

## Peter G. White

Mr. White is manager of the Electro-Optical Sensors Department of TRW Systems in Redondo Beach, California. He has directed a number of programs in the remote sensing of water bodies, in order to relate the remotely sensed data to the quality of the water. Most of these programs have involved the use of spectrometers, cameras, and thermal infrared imagers flown in aircraft in conjunction with suitable surface truth measurements obtained from boats.

Mr. White was registered as a Professional Engineer in 1954 by the Association of Professional Engineers of Ontario, Canada. He has published a number of papers on the subject of remote measurement of water quality, and holds patents on two instruments specifically designed to make such measurements.

## REMOTE SENSING OF WATER POLLUTION

By

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Remote sensing, as a tool to aid in the control of water pollution, may prove to be exceptionally valuable in the next few years. It offers a means of making rapid, economical surveys of areas that are relatively inaccessible on the ground. At the same time, it offers the only practical means of mapping pollution patterns that cover large areas.

New sensors and techniques, under development for the past several years, will obtain information about the nature and extent of pollution that previously could only be obtained by water sampling. Some of these sensors operate in daylight only, while others will work either day or night.

Data are presently being obtained from aircraft in conjunction with analyses of water samples taken on the ground to correlate the airborne data with such parameters as sediment count, algae concentration and type, degree of thermal pollution, and oil slick extent and thickness.

Figure 1\* shows the regions of the electromagnetic spectrum of most interest in this type of remote sensing. The right-hand bar indicates the relationship of the ultraviolet, visible, and infrared portions of the spectrum. It should be noted that the radiation which is detected by a passive remote sensor has two different sources - reflected or scattered sunlight, and thermal emission of the water itself. As with the atmosphere, at short wavelengths, light is heavily scattered by the molecules of water, and above 0.7 microns water absorbs most of the energy which reaches it.

Finally, the two left-hand bars show the regions in which we can perform our passive remote sensing after allowing for all the previous effects. The only radiation from beneath the surface which reaches the sensor is constrained to the visible and near ultraviolet. Material floating at the surface, such as oil slicks, can be detected at longer wavelengths, including the infrared region around 10 microns. As the source energy at 10 microns is emitted, rather than reflected, its absolute value is indicative of the temperature and emissivity of the surface, whether it contains floating matter or not.

Detection of oil slicks, thermal pollution, sewage and algae will be discussed in the following paragraphs.

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\* Unless otherwise credited, all illustrations and data used in this report were obtained by TRW Systems Group, in large part under the sponsorship of the Spacecraft Oceanography Project.

## OIL SLICKS

As oil floats on the water surface, it offers the possibility of detection in any spectral region in which a suitable atmospheric window and adequate detectors exist. Optical contrast between oil and water is high in the ultraviolet and sometimes in the thermal infrared regions of the spectrum, as shown in Figure 2. In Figure 2, the upper two images were obtained by a multispectral linescan sensor which simultaneously images many different spectral regions. The lower image is a photograph of the same scene, in this case the large oil spill in the Santa Barbara Channel in early 1969. It can be seen from Figure 2 that the Panchromatic film/K-2 filter combination (sensitive from 0.48 to 0.65 microns) does a poor job of rendering contrast. On the other hand, the Kodachrome II film used in Figure 3 shows good contrast between the oil and water. This is because this film (used without a filter) has good sensitivity in the near ultraviolet region of the spectrum. Some purple tones are evident in Figure 3, indicating a contribution to the signal in the red as well as blue/ultraviolet. This is in agreement with some spectral reflectance measurements made of the oil slick with a spectrometer that indicate a relatively high oil-to-water contrast in the 0.60 to 0.67 micron region of the spectrum.

Although dramatic in appearance, the reverse Infrared Ektachrome print of Figure 4, shows less contrast between oil and water.

In summary, oil slick photography is best accomplished with ultraviolet sensitive film such as unfiltered Kodachrome II or 103-0. If the altitude is very high or haze conditions are such that atmospheric scattering is a problem, thermal infrared imagery obtained with an infrared linescanner should probably be substituted for photography.

## THERMAL POLLUTION

Thermal anomalies are characteristic of many types of pollution. Biochemical action at sewage outfalls is capable of raising the temperature of the surrounding water many degrees. Discharge of cooling water from electrical generating plants has a similar effect. Oil slicks are frequently at a different temperature than the surrounding water, resulting in the contrast shown in the infrared image of Figure 2.

As water, or any other substance with high emissivity and temperature within the range of 0 to 25 degrees Centigrade emits maximum radiation in the spectral region of 10 microns, a detector which is sensitive in the atmospheric window of 8 to 13.5 microns is well suited to this type of measurement.

A simple radiometer containing a temperature controlled reference black body is capable of remotely measuring temperature within an absolute accuracy of better than  $\pm 0.5^{\circ}\text{C}$ . Infrared linescanners can give good imagery of thermal gradients. Figure 5 is a picture showing the thermal diffusion from the cooling water discharge of a large electric generating station. This picture was obtained with an infrared linescanner operating between 8 and 13.5 microns in an aircraft at 1000 ft. altitude. In the picture, higher temperatures are indicated by lighter tones. Temperature differences of about  $0.2^{\circ}\text{C}$  are probably evident.

One of the primary advantages of thermal imagery of the type shown, is that it may be obtained either day or night. As the long wavelength infrared radiation being sensed is emitted by the water itself, sunlight is not required. In fact, sunlight contains virtually no energy in this region of the spectrum. Figure 5 was obtained in the daytime, and as a result, the land areas appear lighter (warmer) than the water as they have been heated by the sun. A similar picture taken on a cool night would show the land areas as darker (cooler) than the water. The thermal patterns in the water itself, however, would remain unchanged.

### SEWAGE AND ALGAE

Particulate and dissolved matter released from sewage outfalls is characterized by various changes in the visible region of the spectrum. Some of the more dramatic visual effects are shown in Figure 6, which was taken with Kodachrome II film. Usually, however, the visual appearance is much less pronounced. Work is currently ungerway to attempt to quantitatively relate these color changes to the condition of the water, with the intention that type, concentration, and distribution of the pollutants may be determined remotely. As water transmits light in the visible spectrum, the signal received by the sensor gives information about the condition of subsurface water instead of only the surface condition.

