.*

The penetration of daylight into the sea is of fundamental significance in the oceanic ecosystem because it controls the growth of the primary plant producers and the behavior patterns of many marine animals. Previous investigations have revealed great variation in the rates of light penetration due to differences in amounts and kinds of materials in the water. In addition, the spectral composition of the light beneath the surface is altered by differential absorption and scattering due to the water itself, and also to whatever dissolved and particulate matter (both living and nonliving) may be present (*1*). Because chlorophyll affects the spectrum in a characteristic way and because it is associated with living plants, spectral measurements of chlorophyll concentration may be used as an index of the amount of phytoplankton present. Regions with high phytoplankton abundance can support large populations of herbivores and of successive links in the animal food chain, many of which are of economic importance to man. Thus, abundant chlorophyll indicates the presence of a potentially productive area (*2*).

The spectral changes imposed on the downwelling daylight by natural waters and by the materials in them have been measured by lowering an upward-directed spectrometer in a watertight case to various depths (*3*). The upwelling, or backscattered, light that can be measured by employing the spectrometer in the inverted position is found to have its spectrum similarly modified by its passage through the water. A portion of the backscattered light escapes upward through the surface, where it has been recorded by an inverted spectrometer suspended above the water from a ship and from aircraft (*4*). Allowance must be made for light reflected from the ocean surface itself or scattered by the stratum of air above the water.

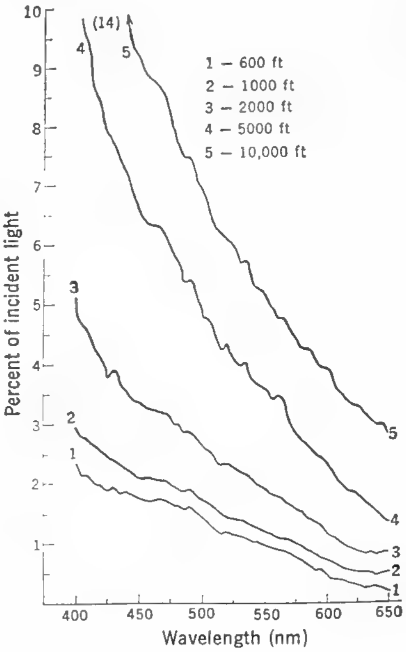


Fig. 1. Upwelling light as received at the indicated altitudes at Station S (Fig. 2) east of Cape Cod, 26 August 1968 between 1345 and 1512 hours, E.D.T.

The possibility thus exists that spectral measurements of backscattered light can be used to delineate water masses, to trace currents, and to determine the abundance of chlorophyll, pollutants, or other significant materials in the water. Because measurements from aircraft or spacecraft can be made over extensive areas much more rapidly than from ships, they are especially suited to the study of small-scale, rapidly varying distributions of oceanic properties (*5*). Tests of some of these possibilities are reported here for water masses of widely different known chlorophyll concentrations off the New England coast.

During the summers of 1967 and 1968, records of the spectrum of backscattered light from the ocean have been made from our research vessel *Crawford* and our C-54-Q research aircraft. The spectrometer used was designed by Peter White of TRW Systems, Inc., and described by L. A. Gore (*6*). R. C. Ramsey of TRW operated the instrument and took part in the reduction of the data and in the interpretation of the results.

The TRW spectrometer is an electro-optical sensor of the off-plane Ebert type with an RCA 7265 (S-20 response) photomultiplier. The spectral range is 400 to 700 nm with a spectral resolution of 5 to 7.5 nm, a scan time of 1.2 seconds, and a field of view of 3° by 0.5°. A continuous curve of the spectrum is provided by a Sanborn recorder for each scan. The spectrum of the incident light from the sun and sky was determined before and after each series of measurements by recording the light reflected from a horizontally placed Eastman Kodak "gray card" with a nonselective reflectivity of 18 percent. A series of tests was made to detect changes in the spectral distribution of incident light during the 3 hours before and after noon due to changes in the sun's altitude and to changes in sky conditions from clear to light cloudiness. Changes found were not great enough to affect significantly our investigation of the differences in backscattered light from the ocean. By taking advantage of the fact that light reflected from a plane surface at Brewster's angle (approximately 53° from vertical incidence for normal sea water) is plane polarized with its vibration plane perpendicular to the plane of incidence, we could reduce the light received as reflection from the water surface. We placed a polarizing filter, oriented at right angles to the major axis of polarization, over the receiving aperture of the spectrometer and tilted the instrument at Brewster's angle (directed away from the sun).

When we operated the spectrometer from our C-54-Q research aircraft, the signal that we wished to measure, namely, the spectrum of the light backscattered from beneath the sea surface, was sometimes difficult to detect because of interference from "noise" caused not only by surface reflection but also by "air light." Air light is light that has been scattered to the instrument by the air and by material in the air between the sea surface and the aircraft. As the altitude of observation increases, the area of the sea from which light can enter the instrument enlarges, reaching the dimensions of about 52 by 9 feet (16 by 3 m) at 1000 feet (305 m). Smaller irregularities in surface reflection or in the nature of the seawater will be averaged out. At the same time interference from air light will increase with altitude because of the greater path length through the atmosphere. The curves shown in Fig. 1 were taken at altitudes ranging from 600 to 10,000 feet (183 to 3048 m) over an area east of Cape Cod (Station S, Fig. 2), where the water was 200 m deep and the estimated chlorophyll content, although not measured at the time, was probably about 0.6 mg/m^3. As altitude increased, the values for upwelling light received increased markedly and regularly in all parts of the spectrum. The remainder of the measurements reported here were made at an altitude of 1000 feet (305 m).

Representative spectral measurements obtained over water with high chlorophyll content (about 4 mg/m^3, Buzzards Bay), with low chlorophyll content (about 0.3 mg/m^3, north of the Gulf Stream), and with very low chlorophyll content (less than 0.1 mg/m^3, Sargasso Sea) are presented in Fig. 3. The values for the backscattered light from these areas have been calculated as percentages of the incident light. The curves display characteristic differences in shape. For the water with high chlorophyll content the backscattered light rose from values mostly about 2.2 percent of the incident light in the blue region of the spectrum to about 2.5 percent in the green, and then dropped to about 0.3 percent in the red. For water with low chlorophyll content the values were higher in the blue, dropped rapidly to much lower values in the green, and continued to drop in the red. Where chlorophyll content was very low, the backscattering was higher at all wavelengths shorter than 500 nm and reached a maximum of 7 percent at 400 nm.

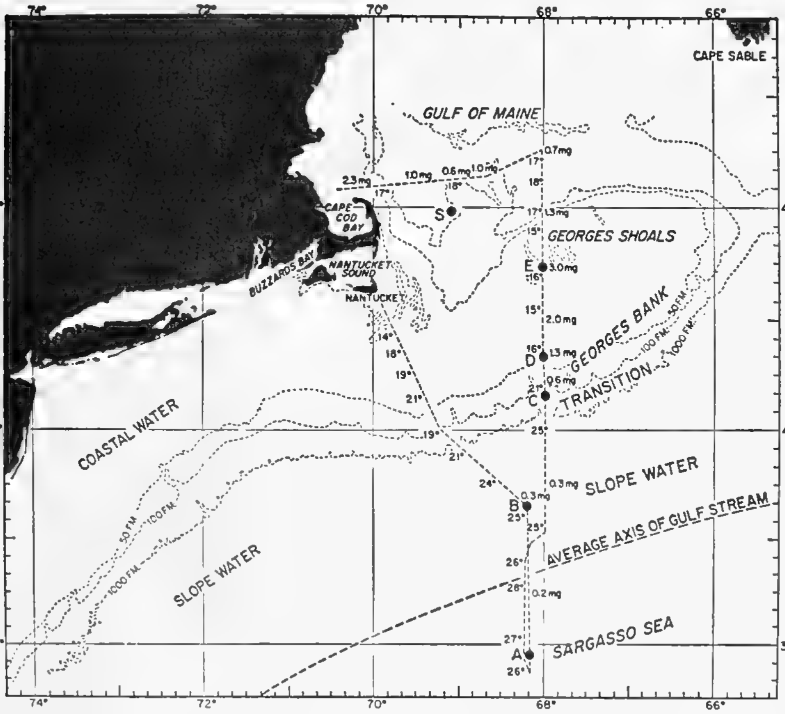


Fig. 2. The flight of the aircraft after leaving Nantucket on 27 August 1968 and the location of Stations A to E. Station S was occupied on 26 August. Representative temperatures measured from the aircraft flying at 305 m are shown to the left or below the flight path; representative chlorophyll concentrations in milligrams per cubic meter measured from the surface ship are shown to the right or above the flight path.

On 27 August 1968 a more extensive survey of the changes in backscattered light from contrasting bodies of water was conducted during a flight from Buzzards Bay and Nantucket Sound to a point in the Sargasso Sea south of the Gulf Stream, then north on a 556-km transect that crossed successively the Gulf Stream, the slope water, a transition zone, Georges Bank, Georges Shoals, and the southern part of the Gulf of Maine, and returned via Cape Cod Bay (Fig. 2). Records of the spectrum were taken at frequent intervals with the TRW spectrometer, and a continuous trace of surface temperature was obtained by P. M. Saunders by means of a Barnes infrared radiometer. A continuous record of the temperature and the chlorophyll concentration of the surface water was obtained from the R.V. *Crawford* by means of a thermistor and a continuous-flow Turner fluorometer (*7*). Water for this purpose was drawn from an intake valve through the hull of the vessel 2 m below the surface. Analysis of these data shows that the surface temperature and the surface chlorophyll of the slope water, the Bank water, and the Gulf of Maine are statistically differentiated to a highly significant degree. We also have evidence from a previous study (*8*) that surface chlorophyll values may be useful as an index of biological productivity. During four cruises in the Atlantic and Pacific, one of us (C.J.L.) collected 91 samples, which covered a range of surface chlorophyll concentrations from 0.04 to 28.3 mg/m^3. Analysis showed highly significant correlations with measurements of the total chlorophyll in the euphotic zone and with the primary productivity of the phytoplankton in the waters studied. Temperature values obtained from the aircraft agreed closely with values obtained from the ship (see Fig. 2). Owing to the relative sterility of warm Gulf Stream water, the lower chlorophyll measurements tend to be associated with higher sea temperatures.

A comparison of the spectra of the backscattered light as a percentage of

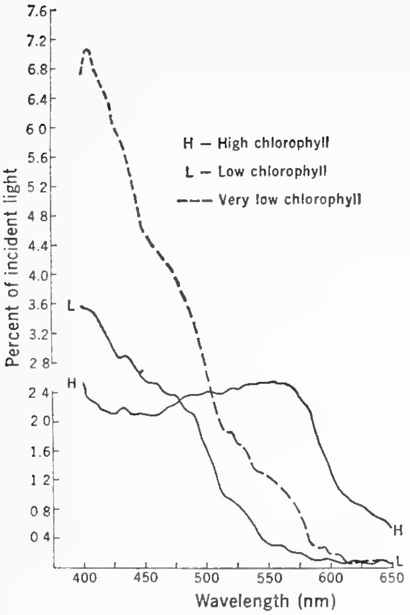


Fig. 3. Data from the high and low chlorophyll curves plotted as percentage of the incident light and compared with data taken on the same day from an area with very low chlorophyll concentration south of the Gulf Stream.

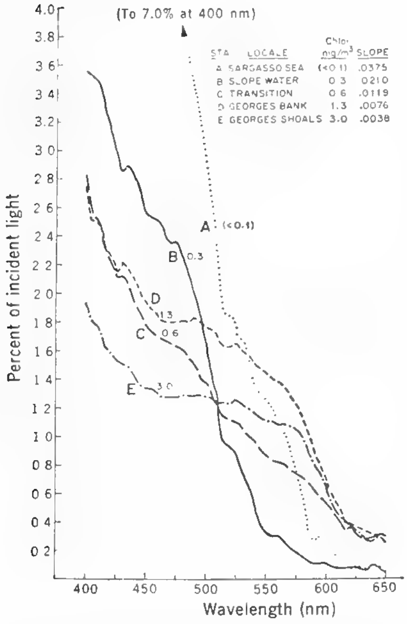


Fig. 4. Spectra of backscattered light measured from the aircraft at 305 m on 27 August 1968 at the following stations (Fig. 2) and times (all E.D.T.): Station A, 1238 hours; Station B, 1421 hours; Station C, 1428.5 hours; Station D, 1445 hours; Station E, 1315 hours. The spectrometer with polarizing filter was mounted at 53° tilt and directed away from the sun. Concentrations of chlorophyll a were measured from shipboard as follows: on 27 August, Station A, 1238 hours; on 28 August, Station B, 0600 hours; Station C, 0730 hours; Station D, 1230 hours.

the incident light at five localities along the flight path of 27 August is presented in Fig. 4. Simultaneous measurements from the aircraft and the ship were made in the slope water at Station B. The ship's observations at Stations C, D, and E were not made until the following day, but the range of chlorophyll values was so great that the differences among the stations can be relied upon for the present comparison. Time did not permit the ship to reach the locality of the aircraft's observation at Station A in the Sargasso Sea south of the Gulf Stream, but the chlorophyll content of the water there was almost certainly lower than in the slope water north of the Stream. Along the entire transect the shape of the spectral curves changed progressively as chlorophyll values increased from south to north. The percentage of backscattered light diminished markedly in the blue region and increased relatively in the green region, with an indication of an inflection point at about 515 nm and with little change in the red region. This result agrees satisfactorily with the calculated values for the effect of increasing amounts of chlorophyll on ocean color presented by Ramsey (*9*). The change in shape with increasing chlorophyll is reflected in decreased mean slope of the spectra. Anomalies in the shape and amplitude of these spectra, and of some taken on other occasions, make it evident that other factors play a role that merits further investigation.

Our investigation shows that large differences occur in the spectra of the light backscattered from the ocean and that they can be recorded from aircraft. In the present instance, the slopes of the spectra correlate quite closely with differences in chlorophyll concentration. The discrepancies are believed to be due to difference in time within paired observations, to differences in surface reflection, to scattered air light, and to the presence in the water of material other than chlorophyll that affected the light selectively. If such interference can be eliminated, or identified and allowed for, spectrometric 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.

GEORGE L. CLARKE
GIFFORD C. EWING
CARL J. LORENZEN

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 20543

References and Notes

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10. Supported by NASA contract NASA 12-631 and by Office of Naval Research contract ONR 241. We thank the crews of our research ship and aircraft; we also thank Miss Anne Bowen, Mr. Carl Fontneau, and Mr. Robert E. Frazel, research assistants. Contribution No. 2394 of the Woods Hole Oceanographic Institution.

12 December 1969

Alfred Conrod
Measurement and Systems Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

We are instrumentation makers and engineers and are involved here at this conference to provide machines, develop user requirements. The bulk of our work is in optical instrumentation.

Kirby Drennan
U. S. Fish & Wildlife
Pascagoula, Miss.

In recent months we have been looking at the problem of direct detection, identification and quantification of pelagic fish stocks through the use of remote sensors. Several approaches are being taken in an effort to establish those characteristics of fish schools which can be observed through the use of remote sensors and to define the sensor requirements and to develop a sensor system which will enable us to assess the resources of large oceanic areas. These include multi-spectral photography, studies of the reflectance spectra of individual fish and fish schools, measurements of the absorption spectra of fish oil films, studies to determine the application of low-level-light sensors, such as image intensifiers, to detect the bioluminescence associated with most fish schools, and in October a series of tests will be conducted with a pulse-gated laser system. A rather extensive photographic program was carried out at Pascagoula which resulted in several hundred aerial photographs of fish schools of various species. Black and white, color, and color infrared films with various filter combinations were used in this program. An effort is now being made to correlate the photographic imagery with the catch data and sonar soundings obtained during the field operation.

In September of 1968, the Pascagoula base and TRW Systems, under contract to Pascagoula, obtained spectral reflectance measurements of fifteen schooling species in the Northern Gulf of Mexico. Observations were made on single fish and fish schools inside an impoundment using a recently developed TRW water color spectrometer. These data indicate that, in general, the reflectances are separable on a species basis and are different from sea water reflectance. The natural phenomenon of bioluminescence which is stimulated in ubiquitous marine organisms by the movement of fish schools appears to offer a promising solution to the problem of locating and possible identifying and quantifying fish schools at night. In recent months, we have used an airborne image intensifier/television system at altitudes of 5,000 feet to detect fish-stimulated bioluminescence, the intensity of which was far below the threshold of the human eye. Therefore, we are interested not only in the physical, chemical and biological factors which affect the color of the ocean, but also the effect that these factors have on the production and transmission of light within the sea.

Gifford C. Ewing
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

Of the various oceanographic parameters that one might attempt to measure remotely from satellites, color has the unique advantage of reacting to the bulk properties of the ocean, thus giving an estimate of its biological and chemical construction. Although this information is limited to the upper 10-20 meters of the sea, less than 1% of the total volume, nevertheless this is the part that is of most direct concern to the majority of mankind. That relatively little is known of the distribution of sea color is due in part to the fact that it is distributed in fairly small patterns and varies with the biological activity at a relatively high rate so that the low sampling rate available to ships is inadequate to observe the day-to-day changes.

Satellite oceanography is inherently directed toward observing the upper layers of the sea, the part that is stirred by the wind and lit by the sun. No matter what ingenious ways may be devised for probing deep beneath the surface, it seems unlikely that such regions will be naturally amenable to exploration by satellite technology. In other words, we are concerned here with a specialized description of a severely limited layer of the ocean.

Fortunately, the layer of the ocean exposed to the overview is far more significant than the above considerations suggest. For one thing, it is the part of the ocean that overwhelmingly concerns the everyday affairs of mankind. It is the site of waves, storm surges, the rise of tide, and the secular changes of sea level. It covers the continental shelves where oil and minerals are being recovered. It is the part of the sea that most concerns sailors, because of currents, destructive waves, dangerous shoals, or drifting ice. It impinges on the beaches, harbors, and estuaries that are important for industry, recreation, and human habitat. It includes the zone that supports the photosynthesis upon which the whole biological resource of the sea depends. Not only is this the only part of the ocean that directly touches the lives of most of mankind, but, conversely, it is mostly at these superficial depths that man acts on the sea by activities such as dredging and fishing, or by contamination with chemical pollutants.

The overview is equally important to the scientific understanding of the marine environment and its multifarious interrelations with the land and atmosphere, which exert a crucial, though somewhat less direct influence on the human environment. Virtually all the energy that controls its inner workings flows across this boundary, and all the water types that constitute the ocean's anatomy have their genesis at the surface, in a region of exposure to sun and sky and wind. Like the sediments of the earth's crust, the sea is composed of tilted strata that outcrop somewhere at the surface. Consequently, a complete map of all these surface outcrops must contain information about all deep-water masses of the sea. Geometrically, the ocean has approximately the proportions of a sheet of letter paper, and, like a sheet of paper, much of its information content is written on its face, exposed to view from afar.

In spite of these obvious advantages, oceanographic exploration from the air is in a very rudimentary stage of development. Compared with forestry, agriculture, terrestrial geography, and meteorology, techniques such as aerial photography and infrared radiometry have as yet found little application to oceanography. The reasons are varied and complex, including the limited operating range of aircraft, lack of suitable sensors, and the special difficulties of acquiring oceanic "ground truth." But more fundamental than all these is the inability of oceanographers to make efficient use of surface maps of the ocean, if such data were readily available and free of error. Although the idea that the sea derives its constitution and motive force at the air/sea boundary is well established in oceanographic theory, in practice the data of oceanic observation have usually been obtained and analyzed in vertical sections. As a result, the instruments, data-handling routines, analytic methods, and, in fact, the oceanographers themselves are all oriented toward vertical rather than horizontal aggregates of information. To establish the basis for satellite oceanography will require a gestation period that may be measured in years or decades, depending on how much effort is invested in this sector of the science. It will not be easy to combine such unrelated technologies as space science and oceanography, and it will not occur spontaneously as it has in agriculture or geography, where air mapping has long been established. Above all, it will require a much greater effort in establishing the validity of data acquired from satellites than is commonly recognized. For many applications, such as in agriculture, "ground truth" can be established by a few flights over selected areas that have been well surveyed. But in oceanography one deals with rapidly changing conditions. For example, high sea states cannot be scheduled months in advance, nor do they persist long enough to permit the leisurely coordination of air and surface activities to record their physical descriptions.

The great strength of the satellite observatory is its ability to look at the world ocean on a time scale that is small compared with that of many important dynamic processes. This ability is greatest in the case of satellites in earth-synchronous equatorial orbit, but even in low polar orbits of several hundred miles altitude the entire ocean can be overflown at intervals of less than one day.

A large assortment of color photographs obtained during the Gemini flights is available at NASA headquarters and at the Manned Spacecraft Center in Houston. Some of these photographs have appeared in nonscientific popular magazines, and NASA has published them in an atlas. These pictures show that space resolution is not limiting from these low orbits. The color photography shows that the color contrast is adequate for many purposes, such as delineating plumes of silt, mud, pollutants, and oily slicks off river mouths and estuaries, and showing areas of shoal water. Some information about the conditions of the sea surface can be obtained from its reflective properties. It is probable that the visibility of the Gulf Stream reported by Glenn on MA-6 was due to differences in the slopes of the wavelets rather than to differences in the water color itself. By suitable filtering, it is even possible to photograph the bottom at controlled optical depths, thus providing some information about shallow depth contours, where the color contrasts are very large.

Over the open sea, color photography has not, as yet, produced much information of scientific value. Due to atmospheric effects and to the film-processing methods in use, the high seas are shown as brilliant blue, devoid of any recognizable color features. Whether this is all that can be done with color photography over the ocean from satellite altitudes, we do not know. If this is the case, its usefulness will be limited to applications close to shore or in shallow water. Only spectroscopic methods would then be of value in mapping water color in deeper water.

Light irradiating the sea surface undergoes reflection and refraction. The reflected portion is polarized in the usual way, that is, the component of the electric vector parallel to the sea surface predominates in the reflected light and, at Brewster's angle, is virtually the only component present. This can be made use of to select either the reflected skylight or the backscattered sunlight upwelling through the water surface, depending on whether the desired information relates to the shape of the reflecting surface or to the optical properties of the bulk water. The refracted portion penetrates the sea and, in the absence of scattering, is eventually extinguished by absorption. In reality, the light is scattered by particles of all sizes, from molecules through the larger colloidal particles and up to large bubbles or, in shallow water, by the bottom. On the high seas, about 5 percent of the incident light is backscattered upward toward the sky. This is about equal to the skylight reflected at near-incident angles and severalfold larger than the fraction of reflected light passing through a suitably oriented polarizing filter.

The backscattered light so recovered, having been subjected to absorption and spectral scattering along a path length that varies with the distribution of scatterers in the sea, is markedly different in color from the incident "white" light. In clearest ocean water, the effective path length is quite long and the upward scattered light is strongly blue, with a dominant wavelength of 4000 Å and a quite pronounced saturation or excitation purity. In coastal regions the water contains many colored absorbers, both inside the bodies of transparent plankters, and as solutes of tannins, chromatins, carotenoids, chlorophyll, and many other "foreign" compounds. In addition, suspended particles of very fine mud scatter the light selectively and add to its color. As a result, the transparency of the water is much decreased, and the dominant wavelength shifts through green into the yellow (at 5700 Å) or even into brown.

The distinctive color of water is a familiar observation and leads to such names as the Black Sea, the Red Sea, the White Sea, the Azure Sea, and the Vermillion Sea. Although water color was used by the earliest navigators to locate familiar water masses and associated current systems, modern navigators depend on more "scientific" (i.e., less natural) methods. For the most part, oceanographers rely on the temperature and salinity of the water and more particularly on their correlation to identify water masses of different origin. Water color is used only as a measure of biological activity, past and present. For example, Steemann-Nielsen found that "the distribution of water color in the open ocean outside influence of land must be closely similar to the quantitative distribution of plankton algae." (Fig. 1)

In air reconnaissance of the ocean, temperature is the only parameter that currently serves as a discriminant of water masses. Thus it is easy to distinguish the Gulf Stream water from the adjacent slope water by its temperature contrast. But for more subtle differences, this will hardly suffice. Surface temperature is quickly altered by air temperature and by radiation, so that water masses having very different histories can have identical temperatures. As an alternative to the correlation of temperature and salinity, it is suggested that the correlation of temperature and color might serve to distinguish different water masses.

An example of the spectral variation of the backscattered light measured at a flight altitude of 500 ft is shown in the accompanying figure 2. To emphasize chromaticity as distinct from brightness, the spectra are presented in terms of their normalized trichromatic coefficients. (As usual, the blue coordinate is omitted.) The color of the ocean water is shown by its relation to the light reflected from a neutral gray card. The displacement of the color toward the green and yellow, relative to the clear ocean water, is also shown. The figure shows the sites over which the spectra were obtained.

