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Photometry Branch
Optics Division

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

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NRL Report 5303

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SUBMARINE-TO-AIRCRAFT SIGNALLING WITH A SUBMERGIBLE TRANSMITTER OF HIGH-INTENSITY, SHORT-DURATION LIGHT PULSES

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ABSTRACT

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A submergible transmitter has been designed and built for automatically generating repetitive high-intensity, short-duration light pulses. When installed on the deck of a submarine for underwater signalling tests, it is easily operated by means of a control panel within the submarine. This transmitter has been employed during underwater-to-air signalling exercises at sea for collecting range data.

Mechanical, electronic, and optical characteristics of the transmitter result from its peculiar use. Most of the components are mounted inside a 200-pound steel cylinder 18 inches in diameter and 21 inches high with a 9-3/4-inch-diameter window at one end. Covering the window, through which the light-pulse beam passes, is a 1-inch-thick disk of Pyrex glass which limits the maximum depth of submergence in water to 150 feet. All seals are made with O-rings. Immediately beneath the window is a flashtube mounted coaxially in a parabolic reflector in such a way that a light-pulse beam having a maximum peak luminous intensity of 18 million candelas is produced by discharging two 0.05-μf high-voltage capacitors through the flashtube. Each light pulse is 1.0 microsecond in duration and the average beam width is 9 degrees. Flashing rate can be preset up to a maximum of 5 flashes per second.

Nighttime signalling ranges through sea water and the atmosphere have been calculated for this transmitter and a sensitive light-pulse receiver using a simplified equation. The computations show that the maximum underwater range is approximately 2530 feet in clearest sea water while in an extremely clear atmosphere the range may be 65 miles, 950 miles being the absolute upper limit to the signalling range for vacuum conditions.

Seventeen runs by an aircraft have been made in clear weather over the submerged transmitter mounted on a submarine in the turbid waters off the coast of Rhode Island. When the sun was above the horizon, no light-pulse signals could be detected. The first detection occurred on a run beginning 44 minutes after sunset on a moonless night, when the horizontal air range was 1.09 miles with the transmitter at a depth of 43 feet and the receiver at 1000 feet altitude. The greatest recorded range was 3.9 miles at a transmitter depth of 13 feet and a receiver altitude of 1000 feet.

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PROBLEM STATUS

This is an interim report on one phase of the problem; work continues.

AUTHORIZATION

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SUBMARINE-TO-AIRCRAFT SIGNALLING WITH A SUBMERGIBLE TRANSMITTER OF HIGH-INTENSITY, SHORT-DURATION LIGHT PULSES

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INTRODUCTION

Signalling between aircraft and submerged submarines has been a problem for the Navy over a number of years. During this period the capabilities of the submarine have increased vastly so that it has developed into one of the most potent forces for waging war at sea today. Likewise, the need for a means of signalling between a submerged submarine and an aircraft has grown in importance. Many schemes for signalling have been proposed and adopted, but the methods now employed are not entirely satisfactory. One such scheme suggests using light because many studies have shown that much of the ocean water is moderately clear, that is, transparent to visible and also near-ultraviolet radiation. The present investigation, called Project Starfish, was established to determine the feasibility of signalling between submerged submarines and aircraft using light.

For this purpose a submergible light-pulse transmitter was designed and built. All the optical and the majority of the electronic components for generating the light-pulse beam are contained in a watertight, pressure-proof steel cylinder. At one end of the cylinder the high-intensity, short-duration light pulses are emitted through a window. The transmitter is mounted on the deck of a submarine and connected to a control panel on the inside with a watertight power cable which must pass through the pressure hull. By means of the control panel, the transmitter can be operated remotely; only a few adjustments are necessary to start it, and thereafter flashing will continue automatically at a predetermined rate with no further attention.

