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THE TRANSMISSION OF ULTRAVIOLET LIGHT PULSES IN SEA WATER

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ABSTRACT

During several recent field trips some laboratory-designed flashlamp equipment and a pulse receiver using a 5819 multiplier tube were used to study the transmission of near-ultraviolet radiation in sea water. On previous trips a steady-source Hg lamp and a photomultiplier receiver unit aboard ship were used for similar experiments. Neglecting such factors as the difference in the clarity of the water, more impressive depths were achieved with the pulse system. During experiments when this system was used the clarity of sea water to near-ultraviolet radiation was found to be high off Key West with an attenuation of seven percent per meter at 3700 A. This corresponds to a value of 0.072 m^{-1} for the attenuation coefficient. With a reduced flash energy of 33 watt-sec the flashlamp was lowered to 200 feet, and from measurements made to this depth an extrapolation was made to show that it is possible to receive signals at the surface from a depth of approximately 540 feet.

PROBLEM STATUS

This is a final report on one phase of this problem.

AUTHORIZATION

NRL Problem NO3-22
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THE TRANSMISSION OF ULTRAVIOLET LIGHT PULSES IN SEA WATER

INTRODUCTION

The transmission of light in sea water has been studied, and fairly extensive information is available on penetration depths as well as attenuation factors due to absorption and scattering. Such attenuation coefficients at wavelengths well down into the ultraviolet region are available from reasonably accurate experiments, and, as may be expected, these data vary widely for the different waters measured close to land[1] and in the open seas.[2] In such areas as the eastern Mediterranean and Sargasso Seas the water has been found to be extremely clear with low attenuation for ultraviolet as well as visible radiation.

As mentioned in NRL Report 3774, the main purpose of this series of experiments by the Optics Division was to explore the possibility of optical communication between a submerged submarine and aircraft flying in an area over the underwater signal. In such a system the signalling could likely be done without visual detection by surface or underwater craft. And even detection by an observer over the water could possibly be difficult when such an observer was not aware of ultraviolet radiation.

Secondly, it is of present-day interest to know more of the light transmission characteristics of sea water in various parts of the world. Such information is needed to make studies of sunlight penetration into the sea and the resulting effects on marine life.

Using the 250-watt mercury lamp described in NRL Report 3774, several additional experiments were performed out of Key West, Florida in March 1951. The water at a depth of 300 feet on the edge of the continental "shelf" was much clearer than Chesapeake Bay water, and the transmission depths obtained were several times those in Bay water. In the 3650 A region of the spectrum, for instance, the measurements were made to approximately seventy feet, and extrapolation gave a possible transmission depth of 130 feet with the 250-watt A-H5 lamp. For the same spectral region the maximum transmission depth obtained in the Bay water was only 32 feet.

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[1] Plymale, W. S., Jr., Dawson, L. H., and Worsley, R. J., "Experiments on the Transmission of Ultraviolet Light in Chesapeake Bay Water," NRL Report 3774 ([redacted]), January 1951

[2] Hulburt, E. O., "The Penetration of Ultraviolet Light into Pure Water and Sea Water," JOSA, 17:15-22 (July 1928); Jerlov, N. G., "Ultraviolet Radiation in the Sea," Nature, 166:111-112 (July 15, 1950); Jerlov, N. G., "Optical Studies of Ocean Waters," Reports of the Swedish Deep-Sea Expedition 1947-1948, Vol III

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At Key West it was demonstrated that more impressive operating depths could be reached when using the continuous mercury lamp with one of the spectral lines isolated by a filter. But, in view of the fact that vertical transmission paths of several hundred feet are needed, it was thought that transmission of peak energies from a flashlamp would increase the range. The advantages of such a system are inherently the same as any system where pulse techniques are used. Very high peak power is made possible, and the duration of the flash is of the order of microseconds which tends to make the source far less visible than would be the case for a steady source with an intensity maintained at the peak value of the flashlamp.[3]

Of course the problems of designing flashlamp equipment for underwater experimentation were multiplied by the additional need of high voltage discharge circuits and large condensers. No commercial units were found adaptable; so it was necessary to design and build a reasonably high energy unit from available parts. This unit was enclosed in a steel tank and proved to be satisfactory although the watertight assembly weighed several hundred pounds.

The problem of finding a suitable flashlamp has been difficult. To date, no lamp is available which fits the needs of the experiment. Nearly all the flashlamps made are the xenon type either with a spiral long-path discharge or short-gap discharge designed chiefly for photography. Six experimental lamps of fused quartz with separate fillings of argon, krypton, and xenon at selected pressures were made for the apparatus by the Research Department of the Cooper-Hewitt Company in April 1951. Some of these lamps, especially the 75-mm argon type, seemed to have fairly high efficiency in the near-ultraviolet region, but they proved very poor in life tests, lasting less than 20 minutes. The trouble seemed to be in the outgassing of the electrodes under heavy discharges.

The GE FT-503 has been used in recent field work and has proved as satisfactory as any commercial type of lamp used. Life tests have been made on one of this type, and the results were excellent insofar as durability is concerned. Peak emission for this tube occurs in the visible region of the spectrum, but enough ultraviolet is emitted to give appreciable energy in the 3000 A to 4000 A region.

The apparatus,composed of the underwater lamp source and the receiving unit placed on the deck of the ship, does not represent equipment engineered for compactness or portability. The efficiency of the source is relatively low for near-ultraviolet emission, but with special lamp design and discharge equipment it should be possible to reduce this unit to at least half size. The receiving unit could possibly be designed to resemble a small oscilloscope. Since the experiments performed were exploratory, it was deemed sufficient to use laboratory units in shock mountings and connected by cables.