If equipment of requisite sensitivity can be developed, it may be possible to see significant ocean-color differences at satellite altitudes and thus to add an observable parameter which, correlated with temperature, will make subtle features detectable over the high seas.

Figure Captions

Figure 1. A series of charts of the South Atlantic Ocean.

(a) Distribution of color of the sea (After Schott);

(b) Distribution of phosphate in mg/m^3 in the upper 50-m layer;

(c) Distribution of plankton organisms, thousands/liter, in the upper 50-m layer, (After Hentschel and Wattenberg, 1930);

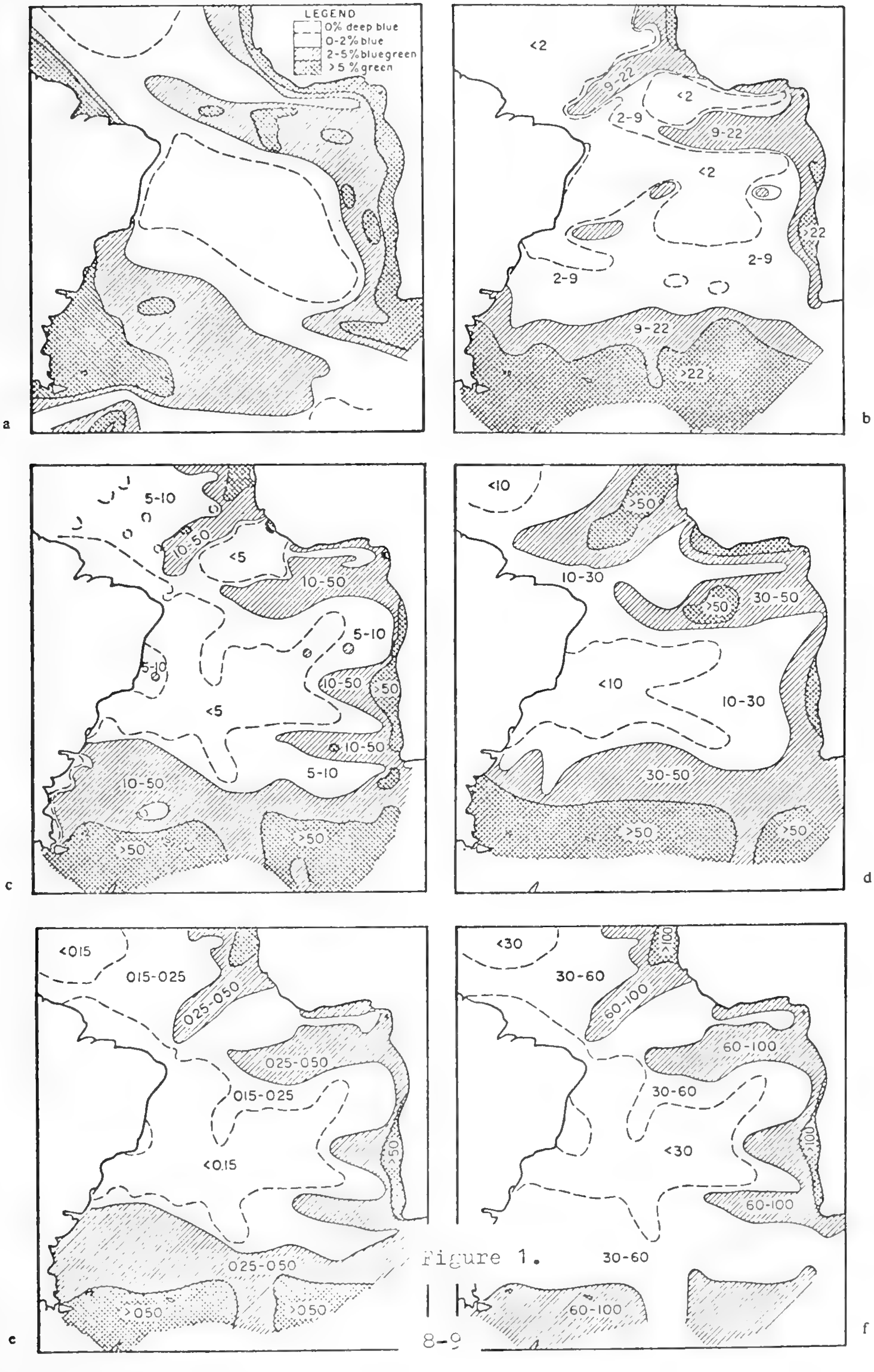
(d) Distribution of zooplankton (metazoa), numbers per 4 liters, in the upper 50-m layer (After Hentschel, 1933);

(e) Distribution of organic gross production in summer, g. C/ m^2/day; and

(f) Distribution of annual net production, g C/m^2 E. Steemann-Nielsen, Galathea Rept., Vol. 1, Fig. 20, pp. 78-79.

Reference: After National Academy of Sciences, Useful Applications of Earth-Oriented Satellites, Vol. 5, Oceanography, National Academy of Sciences, National Research Council, Washington, DC, 1969.

Figure 2. Example of spectral variation of backscatter light measured at a flight altitude of 500 ft (WHOI Report, unpublished). After the reference given in Fig. 1.


LEGEND
0% deep blue
0-2% blue
2-5% bluegreen
>5% green
a
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d
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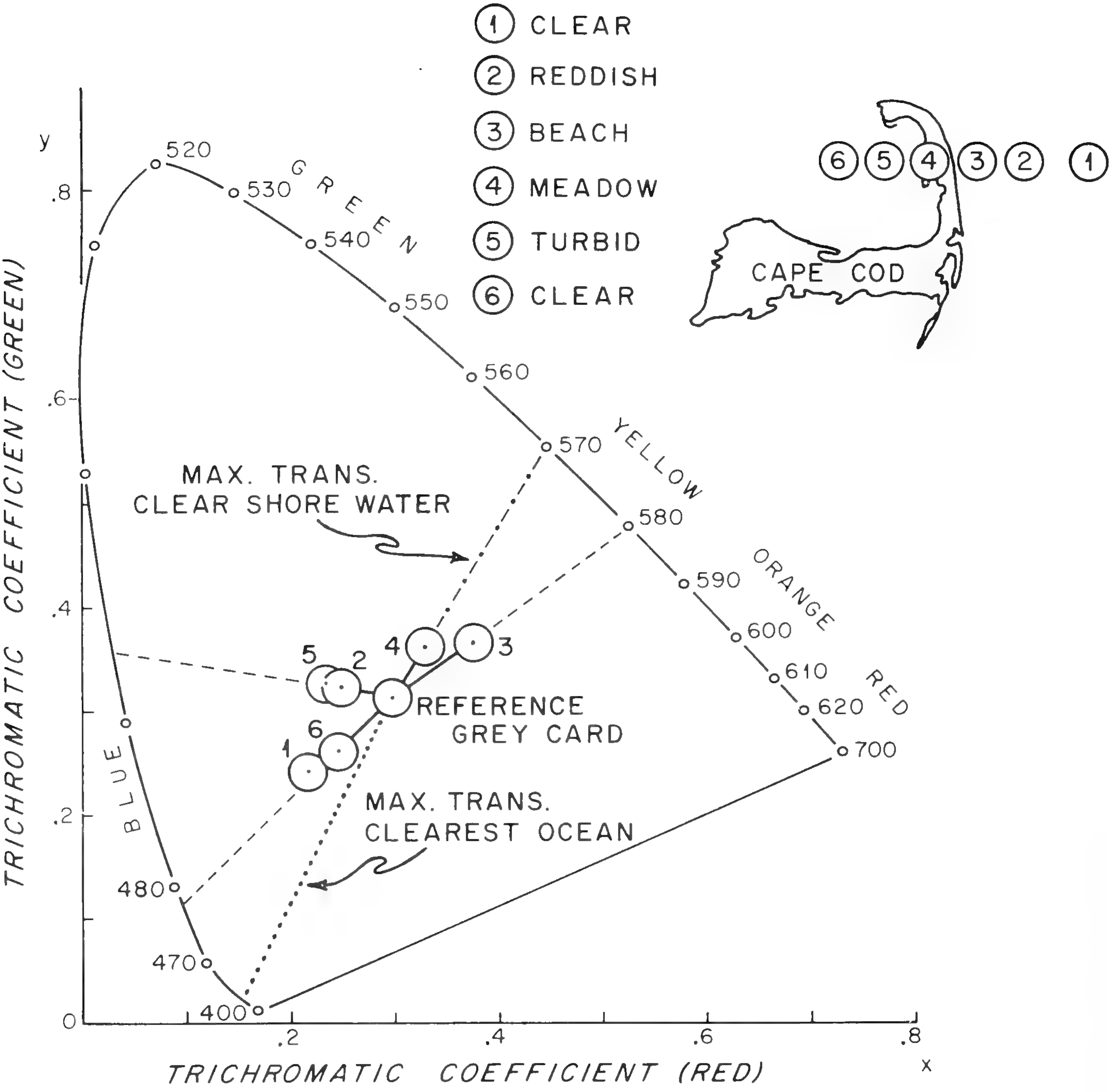
Figure 1.



CHROMATICITY DIAGRAM

Figure 2.

Frank Hebard
Bureau of Commercial Fisheries
Miami, FL 33149

The major research effort at the Tropical Atlantic Biological Laboratory is the study of tuna distribution in the Tropical Atlantic Ocean and to determine how their distribution is affected by the physical and biological features of the ocean. During a recent cruise to west African waters (September-December, 1968), an attempt was made to use satellite derived APT data and ship-borne infra-red sea surface temperature data to supplement routine oceanographic observations in the location of the Gabon-Angola oceanic front. This front, represented by the 24°C sea surface isotherm, undergoes a seasonal north-south migration and has been reported to affect the aggregation of tunas.

The front was located and its migration followed during the cruise by monitoring changes in the location of the 24°C sea surface isotherm as determined by thermometer and by infra-red sensors aboard ship. One-hundred twenty-three (123) Essa 6 APT transmissions were received and photographed aboard ship and an attempt was made to relate the distribution of the Gabon-Angola front to features revealed on these photographs.

We were unable to use the satellite photos to locate the Gabon-Angola oceanic front, probably because the temperature gradient associated with the front was not strong enough to affect cloud formation. In areas of upwelling where a strong temperature occurred, the photos showed that there was an effect on cloud distribution.

In the future we will continue in our effort to monitor from aircraft and from satellite both physical and biological oceanographic conditions by means of remote sensing techniques. Of particular interest is the sea surface temperature, distribution of currents, distribution of fresh water runoff from selected streams, monitoring phytoplankton and zooplankton standing crops, and location of tuna schools as a means of reducing search time for the fishermen.

Rudolph Hollman
Dept. of Meteorology and Oceanography
New York University
Bronx, N. Y.

Over the past years we have made a study of the albedo of the sea surface, that is, the ratio of the upward radiant flux to the downward radiant flux, over the rather broad spectral band of approximately 0.35μ to 2.5μ. The instrumentation consisted of two Epply pyranometers, a pyrheliometer, and a photocell. The two pyranometers were mounted back-to-back on a gimbal mounting affixed to a long boom that was extended over the bow of the research vessel. The upright pyranometer sensed the total downward radiant flux (irradiance) or global radiation and the inverted pyranometer sensed the upward radiant flux from the sea surface. The ratio of these two irradiances is defined as the albedo. The pyrheliometer measured the direct solar radiation so that the difference between the global and the direct radiation yields a measure of the diffuse sky radiation. The calibrated photocell was mounted on a float and provided a measure of the upward radiant flux due to scattering within the water. These measurements were largely carried out over the waters of Eastern Long Island Sound.

The results of these measurements show that the backscattered light contributes significantly (25 to 50%) to the albedo. We know that the albedo depends upon the solar altitude but we found the albedo also depends upon the state or condition of the atmosphere, that is, cloud conditions, turbidity, etc. An index of the state of the atmosphere is the amount of sky radiation present in the global radiation. The measurements also indicate that the reflectance of sky radiation is not constant but depends upon the solar altitude and the angular distribution of the sky radiation itself. These results agree with the results derived from Kimball's data for the distribution of sky radiation.

George Huebner
Dept. of Oceanography & Meteorology
Texas A & M University
College Station, Texas

For about four years we have had a program in remote sensing for oceanography sponsored by the Navy Oceanographic Office and Office of Naval Research. Personally, I am interested in the microwaves area--microwave parameters of the ocean. Our program has used NASA data and photo data from ships. Recently, we were funded in a program investigating sensors planned for orbiting vehicles and various ways to employ these even in cases not specifically designed for oceanography. I am here to learn about interests and efforts in color photography of the ocean to aid this project goal.

N. G. Jerlov
Institute of Oceanography
University of Copenhagen
Denmark

The Institute of Oceanography is five years old and has two specialties:

1. Turbulent diffusion of the sea
2. Optics of the sea

These are related because diffusion is studied by optics. Observations are made of attenuation, scattering, polarization and fluorescence of the sea. Optics are used to characterize water masses and study their spreading in the sea. The distribution of scattering particles may be related to primary production. Quantameter work.

Mahlon G. Kelly
Department of Biology
New York University
University Heights, N. Y.

My interest in light in the ocean started about seven years ago. At first this interest concerned the distribution of bioluminescence, but since has shifted to the use of aerial photography for studying coastal regions. Many benefits are to be gained by using such methods. The large-scale distribution of bottom cover has been much neglected in studies of bottom ecology, and photography aids greatly in studying this very important aspect of coastal areas.

I have been studying bottom biota at locations in the Bahamas, near Miami, and in the Florida Keys, and am now starting work on the distribution and ecology of suspended materials in polluted coastal areas. The work has benefited greatly from the help and cooperation of instrumentation engineers and workers interested in coastal land use. It is such cooperation that will allow optimal use and design of remote sensing techniques.

AERIAL PHOTOGRAPHY FOR STUDY OF NEAR-SHORE BIOTIC DISTRIBUTIONS

by

Mahlon G. Kelly

Although coastal areas contain some of our more valuable resources, synoptic study of the large-scale distribution of shallow-water bottom features is very difficult because over-lying water limits survey and sampling. Surprisingly, although technology is available for photographing through the water to depths of more than 100 feet, little use has been made of such photography for the study of biological resources and of marine ecology. Nonetheless, it is the biological features that are most immediately and drastically affected by pollution and man's activities along our coasts. Synoptic photography of shallow-water bottom biota needs to be developed to monitor and study environmental conditions and change.

Color photomosaics have been obtained of approximately 200 square miles of shallow water area on the west edge of the Bahama Banks south of Bimini and in Biscayne Bay, south of Miami, Florida. These mosaics allowed identification and mapping of the major biotic cover on the bottom. This would have been nearly impossible using conventional survey techniques. In addition, distributional features were identified that could only be detected using the perspective obtained with remote photography. Although some of these features are incompletely explained, they show important relationship to such environmental conditions as water depth, sediment and bottom geology, current scouring, wave exposure, etc. Also, man-made effects such as siltation due to dredging operations, canal drainage, and the effects of thermal outflow from power plants were reflected in the types and distribution of the plant communities.

Although there is some possibility that spectral signature analysis may help in studying these distributions, this approach is limited by the selective and variable spectral absorption and scattering of sea-water; any signatures are modified by the overlying water. Photography is limited by the absorption of available light by the water and by contrast and resolution reduction due to turbid light backscatter. Nevertheless, bottom features may be resolved at considerable depths even in relatively turbid waters.

Although instrumental analysis of photography and images and multispectral photography may be of value, their use is at present limited by the lack of even the most fundamental knowledge of large-scale distributions of the bottom biota. Background information is needed in primary photointerpretation using tone, hue, texture, and pattern recognition before more advanced technologies may be applied to their fullest, although photoenhancement techniques, instrumental analysis and multispectral photography may be invaluable as aids to interpretation. In short, sea-based photointerpretive studies are badly needed under diverse conditions to provide a backlog of information on the application of large-scale photography to the study of coastal biological resources.

We are continuing work in the clear waters off Florida as well as in the very disturbed conditions near New York City. It is hoped that studies in such diverse conditions will prove valuable both to marine ecologists and to those concerned with management and monitoring of the conditions near our coasts.

Note:

The presentation given above was an informal and slightly expanded version of a paper presented at meetings of the American Society of Photogrammetry, June 9-11, 1969, and published in the Seminar Proceedings[1]. The abstract given above is identical to that of the previously presented paper.

Reference

1. Kelly, M. G., 1969. Aerial Photography for the Study of Near-Shore Ocean Biology, *in*: *New Horizons in Color Aerial Photography*, Seminar Proceedings. American Society of Photogrammetry, pp. 347-355.

Leonard N. Liebermann
Department of Physics
University of California, San Diego

The NASA-National Academy of Sciences Study Panel on Oceanography asked us to rate what could be done from satellites for oceanography. We found the following results were obtainable:

1. Global heat-budget studies of the surface layer,
2. General circulation of the ocean,
3. Analysis and prediction of sea-surface temperature,
4. Analysis and prediction of sea-surface roughness and sea state,
5. Description of ocean-wide distribution of surface productivity.

Conclusion:

1. One of the most rewarding, practical studies will be that of the color of the ocean. We made instrumentation for measuring chlorophyll by means of 6750 Å band consisting of a spectroscope, prism and vibrating mirror, slit scanned spectrum by a photocell.... sinusoid wave, looked for second harmonic in vibrating mirror.

2. What can be learned about the nature of waves by photography? Using transparent points of sea surface photos, as a hologram, one obtains patterns showing the spectrum of wave lengths.

3. Measurements of wave heights by laser beam from a satellite may be feasible if power requirements can be met.

C. J. Lorenzen
Woods Hole Oceanographic Institution
Woods Hole, MA

The Biological Significance of Surface Chlorophyll Measurements

The possibility of obtaining surface or near surface measurements of chlorophyll by remote sensing raises the question of the ecological importance of these measurements. Certain measurements, i.e., euphotic zone chlorophyll and/or productivity, are of much greater interest and importance in biological studies of the ocean.

It is possible to test the correlation of surface chlorophyll concentration with these other parameters with data on hand and this was done. The data was obtained from both the Atlantic and Pacific Oceans and covered the range of values one might reasonably expect to encounter in the oceans. The values are:

euphotic zone	10-91 meters
surface chlorophyll	0.04-28 mg m^{-3}
euphotic zone chlorophyll	7.0-277 mg m^{-2}
primary production	0.06-11 gm C m^{-2} day $^{-1}$

The data was transformed into the natural logarithm and entered into Least Squares Regression. The results are summarized below.

TABLE 1.	n	F	r^2
ln E chl = 3.49 + 0.62 ln Surf. Chl.	91	398**	0.82**
ln Euphotic zone = 3.46 - 0.29 ln Surf. Chl.	91	388**	0.81**
ln primary prod. = 0.43 + 0.48 ln Surf. Chl.	87	99**	0.54**

The conclusion of this exercise is:

Surface chlorophyll estimation on a continuous basis is a worthwhile objective, since it is a reasonable good estimator of euphotic zone chlorophyll and euphotic zone primary productivity.

The measurement of either chlorophyll or productivity in the ocean is of great ecological importance, and the point doesn't have to be discussed here. Let it be sufficient to say that in some circumstances chlorophyll measurements may help to delineate areas where certain fish resources might be found (see comments by Blackburn), depending on meeting certain biological restrictions. On the other hand, obtaining chlorophyll information regularly over large areas of the ocean would be very interesting and helpful in solving certain problems involved in the study of food chain ecology.

One other interesting feature of the statistical analysis was the strong relationship between surface chlorophyll and euphotic zone depth (the depth to which 1% of the surface irradiance reaches). Apparently, most of the extinction of visible light in the ocean can be related to chlorophyll (contained within algae).

Paul M. Maughan
Special Assistant for Marine Resources
Bureau of Commercial Fisheries
Washington, DC 20240

Bureau of Commercial Fisheries remote sensing programs, such as the space-photo interpretation of Dr. Robert Stevenson's at Galveston and the fishery intelligence program of Mr. Kirby Drennan's at Pascagoula, are coordinated through the BCF Central Office in Washington, D.C.

The remote sensing programs are proceeding in two study areas: 1) direct detection of fish stocks in their natural environment and, 2) indirect detection of fish stocks using a knowledge of the physical parameters (such as areas of upwelling and convergence zones) to determine where fish are without actually observing the fish. Current plans are to investigate newer remote sensing techniques and to specify "fish sensors" for the proposed oceanographic satellite. There is no doubt that a real benefit to the fishing industry can be made through observations from a satellite system.

One study at Oregon State University currently in progress which BCF is sponsoring, is observing the well-defined Columbia River plume flowing south along the Oregon coast and an adjacent area of upwelling, and relating these to the presence of albacore tuna. The first of three phases is now underway and involves the use of multi-spectral photography, IR (PRT5) temperature data, and standard color photographs from aircraft. OSU scientists have found major color differences between the plume and ocean water. Nimbus III HRIR satellite data will be used to determine the sea surface temperature. In conjunction with the albacore study, a forecast network issues a daily bulletin to the tuna fleet. This study is a combination of applied and basic research and has a real monetary advantage to the fishing industry.

William J. Merrell, Jr.
Department of Oceanography
Texas A & M University
College Station, Texas

I am interested in identifying physical parameters and features in the ocean through color photography and other remote sensors. My most recent work has been related to identifying oceanographic features in Apollo photography and in multisensor data taken in Mexico and Brazil with NASA aircraft.

(The following is taken from a letter dated August 26, 1969 from W. J. Merrell to G. C. Ewing.)

"Apollo VI (See Notes 1 and 2 on p. 17-3)

This was an unmanned flight, so we have the highest percentage of photographs over the deep ocean. Although there also seemed to be a high percentage of cloud cover, some frames definitely show evidence of color boundaries. The Texas A & M team (Paris, Chmelik, Merrell, and Arnold) mention one (frame 1495) in a paper to be published in the final Apollo VII report. (This was turned in to NASA over a year ago and has not been released yet.) Frames 1499-1501 and frames 1495-97 definitely show some sort of color variation or boundary. The overlap of the frames is very nice in that it gives added assurance that the feature is not due to some mishap in the development of the photograph. Dr. Stevenson's slides were probably taken from one of these sequences. The location of these color features is at least 700 kilometers offshore.

"Apollo VII

There are no photographs which show color boundaries because there are no vertical photographs in the deep ocean that are not almost completely cloud covered.

"Apollo IX (See Note 3 on p. 17-4).

Although few photographs of the deep ocean were taken, a definite color formation is present in one. Frame 3588 was taken from 107 N.M. at 12°N and 50°W. I believe that the white streak in the center of the photograph is a result of some error in the development of the photography and not a feature in the ocean or atmosphere. I reviewed satellite pictures of contrails from aircraft and found them to be much thinner and having a shadow. However, this brings up the question of why the astronaut took the photograph, as no other photographs were taken offshore without interesting cloud formations, etc. Perhaps the change in the glitter pattern caused by a convergence zone or wind shear zone caught his eye. It seems to be toward the center of the photograph. Anyway, the color feature I referred to is on the right-hand side of the photograph and appears to be in the general form of a large eddy.

I believe that color boundaries in the open ocean have definitely been recorded in the previously mentioned Apollo photographs. How general these few photographs are of the total world ocean is impossible to say. No good satellite photographs are available for the Central Pacific Ocean. (It was night in the Pacific when the Apollo VI photographs were taken.) I am sure that some may argue that the color boundaries I have mentioned may be from the outflow of the Amazon or from a large buildup of floating material sometimes found in these regions of the Atlantic and are not indicative of the color changes and boundaries in the world ocean. This may be true; but as of now, it is impossible to prove. I believe the important facts to be considered when we review these photographs are that they were taken far from shore and definitely seem to describe ocean features solely by changes in ocean color. More missions are needed to answer the general question of how common these color boundaries are in the world ocean and more specific questions such as why do these color boundaries usually appear in photographs which also record what seems to be a convergence zone or roughness boundary. A satellite color sensor similar to the one discussed at the workshop could help answer these questions if it were utilized over the central portions of the ocean."

Notes Added by Compiler:

Note 1

NASA photographs are available from:

J. R. Dunlop, Inc.
2321 4th Street N.E.
Washington, DC 20002
(202) 526-5000

Give the photo number and spacecraft flight. The prices vary but are around $3.00 for a glossy print to $0.35 for a 35 mm slide. Super slides are around $3.00. Mr. Merrell gives the numbers of several good photographs.

Note 2, (Dec. 19, 1969).

AS6-2-1495, AS6-2-1496, AS6-2-1501, AS6-2-1502

These photographs of the Atlantic Ocean were taken from the Apollo 6 spacecraft, an unmanned, orbiting vehicle, on April 4, 1968. Solar time for each photograph was 1011, 1013, 1027, 1030, respectively; spacecraft altitude was approximately 190-192 kilometers. The camera used was a J. A. Maurer, 70 mm. with a Kodak Ektar, 76 mm, f/2.8 focal length lens.