TRANSMITTER CHARACTERISTICS

Mechanical Features

A steel cylinder in two sections encloses all transmitter components except the few which are mounted on the control panel. Within the cylinder are housed the light source, reflector, high-voltage charging and discharge circuits, trigger circuit, and power supply. A window is provided at one end through which the light beam passes, and an outlet for an electrical power cable is welded to the bottom side of the cylinder. Figure 1 shows both an external and internal view of the transmitter which has a diameter of 18 inches, a height of 21 inches, and a total weight of 200 pounds. The 100-pound casing (C in Fig. 1a) is 1/4-inch-thick stainless steel onto which is welded a 3/4-inch-thick flange Fℓ of the same material. In a circle around the flange's top surface is cut a groove approximately 15 inches in diameter to accept an O-ring. An electrical outlet O is welded into the lower side of the casing where a special underwater connector U, designed for a water pressure of over 434 psi, can be inserted.

The transmitter head (Fig. 1b) consists of a steel framework S for mounting the optical and electronic components and a 3/4-inch-thick plate Pℓ welded together. With all components in place the head weighs 100 pounds. A hole, 9-3/4 inches in diameter, is centered in the plate (Fig. 1a), thereby creating a window W which is covered by a 1-inch-thick and 11-inch-diameter Pyrex glass disk G seated on a 10-1/4-inch-diameter

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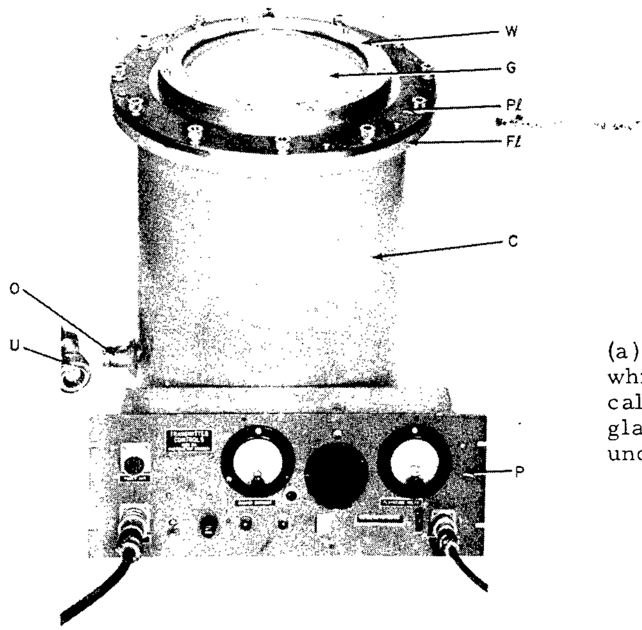
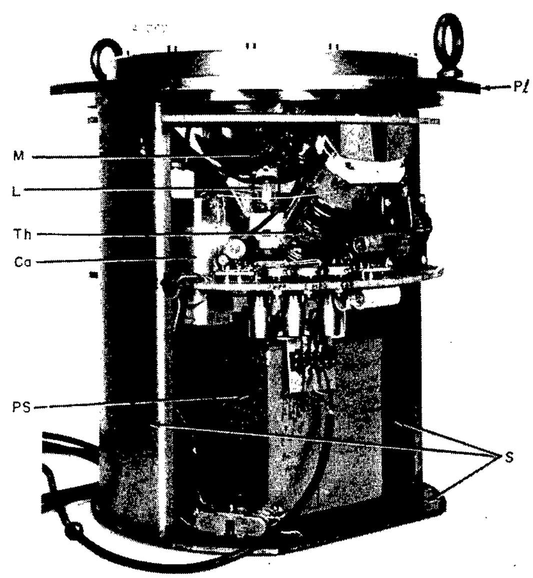


(a) Exterior view showing casing C, onto which is welded the flange Fℓ and electrical outlet O, and control panel P. Pyrex glass G covers the window W. U is an underwater connector.



(b) Electronic and optical components are mounted on the head which consists of plate Pℓ and steel framework S. Energy storage capacitor Ca, thyratron Th, and high-voltage power supply PS are electronic components. Two optical components are flashtube L and reflector M.

