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Airborne Searchlight Signals Measured Underwater in the Chesapeake Bay

G. L. Stamm, C. F. Wingquist, R. L. Denningham,
and S. S. Souser

Radiometry Branch
Optics Division

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U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

ABSTRACT

Measurements have been made of the slant ranges over which light signals from an airborne searchlight were detectable at an underwater receiver in the Chesapeake Bay. These measurements were conducted as part of an investigation being carried on to develop an aircraft/submarine communication system.

At night, light signals were successfully transmitted from an airborne searchlight at a maximum altitude of 5000 ft to a receiver 10 ft underwater over a maximum range of approximately 14 naut mi. The beam intensity was one half million candelas. The average of three maximum ranges measured at flight altitudes of 1000, 2000, and 5000 ft was 11.2 naut mi. At a reduced intensity of one tenth million candelas, the average range was 8.3 naut mi.

Water in the vicinity of the submerged receiver was murky, and the water surface was agitated by a steady wind. Atmospheric clarity was good, and there was no moonlight.

PROBLEM STATUS

This is an interim report on one phase of the problem. Work on this problem is continuing.

AUTHORIZATION

NRL Problem N03-12
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AIRBORNE SEARCHLIGHT SIGNALS MEASURED UNDERWATER IN THE CHESAPEAKE BAY

INTRODUCTION

Water is relatively transparent in the visible region of the spectrum; hence it is possible under certain conditions to transmit light signals from a submerged submarine to an aircraft. Experiments have been performed by the U.S. Naval Research Laboratory (1,2) to measure the slant ranges at which pulsed signals from a light source under the ocean surface can be detected in an aircraft. During nighttime measurements (2), signals have been detected out to ranges of approximately 17, 9, 5, and 3 naut mi at light-source depths of 100, 200, 300, and 400 ft respectively. Aircraft altitudes were 1000, 2000, and 5000 ft.

More recent experiments have been performed to measure the ranges over which light signals from an airborne searchlight can be detected at an underwater receiver. The receiver was lowered to a depth of 10 ft in the Chesapeake Bay, where the water was very murky. Light signals were detected when the searchlight was as far away as approximately 14 naut mi for a searchlight altitude of 5000 ft. The beam intensity was one half million candelas. The air was clear, and there was no moonlight.

EQUIPMENT

The searchlight projected a nutating light beam at a slight depression angle aft of a C-54 aircraft. As the beam nutated in flight, it swept through a cone-shaped volume of atmosphere; the searchlight was at the vertex of the cone. The cross section of the beam on the water surface circumscribed an elliptically shaped pattern. A 1000-watt ac mercury-xenon arc lamp mounted in front of a 12-in.-diameter reflector (focal length 5-3/4 in.) created the beam. Nutation was achieved by rotating the reflector off axis. By increasing the off-axis angle to which the reflector was set, the beam could be made to sweep over a larger expanse of water surface. Beamwidth and beam intensity could be adjusted by changing the lamp position. Also, it was possible to change the depression angle so that the beam could be pointed at any angle between horizontal and straight down. The searchlight assembly was supported by an elevator arrangement which could be lowered through a hole in the bottom of the aircraft to avoid shadowing by any part of the aircraft.

Horizontal and vertical angular beam-intensity measurements were made for six positions of the lamp along the reflector optical axis. Resulting patterns showed some similarities, such as decreased intensities near the beam centers and highest intensities near the edges. The cross sections of the beams were generally bright rings with darker areas in the middle. With the lamp at the reflector focal point, the dark spot was not noticeable, and maximum intensity occurred at the beam center.

Two positions of the lamp were used during the range measurements; it was set 3/8 in. beyond and 1-3/4 in. within the focal point, to project 10- and 23-degree-wide beams respectively. The 10-degree beam had an average maximum intensity of 5×10^5 candelas, and the 23-degree beam had an intensity of 10^5 candelas.

