SECTION 107

PRACTICAL UTILITY OF THE BLUE SPECTRAL REGION

by

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INTRODUCTION

Optical filters have been used in aerial photography to reduce the effects of atmospheric luminance (haze), thereby improving contrast and apparent spatial resolution in images intended for visual interpretation. Unfortunately, such filters also prevent the recording of scene radiances in the blue spectral region below 500nm.

Interpretation is, however, no longer dependent on visual methods, and many devices and techniques are now available for detecting image data which are below the threshold of visual recognition.(1)

In oceanography, information of vital scientific and economic importance is in the 400-500nm band; information on water clarity, color, biological activity, depth, bottom composition and topography, currents, sediment transport and many other features is found in the blue region.

It had been thought that atmospheric effects would completely degrade scene radiance values in blue spectral records taken from altitudes above 50,000 feet, particularly from space platforms. Gemini, Apollo and NASA/Ames U-2 photography show this is not invariably the case.

Some aspects of multispectral photography in the blue region are discussed briefly, and sample images from past and present work are submitted to demonstrate the potential utility of the blue multispectral record for oceanography.

Much of the work reported herein has been supported by past contracts with NAVOCEANO, Spacecraft Oceanography Program, and by the successor organization, NRL Remote Sensing Oceanography Project, on Contract N62306-71-C-0045.

FILTER BANDS, AND LIGHT IN AIR AND WATER

The behavior of light in air and water is a complex subject, touched on briefly here as a reminder of some salient factors affecting remote sensing of ocean subjects. Comprehensive treatments are given in references (2) and (3).

Light in the Atmosphere.- Sunlight incident on the scene, and image light reflected by it toward the camera is scattered and absorbed by atmospheric gasses and aerosols throughout the whole photographic spectrum, including the infrared. Rayleigh scattering is wavelength dependent, is worst in the blue region, and can be predicted. Mie scattering and absorption by aerosol particles which vary widely in size, mixture and concentration on a diurnal and seasonal basis, is seldom predictable, or even measureable in most operational situations. Depending on the aerosol condition, Mie effects can be as serious in the green as in the blue region. Mie scattering is normally the most important contributor to atmospheric haze, and the consequent degradation of image contrast in photography, and depressed S/N ratios in direct radiometric sensing. Limited evidence(4) suggests lower concentrations of aerosols may predominate over open ocean areas. Highest concentrations are probably worst over humid tropical forests, and are least over desert and arid landmasses. Mie scattering is usually restricted to altitudes below 50,000 feet.

In summary, image-forming light in the air is subject to spectral absorption, and scattering; and is embedded in non-image haze-light on its passage to the camera. Degrading effects vary widely in the blue and green regions, but are usually more serious in the former.

Light Transmission in the Water.- Light is attenuated and scattered in the water by process similar to those in the atmosphere, but to a much greater extent.

The water acts as an optical filter, and the spectral passband changes with turbidity. The marked difference between mean oceanic and coastal waters is shown in Figure 1. As turbidity increases attenuation rises sharply and peak transmission shifts toward the longer-wavelength green or yellow region.

Light from the Water.- Where turbidity and scattered light in the water are sufficient to deny deep penetration, the spectrum of light from the water can often be associated with and form part of water color assessment, sediment transporting mechanisms, flow and discharge patterns, upwelling, biological activity and similar phenomena; in this case scattered light can provide useful information.

A calm water surface reflects about 3 to 6% of the diffuse skylight toward the camera at sun altitudes of 30° or above, throughout the visible spectrum. Waves complicate the situation, and also optically refract subsurface detail; hardly of consequence in small-scale imagery.

To recapitulate, light from the subsurface is characterized by low radiance levels viewed through surface effects which lessen an already low subject contrast. The spectral window in average clear water is in the 450-470nm region, and in more turbid water around 530-550nm.

Filter Bands.- Practical experience has shown that red filters which block light below 600nm limit subsurface photographic penetration to a few feet. Useful penetration is obtained in the green region, and filters which transmit in the 500-570nm band are optimum. Light admitted in the 580-600 nm band dilutes green chromatic contrast in additive color analysis by adding yellow, and should be excluded.

Relating these practical considerations to Figure 1, the attenuation coefficients for coastal and ocean waters at 570nm in the green are nominally 0.0032 and 0.001, respectively on the scale illustrated. The same orders of attenuation are found at 490nm for coastal, and 410nm for oceanic waters. A green record acquired in the 500-570nm band would thus be optimum for both water types.

If the same attenuation factors are used to select an equivalent blue band between 400 and 500nm, little if any penetration could be expected in coastal water, but would be at a maximum in clear water between 410 and 500nm, with a peak near 460nm, where the worst atmospheric effects occur.

Lepley(5) analyzed large amounts of Secchi disk data on worldwide coastal water clarity available at the Naval Oceanographic Office and estimated the following:

Percent Transmission per Meter	Secchi Depth	Percentage of World Coastlines
0 - 70%	0 - 5m	15%
70% - 92%	5 - 20m	50%
More than 92%	Over 20m	35%
(More than 95%	Over 30m	10%)

Thus, a large percentage of coastal waters appear to have significant transmission in the blue region.

In any case, where a synoptic image may include 10,000 square miles of ocean, many water classes will be found, and a blue spectral record is required if water color assessment is to be attempted.

NATURAL COLOR AND MULTISPECTRAL OCEAN PHOTOGRAPHY

In view of the behavior of light in the water and air, it would seem doubtful that a useable image for oceanography could be obtained in the blue band. However, there are available hundreds of images taken from space and from high altitude aircraft in NASA files which permit an evaluation of feasibility.

Gemini and Apollo Photography.- Many 70mm images of ocean subjects were made with natural color film on these missions. Figure 2 shows color sensitivity curves for a typical Kodak Ektachrome film and the spectral transmission of a lens of the type used. On some, but not all, missions haze filters were used. These do not substantially reduce the blue passband below 400nm; only the transmission. For example, Wratten haze filters HF-3 and HF-5 combined permit 10%T at 400nm, 40%T at 430nm and 60%T at 490nm. The sensitivity of the blue layer in the color films integrated with lens and filter transmission factors thus permitted a peak response at 430-450nm in the Gemini and Apollo photography, where the worst effects of atmospheric haze should occur.

While natural color film does not record spectral information as accurately as is possible with multispectral systems, its response in the blue, green and red regions can each be separated in the laboratory by simple methods to determine relative spectral scene brightnesses.

Color Separation of Images.- The information potential of the blue spectral region in remote ocean sensing was first reported in 1967(6). A third generation Gemini V image of the Tongue of the Ocean was color-separated by narrow-band interference filters and control sensitometry, using cloud as the density reference. The photograph is an oblique, taken through more than one air mass. The center of the image is about 140 nautical miles from the camera, and maximum haze effects could be anticipated. Four bands were extracted and were reproduced at the same gamma in Figures 3A (450nm), 3B (500nm), 3C (550nm) and 3D (650nm).

The original separations show that better clear water penetration is obtained at 450nm than at 500nm, and at 500nm than at 550nm, while in the 650nm record only the shallowest or above-water features remain. This is consistent with the known spectral transmission of clear water of this kind, as shown in Figure 1. Also, as expected, the visual contrast is least in the blue and improves with each longer wavelength spectral separation.

The most important point is that, as Figure 3A clearly demonstrates, a great deal of subsurface information was recorded in the blue-sensitive layer of the colorfilm, through the atmosphere. Since 1967, dozens of other ocean images taken from space have been color-separated and similar results have been obtained in the blue band. A few enlarged images are illustrated in Figures 4, 5, and 6.

NASA/Ames U-2 Multispectral Photography.- During 1971, in support of NASA/Ames earth resources photographic operations, an I^2S Mark I Multispectral Camera was flown at 65,000 feet in a U-2 on several occasions over California coastal waters. Considerable haze is normally found in this area. The black-and-white Wratten filter spectral bands were 47B-blue, 57A-green, 25-red, and 88A-infrared. A set of these images is shown in Figure 7. The dominant wavelength of the blue filter is 449.4nm for daylight.

The gammas of the original blue, green and red images are matched within a 1.60 - 1.70 range, preserving the relative scene brightness ratios between the three spectral bands, as received at the camera station. Non-image-forming light in the atmosphere has veiled the blue record, and reduced the contrast of detail to the point where visual interpretation is difficult; this has been rectified in Figure 8 by increasing reproduction contrast to show variations in water radiance which the image actually contains.

Image Pre-Processing. As atmospheric effects seriously reduce ocean scene contrast in the blue and green bands, it is usually necessary to "enhance" the images for maximum utilization during analysis, whether this be by visual, electronic or photographic density-slicing, additive color or other methods now available. The simplest means of pre-processing is to reproduce the image at higher contrast on photographic materials used in process line copy work. A tone reproduction cycle of this kind is shown in Figure 9.

