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An Experiment in Underwater Light Transmission

[Unclassified Title]

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ABSTRACT

A new technique for optical communication between two submerged points has been proposed and tested successfully in a limited test. The technique is to transmit light out of the water into the atmosphere, where some of it is scattered by the atmospheric aerosol back into the water at a distant point where the light is detected. In night tests, light signals have been transmitted over a separation distance of 14,000 yd between two points submerged in 6 to 18 ft of water in the Chesapeake Bay. The tests were made with a xenon flash lamp source and a photomultiplier receiver. The variation in the signal S with distance D was given by $S \propto D^{-n}$ where n varied from 1.44 to 1.93.

It is estimated that a more intense light source and a well-designed receiver system would have given an improvement in signal strength by a factor of 100. Such a gain increase is reasonably practical of achievement and would permit an ocean-going system to operate at greater depths and separation distances.

PROBLEM STATUS

This is an interim report on one phase of the problem; work on this and other phases is continuing.

AUTHORIZATION

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AN EXPERIMENT IN UNDERWATER LIGHT TRANSMISSION

BACKGROUND

A problem of continuing interest to the Optics Division of the U.S. Naval Research Laboratory is the transmission of light signals in the atmosphere and in water. Recent NRL work (1,2) on the transmission of light signals beyond the horizon has been concerned with forward scattering by the atmospheric aerosol. In addition, there has been some recent work (3,4) on the transmission of light through water. Some of these latter measurements (3) were made with ruby laser light at 6943A, which was found to be attenuated by a factor of 10 for every 15 ft of water path in the David Taylor Model Basin. In the most transparent spectral region for water, the blue-green at about 5000A, the attenuation coefficient relative to 6943A may be as much as a factor of 10 lower. So the blue-green light would be attenuated by only about a factor of 10 for every 150 ft, corresponding to a beam attenuation of 10^{-35} per mile of water. However, this much attenuation obviously precludes the transmission of light through a mile of water.

If the problem is one of transmitting signals between two points only slightly submerged (say, 10 ft), it might be possible to send the signal out of the water into the atmosphere and have it re-enter the water at the receiver, after being scattered in the forward direction toward the receiver by the atmospheric aerosol. Since the atmospheric loss is inconsequential compared to the loss in the water path, the feasibility of the technique would depend on the atmospheric scattering factors and on losses at the two air-water interface crossings.

PREVIOUS WORK

A two-phase experiment (5) was conducted in calm water in the Patuxent River at night, utilizing the NOL Test Facility at Solomons, Md. The first phase of the experiment was a determination of the loss factor at the air-water interface. A flash lamp, which had a 40-degree-wide beam in air, was submerged in 10 ft of relatively clear water and pointed toward a land-based receiver located 5 ft above water level and 2800 ft away. The receiver consisted of an unfiltered RCA 6342 photomultiplier (with an S-11 response surface, covering the wavelengths 4500-6000A) at the focus of an f/1 collecting mirror having a 24-in. diameter. Signals were measured for various lamp and receiver angular elevations. Measurements were also made with the lamp in air about 5 ft above water level and pointed toward the receiver.

The results showed that the strongest signals from the submerged lamp were received when the lamp was elevated 60 degrees and the receiver was at its lowest elevation of 10 degrees. When the maximum signal received from the submerged lamp is compared to the signal for the lamp in air, the air-water interface and atmospheric scattering loss factor was estimated to be about 40, which includes an estimated 50-percent loss through 10 ft of water.