Fig. 1 - The watertight, pressure-proof transmitter which can be mounted on the exterior of a submarine

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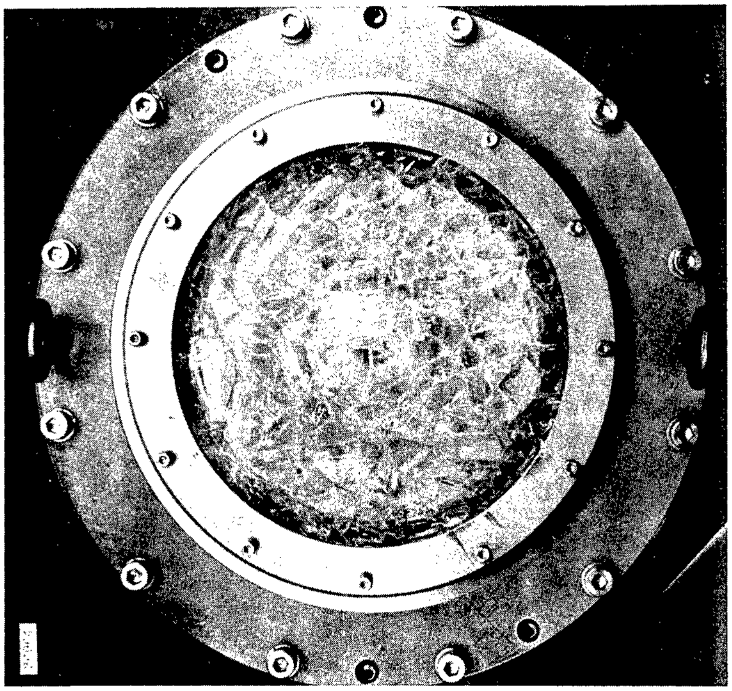

Fig. 2 - Fractured tempered-glass disk on transmitter after application and subsequent release of 295-psi water pressure

O-ring. A watertight, pressure-proof seal is assured by drawing the glass disk down onto the O-ring. Other dimensions on the plate are matched to the flange on the casing. When the head is placed over the flange and the O-ring compressed by bolting them together, and when the underwater electrical connector and glass cover are inserted properly, the transmitter is watertight and able to withstand external water pressures up to 65 psi, which is equivalent to a depth of 150 feet. The pressure limit is determined by the strength of the glass cover.

The effectiveness of various glasses in withstanding externally applied water pressure were tested in a diving chamber. Figure 2 is a view of what happened to a disk of tempered glass secured over the transmitter window and subjected to a water pressure of 295 psi. Oddly enough the fracturing did not occur until the pressure had reached 80 psi as it was being lowered from the above maximum value. The glass did not implode, and only a small amount of water seeped into the transmitter through the many cracks. On another occasion, a commercial Pyrex glass disk imploded violently at the maximum applied pressure resulting in the flooding of the entire interior of the transmitter. In connection with the pressure tests, total force rather than pressure on the outside glass surface is a more relevant quantity to discuss since glass area is then taken into account. On the unsupported surface within the O-ring at 65 psi, the total force is 2.7 tons and at 295 psi, it is 12.2 tons. Fortunately, the force is evenly distributed over the entire glass surface.

Controls for the transmitter are mounted on a 7-1/2 x 9 inch panel P, Fig. 1a. It is lightweight and fitted for mounting in a standard rack.

Electrical Circuits

Light production results from the discharge of two energy storage capacitors into a flashtube. To do this requires charging the capacitors with the necessary energy and controlling the release of this energy through the flashtube. These functions are performed through the circuits of Figs. 3 and 4. Except for the few components on the right side of Fig. 3, everything is located within the watertight transmitter.