At the lower right (A) the sensitometric spectral response of the blue layer in a positive color transparency has been plotted from a NASA/MSC control tablet. The density positions of two points of interest, shallow and deep water as measured in the image, are noted on the curve, the difference being 0.22. In the first stage of contrast enhancement, the blue image was color-separated from the original on a process film (B) and the density difference between the two water areas was increased to 0.80. The separation negative was then reproduced, again on high-contrast film, to provide a workprint in which the 0.22 density difference of the original is now 1.77; or eight times as great. Density differences as small as 0.01 have become 0.08, and more readily detectible for any method of analysis.(C)

The original film recorded this part of the scene at a gamma of 2.0, that is at twice the scene contrast apparent at the camera station. The workprint has an effective scene gamma of 16.0.(D)

Contrast and Haze: Haze affects the recording of low scene radiances more than higher values with all sensors, causing non-linear distortions in the reproduction(7). While this cannot be corrected unless haze factors are known accurately, increasing contrast in the photographic image in effect improves the ratio significantly between the background noise (haze) and the low radiance levels common in ocean photography.

BLUE SPECTRAL IMAGE ANALYSIS

It is not the purpose of this paper to detail the many specific ways in which a blue spectral record contributes to the analysis of ocean phenomena, but only to show that it is possible to obtain useful imagery in this region from orbital altitudes. Interpretation is a matter for the oceanographer. However, a few practical applications are discussed below.

Water Color Assessment.- The color of water is a key indicator to many ocean phenomena and energy processes. Clear water, barren of biota and inert suspended material, appears deep blue; the degree to which color shifts toward the green indicates an increasing content of plankton, sediment or similar materials. Apparent color may vary with the type of bottom and water depth, mixing of water masses and many other causes. A blue spectral record, which by various methods can be compared with the green record, is required for assessing water color (In coastal waters a red record is also needed for determining the red and brown contributions from estuaries and rivers).

Although the blue image may not be a faithful linear representation of scene radiances, accuracy is not essential if differences between the blue and green bands can be detected; these indicate variations in the water mass from whatever source. In small-scale images, many areas of color variation can be detected rapidly by additive color viewing with high-contrast images. The degree of contrast enhancement depends on the quality of the original, and no set rule can be offered; but contrast should be sufficient for accentuating chromatic differences. The green image suffers from atmospheric distortion effects less than the blue, and usually can be reproduced at a lower contrast.

In additive viewing, false color modes aid detection of color changes. The green record can be projected as red and the blue as blue or green as shown in Figure 10, to more clearly show the patterns of water color change for qualitative evaluation.

Image digitizing and computer processing promise methods for improved quantitative analysis of the blue-green color ratios where atmospheric radiance corrections can be applied from models or direct measurements.

Bathymetry.- In areas of clear water and homogeneously reflecting bottom, water depth contours which agree with hydrographic charts have been derived from space photographs by density-slicing techniques(6)(8). As the blue sensitive layer in the colorfilm records in the region of highest transmission in the water, the deepest penetration is obtained, and blue color separations are frequently used for this work. Clear water also has substantial green transmission, and a 44A separation filter is often used to include color information from 420nm to 560nm.

In several cases correlation of charted depths with density slices at 120 and 180 feet appear to be valid. An example is shown in Figure 11. Since the bottom can be seen in standard, un-enhanced color photography at depths of 140 feet, taken from 60,000 feet in the Bahamas, there is no reason to doubt that similar results can be obtained from space with appropriate blue region sensors, and that in many areas bathymetric contours can be derived with minimal ground truth spot checking. There are hundreds of "doubtful soundings" where much lesser depths are reported, and which may be examined by this method in future.

Chlorophyll Detection.- The concentration of phytoplankton in the ocean is related to commercial fishing areas, and is usually associated with upwelling, currents, water chemistry and other features of interest in physical oceanography. Experimental scanning radiometers flown in aircraft have been successful in detecting and measuring chlorophyll concentrations(9)(10).

One method of data reduction electronically differentiates the green and blue water radiances to detect a chlorophyll absorption band around 440nm(10). By comparing the blue measurements with reference data taken simultaneously at 525nm where chlorophyll is transparent, as shown in Figure 12, radiance data from surface effects and scattered light similar to both channels can be cancelled. The remaining relative radiance values in the blue channel are then attributable to chlorophyll absorption and concentration.

There are analogous photographic processes where positive and negative images are combined to mask out similar reflectance values of the same scene taken in two spectral bands, permitting only that which is different to be printed(8). Whether this can be used for detecting chlorophyll remains to be tested, but some data are available which show promise. Figure 13 is of red, green and blue multispectral images taken from an altitude of 1500 feet near La Jolla, California, during an experiment for Scripps Visibility Laboratory in December 1970. The negative images are reproduced at normal contrast, and the positives at high contrast. The red band (25 filter) clearly shows a "red tide" phytoplankton bloom as the white areas in the positive, while the absorption of light by chlorophyll in the blue band makes the same areas appear dark. In this instance, the green band (57A filter)* is not suitable for masking the blue record, as its transmission (**Figure** 12) overlaps part of the chlorophyll absorption band and would tend to mask useful data. Enlarged sections of images taken of the same area from 12,000 feet are compared in Figure 14, where the strong absorption effect is still seen and relative chlorophyll concentration can be estimated within the image. Under these atmospheric conditions there is little question that this bloom would have been detected from 60,000 feet or higher.

Intense phytoplankton blooms of this kind contain much higher concentrations of chlorophyll than normal. Experiments supported by ground truth will be required to determine the lower limits of detection with multispectral photography from higher altitudes, by applying masking processes and other more refined methods of analysis and display.

Coastal Processes.- In the analysis of the Apollo IX image AS9-20-3128, Pamlico Sound and the North Carolina Coast, Mairs(11) provides a classical example of what it is possible to infer about coastal and ocean processes from a space image. Using the natural color photograph and red, green and blue color separations as an aid in determining the probable depth and concentration of sediments, and their sinking, mixing and diffusion rates, he was able to develop a model which incorporated jet theory, surface temperatures, currents, climatological factors, color differences, tidal cycles and other phenomena to account for the form, distribution and juxtaposition of the water-borne sediment masses and their apparent radiance.

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*The experiment was to record the submerged target near the boats with a 57A filter, which has a passband closely resembling the response of the ERTS Return Beam Vidicon "green" camera. The red tide bloom was fortuitous.

At a later date, a color separation of this image was density-sliced, Figure 15. Each density level could be separated from those adjacent, in effect contouring the sediment depth by luminosity levels; a distinct aid in analyzing images of this type for examining similar coastal processes which occur on a worldwide basis, related directly to beach building, erosion, current flow and many other factors which bear not only on scientific studies, but on shipping traffic, fisheries, coastal utilization, pollution detection and other practical applications.

Water Pollution.- Experimental data are available from radiometric sensors and multispectral photography to show that the blue is one of the best spectral regions in which oil spills can be detected. Oils modify surface characteristics, affecting the reflectance of skylight in the blue band. Samples from high altitudes are not yet available. As in the case of chlorophyll detection, the possibility of monitoring such disasters from orbital altitudes needs investigation.

Industrial water pollution detection and control will be aided by using a blue record as one of the primary bands for assessing water colors which deviate from the norm. Excessive algal growth encouraged by phosphate or other pollutants provide one example.

BLUE RECORD OF LAND AREAS

Enhanced ocean blue records show marked improvement in the contrast of adjacent land areas, aiding interpretation of coastal processes. Features related to geology, agriculture, forestry, land use and many other applications are displayed in an improved form. A blue record is of particular value in geological interpretation, and many man-made features are emphasized in this spectral region. Oceanography is, therefore, not the only earth science which can use a blue image to advantage.

The recording problem is minimized in arid areas, but even in the tropics it is possible to make a blue record of useful quality. Two examples are given in Figure 16. The duplicate 70mm color films from which the enlarged sections were made were chosen as examples of severe tropical blue haze, which masks land form and detail almost completely.

It was necessary to enhance both the green and blue color separations to show the amount of detail actually present in images of this poor quality.

CONCLUSIONS

Sufficient practical evidence is on hand to prove the feasibility of making a blue spectral record from aerospace altitudes which is not only useful, but essential for obtaining vital oceanographic information. The problems of atmospheric luminance in degrading the image cannot be overlooked, but means for significantly enhancing the blue record are available. Electronic and photo-optical image enhancement techniques are necessary for extracting maximum information from blue (and green) multispectral photographs, and should be applied as standard analytical procedures.

While haze effects vary, the probability of securing a useful image is likely to be as good as the probability of having suitable cloud-free conditions; possibly better.

A minimum passband of 460 to 500nm is required, but photographic evidence suggests cut-on could begin as low as 440nm to provide additional information.