The film used was Eastman Kodak, Ektachrome, SO-121 high resolution aerial, 70 mm. The camera was operated by automatic control and was mounted inside the cabin of the spacecraft.

Note 3, (May 8, 1970)

The white streak in frame 3588 of Apollo IX has been identified as the wake of a nuclear submarine by the Navy.

Richard C. Ramsey
TRW Systems
One Space Park
Redondo Beach, California

I have been involved in ocean color for two to three years. In 1967 I made a study on application of remote sensors to measurements of ocean color (Study of the Remote Measurement of Ocean Color, Final Report, Contract No. NASW- 1658, prepared for NASA Headquarters, Washington, D.C., 26 January 1968).

"The general tasks envisaged at the beginning of the program were:

> Task 1 - Analysis
>
> Conduct analysis of the spectral variation of the optical characteristics of the sea water as viewed from a location in or above the earth's atmosphere. This analysis was to include evaluation of the effects of surface conditions. If necessary, simple laboratory tests using TRW owned equipment would be used to evaluate the effect of surface roughness.
>
> Task 2 - Definition of System Requirements
>
> Based on the analysis of Task 1, a set of requirements would be prepared for a system capable of measuring the spectral characteristics of water from a moving vehicle. Both aircraft and spacecraft would be considered.
>
> Task 3 - System Definition
>
> Based on the requirements of Task 2, a preliminary design of a system to best meet these requirements would be performed. This design would include specification of major components and a preliminary evaluation of weight, dimension, and power requirements.

"It is felt that these tasks have been completed during this study. It was not considered necessary to perform the laboratory tests of the effects of surface conditions because some previous measurement data were available in the literature and because of the difficulty in simulating real conditions."

In 1968 and 1969 I participated in airborne measurements of ocean color at Woods Hole, as reported herewith by Clarke, Ewing and Lorenzen (Spectral Measurements from Aircraft of Backscattered Light from the Sea in Relation to Chlorophyll Concentration as a Possible Index of Productivity. George L. Clarke, Gifford C. Ewing and Carl J. Lorenzen, SCIENCE, p. 4, in press.)

In correspondence with C. F.Hagelberg, 8 July 1969, I set forth "calculations [which] relate the visible spectrum of the total upwelling light from the ocean waters to the chlorophyll content of the water...... These calculations, which produce results that correlate well with measurements with the water color spectrometer, indicate that the use of a minimum of only two bands should result in a chlorophyll determination."

Donald S. Ross
Philco-Ford Corporation
Space & Re-entry Systems Division
Palo Alto, California

Primary interests lie in acquisition and data processing of all types of earth sciences aerospace imagery, but with particular emphasis on oceanographic subjects. Data processing is accomplished by a variety of photographic, optical and electronic techniques, whereby image grey levels are converted from analog to digital form to emphasize or suppress pre-selected sets of information. "Data processing" as used here includes enhancing images to aid visual interpretation, as well as quantizing grey levels for assessing luminance characteristics of the subject. Similar treatment is given to images taken in different spectral bands which are added to or subtracted from each other to enhance the information.

For oceanographic applications, a typical example would be optical or electronic digitization of variations in scattered light intensity within the water (as recorded by the camera) and conversion of each level into highly contrasting colors, for relative water depth assessment. In another example, the image of the water surface, taken in an infra-red spectral band, would be combined in opposite sign (positive-to-negative masking) with an image taken simultaneously in a blue or green spectral band, to suppress image information common to both spectral bands; in this case the image of the water surface. The remaining image is that of sub-surface illumination which is not recordable in the infra-red spectral band, but which is found in the blue and green bands.

The photo-optical image enhancing methods retain, or even yield apparent improvement of, the inherent resolution of the input image; but laboratory processing time is required. Electronic false color image enhancement is done in real-time; however, while the resolution of the cathode ray tube enhanced color image is substantially better than commercial color television, it cannot provide the high resolution of the photographic process.

The present and future activities of our group, relating to ocean color, include planning and flying 4-band multispectral photography with our own camera for the practical testing of suitable films, filters and processing chemistry, to improve the recording of small color changes in the water, and aid in the selection of spectral bands for maximum depth penetration. Continuing programs include the separation, enhancement and analysis of Gemini and Apollo photography for oceanographic subjects such as bathymetry, sediment flow patterns, shoreline discrimination, emphasis of water color changes for delineating current boundaries and areas of upwelling, enhancing bottom features and topography, clarifying wave diffraction patterns.

Methods of enhancing color differences are also under continuous development and improvement in our laboratory.

Abstract of Formal Presentation:

While the development of equipment capable of accurately measuring water color and chlorophyll concentrations from orbital altitudes is under way, it is recognized that considerable work, experimentation and time will be involved before reliable working devices can be orbited.

In the meantime the contributions which existing imaging sensors can make to the detection and assessment of water color changes should be neither underestimated nor overlooked.

The catalog of Gemini and Apollo 70 mm color photography contains hundreds of images which demonstrate in a most graphic way changes in water color in the open ocean and its shorelines.

The changes in water color in many of these images are clearly associated with features such as currents, upwelling, sediments, depth variations, changes in bottom composition, and so forth. The value of these images lies in their ability to indicate important oceanographic phenomena, through variations in water color. For this form of interpretation, it is only necessary to detect and record a color change; it is not necessary to be able to measure it accurately in the radiometric sense.

The natural color film images taken from space which provide the most useful information for oceanographic purposes (through variations in water color) depend on blue and green sensitive layers, to record the differences in the ratios of blue and green light in the water.

However, hardware systems currently proposed for orbit do not include imaging sensors operating in spectral bands below 500 mμ, in the blue and blue-green region. The degrading effect on the atmosphere on image contrast below 500 mu has been considered to be so severe that images obtained in this spectral

region would be of little value. This is unfortunate, since a blue or blue-green band is essential (in addition to a green spectral band) for detecting water color differences of primary significance. The blue and blue-green spectral region is also where the attenuation of light in clear water is least, and greatest photo-optical depth penetration is possible.

In the course of image enhancement work in our laboratory, numerous Gemini and Apollo natural color film images of oceanographic subjects have been color-separated by photo-optical means. It has been found that the blue-sensitive layer in these films contains substantial information despite the effects of the atmosphere. Examples are shown in Figures 1A, B and 2A,B; where blue and green separations made from typical images, taken from orbital altitude, are compared.

It is concluded that it is quite feasible to utilize a spectral band in the 460-500 mμ region for remote sensing in oceanography; and if the many important oceanographic phenomena associated with water color are to be detected, it will be essential to record and couple this spectral band with a green record.

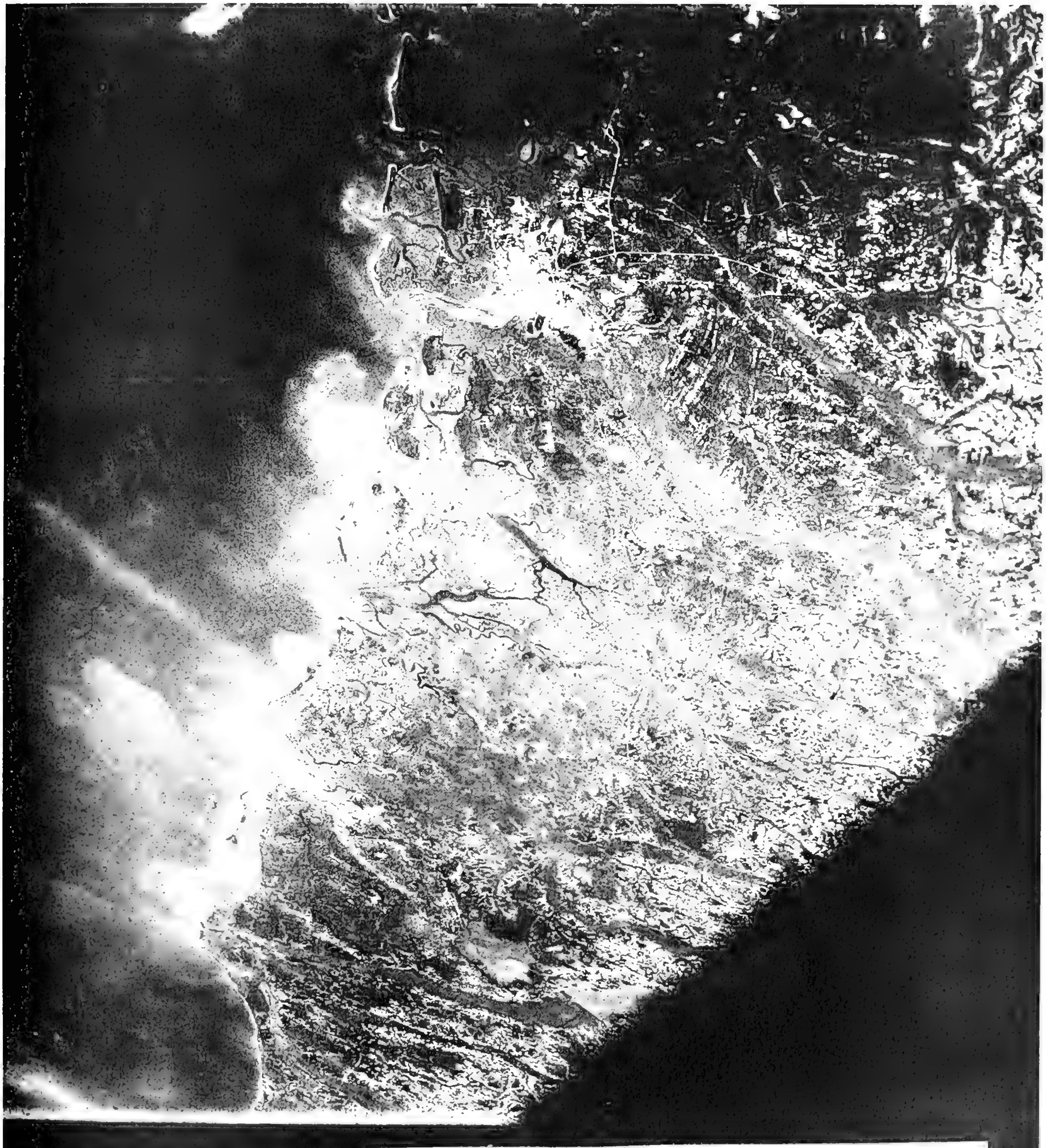


Fig. 1A *

Apollo IX Color Photo

Green Separation

Frame [illegible]

Georgia, So. Carolina, Savannah

(See Note 1 on p. 17-3)

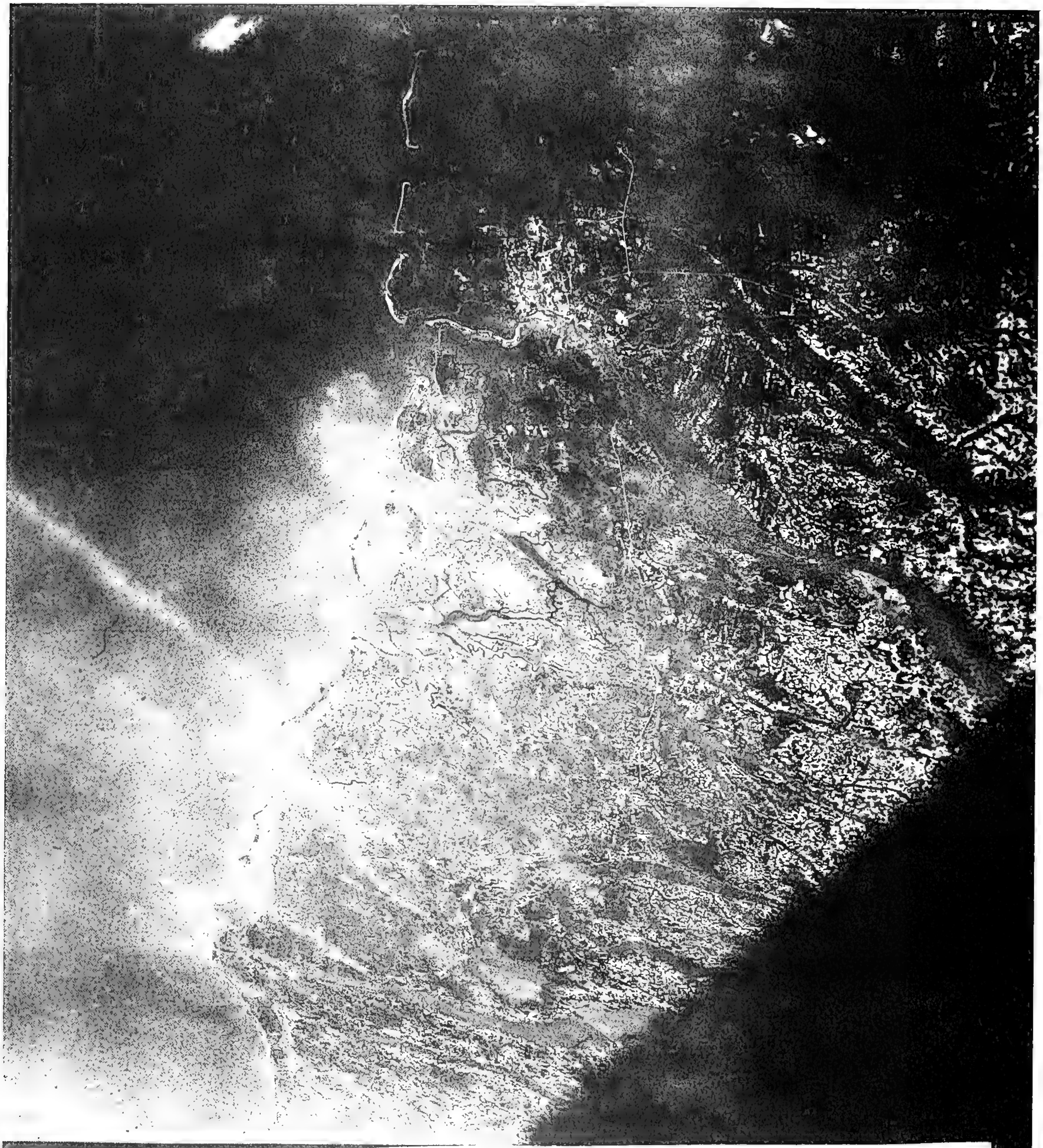


Fig. 2.*

Apollo IX Color Photo

Blue Separation

Frame No. AS9-3148

Georgia, So. Carolina, Savannah

*(See Note 1 on p. 17-3).

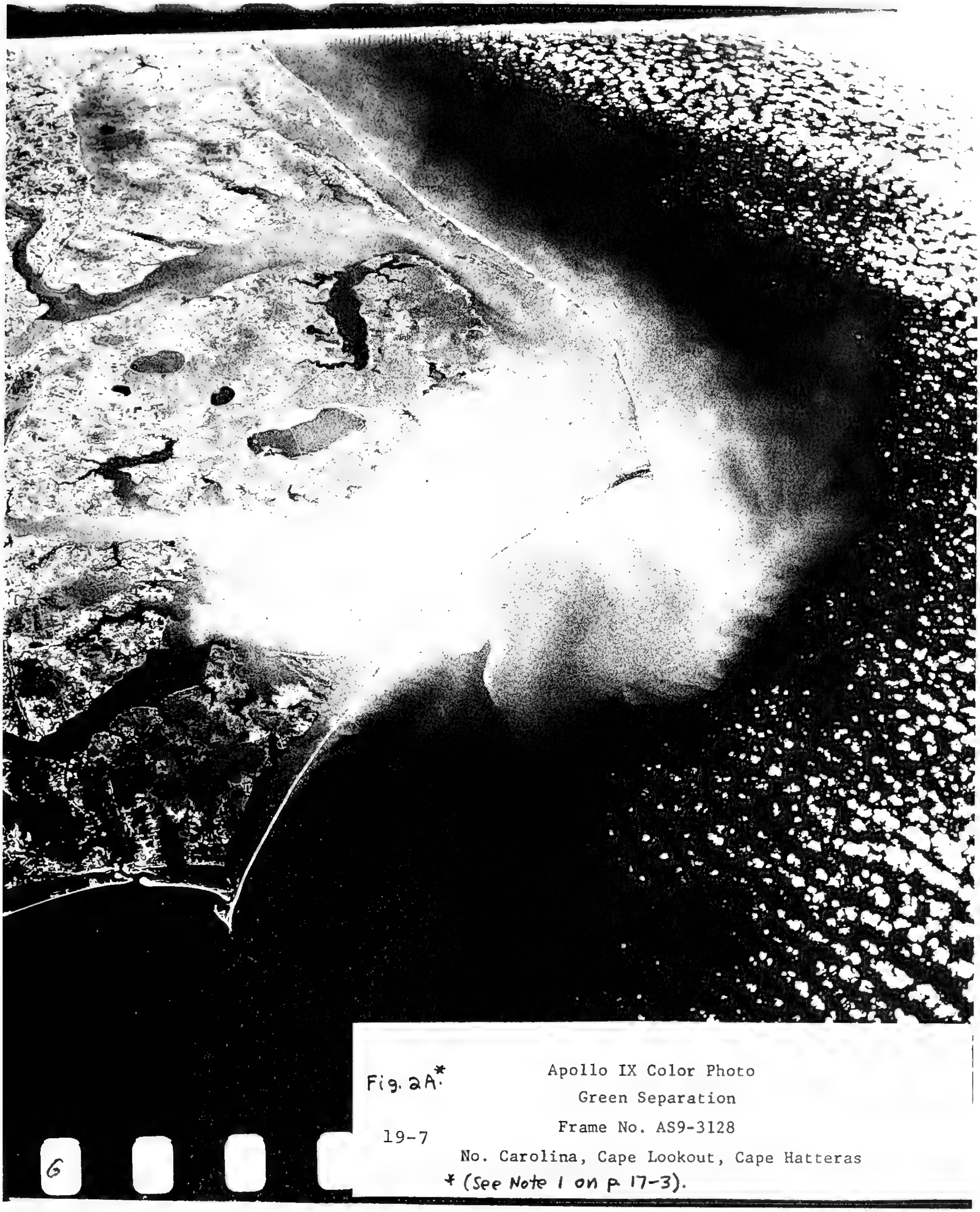


Fig. 2A*

Apollo IX Color Photo
Green Separation
Frame No. AS9-3128
No. Carolina, Cape Lookout, Cape Hatteras

* (See Note 1 on p. 17-3).

Fig. B*

Apollo IX Color Photo

19-8

Blue Separation

Frame No. AS9-3128

No. Carolina, Cape Lookout, Cape Hateras

*(See Note 1 on p. 17-3)

Peter M. Saunders
Woods Hole Oceanographic Institution

I am a meteorologist with an interest in exchange processes between ocean and atmosphere. Currently Mr. Richard Payne and I are attempting to make a definite measurement of the short wave albedo of the ocean. Albedo is the ratio of the upward to the downward irradiance close to the sea surface. Upward irradiance has two components:

1. Energy reflected from the surface, and
2. Energy scattered internally which escapes through the surface.

In our measurement program we separate these. Above the surface we measure total and diffuse downward and upward irradiance using pyranometers, and just below the surface we measure the backscattered irradiance on a transparent floating buoy. Broad band sensors are used, namely thermopiles with uniform sensitivity from .3 to 3 microns; thus, we measure the energy fluxes into and out of the ocean.

On the theoretical side I have studied the interaction of electromagnetic waves with the sea surface, following the work of Cox and Munk. By extending their work to oblique viewing, where the problems of multiple reflections and shadowing are important, I have given an explanation of the existence of the ocean horizon, predicting the radiance contrast between the sea and the sky there.

The theoretical studies (together with the experimental measurements) show that the following factors influence albedo:

1. Roughness
2. Directionality or diffuseness of illumination.

We will compare theoretical surface reflection properties with our measurements, and attempt to relate the backscattered light within the ocean to other oceanic properties.

John W. Sherman, III
Spacecraft Oceanography Project
Naval Oceanographic Office (Code 7007)

The Spacecraft Oceanography (SPOC) Project plans and recommends to NASA a program in remote sensing oceanography and coordinates air and spacecraft experiments for oceanographic users in the NASA Earth Resources Survey (ERS) Program.

The critical areas of sensor application that are important to oceanography are: (1) ocean color and (2) microwave exploration. In the area of ocean color, what needs to be experimentally accomplished must be documented by meetings such as this and the appropriate aircraft remote sensors obtained. A critique is invited of instrumentation for space and aircraft sensors related to color measurements. In the ERS Program, for example, the Department of Agriculture is a clear "user" group, but there are 13-17 government agencies involved in oceanography, with no one, single user. The SPOC Project attempts to act as the technical focal point for NASA in the ERS Program. Thus, the requested instrumentation critique is in reality an attempt to insure that oceanographic user requirements are met.

Raymond C. Smith
Visibility Laboratory
Scripps Institution of Oceanography
San Diego, California

Lately, we have been measuring chlorophyll content and total particulate matter simultaneously with our spectral irradiance data. Also, we have a new instrument which measures radiance distributions under water. The radiance distribution data allows many optical properties of natural waters to be calculated.

Robert Spiers
Langley Research Center
National Aeronautics and Space Administration
Hampton, Virginia

Our earth resources activities are identified with remote sensor problems of research organizations:

1. Working directly with the U. S. Fisheries, we are developing a spectrophotometer to measure the reflectivity of fish schools and ocean water. Output: reflectivity vs. wavelength. An electronic signal processing technique is used to filter radiance noise from ocean measurements.

2. Working with Virginia Institute of Marine Sciences, we will launch a balloon carrying four cameras with color filters to photograph Chesapeake Bay and the Atlantic. These photographs will be analyzed using ship measurements of ground truth.

3. Working with Old Dominion College, we will measure changes in off-shore bottom contours with time.

4. We are employing PhD's from various disciplines to perform a preliminary design of ERS systems.

Joachim Stephan
Battelle Institute
Columbus, Ohio

Remote sensing applications to biota and wildlife on and near Amchitka Island in the Aleutians are presently being studied. We are currently photographing areas from a low-flying helicopter near shore to determine species of the algae and to determine if man-made effects disturb any of this. With marginal weather photography prevalent, never above 1,000 feet altitude, we can distinguish different algae populations.

Robert E. Stevenson
Bureau of Commercial Fisheries
Galveston, Texas

We are concerned with the interpretation of color photography from manned spacecraft to determine the significance of the view from space to the fisheries. We are working primarily toward the development of a satellite system to provide real time information to all users. My purpose here is to learn actual applications of color photography to this goal.

Martin J. Swetnick
National Aeronautics and Space Administration
Office of Space Applications

At NASA headquarters, in the office of Space Science and Applications, I am responsible for the Earth Resources Survey Program Oceanography discipline.

One of the functions of an Earth Resources Survey Program staff scientist is to prepare and provide material for selling the concept of satellite oceanography to NASA management, Congress, and segments of the oceanographic community both within the government and the private sector.

Interest in getting an Earth Resources Technology Satellite (ERTS) flight program underway as early as possible has been expressed by several members of Congress. Planning an ERTS oceanography mission will be somewhat difficult in view of the lack of a focal point for oceanographic activities within our government. The identification of potential users of ERTS oceanography data is another problem that needs to be resolved.

NASA is an R & D agency. One of the missions of NASA is to apply space technology to global synoptic observations of remote sensor techniques for use on satellites. It works with other agencies who can evaluate the capabilities of various remote sensors for providing data on ocean parameters or processes.

NASA plans to carry out an ERTS program calling for a series of four remote sensing missions. The first two satellites (ERTS A and B) will be directed toward landing mass observations. These satellites will carry a three-color high resolution television camera system and a multi channel imager. Although this instrument payload is not optimum for ocean observations, there will be a need to determine whether it could provide some meaningful information about the oceans. The third satellite (ERTS C) will be used for ocean survey. Serious consideration will be given to the selection of remote sensors. This will involve discussion with interested people and potential users of the data.

NASA relies on the Spacecraft Oceanography Project (SPOC) in NAVOCEANO for the daily technical administration and monitoring of the NASA funded research programs at universities, private organizations, and other government agencies and for coordinating the work of scientists, participating in the NASA aircraft missions supporting the checkout of remote sensors during overwater flights and, where possible, the acquisition of ground truth information.

O. Lyle Tiffany
Chief Scientist
The Bendix Corporation
Aerospace Systems Division

Our division of Bendix is working in the fields of thermal and multispectral imaging for earth resources.

In instrumentation we make commercial thermal mappers with a variety of infrared detectors as options. We have built our own 9 channel visible and near infrared scanner which is now flying in a company Beechcraft. We are at the present time engaged in the design and fabrication of a 24-channel scanner from the near ultraviolet through the visible and out to 13 microns in the infrared for the NASA Houston.

On the research side we are flying our multispectral scanner and thermal mappers to collect data to be compared with ground truth for a variety of disciplines.