Only two field trips have been made to determine the possibilities of this experimental light-pulsing equipment. Attempts were made in Long Island Sound off New London, Connecticut on October 9 and 10, 1951, to get an idea of the limits to be expected when pulsing techniques are used. Due to rough weather and amplifier failure it was impossible to get any definite results other than to receive a few signals from a depth of from 100 to 150 feet. The equipment was rebuilt almost completely after this trip and the apparatus described below is that used on a recent trip (April 1952) off Key West, Florida.

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[3] Hartline, H. K., "The Nerve Messages in the Fibers of the Visual Pathway," JOSA, 30:239-246 (June 1940); Sweer, John, and Hulburt, E. O., "Signalling with Pulses of Light," NRL Report H-1623 ([redacted]), 6 June 1940

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THE UNDERWATER UNIT

In Figures 1 and 2 are shown the interior and exterior of the flashing unit which was lowered by a boom from the deck of a ship. A three-wire rubber cable was used to supply 110 v ac to the submerged tank so that the flash intensity could be controlled from the main panel located on the deck.

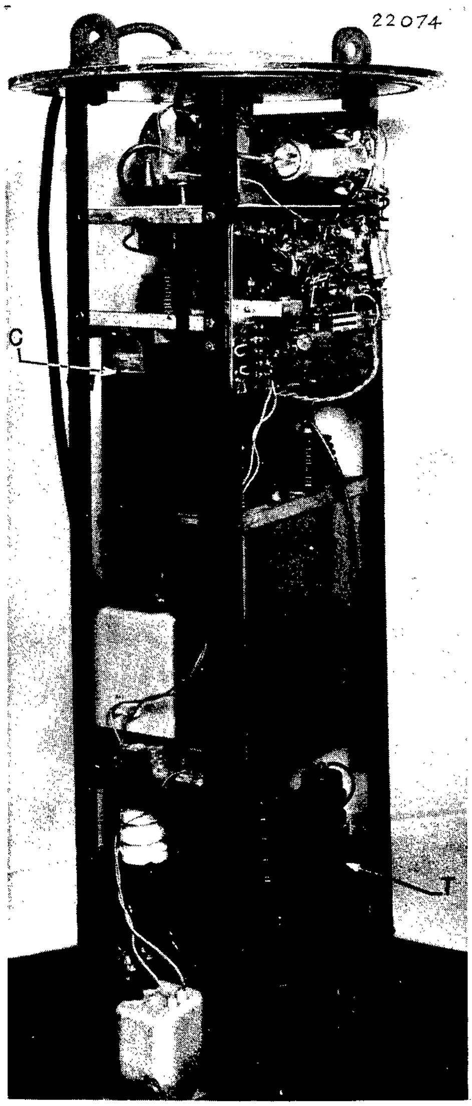

Figure 1 - Power supply and electronic panel for flashing the lamp underwater. T is the plate transformer and C is the discharge condenser.

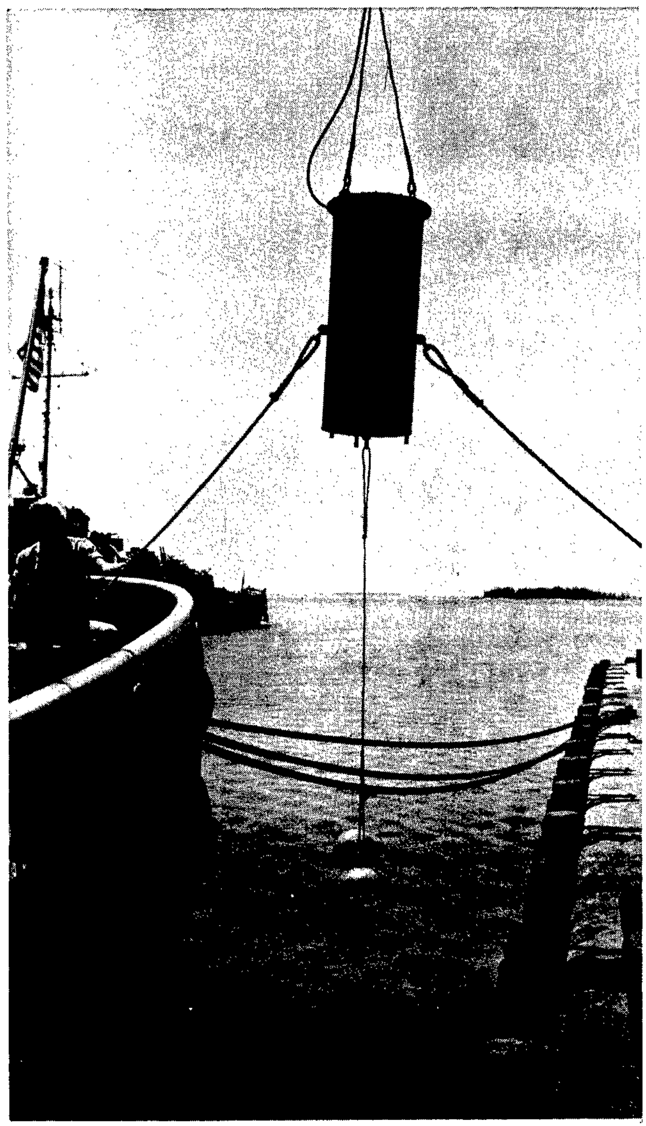

Figure 2 - Assembled underwater unit being lowered from the side of a ship

The schematic diagram of the circuit used for automatic flashing of the lamp is given in Figure 3 and a picture of the flashlamp is shown in Figure 4. A six-inch spherical mirror was placed under the lamp and the light was transmitted through a quartz window