Probably the most useful instrument for this type of measurement is the rapid scanning airborne spectrometer. When pointed at an area on the surface of the water, it gives a continuous scan through the visible spectrum in about one second, measuring spectral radiance with good spectral resolution. When the resulting signal is divided by a similar scan of a known surface of constant reflectance, the spectral reflectance of the water body is obtained.

Current tests are underway to relate these remotely obtained spectral signatures to measurements made at the water surface. Figure 7 is a map of Los Angeles Harbor showing areas in which spectrometer scans were made from 1000 feet altitude (shown as rectangles on the map) and points at which turbidity measurements were made from a boat (shown as dots on the map). Figure 8 is a photographic montage of the area taken from 8000 ft. altitude within 30 minutes of the spectrometer measurements. The positions of the spectrometer scans are marked on the picture. Two distinct types of matter can be seen in the water. Particulate matter from three sewage outfalls is evident near the top of the picture. Algae of a type known as gonyaulax or "red tide" may be seen in the lower half of the harbor and also outside of the breakwall.

Spectral signatures from scans 2, 5, and 11 (positions indicated on Figure 8) are shown in Figure 9. Scans 2 and 5 are from regions of high particulate matter from the sewage outfalls, while scan 11 is from an area with a high algae concentration. Absorptions in the algae signature indicate the presence of pycobilin pigment and chlorophyll- $\alpha$ , both present in the algae gonyaulax. Characteristic features of the other signatures are still under investigation.

In order to utilize the airborne spectrometer measurements to obtain quantitative data about the type and concentration of the water pollution, correlation must be obtained between certain characteristics of the spectral signatures and the data obtained at the water surface itself. In the tests currently underway,

water samples are taken from one foot beneath the surface and at the surface. Portions of the samples are fixed with formaldehyde and counts made under a microscope of different organisms and particles. As another measure of water turbidity, a Secchi disk is lowered into the water until the depth is reached at which it is no longer visible to observers in the boat.

Certain parameters have been selected to characterize the spectrometer curves. Figures 10, 11, and 12 show these parameters plotted against the Secchi depth, which is a measure of water turbidity. The parameters have been defined as follows:

$$K_1 = \frac{R_{4000\text{\AA}} - R_{5250\text{\AA}}}{R_{5700\text{\AA}}}$$

$$K_2 = 1 - \frac{R_{5250\text{\AA}}}{R_{5700\text{\AA}}}$$

$$K_3 = \frac{R_{7000\text{\AA}} - R_{6700\text{\AA}}}{R_{5700\text{\AA}}}$$

In all cases  $R_\lambda$  is the reflectance of the water at wavelength  $\lambda$ .

$K_1$  (Figure 10) was selected to indicate the amount and direction of the slope of the reflectance curves in the blue-green region of the spectrum. High concentrations of sewage result in a rising reflectance with increasing wavelength in this spectral region whereas high concentrations of algae produce a decreasing reflectance. The parameter can be seen to relate to concentrations of sewage, but not to concentrations of algae, at least in high concentrations.

$K_2$  (Figure 11) is a measure of the drop in reflectance due to absorptions around 5250Å. It is in this region that pycobilin pigment of the type from the algae gonyaulax is found. In this case a correlation is apparent with high concentrations of algae as well as a different correlation with sewage.

$K_3$  measures the chlorophyll- $\alpha$  absorption at 6700Å and again shows different correlations with sewage and algae.

It is expected that as better, faster, methods of analyzing many water samples become available, better correlations with spectrometer data will be obtained. However, the present data is most promising in that it indicates a capability to differentiate between types of pollution and at the same time give a measure of the concentration of each type.

A factor which can contribute to the inaccuracy of this type of measurement is the speed of the spectrometer in taking each spectral scan. As the aircraft is moving at a velocity of some 150 ft/sec., within a one-second scan time, the area on the surface being viewed by the spectrometer has moved 150 ft. To illustrate this effect, Figure 13 is a photographic montage of the northern portion of the test area in Los Angeles Harbor described earlier. The distance

that the aircraft has moved during each scan is marked on the picture. In some areas, these lines cross boundaries in the water. This will result in a spectrum composed at short wavelengths from one type of water and longer wavelengths from another. To overcome this difficulty, faster scanning spectrometers are under development.

#### NEW DEVELOPMENTS

Certain other instruments and techniques are in various stages of development. One of the most promising new instruments is the imaging spectrophotometer. This device is capable of sensing radiation from many small areas on the surface simultaneously and obtaining a spectral signature from each. After properly processing the data, maps of pollution concentration may be prepared. The imaging spectrophotometer and associated data processing techniques are currently being developed.

Certain other techniques are in early stages of investigation. Image intensifiers and low light level television cameras which are sensitive to extremely low levels of illumination may be used to detect phosphorescence of decaying material at night. Some investigations currently underway are attempting to utilize the very narrow regions of the solar spectrum in which no light reaches us from the sun (Fraunhofer lines) to measure fluorescence during daylight. These techniques offer interesting possibilities for the future.

In summary, remote sensing of water pollution is rapidly progressing to the point where quantitative measurements may be obtained from aircraft. The benefits which will be derived from the ability to rapidly monitor and evaluate the condition of our environment will be of major value.

GLOSSARY

Algae - Microscopic living organisms found in oceans and lakes

Atmospheric Window - Portion of the electromagnetic spectrum in which the atmosphere does not attenuate radiation.

Emissivity - The fraction of radiation emitted by a body, compared to a perfect radiator of the same temperature.

Oil Slick - The film formed on a water surface by oil.

Reference Black Body - A perfect thermal radiator.

Sediment Count - The number of particles per unit volume of water sample.

Thermal Anomaly - A localized region of different temperature from the surrounding water.

Thermal Emission - Radiation given off by a body due to its temperature.

Thermal Pollution - Water of a higher temperature which is added to a body of natural water, usually as a by-product of an industrial process.