REFERENCES

1 - Ross, D. S. - Enhancing Aerospace Imagery for Visual Interpretation - SPIE 15th Annual Technical Symposium Proceedings, Vol. 3, Sep. 1970

2 - Duntley, S. Q. - Light in the Sea, JOSA, 53, (2), Feb 1963

3 - Turner, R. E., et al - Importance of Atmospheric Scattering in Remote Sensing - Proceedings Seventh International Symposium on Remote Sensing of Environment, U of Michigan, Vol III, May 1971

4 - Junge, C. E. - Atmospheric Chemistry, Advances in Geophysics, Vol 4, 1958

5 - Lepley, L. K. - Coastal Water Clarity from Space Photographs, Photogrammetric Engineering, Vol XXXVI, No. 7, Jul 1968

6 - Ross, D. S. - Color Enhancement for Ocean Cartography, Ocean from Space Symposium, Am. Soc. for Oceanography, Houston, April 1967

7 - Brock, G. C. - The Physical Aspects of Aerial Photography, Dover ed. 1967

8 - Ross, D. S. - Image Tone Enhancement, Papers, 36th Annual Meeting, American Society of Photogrammetry, Mar 1970

9 - Clark, G. L., Ewing, G. C. & Lorenzen, C. J. - Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration, Science, 167, 1119-1121 (1970)

10 - Arveson, J., Millard, J. P., Weaver, E. C. - Remote Sensing of Chlorophyll and Temperature in Marine and Fresh Waters, Proceedings XXII International Astronautics Congress, Brussels, Sept 20-25, 1971

11 - Mairs, R. L. - Coastal & Sedimentologic Interpretation of Apollo IX Space Photography; Carolina's Continental Shelf, USA, Photogrammetric Engineering, Vol XXXVI, No. 10, Oct 1970

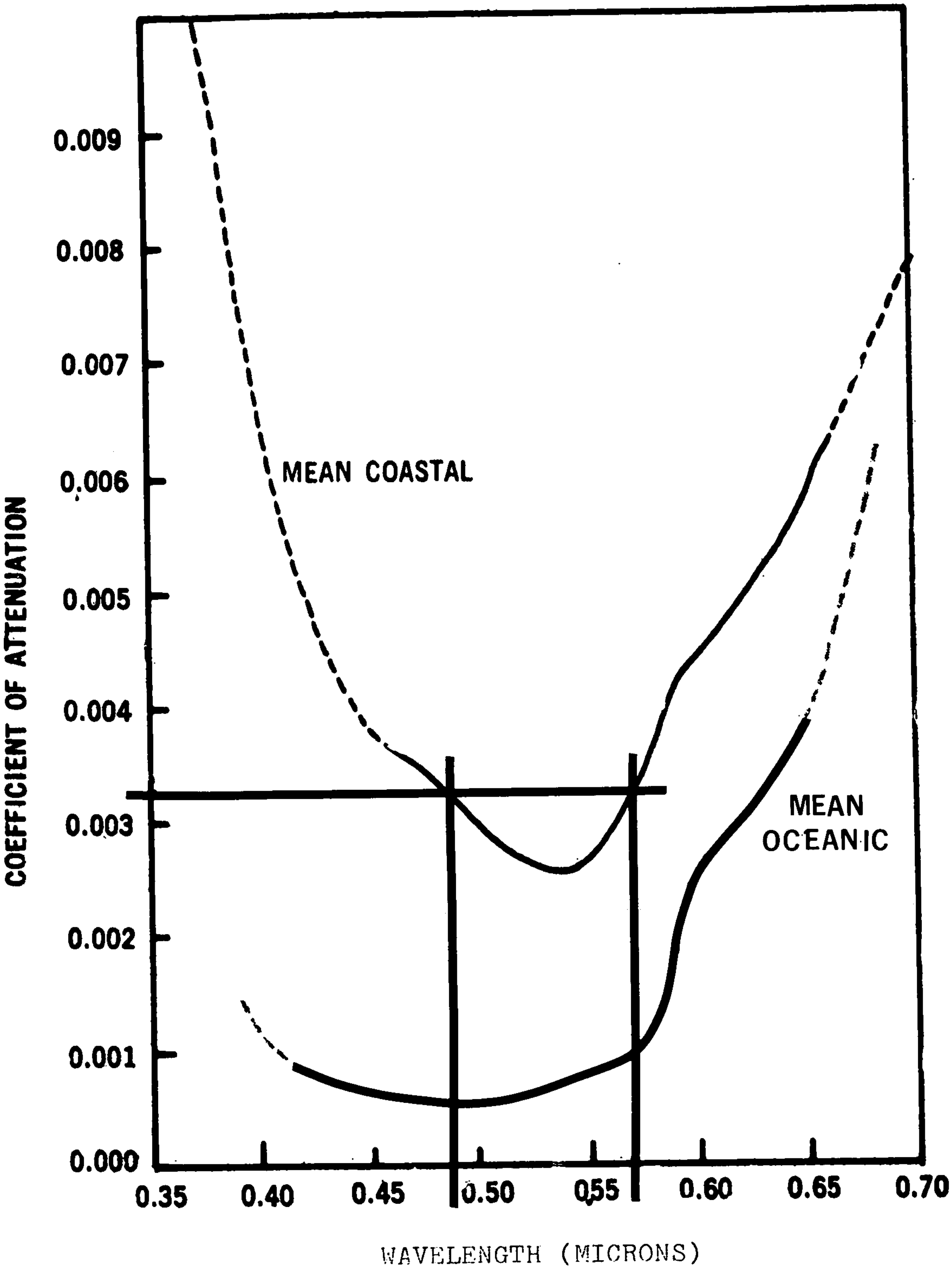


Figure 1.- Attenuation of Light in Seawater

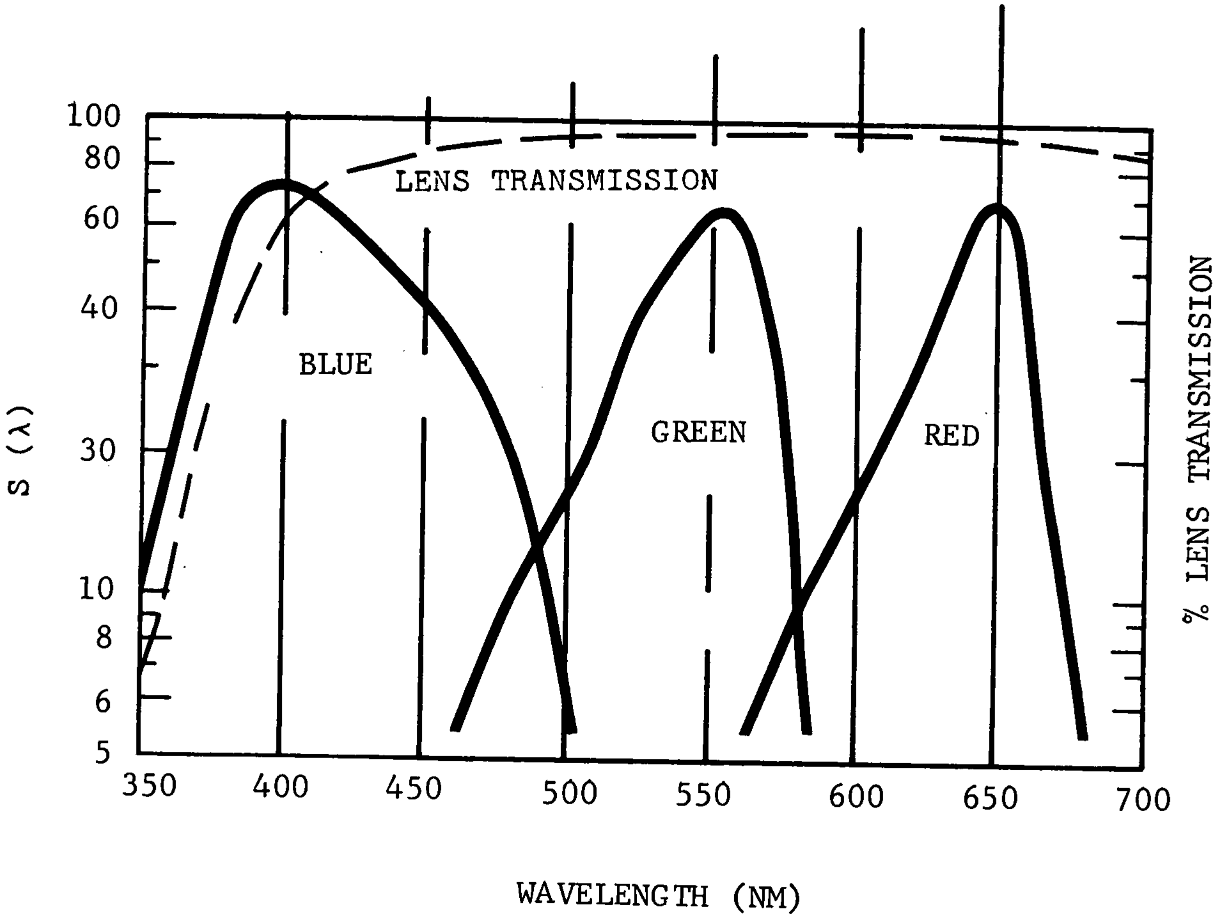


Figure 2.- Relative Sensitivities of blue, green and red layers in an Ektachrome natural color film, compared with spectral transmission of a Feiss Planar 80mm focal length lens. Note peak blue film response at 400 nm.