PRELIMINARY NOTES ON THERMAL MAPPING AND MULTISPECTRAL SENSING IN OCEANOGRAPHY

Resource survey missions for the purpose of exploring the value and utility of multispectral data are conducted at Bendix in a company aircraft which is a Beech D18. This aircraft is instrumented with an infrared scanner, and a 9-channel UV, visible, and near infrared multispectral scanner. The supporting equipment includes a 70-mm aerial survey type sequencing camera. The video from the infrared single channel thermal mapper and from the 9-channel multispectral scanner are recorded on wide-band FM tape. After the mission this tape is returned to the laboratory for detailed studies of the multispectral data which includes conversion to a digital format and statistical studies using a large computer such as the IBM 360. Imagery can be produced from the multispectral data using the film recorder in the laboratory directly from the tape recorded video. The data produced by a multispectral line scanner is particularly well adapted for studies of image enhancement and target classification because linear combinations of the electronic video can be formed using analog circuitry. The result of such linear combination can be fed directly to the film recorder for the production of enhanced imagery. The particular formula used in forming any given linear combination is determined from a statistical study of the digital samples of the multispectral data.

The results from three different missions will be illustrated briefly in this talk. The first from the Thermal Mapper shows Boston Harbor in the infrared as observed during a night time flight at low water ebb tide. The other two examples are taken from multispectral missions. One is in the area of agriculture and the other in the area of limnology.

On the morning of 11 June 1969 at 0230 hours a Bendix airplane equipped with a Thermal Mapper flew a total area cover mission of the Boston Harbor area. The time of the flight was selected to give coverage at low water slack tide. The detector in the mapper was an indium antimonide device cooled with liquid nitrogen. It was operating unfiltered. In the absence of reflectance solar IR this gives thermal coverage out to about 5.5 microns. Figure 1 is a sample of this imagery.

Excellent thermal contrast was obtained in the water of the harbor. In this imagery the dark areas correspond to warmer areas and the lighter areas correspond to cool spots. In general, the water was warmer than the land. When the complete set of data is assembled in an area cover mosaic the spatial distribution of the thermal mixing is expected to show the flow patterns into and out of the harbor as the tide flows.

LARS, the laboratory for agriculture remote sensing at Purdue University, maintains a set of ground truth over a number of well defined flight lines in rural Tippicanoe County where Lafayette, Indiana, is located.

Multispectral data was obtained over this test site on 13 November 1968 to evaluate the Bendix 9-channel scanner for use in crop classification studies. Six of the nine channels were recorded on the seven-channel analog tape recorder used at that time and subsequently played back in the electronic processing laboratory. A grey scale presentation of the reflectance in each wavelength region was in the resulting imagery. The reflectance range in each channel is known from preflight calibration and allows reflectance values to be placed on each resolution element on the ground. The analog processing laboratory allows any channel or combination of channels to be recorded on film and permits processing coefficients to be applied to any channel. The coefficients may be selected from digital data extracted from the original analog tape after computerized statistical analysis has been performed. In this way targets of interest are enhanced and the backgrounds suppressed.

Two statistical methods were employed in an attempt to enhance the agricultural targets of interest. Before the data was analyzed it was submitted to processing to produce unenhanced imagery for selection of the areas to be sampled. Seven thousand digital samples of the selected areas were then obtained for which ground truth was available in the form of crop identification. The first statistical method applied was factor analysis. The linear combinations of the original data channels specified by factor analysis are intended to make it possible for the user to identify physical phenomena responsible for variation in the data to be identified with particular factors. Upon completion of this statistical analysis the processing coefficients thus specified were input to the analog processing unit and film showing the variation in the first three factors was produced. The results of this factor analysis are shown in Figure 2. The ground truth collected by Purdue University identifies the dark areas in the factor 1 imagery as corn fields. In factor 2 the dark areas correspond to fields of bare soil. The second statistical analysis employed with respect to this data was multiple linear regression analysis. Samples of this imagery are shown in Figure 3. The middle strip identified at the top with the caption "corn equals white" corresponds rather well with the factor 1 imagery from figure 2. Corn is enhanced in both cases. The sense of the enhancement is changed however so that in the case of regression, corn appears as the lighter color fields. With the aid of the ground truth, wheat fields were also identified. The regression analysis was performed to determine linear combinations which would enhance wheat fields. This is also identified in Figure 3. Finally, bare soil was enhanced in much the same manner as found in Figure 2. Again, however, the sense of the enhancement is reversed so that bare soil appears as the light color in the regression imagery while it appears as a dark color in the factor analysis imagery.

More recently Bendix has been studying the apparent color change of water with water depth using the multispectral equipment. This data collection activity is being conducted in support of a data analysis program being conducted for the Electronics Research Center in Boston. This data was collected at Pentwater which is a small port on the eastern shore of Lake Michigan during the week of 21 July 1969. Lake Michigan was selected as a test site because the water is relatively clear and clean, making the bottom visible out to depths of perhaps 20-30 feet. It was also desired that the test site have a very uniform bottom in order to remove one of the variables from the experiment. The entire eastern shore line of Lake Michigan has an extremely sandy and uniform bottom. The currents flowing north and south along this shore provide an interesting structure for study with multispectral devices. Figure 4 illustrates this structure. The picture is an enlargement of 70-mm imagery from channel 4 of the multispectral scanner. The scanner was calibrated in such a way that reflectance values ranging from 0 to 15% would completely fill the dynamic range of the video. The wavelength boundaries of channel 4 extend from about .56 to .62 microns. This range includes the wavelength which has the greatest water penetration in the visible region. The characteristics sandbar structure of the eastern shore of Lake Michigan is clearly visible in this picture.

The NASA contract in support of which this data was collected has as its objective the quantitative measurement of water depth using multispectral video and multiple regression as the necessary tools.

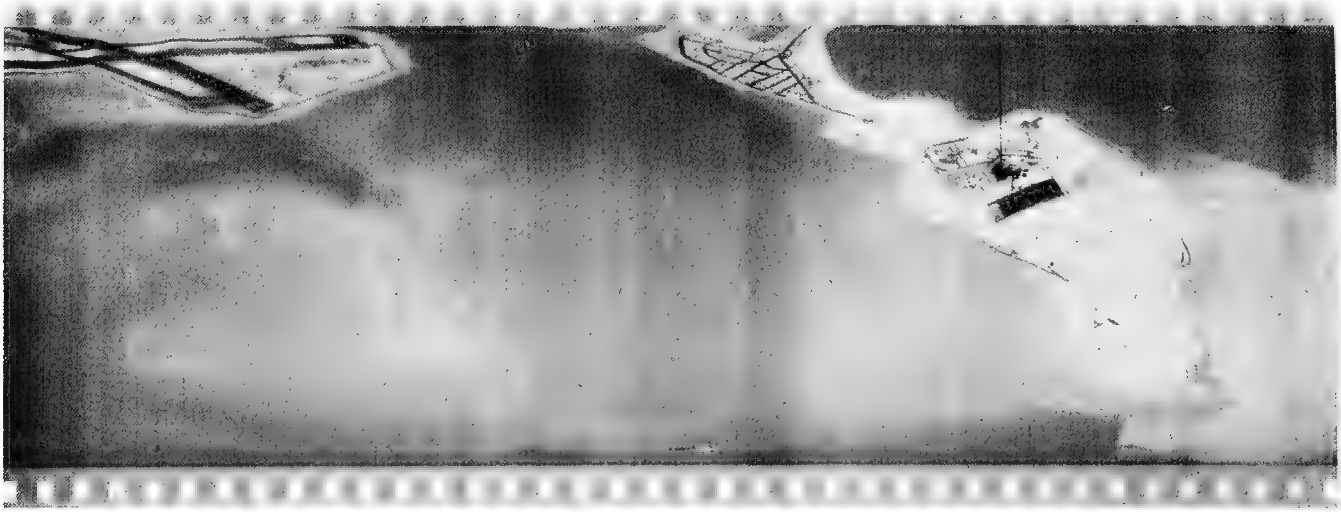
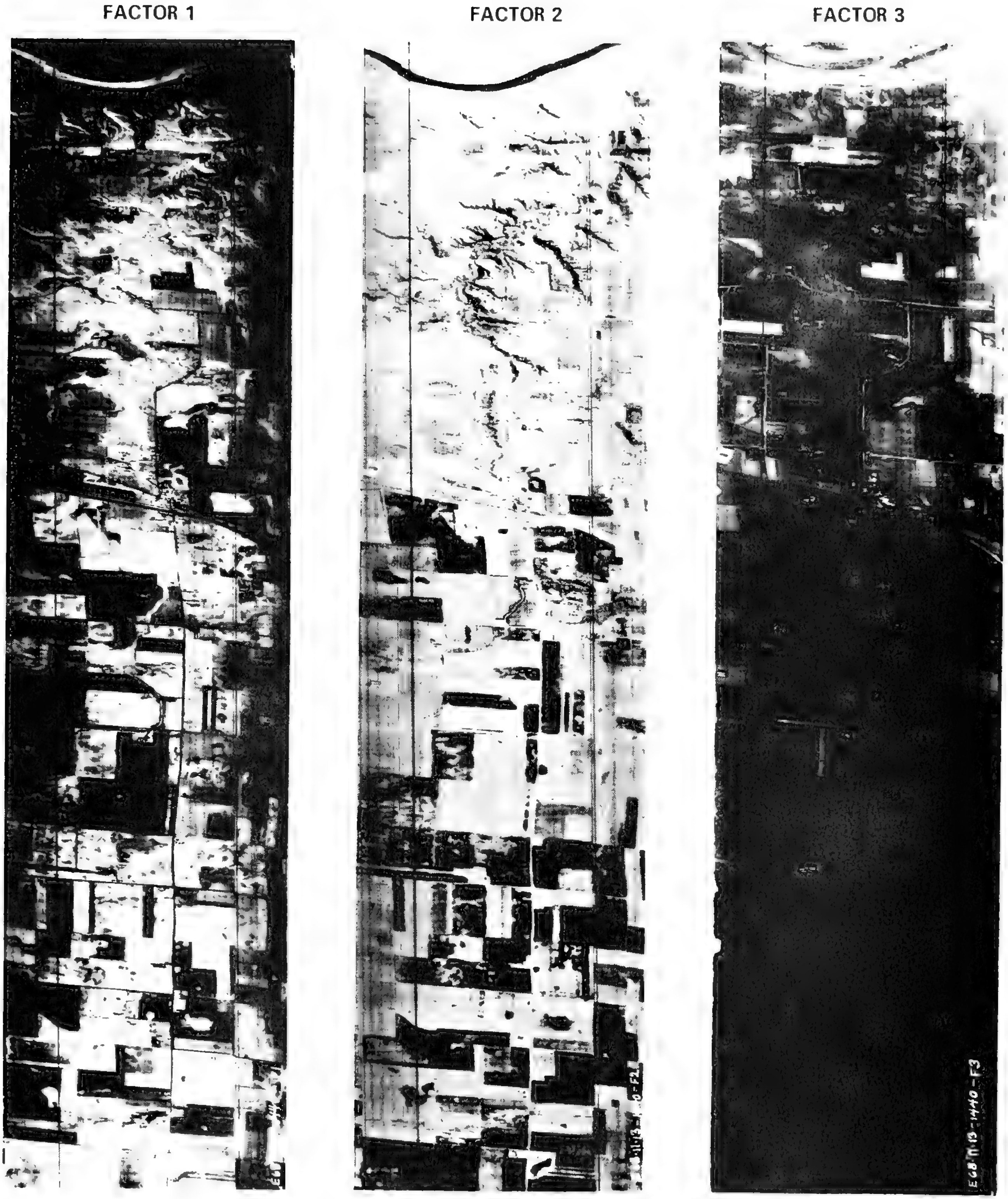


Figure 1 Thermal Imagery of Boston Harbor



FACTOR 1

FACTOR 2

FACTOR 3

Figure 2 Factor Analysis of Agricultural Data

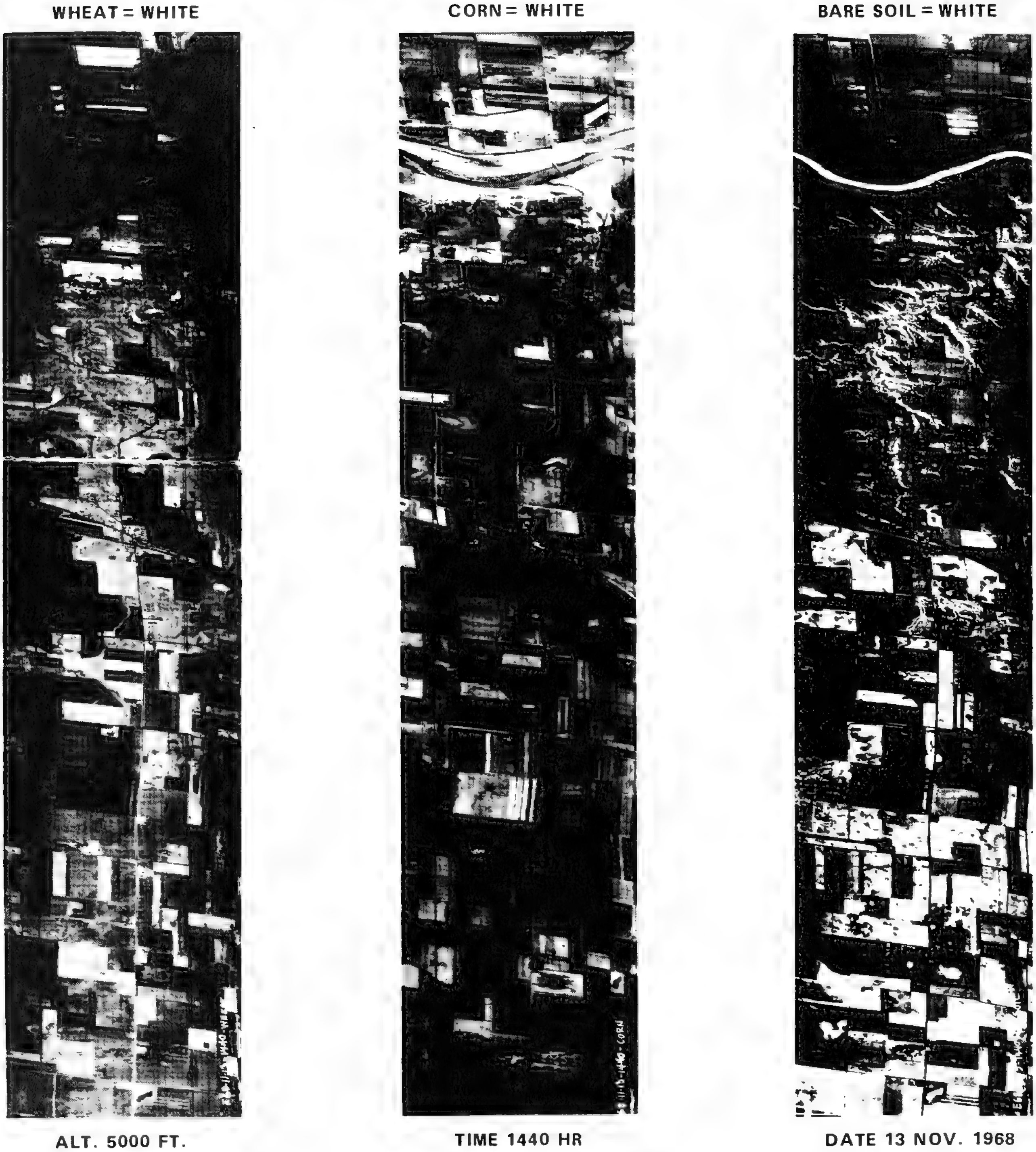


Figure 3 Regression Analysis of Agricultural Data

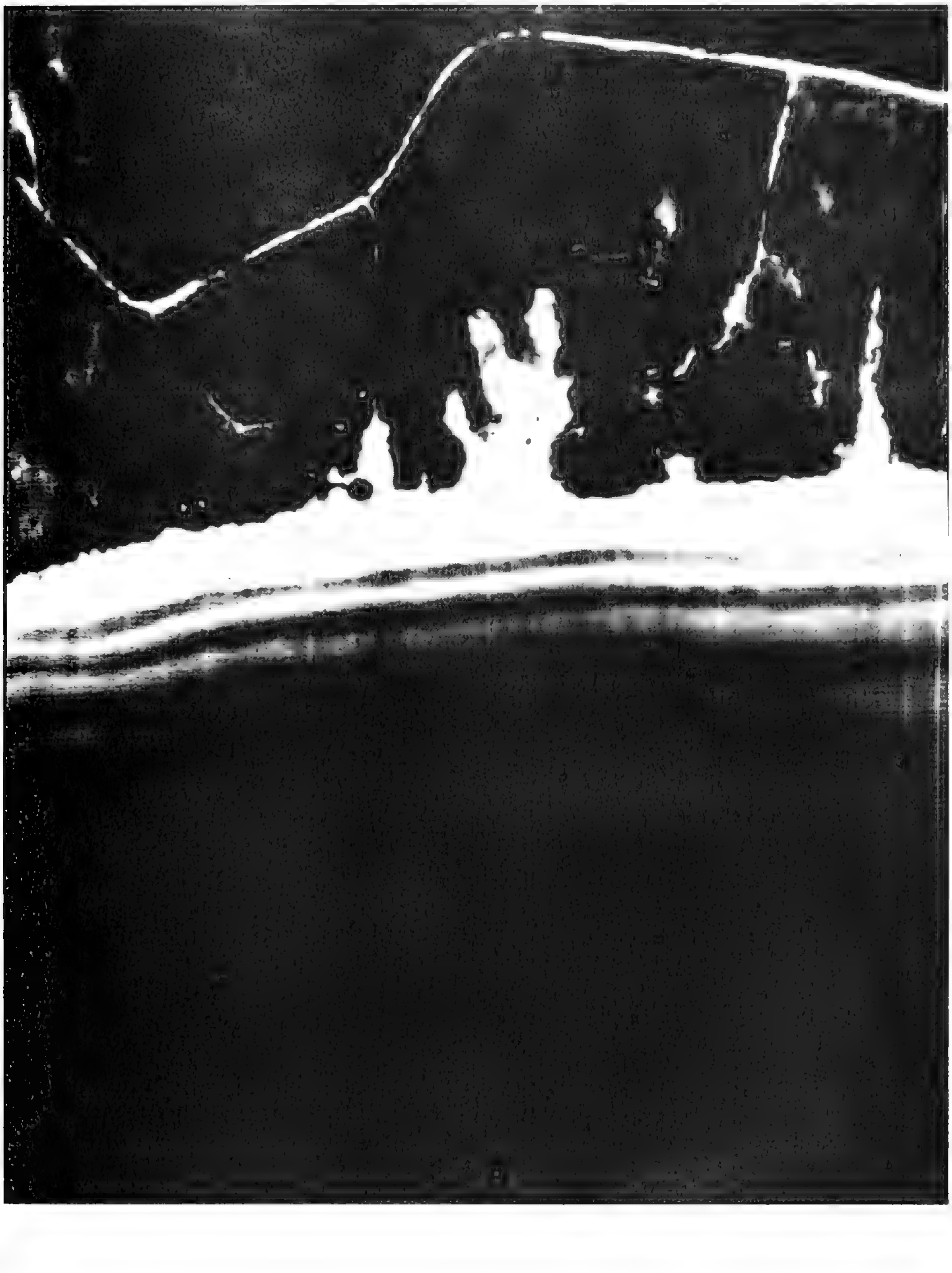


Figure 4   Sand Bars in Lake Michigan

John E. Tyler
Visibility Laboratory
Scripps Institution of Oceanography

Our group has been actively engaged in making measurements of spectral irradiance underwater for the last three or four years. We have accumulated a considerable body of data not only on radiometric data but also on other oceanic variables such as: chlorophyll concentration, primary productivity, total particulate matter, temperature profile and transmittance.

We are interested in both biological and physical aspects of radiant energy in the sea. Our data give the energy available for photosynthesis. At the same time our data quantitatively specify the optical signature available underwater for the detection of surface chlorophyll from above the water.

We now have pending two major publications; viz., a report on the results of an expedition conducted by S.C.O.R. Working Group 15, which will be published by The Office of Oceanography, UNESCO, Place de Fontenoy, Paris 7^e, France, and a monograph entitled "Measurements of Spectral Irradiance Underwater" to be published by Gordon and Breach Science Publishers, 150 Fifth Avenue, New York,New York 10011.

Morris Weinberg
Block Engineering, Inc.
19 Blackstone Street
Cambridge, Massachusetts

I have not applied remote Raman spectroscopy to the sea surface. My role at Block is in data analysis, quantitative spectral analysis, field programs, etc. Quantitative analysis is remotely possible for surfaces and gases.

OCEAN IRRADIANCE MEASUREMENTS USING AN INTERFEROMETER SPECTROMETER

Before discussing the data, I'd like to briefly familiarize the reader with the mechanism of data reduction for this experiment. The first plot shows the actual interferogram used for obtaining this example (Spectrum 20). The next plot shows an uncorrected reduction of Spectrum 20. At this point, the wavelength scale is established but the ordinate scale (spectral radiant emittance) is not yet calibrated. (NOTE: The wavelength scale obtained from the interferometer spectrometer is really linear in wave number. Therefore, in interpolating between wavelength points presented on each spectrum this fact should be incorporated). The next plot shows the actual instrument response function of the I4PM spectrometer used in the measurements. Each uncorrected spectrum is divided by this function to properly display the actual data. Note that the instrument response function is "bell shaped". Thus, we would expect the final structure in the corrected spectrum to be somewhat modified from the uncorrected data. This fact is best typified in the final, corrected spectrum in this set. The final corrected spectrum has its shape modified in addition to corrections for field-of-view, attenuation, number of scans, etc. I should be quick to make two points:

1. Every spectrometer has an instrument function and this function should be removed before attempting diagnostics with the data. The interferometer spectrometer function closely resembles that of the photomultiplier tube, alone, since there are no dispersing elements. Hence, a "smooth" function results.

2. Since instrument calibration corrections are required for quantitative spectroscopic studies, compute reduction of the data is really the most advantageous route to follow. Hence, the necessity of performing Fourier transformations on the computer in the case of this class of instruments poses no constraint since one would resort to the computer for the other corrections.

The enclosed figures contain the computer reduced spectra number's 19-26. All of these spectra were obtained in 75 seconds with attenuation factors ranging from approximately 10^5 to 10^7. As you can see, the spectrometer was hardly taxed during the experiment.

Spectra 19, 23 and 24 were taken at the surface of the water using the modified light shield basket we brought. There was no glass bottom on the basket. Hence, these three spectra measure the zero depth upwelling irradiance at Eel Pond during this time period. The measurements were taken at about an 80° depression angle looking down into the water.

Spectra 20, 21 and 22 were taken at the surface of the water. These spectra would have contributions from upwelling and reflected light. Again, the depression angle of the spectrometer was 80°.

Spectra 25 and 26 were obtained by depressing the spectrometer by about 80° and viewing the gray card. These measurements indicate the downwelling irradiance at the time of the measurements. The gray card is assumed to have 0.18 diffuse reflectivity coefficient over the spectral response of the instruments.

1. All spectra should be matched in wavelength scales when overlaying for comparison.

2. The irradiance scales on all spectra have been normalized to 9 inches. Hence, structural details between spectra can be compared readily while quantitative irradiance differences are not well obtained by direct overlay.

3. The weak structure residing on top of the broad spectra is probably noise and should be treated as such unless it has regular repeatability from spectrum to spectrum.

4. The data from 7000 Å to 8000 Å is noise dominated.

5. As a first step, the internal consistency of the experiment is best validated by comparing 25 and 26 (gray card). A direct overlay shows almost identical spectral structure versus

wavelength between these two spectra. I would estimate the signal to noise at 5500 Å to be 20/1. The irradiance varies by about a factor of 4 to 5 between these spectra. Most of this variation is probably due to cloud cover changes. I would conclude that there is a high degree of consistency in spectral structure in the resultant data. Cloud cover variation does not appear to alter spectral shape.

6. The paper by Smith and Tyler in the Journal of the Optical Society of America, <u>57</u>, 589 (1967) will be used as a guide in validating the Woods Hole experiment.

7. Our average Gray Card irradiance value at 5000 Å is 2.4×10^3 μ watts/cm^2 μ. Considering a diffuse reflectivity of the Gray Card of 0.18 we obtain a downwelling irradiance value of 1.3×10^4 μ watts/cm^2 μ. Tyler, at Crater Lake, obtained a value of 2×10^5 μ watts/cm^2 μ. I would be inclined to accept this factor of 10 difference as partially being due to differences in cloud cover (perhaps, a factor of 3) and the remaining factor of 3 or 4 as a possible error in our calibration due to the stacking of many neutral density filters. All in all, we could not have hoped for much better results in the short time period for the work. I'm very encouraged with this comparison.