In the second phase of this work, carried out on a subsequent night, the lamp and receiver were submerged and the separation distance was increased to 1 mi. The flash lamp was submerged in 9 ft of clear water and pointed toward the receiver, which was

submerged in 4 ft of somewhat murky water. The receiver had a 7-degree field of view and was pointed toward the lamp. Both the lamp and receiver were pointed at a 60-degree elevation. In this experiment the receiver was an RCA 6342 photomultiplier located at the focus of a 4-in.-diam f/3 collector lens. A Corning glass filter (No. 3384) was used in order to achieve some spectral isolation in the 5000A spectral region. The filter and photosurface spectral response combination was chosen to give a spectral bandpass similar to the spectral banpass of 30 ft of clear Chesapeake Bay water. The water transmission in the vicinity of the receiver at the time of the experiment was not measured, but it was poor – the front end of the receiver in 4 ft of water was not visible in daytime. The transmission of the water at the projector, which was in deeper water, was estimated to be 50 percent at 5000A for 10 ft of water path.

This experiment yielded a maximum signal to noise ratio (S/N) of 200 when the underwater lamp was at an angular elevation of 60 degrees. A comparison of the maximum water-air-water signal from the submerged lamp and detector system with the direct line-of-sight above-water signal gave an effective attenuation factor of 10^{-5} for the water-air-water path. When this is compared to the 10^{-35} factor for one mile of average ocean water, the attenuation advantage of the water-air-water path is obvious.

RECENT EXPERIMENTS

More recent experiments on the detection of scattered light with a submerged detector have been carried out in the Chesapeake Bay area, at the NRL Chesapeake Bay Annex (CBA). The light source was a modified General Radio Strobolume with the flash lamp incased in a watertight housing and connected to the power supply through a 50-ft power cable. The light source in the Strobolume is a General Electric FT220 xenon flash lamp with a maximum input rating of 200 watt-sec per flash, a maximum anode voltage of 2500 volts, and a maximum power input of 7 watts. In this application the lamp was operated at 2500 volts with an input of 125 watt-sec per flash and a pulse duration of 100 μsec, which corresponded to a peak power input of about 10^6 watts. The lamp has a beamspread of 45 degrees, in air, at the 50-percent intensity points and this relatively wide beamspread made the pointing of the submerged light a noncritical factor. Actually the maximum signals were obtained when the lamp was pointed toward the receiver at an inclination of about 30 degrees from the vertical. But for pointing angles of as much as 10 degrees to either side of the 30-degree setting, this maximum signal varied by only 10 percent.

Figure 1 is a sketch which illustrates the experimental arrangement. The light source was submerged to depths which ranged from 6 to 18 ft of water, was from 10 to 22 ft above the bottom, and was at the end of a retractable boom which was attached to a small boat, as shown in Fig. 2. A universal mount permitted an operator to hand point the submerged light toward the receiver during the measurements. These measurements were made only in calm water so that the direction of the vertical and the pointing of the light were easy to maintain. The receiver was an RCA 6342 S-11 surface photomultiplier located at the focus of an f/0.5 24-in.-diam back-surfaced mirror, as shown in Fig. 3. This assembly was submerged 1 ft above bottom in 7 ft of water at a permanent platform located about one mile off shore (Fig. 1). The photomultiplier was in a watertight housing, but the mirror was in direct contact with the water.

Prior to the second series of measurements it was postulated that the mirror was probably of little help, and at the end of the second series it was indeed verified that the signal with the bare phototube was as great as, or greater than, that with the mirror.