A. 450 mμ

B. 500 mμ

Figure 3 Color Separation Prints

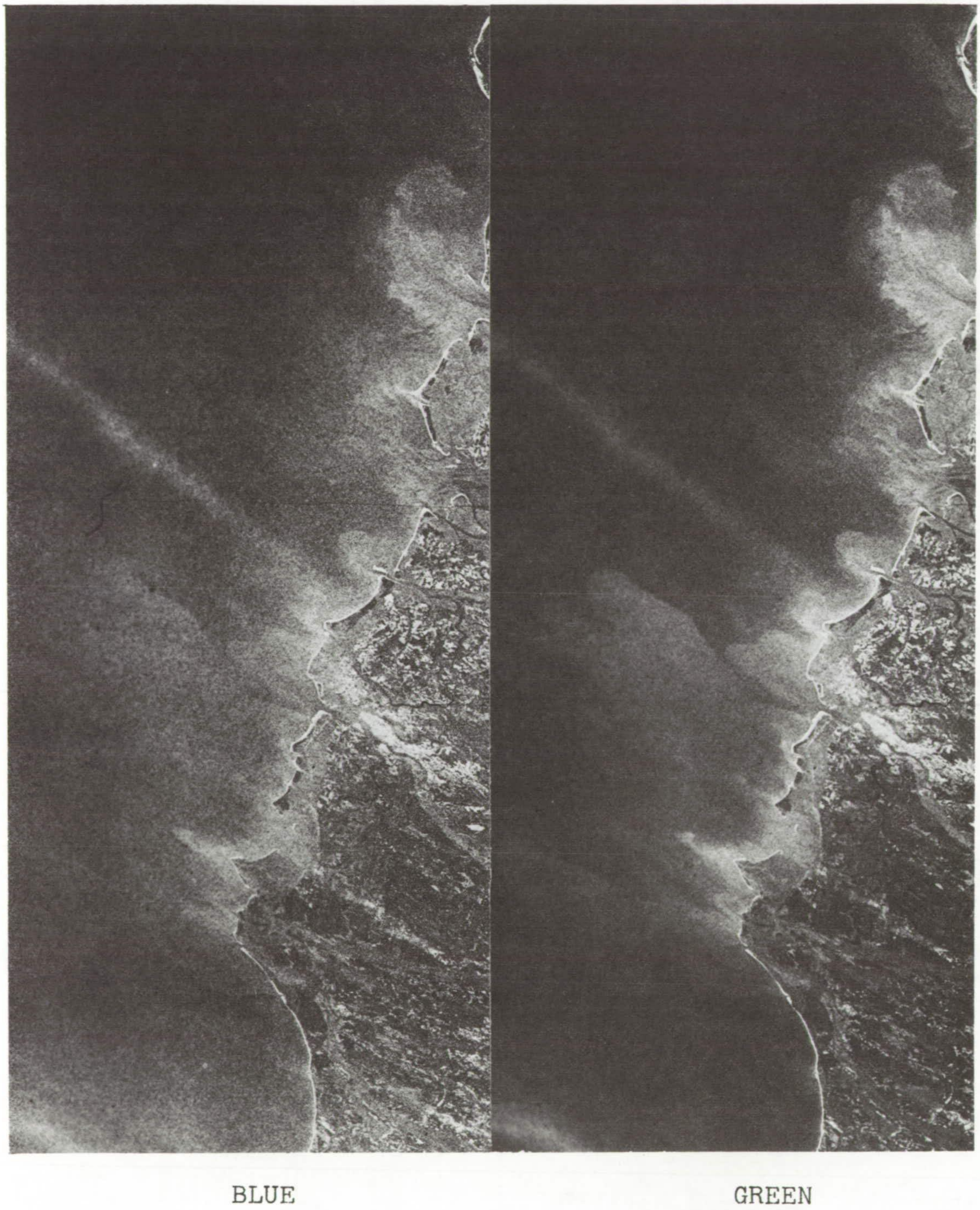
C. 550 mμ

D. 650 mμ

Figure 3 Color Separation Prints (Continued)

BLUE GREEN

Figure 4.- Enlarged portions of color separations, AS9-20-3127, Cape Lookout, S. Carolina. Note visible water difference in blue image.



BLUE GREEN

Figure 5.- AS9-20-3148, coast of Georgia, S. Carolina. Differences in light absorption and scattering in the water show clearly.

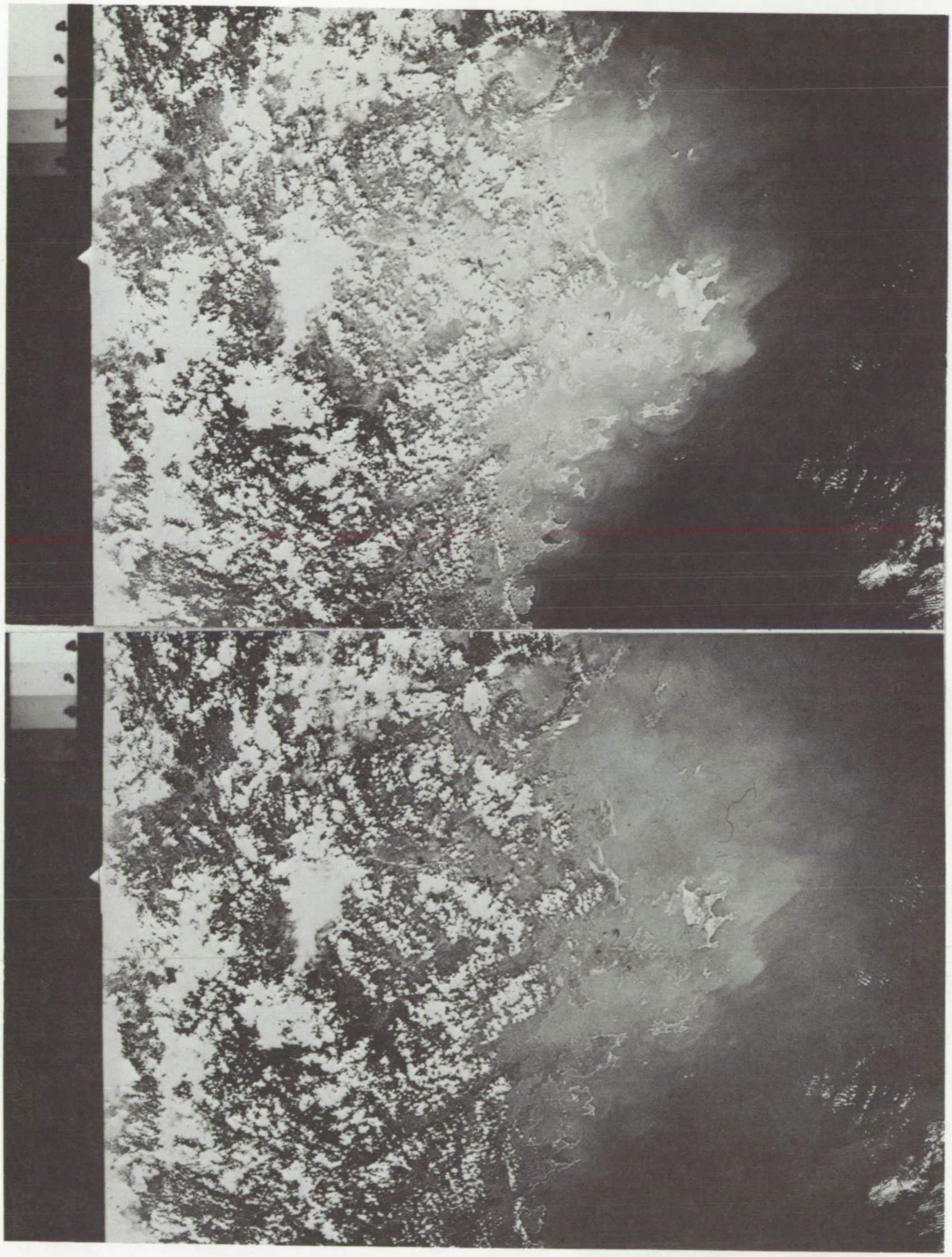
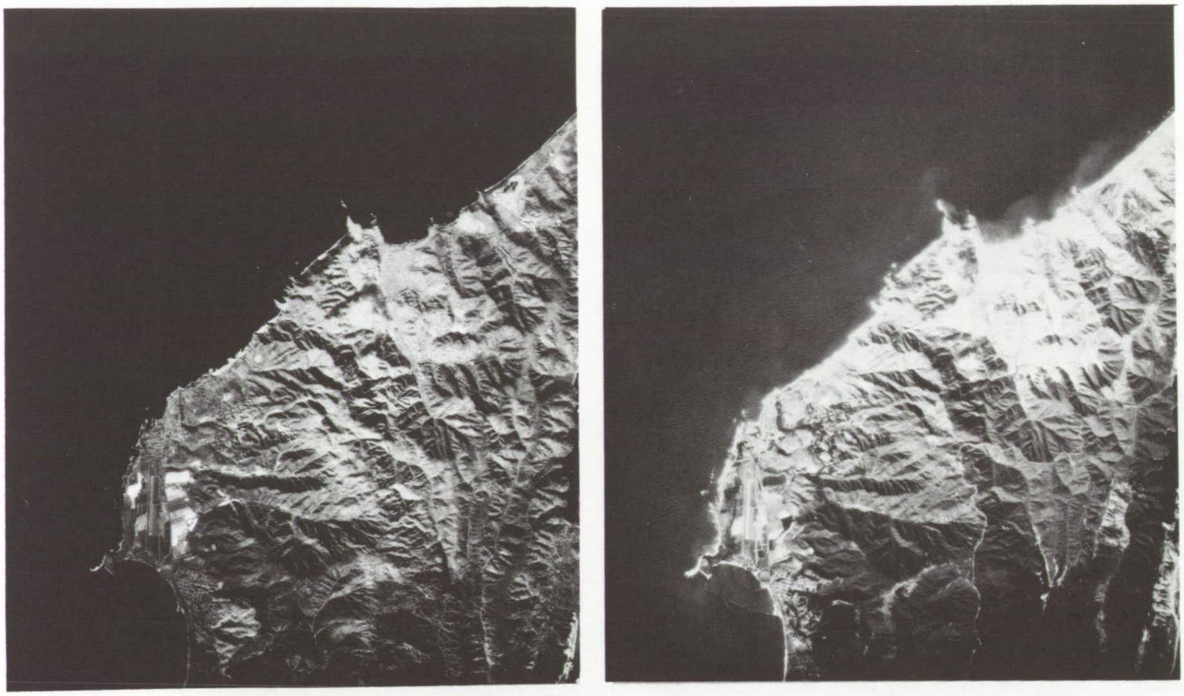
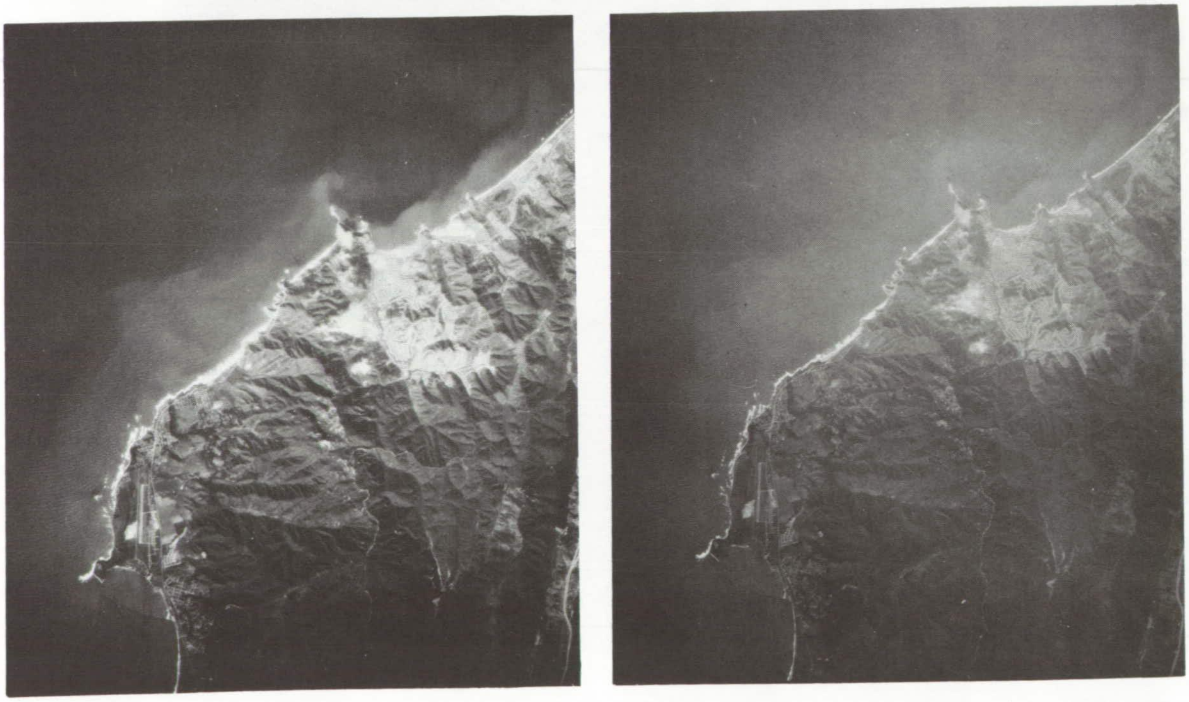