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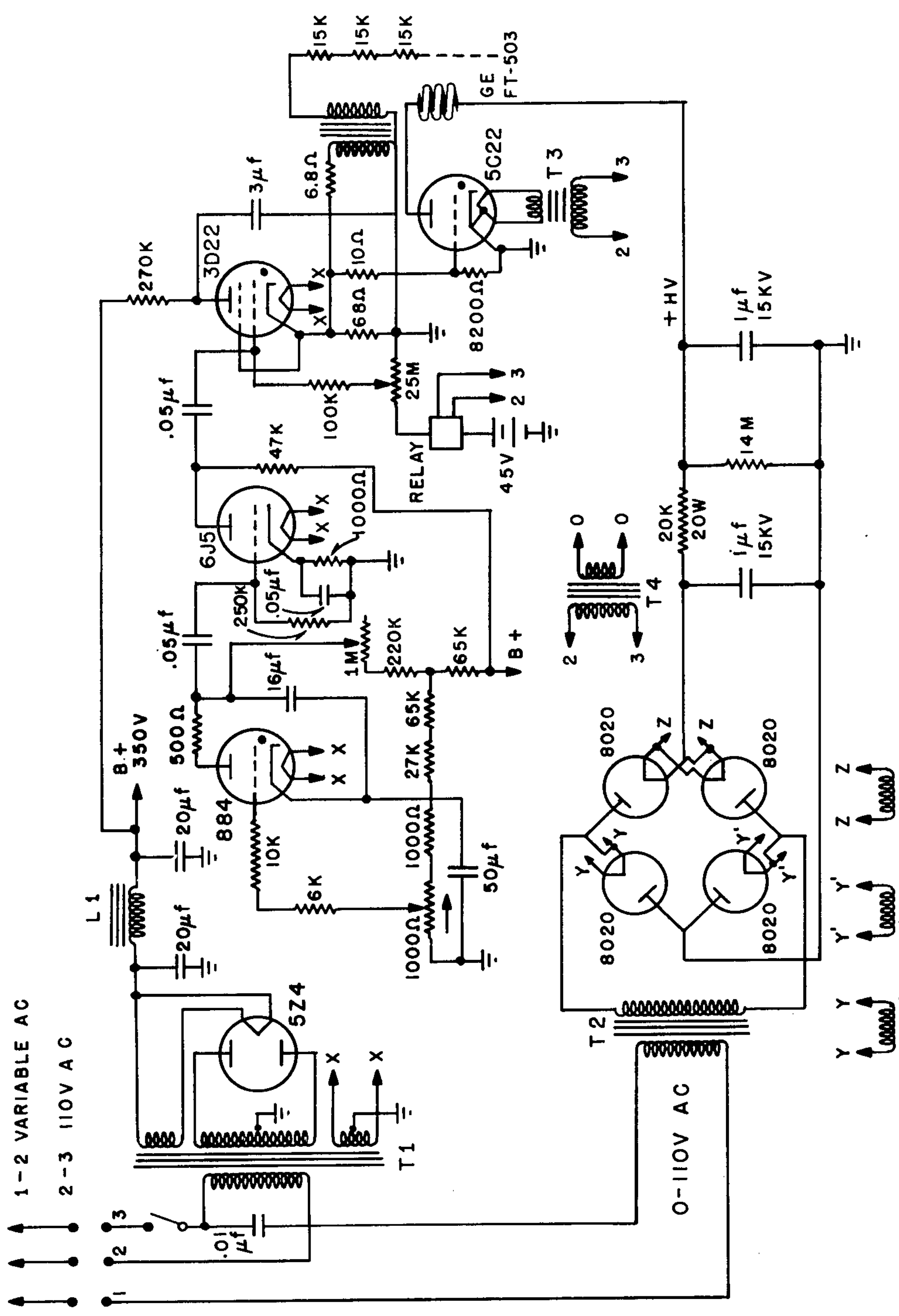

Figure 3 - Schematic diagram of the triggering and flashing unit

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located in the top of the tank. This simple optical system gave upward rays which were essentially divergent above the source. In the experiments on ultraviolet transmission, a Corning No. 5874 glass was used over the window. A transmission curve for this glass is given in Figure 5.

The flashing rate could be varied from about two flashes per second to one flash every two seconds. The setting was made for approximately $1\frac{1}{2}$ flashes per second and the triggering circuit performed very satisfactorily during the experiments.

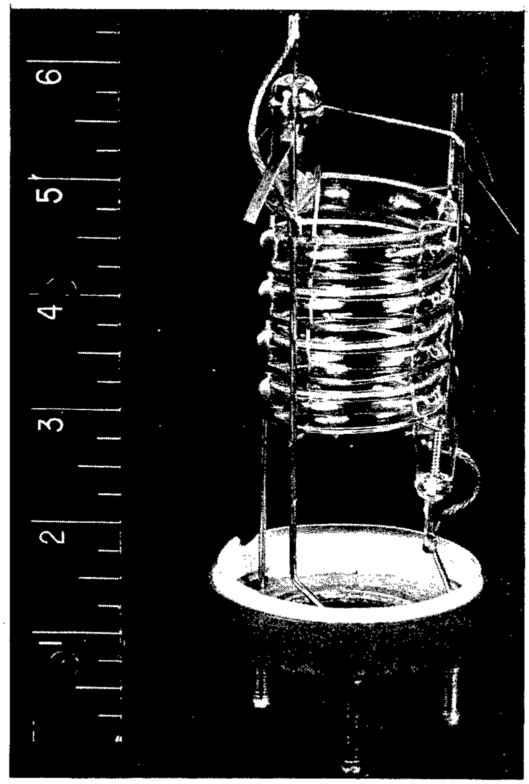

Figure 4 - The GE FT-503 flash lamp

Since it was desirable to reduce the time of flash to as small a value as possible, a single discharge condenser (C) of 1.5 μf was used at voltages up to 15 kv. This made it necessary to fire the FT-503 tube through a 5C22 thyratron with triggering pulses applied simultaneously to the grid of the thyratron and a high voltage spark coil. The secondary of this coil was connected to a wire which had one end wound around the spiral tubing of the lamp. In this way glow discharges could be produced in the lamp by pulsing the coil so that the flashing was more uniform than was the case when triggering was effected only through the thyratron.

