

SECTION 106

SURFACE TRUTH MEASUREMENTS OF OPTICAL
PROPERTIES OF THE WATERS IN THE NORTHERN
GULF OF CALIFORNIA

by

Roswell W. Austin
Visibility Laboratory
Scripps Institution of Oceanography
University of California, San Diego

ABSTRACT

Due to the clear, cloud-free atmosphere which prevails over the southwestern United States and northwestern Mexico, many excellent photographs of this area have been obtained from Gemini and Apollo space flights. Several of these show the delta of the Colorado River and the northwestern Gulf of California with remarkable clarity. The clearly discernible water coloration in the imagery has led to the suggestion that remote sensing techniques may be usefully applied in such areas to determine bathymetric information.

Measurements of the optical properties of the water in this region obtained on the Fresnel II cruise of the SIO R/V ELLEN B. SCRIPPS in March 1971 showed that generally low transmissivities prevailed and at no station did the beam transmittance for the total water column exceed 2.5×10^{-8} . In such water, no significant portion of the surface light can be attributed to bottom reflection and any correlation between water depth and spectral radiance at the surface must result from secondarily related phenomena.

INTRODUCTION

The availability of space photography of coastal waters has prompted numerous investigators to examine the possibilities of using such imagery to gather information about the near-shore bottom topography and about the coastal water itself. There are many excellent examples of Gemini and Apollo photography where bottom features are clearly and unmistakably discernible. Demarcations between deep water and shoal water areas can be readily determined. Features

visible within the shoal water areas can be located for subsequent investigation from surface vessels. Other space photography of coastal areas has shown marked water coloration features which can be interpreted as being due to turbid water effluent from rivers and harbors. From such photography, much can be learned about the areal extent of sedimentation from river systems and an excellent synoptic insight can be gained into coastwise currents, insight which could probably never be obtained from a surface-vessel survey. However, one cannot always, in a photograph obtained from orbital altitude, differentiate simply between those variations in image density which are caused by bottom effects and those caused by water effects.

A case in point might be the Gemini 5 and Apollo 9 photographs which have been obtained of the northwestern Gulf of California and the delta of the Colorado River. Excellent photography of this area has been acquired because of the high frequency of orbital coverage and because of the unusually high incidence of clear, cloudless days which the region enjoys. The possibility of using such imagery to obtain bathymetric information directly, or as an aid in acquiring such information, has occurred to numerous investigators. Ross (1) using a density slicing scheme, found some interesting correlations between isodensity contours and reported water depths for this area. Yost (2) also examined the Apollo 9 SO65 experiment imagery of this region and found a correlation between image density and water depths up to about 12 meters.

Unfortunately, the spatial variations in the radiance of the ocean surface, which after modification by the atmosphere are responsible for the image density pattern in the space photograph, are not solely dependent on water depth. Obviously variation in bottom reflectance and in the transmission and reflectance properties of the overlying water will also affect the radiance exiting the water surface. It is, therefore, necessary to demonstrate that these properties are essentially invariant over the region of interest in order to relate uniquely the radiance at the water surface to water depth. We will show that in the northwestern Gulf of California the water properties were not only highly nonuniform but the optical transmittance of the total water column was so low at all locations for which measurements are available that no significant portion of the surface radiance was attributable to light leaving the bottom.

DESCRIPTION OF REGION

The Gulf of California is roughly 600 nautical miles long and averages less than 100 miles in width. In the south, depths as great as 3700 meters are found, while in the north above Tiburon Island, depths are mainly less than 200 meters. In the extreme northern end, sediments from the Colorado River have reduced the depth to less than 40 meters over extensive areas (3). The Colorado River no longer transports any significant quantities of river detritus into the Gulf, however. Since 1935, the formerly large river detrital load has been trapped in Lake Mead. Much of the river water below Hoover Dam has been diverted to agricultural uses for many years and only a minor portion of the total river flow now reaches the Gulf of California (4).

The size and shape of the Gulf provides a resonant system to the semi-diurnal tidal cycle with the result that an 8 to 10 meter tidal range is found in the northern reaches of the Gulf. When the river was still active, spring tides were accompanied by a tidal bore 2 to 3 meters high that swept up the river estuary at speeds of 6 to 8 knots (4). Now, this tidal action on the silted bottom and mud flats of the estuary serves to keep a tremendous sediment load in continual circulation. Tongues of turbid water appear near the surface at the river mouth and farther south flow on the bottom or at intermediate depths with clearer water overlying them.

SURFACE TRUTH MEASUREMENTS

In March 1971 the Visibility Laboratory of the Scripps Institution of Oceanography (SIO) conducted a program of measurements of the optical properties in the waters of the Gulf of California. This cruise, named Fresnel II, was conducted on the SIO R/V ELLEN B. SCRIPPS. The track for the complete cruise is shown in Fig. 1. Stations 8, 9 and 10 were located at the northern end of the Gulf. Two transects were made across the Gulf on successive days, the first at 31° North and the second at $31^{\circ} 20'$ North. Stations were made at approximately 30-minute intervals along each of the transects (Fig. 2). Individual stations were designated 8A through 8S and 9A through 9P.

At each station, a vertical profile of the water transmissivity at a wavelength of 530 nanometers was obtained with the Visibility Laboratory transmissometer (5). This instrument provides an output on an

"x-y" plotter of the transmittance per meter for image-forming light as a function of depth. A thermistor sensor and a second pen provide a simultaneous record of the temperature profile. At each location, a subjective color determination was made against a Munsell color scale. At noon on each day, a longer station, 8-I and 9-I, was maintained while transmittance profiles were obtained at five discrete wavelengths from 450 nanometers to 611 nanometers. At these noontime stations, the Scripps submersible spectroradiometer (6) was used to determine the downwelling spectral irradiance at two depths and the upwelling spectral irradiance at two depths over the wavelength range from 350 to 700 nanometers. While transiting between stations, a continuous record was obtained of the water depth with a precision depth recorder. Station locations were determined by radar fixes on Rocas Consag in the middle of the Gulf and on prominent shore features.