8. The two absorption dips at 3900 Å and 4300 Å are real and due to actual dips in the solar spectral irradiance (see all spectra 19-26 for the intense absorption near 4000 Å).

9. The structural consistency for the Top of Water spectra is excellent (compare 20, 21 and 22).

10. The irradiance variation on 20--22 ranges over a factor of about 5. This factor compares favorably with the Gray Card data and is probably due to changing cloud cover. Therefore, I would accept this variation as being real.

11. Considering 20 as the best Top of Water spectrum and comparing with the Gray Card data (25 and 26) at 4500 Å we find an irradiance of 8.3×10^2 μ watts/cm^2 μ for 20 and an average of 3×10^3 μ watts/cm^2 μ for 25 and 26. Since the Gray Card reflectance is known as 0.18 one concludes that the reflectance at the surface of the water is 0.04. Admittedly, many meteorological changes were taking place during this time period. Nevertheless, our value of 0.04 at 4500 Å compares favorably with Tyler's value of 0.09 for Crater Lake.

12. Spectra 20--22 are "peakless". Tyler observed the same effect in his work.

13. Compare 20 and 25. Very little difference seen between Gray Card and Top of Water in structural detail.

I see no evidence of chlorophyll. Perhaps, if upwelling irradiance were subtracted from the reflected light from the surface of the water, the 6750 Å absorption would be seen.

14. The structural content in the Under Water data compare almost identically (compare 19, 23, and 24).

15. Irradiance has very slight variation in these Under Water data. The peak value changes from 36 to 52 μ watts/cm^2 μ for these spectra. I would expect a greater variation since the cloud cover changed over the time period from 1:15 to 1:45. Perhaps, we were inadvertently "shadowing" the water thus negating cloud cover changes.

16. The Under Water spectra have a definite "peak" at about 5100 Å (compare 19, 23 and 24).

17. I doubt if the irradiance values measured are truly upwelling. Tyler obtained a value of about 3 x 10^3 μ watts/cm^2 μ for zero depth upwelling irradiance at Crater Lake while we obtained about 45 μ watts/cm^2 μ on 19, 23 and 24 at 5000 Å. Either the ocean upwelling irradiance is lower by a factor of 50 or we were indeed, shadowing the irradiance (see Statement 15).

18. There is a definite strong absorption evident in the Under Water data that sets in near 5500 Å and attenuates the irradiance from 6000-7000 Å.

I certainly hope you find these spectra as interesting as we did. I think that for such a short period in which to prepare and acquire the data, we should be happy to obtain this information return.

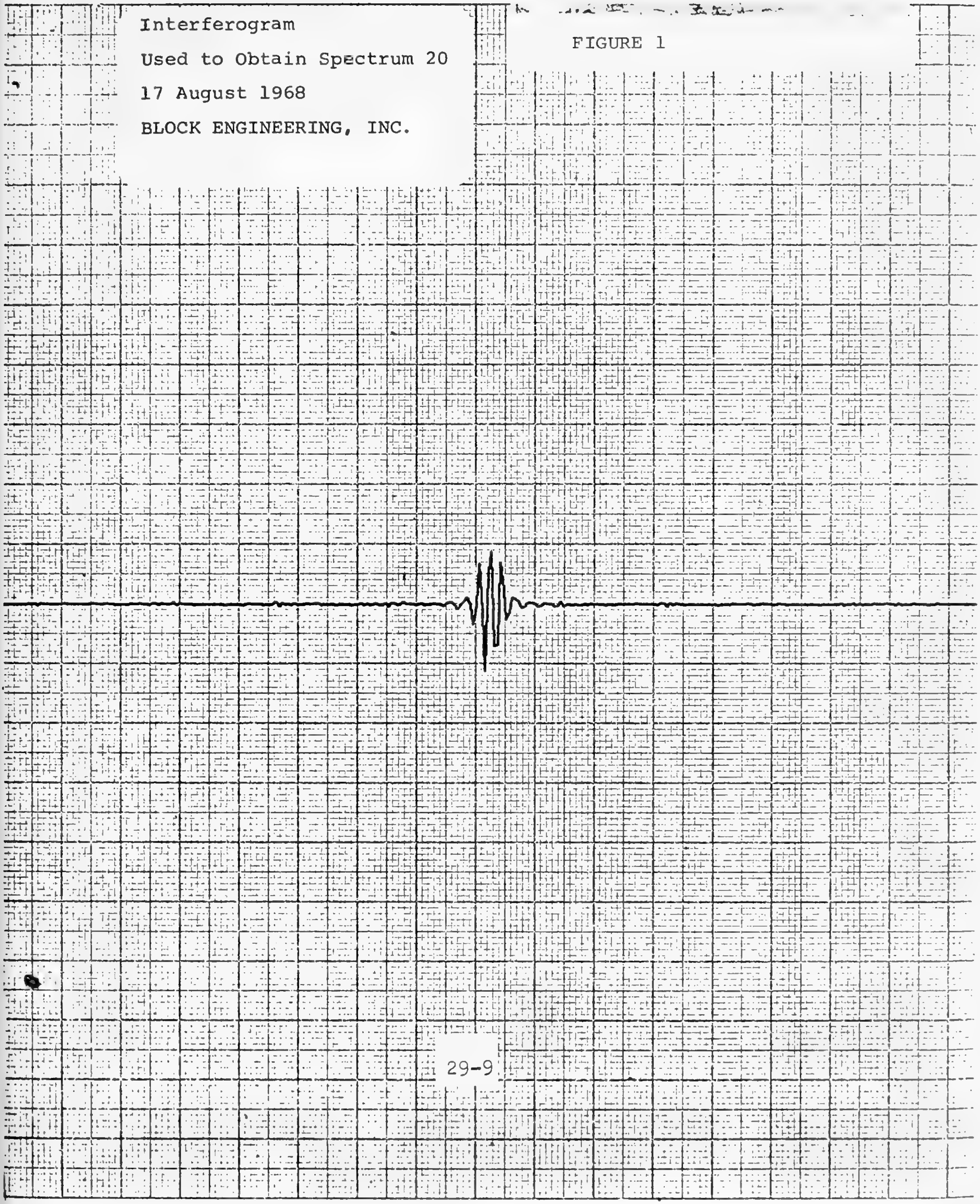
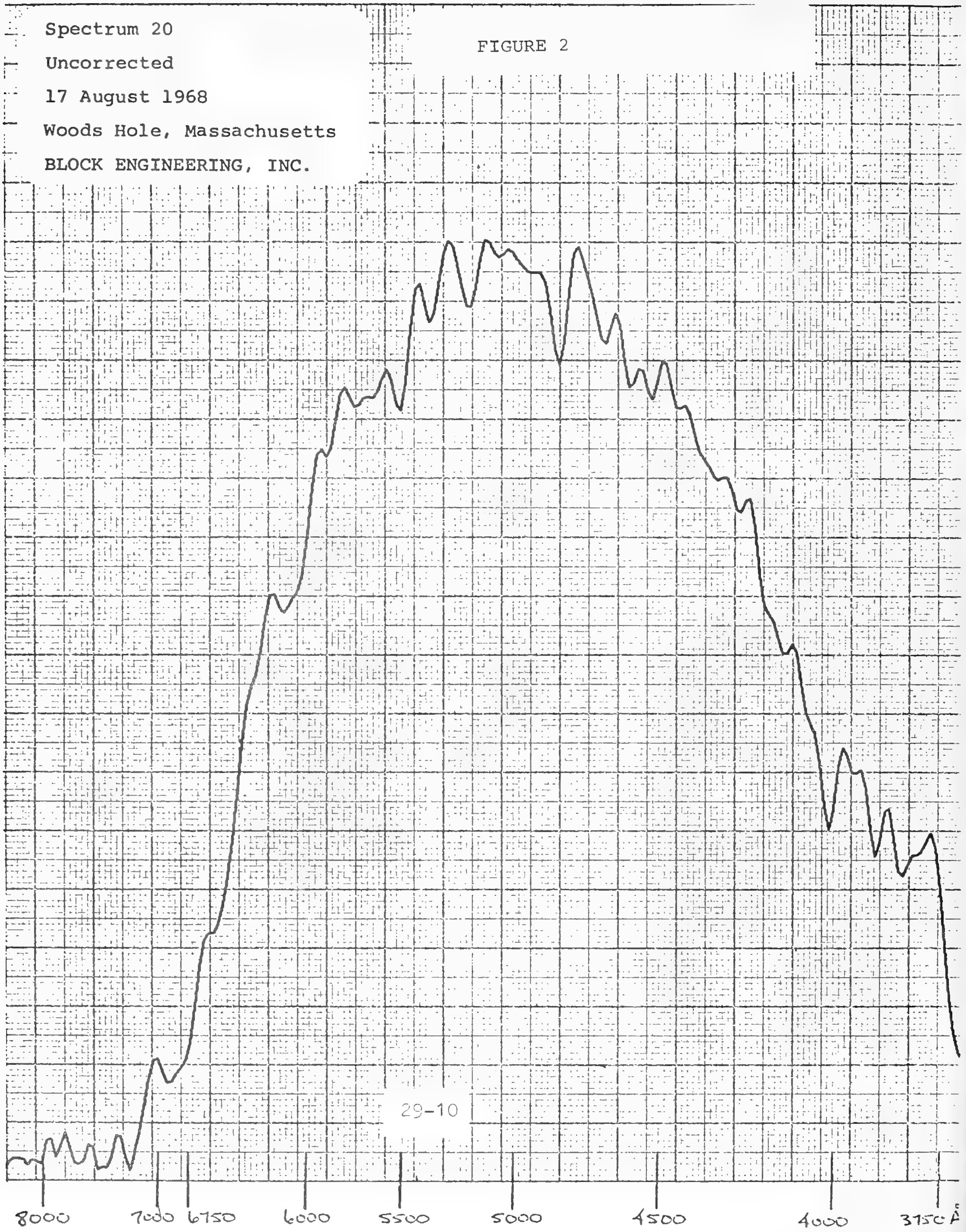


FIGURE 1

Interferogram
Used to Obtain Spectrum 20
17 August 1968
BLOCK ENGINEERING, INC.

FIGURE 2



Spectrum 20

Uncorrected

17 August 1968

Woods Hole, Massachusetts

BLOCK ENGINEERING, INC.

Spectral Response Curve
I4PM Interferometer
Spectrometer
17 August 1968
BLOCK ENGINEERING, INC.

FIGURE 3

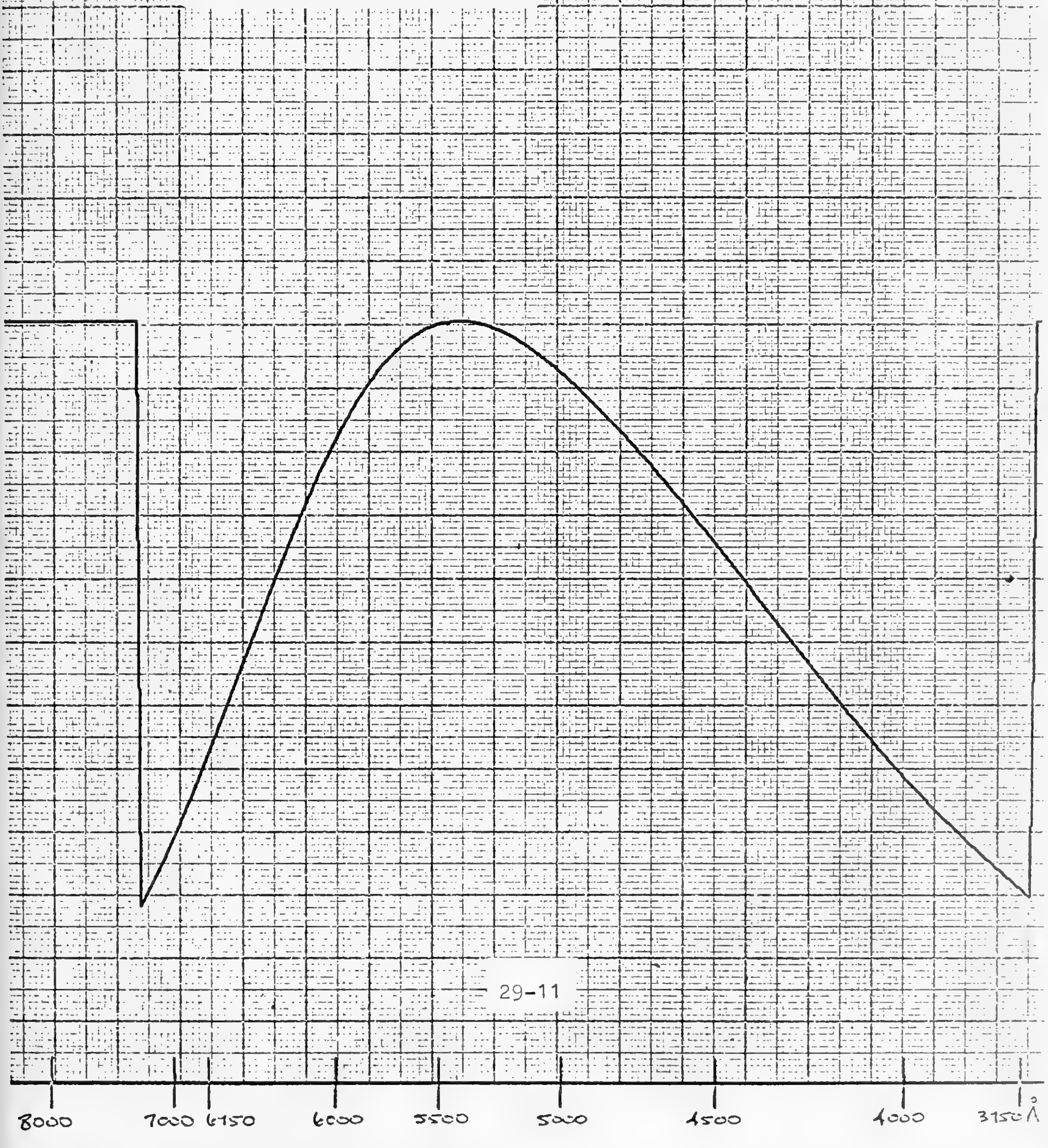


FIGURE 4

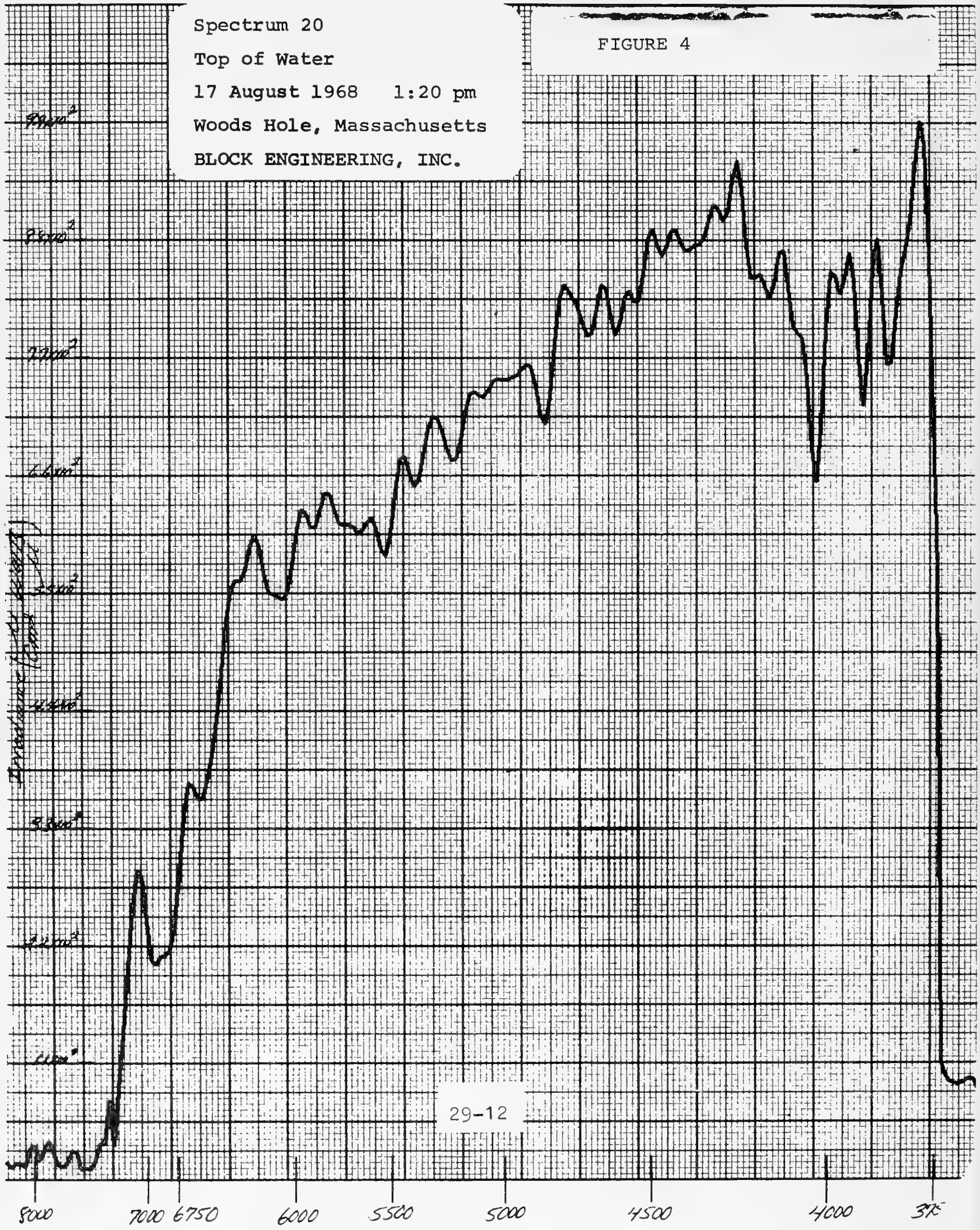

Spectrum 20
Top of Water
17 August 1968   1:20 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

FIGURE 5

Spectrum 19
Under Water
17 August 1968 1:15 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

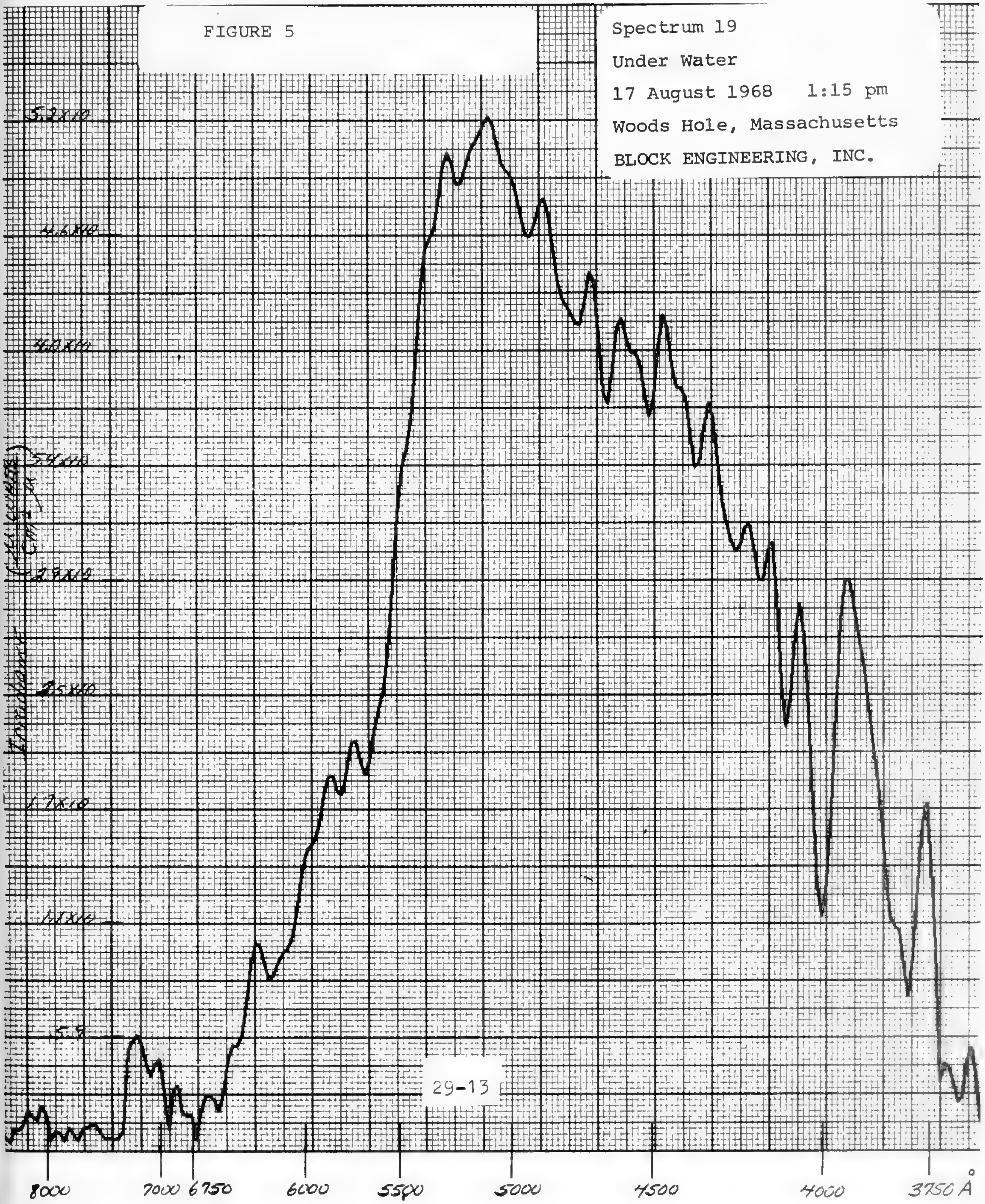


FIGURE 6

Spectrum 21
Top of Water
17 August 1968   1:30 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