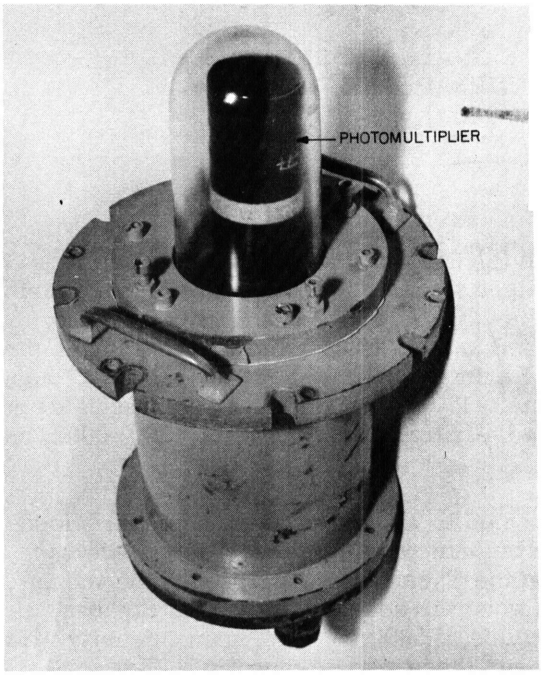

Fig. 1 - Underwater receiver, showing photomultiplier mounted in a watertight glass and steel enclosure

Light from the ac arc lamp was blue-white and was modulated at 800 cps. The spectral distribution was such that much of the light was emitted at wavelengths where water is most transparent. Power for the lamp was obtained from the 110-volt, 400-cps supply of the aircraft.

As the beam swept over the water surface, its light was detected by an underwater receiver. The weak, modulated light signals were converted to electrical signals of the same modulation frequency and transmitted through a cable to a narrow-band, frequency-sensitive voltmeter above the water surface. The receiver was designed to operate at low levels of illumination, such as prevail at sea at night; it required power to be supplied at 115 volts, 60 cps.

The underwater receiver consisted of a photomultiplier and a cathode follower mounted in a watertight glass and steel enclosure (Fig. 1). No optical collecting system was used; therefore light could be detected from any direction in a hemisphere as long as it fell on the 2.2-sq-in. flat photosensitive surface. The spectral response of the phototube was high at wavelengths where the water is relatively transparent and where the light source emits much of its energy.

SIGNALING RANGES

Maximum slant ranges* at which light signals were detected by the underwater receiver were measured at night on May 6, 1964. Flights were made over a rigid platform standing in 12 ft of water and located in the Chesapeake Bay near the Chesapeake Bay Division of the U.S. Naval Research Laboratory. The receiver was lowered into the

*Maximum range was determined from a signal-to-noise criterion described in a subsequent section.

water to a depth of 10 ft from one side of the platform, with the light-sensitive surface facing upward and the normal to that surface making an angle of 60 degrees with the vertical.

Atmospheric conditions were favorable; the air was clear, and there was no moonlight. Estimates of atmospheric transmissivity based upon the disappearance distance of a point light source of known intensity yielded an average value of approximately 80 percent per mile. To make the above estimate, the steady white tail light of the aircraft was viewed as the aircraft flew away from an observer on the platform. From measurements of the intensity of the tail light, the distance at which it disappeared, and the brightness of the sky background against which it was viewed, the approximate atmospheric transmissivity was found from a nomograph in a report by Knoll, Beard, Tousey, and Hulburt (3). The sky luminance varied between 0.3 and 0.4 microlambert, slightly high for a dark night, probably because of scattered light from cities nearby. The water-surface luminance was approximately 0.1 microlambert. Total illumination falling on a horizontal plaque on the platform was 0.1 microlumen/cm^2.