Figure 3 shows a vertical section along the track at 31° North latitude. The solid bottom contour between stations A and S represents our determination of bottom depth. The dotted line is bathymetry which was presented by Thompson in 1965 (4).

Figure 4 is a transmissometer profile showing the transmittance per meter as the ordinate plotted against depth for Station 8-C. Note that the surface transmission is 70 per cent per meter, but that below 4 meters the transmission drops abruptly to less than 1 per cent per meter at 10 meters and continues at essentially zero transmission until the bottom is found at 23-1/2 meters. Only 2×10^{-6} of the image-forming light starting up from a depth of 10 meters will reach the surface without scattering or absorption. The transmission of the remaining 13-1/2 meters is below the measuring capability of our instrumentation. We can state without equivocation, however, that no sensible image-forming light was reaching the surface under this circumstance. The implication of this curve is that there is a moderately clear layer of water overlying a heavy, silt-laden tidal current. The same types of profiles were found at the western stations on both days. The surface water on this station, No. 8-C, was clearer than the ones to the west and north, however. The next profile, Fig. 5, obtained at Station 8-K, shows much more structure in the vertical column, but again we have clear water at the surface overlying layers of varying turbidity and a second layer of relatively clear water between 55 and 65 meters. An image of a feature on the bottom here would be attenuated by about 5×10^{-33} before reaching the surface.

Figure 6 shows the vertical section at 31° 20' North, along the track of the northernmost transect on March 23. The transmittance

profiles on the east shore showed evidence of more vertical mixing, as they had relatively uniform transmittances all the way to the bottom. Transmissivities were generally between only 10 and 30 per cent per meter in this area. Station 9-D was somewhat clearer, however, with transmittances upward of 54 per cent per meter near the surface (Fig 7). This station had the highest total path transmission of any of the stations on the two transects. The total vertical column transmittance for an image at this station was still only 2.5×10^{-8} .

The profile in Figure 8 was obtained at Station 9-J and again shows a reasonably clear layer at the surface with an underlying layer of very turbid water at a depth of about 10 meters. Such a layer not only attenuates bottom images being transmitted through it, but because of its sediment content, it has a higher reflectivity than the overlying water and it might well give a radiometric signal that could be misinterpreted as coming from the bottom.

DISCUSSION

In order to remotely sense water depth, the change in the sensed signal resulting from a depth change equal to the required resolution of the measurement must be larger than those signal changes caused by variations in bottom reflectance or water properties. The effective reflectance of the bottom will change with the type of sands, silts, rocks, etc.; with the roughness and general morphology of the area; and very markedly with the presence or absence of bottom vegetation. The primary water properties involved are the volume absorption coefficient and the volume scattering coefficient. Changes in these will affect both the amount of light reaching the bottom and the attenuation of the reflected light on its return passage to the surface. Additionally, changes in the scattering properties will result in changes in the reflectance of the water as suggested in the previous section.

Information about the bottom reflectance of this region of the Gulf is quite limited. The bottom is composed of sands, silts, and clays in various combinations. They are mostly of terrigenous origin with only a small fraction of biogenous material. The color of those bottom samples reported by Thompson (4) and of the four samples obtained on the Fresnel II cruise were all very similar. The reflectance of all samples as determined by comparison with the Munsell color scale, and for one sample by measurement with a reflectometer, was between 12 and 13 per cent. The incidence of rocks is undoubtedly very small because of the deep layers of sediment deposited by the

Colorado River. The continued scrubbing action of the strong tidal currents prevents extensive growth of bottom vegetation.

Separate absorption and scattering data for the 36 stations in the northern Gulf were not obtained, as such measurements would have been difficult and too time-consuming. Instead, the beam transmittance profiles discussed under "Surface Truth Measurements" were obtained, from which the total volume attenuation coefficient may be computed.

This attenuation coefficient is the sum of the absorption and scattering coefficients and with it one may compute the transmittance of image-forming light through the water column. This is the transmittance for those portions of an image subtending small angles, i. e., for the high spatial frequencies. To compute the transmittance for the general or average radiance level of its bottom, i. e., for the low spatial frequencies in the image, the attenuation coefficient for the diffuse light field must be used. This was determined from the measurements of ambient spectral irradiance versus depth obtained with the submersible spectroradiometer at the two noontime stations. It was found that the attenuation coefficient for irradiance determined by this method was one-fifth the attenuation coefficient for image-forming light, as determined from the transmissometer data, when computed for the same wavelength and over the same water path. It will be assumed that this ratio prevailed at all depths and for all stations in this region.

The need for scattering coefficient data can be eliminated by a direct determination of the water reflectance. This may be accomplished by taking the ratio of the upwelling spectral irradiance to the downwelling spectral irradiance as measured at a single depth by the spectroradiometer. Using the irradiances measured at about 5 meters the reflectances at 530 nanometers were between 1.3 and 1.5 per cent for the two noontime stations.

The above concepts are shown in analytical form in the following. Reference should be made to Fig. 9 for explanation of the terminology. The daylight irradiance, $H_-(0)$, incident on a plane just below the water surface is transmitted to the bottom at depth Z_b with a transmittance for the total path $*T$. The resulting irradiance on the bottom is

$$H_-(Z_b) = *T \times H_-(0).$$

This is reflected upward by the bottom reflectance $_bR$, resulting in an upwelling irradiance at the bottom of $H_+(Z_b)$ which may be written as

$$H_+(Z_b) = *T \times _bR \times H_-(0).$$

Now the parameter of interest is the upwelling bottom radiance,

$${}_b N_+(Z_b).$$

As the bottom will approximate a diffuse or Lambert reflector, this radiance may be written as

$${}_b N_+(Z_b) = \frac{H_+(Z_b)}{\pi} = {}^*T_b R \frac{H_-(0)}{\pi}.$$

If the bottom is essentially featureless so that the average radiance level of the bottom rather than image details of high spatial frequencies is to be transmitted, then the bottom radiance will be transmitted upward with the same diffuse transmittance *T used to determine the transmission of irradiance to the bottom. Therefore we may write

$${}_b N_+(0) = {}^*T_b^2 R \frac{H_-(0)}{\pi}$$

for the component of the radiance just below the surface due to the bottom.

