SECTION 51

EXPERIMENTS IN OCEANOGRAPHIC AEROSPACE PHOTOGRAPHY

BEN FRANKLIN SPECTRAL FILTER TESTS

Contract N62306-69-C-0072

for the

Spacecraft Oceanography Program
U.S. Naval Oceanographic Office

Prepared by

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Presented by Reece C. Jensen at the Second Annual Earth Resources Aircraft Program Review on 16-18 September 1969.

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ABSTRACT

The spectral region of primary interest for oceanographic remote imaging sensors occurs within a passband approximating 400 to 580 mμ. This includes the region of least light attenuation in clear water and a large percentage of coastal waters, where maximum depth penetration is possible and significant changes in upwelling luminosity occur. The practice in black-and-white aerial photography, however, is to reject image light at wavelengths shorter than 500 mμ in order to suppress effects of atmospheric haze.

Photographic color separation of many Apollo and Gemini color film images taken from space has shown that the blue record contains information significant in oceanography, despite atmospheric haze. Four-band multispectral photography with red, green, blue, and blue-green filters -- taken on flights over the BEN FRANKLIN submersible when on the surface and at 10, 15, and 25 meters in the Gulf Stream -- produced data confirming the utility of a blue filter band for oceanographic purposes. In addition, the results of the photographic evaluation were confirmed by measurements of the downward spectral irradiance made from within the submersible using a scanning spectroradiometer.

For recording ocean water color and optimizing penetration two spectral bands are recommended: 460-510 mμ and 510-560 mμ. If only one passband is feasible, the 460-580 mμ region should be included.

ACKNOWLEDGEMENT

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PURPOSE OF BEN FRANKLIN EXPERIMENT

Photographic flights were made over the BEN FRANKLIN - the largest civilian research submersible in service today - to obtain quantitative data on the possible gain that might be achieved by including more of the blue-green spectrum in oceanographic imagery from space. The data are also applicable to normal oceanographic aerial photography.

The experiment was made possible through the cooperation of the Grumann Aircraft Engineering Corporation, builder and owner of the vessel, and the active assistance of their Ocean Systems Division staff and c... at Riviera Beach, Florida.

Target Area. The BEN FRANKLIN's length of 48.7 feet and beam of 13.3 feet offered a useful target size for aerial photography. For the experiment the deck was painted with a matte white paint* (it was originally coated with a yellow anti-fouling paint) to ensure a large, diffuse, spectrally nonselective reflecting surface in the visible region. The target area was 13 x 28 feet, with the flat part of the deck 4 feet wide. A diagram of the BEN FRANKLIN is shown in Figure 1.

The sides of the hull were freshly painted with white epoxy shortly before the operation. The sail remained yellow.

Spectral Measurements. Spectral measurements were made on a large sample surface of the paint with an EG&G Scanner Spectroradiometer, which was installed inside the submersible looking up through a porthole. The instrument was used to measure the downwelling spectral irradiance in the range 350-750 mμ. Several readings of the downwelling light were taken at each depth to which the submersible was stabilized.

PHOTOGRAPHIC COVERAGE

Multispectral Camera. The Four-Lens Multispectral Camera (R4-B) used in the tests (Figure 2) was equipped with Schneider Xenotar f/2.8 lenses of 152 mm focal length (6 inches), to provide simultaneous images 3-1/2 inches square in four spectral bands. Camera characteristics are itemized below:

a. Four simultaneous images on same film
b. Image format, 3-1/2 x 3-1/2 inches, 40° diagonal field, 32° square field
c. Lenses, 150 mm (6 inch) f/2.8 Schneider Xenotars

*3-M Nextel Velvet Coating Series 110-A10 (white).

d. Spectral bands: Variable, as required
   Nominal, Wratten 47 or 47B (Blue)
   58 or 61 (Green)
   25 or 29 (Red)
   89B, 88A, or 87 (Infrared)
   Blocking filters are used in conjunction with Wratten filters, to suppress transmission in secondary spectral regions, permitting the use of extended red and infrared films with Wratten filter passbands of shorter wavelength.
e. Frame rate, 2 second cycle, nominal
f. Shutter speed, 0.006 to 0.0013 sec
g. A5 film magazine type

K17 Camera. A standard K17 camera, with a 6-inch focal length f/6.3 Metrogen lens and an image format of 9 x 9 inches, was also flown. As directed by the suppliers, no filter was used with the special Ansochrome film loaded in this camera.

Multispectral Camera Film and Filters. Three of the bands in the multispectral camera were equipped with standard color separation filters, Wratten Nos. 47B (blue), 58 (green), and 25 (red). The fourth band had a 2E+38 combination, which effectively bridges the zone between the blue and the green filters. Transmission curves for the filters are given in Figure 3. The 2E+38 combination has a high transmittance in a region of particular interest, 480 mμ (blue-green), where clearwater light attenuation is least. Natural color films have a sensitivity at this point which is about 50% less than in their blue and green peaks.

The 2E+38 combination transmits more light than desired above 580 mμ and in future tests will be replaced with an interference filter to reduce the surface reflectance component in this region.

The spectral sensitivity of the 2484 emulsion film used in the experiment has a peak transmission of the blue (47B) and green (58) filters at almost the same density of 1.0 above fog. The emulsion has a lower RMS granularity factor than Aerial 8403 Tri-X (37 vs. 48), despite its high sensitivity.

Special Anscochrome Film. The K17 camera was loaded with a special GAF Color film, provided through the courtesy of W. E. Vary, U.S. Naval Oceanographic Office. The film is based on Anscochrome D-500, a high-speed, natural-color film. In this version the blue-sensitive layer is omitted during manufacture. The normal yellow dye filter layer is retained to reduce sensitivity of the green layer in the region below 500 mμ.

OPERATIONS

On May 19, 1969, the BEN FRANKLIN was towed from her dock at Riviera Beach, Florida, to a position in the Gulf Stream about 8 nautical miles east of West Palm Beach, at approximately 26°51' N, 79°58' W, where water depth is in the order of 800 feet.

Four photo runs were made on the BEN FRANKLIN, while under tow, to obtain images of the deck above water. Photography of the submerged vessel began 1 hour and 20 minues later than the surface photography.

Sun Elevation. Sun elevation for the surface photography was about 43° (1824 GMT). Changes in sun elevation during the submerged period were:

10 meters (1939 - 1939 - 1946 GMT)	41° - 40°
15 meters (1955 - 2001 GMT)	40° - 39°
25 meters (2013 - 2017 GMT)	38° - 37°

Illumination. Three layers of cloud overcast persisted during the operation, effectively blotting out direct sunlight. Under these conditions, while illumination is diminished by a factor of 3 or more from direct sunlight, less variance is found with changing sun elevation, and relative spectral irradiance on the scene is not altered significantly although the overcast sky reduces energy in the blue region somewhat. The lowest layer of cloud was between 1,100 and 1,600 feet ASL during the flights.

For practical purposes, scene illumination during the 40-minute submerged period is considered to have been constant, possible variations being within system measurement error.

Camera Exposure. The four-band camera shutter was set at 1/400 sec (0.0025 sec), with lens apertures as follows:

Band 1	Band 2	Band 3	Band 4
(47B-Blue)	(58-Green)	(25-Red)	(2E+38-Blue-Green)
f/5.6	f/5.6	f/4	f/8

The blue-green band received one full aperture stop less exposure than bands 1 and 2, while the red band had one stop more exposure. Bands 1 and 2 were oriented in the camera orthogonal to the focal plane shutter travel, to ensure that each received the same exposure, irrespective of variations in shutter acceleration. The special Anscochrome film in the K17 camera was exposed at f/6.3, 1/150 sec.

Environment. Surface winds were less than 10 knots, seas 2 to 4 feet, with moderate swell. Visual water color was blue, identifiable as the Gulf Stream. Surface current in this vicinity is shown on the charts to be about 2-1/2 to 3-1/2 knots.

Navigation. When submerged, the submersible was not visible to personnel on the PIONEER chase vessel, and her positions were called out to the surface vessel by the aircraft pilot. Navigation problems for photo flight lines were encountered as soon as visual contact with the BEN FRANKLIN was lost by the aircraft, below 25 meters.

As the surface and submerged vessels were drifting apart at different rates, changing relative headings by the minute, attempts were made from the bridge of the PIONEER to vector the aircraft by VHF onto the BEN FRANKLIN position at depths below 25 meters by means of sonar range and bearing. The distance between the two soon exceeded the maximum 1000-foot limit in the operations plan; at one stage the BEN FRANKLIN was judged to be 3200 feet from the PIONEER. Analysis of flight-line data makes it unlikely that the aircraft was able to include the BEN FRANKLIN's position in any photography at depths greater than 25 meters because of cumulative vector errors of only a few degrees.

Multispectral Images Acquired. Four sets of four-band images were taken of the BEN FRANKLIN on the surface. The submersible appears in nine sets taken at 10 and 15 meter depths, and in eight sets at 25 meters. No images were acquired in the red (25) filter band below the surface. Enlargements of typical images at each depth are shown in Figures 4a through 4d.*

DENSITY READINGS

Densities were measured on the original BEN FRANKLIN images with a MacBeth Quantalog densitometer, using a 1.0 mm aperture. This instrument has an error of about ±0.02 and repeatability of about ±0.01. Readings were made by two observers on different occasions. Only one set of reading, made by one observer, is used in the analysis, and no attempt has been made to favor a trend or to select "best" readings from other sets.