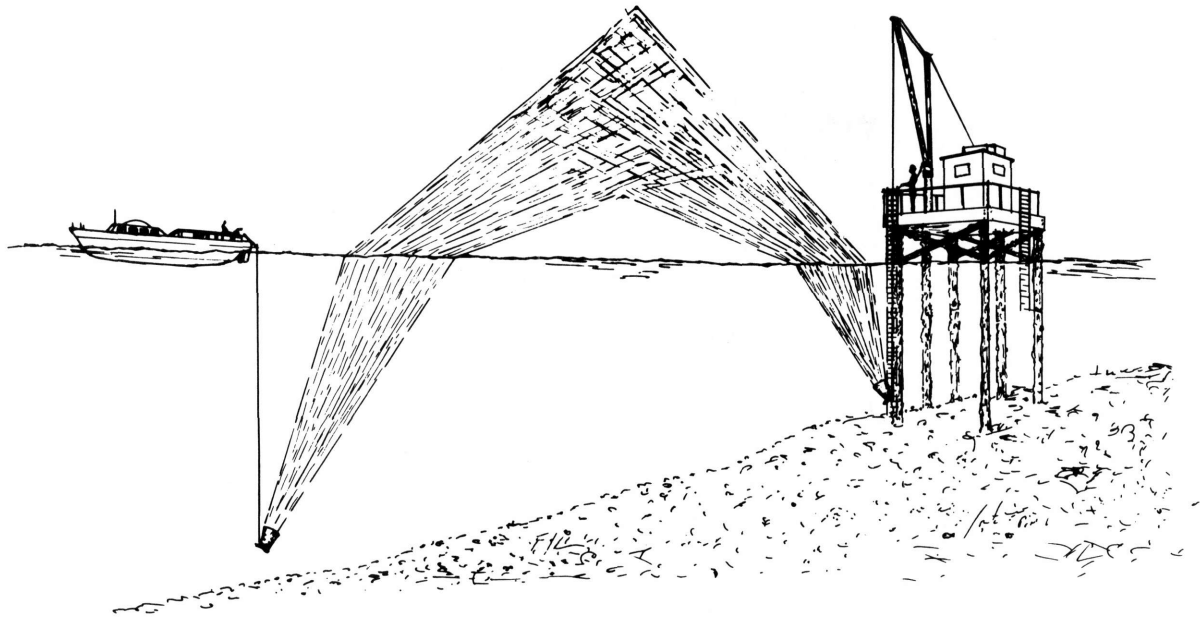

Fig. 1 - Schematic of experimental arrangement showing submerged light source and receiver and a representation of the water-air-water optical path

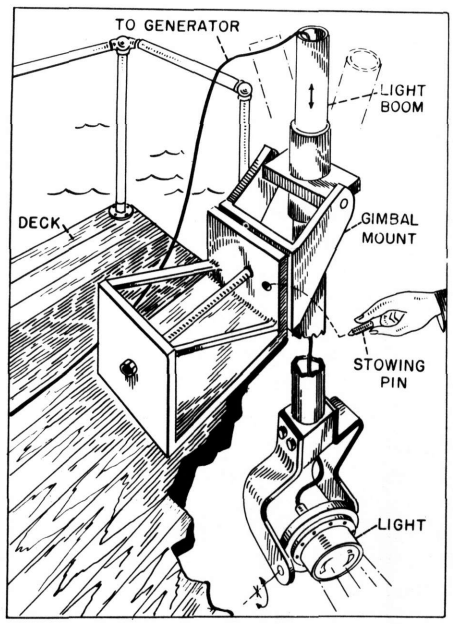

Fig. 2 - Schematic of light assembly and boom on small boat

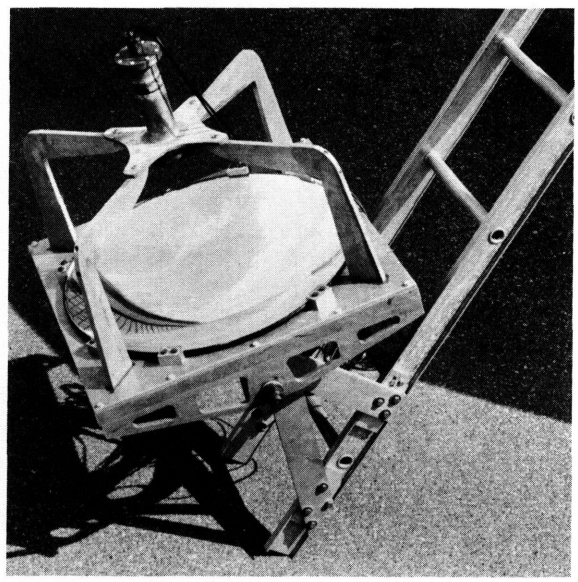

Fig. 3 - Photograph of original mirror-receiver assembly

Fig. 4 - Experimental arrangement at receiving platform showing final photomultiplier detector assembly without collector mirror