Added to this will be the upwelling radiance contributed by the water ${}_w N_+(0)$. Here also we can make the assumption that the angular reflectance properties of the water are such that we can treat it as a diffuse reflector and therefore write

$${}_w N_+(0) = {}_w R \frac{H_-(0)}{\pi}.$$

Fortunately ${}_w R$ is not strongly dependent upon depth so that we may use the values computed from irradiance measurements at 5 meters to approximate the reflectance just below the surface.[†]

Summing the contributions from the water and the bottom, the total upwelling radiance at the surface is

$$\begin{aligned} N_+(0) &= {}_b N_+(0) + {}_w N_+(0) \\ &= \left[{}^*T_b^2 R + {}_w R \right] \frac{H_-(0)}{\pi}. \end{aligned}$$

† It should be noted that the effect of interreflection of the upwelling light at the surface is neglected in this development for simplification. Although this effect is not trivial in general, its neglect here does not affect the conclusions.

The radiance $tN_+(0)$ is the signal which, after passage through the atmosphere, is remotely sensed and therefore must be functionally related to depth. The diffuse transmittance, $*T$ is, of course, the variable which is depth dependent. Using the five to one ratio found between the attenuation coefficients for image forming and diffuse light the transmissometer profile data was used to compute diffuse transmittances for the total water column, $*T$ at all stations. The highly nonuniform nature of the transmittance profiles as shown in the examples given in Figs. 4, 5, 7 and 8 results in $*T$ values for the various stations which are more dependent on water properties at the particular location than on water depth. Moreover the $*T^2$ term at all stations was so small that radiance resulting from the water reflectance was overwhelmingly larger than that from the bottom, i. e.

$$w_+ N_+(0) \gg b_+ N_+(0).$$

We have placed the requirement that the horizontal variability in $*T$, bR , wR and $H_-(0)$ must result in smaller changes in $tN_+(0)$ than the change which results from a depth increment equal to the resolution of the measurement. It is patently clear that at the 36 stations where surface truth data was obtained the requirement cannot be met.

If we define a ratio F such that

$$F = \frac{b_+ N_+(0)}{tN_+(0)},$$

then

$$F = \frac{bR \times *T}{bR \times T^2 + wR}.$$

For the cases where $wN_+(0) \gg bN_+(0)$

$$F = \frac{bR \times *T^2}{wR}$$

The ratio, F , was calculated for all stations. It was never larger than .01, meaning that at no station on the track did the bottom irradiance signal contribute as much as 1 per cent to the total signal available from the water surface. Thus 99 per cent of this radiance had its genesis in the backscatter from the water itself. Under these circumstances the remote sensing technique may be useful for delineating and tracing turbid water but is unlikely to be of significant value for bathymetric purposes.

One additional interesting computation was performed which illustrates the problem of estimating depth in water with variable transmittance properties. Assuming a bottom with uniform 13 per cent reflectance and a water mass with uniform 1.3 per cent reflectance the depth was computed at each station such that $F = 0.01$. Actual beam transmittance profile data was used with the five to one coefficient conversion mentioned earlier. If the water were uniform in transmittance--which is the assumption which must be made for remote sensing--the depth would be constant. Figs. 10 and 11 show how this imaginary bottom varied in depth due to the water variability.

CONCLUSIONS

Only under circumstances where the variability in bottom reflectance, water reflectance and water transmittance is small over the area of interest can water depth be effectively sensed remotely. Under most situations the signal at the surface which originated at ocean floor must be much larger than that component of the signal generated by backscatter from the water.

In areas such as the delta of the Colorado River, where tidal currents carry tremendous sediment loads rendering the water essentially opaque, any correlation between the sensible variations in the image of the water area and bottom topography must be attributed to secondary relationships as, for example, the proximity to the surface of a reflective, silt-laden tidal current.