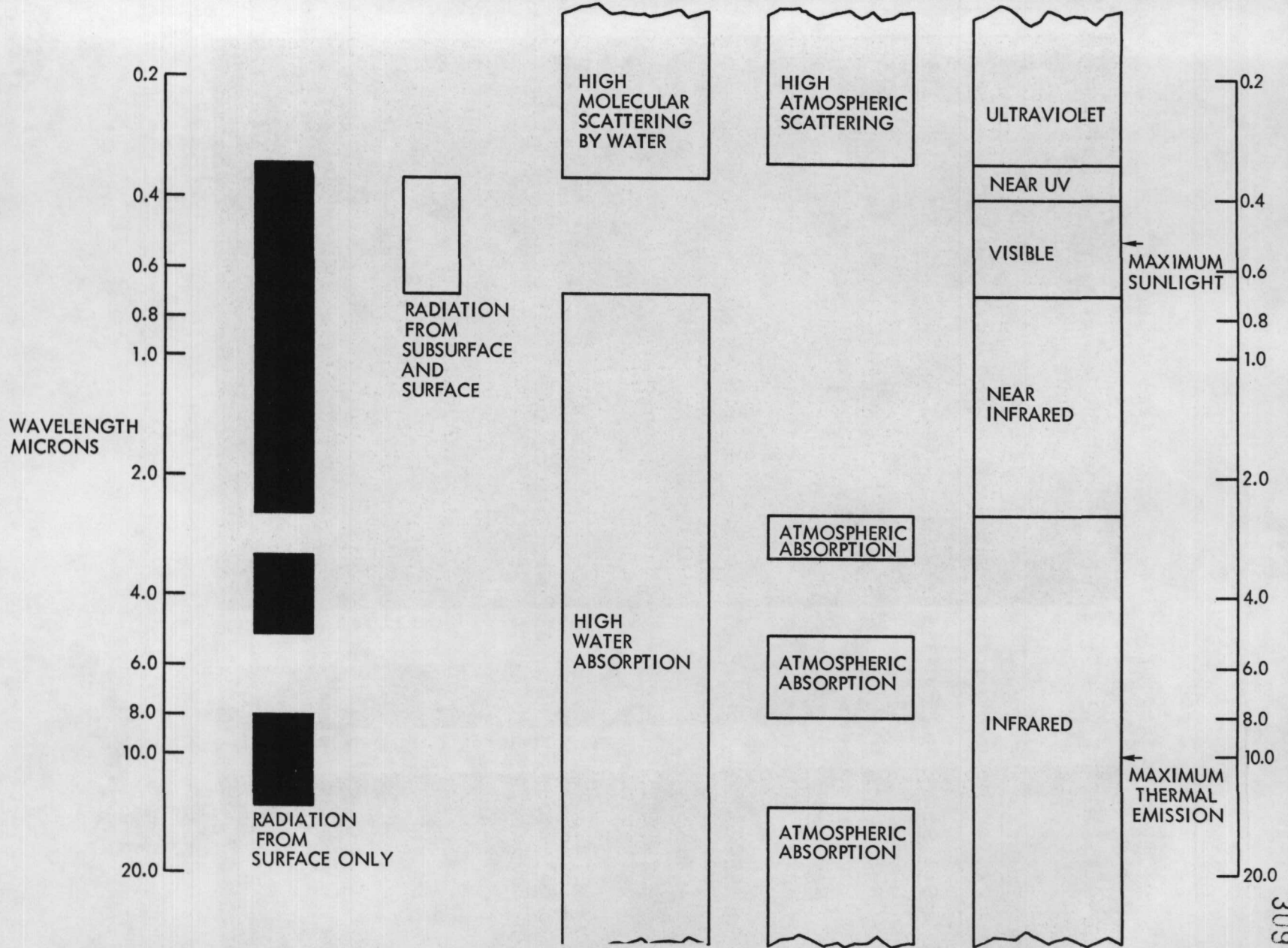
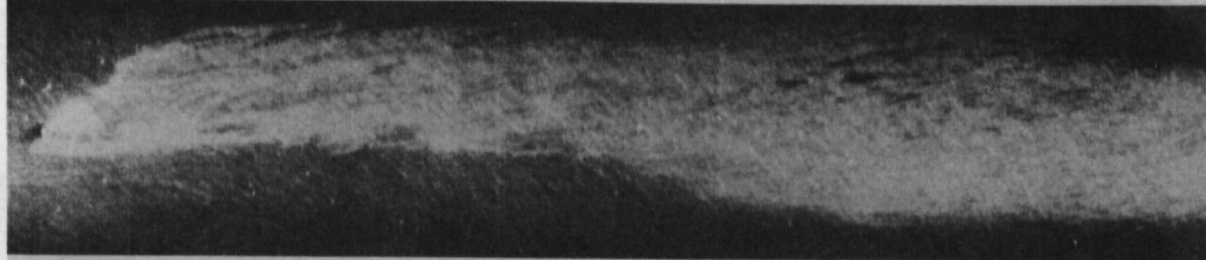


Figure 1 Electromagnetic Spectrum Relative to Water Pollution.



MULTISPECTRAL LINESCANNER IMAGE 0.32 to 0.38 $\mu$



MULTISPECTRAL LINESCANNER IMAGE 8.0 to 13.5 $\mu$



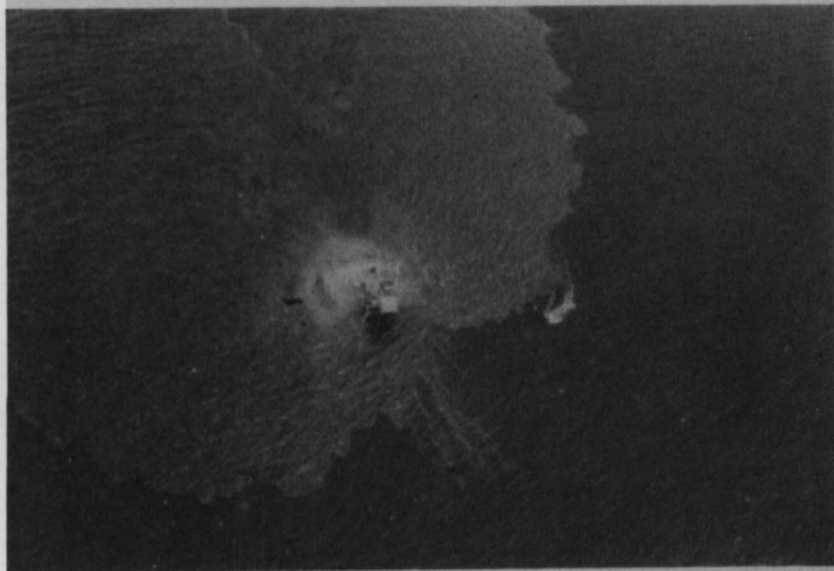
PANCHROMATIC PHOTOGRAPH K-2



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Figure 2 Santa Barbara Oil Slick.