The discharge circuit consists of two 0.05-μf 16-kv capacitors and two 4C35 thyratrons arranged symmetrically around a flashtube in a parallel electrical circuit, Fig. 3. One of the capacitors Ca and one thyratron Th are clearly visible in Fig. 1b. To minimize inductance, special capacitors were chosen and much care was taken in arranging the discharge circuit. In operation the capacitors are charged to 10 kv, which is greater than the breakover voltage of the flashtube, but they do not discharge until the hydrogen thyratrons have been fired by means of a positive pulse on their grids. Once the thyratrons are placed in a conductive state, the grids no longer have control over the flow of discharge current and the stored energy is released instantaneously through the thyratrons and flashtube. Immediately after the capacitors discharge, current flows from the high-voltage power supply to recharge them. However, this charging current flow is limited by a resistance of 1.25 megohms to allow the thyratrons to regain full control in the discharge circuit. The RC charging time constant is 1/8 second so that, at the maximum flashing rate of 5 flashes per second, there is ample time for the capacitors to become almost fully charged between flashes. Attention should be drawn to the fact that the maximum flashing rate is limited by the power and peak current that can be supplied by the 15-kv 5-ma high-voltage power supply (PS, Fig. 1b). Much of the energy supplied is not stored in the capacitors because of its dissipation as heat in the charging resistor.

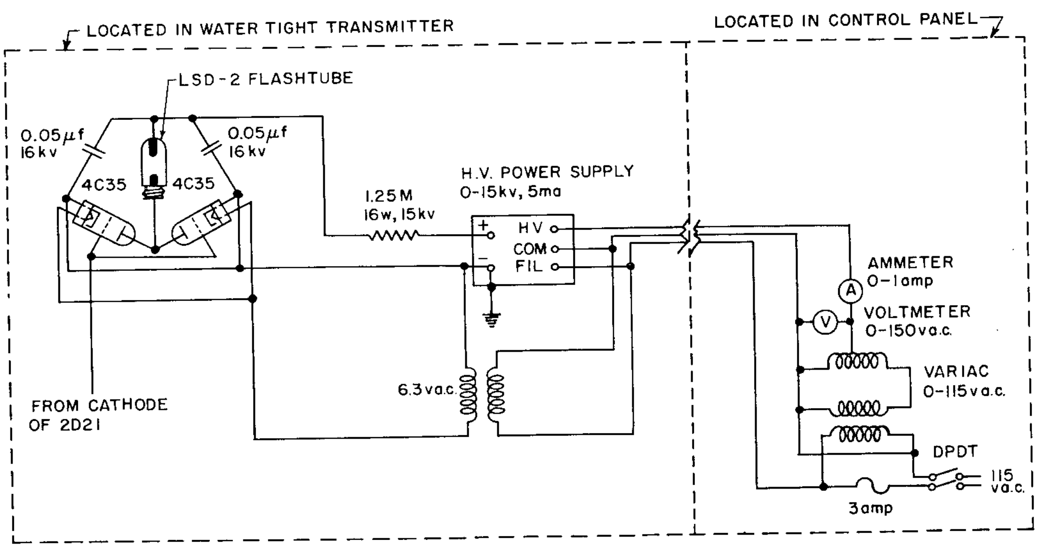

Fig. 3 - Circuit for the charge and discharge of the energy storage capacitors

Precautions must be taken in designing and building the high-voltage charging and discharge circuitry to preclude corona discharges and breakovers. Most important among these are the use of insulating compound where necessary, for example in the flashtube socket; making all high-voltage points round and smooth; using wire insulated for high voltage; separating bare high-voltage points from other surfaces by a sufficient distance; and ensuring that all high-voltage surfaces are clean and dry. These precautions are especially applicable to a submergible transmitter where the environment of salt water and salt-laden, moist air are conducive to failures in high-voltage circuits. For this reason the transmitter should be filled with bags of a desiccant, sealed in a dry atmosphere, and never opened at sea unless absolutely necessary.

Located in the transmitter control panel are components for adjusting the high-voltage power supply output and for checking the operation of the flashtube. By means of a variable auto transformer the high voltage output is raised or lowered, and its numerical value is read on a calibrated voltmeter. If the light pulse cannot be seen, the only positive means for ascertaining whether a discharge occurs is by means of a panel-mounted ammeter which registers the current drawn by the high-voltage supply to recharge the capacitors after each flash. All current supplied to the transmitter from the control panel flows through a watertight cable.