REFERENCES

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- (5) Petzold, T. J., and R. W. Austin, An Underwater Transmissometer for Ocean Survey Work, Scripps Institution of Oceanography, SIO Ref. 68-9, April 1968.
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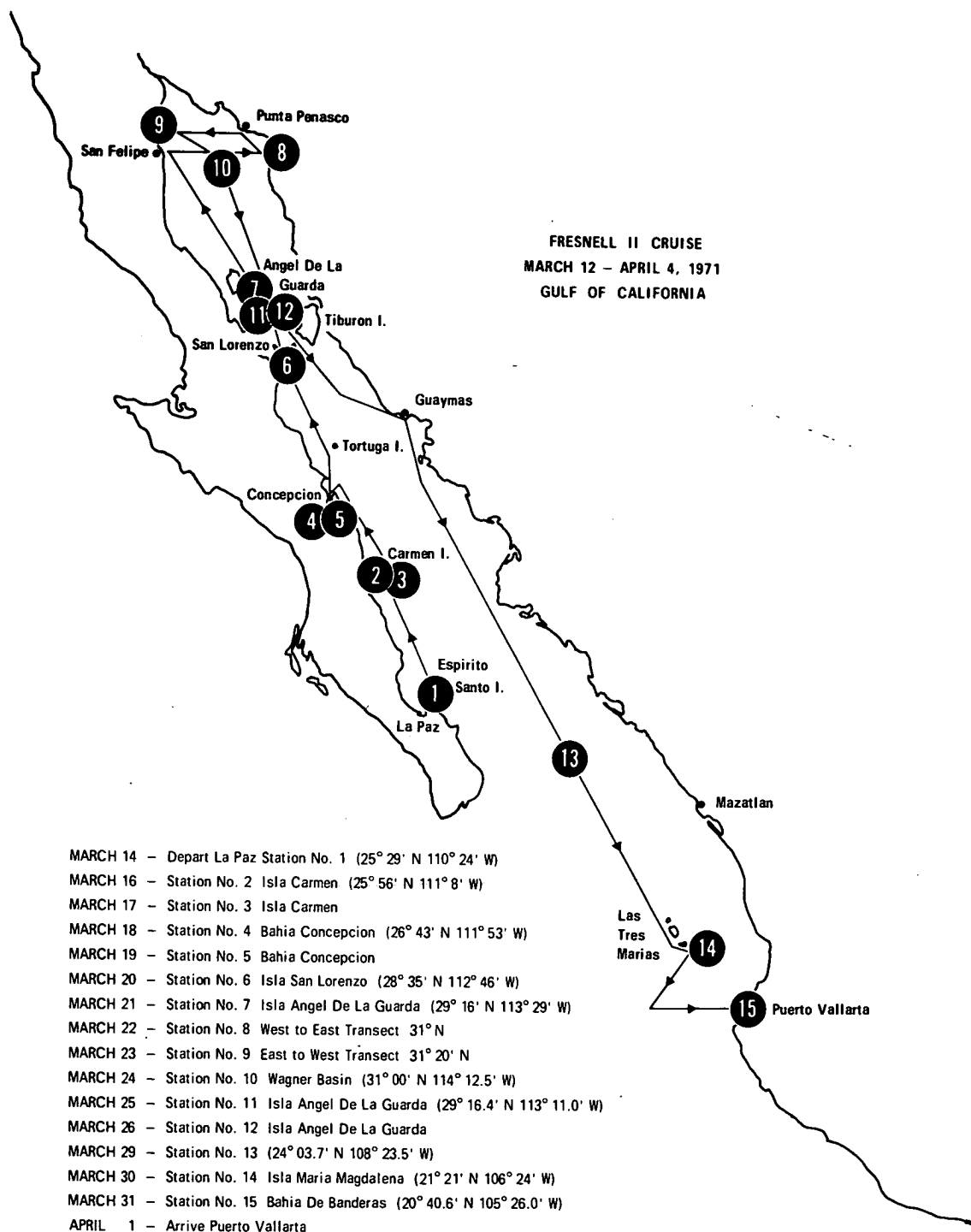
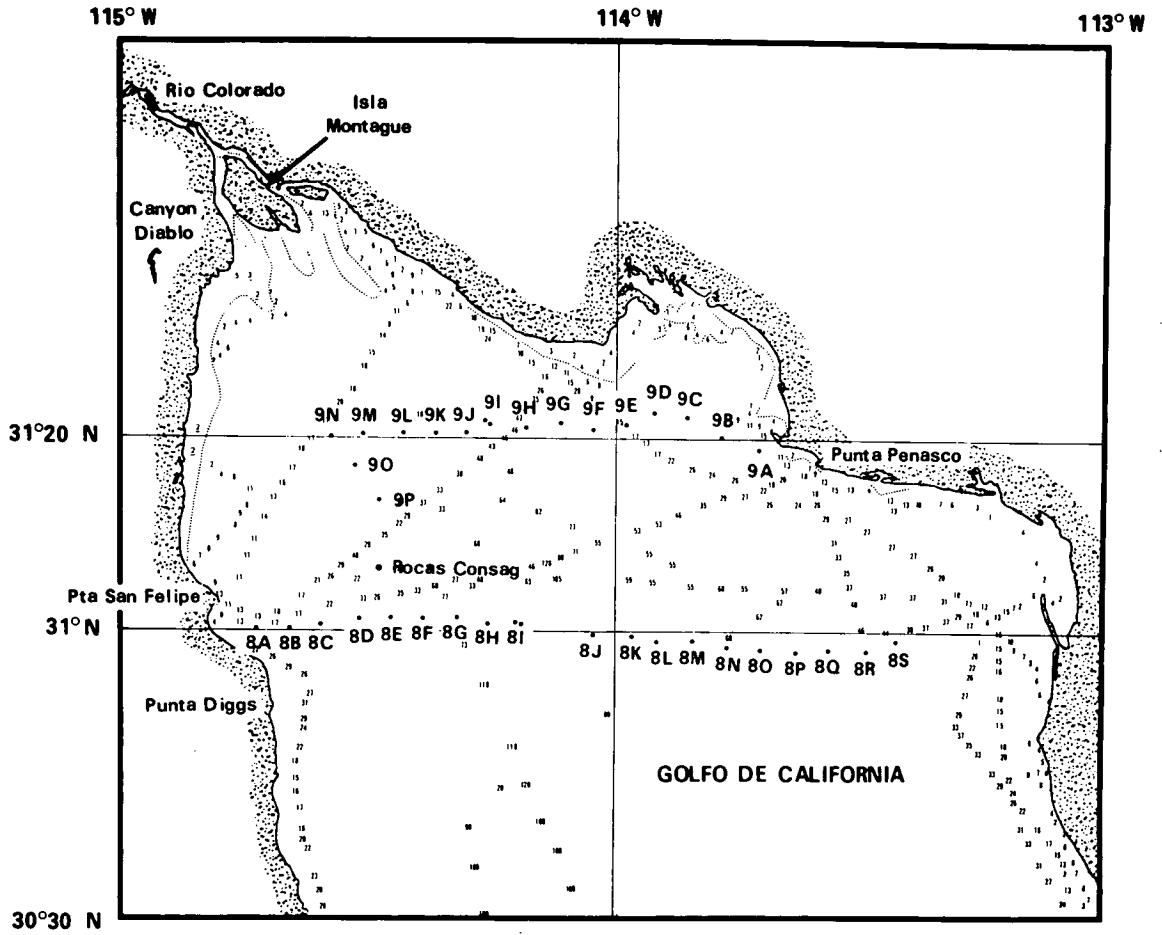


Figure 1. – Track of Fresnell II Cruise.