Seventeen runs were made over the platform by the aircraft at altitudes of 1000, 2000, and 5000 ft. Twelve of the runs were made for the purpose of measuring maximum slant ranges at which light signals could be detected; six of these were made with the receiver ten feet underwater, and six were made with the receiver raised to a position over the water surface. The remaining runs were made to estimate atmospheric transmissivity and to calibrate the aircraft doppler radar between two ground stations which were a known distance apart. Data were always recorded when the aircraft was flying outbound on a straight line away from the receiver, which was pointed in the direction of the outbound aircraft. As the aircraft flew away, the light signal became weaker. During a run, the interval was measured between the time when the aircraft was directly overhead and the time when the light signals were no longer detectable. By multiplying the average aircraft ground speed by the time required for the aircraft to fly to the most distant point at which signals were no longer positively detected, the maximum slant ranges of detection were calculated. These range calculations were compared with ranges recorded by doppler radar navigation equipment aboard the aircraft; the maximum ranges measured by the two methods differed by an average of 3.6 percent.

The aircraft was tracked by means of a telescope on the platform and thereby directed to a prescribed course. This arrangement was found to be necessary because over a flight distance of 10 to 20 miles the aircraft would drift off course, and the light beam would no longer sweep over the water surface above the underwater receiver. Directions concerning corrections to be made in aircraft heading were radioed to the pilot as necessary. In this manner, the aircraft was kept on the prescribed course to within ±2 degrees.

Table 1 shows the maximum slant ranges measured with the airborne searchlight at various altitudes and with the beam adjusted for two different intensities and widths. The longest range measured was 13.9 naut mi; for this range the beam intensity was 5×10^5 candelas, and the searchlight was 5000 ft above the water. The average maximum slant range for the three altitudes was 11.2 naut mi at a searchlight intensity of 5×10^5 candelas and 8.3 naut mi at a reduced intensity of 10^5 candelas. One range, 6.3 naut mi, is low; the reason for this probably is that the aircraft wandered too far off course and could not be directed to correct because of a temporary loss of communications.

SIGNAL STRENGTHS

Figure 2 is a trace of the 13.9-naut-mi run, showing the recorded signals and noise. Near the beginning of the run, on the right side of the trace, the signal strength is high

Table 1
Maximum* Slant Ranges Over Which Light Signals Were Transmitted from an Airborne Searchlight to an Underwater Receiver in the Chesapeake Bay, Receiver Depth 10 ft

Searchlight Intensity (candelas)	Searchlight Beamwidth (degrees)	Searchlight Altitude (ft)	Maximum Slant Range (naut mi)	Average Maximum Slant Range (naut mi)
5×10^5	10	1000	9.6	
5×10^5	10	2000	10.0	11.2
5×10^5	10	5000	13.9	
10^5	23	1000	6.3	
10^5	23	2000	8.5	8.3
10^5	23	5000	10.2	

*The maximum range was taken to be that at which the S/N was 2 or close to 2.

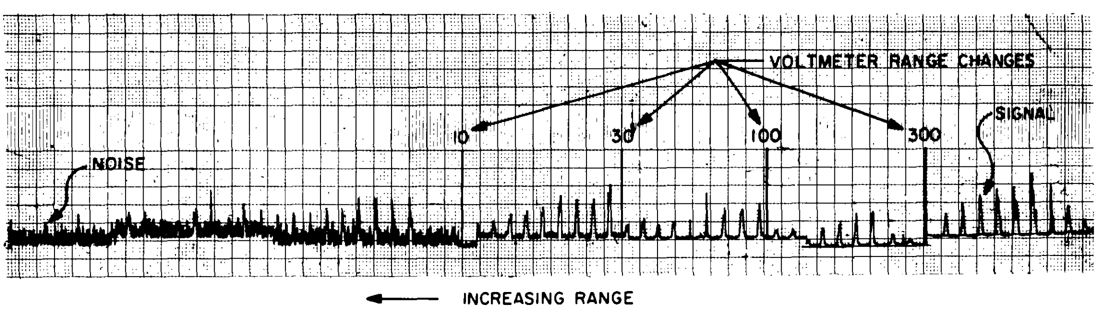

Fig. 2 - Typical recorded signals and noise produced by the underwater receiver and passed through a narrow-bandwidth electronic filter