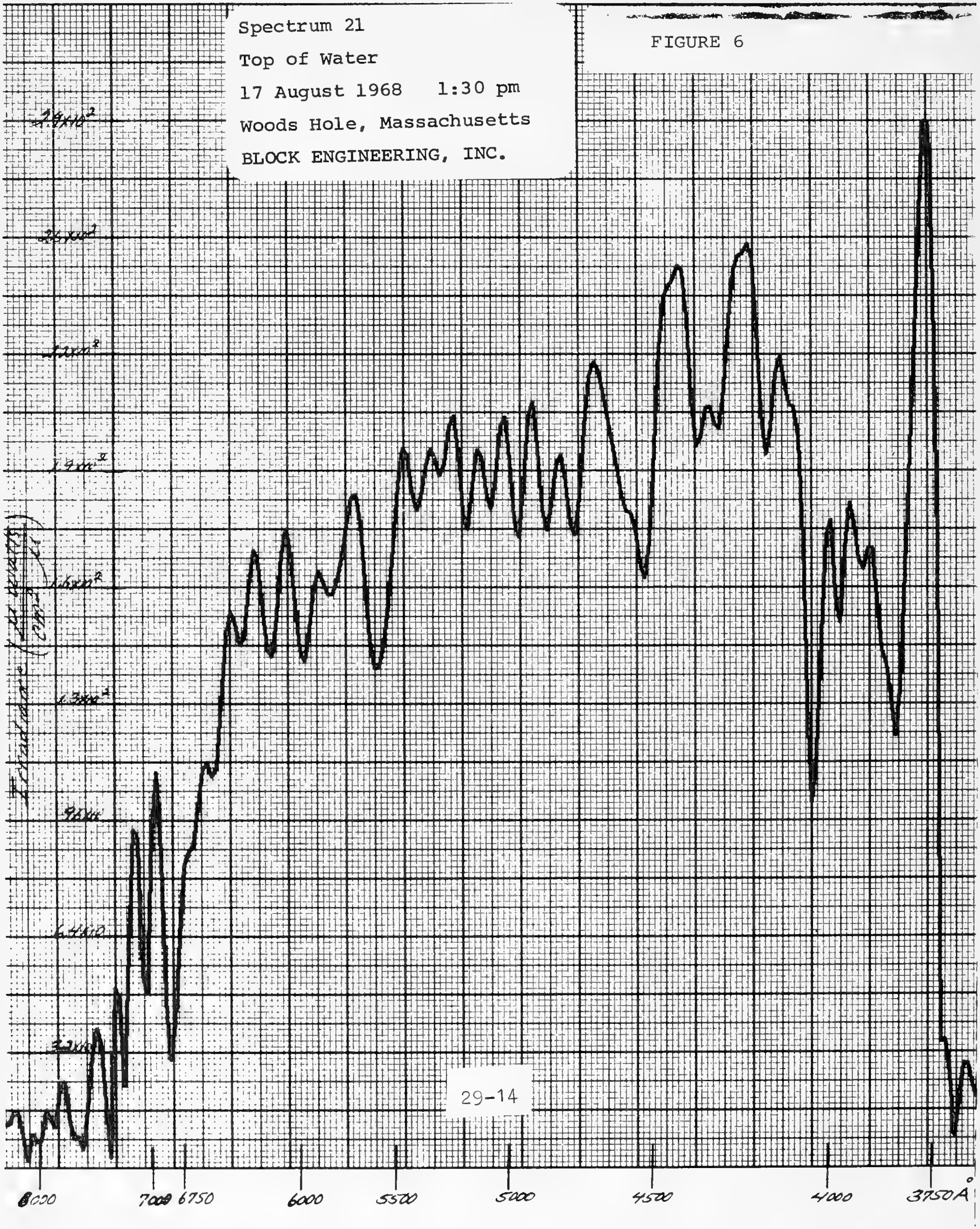
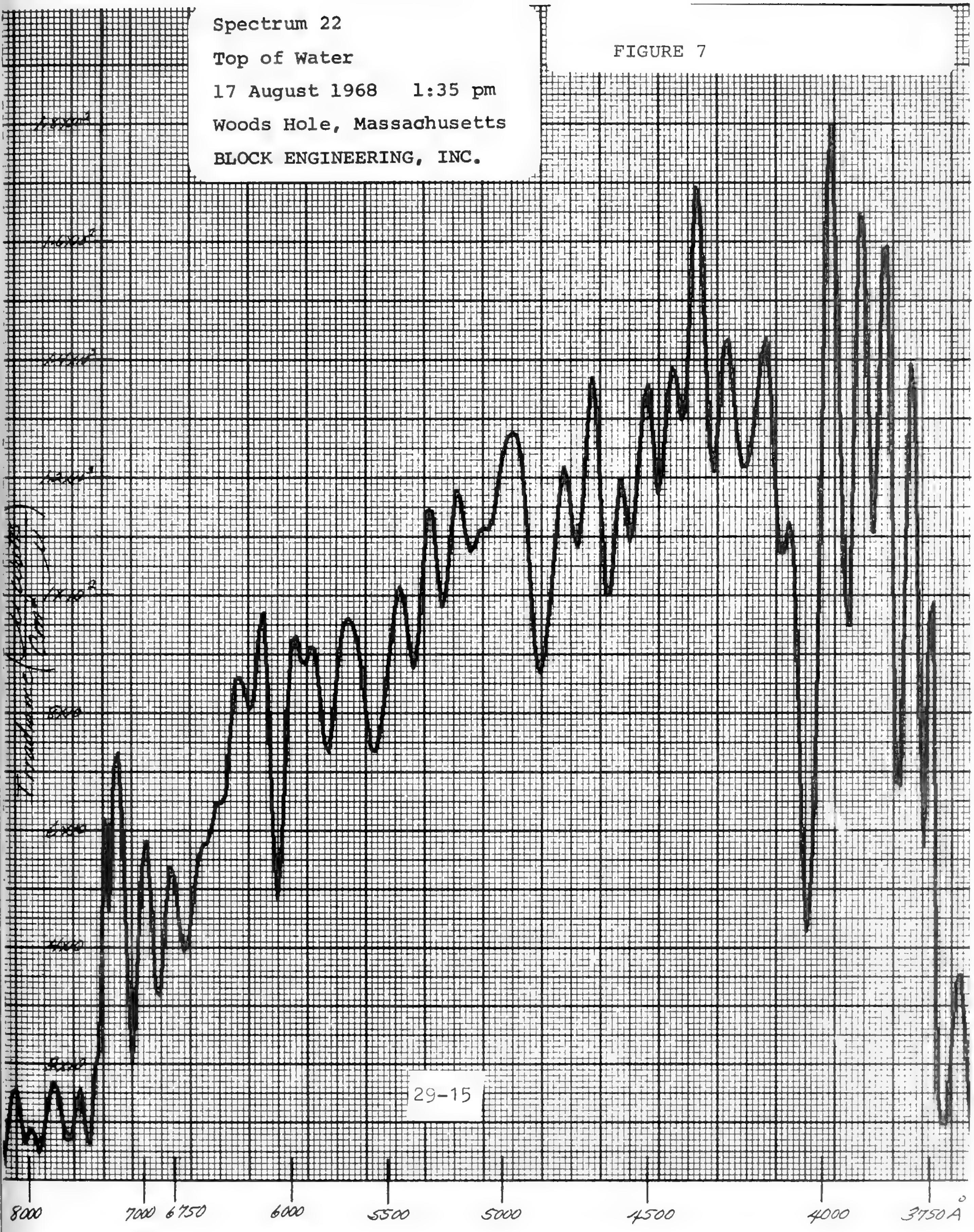


FIGURE 7



Spectrum 22
Top of Water
17 August 1968   1:35 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

29-15

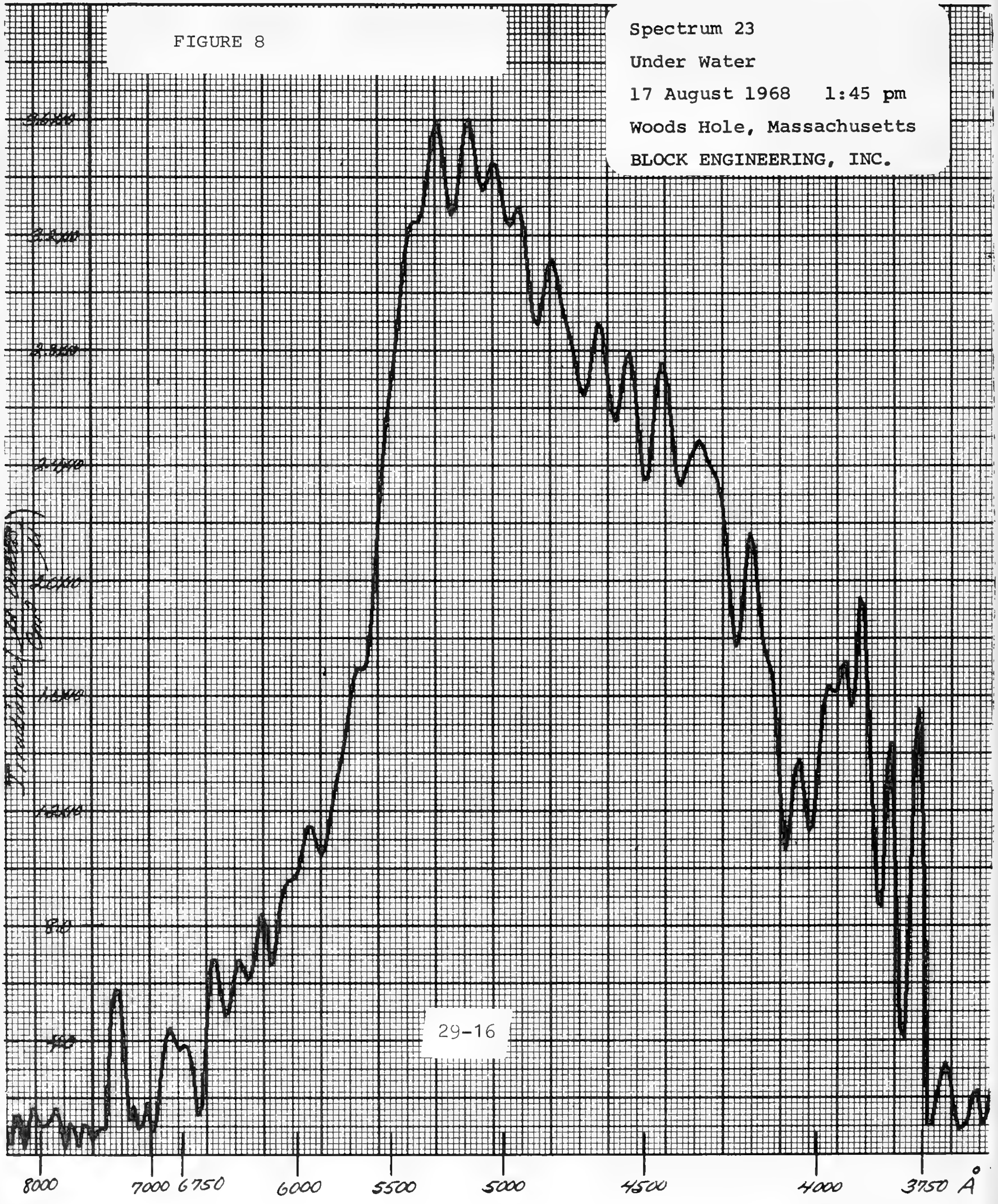
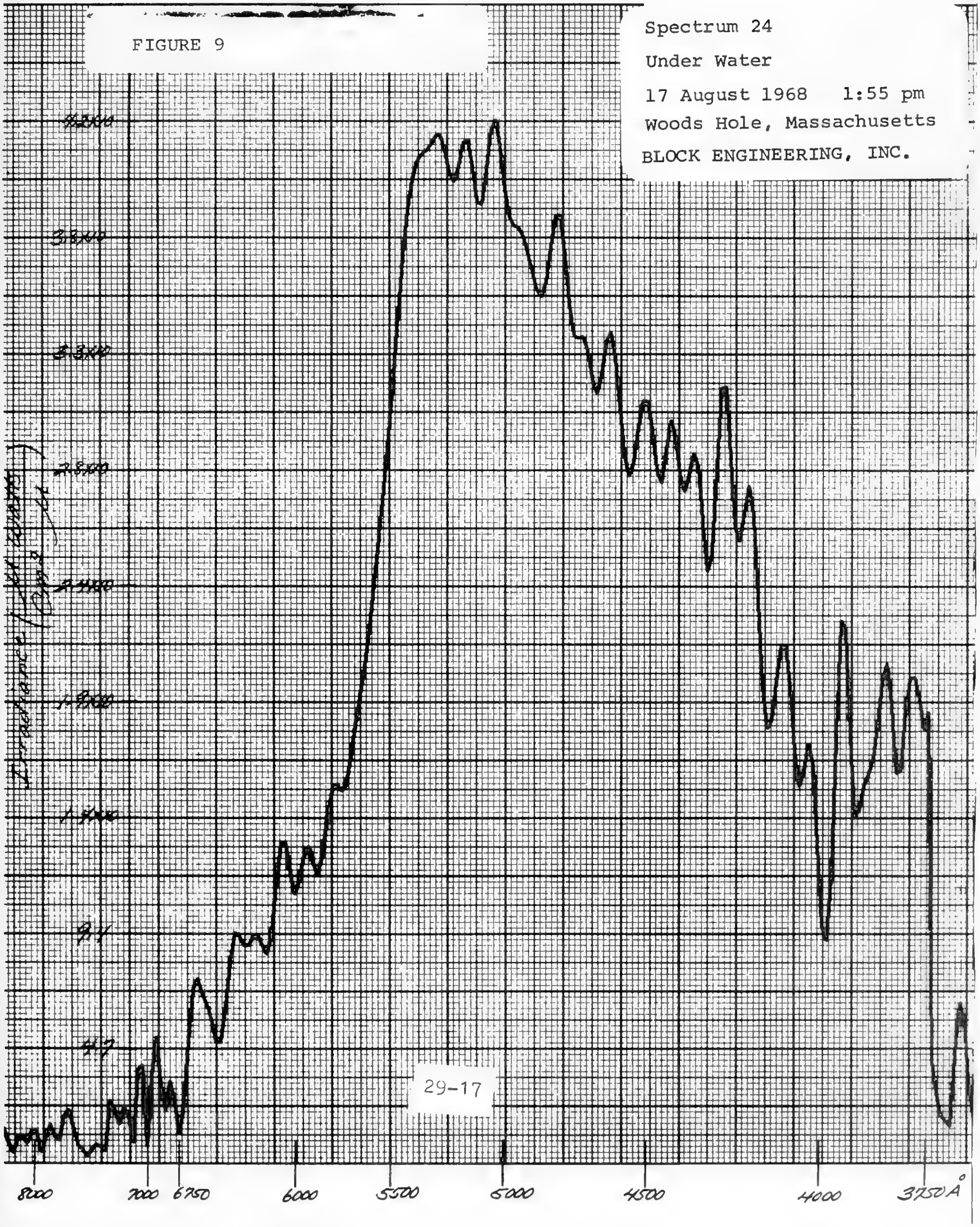


FIGURE 8

Spectrum 23
Under Water
17 August 1968   1:45 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

29-16

FIGURE 9



Spectrum 24
Under Water
17 August 1968   1:55 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

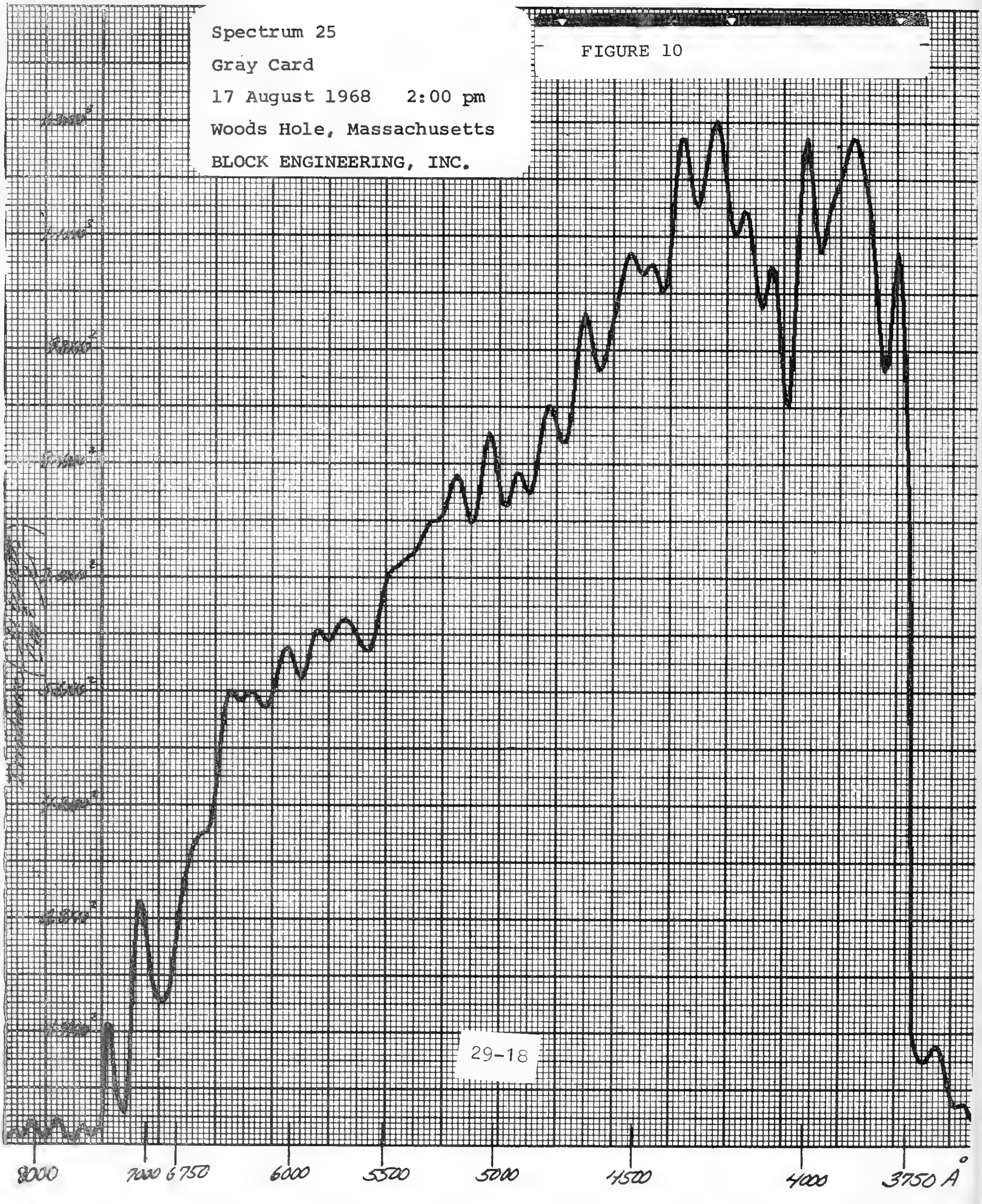


FIGURE 10

Spectrum 25
Gray Card
17 August 1968   2:00 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

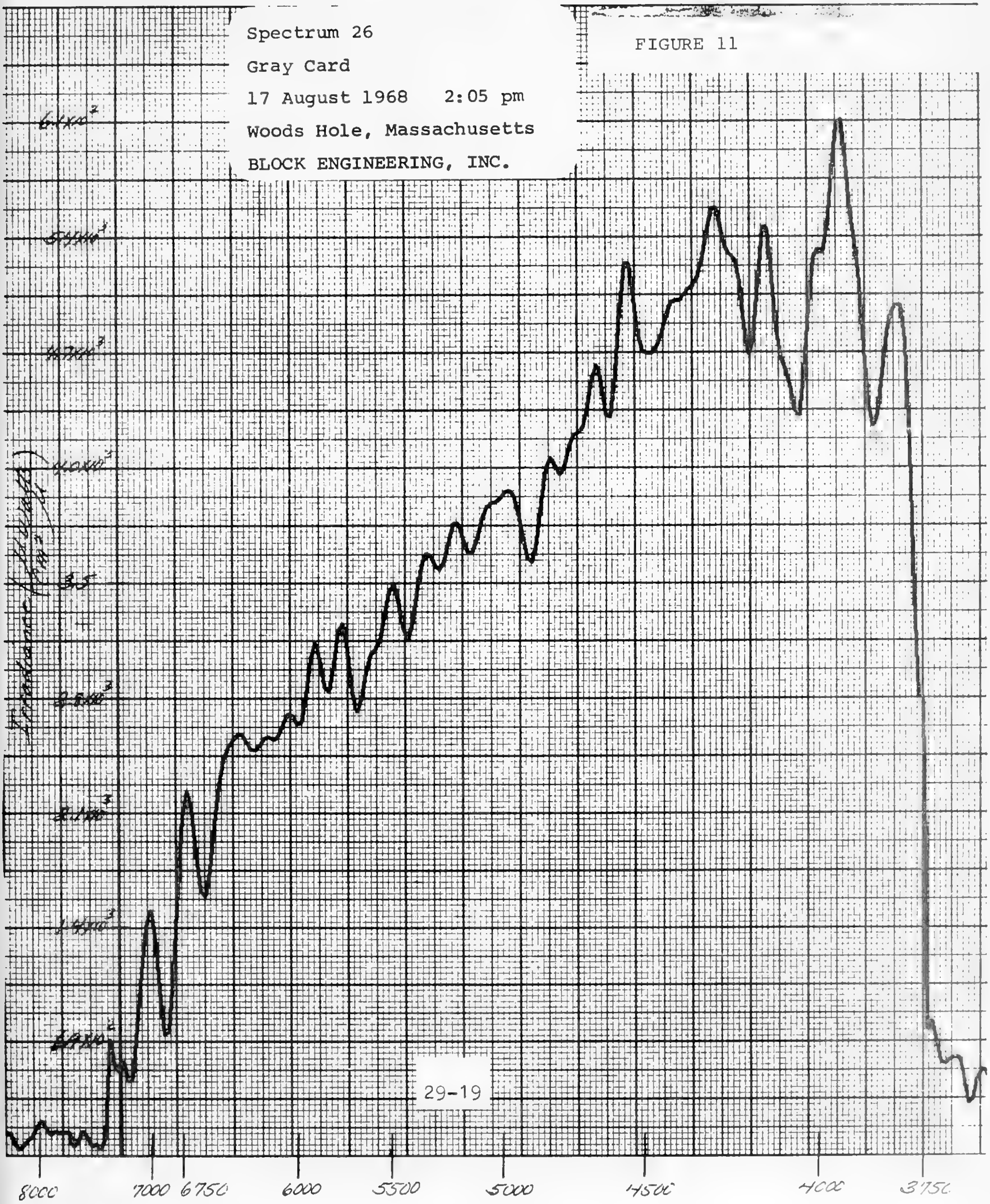

Spectrum 26
Gray Card
17 August 1968 2:05 pm
Woods Hole, Massachusetts
BLOCK ENGINEERING, INC.

FIGURE 11

Peter G. White
TRW Systems
One Space Park
Redondo Beach, California

The bulk of my activity deals with remote sensors--most for space vehicles, some for air and ground. My interest lies in ocean color, with studies beginning four years ago--studies of sensing problems, design and instrumentation specifically for ocean color measurements. Currently I am determining requirements of instrumentation for ocean color mapping systems.

Charles S. Yentsch
Physical Oceanographic Laboratory
Nova University
Fort Lauderdale, Florida

Studies in our laboratory concern photochemical events that occur in Natural Ocean waters. The principal reaction is photosynthesis; however, we are becoming aware of other reactions that are driven by light energy. In the course of these studies we have developed photographic techniques which may be of interest to this group.

To be brief, we have been able to convert three color densitometry values taken from common color film into monochromatic data (see papers by Baig and Yentsch and De Marsh in this volume). The technique depends upon establishment of a mean monochromatic curve for the images to be studied. In our case the image is the spectral absorption curve typical for marine phytoplankton. The dominance of chlorophyll α absorption in these spectra allows the establishment of a mean curve where the deviation from the mean, at certain wavelengths is quite small.

We have also examined the amount of light and its spectral characteristics, backscattered from the Bahamana Banks. These data show that the influence of bottom reflection is of prime importance to a depth of about 25 meters. Below this depth, total volume scattering from the water column is the important factor.

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A Photographic Means of Obtaining Monochromatic Spectra of Marine Algae

S. R. Baig and C. S. Yentsch

Oceanographic Center, Nova University, Fort Lauderdale, Florida 33316.
Received 16 July 1969.

There are many cases in which it is time-consuming or difficult to measure routinely the visible absorption spectra of a large number of samples. Multivariate analysis of color photographs of the samples provides a simple method by which it is possible to reconstruct the spectra once the material of interest has been spectrophotometrically calibrated. It is then only necessary to take a photograph and measure the density of the three dye layers in the film with a three-color densitometer. From these data the absorption spectrum can be generated.

The original application of characteristic vector analysis to photographic problems was made by Simonds.[1] He was able to reconstruct any one of over 100 Hurter-Driffield curves (density vs log exposure) using the mean curve of the samples and four vectors and their corresponding scalar multipliers. The mathematical technique is outlined and an example calculated in his paper.

Table I. Mean and Vectors. Linear Regression Formulas for Calculating Scalar Multiples from Log Exposure Values

λ(nm)	Mean	V_1[a]	V_2[b]	V_3[c]
400	58.1	66.34	−3.183	−14.08
410	60.5	66.93	−8.025	−7.92
420	61.8	68.33	−12.73	−4.10
430	63.0	69.75	−18.17	−0.77
440	61.9	71.17	−21.23	0.26
450	56.8	69.76	−18.11	1.398
460	53.5	68.02	−17.36	3.952
470	50.7	68.07	−14.10	5.262
480	48.8	67.66	−12.65	6.771
490	47.5	65.99	−10.67	6.281
500	42.6	63.20	−4.889	3.852
510	35.1	57.97	1.512	0.4849
520	27.4	46.12	5.981	−0.2175
530	22.8	35.43	7.205	0.1375
540	20.0	28.41	8.184	2.656
550	17.7	24.51	8.779	4.421
560	16.8	24.33	9.102	4.346
570	17.4	28.48	9.015	3.498
580	18.1	34.39	6.785	1.752
590	18.6	38.09	7.008	1.439
600	19.1	40.49	6.892	1.257
610	20.6	43.98	7.009	1.632
620	22.2	47.18	6.745	2.156
630	22.5	47.61	6.512	2.300
640	22.7	49.85	8.216	5.226
650	24.7	57.61	11.90	10.50
660	29.5	60.73	11.59	14.33
670	37.3	68.79	8.026	16.44
680	36.3	68.15	6.065	13.37
690	24.2	49.14	8.607	6.547
700	12.8	25.32	7.053	0.2942

[a] $V_1 = 0.799$ log exposure $R + 0.133$ log exposure $G + 0.832$ log exposure $B - 0.679$.

[b] $V_2 = 3.010$ log exposure $R + 1.887$ log exposure $G - 3.192$ log exposure $B + 0.596$.

[c] $V_3 = 3.625$ log exposure $R - 0.550$ log exposure $G - 2.683$ log exposure $B + 0.650$.

We have successfully applied the technique to the reconstruction of visible absorption spectra of a group of nine cultured marine algae. We filtered 50 ml of each culture onto a plain white glass-fiber filter, 25 mm in diameter. The absorption spectrum of each filtered sample was measured in a Beckman DK-1A spectrophotometer according to Yentsch's method.[2] Within 10 min a photograph was taken of each of the filtered algae. The film was Eastman 5242, Ektachrome EF, type B; illumination was by electronic flash with an 85B filter used over the 35-mm camera lens. A gray scale and a blank glass-fiber filter were also photographed for calibration and reference. The Welch Densichron was used to measure the tri-color densities. It was calibrated against a step wedge of known densities. The error in measurement was ±0.01 optical density.