PHOTOS COURTESY WILLOW RUN LABORATORIES, U of M



HEAVY OIL SLICK



LIGHT OIL SLICK

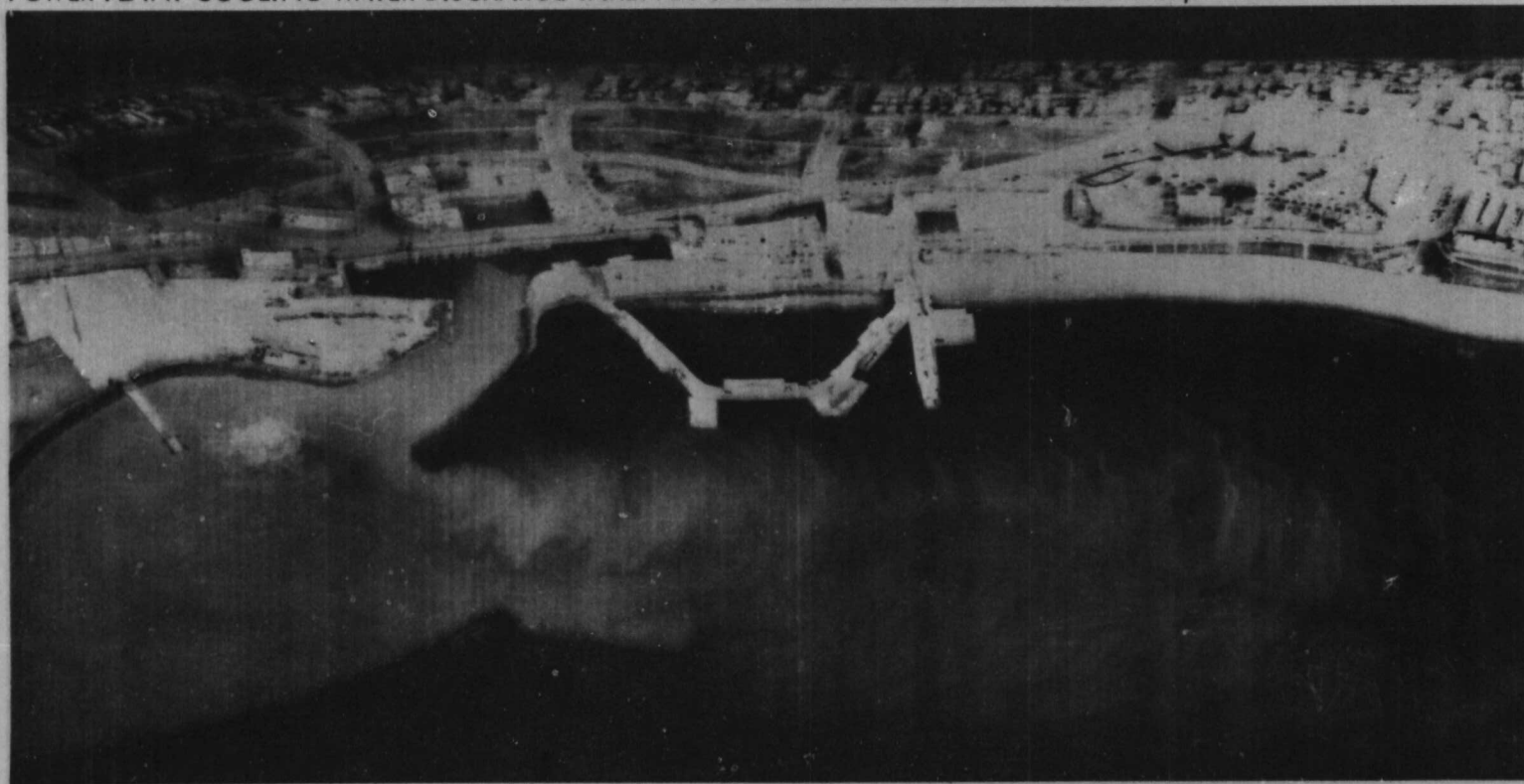
Figure 3 Santa Barbara Oil Slick - Ultraviolet Sensitive Film.



Figure 4 Reverse Infrared Ektachrome Print of Oil Spill.

PHOTO COURTESY U.S.G.S.

POWER PLANT COOLING WATER DISCHARGE TAKEN BY INFRARED LINESCANNER 8.0 to 13.5 $\mu$



TRW PHOTO

Figure 5 Example of Thermal Infrared Imagery.