and the noise is not readily apparent, but as the end of the run is approached, the signal gradually becomes buried in the noise. No signals are recorded for an interval of time at the very beginning of the run (not shown in Fig. 2); this is because the receiver was not illuminated by the sweeping searchlight beam at very close ranges. Throughout a run, the noise level remained constant, although the recorded noise appears to increase toward the end of the run in the trace in Fig. 2. The apparent increase was caused by step changes of the voltmeter range sensitivity, as indicated at certain points along the trace.

The basic noise is believed to be caused by the random emission of electrons by the photosensitive surface being illuminated by ambient light; this effect is commonly called shot noise. Some noise peaks may be caused by luminescent flashes of light in the water, but these probably do not contribute much to the recorded noise, and they do not occur very often. As produced by the photomultiplier, the noise is broad-band, but as seen in the trace in Fig. 2, the signal has been passed through an electronic filter having a bandwidth of 7-1/2 cps with a center frequency of 800 cps.

Figure 3 is a plot of signal-to-noise ratio (S/N) at various ranges for the run recorded in Fig. 2; S/N was computed by dividing the recorded signal peak amplitude by the

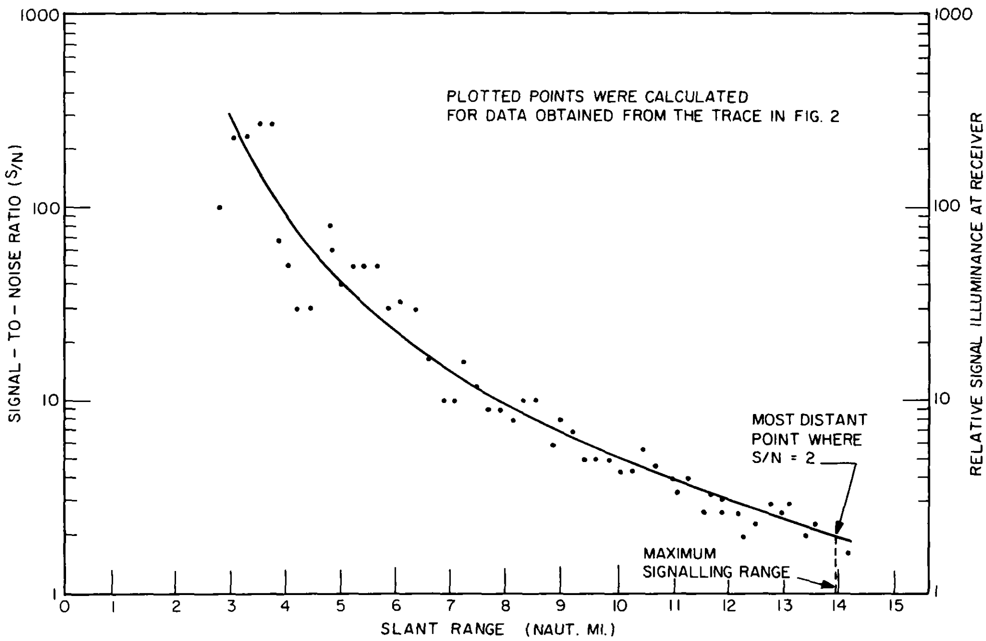

Fig. 3 - Signal-to-noise ratios and relative signal illuminances at the sensitive surface of the photomultiplier when submerged 10 ft below the water surface in the Chesapeake Bay. Light signals were transmitted from an airborne searchlight at continuously changing ranges.

peak-to-peak noise amplitude. Each point in Fig. 3 represents a detected light signal caused by the searchlight beam being swept across the receiver. Although there is considerable variation in S/N from one signal to another, the decrease in S/N is readily apparent as range increases. No points are plotted at the beginning of the run, because the light beam did not sweep over the receiver at these close ranges. The depression angle of the light beam was adjusted to illuminate the receiver to the best advantage at intermediate and longer ranges.