A trigger circuit which automatically generates a repeating positive electrical pulse of sufficient peak voltage to trigger the 4C35 thyratrons and thereby initiate a light pulse in the flashtube is shown in Fig. 4. Since all components are housed within the underwater transmitter, the pulse rate cannot be changed in the field without breaking the seal in the transmitter. However, this rate can be easily preset over a wide range.

Three stages are incorporated into the trigger circuit along with a B^+ power supply. In the first stage, saw-toothed negative pulses are generated by discharging a 0.47-μf capacitor through 100 ohms and a 2D21 thyratron. Once the proper voltages are applied the pulses are produced automatically and repeatedly, the repetition rate being determined by the charging time of the capacitor and the grid voltage on the thyratron. By means of variable potentiometers, 1000 ohms in the grid circuit and 1 megohm in the plate circuit, the pulse rate can be adjusted with fine control. After passing through a resistance-capacitance voltage divider, a negative pulse of 1.7 peak volts is applied to the grid of a 6C4 triode in the second stage and is inverted to a positive pulse of 21 peak volts. The purpose of the third stage is to convert the second stage output pulse into one of sufficiently high peak voltage and energy to fire the 4C35 thyratrons positively. To do this, the previously generated positive pulse is placed on the grid of another 2D21 thyratron which allows a 0.47-μf capacitor to be discharged through a 180-ohm resistor. The resultant pulse, measuring 150 peak volts under no-load conditions, is applied to the parallel-connected, floating grids of the two 4C35 thyratrons in the discharge circuit.

Power for the entire transmitter is supplied through the control panel. A 60-cycle source supplying 300 watts at 115 volts is necessary.

Optics

Upon discharge of the energy storage capacitors through the flashtube, a light-pulse beam is emitted from the transmitter with characteristics which are determined by the flashtube, discharge circuit, reflector, and glass cover over the transmitter window. These characteristics are stated below and will be described in more detail along with the optical components.