Figure 6.- GT X, S66-45953. Formosa Strait. Green separation (upper) compared with blue record.



A - Infrared Record (88A)

B - Red Record (25)



C - Green Record (57A)

D - Blue Record (47B)

Figure 7 .- Moss Beach, Ca. from 65,000 ft., 6-inch lenses I^2S Multispectral Camera. NASA/Ames. Sections of 3.5-inch square images at contact scale.

Figure 8.- Enlarged section of I^2S Blue Record shown in Figure 7(D). Contrast enhanced to emphasize variations in light in water.

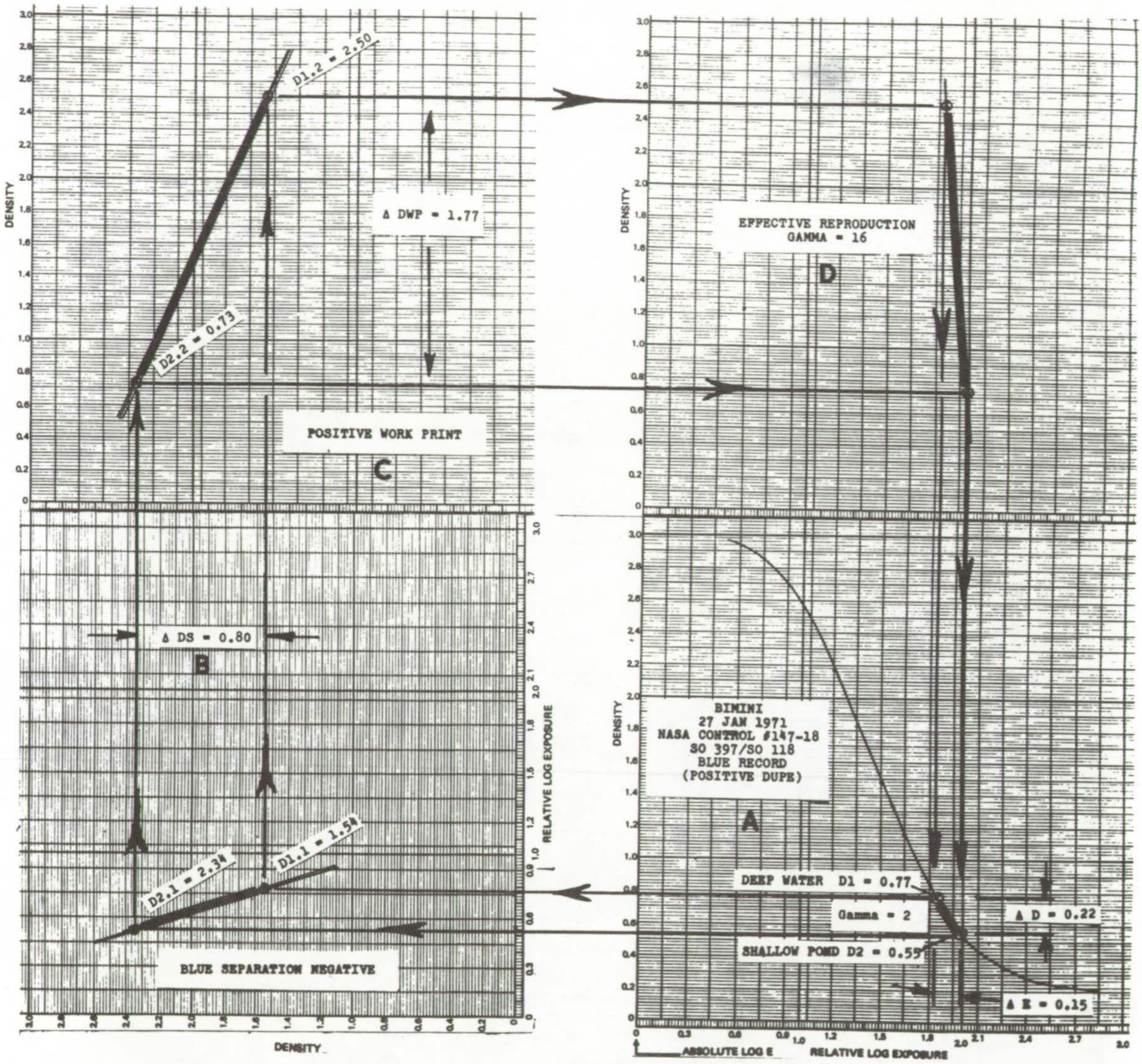


Figure 9. - High contrast photographic color separation and reproduction greatly increase small density differences and scene contrast for improved visual interpretation, as well as for other enhancement techniques. Density differences in the original at (A) have been converted from 0.22 to 1.77 in the workprint in the tone reproduction cycle illustrated above.