It was determined that an S/N equal to approximately 2 was the minimum for positive identification of a detected signal. Therefore, the maximum signaling ranges given in this report are for the most distant point for which an S/N of 2 or a value closest to 2 was calculated. These ranges can be read from plots of S/N versus range, such as Fig. 3, where the maximum signaling range is indicated at S/N equal to 2. Since the noise was constant throughout any given run, S/N is a direct measure of signal strength, and the relative strengths of signals at various ranges can be found. Also, since receiver sensitivity was kept constant throughout a run, signal strengths are proportional to the illumination falling on the receiver photosensitive surface, which means that the ordinate of Fig. 3 could be labeled relative signal illuminance at the receiver photosensitive surface.

A curve has been drawn through the points plotted in Fig. 3 to show how the illumination at the receiver photosensitive surface decreased as the range increased. The decrease in illuminance was greatest near the beginning of the run and gradually became less toward the end. On the average, illuminances were 100 times higher at the close range of 3 naut mi than they were near the end of the run, at 12 naut mi.

The points in Fig. 3 do not fall on a smooth curve; instead there is a spread in S/N. Near the start of a run the spread is largest because of the problem encountered in

Table 2
Maximum* Slant Ranges Over Which Light Signals Were Transmitted from an Airborne Searchlight to an Above-Water Receiver

Searchlight Intensity (candelas)	Searchlight Beamwidth (degrees)	Searchlight Altitude (ft)	Maximum Slant Range (naut mi)	Average Maximum Slant Range (naut mi)
5×10^5	10	1000	24.2	
5×10^5	10	2000	26.3	25.3
5×10^5	10	5000	25.5	
10^5	23	1000	18.5	
10^5	23	2000	21.0	21.8
10^5	23	5000	26.0	

*The maximum range was taken to be that at which the S/N was 2 or close to 2. Receiver sensitivity was 1/15 that for data in Table 1.

directing the aircraft onto a prescribed course. The aircraft often did not pass directly over the platform; consequently, some maneuvering was required to put the aircraft on course. During this period of maneuvering the searchlight beam was not always properly pointed. A variation therefore existed in signal strength which was greater than at later times. Other causes of S/N variation are not positively known; but several possible explanations for them are suggested. Parts of the light beam having different intensities may have swept over the water surface above the receiver from one sweep to another due to slight changes in aircraft heading because of wind gusts. Also, atmospheric twinkle may have caused some light signals to be transmitted more effectively than others. Since it was found that there is a similar spread of S/N for signals detected both above and below the water surface, it appears that the water surface had very little effect upon the point spread shown.

On alternate runs the receiver was lifted to a position above the water surface, where light signals were detected after they had been transmitted only through the atmosphere. Table 2 shows the maximum above-water slant ranges measured when the searchlight was adjusted for two intensities and flown at 1000, 2000, and 5000 ft. The longest range is shown as 26.3 naut mi, when the searchlight was at 2000 ft and adjusted for an average maximum intensity of 5×10^5 candelas. By averaging the maximum slant ranges at the three altitudes, average maximum slant ranges of 25.3 and 21.8 naut mi are obtained for intensities of 5×10^5 and 10^5 candelas respectively.

DISCUSSION

The light from the airborne searchlight was attenuated in the atmosphere, reflected and scattered at the air-water interface, and attenuated in the water along its path to the underwater receiver. Because of the latter two effects, the average maximum slant ranges measured with the receiver above the surface were greater than with it submerged. In the case of a searchlight intensity of 5×10^5 candelas, the average range was approximately 2.3 times greater when the receiver was out of the water, and for an intensity of 10^5 candelas the range was 2.6 times greater.