The mirror was subsequently discarded, which greatly simplified the final receiver assembly shown in Fig. 4. The lack of improvement in signal level when the mirror was used indicates that the received signal came from a large-area effective source which filled the receiver field of view for those separation ranges at which the measurements were made. The mirror system had a field of view of 8 degrees in air; when the multiplier was used without the mirror, the field of view was about 75 degrees in air.

A typical experimental run consisted of a series of measurements of underwater irradiances for the light source at predetermined distances from the receiver. Initial measurements were usually made when the lamp was about 300 yd from the receiver, the lamp being at a depth of 18 ft and the receiver at a depth of 6 ft. For other separation distances the lamp depth was varied from 9 to 18 ft. The maximum distance at which a signal was detected was 14,000 yd on a hazy night when the meteorological range was about 5 naut mi. The maximum distance appears to be primarily influenced by the atmospheric meteorological range and water transparency.

Four series of measurements were made during the period of June 8 to July 6, 1964. Two of the runs were made when there was a clear atmosphere and the meteorological range was 20 to 22 naut mi; The water surface was calm on the first run and choppy on the second. The third and fourth runs were made when there was a hazy atmosphere and the meteorological range was 5 to 6 naut mi; the water surface was calm for both these runs.

The transmission of the water was measured only for the set of measurements shown by the June 20 curve of Fig. 6. Transmission was measured during the second run by lowering the receiver a known distance, with the projector at constant depth, and conversely by lowering the projector, with the receiver at constant depth. These measurements gave an attenuation coefficient (to the base e) of about 65×10^{-4} cm^{-1} in the effective spectral passband of the receiver cathode and water transmission combination. Visual observations indicated that the water for the second run was much clearer than during run number one – the receiver was visible in 5 ft of water. Transparency measurements of Chesapeake Bay waters made previously by Hulburt (6) showed attenuation coefficients of 32.3×10^{-4} cm^{-1} in the spectral region of maximum transparency at about 5600A, i.e., about 1/2 the value determined above. This corresponds to transmission factors of 0.56 and 0.18 for 6 and 18 ft of water, respectively. However, when the detector has an S-11 cathode surface, the wavelength of maximum response through 6 ft of Chesapeake Bay water is shifted to 5000A, as shown in Fig. 5 where relative signal is plotted as a function of wavelength.

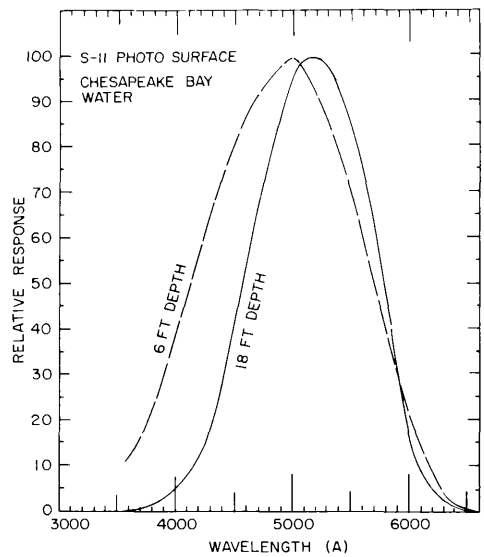

Fig. 5 - Photomultiplier spectral relative response modified by 6 and 18 feet of Chesapeake Bay water