The density readings were corrected for gamma, filter factor, and changes in sun elevation angle, then normalized to the deck of the submersible while on the surface. Table I compiles all density data on a common base at $\gamma 1.0$ compensated for filter factors and changes in illumination, with the white deck of the BEN FRANKLIN as an equal-energy spectral irradiance reference for each filter band.

INTERPRETATION OF THE PHOTOGRAPHIC DATA

For detecting the underwater object, or in recording differences in the luminance of upwelling scattered light, photographic density of the subject must be higher than the density of the water surface. Image densities in Table I show the relative merits of bands 1, 2, and 4 in this respect, at $\gamma 1.0$. With other films and different processing, higher gammas can be achieved, and the ΔD's would be multiplied by the higher γ factor. The linear portion of Plus-X Aerographic film, for example, reaches $\gamma 2.2$ (white light exposure), and the green-sensitive layer in the GAF Anscochrome D-500 is in the same order. As mentioned earlier, γ can also be raised to a considerable extent during reproduction.

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*A complete index of the BEN FRANKLIN imagery, as well as related oceanographic photography from the Florida coast and keys, the Bahamas, and the Georgia and Carolina coasts, is contained in Appendix A to Philco-Ford SRS Division Technical Report TR-DA2108, "Experiments in Oceanographic Aerospace Photography, I - BEN FRANKLIN Spectral Filter Tests," 29 August 1969.

While the ΔD's can be increased substantially by these means, they will remain proportional to each other in each spectral band. Since this is so, the ΔD's provide a direct figure of merit for each spectral band. Figure 5 plots the density of the BEN FRANKLIN's image for each band at each depth, extrapolated to the densities of the water surface in the respective bands. The figure illustrates two factors:

a. The gradient of the downward slope indicates the rate of decrease in photographic density with depth; the steeper the slope, the greater the attenuation of upwelling irradiance in the spectral band concerned. The blue band clearly shows less attenuation than the green band, while the blue-green band 4 is midway between.

b. The value of ΔD will vary with the subject, its configuration, scale, and other variable factors. By photographic enhancement or other means, density differences in the 0.01 to 0.03 range can be separated from the image. In this case, when the densities of the BEN FRANKLIN images recorded at 25 meters are extended to meet the water surface densities in each band, it can be seen that band 2 (green) is rapidly approaching an extinction point short of 30 meters where the density of the FRANKLIN's image would be indistinguishable from the water surface. Band 1 (blue) and 4 (blue-green) would have reached their end points around 35 meters. Therefore, at any other proportionately higher gamma, the blue and blue-green bands would continue to outperform the green band in penetration.

It is important to understand that these data are relative and pertain to the conditions existing at the time of the tests, when downward illumination was less than normal by a factor of 3 to 5 times. In full sunlight, much deeper penetration would be obtained in each spectral band; nevertheless, the relative merits of each to "penetrate" would remain at or very close to the same ratio.

The photography was taken at low altitude, where atmospheric haze effects were insignificant. Most of the deleterious effects of haze in aerial photography arise at altitudes of less than 30,000 feet. The most serious absorption and scattering is caused by Mie particles, water droplets, pollen, dust, salt nuclei, and these are seldom found in serious concentrations above 15,000 feet. To obtain a better insight on the effects of haze in ocean areas on the quality of images taken with the same spectral bands, coverage was obtained from 20,000 feet and with the same multi-spectral camera along the Bahama cays and from the Florida, Georgia, and Carolina coasts to Cape Hatteras. About two-thirds of the worst atmospheric effects were below the camera.

Visual assessment of the imagery as directly recorded is not valid, since the blue record is invariably of lower contrast than the green image in this system. In Figure 6a, the blue record of a sample multispectral image set has been raised in underwater scene contrast to match that of the green (Figure 6b). It can be seen that each spectral band contains useful subsurface information. The results in "penetration" obtained in these two images taken simultaneously from 20,000 feet are very similar to the blue and green separations of a color film made from an altitude of over 100 nautical miles.

It could be argued that haze varies, and is worse on some occasions or in some regions of the earth than in others. This may be true. And the same argument can be applied to cloud cover. The Gemini and Apollo photography has amply demonstrated that despite cloud, the acquisition of earth resources imagery is feasible. It is also considered that the same photography proves the practicability of including a blue record, despite atmospheric haze, as a spectral band of great value in oceanographic remote sensing.

The failure of band 3 (red) to penetrate to a 10-meter depth is normal, as the absorption factor of water for light in this spectral region is 4 to 5 times greater than in the blue and green. Because of the high attenuation factor, the contrast of detail in shallow water appears higher in the red than in the green; however, the same information can be recorded at the same depths in either the blue or green bands, and there is no special virtue in having a red record for penetration per se. The red record is useful for aiding detection of sediments in depths down to 6 or 8 meters, and in discriminating surface effects.

ON-BOARD LIGHT MEASUREMENTS

The basic objective of the instrumentation on board the submersible was to measure the spectral distribution of a portion of the downward irradiance incident on the deck of the submersible. These measurements were to be made at a number of different depths ranging from the surface down to 45 meters. The nature of the instrument used for measurement of downward irradiance and the geometry and orientation of the instrument in the submersible were such that only the irradiance in some narrow region of the zenith direction was actually determined. The spectroradiometer used for the experiment was mechanically scanned over the visible spectrum from 350 to 750 mμ in 25 mμ steps. At each wavelength the instrument was allowed to stabilize, and at least two independent readings were taken. An x-y recorder was provided for recording the resultant data, but various instrument mounting problems prohibited the recorder from being used and all results were manually recorded.

Instrument Characteristics. The instrument used to measure downward irradiance was an EG&G Spectroradiometer Model 585. Its characteristics are:

Quantity	Value
Wavelength covered	350–750 mμ
Detector photo surface	S-5
Slit size: Entrance	5.36 mm
Exit	3.0 mm
Grating bandwidth	20 mμ
Beam input	*5.0°
Hooded Filter Holder Cone Angle	14.0°

*This is not the effective field of view of the instrument. A discussion of the effective field of view of the instrument is provided in Section IIIB.

Quantity	Value
Filters (Corning)	
Range (350 - 550 mμ)	CS-0-54
(550 - 800 mμ)	CS-3-69
Instrument reading for steady source	amps
Minimum power for full scale deflection	$1.1x10^{-8}$ (watts/cm^2-mμ) at 450 mμ
Minimum instrument reading	$1.0x10^{-11}$ amp

The instrument measures the energy from a given source either point or finite at any desired wavelength with a discrete known bandwidth.

Determination of the Effective Aperture of Spectroradiometer (S/R). The instrument response curve derived from the instrument manufacturer (Figure 7) shows the percent of peak response as a function of the half angle of field of view. The two curves provided are for the cases where the hood is in place and removed. At approximately 12° off axis the instrument response is only 10% of the peak response with the hood in place. Since in the actual installation of the S/R in the submersible the field of view was restricted by the port (see Figure 8), the actual effective field of view was considerably less than that predicted from Figure 7. Because no actual readings were made to establish the instrument response curve, once the S/R was installed in the submersible, the actual field of view can only be estimated. It is safe to say, however, that the field of view was no smaller than 10° and certainly no larger than 20°. Since for purposes of the underwater energy measurements the energy distribution is itself falling off logarithmically from the zenith direction, an effect value for the instrument field of view of 10° was selected as best representing the 90% energy collection angle for the instrument.

Instrument Installation in Vessel. The EG&G Spectroradiometer was mounted on Bunk 3 with its optical axis pointing directly up through the port. The field of view of the S/R was essentially reduced to 10° by the port geometry. Figure 8 provided by Grumman Aircraft shows a cross section of the BEN FRANKLIN at the location of the S/R. Figure 9 shows an actual photograph of the instrument in place as it was finally installed.

Two originally planned features of the installation were not possible in the final installation. First, the distance between port and Bunk 3 did not permit the use of the standard hooded filter supplied with the instrument. In place of the hood a black shroud was installed between the port and the S/R. Second, the x-y recorder could not be used because of mounting location problems. All data had to be recorded by hand, but several independent readings were taken at each depth to minimize human errors. The shroud was equally as effective as the hood since the light level inside the submersible was quite low during the experiment.

In Figure 9 is shown a photograph of the BEN FRANKLIN on the surface with the view port for the S/R painted black. This was done to minimize the effects of stray outside light on the measurements.

DATA PROCESSING

The following is a brief description of the computer program written for processing the S/R data. The program draws a log-paper grid.

The calibration curves are tabulated in DATA statements in the program as the arrays A, B, C, D, and E. Tabulated values are in units of millimicrons and amp/(watts/cm^2-mμ). The curves are interpolated by walking a quadratic,

$$\log w = a_1 + a_2 x a_3 x^2 ,$$

along the monotonically stored data points. The first point to be parabolically fit is the first tabular wavelength preceding the wavelength to be interpolated for.

The intensities are stored in the array PDATA with their corresponding wavelengths from the input card. The listed output is

N	Curve number, NC (Filter 3 or 4)
WAVE	wavelength (mμ)
METER	test lamp (amp)
XI	first wavelength of tabulated curve used to fit
(Quad. Fit Coeff)	a_1, a_2, a_3 in the equation above
W(CURVE)	interpolated spectral response
Irradiance	I = z/w
Scaled Irradiance	log I

CORRECTION FOR LARGER SLIT-SIZE CALIBRATION

The calibration curve for the instrument using the S-5 detector and standard slit sizes is shown in Figure 10. A standard WI lamp at 2900°K was used to obtain a correction factor for the effect of using the wider slits. The resultant calibration data is shown in Table II.