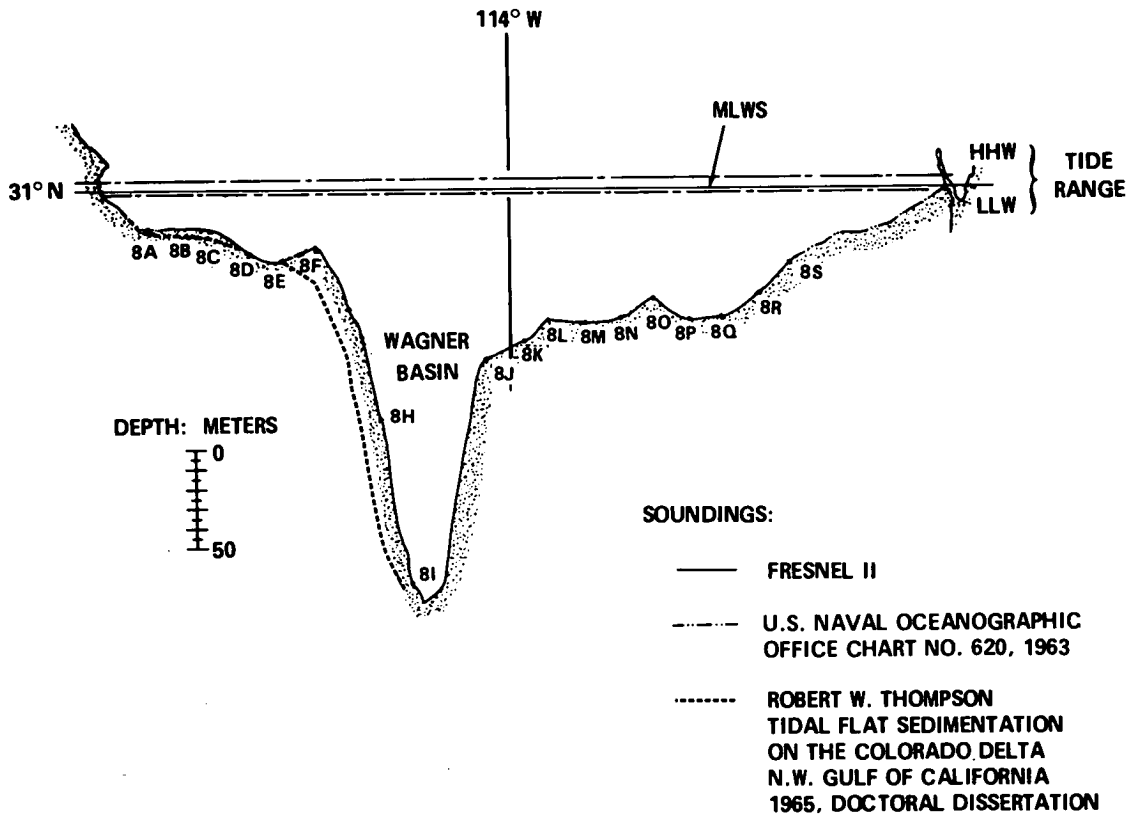


Figure 3. — Depth profile of a section through the Gulf of California at 31° North latitude. Stations 8A — 8S, March 22, 1971.

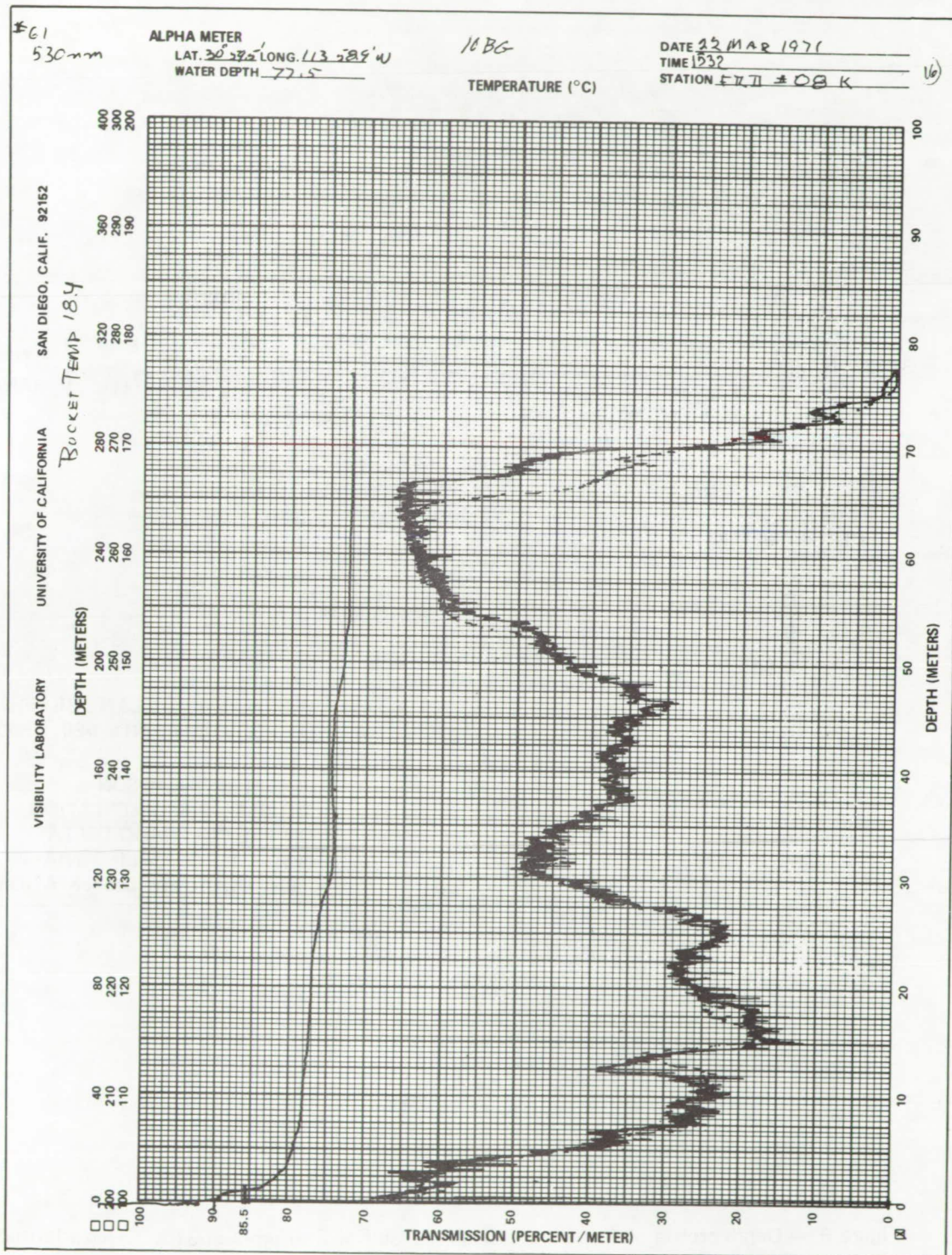


Figure 5. - Profile of transmittance and temperature versus depth at Station 8K.