The FT-503 tube has a rating of 5000 volts and a maximum discharge energy rating of 2000 watt-sec. This energy rating is given by the relation $W = \frac{1}{2}CV^2$, where C is in farads and V is volts. In the illustrated unit of Figure 1 the discharge condenser (C) is rated at 1.5 μf and 15 kv. This choice of condenser imposed a higher flash voltage on the FT-503 tube than its normal rating. However, some of these tubes could withstand up to 15 kv with 100-watt-sec energy of discharge and, for experimental purposes at least, the FT-503 tubes were used at voltages from 6 to 15 kv.

THE RECEIVER AND CONTROL PANEL

The deck-mounted receiver and control panel is illustrated in Figure 6. A synchroscope (Navy Model TS-28/UPN) was used to indicate visually the pulse as received and preamplified by the portable unit which was connected to the synchroscope by movable cables. This pick-up unit contained an RCA 5819 photomultiplier tube connected into a single amplifier stage and cathode follower. A schematic diagram of the tube and circuit is given in Figure 7.

The two points considered in the designing of the circuit were the obtaining of proper gain and amplifier characteristics with short enough rise time to permit the amplification of pulses with a rise period of the order of a microsecond. The over-all response of the receiving equipment proved to be good, with the sensitivity limited only by the noise in the photomultiplier tube. As far as possible, the best impedance matching and other improvements were incorporated for good pulse amplification.

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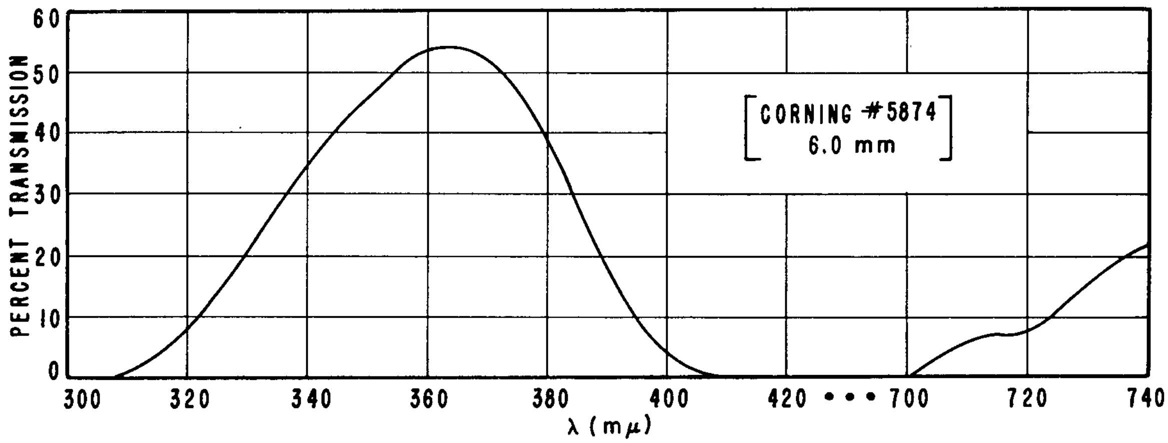