From the gray scale the D log E curves are constructed for each of the three layers of the film. These provide a check on processing operations and film sensitivity (ASA speed). The 18% gray patch imaged with each filter is used to correct for inevitable variations in exposure. The first 18% gray patch is used as a standard for each roll of film. Any variations in the tri-color densities of subsequent patches are converted to log exposures. The same log exposure correction is made for the filter image. In this way all filters are reduced to the equivalent exposure.

The actual absorption spectra were subjected to characteristic vector analysis using an IBM 1130 computer. The operation in outline was as follows:

(1) Write the r optical densities of the n algal spectra in rows, one spectrum per row. The r columns are then the optical densities at 10-nm increments.

(2) Find the mean optical density of each column.

(3) Subtract the mean optical density from all of the optical densities in the corresponding column. This array is called the n-row by r-column mean corrected data matrix.[1]

(4) Prepare the transpose of the matrix generated in step 3. This new matrix has r rows and n columns. Each element $a_{n,r}$ of the step 3 matrix becomes the element $a_{r,n}$ of the transpose.

(5) Premultiply matrix 3 by matrix 4 (its transpose) to yield an r by r matrix.

(6) Calculate m eigen-vectors and -values of matrix 5. Weighing coefficients w_m are calculated by dividing each element of each vector by the corresponding root to yield an $l \times r$ matrix. Scalar multiples $y_{m,n}$ are calculated by summing the products of $w_{n,r} \times (\text{mean o.d.})_{n,r}$. The scalar multipliers indicate how much of each vector is needed to add to the mean to reconstitute any particular absorption spectrum. Table I shows the average values and the three eigenvectors for a group of algae.

The three-layer color film can be thought of as a three-channel synchronous recording device. To see if three vectors are enough to account for all the variation among samples it was only necessary to see what percent of the trace of the determinant of the above matrix was accounted for by each root. The first root accounted for 92.28%, the first two for 96.91%. No substantial improvement was observed by increasing the number beyond three, which gave a total of 98.11% for the trace.

The red, green, and blue (Wratten 92, 92, 94 filters) densities were converted to log exposure of each picture and these were regressed in turn upon each of the three corresponding scalar multiples to give a least-square fit. Examples of reconstituted spectra and their fit with the original spectra are shown in (Fig. 1. The scalar multiples for these fits are calculated from film densities.

Good fits of the actual spectra were found for most algae because of the dominance of chlorophyll a in determining the mean. It is noted that less perfect agreement is obtained in the region in which the accessory pigments, carotenoids, and chromoproteins, absorb. The over-all fit of reconstructed spectra can be

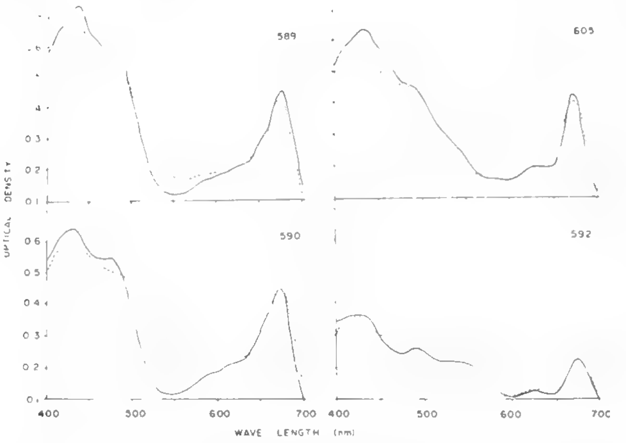

Fig. 1. Absorption spectra of four marine algae. 589 is *Nannochloris atomus;* 590 is *Aphanizamenon holsgaticum;* 592 is *Porphoridium* sp.; and 605 is *Phacodactylum tricornutum.* The solid line = measured spectra, and the dotted line = reconstituted spectra.

improved by deemphasizing the role of the accessory pigments. This can be done by increasing the step width to 20–50-nm increments in the region wherein they absorb. (Preliminary results with a much larger algal set indicate that only two vectors account for most of the variation. The 400–580-nm region was sampled in 20-nm steps. The 600–700-nm region was sampled in 5-nm steps.)

The usefulness of the method lies in its ability to produce visible absorption spectra of a large number of samples which must be examined simultaneously. The number of samples that can be examined simultaneously is only a function of film dimension and image size, the inter- and intralayer diffusion of the dyes in the film providing a lower bound to image size. Camera and lens combinations establish an upper bound to film dimension.

Subjects in which a visible change occurs with time are especially amenable to this treatment. Instead of correlating film densities of photographs of a number of different subjects, one would be dealing with varying concentrations of the same subject. Once spectrophotometrically calibrated it would not be necessary, for example, to remove the subject from a transparent enclosure. The film furthermore provides an accurate record of any visible change. An important advantage gained by the method is that the photograph can be taken in a fraction of the time needed for a spectrophotometric scan. Times of the order of 0.01 sec are usual. This permits surveillance of fast changing stationary subjects. If the scale of reproduction desired in the photograph is too large to permit a single photograph to be made, smaller areas may be photographed in a fraction of the time it would take to scan them spectrophotometrically. The photographic technique has obvious advantages and is important in aerial surveillance, since it is possible to preserve a degree of micro-variation over wider areas.

We thank LeRoy DeMarsh of Eastman Kodak Research Laboratories for his continuing assistance with this work.

This work was supported by the National Science Foundation (#GB-7088) and the Atomic Energy Commission [#AT-(401)-3845].

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1. J. L. Simonds, J. Opt. Soc. Amer. **53,** 968 (1963).
2. C. S. Yentsch, Limnol. Oceanogr. **7,** 207 (1962).

Color Film as an Abridged Spectral Radiometer

Spectral measurements are used in many research problems. Can color film be used to make these measurements? The answer is yes for some problems. In many instances the problem is not one of identifying one particular spectral curve from an infinity of possible ones. More often one is working with a fairly well-defined population of possible spectral curves. Two examples of such populations are the spectral absorbances of algae samples and the spectral distribution variations of natural daylight.

A color film measures the amount of red, green, and blue light it sees reflected from an object. These measurements, the red, green, and blue layer exposures of the film, then control the amount of cyan, magenta, and yellow dye that are formed in the layers. If we measure the spectral density curve of a film image and compare this curve with that of the original object, we usually find a poor correlation. Such a comparison is shown in Figure 1. The absorbance curve of an algae sample is shown as a dotted line, the film image as a solid line. This is obviously not the way to use a color film for a spectral measuring device, although it has been tried. A color film does not need to produce a spectral match to the objects it records. Color films do attempt to produce an image which looks like the original object.

Let's take a closer look at this film image. The film image is produced by combining three dyes. This image of an algae sample consisted of the dye amounts shown in Figure 2. All the images produced by this film are produced with various amounts of these three dyes. When I want to measure the spectral density curve of a color-film image, I do not need to use a spectrophotometer. I know that the film image contains only three dyes. I can calculate the amounts of the dyes in an image from three measurements--the red, green, and blue densities of the film sample. These analytical densitometry techniques are familiar to most photographic engineers. From the dye amounts and the spectral density curves of the individual dyes, I can compute the spectral density curve of the film sample. Thus I can construct the entire spectral density curve from three measurements

This same idea can be applied to other spectral measuring problems. The question is, "Can the population of spectral curves being studied be analyzed as though it were being produced with combinations of three or fewer components?" To be more specific, "Can the population of spectral data be matched with linear combinations of three basis curves?" Characteristic vector analysis can be used to answer this question.

Simonds[1] has described the application of characteristic vector analysis to optical response data and illustrates in detail a procedure for calculating characteristic vectors. For this analysis we first compute the average curve for the population and subtract this average curve from each of the samples in the population. An iterative procedure is then used to compute a set of basis curves or vectors. These vectors describe the variations of the population about the average. A small number of characteristic vectors can often describe a complex set of data. In the procedure described by Simonds, one computes the vectors in order of decreasing significance. That is, the first vector describes the largest part of the variation, and subsequent vectors describe smaller parts of the variability.

The question for our spectral measuring problem is, "Can the first three vectors describe our population of data with sufficient accuracy?" The average curve and the first three characteristic vectors for a population of algae curves[2] are shown in Figure 3. The values of these curves are shown plotted versus wavelength. These vectors can be thought of as the "dyes" which combine to make up the various algae spectral curves. These vectors fit the algae curves with a standard error of .03. Each of the spectral absorbance curves in the population can be matched by combining the average curve and some amount of each of the three vectors.

$$A_\lambda = Av_\lambda + Y_1 * V_{1\lambda} + Y_2 * V_{2\lambda} + Y_3 * V_{3\lambda} \qquad (1)$$

A = the spectral absorbance curve

Y_1, Y_2, Y_3 = the amounts of the vectors

$V_{1\lambda} V_{2\lambda} V_{3\lambda}$ = the characteristic vectors

The reconstruction of one of the algae curves is shown in Figure 4.

Judd, MacAdam, and Wyszecki[3] have shown that the variations which occur in natural daylight (sunlight + skylight) can be fitted with two characteristic vectors. The average curve and the first two characteristic vectors for their data are shown in Figure 5. The spectral energy distributions of 622 samples of daylight can be matched by linear combinations of these curves.

Characteristic vector analysis reduces the dimensionality of a set of data to a minimum. Each of the daylight spectral distributions can be represented by a point in a two-dimensional space. Each of the algae absorbance curves can be represented by a point in a three-dimensional space. This is illustrated in Figure 6. The coordinates of this three-dimensional space are the vector amounts Y_1-Y_2-Y_3. Three points are shown plotted in Figure 6. The locations of each of these points is determined by how much of each of the vectors are required to match that sample.

The spectral sensitivities of a color film define another three-dimensional space. The coordinates of this three-space (Figure 7) are the red, green, and blue layer exposures of the film. Each of the algae samples when photographed will result in some red, green, and blue exposure and hence can be represented by a point in this space. If we can find a transformation between these two three-dimensional spaces, then we can compute the vector scalars Y_1, Y_2, Y_3 from the film exposures R,G,B.

$$\begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix} = f \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad (2)$$

One potential problem here is a situation where two samples have different spectral curves and hence plot at different points in the vector space, but give the same film exposures. If such metamers exist, there can be no transformation between the two coordinate systems. Assuming that a transformation can be found, we can compute the vector scalars from the film exposures and then construct the spectral curve from the vector amounts-- Y_1, Y_2, Y_3 and the vectors V_1, V_2, V_3 plus the average curve Av (Eq. 1).

How can we calibrate a film to apply this procedure? First, it is necessary to obtain spectral curves of a number of samples which represent the population to be studied. The number of samples required would depend on the nature of the population.

The three characteristic vectors and the amounts of the vectors required to match each sample are calculated from these data. The film exposures can be determined in one of two ways. If all the physical data are available, we can compute the film exposures directly. Lacking the physical data, we can photograph the calibrating samples and derive the film exposures by photographic photometry as shown in Figure 8. The transformation between the two coordinate systems can then be estimated by multiple regression analysis.

The transformation between color film exposure and the algae vector space is shown in Equations 3.

$$\begin{aligned} Y_1 &= 0.7324*R + 0.2901*G + 0.7944*B - 0.6980 \\ Y_2 &= 3.4640*R + 2.4240*G - 3.6570*B + 0.7389 \\ Y_3 &= -5.5420*R + 6.8750*G + 6.3600*B - 0.6450 \end{aligned} \tag{3}$$

The algae curve shown in Figure 1 and a curve computed from film exposures is shown in Figure 9. The original curve is shown as a solid line, the reconstruction from film data as +.

The transformation between film exposures and daylight vector space is shown in Equations 4.

$$\begin{aligned} Y_1 &= -0.09202*R - 2.7300*G + 3.0370*B \\ Y_2 &= 16.100*R - 19.360*G + 6.6440*B \end{aligned} \tag{4}$$

The reconstruction of a daylight energy curve from film exposures is shown in Figure 10.

These two examples illustrate a method whereby a color film can be calibrated and used as an abridged spectral measuring device. It must be emphasized that this procedure must be used with caution. Each problem must be analyzed and specific calibrations derived for that problem. The four main requirements which must be met for the application of this procedure are listed below:

1. The population of spectral curves must be specifiable. Only curves drawn from this population can be measured.
2. Three characteristic vectors must describe the population of curves with sufficient accuracy.
3. The population of curves contains no metamers, in terms of the film spectral sensitivities.
4. A transformation between the vector space and the film exposure space can be found.

If more than three vectors are required to describe the population, a color film cannot be used. A panchromatic black-and-white film exposed through several narrow band filters could be used for more complicated systems.

Comparison of Spectral Density of a Film Image with the Obects

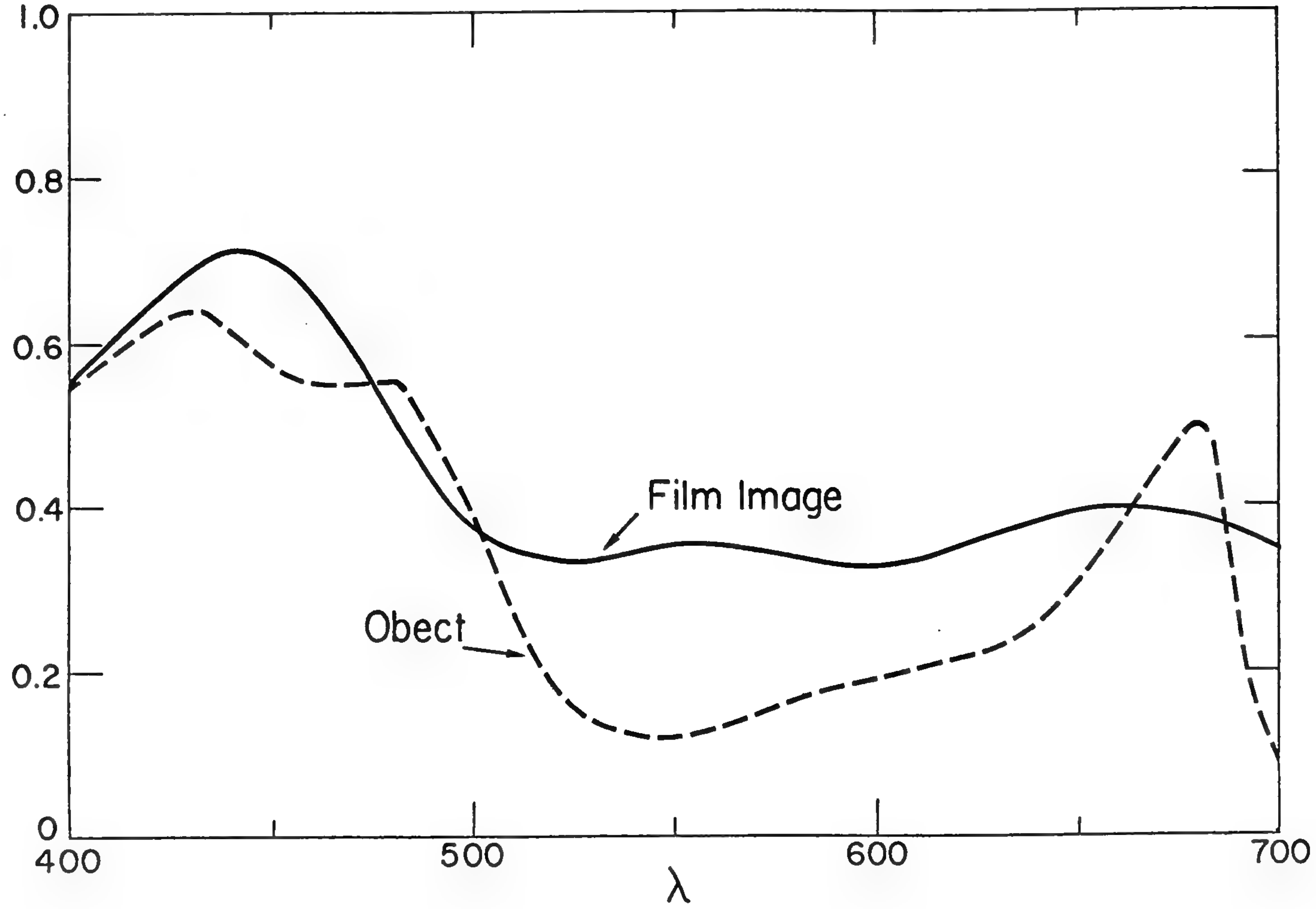


Figure 1.

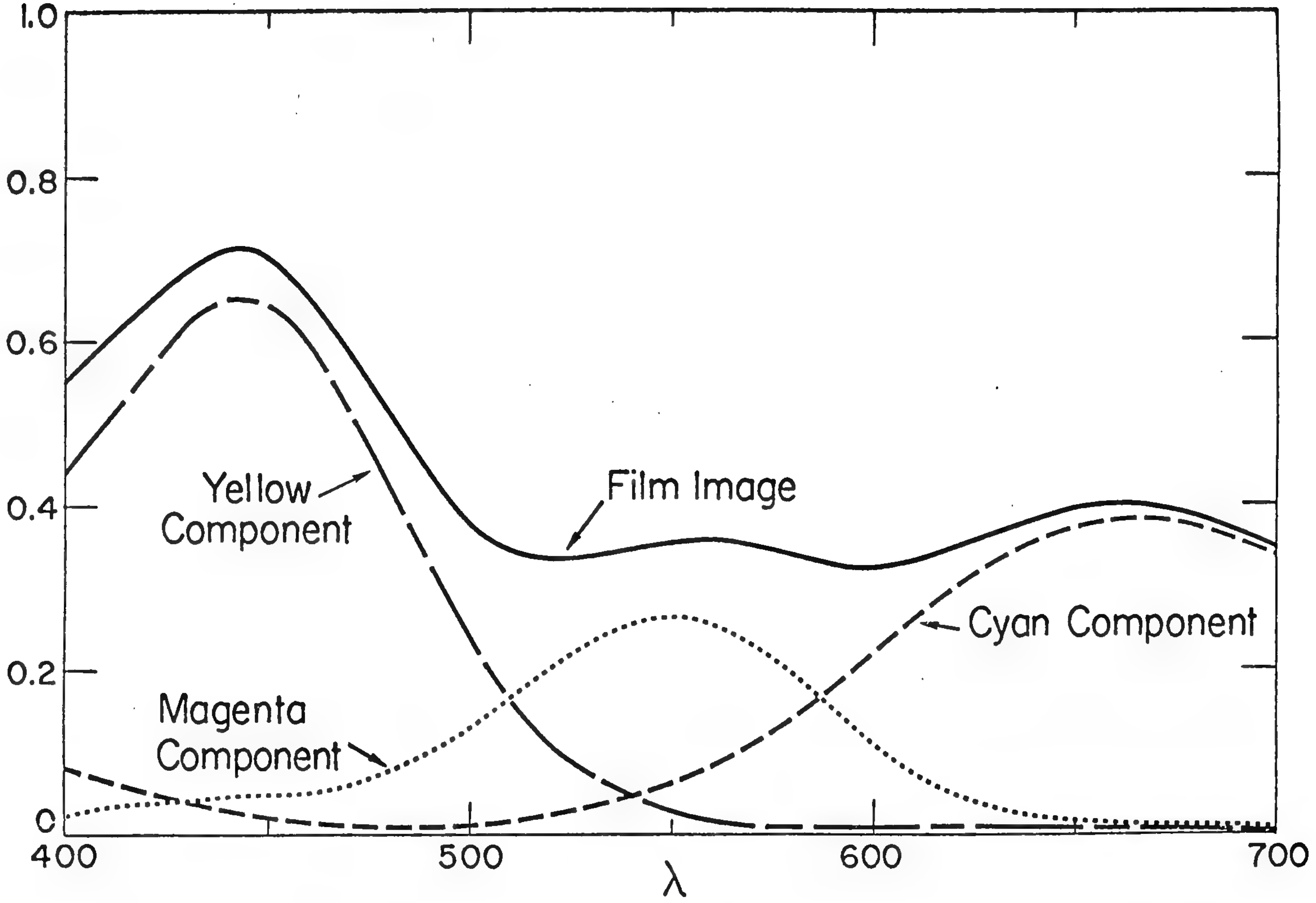

1.0
0.8
0.6
0.4
0.2
0
400
500
600
700
λ
Yellow Component
Film Image
Magenta Component
Cyan Component

Figure a.

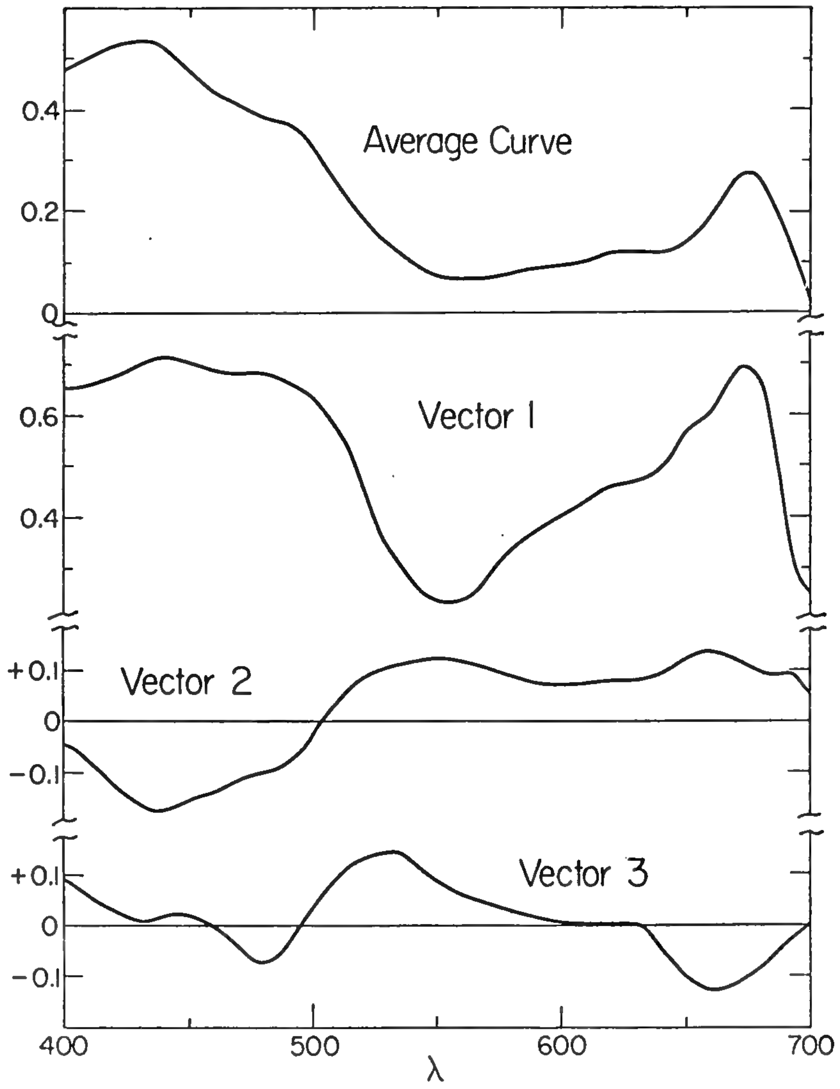

Average Curve
Vector 1
Vector 2
Vector 3
0.4
0.2
0
0.6
0.4
+0.1
0
−0.1
+0.1
0
−0.1
400
500
600
700
λ

Figure 3.