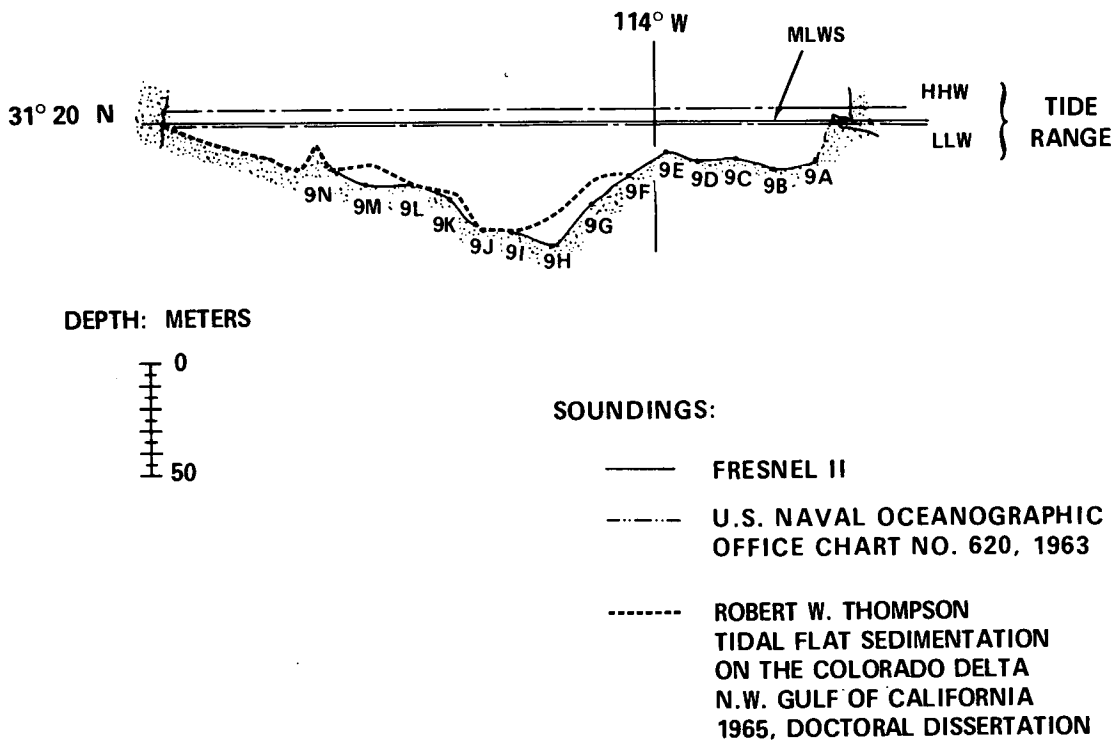


Figure 6. – Depth profile of a section through the Gulf of California at 31° 20' North latitude. Stations 9A – 9N, March 23, 1971.