CORRECTION FOR WINDOW ATTENUATION AND INSTRUMENT GEOMETRY

The light losses in passing through the window of the submersible were originally to be evaluated by (1) making irradiance measurements through the window from inside the submersible while at the dock, and (2) repeating this process outside the submersible looking straight up at a clear sky. Some difficulty was encountered with the data taken at the dock site due to the intermittent passing of smoke over the dock from the adjacent powerplant. Hence after the experiment had been completed in Florida, tests were conducted on a spare window from the BEN FRANKLIN which was borrowed from Grumman Aircraft. A jig was made to hold the window in the same geometry as it would be in the submersible, and a series of runs was made using the S/R with and without the window in place.

An approximated reduction in irradiance of 20 percent was obtained as a result of the window being in the light path. This correction factor as a function of λ was then applied to all data in a similar manner as the slit correction. The slit correction required a reduction computed energy of approximately 4 and the window correction required an increase in the computer energy of approximately 20 percent. Of course, the window correction was applied only to data taken from within the submersible.

INTERPRETATION OF SPECTRORADIOMETRIC DATA

Evaluation of the S/R Data indicates that the energy level in most cases peaks out between 450 and 550 mμ; the maximum energy being received by the instrument was at or near 475 mμ. Since the instrument as previously described measures energy over a 20 mμ portion of the spectrum, the significance of a specific value for the wavelength for maximum energy transmission is not meaningful. However, the band of 450-500 mμ certainly seems to contain the region of maximum energy transmission.

Figure 11 is a composite of the average energy curves taken when the vehicle was below the surface. The curves are consistent with increasing depth and they seem to indicate a higher energy transmission in the blue 430 mμ than in the green 530 mμ for all depths. All of the curves seem to have a noticeable bump near the point of peak energy transmission. This bump seems to be more pronounced for the deeper measurements.

Another characteristic of the data is the apparent increase in energy that occurs at or near 650 mμ. In several cases the energy rises sharply in this region. This effect is apparently due to the very steep detector sensitivity in this region. The last section of the detector response curve 650-750 mμ is quite sensitive to the wavelength setting in this region. For this region of the spectrum and these energy levels, an S-20 detector should probably have been used. The consistency of the increase does, however, leave the question open for discussion.

Figure 12 shows the average of the measured downward spectral irradiance for the blue and green bands as a function of water depth. The interesting feature of these results is that they confirm the photographic results that indicate the additional energy in the blue over the green as the depth increases. Again a bump or increase in energy appears to have existed at or near 35 meters, which might be explained by some form of layer in the water at this depth. The fact that it occurred in both the blue and green bands rules out the effect as being measurement uncertainty.

CONCLUDING REMARKS

Current planning for multispectral remote earth resources sensing is based on images acquired in three spectral bands, essentially, green, red, and infrared. Information useful in oceanographic interpretation can be found in varying degree in each of these spectral regions. However, unless a blue spectral record is also included, much oceanographic information of fundamental importance will not be obtained.

The blue record combined with the green permits water color and its changes to be detected and evaluated in the blue and blue-green spectral regions. This part of the spectrum is where the color of the largest percentage of the world's oceans is found, where clear water penetration is greatest, and where small changes in color are related to major ocean phenomena. It is therefore recommended that:

a. Two spectral bands be used for oceanographic imaging, to be obtained with sharp cut-on and cut-off interference filters. Variations in the passband with angle is not of significance with lens field angles now contemplated for orbital sensors.

b. The two suggested passbands are 460-510 mμ and 510-560 mμ.

The results from the measurements taken from within the submersible indicate that a very useful purpose can be served by this form of data. If an experiment of this type is to be meaningful, energy measurements must be taken. Such measurements should include both upward and downward irradiance as a function of depth below the surface, as well as the irradiance distribution function $f(\theta)$. The implementation of a mobile platform* should contain as a minimum a narrow-field-of-view spectroradiometer that could be scanned in both frequency and the direction of view automatically from the surface. The addition of this form of energy measurement would greatly help to increase the understanding of how remote sensors in the visible spectrum may best be applied to water color and water depth penetration applications of oceanography.

*A complete index of the BEN FRANKLIN imagery, as well as the related oceanographic photography from the Florida coast and keys, the Bahamas, and the Georgia and Carolina coasts, is contained in Appendix A to Philco-Ford SRS Division Technical Report TR-DA2108, "Experiments in Oceanographic Aerospace Photography, I - BEN FRANKLIN Spectral Filter Tests," 29 August 1969.

TABLE I

SUMMARY OF NORMALIZED DENSITIES

Roll No. 69001	BEN FRANKLIN 4-BAND MULTISPECTRAL PHOTOGRAPHY - 19 MAY 1969											
	Blue			Green			Red			Blue-Green		
	Band 1 - 47B			Band 2 - 58			Band 3 - 25			Band 4 - 2E + 38		
	Ben F.	Water Surface	ΔD	Ben F.	Water Surface	ΔD	Ben F.	Water Surface	ΔD	Ben F.	Water Surface	ΔD
Surface	2.00	1.33	0.67	2.00	1.07	0.89	2.00	0.96	1.02	2.00	1.20	0.73
10 Meters	1.73	1.33	0.41	1.55	1.07	0.48	----	0.96	----	1.74	1.20	0.44
15 Meters	1.62	1.33	0.30	1.32	1.07	0.26	----	0.96	----	1.50	1.20	0.31
25 Meters	1.47	1.33	0.14	1.16	1.07	0.10	----	0.96	----	1.34	1.20	0.14

NOTES:

1. The RMS density values in the ΔD columns were calculated from the density differences of individual negatives and not by subtracting the RMS water densities from the RMS BEN FRANKLIN densities.

2. All densities were referenced to the photography of the BEN FRANKLIN while on the surface. Primary reference was BEN FRANKLIN'S deck, and all have been made to = D.2.00. Secondary reference was established as the density of the water surface relative to the deck. Submerged BEN FRANKLIN densities have been adjusted to the secondary reference.

3. All densities are on a $\gamma 1.0$ response curve to scene luminance, and can be read in terms of lens aperture stops (0.30 unit).

TABLE II

CALIBRATION DATA FOR WIDE SLITS

Wavelength (λ) (mμ)	Instrument Reading (amps) Narrow Slits	Wide Slits	Ratio* (A_w/A_n)
350	6.99×10^{-10}	2.8×10^{-9}	4.00
375	1.67×10^{-9}	6.43×10^{-9}	3.85
400	3.17×10^{-9}	1.24×10^{-8}	3.91
425	5.18×10^{-9}	2.03×10^{-8}	3.92
450	7.37×10^{-9}	2.88×10^{-8}	3.91
475	9.28×10^{-9}	3.54×10^{-8}	3.81
500	1.07×10^{-8}	4.07×10^{-8}	3.80
525	1.14×10^{-8}	4.34×10^{-8}	3.81
550	1.03×10^{-8}	3.92×10^{-8}	3.81
** 550	9.69×10^{-9}	3.64×10^{-8}	3.76
575	8.14×10^{-9}	3.08×10^{-8}	3.78
600	4.21×10^{-9}	1.68×10^{-8}	3.99
625	8.48×10^{-10}	3.62×10^{-9}	3.90
650	2.38×10^{-10}	9.30×10^{-10}	3.91
675	7.65×10^{-11}	2.99×10^{-10}	3.91
700	2.70×10^{-11}	9.50×10^{-11}	3.52
725	1.26×10^{-11}	3.45×10^{-11}	2.74
750	0.82×10^{-11}	1.65×10^{-11}	2.01

*The ratio of A_w/A_n represents the increased amount of energy at the detector as a result of essentially doubling the inlet and exit slit areas. This ratio was then used to correct all data as a function of wavelength.

A_w = instrument reading using wide slits
A_n = instrument reading using narrow slits

**Filter change.

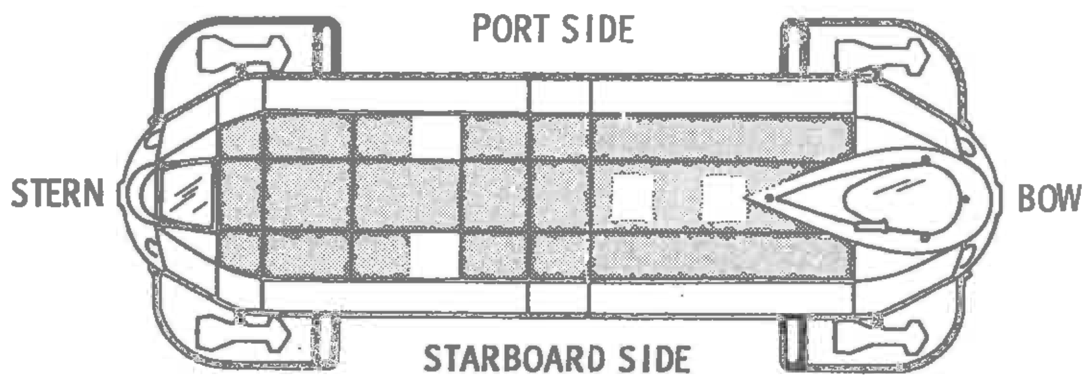


Figure 51-1.- Top deck of Grumman submersible, Ben Franklin.