Figure 5 - Transmission curve for the glass filter used over the flash lamp

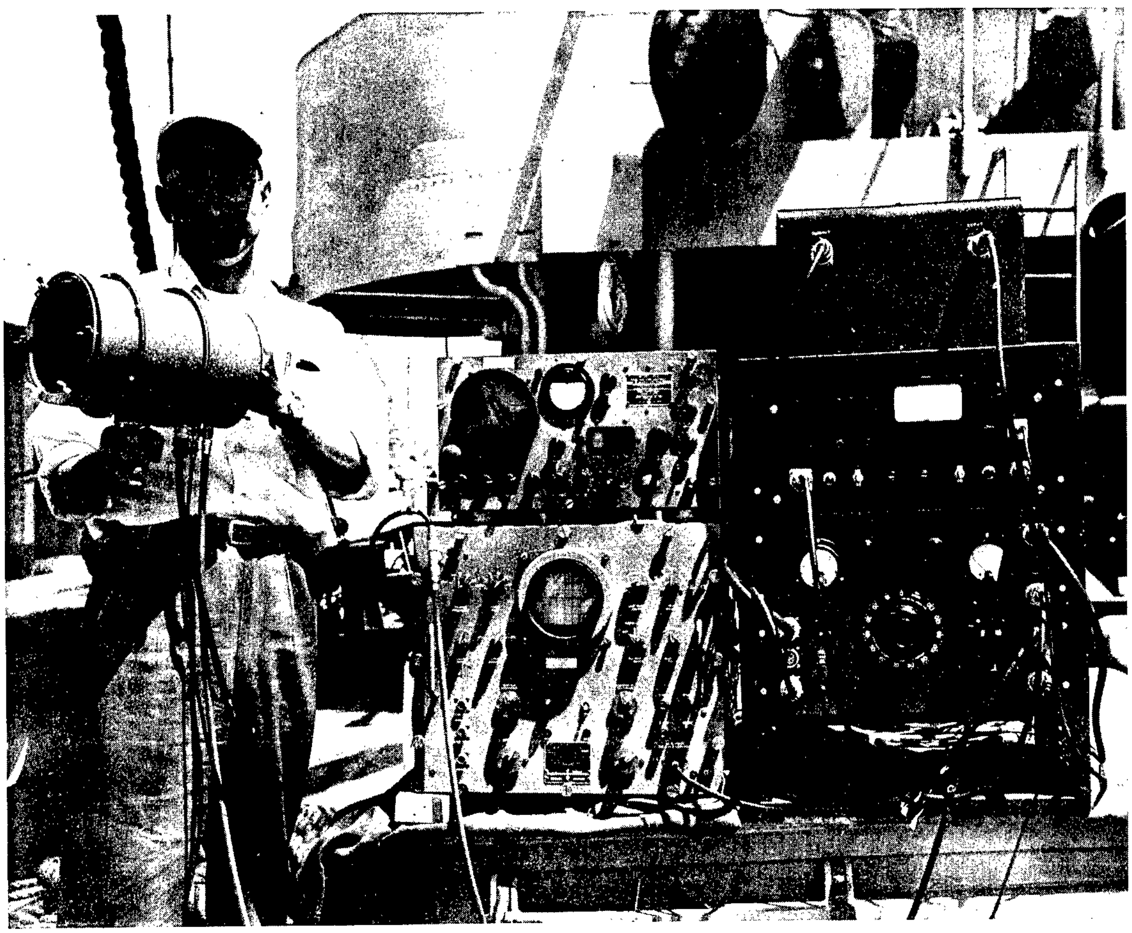

Figure 6 - Receiver and control panel

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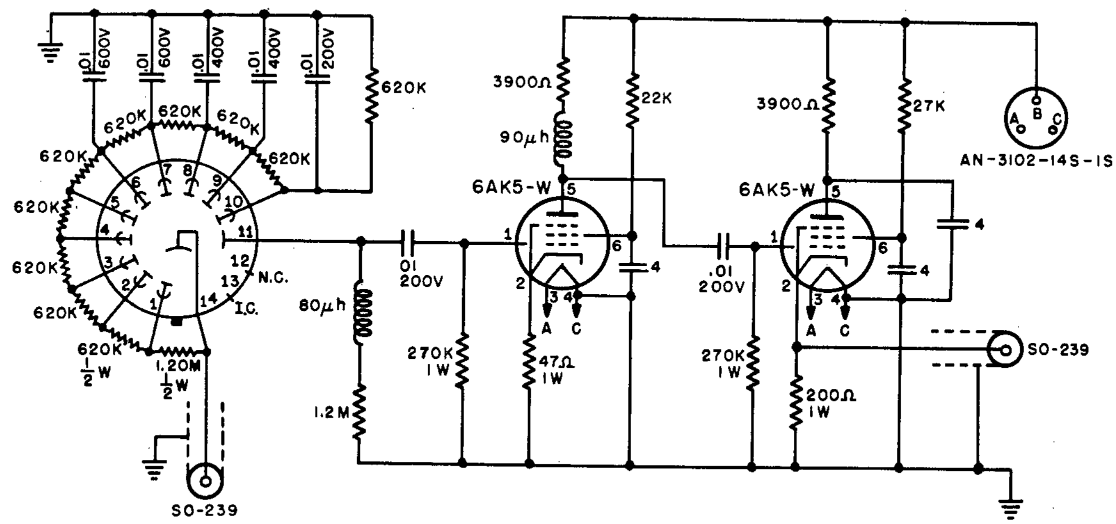

Figure 7 - Schematic diagram of the receiver tube and amplifier

In the control pack was mounted a low voltage power supply for the preamplifier and a stabilized voltage supply for the dynodes. This voltage supply could be varied from 75 to 1250 volts and served as a gain control for the receiver. Since a logarithmic variation exists between dynode voltage and multiplier tube sensitivity it was possible to calibrate the receiver over a very wide range by varying the voltage on the dynodes and using two positions of the gain switch on the front of the synchroscope.

In calibrating the receiver it was found convenient to choose a fixed pulse amplitude on the screen of the synchroscope for all the measurements. A calibration curve showing input intensity vs. dynode voltage was made in a 100-foot light tunnel by the use of a small lamp and filters. In this way it was possible to use the equipment in the field by merely adjusting the dynode voltage and gain switch to produce the fixed amplitude pulse as originally chosen at the time of calibration.

Calibrations were first made with a pickup unit using a 1P21 multiplier tube without any optical gain at the input. Another pickup arrangement using a 5819 tube and a mirror was later used and proved to be about thirty times more sensitive than the first unit. A diagram of this optical arrangement is shown in Figure 8, and the complete assembly may be seen mounted in a cylindrical case in the photograph of Figure 6.

No attempt was made to construct a large collecting mirror with careful focusing into a selected 1P21 tube. Such an arrangement could appreciably improve the receiving sensitivity especially if the background noises due to scattered and reflected light were not too objectionable. The light-gathering area of the system shown in Figure 8 is approximately 93 square inches which is not very great when compared to many collecting areas. The transmission curve of the filter used in the system is given in Figure 9.

COMPARATIVE RESULTS OF SEVERAL FIELD TRIPS

As the experiments off New London in October 1951 were performed with difficulty, it was not possible to get good quantitative results. The performance of the receiver equipment mounted on the USS PCER 852 was very unsatisfactory, and no accurate results can

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be reported except that some pulses were received at slightly better than 100 feet. The flashlamp was lowered in 250 feet of water in Long Island Sound about three miles west of Fisher's Island. Under the circumstances no computation could be made of the attenuation coefficient in the near-ultraviolet for this water, but it had a murky appearance suggestive of inland water.