CONVENTIONAL COLOR PHOTOGRAPHY

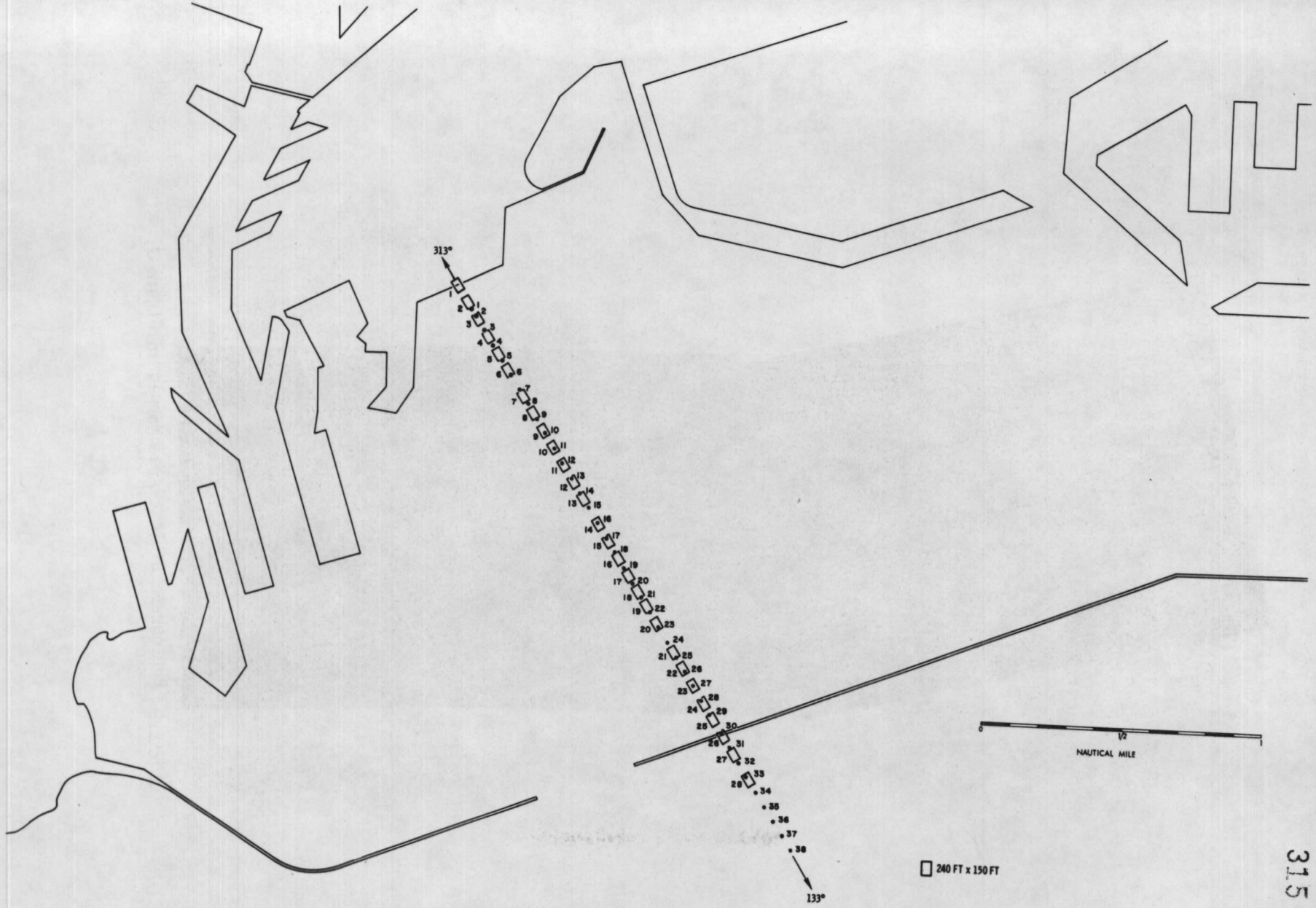
INNER CHANNEL - LOS ANGELES HARBOR 8000 FT



SEWAGE OUTFALLS - LOS ANGELES HARBOR 3000 FT



Figure 6 Conventional Color Photography.



**Figure 7** Map Showing Locations of Spectrometer Scans and Surface Test Stations.

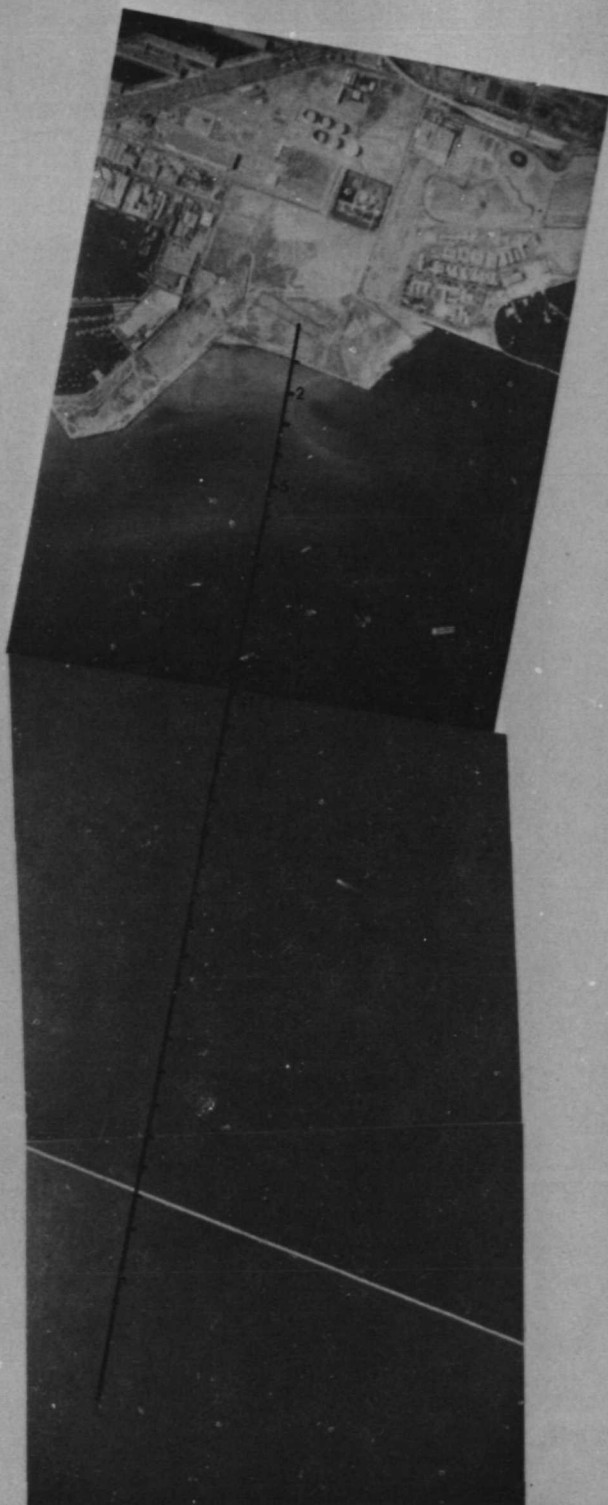


Figure 8 Photograph of Test Area Mapped in Figure 7.