Figure 5 shows the relative signal as a function of wavelength for the S-11 surface and for 6 and 18 ft of Chesapeake Bay water. For the 18-ft depth, the wavelength of maximum response is shifted slightly to the longer wavelength at 5200A. These calculations are all based on Hulburt's data taken on water samples from a deeper and clearer region of the Bay than where the present experiments were performed. Actually, at the time and location of these experiments the water was murky and dark, an indication of this being that the detector assembly was invisible from the surface in daytime when it was in 6 ft of water. The water at the transmitter was about 30 ft deep and was visually clearer than the water at the receiver. It is estimated then that the transmission factors were much lower than the calculations from Hulburt's data, perhaps by a factor of 10. This would then give transmission values of 0.056 and 0.018 for 6 and 18 ft of water, respectively, at the spectral region of maximum transmission, assuming that there was no change in the spectral characteristics of the water.

RESULTS AND DISCUSSION

The results of four runs are shown in Fig. 6. On hazy nights when the atmospheric meteorological range was 5 to 6 naut mi and the water was calm, the signals were detected up to 14,000 yd (June 8 and June 20 curves), where the S/N ratio was unity. For both of these runs the data show the relationship

$$S \propto D^{-1.44}$$

where S is the relative signal and D is the source-to-receiver distance in yards. However, the signal level for all points of June 20 is 1/3 that for corresponding ranges on June 8, which suggests that the difference is caused by a constant attenuation factor such as the degradation of the water transparency between these two runs. The June 17 curve shows relative signal as a function of distance when the atmospheric meteorological range was 22 mi and the water surface was calm. Here the signal was detected out to 7000 yd and the curve has the relation

$$S \propto D^{-1.93}$$

The July curve shows relative signal as a function of distance when the atmospheric meteorological range was 20 mi, the water surface was choppy, and the water was muddier than usual. The visual observation of water opacity is borne out by the overall signal level, which is only 1/5 that measured during the run of June 17. Here the signal was detected out to only 2000 yd and the signal-vs-distance relationship is similar to the June 17 relation.

An interesting aspect of the results shown in Fig. 6 is the fact that for similar surface conditions the signals and ranges improved as the meteorological range decreased. This is readily seen by comparing the June 8 and June 20 data with June 17, all of which represent data taken when the water surface was judged calm. Signal levels and maximum ranges were greater for June 20 and June 8 when the meteorological range was 5 naut mi than they were for June 17 when the meteorological range was 20 naut mi.

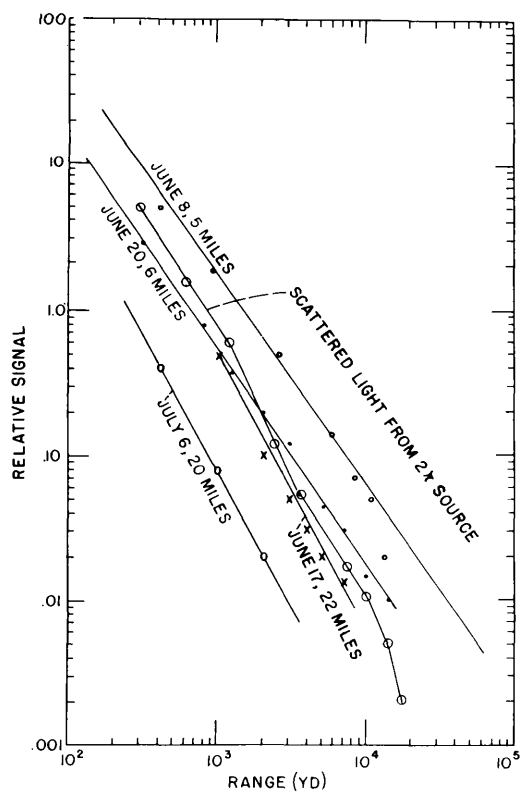

Fig. 6 - Experimentally determined relative light signal as a function of separation distance (range) between receiver and light source measured on the dates and for the meteorological ranges shown