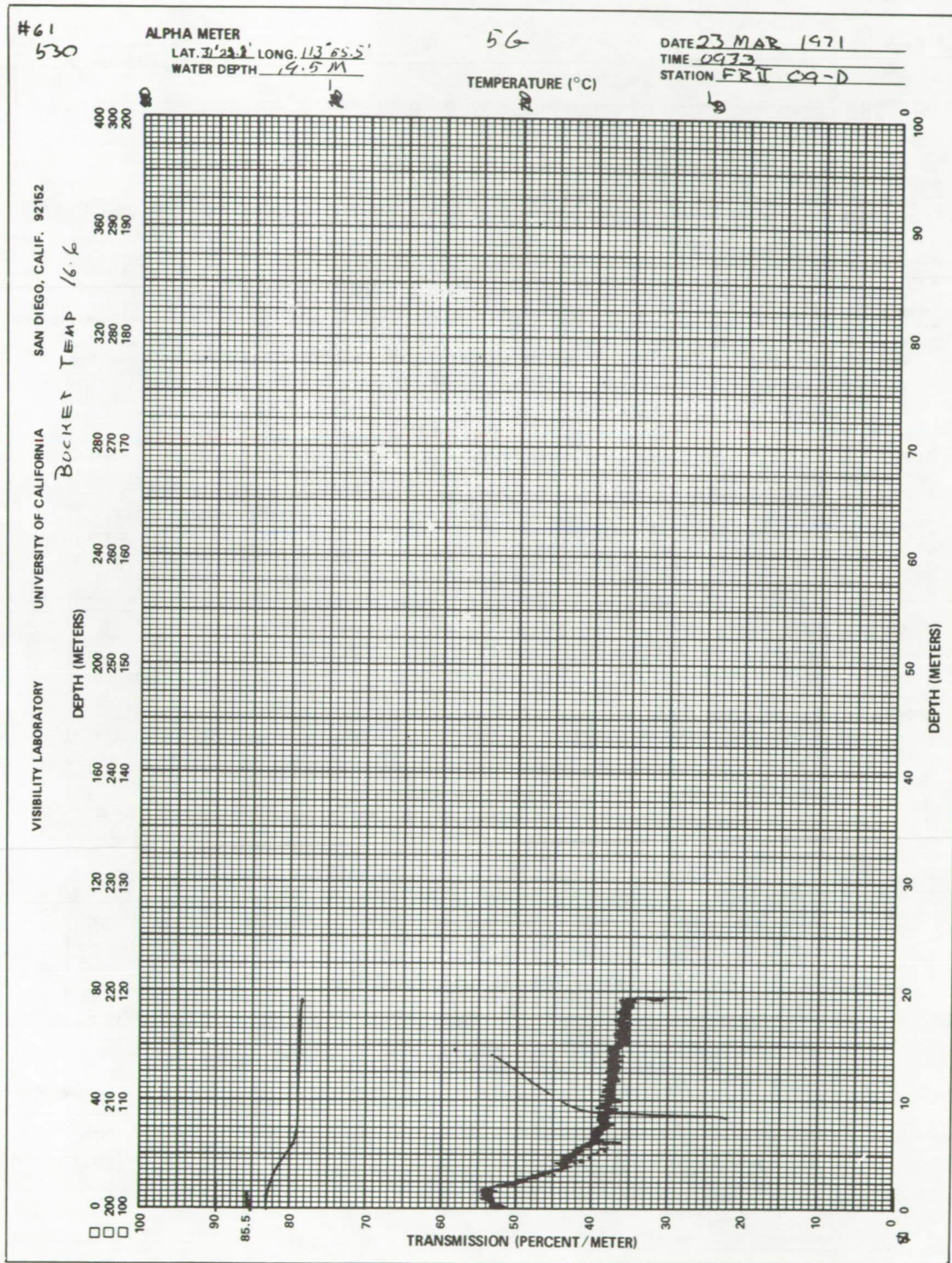


Figure 7. - Profile of transmittance and temperature versus depth at Station 9D.

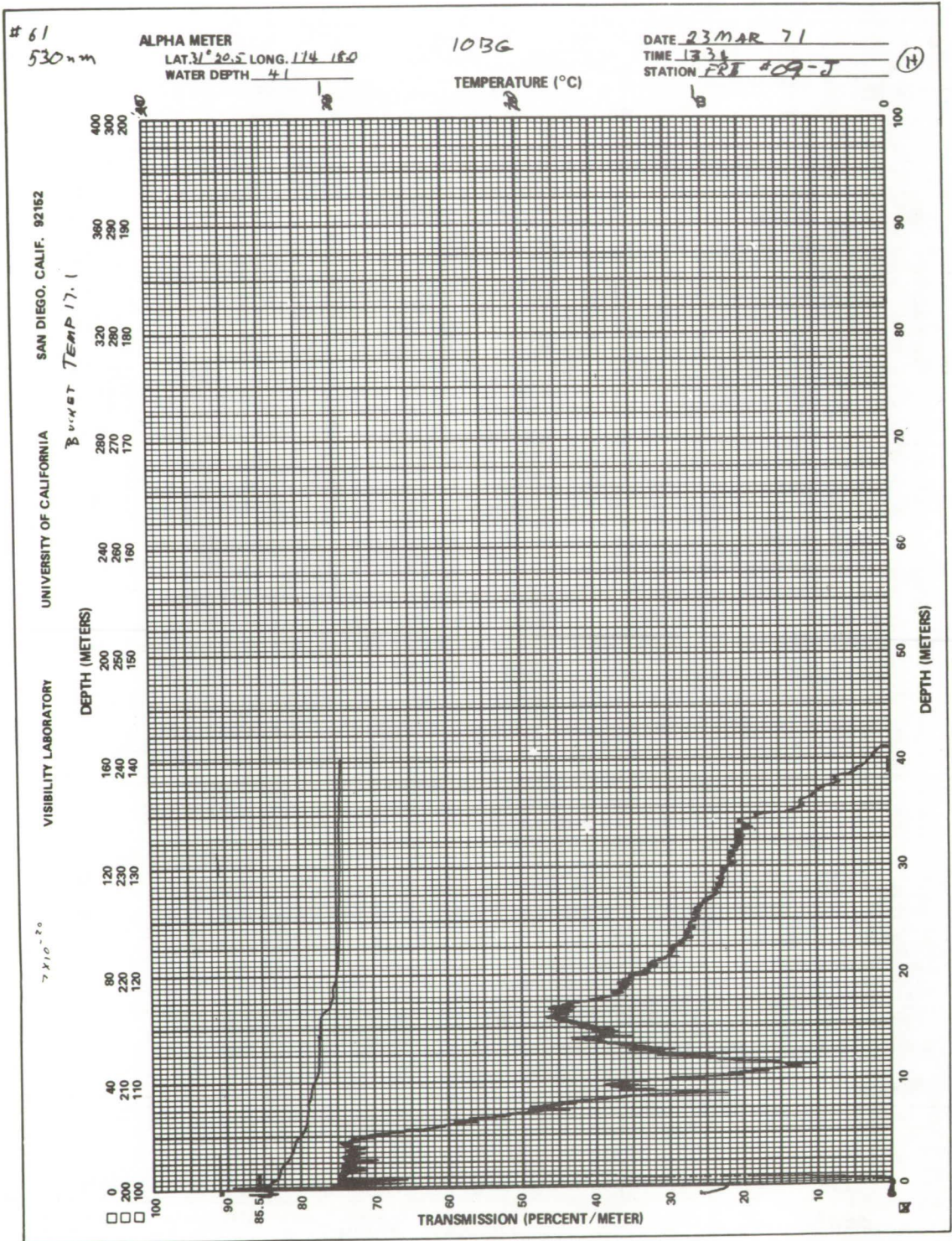
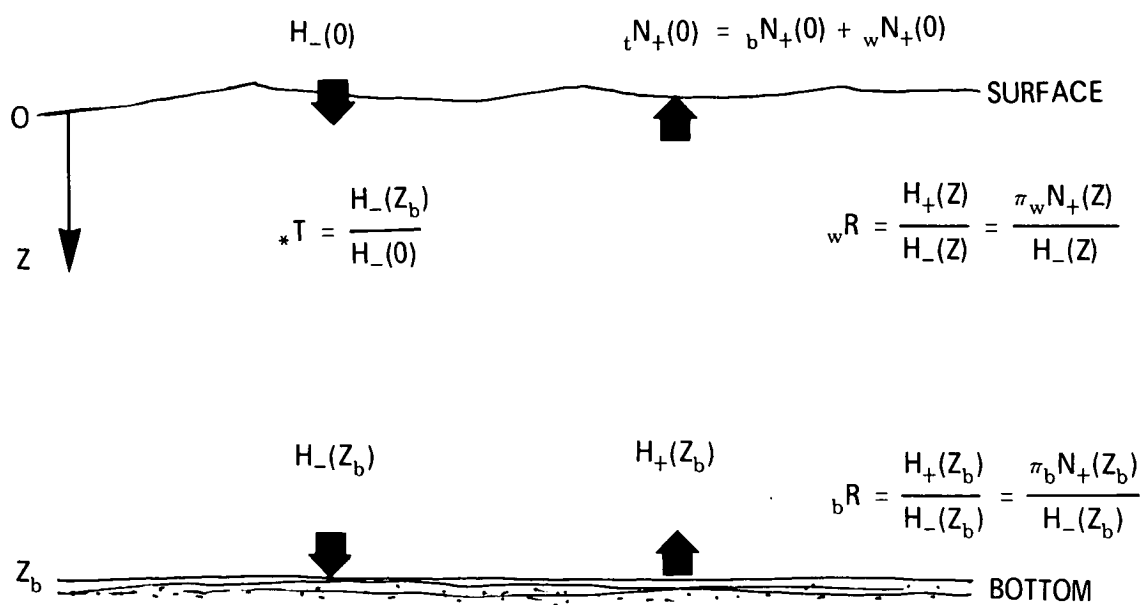