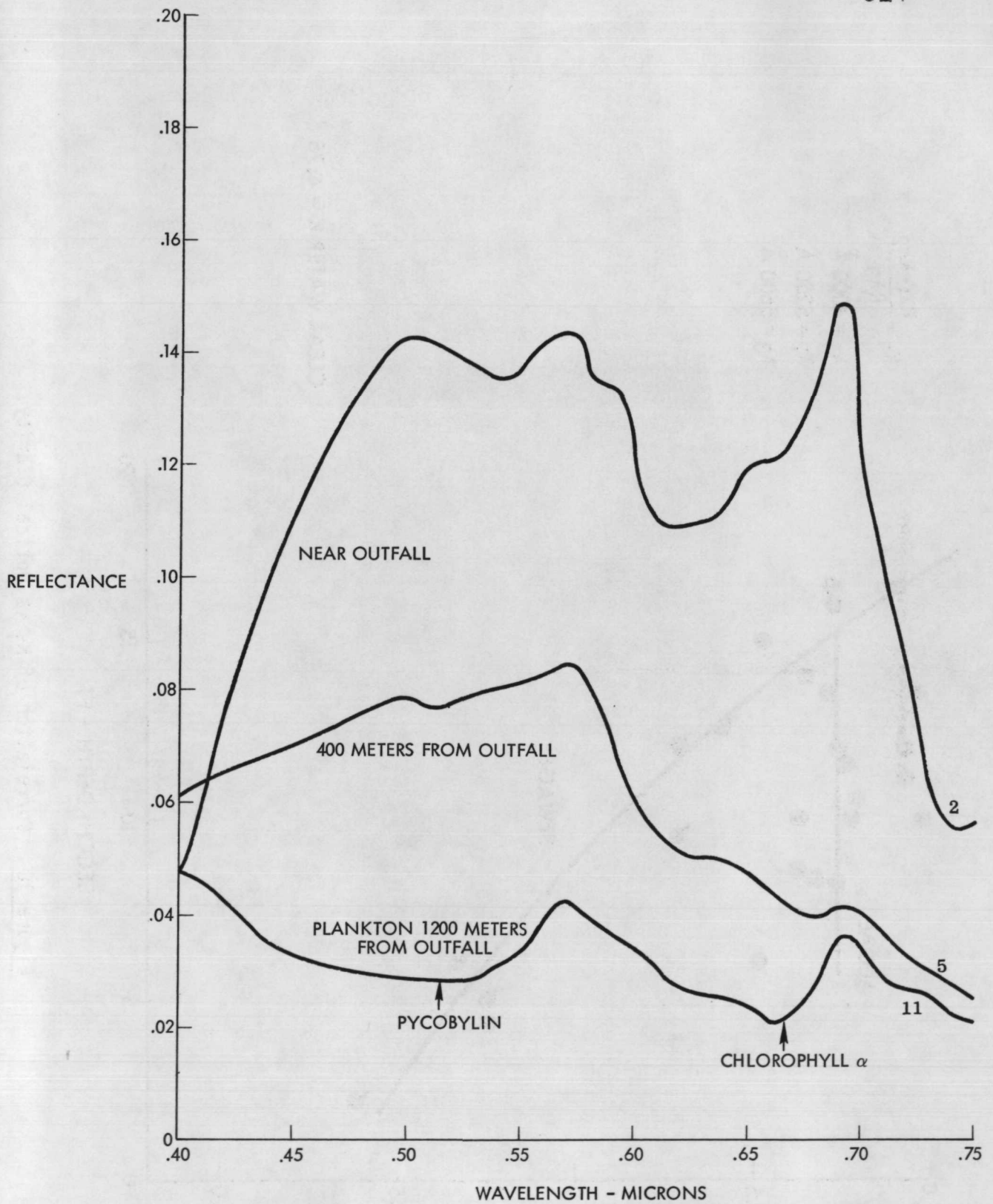


Figure 9 Reflectance Curves From Three Locations.