A possible explanation of the above behavior is that, for the meteorological ranges and relatively short distances which are of concern here, the absolute magnitude of the scattered light is predominant and overrides the usual atmospheric exponential attenuation loss. This is illustrated in Fig. 7 which shows the computed relative scattered light signals (at 5500A), in air only, as a function of distance between receiver and light source when the meteorological range is 5 and 20 naut mi and the scattering volumes and angles are assumed constant. The latter assumptions affect only the shape and slope of the curve. The curves show a stronger expected signal for conditions of poorer meteorological range, up to a crossover point at 4000 yd. Beyond this distance the expected signal is greater when the meteorological range is 20 naut mi, and it remains relatively stronger with increasing separation distance. In underwater experiments the position of the crossover would, in addition, also be affected by the transparency of the water.

Another interesting feature of the data in Fig. 6 is the good exponential relationship ($S \propto D^{-1.44}$ and $S \propto D^{-1.93}$) that exists between the received signal S and the separation distance D between light source and receiver. The exponential signal decay also seems to be a function of the meteorological range, showing a tendency to increase as the meteorological range increases. This is a somewhat surprising conclusion that requires further study.

A comparison of Figs. 6 and 7 shows, respectively, the marked dissimilarity between the slope and shape of the experimental and computed curves. There is an indication of a previous crossover between the June 20 and June 17 curves in Fig. 6. However, in this case, the signals beyond the crossover are stronger for the meteorological range of 5 naut mi, i.e., the curves show just the opposite of what is predicted in Fig. 7. This would seem to indicate that the above assumptions of constant scattering volume and scattering angle do not apply to the experimental conditions. Indeed, it is reasonable to assume that both the scattering volume and scattering angle are changing with separation distance, but these changes are unknown at the present time.

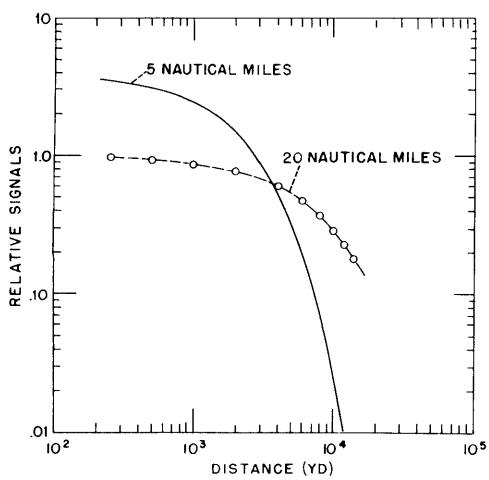

Fig. 7 - Relative scattered light signal as a function of receiver-to-source separation distance (range) computed for meteorological ranges of 5 and 20 naut mi

The results of an attempt to obtain experimental data on the variation of scattered light signals as a function of the source-to-receiver separation distance is shown in the "2π source" curve of Fig. 6. Here the experimental results of scattered light (4500 to 6500A) signals are shown as a function of distance from a 2π source when the meteorological range was 15 naut mi. The light source was a high-intensity flash lamp which was mounted on the cabin of a small boat. Scattered light signals were received by a 12-degree field-of-view photomultiplier receiver system which was pointed 6 degrees above the horizon so that no direct light from the source entered the receiving system. The data from this experiment, indicated by the 2π source curve, shows a general similarity to the experimental data from the underwater experiments. It appears that the exponential relationship in the underwater experiments is fortutitous and results from changes in the scattering angle and scattering volume as the separation distance is varied.