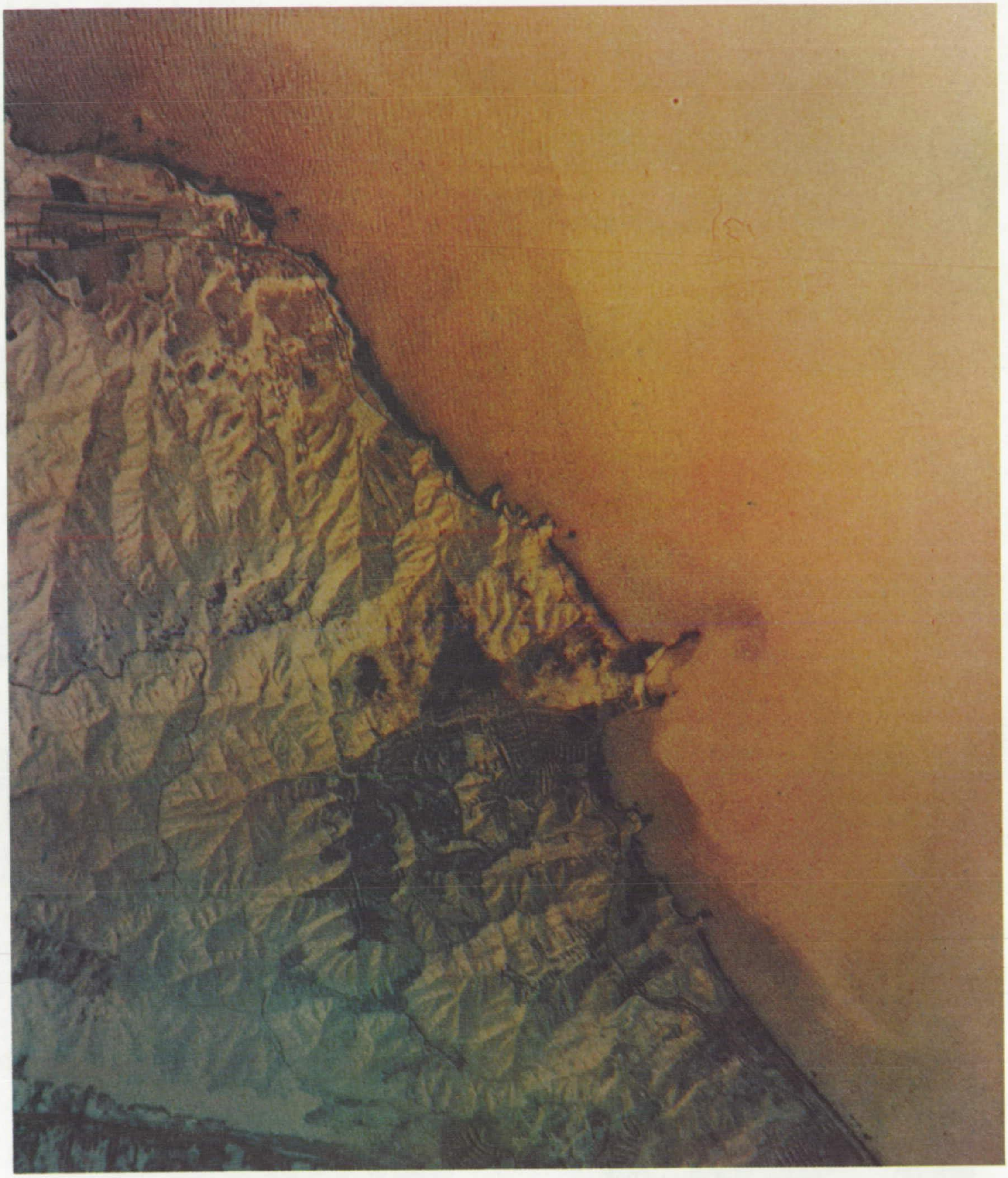


Figure 10 - Moss Beach, Ca. NASA/Ames U-2 photograph from 65,000 ft. ASL, I^2S Mark I Multispectral Camera. Additive color projection of blue and green negatives on screen of Mini-Addcol Viewer. Blue record projected as blue, and green as red. See also Figure 7.

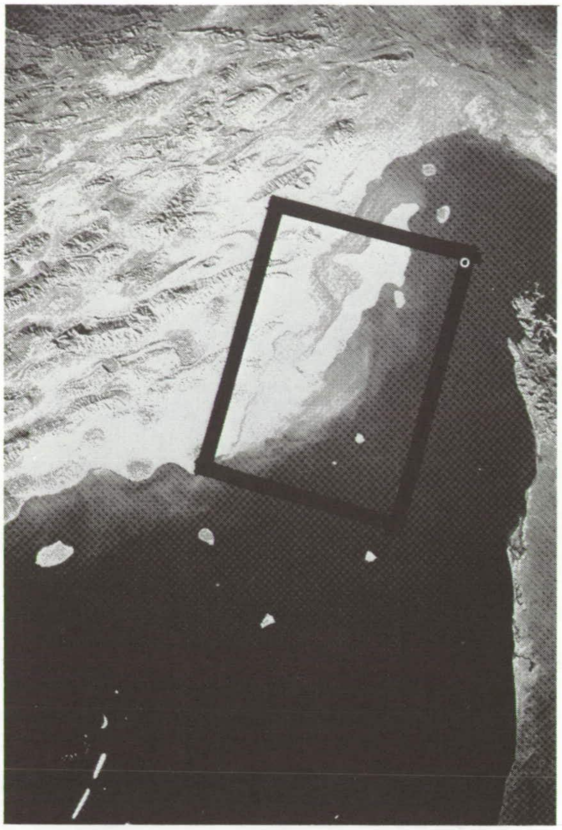


Figure 11A NASA/MSC No. S66-63485 Iran – Trucial Coast, Persian Gulf; Qeshm Island, Astronauts Lovell and Aldrin, Gemini XII, November 1966, Hasselblad Camera, 38 mm, Zeiss Biogon Lens. Altitude about 110 NM. Original scale about 1:8,000,000.

(U. S. NAVAL OCEANOGRAPHIC OFFICE - SPACECRAFT OCEANOGRAPHY PROJECT)

Figure 11B Enlarged, enhanced section of Figure 11A; density levels at 10-20 fathoms

Figure 11C Density levels at approximately 20-30 fathoms

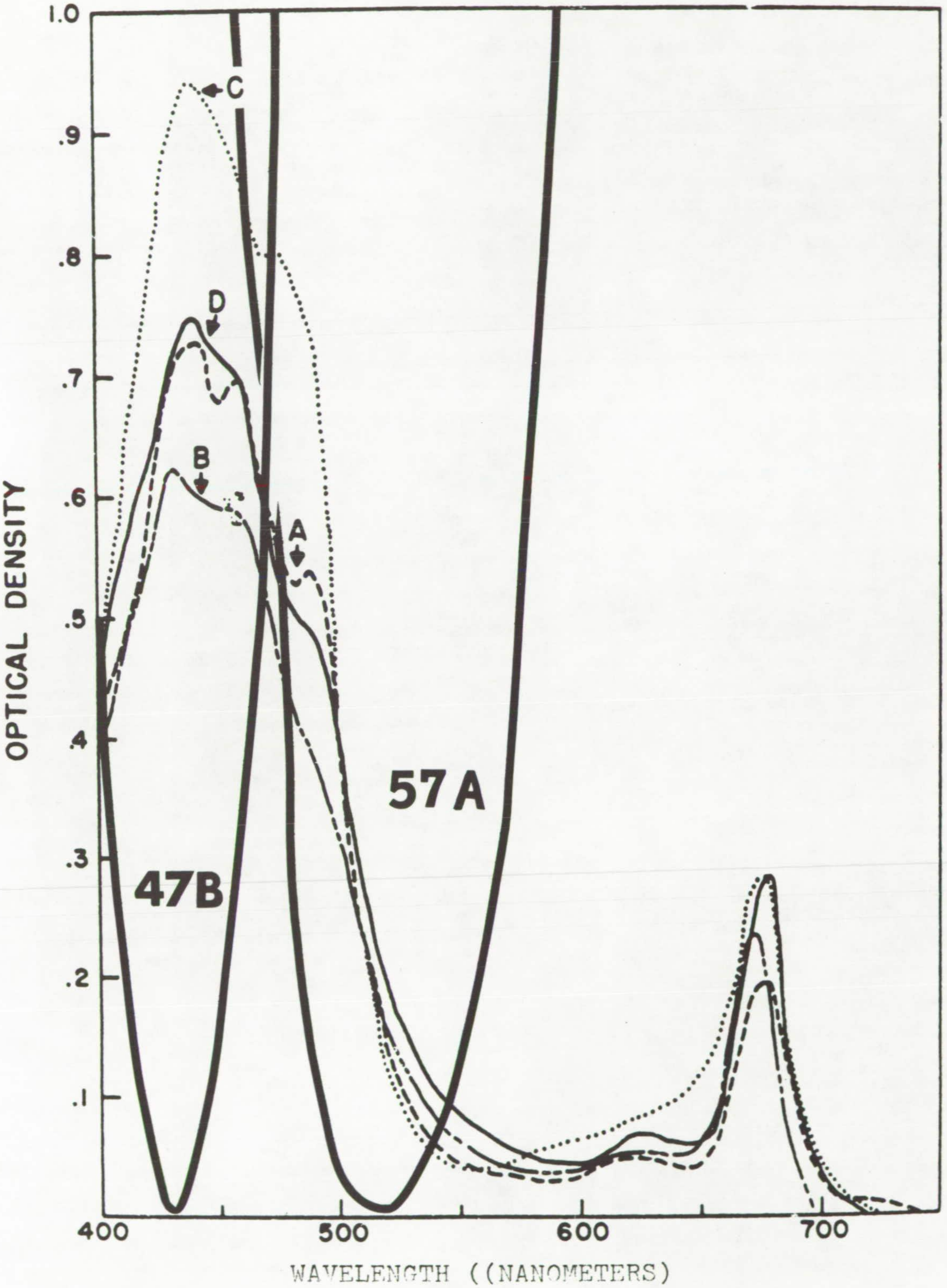


Figure 12 - Absorption spectra of extracts of several plankton species, (A),(B),(C);(D) is from a natural population sample, Woods Hole waters (Yentsch, 1960), Compared with normalized densities of Wratten filters 47B-blue and 57A-green.