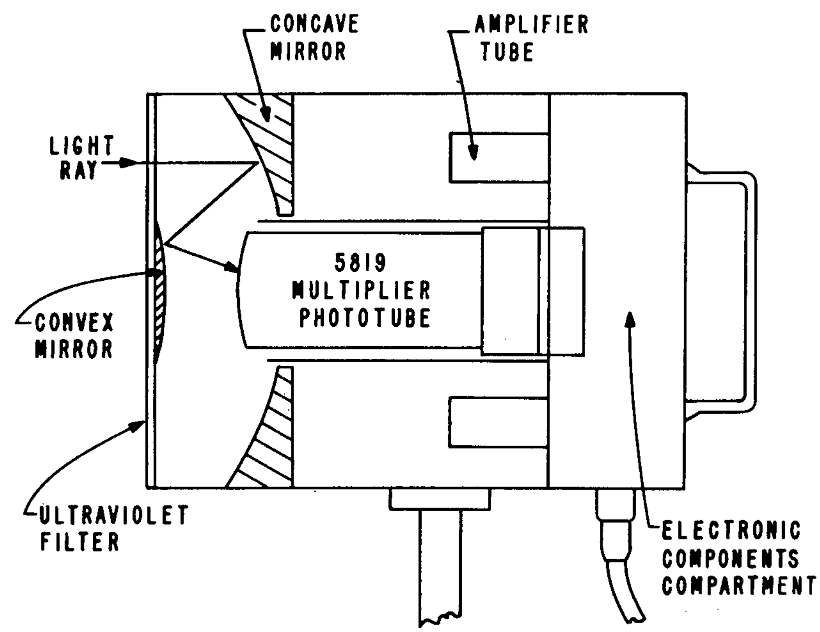

Figure 8 - Diagram of the optical system of the pickup unit

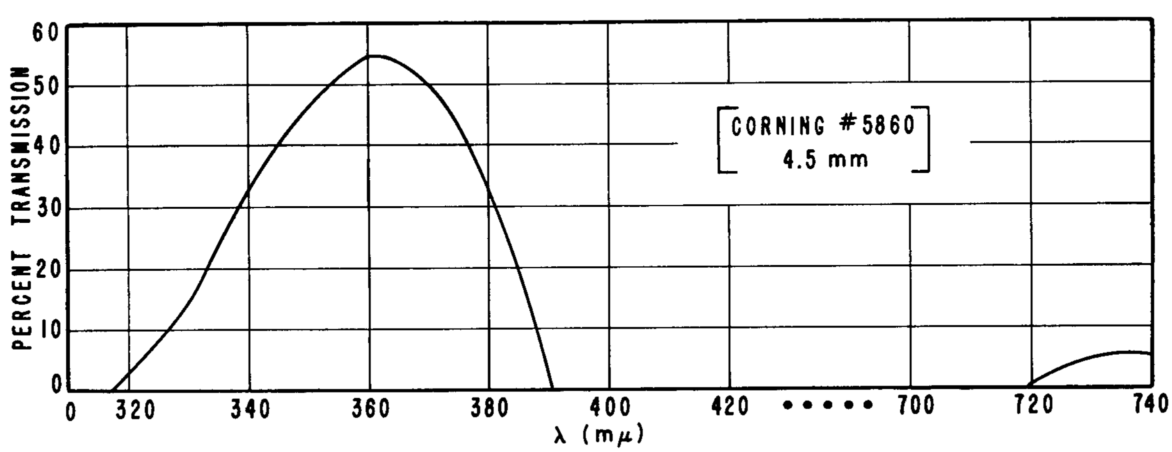

Figure 9 - Transmission curve of the filter used over the pickup tube

The trip off Key West, Florida, made recently with the equipment mounted on the USS Salinan, was performed with success although the sea was fairly rough. On the night of April 11, 1952, the tank containing the flashlamp was lowered in 660 feet of water at a point

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24° 21′ 42″ N and 81° 48′ 38″ W which was located on the edge of the Gulf Stream south of Key West. With extra weights on the tank and careful handling of the ship it was possible to make several vertical measurements underwater to a depth of 200 feet. This was the limit of the power cable since only a 250-foot length was available from the reel. As it was, the pull of drift currents and the weight of the cable itself proved to be limiting factors for lowering the tank to a depth much below 200 feet.

With the combination of filters, the transmission curves of which are given in Figure 5 and Figure 9, a series of intensity measurements were made of the submerged source operating at 6.6 kv, giving a flash energy of 33 watt-sec.

The pickup unit was located about 15 feet above the water and readings were taken for lamp depths from 25 to 200 feet. In this range the signals were so strong, even for 33-watt-sec flashes, that it was difficult to attenuate the receiver properly; and for the 200-foot depth, less than 280 volts were required for the total dynode volts. Laboratory calibration of the instrument had originally been made, but the intensities of the pulses received from the lamp above a depth of 150 feet were greater than had been anticipated.

With a recheck on the receiver sensitivity after the trip it was possible to produce a table of pulse intensities and corresponding depths:

TABLE 1
Variation of Pulse Intensity with Depth

Depth of Water (ft)	Dynode Volts	Relative Pulse Intensity
29	75*	4×10^6
54	90	3.9×10^6
79	210	1.48×10^6
104	160	3.7×10^5
129	180	1.3×10^5
154	200	5.4×10^4
179	215	3.1×10^4
204	280**	- -

*Reading not valid
**Value too high

A graph of the points in Table 1 is given in Figure 10. The scale was chosen to permit an extrapolation to depths greater than the maximum depth reached in the experiment. With the assumption that the attenuation coefficient remains constant for several hundred feet below the range covered by the experiment, it is perhaps within reason to introduce an extrapolated curve as shown.

The points along the solid portion of the curve represent the best values of intensity vs. depth taken over the limited range. By using the equation,

$$I = I_0 \frac{(x' + 4)^2}{(x + 4)^2} e^{\alpha(x' - x)}, \qquad (1)$$

where I_0 = initial intensity corresponding to depth x′ in meters and I = intensity corresponding to depth x in meters, it was possible to compute the attenuation coefficient α from any two points. For more precise computations the four meters of travel in air were also taken into account.