The problem now arises as to whether a useful communication link can be developed from this technique. Such a system should have a high degree of all-weather reliability,

operate at night or during the day for various seas and sea-state conditions, and be useful perhaps at submerged depths and over ranges greater than those in these preliminary observations. There remains the question of whether the system would be of any value even if it worked; this is a tactical, not a technical, question and cannot be evaluated here. Obviously, the small amount of data available permits only a very general analysis of the problem. Since the measurements were carried out successfully in dirty shallow water in the Chesapeake Bay, it is reasonable to assume that successful results would be obtained at greater depths in clearer ocean water. The effect of sea state is at present unknown, but it would appear to be a critical factor. If "all-weather" is considered to refer to meteorological range alone, the experimental data show the system will work at 14,000 yd when the meteorological range is 5 naut mi. Hence, the all-weather reliability at 14,000 yd is a function of the probability of the meteorological range being 5 naut mi, or more, in the communication area. The applicability of the system for daytime operation has not been investigated. However, experience gained in transmission of signals over the horizon in daytime indicates that, all things being equal, the system will work in daytime with a maximum range estimated to be 25 percent that for nighttime operation. (As a matter of fact the technique of the water-air-water link is a sort of right-angle extension of the over-the-horizon system.)

If one speculates on system improvements to increase maximum range, several improvement areas are readily apparent. From Fig. 6 it is seen that the signal S varied with separation distance D as $S \propto D^{-n}$, where n varied from 1.44 to 1.93. If we assume an average meteorological range of 12 naut mi, where S would be proportional to $D^{-1.68}$ by interpolation, then the maximum range would be increased by 50 percent with a doubling of the S/N ratio. A rough and somewhat optimistic extrapolation indicates that the experimental S/N ratio could be improved by a factor of 100. This would come from a factor of 10 increase in light intensity and another factor 10 which could be obtained at the receiver by increasing the receiver cathode collecting area and by an optimum design of the receiver electronic system. With this gain factor of 100 it should be possible, for example, to maintain the nighttime 14,000-yd link when the meteorological range was 1 naut mi. Or perhaps this gain factor would permit operation at greater depths.

There are many elements in the problem that should be investigated before an evaluation of this technique can be made. Some of these areas are:

a. the effect of sea state

b. the influence of light source geometry and orientation at various depths

c. the influence of receiver geometry and orientation at various depths

d. the variation of signal and range with depth of receiver and source

e. the atmospheric illumination pattern from the submerged source

f. the optimum spectral passband at various receiver and source depths for daytime and nighttime operation

g. the effect of meteorological range on maximum distance when source and receiver are at various depths.

A proper evaluation of these factors requires that the investigations be carried out in situ in deep natural waters.

CONCLUSION

These experiments have demonstrated that under certain conditions, it is possible to send signals between two submerged points separated by distances of 14,000 yd or more by sending light signals out of the water into the atmosphere and then have the atmospheric aerosol scatter the light back into the water. Although in these experiments the receiver and projector were only in shallow water in the Chesapeake Bay at depths of 6 to 18 ft, there is reason to expect that these same ranges will result in the much clearer ocean waters with the receiver and projector at depths of 50 to 100 ft. The single-path beam attenuation factor for 14,000 yd of clear ocean water at its most transparent spectral region is estimated to be about 10^{-280}, while the loss factor in the water-air-water link for a 14,000-yd range in these experiments is estimated to be 10^{-9}. The attenuation advantage of this new technique is obvious. However this advantage must be tempered by the fact that the water-air-water link is still highly attenuating and it is uncertain whether a useful underwater-to-underwater signaling system could be based on this technique.

Much additional effort would be needed on this problem in order to clarify the overall problem. In particular, there is an interest in the variation of signal with separation distance in ocean waters where the receiver and source are at greater depths. There is a concern with evaluating daytime background limitations and also an interest in conducting some experiments in ocean waters to determine the optimum spectral region. Because the signaling system is affected by a combination of factors, including atmospheric scattering, water transparency and daylight background, the optimum spectral region may be removed from the spectral region of maximum water transparency and may very well be dependent on depth and geographic location.

The present experiments have given encouraging results with a light source of modest power and a single receiving system. It is estimated that a more intense light source and a well-designed receiver system could give a hundredfold improvement in signal strength in these experiments. This is an important gain factor which appears to be reasonably practical and would permit a system to operate at greater depths and separation distance.

ACKNOWLEDGMENTS

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