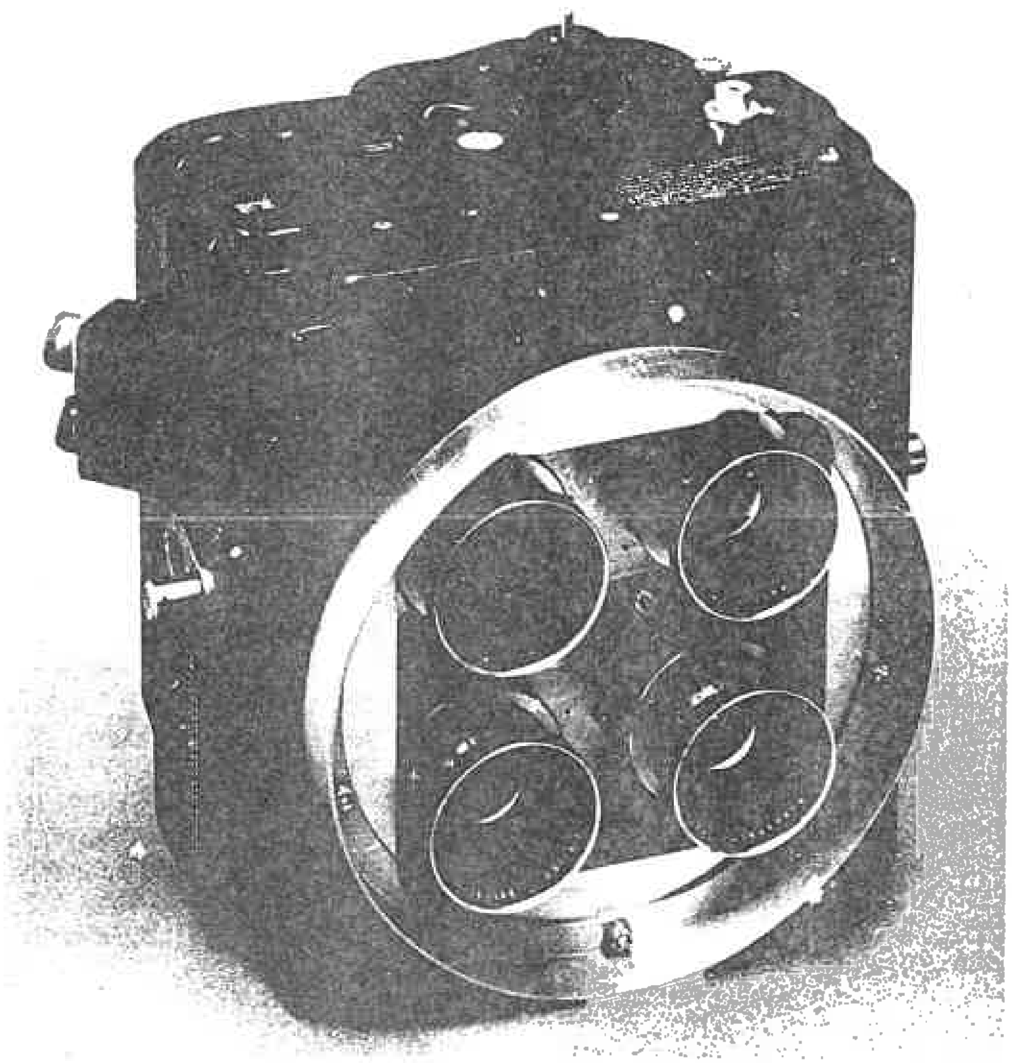


Figure 51-2.- R4-B four-lens multispectral camera.

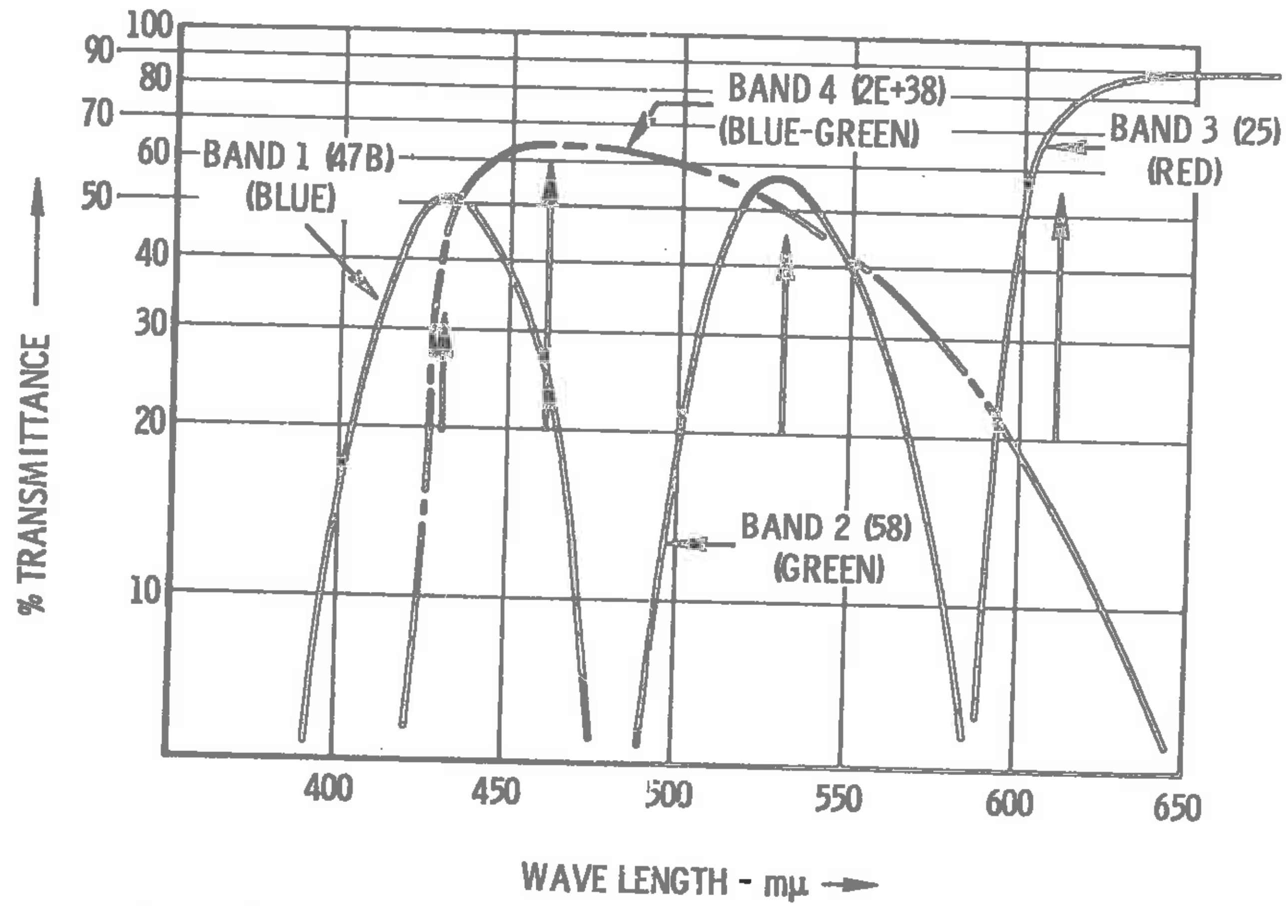


Figure 51-3.- Transmittance of filters in R4-B multispectral camera for Ben Franklin experiment.