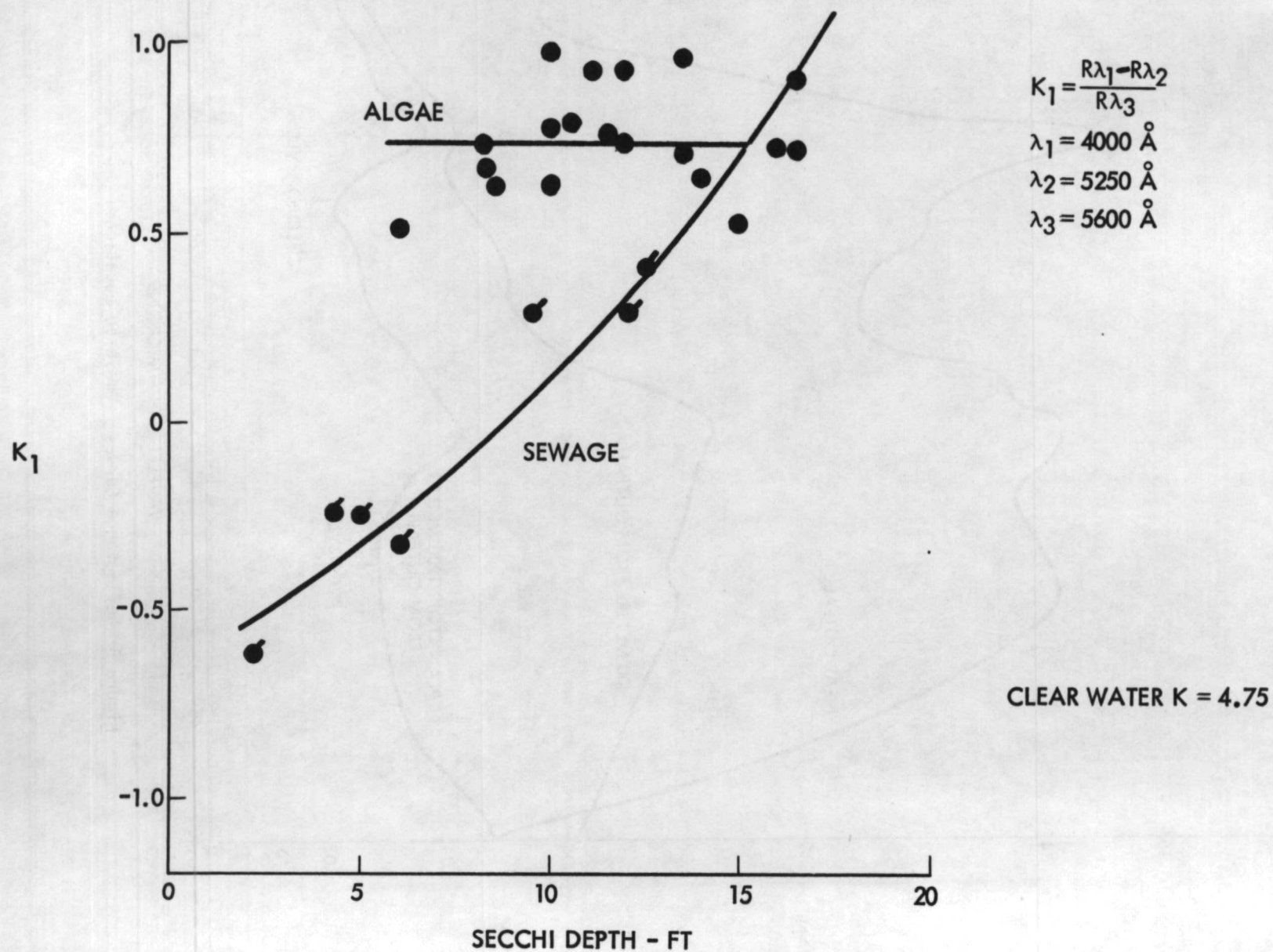


Figure 10 Correlation of  $K_1$  vs Optical Clarity.

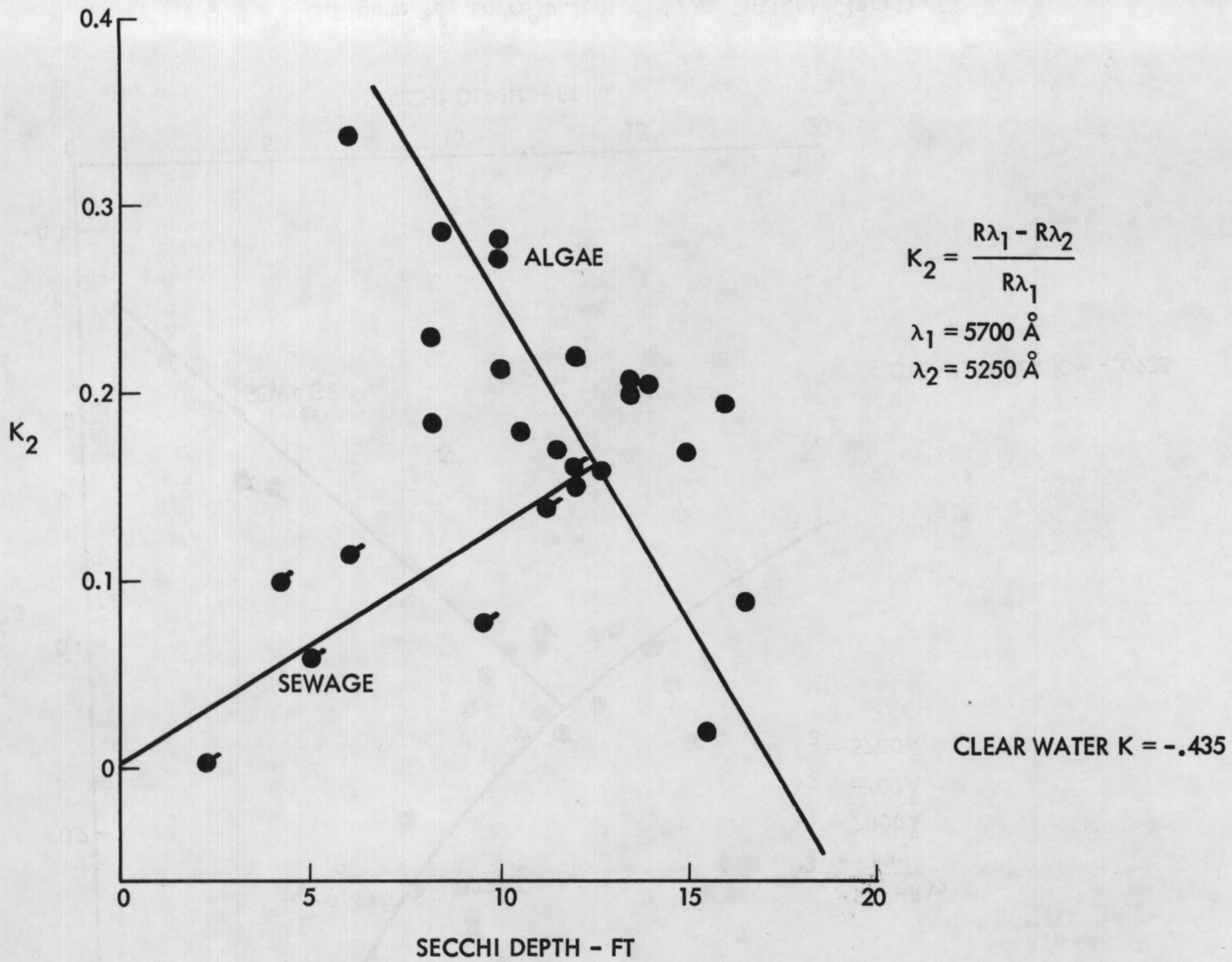


Figure 11 Correlation of  $K_2$  vs Optical Clarity.