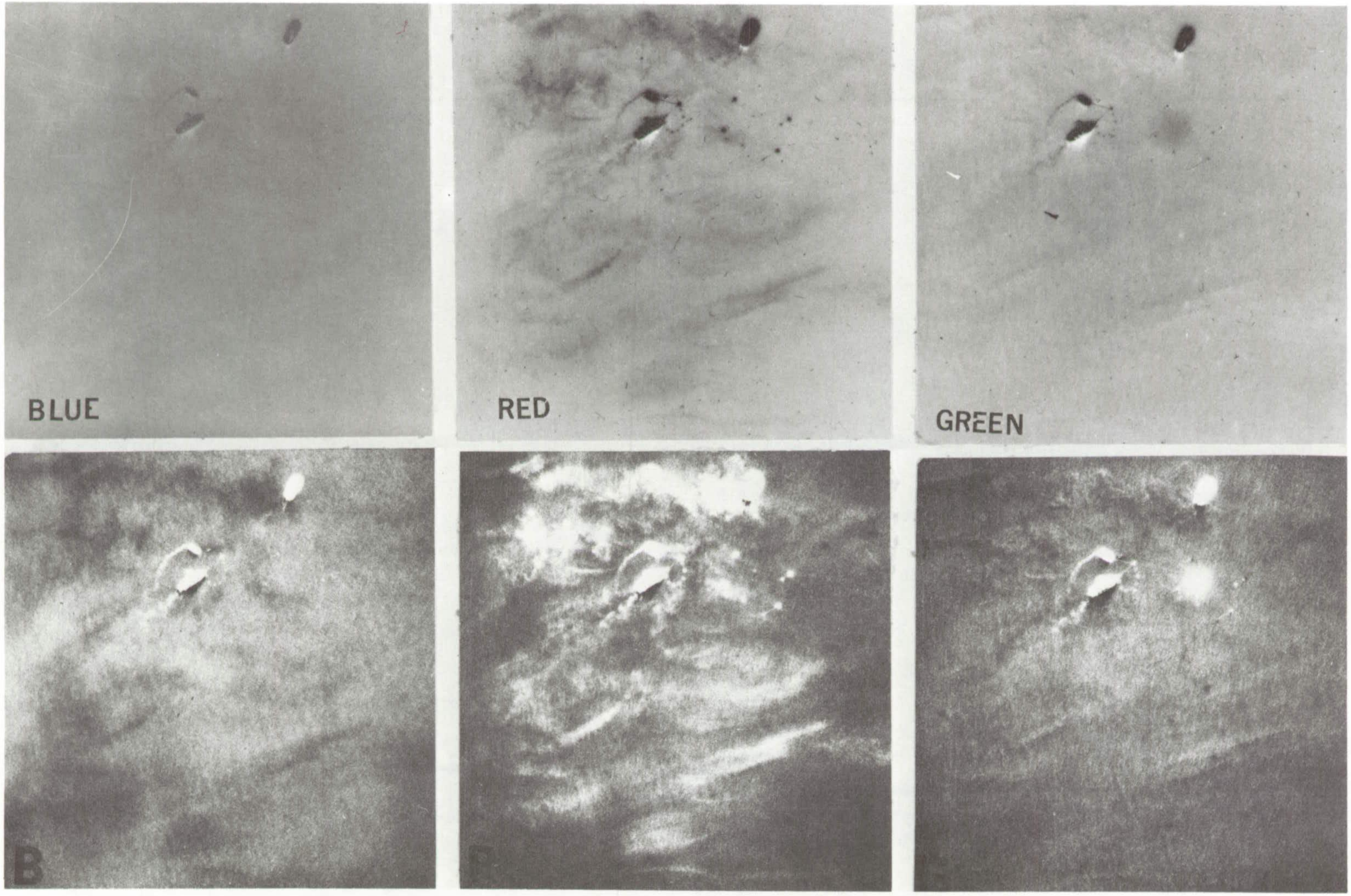


Figure 13. - Normal contrast multispectral negatives and high contrast positives of red tide bloom, 1500 ft. ASL. Chlorophyll absorption shows strongly in the blue image.

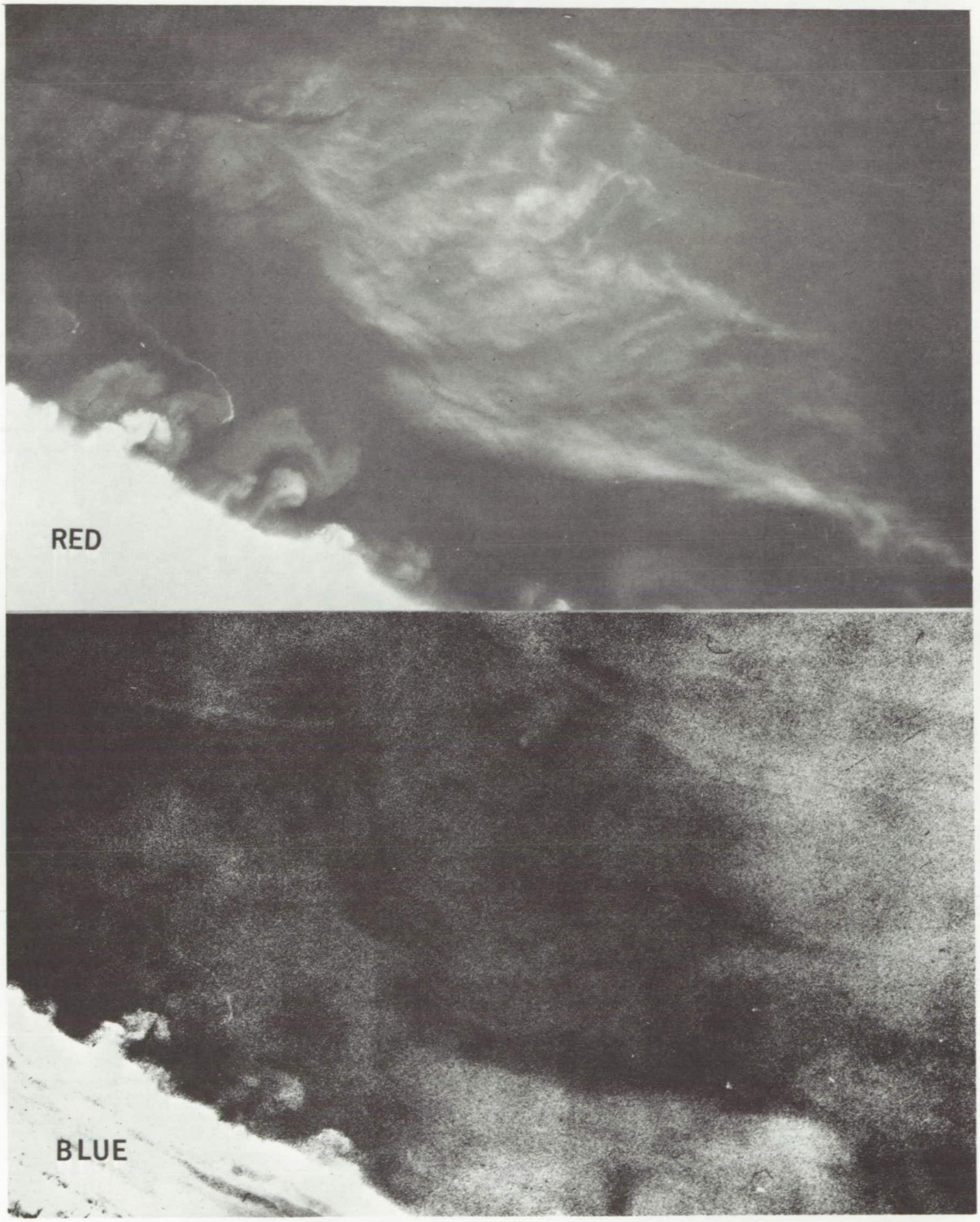


Figure 14. - Area of red tide bloom shown in Figure 13 as recorded from 12,000 ft. ASL.