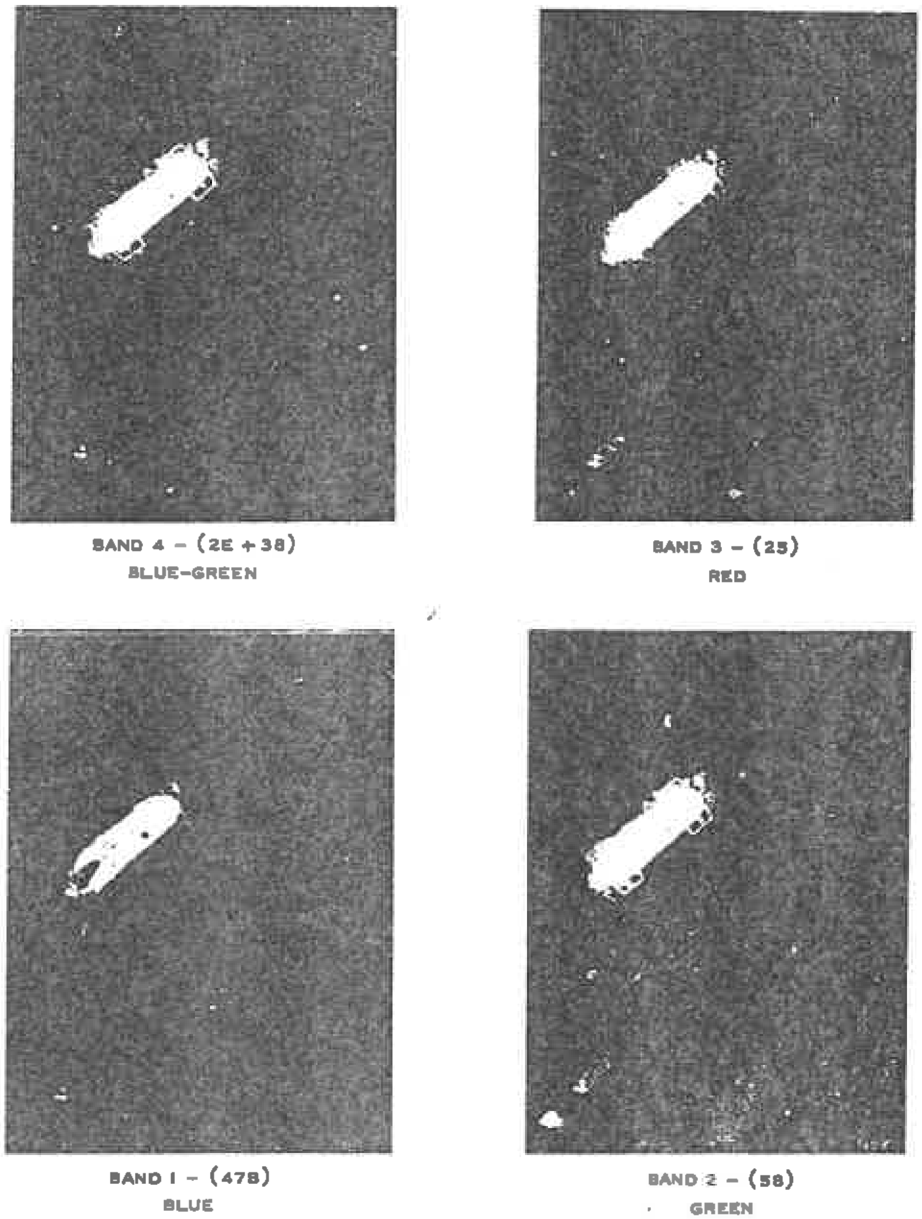
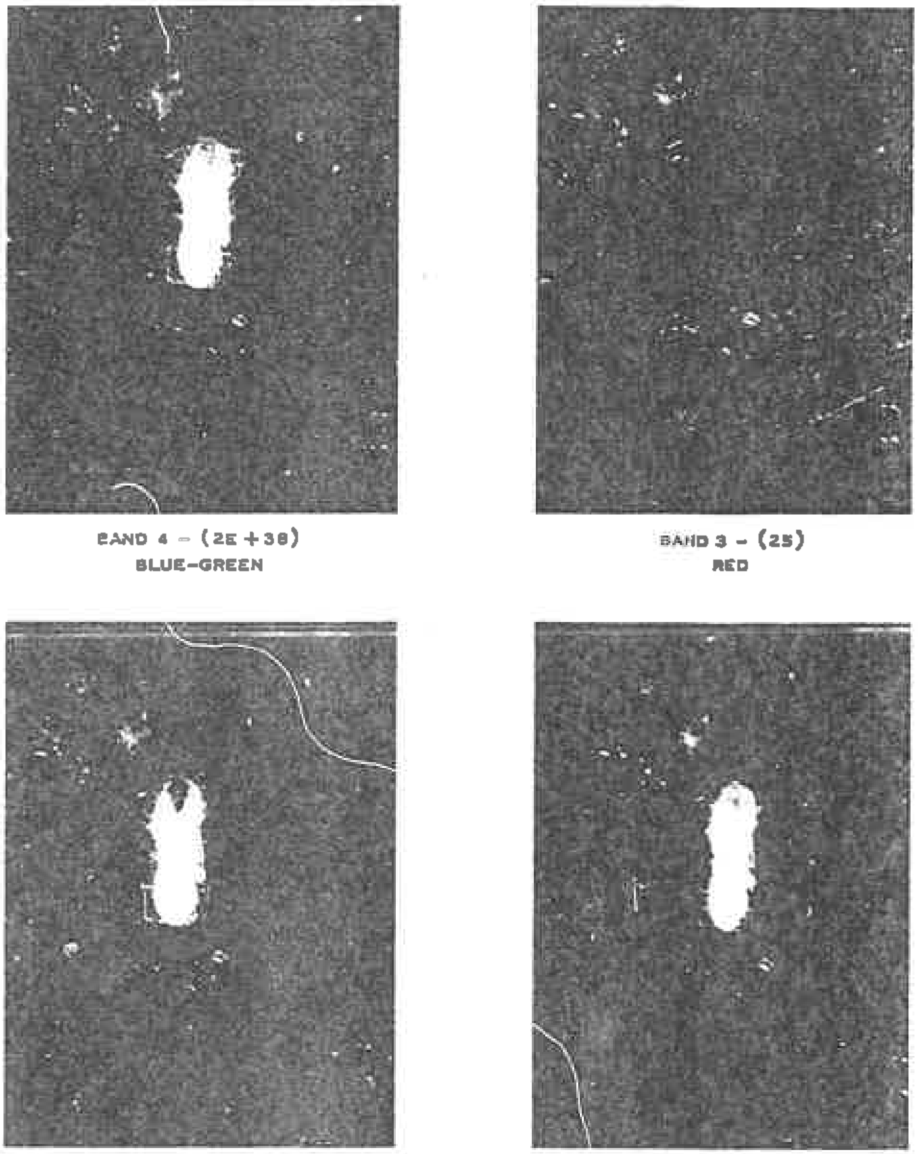


Figure 51-4a.- Ben Franklin on the surface.



BAND 4 – (2E + 38)
BLUE-GREEN

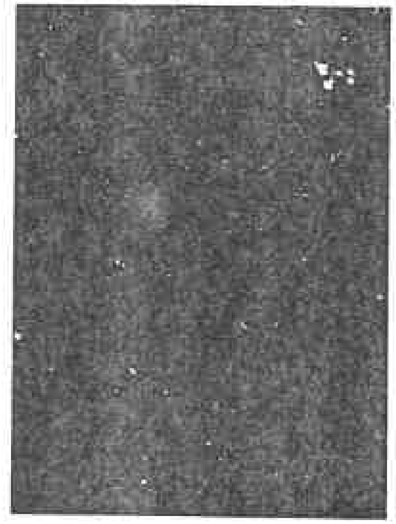
BAND 3 – (25)
RED

BAND 1 – (47B)
BLUE

BAND 2 – (58)
GREEN

Figure 51-4b.- Ben Franklin at 10 meters.

BAND 4 – (2E + 3B)
BLUE–GREEN



BAND 3 – (25)
RED

BAND 1 – (47B)
BLUE

BAND 2 – (58)
GREEN

Figure 51-4c.- Ben Franklin at 15 meters.

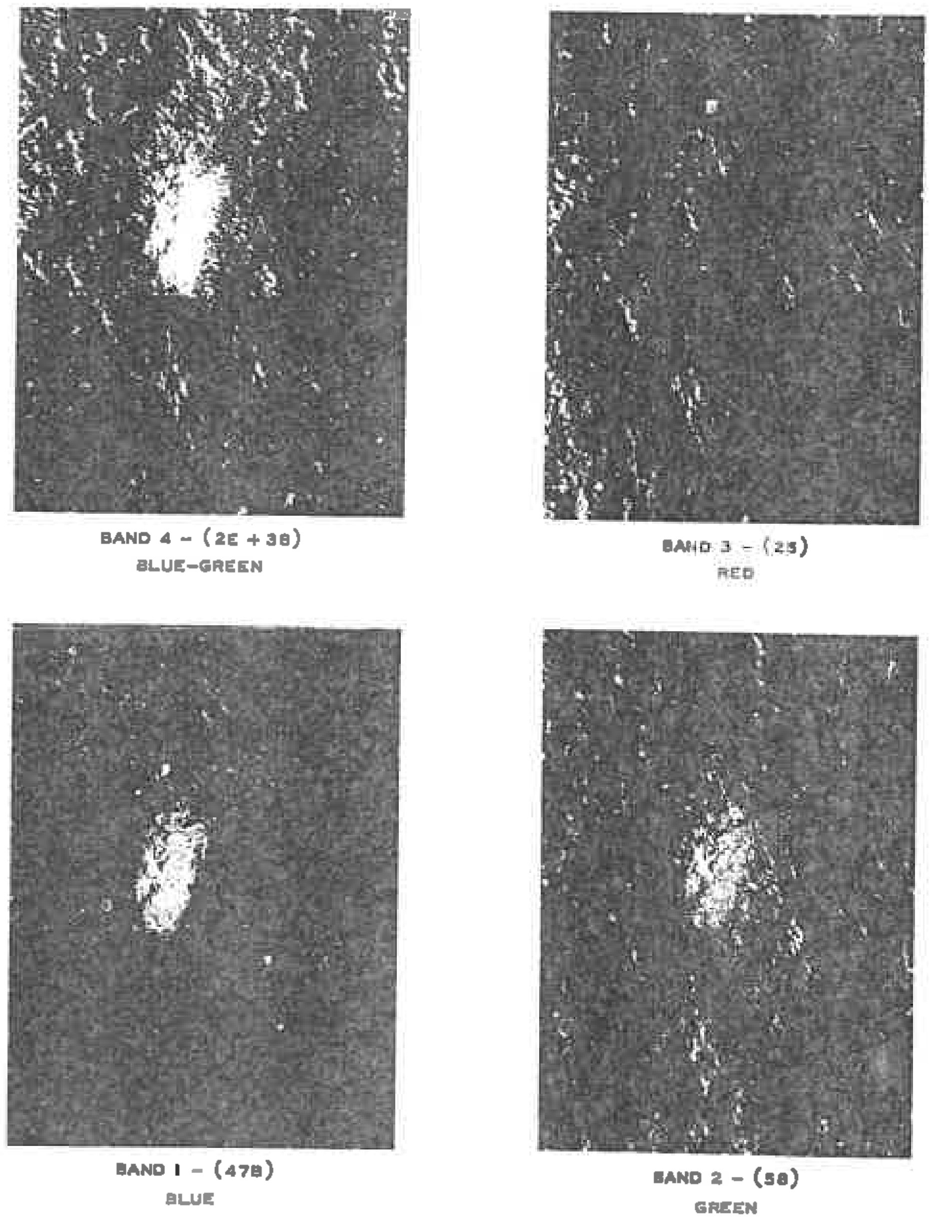


Figure 51-4d.- Ben Franklin at 25 meters.