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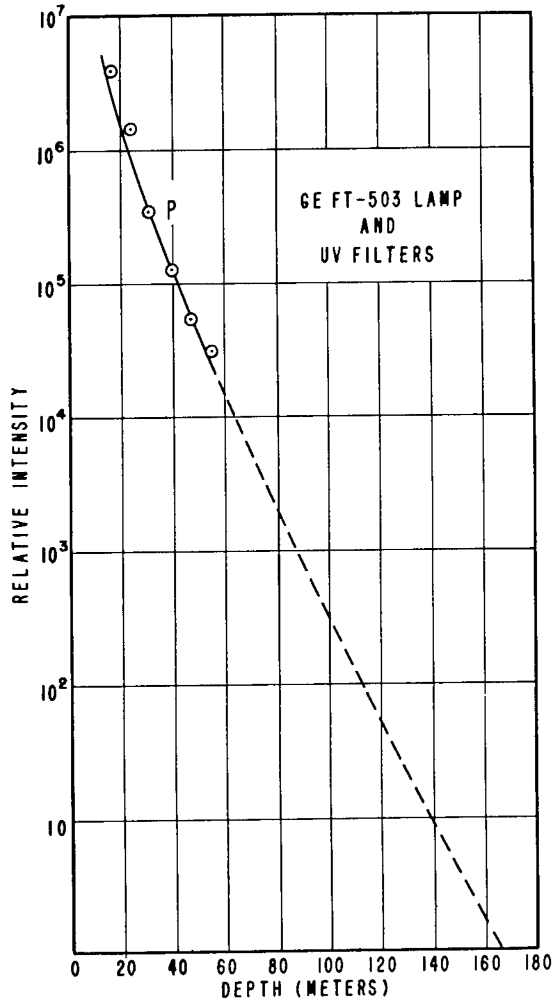

Figure 10 - Plot of relative pulse intensity vs. depth. extrapolation is indicated by the dotted portion of the curve.

In Table 2 below are given five values for α as computed from the several depth points. No exact wavelength can be assigned to the transmitted light, but by considering the flash-lamp spectrum and the two transmission curves of the filters it is possible to give an approximate value of 3700 A as the gravity center of the light.

TABLE 2
Attenuation Coefficients for the Depth Ranges Indicated

Depth Range (meters)	Attenuation Coefficient $\alpha(m^{-1})$
16.5 - 24.1	0.040
24.1 - 31.7	0.12
31.7 - 39.4	0.085
39.4 - 47.0	0.072
47.0 - 54.6	0.035

The coefficients given in Table 2 are comparatively low, indicating clear water. In terms of attenuation per unit depth, the average value of 0.074 m^{-1} gives a value of seven percent attenuation per meter. This compares favorably with the transmission of the clearest sea water described by Jerlov and others.

In the extrapolation, the point P was chosen as a representative point, and with $\alpha = 0.072$ m^{-1} the curve was extended by use of the formula outlined above. A plot on semilog paper shows the extrapolated portion of the curve to be almost a straight line. At a single intensity slightly above noise the maximum obtainable depth may be estimated to be near 165 meters (540 ft).

In contrast, the experiment of a year earlier (March 1951) at a point several miles closer to Key West may be briefly described. It was performed in shallower water in a location given as 24° 49′ N and 81° 49′ W with the Bay apparatus mentioned earlier. By isolating three of the Hg lines it was easy to get the attenuation coefficients at 2975 A, 3650 A, and 4050 A for sea water near the surface. A plot of the points showing the relation between intensity and depth in the 3650 A region is given in the graph of Figure 11.

It is seen that the points are plotted to a depth of 18 meters so that a straight line can be drawn from around six meters to 20 meters with certainty. By assuming water of equal transmission characteristics below the latter depth,it is possible to extend the line on semi-log paper to a point where the deflection is one scale division. This corresponds to a depth of approximately 30 meters.

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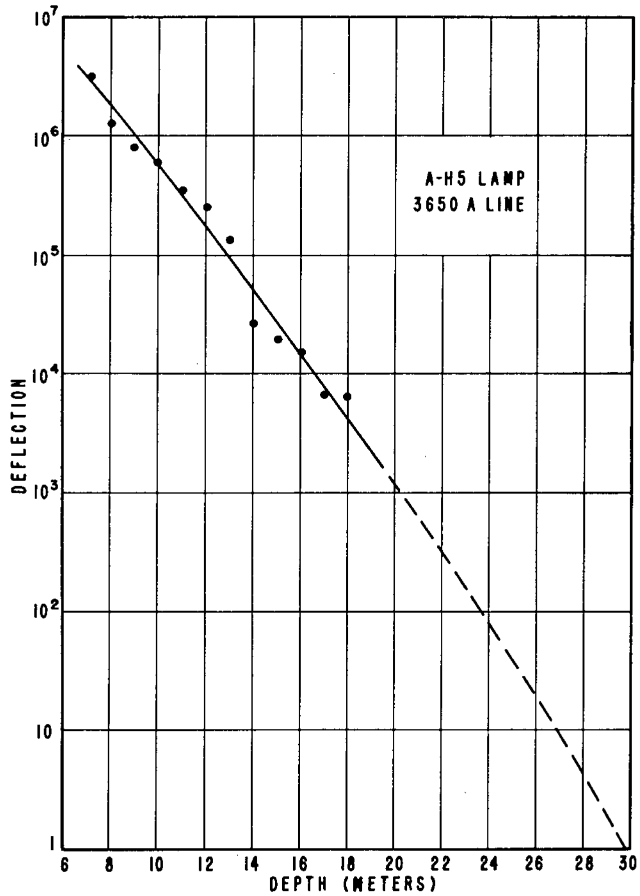

Figure 11 - Plot of deflection vs. depth for measurements made with 3650 A line of Hg with the A-H5 lamp, Data was taken from the March 1951 experiments.

Strong drift currents carried the lamp away from the ship as the depth was increased, but it was possible to get fairly accurate readings to depths of approximately 20 meters. From these data a computation was made for the attenuation coefficients at wavelengths of 2975 A, 3650 A, and 4050 A. The results are given in Table 3 where α represents the average value of the particular coefficient in the short range covered.