The signal illuminance on the photosensitive surface of the receiver became less as the range to the airborne searchlight increased, and at the maximum range the signal

Table 3
Reduction Factor* by Which the Illuminance on the Photosensitive Surface of the Receiver Above Water Differed from that when the Receiver was Submerged

Searchlight Intensity (candelas)	Searchlight Beamwidth (degrees)	Searchlight Altitude (ft)	Illuminance-Reduction Factor	Range for Which Reduction Factor was Computed (naut mi)
5×10^5	10	1000	140	9.6
5×10^5	10	2000	146	10.0
5×10^5	10	5000	84	13.9
10^5	23	1000	385	6.3
10^5	23	2000	200	8.5
10^5	23	5000	134	10.2
			Average = 181	

*Signal amplitudes were normalized since the receiver sensitivity was 15 times greater when submerged than above water.

illuminance was minimum whether the receiver was above or below the water. Lower signal illuminances could not be positively detected. It was possible to increase the receiver sensitivity by a factor of 15 after submergence, because the ambient illumination was less under water than above. One result of increasing receiver sensitivity was that the minimum signal illuminance which could be detected by the submerged receiver was 15 times smaller than could be detected above water.

When the airborne searchlight was at the maximum range, the illuminance detected by the submerged receiver was less than that which arrived at the water surface. The factor by which the illuminance was reduced (illuminance-reduction factor) was calculated from measurements of the average relative signal amplitudes and the relative sensitivities of the receiver when submerged and above water. Average relative signal amplitudes read at the appropriate ranges from curves such as the one in Fig. 3 were normalized, since the receiver was made 15 times more sensitive when submerged than when it was above the water. Table 3 gives the illuminance-reduction factors for different searchlight intensities, beamwidths, and altitudes. In each case the factor was computed for the condition in which the searchlight was at the maximum signaling range measured with the receiver underwater, and the illuminance was in the plane of the inclined photosensitive surface. Although the average reduction factor is 181, there is a large difference in the six values given. The largest factor, 385, is probably too high, because unusually low signal amplitudes were recorded when the aircraft wandered off course during the run when the receiver was underwater. The maximum range of 6.3 naut mi (Table 1) is also short for this run.

Water in the Chesapeake Bay was not clear when compared with ocean water. Secchi disk readings from the platform in the bay during the day previous to the nighttime range measurements gave a disappearance depth of 6 ft. This reading may be compared with similar readings taken at the Argus Island research tower in the Atlantic Ocean near Bermuda, where the disk-disappearance depth was 75 ft. The water surface was roughened by a strong wind which had blown during the afternoon and early evening before the measurements. Therefore, it is likely that the shallow water close to the platform (12 ft deep) had a large amount of bottom sediment suspended in it, causing it to be much less transparent than reported by Hulburt (4). He found Chesapeake Bay water to have a maximum transmissivity of approximately 72 percent per meter at a wavelength of 560 mμ, whereas clear ocean water has been reported (5) to have a maximum transmissivity of over 95 percent per meter.

FUTURE PLANS

Further optical slant-range measurements in the open sea are planned, making it possible to study the effect of depth on range. Argus Island, which is an oceanographic research tower located in 192 ft of water 30 mi southwest of Bermuda, has been chosen as the site for installation of a facility to conduct this work. Besides the greater depth to which equipment can be lowered, the water is clear, and the experimental conditions, including those of the sea surface, are typical of the open ocean.

Slant-range measurements are only the initial phase of a research program aimed at the development of an optical communication system for use between aircraft and submarines. Subsequent to the range measurements, optical and electronic component characteristics will be studied, so that an experimental system can be built to demonstrate Morse code signaling.

ACKNOWLEDGMENTS

Arrangements for the installation of equipment and the transfer of personnel to the Chesapeake Bay platform were made by T. Cosden. Checkout and range measurements were made aboard the NRL C-54 aircraft flown by officers and men at the Laboratory. E.J. Williams at the CBD control tower assisted with communications between the platform and the aircraft.

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