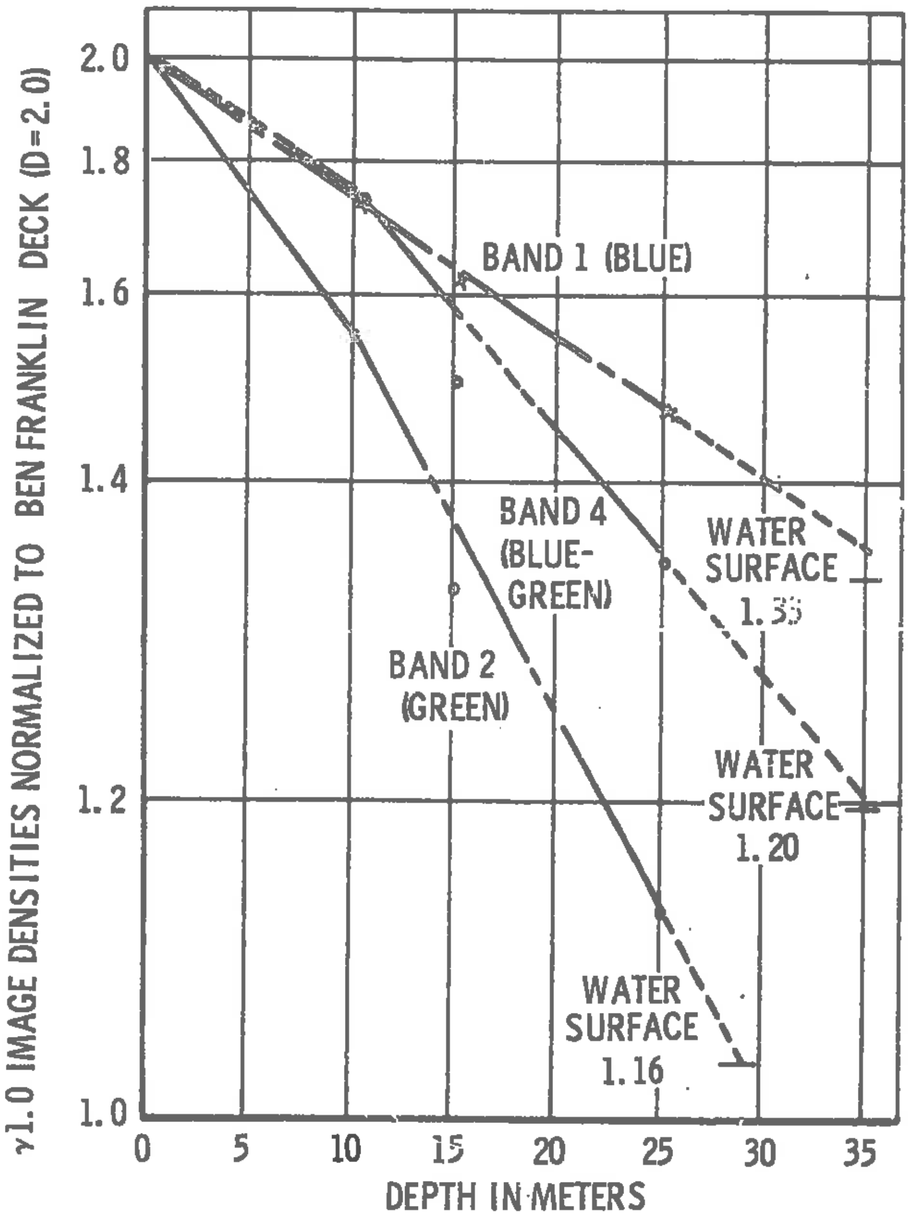


Figure 51-5.- Log decrease of Ben Franklin image density with depth by spectral band.

Figure 51-6a.- Bimini Island area - blue filter.

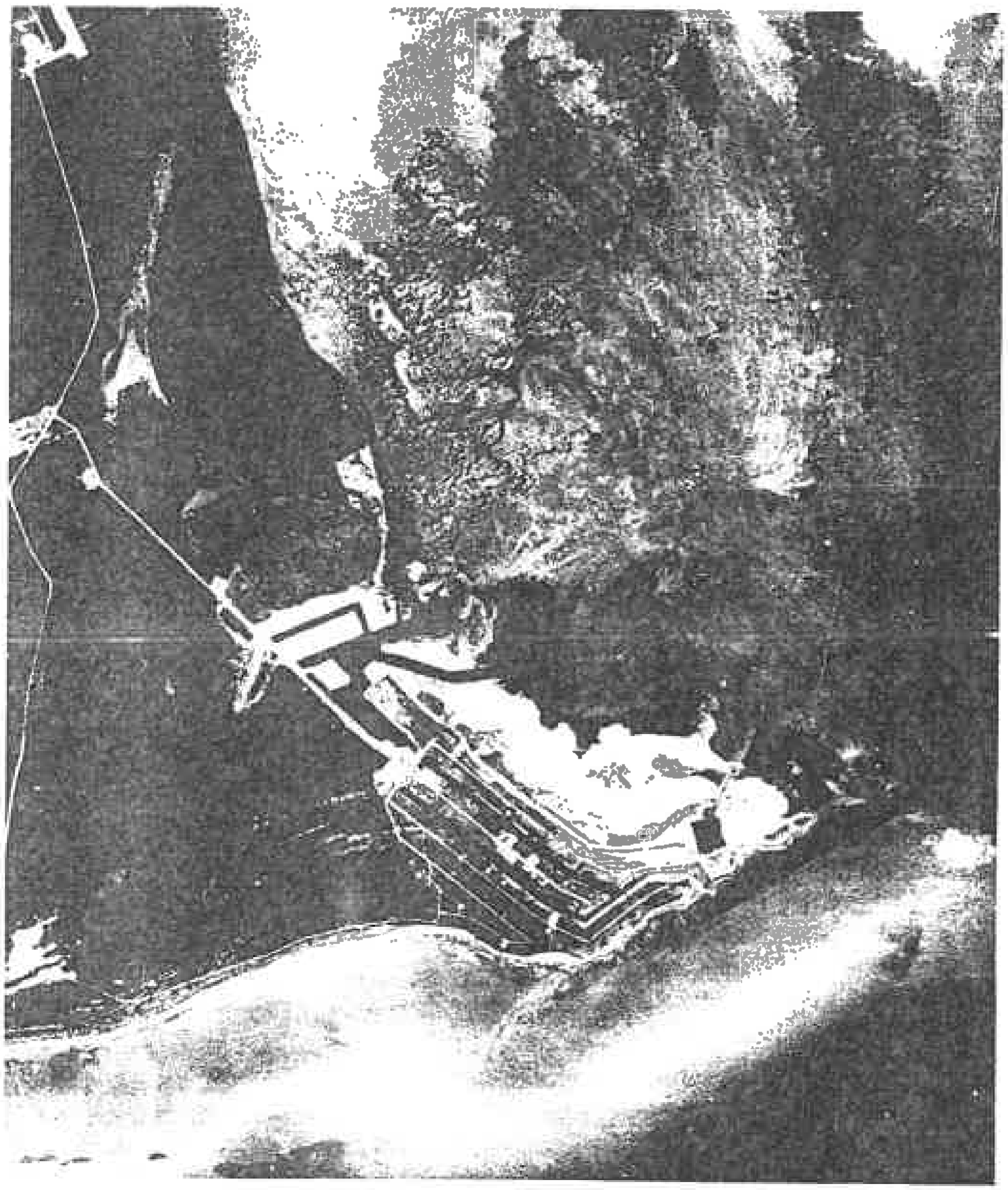


Figure 51-6b.- Bimini Island area - green filter.