Figure 8. - Profile of transmittance and temperature versus depth at Station 9J.



| | |
|----------|---|
| Z | Depth, 0-Surface, Z_b Bottom Depth |
| $H_-(Z)$ | Downwelling Irradiance at Depth Z |
| $H_+(Z)$ | Upwelling Irradiance at Depth Z |
| $N_+(Z)$ | Upwelling Radiance at Depth Z |
| $*T$ | Irradiance (or Diffuse Light) Transmittance for Z_b |
| ${}_wR$ | Water Reflectance |
| ${}_bR$ | Bottom Reflectance |

Figure 9. – Definitions and Symbology.

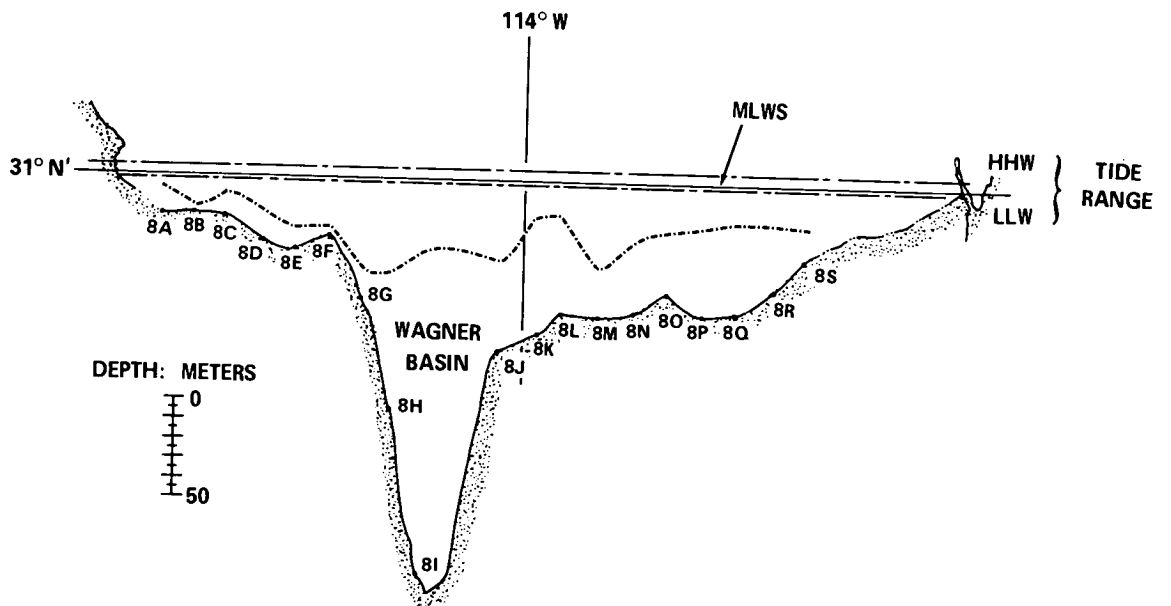


Figure 10. — Section through the Gulf of California at 31° North latitude. Dotted line shows bottom contour necessary in order for bottom to contribute 1 percent to the total upwelling radiance.

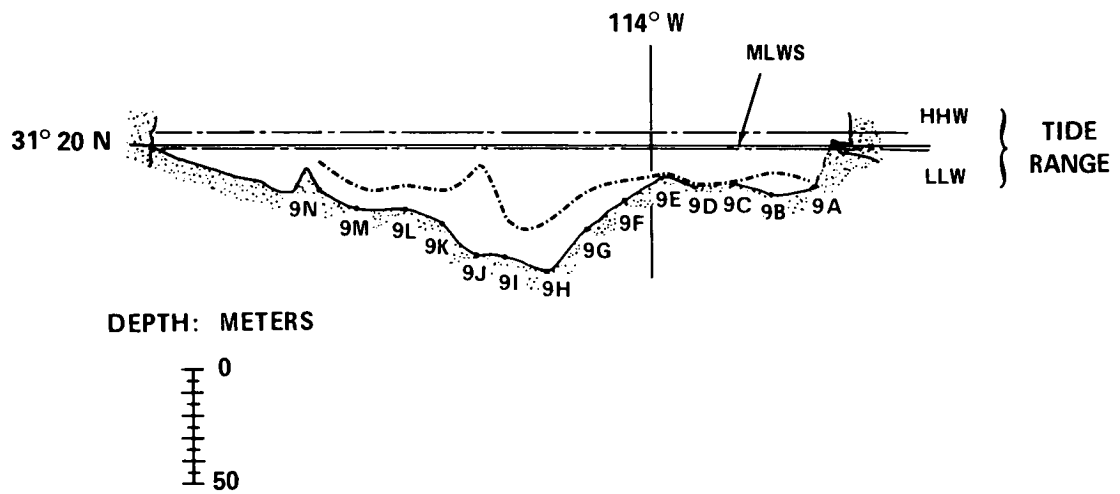


Figure 11. — Section through the Gulf of California at 31° 20' North latitude. Dotted line shows bottom contour necessary in order for bottom to contribute 1 percent to the total upwelling radiance.