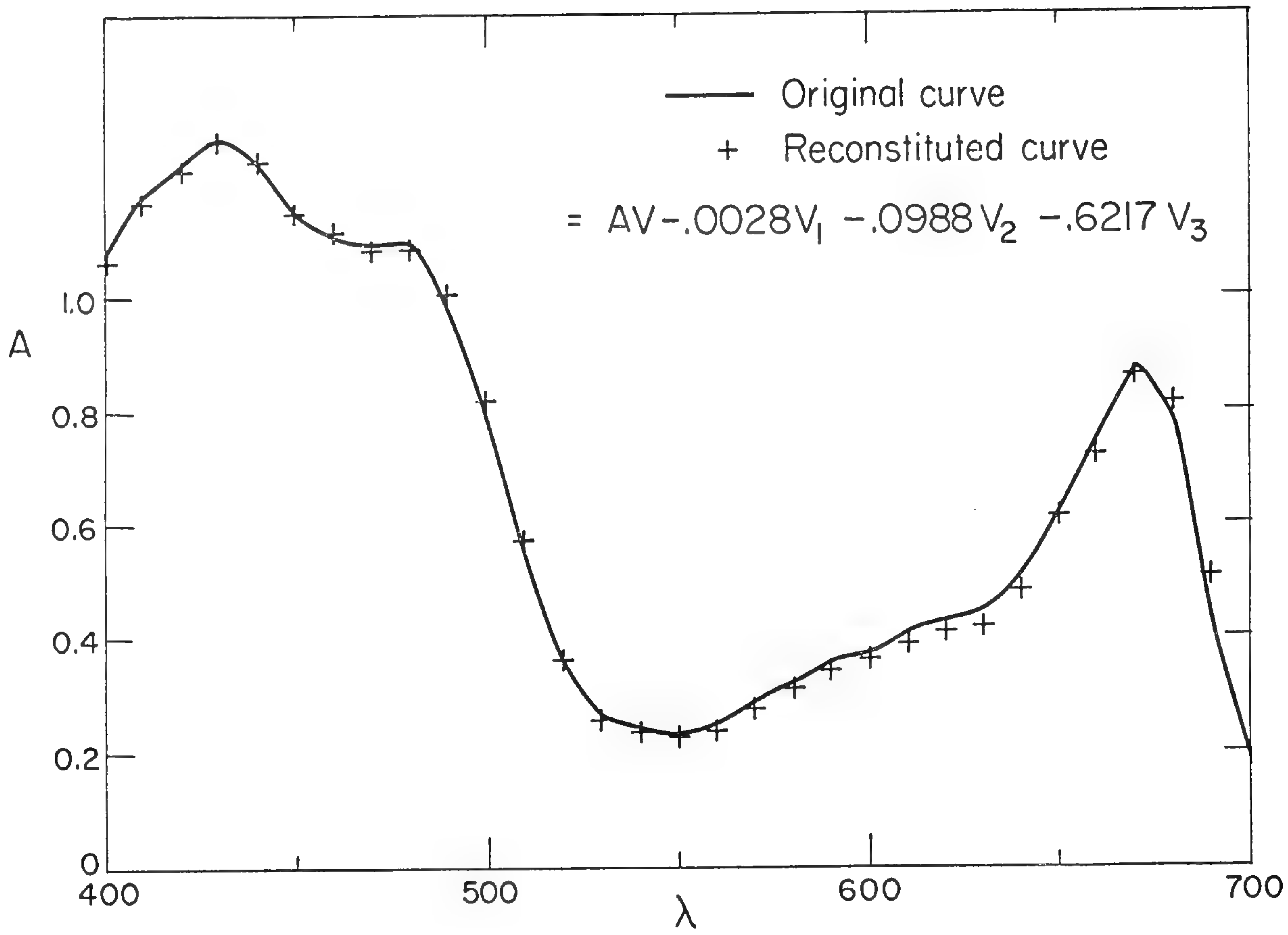

Original curve
+ Reconstituted curve
= AV-.0028V₁ -.0988 V₂ -.6217 V₃
A
1.0
0.8
0.6
0.4
0.2
0
400
500
600
700
λ

Figure 4.

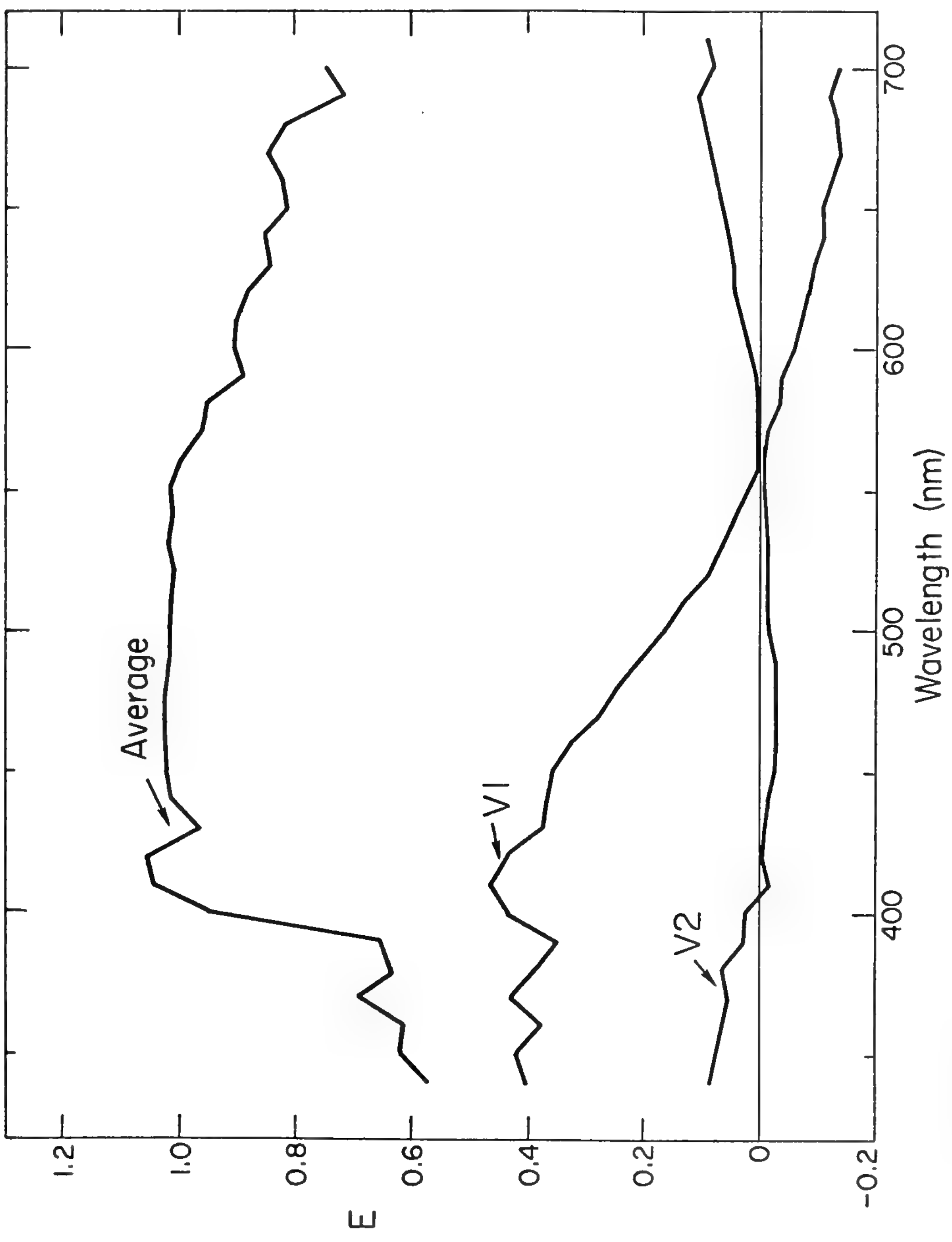

E
1.2
1.0
0.8
0.6
0.4
0.2
0
−0.2
400
500
600
700
Wavelength (nm)
Average
V1
V2

Figure 5.

Three - Dimensional Vector Space

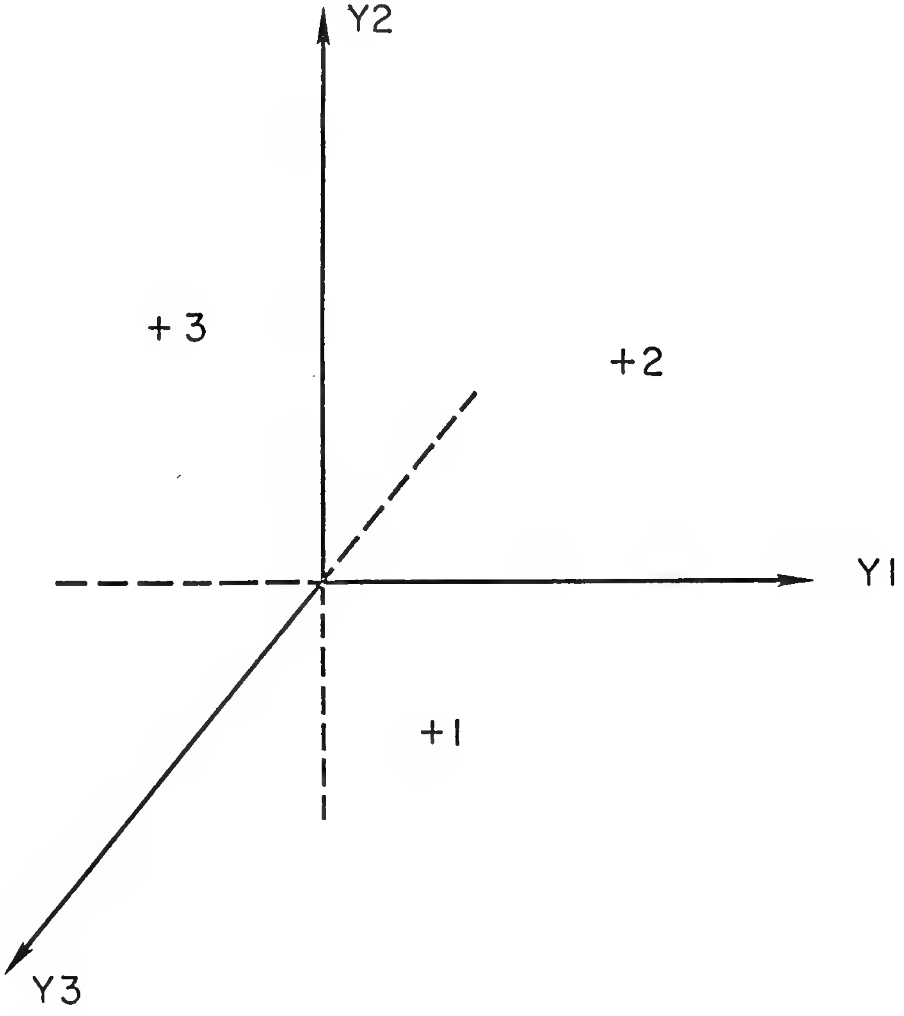
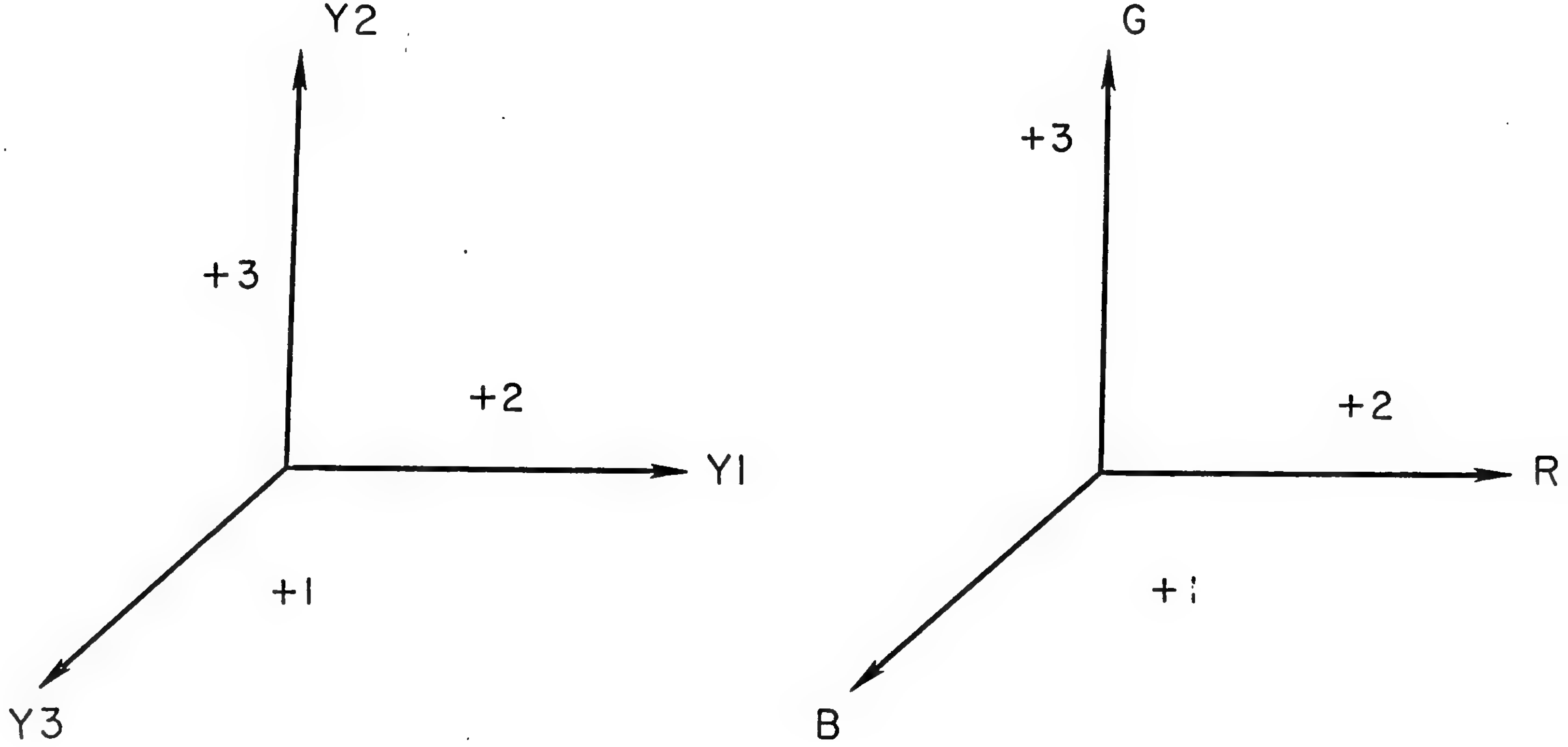


Figure 6.



Vector Space

Film Exposure Space

Figure 7.

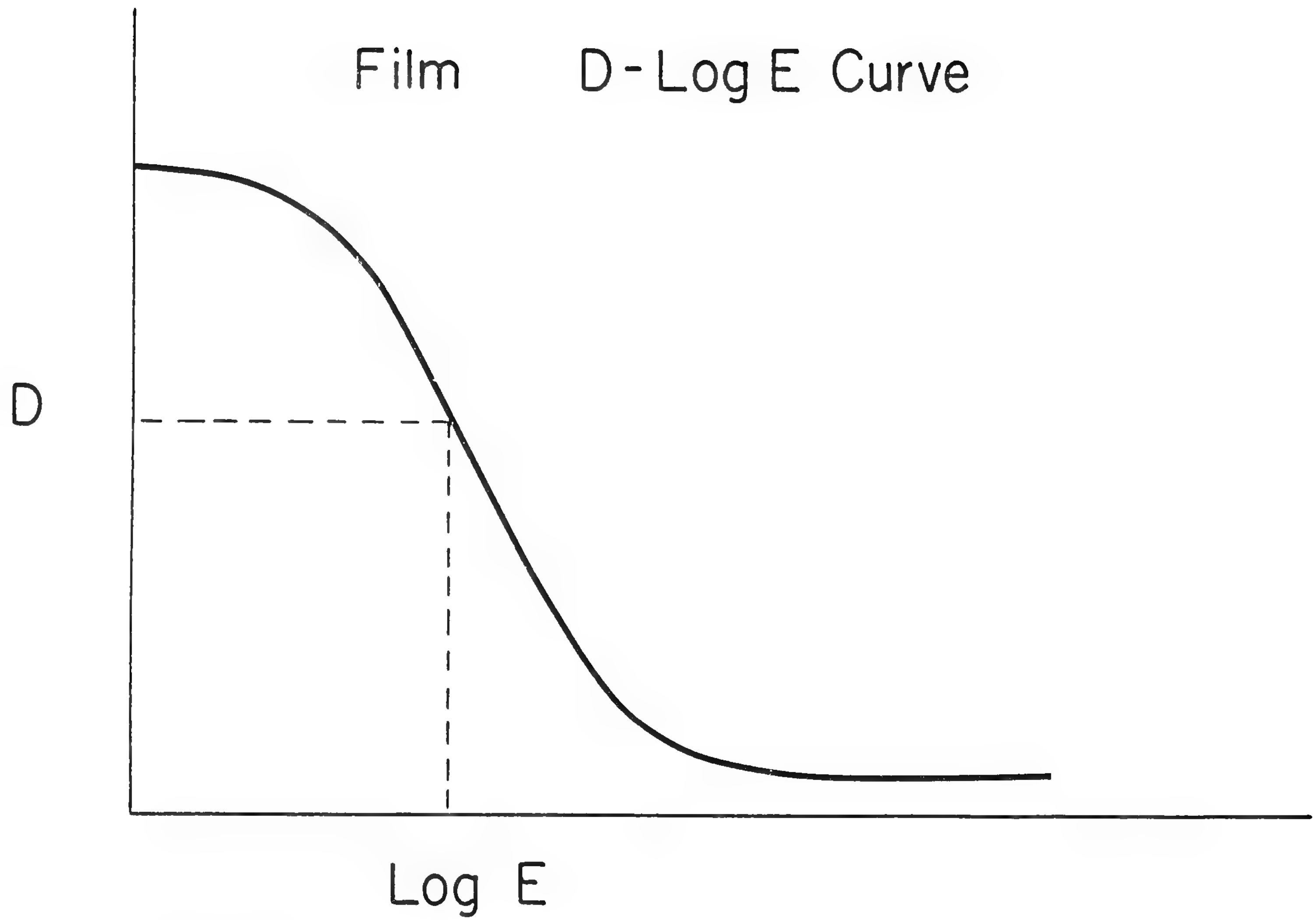
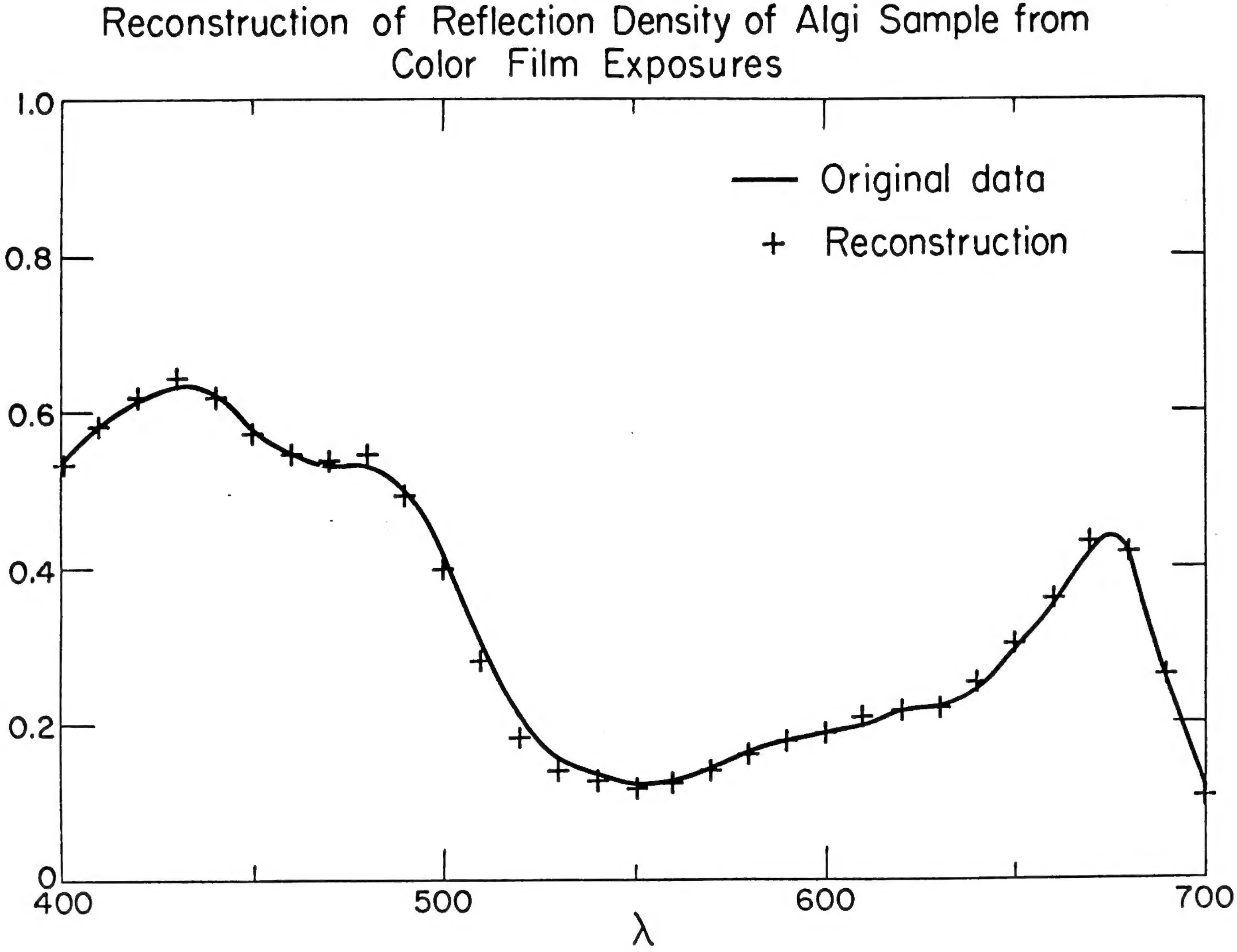


Figure 8.



Reconstruction of Reflection Density of Algi Sample from Color Film Exposures

Figure 9.

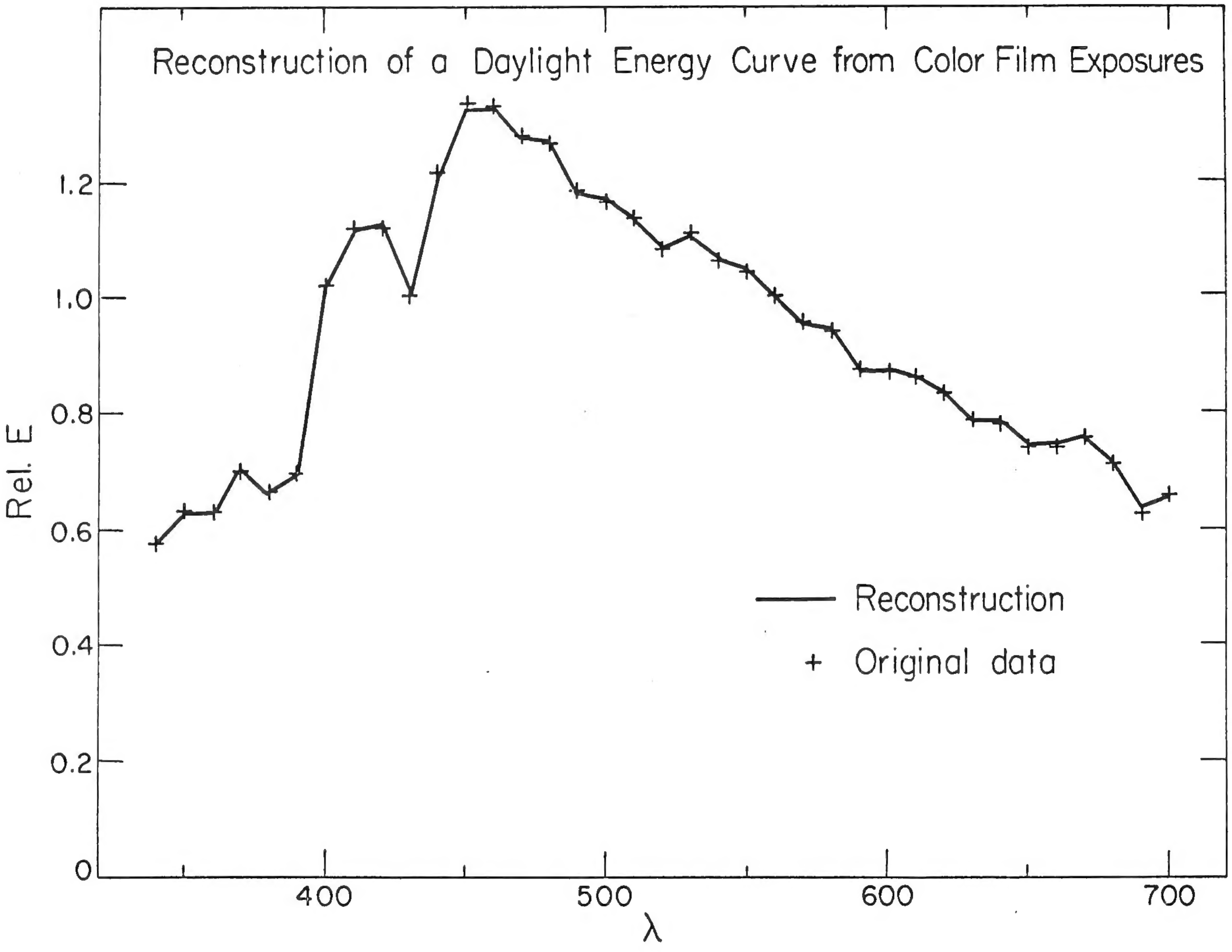

Reconstruction of a Daylight Energy Curve from Color Film Exposures

Figure 10.

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