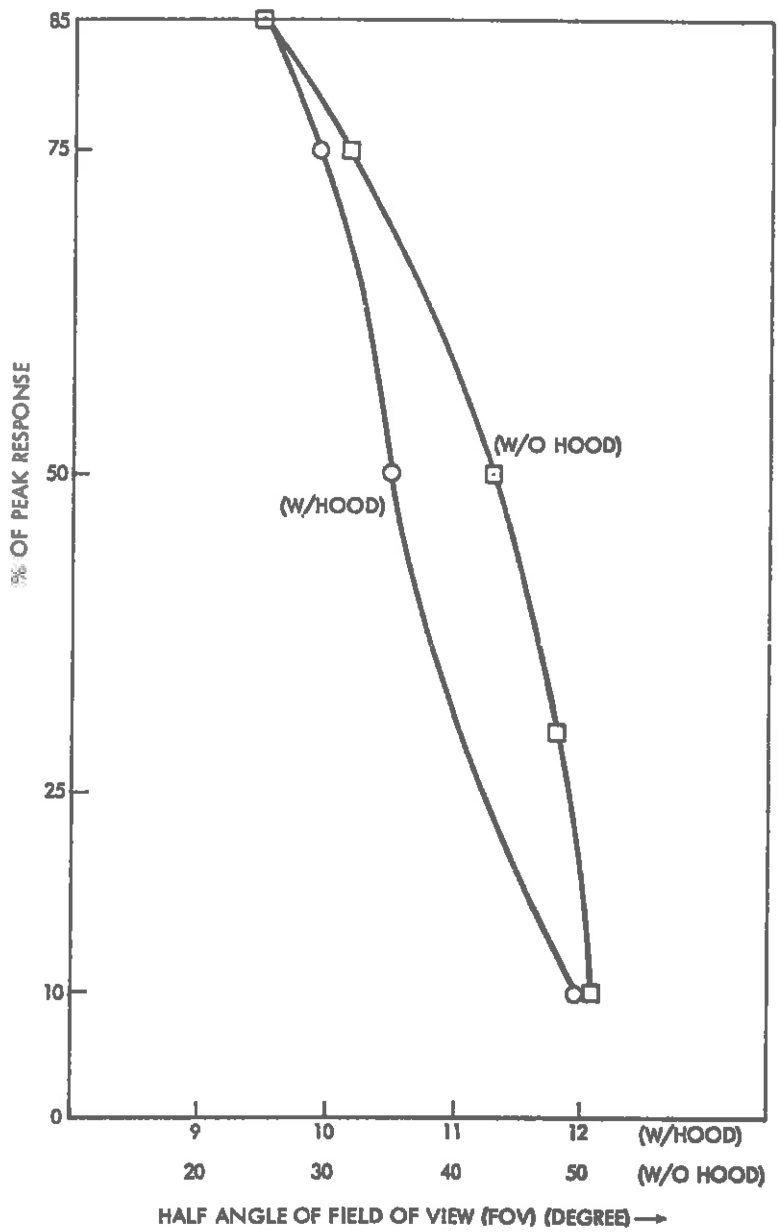


Figure 51-7.- Instrument response curve.

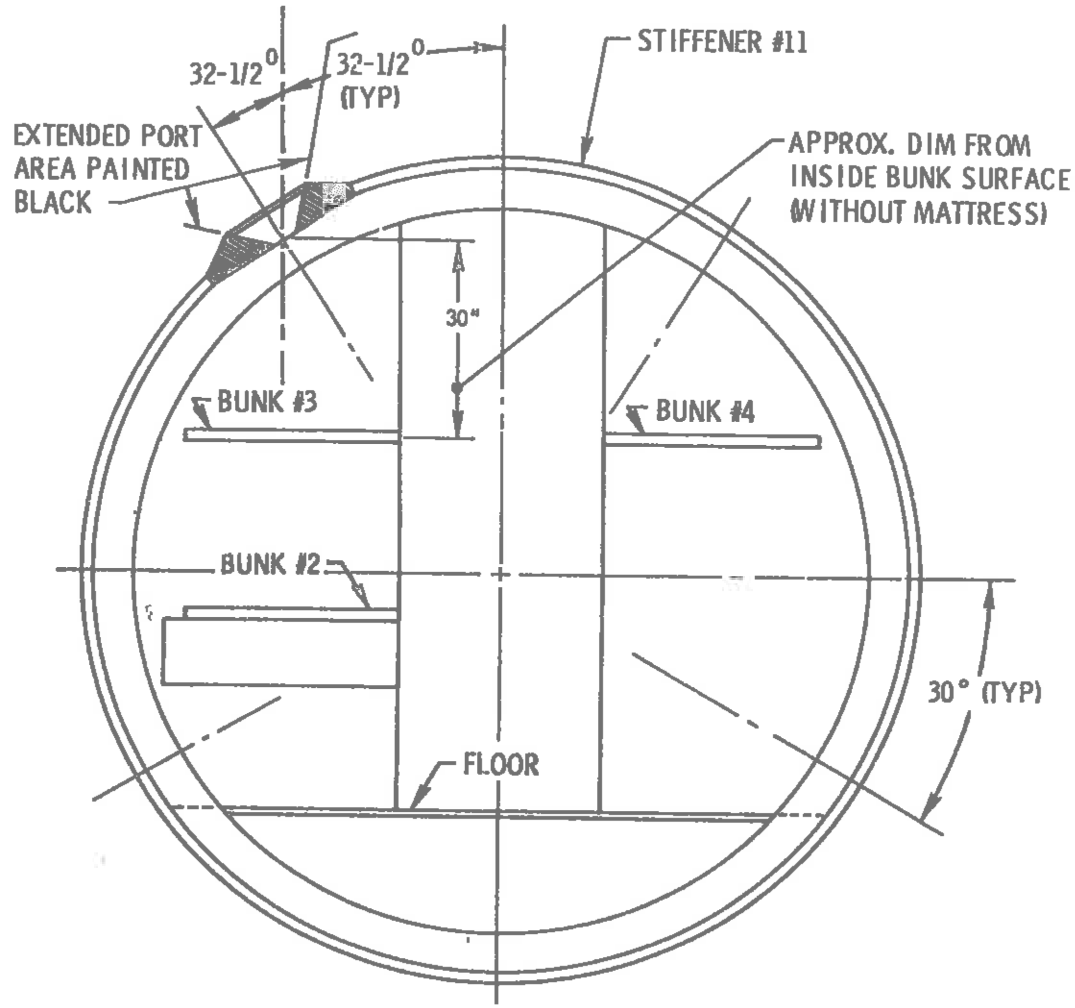
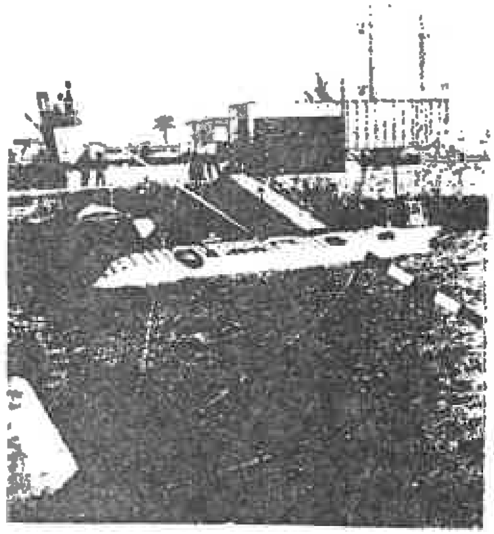
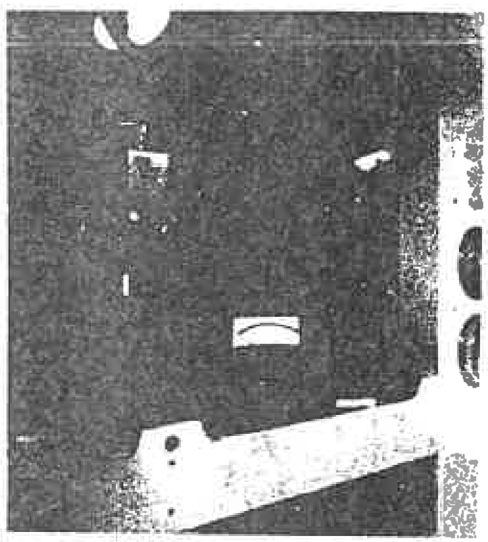


Figure 51-8.- Cross-sectional view looking forward.



a.



b.

Figure 51-9.- (a) Ben Franklin on surface showing Black Port; (b) S/R instrument mounted in Ben Franklin.