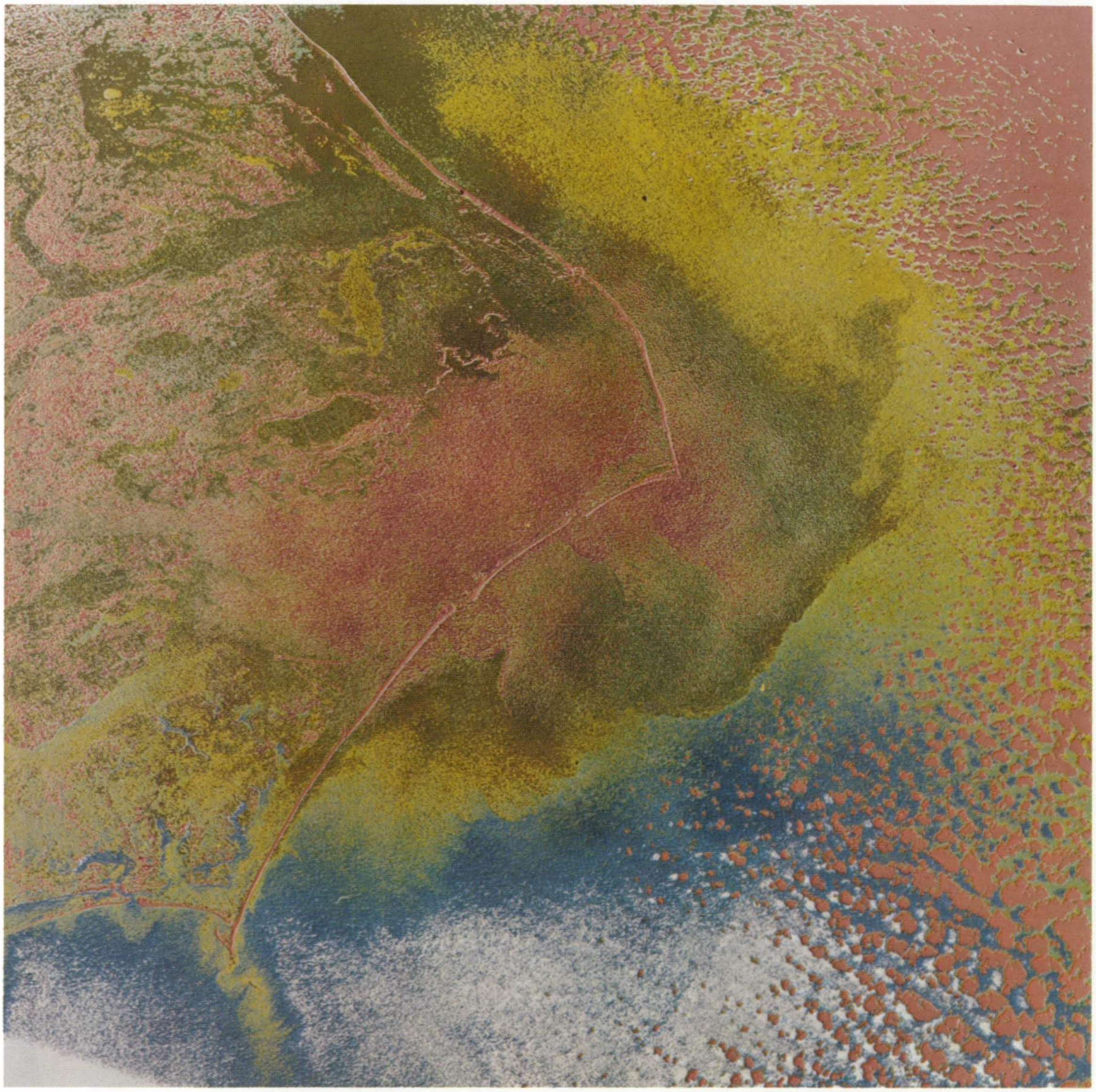
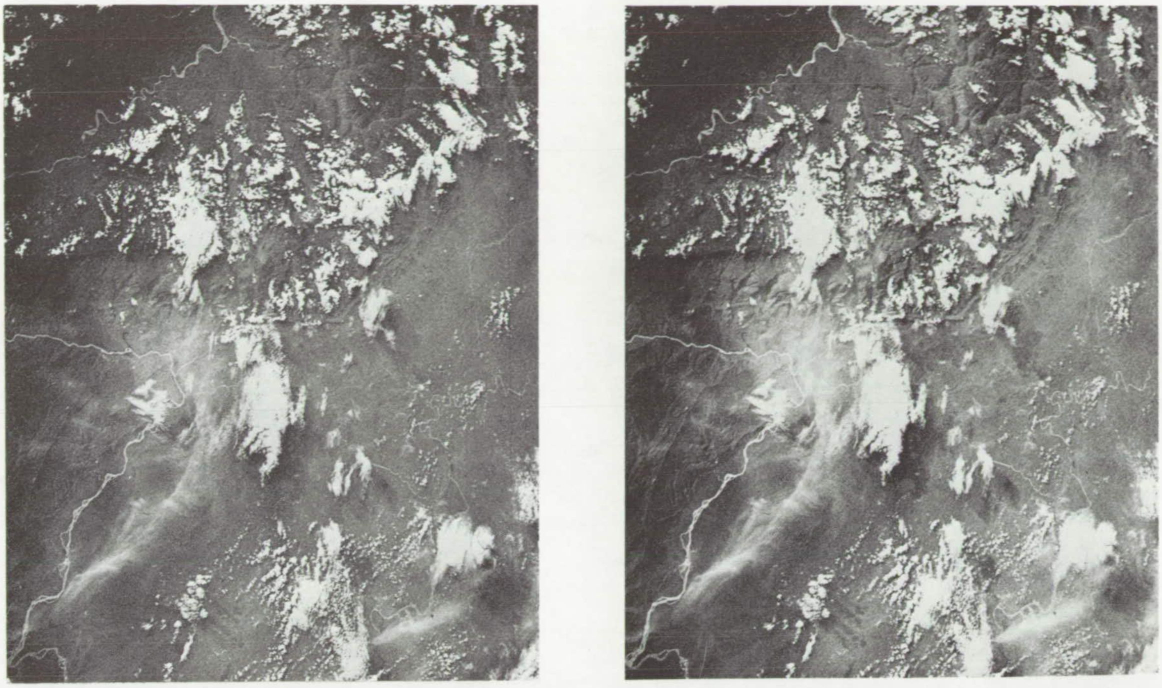
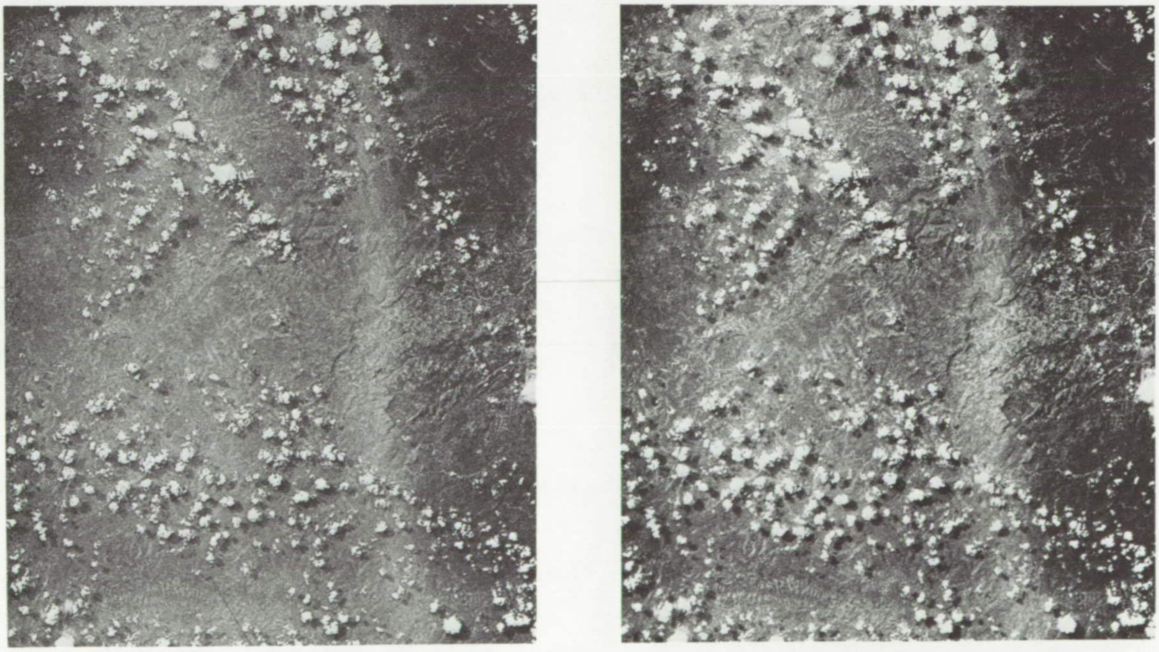


Figure 15.- AS9-20-3128. Pamlico Sound, Cape Hatteras, N. Carolina Coast. Photo-Optical false color density slicing. Colors peel apart in the original to show ten separate brightness contours in the water area.



BLUE GREEN

AS9-20-3165 - Peru, 12°S, March 1969



BLUE GREEN

GT VII, S65-63934, 15°S, Brazil, Mato Grosso, Dec. 1965

Figure 16. - High-Contrast Color Separations of Land