TABLE 3
Variation of Light Absorption
with Wavelength for Coastal Waters

Wavelength (Angstroms)	$\alpha(m^{-1})$
2975	1.3
3650	0.44
4050	0.40

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No striations were detectable in the water between depths of four and twenty meters where the readings were taken. The attenuation at all three wavelengths was much less than in the Chesapeake Bay, but, compared to the results of the most recent experiment, the water seemed very poor for the transmission of near-ultraviolet light. At 3650 A the attenuation was 27 percent per meter which is much higher than the five percent commonly associated with clearest sea water.

CONCLUSIONS

The results given in Tables 1 and 2 are the best to date. A comparison of the attenuation coefficients in Table 2 with all the others shows that the water encountered in the experiments of April 1952 was the clearest found so far. The advantages gained from using pulse methods as described are partially obscured by the fact that the water was so much clearer for this experiment than for the others. Nevertheless, the extrapolation on the graph of Figure 10 gives the impressive depth of 540 feet. This depth could possibly be obtained by direct experimentation in similar water, but 540 feet is admittedly a value obtained by extrapolation. Any change in the absorption coefficient produces a marked change in the transmission as this coefficient is in the exponent of Equation (1). In some sea water it may be possible to obtain a transmission depth somewhat greater than 540 feet, but it must be pointed out that waters near the shore will, in general, give transmission depths which will be only a fraction of the best obtained.

With an A-H5 lamp and shutter arrangement it may be predicted that depths of around 300 feet could be obtained in the clearest water. However, the disadvantages of continuous lamp operation for the source and the problems of dc amplification at the receiver end would seem to make a pulsing method superior in actual operation. Then too, from work done thus far, it appears that practically the same results could be obtained by using much smaller equipment for both the flashing unit and receiver. The flashing unit could probably be made to fit into a tank of about four cubic feet so that the combined weight would be near 500 pounds. It is difficult to estimate the size of the receiver, but it would probably be very nearly the size of an average portable oscilloscope. This would be in addition to a pickup box similar to the cylindrical unit in Figure 6.

The effect of taking the receiving apparatus high above the surface of the water is shown in Figure 12. The transmission of the radiant energy emitted from the water is, of course, greatly changed in air. The attenuation coefficient of near-ultraviolet light was so much lower in air that it is possible to speak in terms of kilometers instead of meters for transmission distances.

The curve in Figure 12 was computed by taking the attenuation coefficient as $0.072\ m^{-1}$ for water at 3700 A and the attenuation coefficient of $0.2\ km^{-1}$ for air at the same wavelength.

Atmospheric transmission is of course greatly dependent on the weather. The data from which the curve of Figure 12 was computed are representative of good ultraviolet transmission on a clear day.[4] For less favorable conditions, it is evident that the altitudes would be greatly reduced, but the distances represented on the ordinates of Figure 12 are perhaps greater than those ordinarily needed in practice. At any rate, the receiver can be considered operative for a range of intensities below those easily detected by the eye.

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[4] Dunkelman, L., "Attenuation of Ultraviolet Light by the Lower Atmosphere," NRL Progress Report, February 1951

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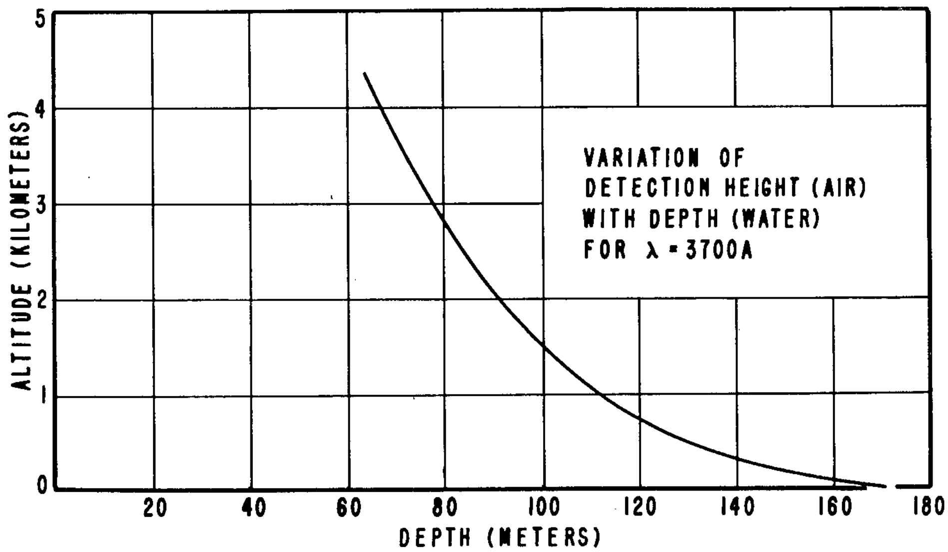

Figure 12 - Graph showing the heights in air of minimum detection for given depths of the lamp under water

A compromise wavelength around 3500 A to 3700 A seems desirable from the standpoint of transmission and spectral emission characteristics of flashlamps. The attenuation coefficient increases with decreasing wavelengths below the visible region, and a point is reached where only visible radiation due to luminescence can be detected at the surface.

Except on areas near fresh water outlets, the practice of getting near-ultraviolet radiation from a submerged source should not be difficult. Predicted depths would range from 40 to 50 to several hundred feet a few miles off shore.

PRESENT STATUS OF THE PROBLEM

From the work to date it may be said that some attenuation coefficients at given wavelengths have been added to the list. In addition, it may perhaps be stated that the exploratory phase of the work has been completed. The estimates as given suggest the feasibility of using some specially designed equipment for underwater-to-air signalling under conditions when the process may be considered practically invisible. Further effectiveness in using such apparatus would depend on the development of a more efficient source and a more compact receiver.

The flashlamp used was a GE FT-503 but it was designed for the visible region. Possibly a compact lamp using argon at several hundred millimeters pressure would serve quite well, but at this date no certain lamp can be considered as filling all the requirements.

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NAVY-DPPO PRNC. WASH., D.C.