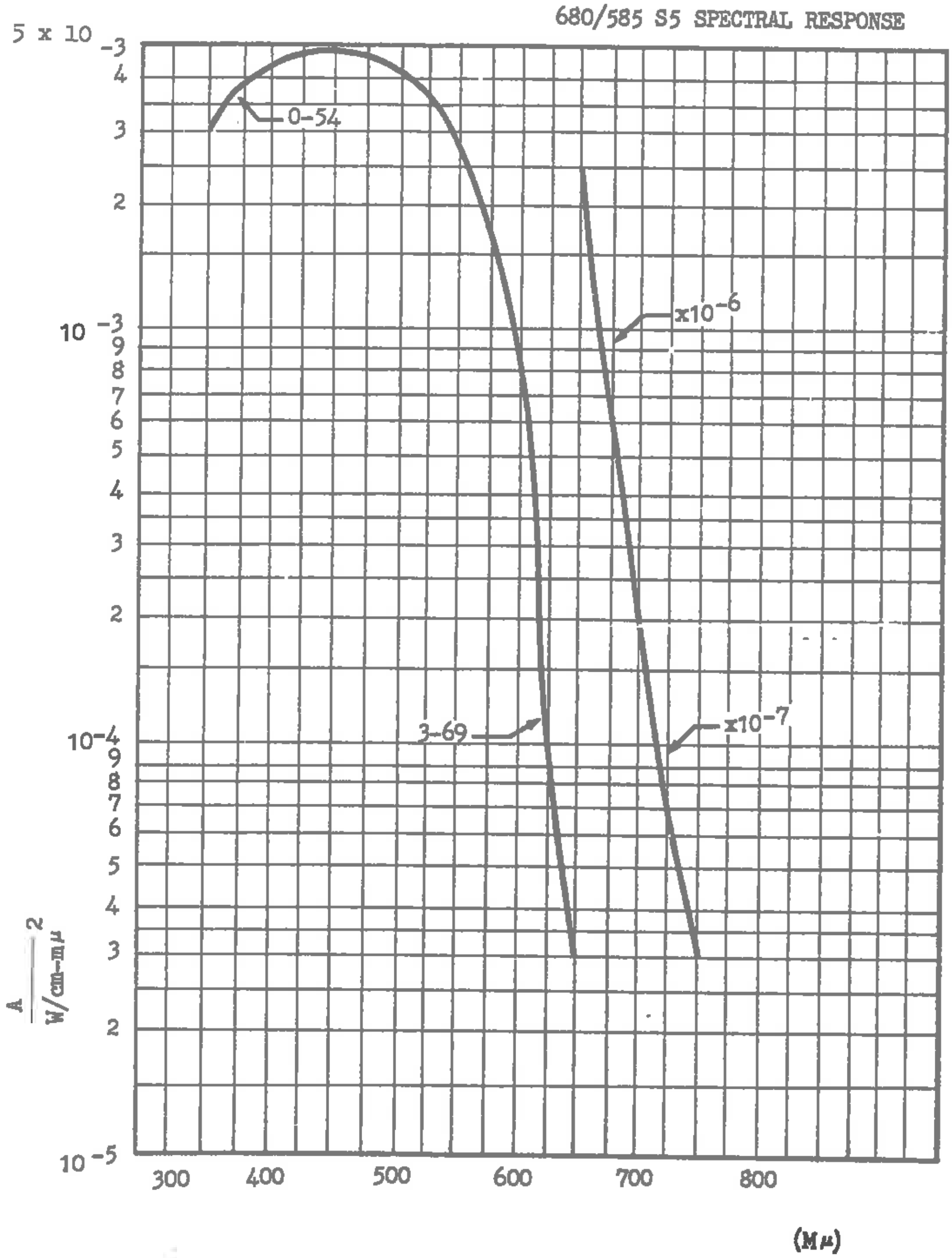


Figure 51-10.- Spectral Response

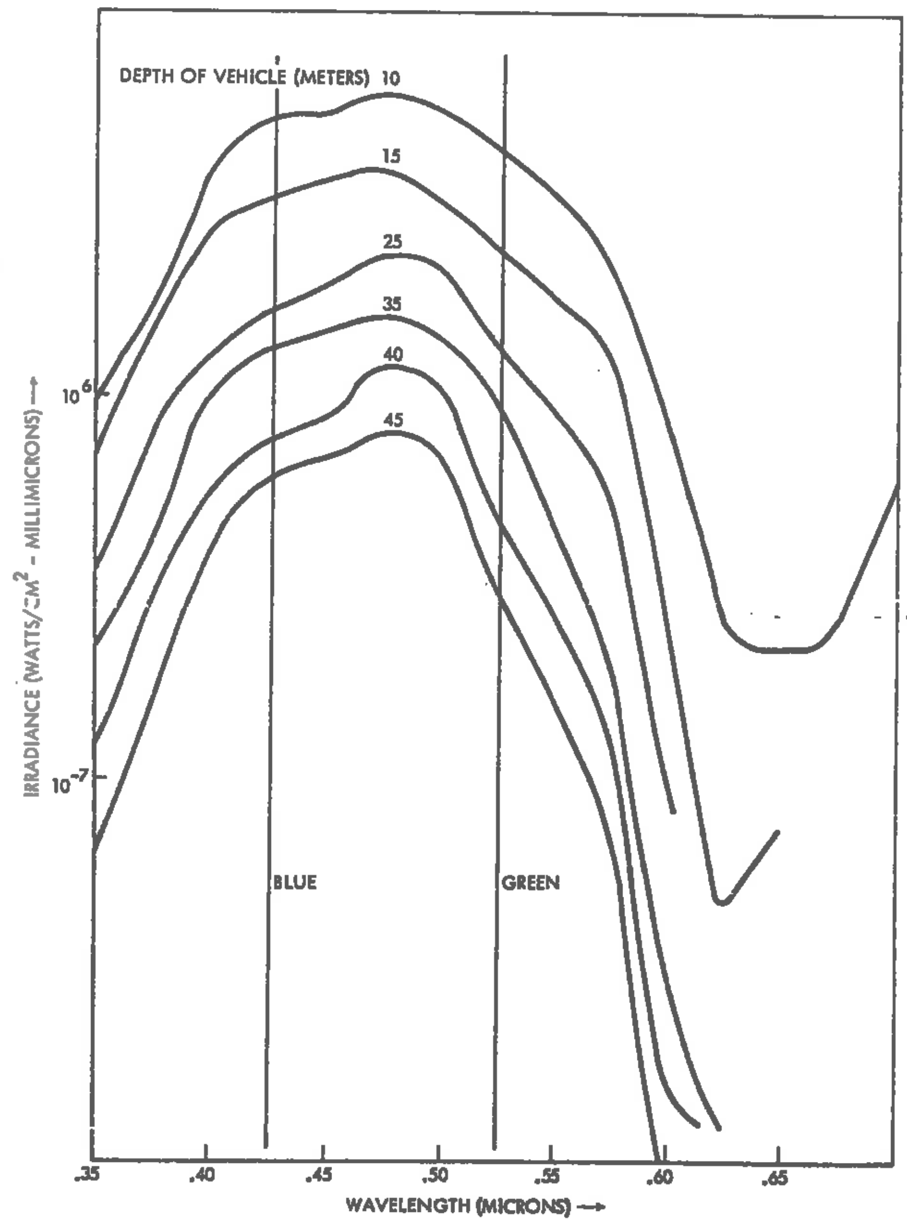


Figure 51-11.- Composite of fully correct irradiance measurements as a function of vehicle depth.

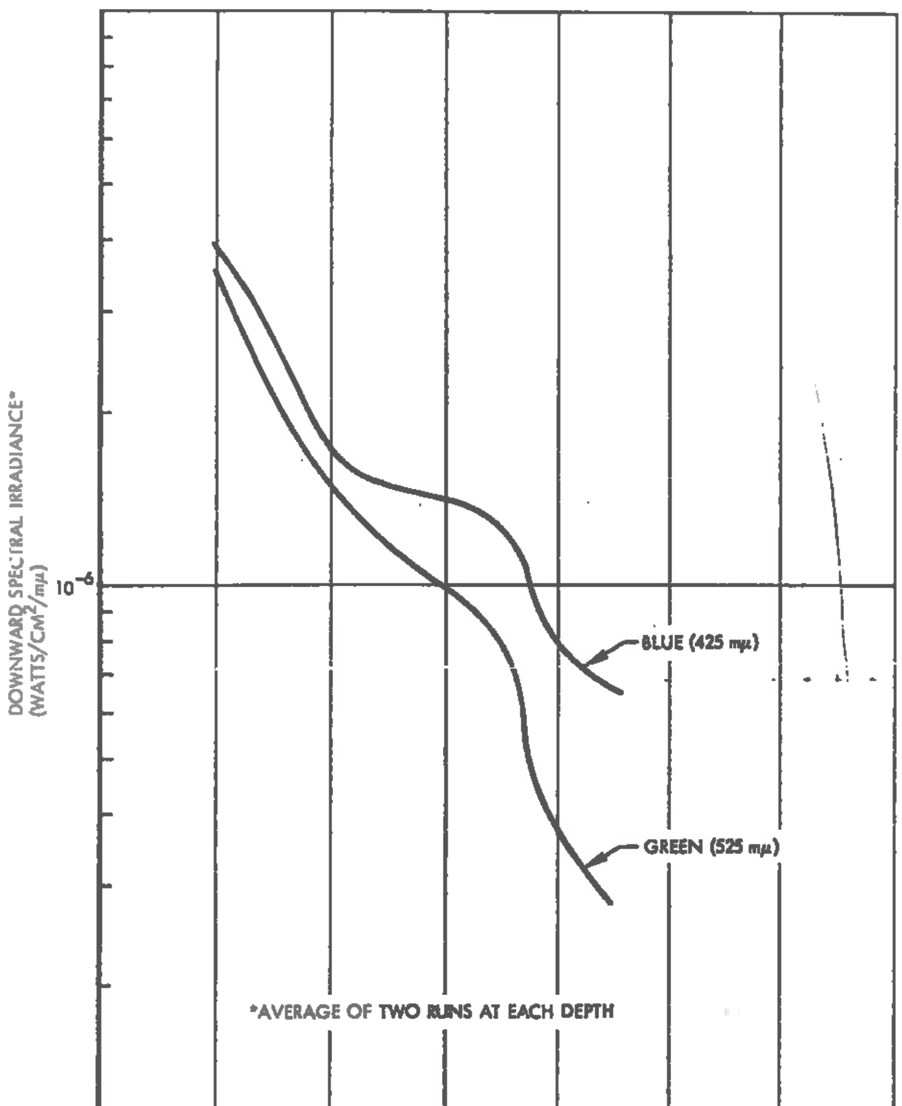


Figure 51-12.- Downward spectral irradiance in two bands as a function of water depth.