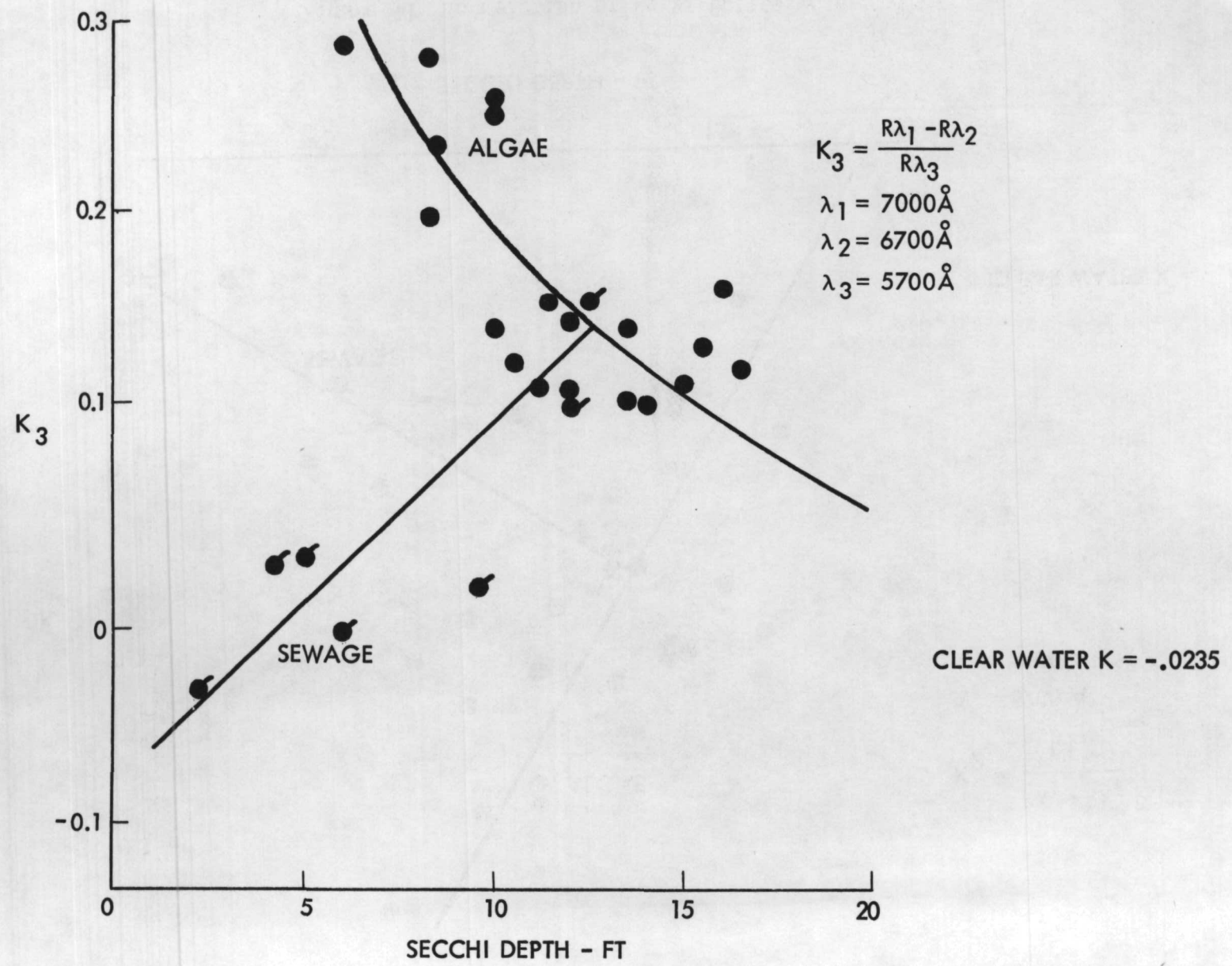


Figure 12 Correlation of K<sub>3</sub> vs Optical Clarity.

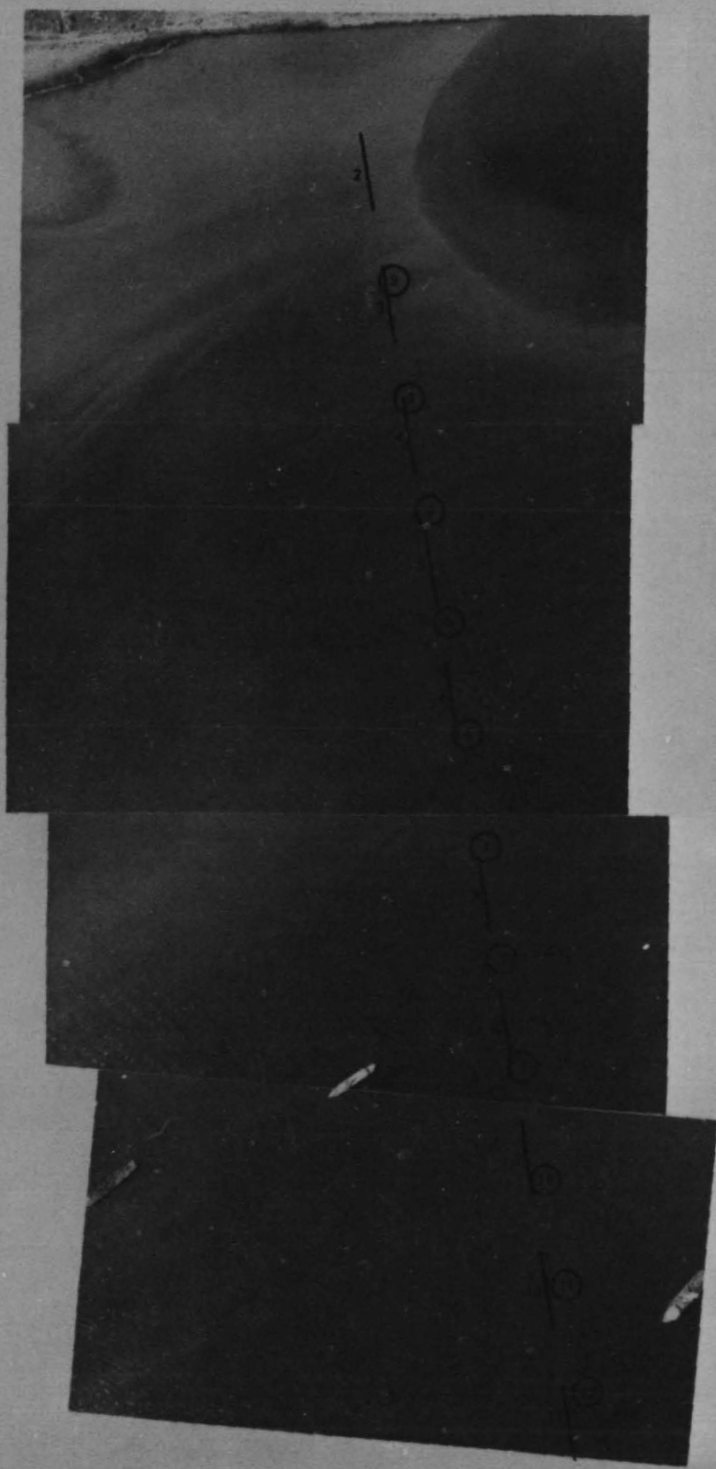


Figure 13 Location of Spectral Scans on Photograph of Northern Portion of Los Angeles Harbor.