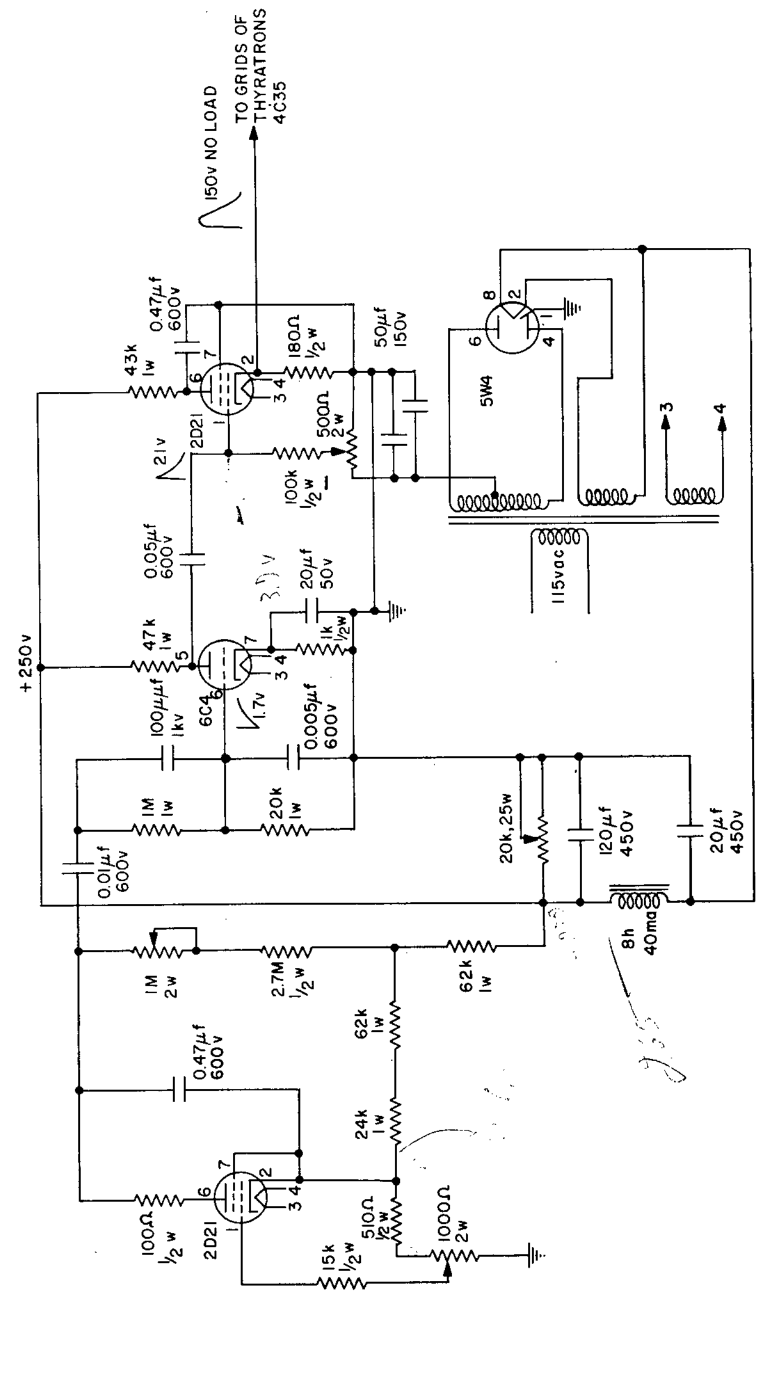

Fig. 4 - Trigger circuit for the generation of an automatically repeating electrical pulse to trigger the thyratrons

Maximum flashing rate	5 flashes/sec
Discharge voltage	10 kv
Energy storage capacitance	0.1 μf
Stored energy	5 watt-sec
Flash duration	1.0 μsec
Maximum peak beam radiant intensity (330 to 680 mμ)	$1.9 \times 10^5 \frac{\text{watts}}{\text{ster}}$
Maximum peak beam luminous intensity	1.8×10^7 candelas
Average beamwidth	9 degrees

The light source is a commercially available straight-gap, medium-pressure flashtube (Fig. 5) called the LSD-2. Its average outside dimensions are 5-1/2 inches in length and 1-1/8 inches in diameter, and the electrode spacing is 4 centimeters. Connections to it are made through a standard medium screw base at the cathode and a cap at the high-voltage anode. A trigger electrode surrounds the cathode, but is not used in the present application. The glass envelope is filled to a pressure of 750 mm Hg with a mixture of 95% argon and 5% hydrogen. The position of the flashtube in the transmitter is shown by L in Fig. 1b.

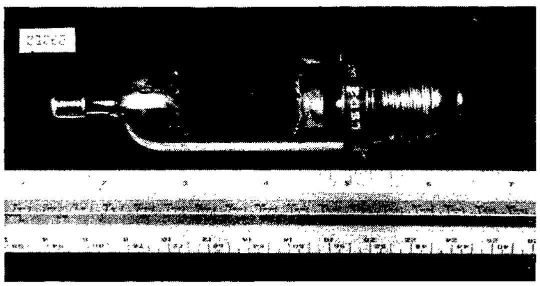

Fig. 5 - The LSD-2 flashtube which is the transmitter light source

Light-pulse intensity from the flashtube is dependent directly upon the energy stored in the high-voltage capacitors. As used in the transmitter, two 0.05-μf capacitors connected electrically in parallel are charged to 10 kv making available a total stored energy of 5 watt-seconds according to the equation

$$e = 0.5\ cv^2,$$

where e = stored energy,
c = energy storage capacitance, and
v = discharge voltage.

Not all of this energy is radiated into a useful part of the electromagnetic spectrum. Some energy is lost in the wiring and thyratrons in the discharge circuit and also in the capacitors themselves, but, by taking precautions in arranging the components and wiring, energy loss due to inductance has been reduced to a low value.

Two other light-pulse characteristics which are affected somewhat by inductance are the duration and rise time. The change of intensity with time during one typical light pulse is shown in Fig. 6 where the duration is seen to be 1.0 microsecond and the rise time is 0.2 microsecond. Duration is used here to denote the time between the points on the intensity-time curve of the light pulse where the intensity is one-third of its peak value. Rise time is referred to as the time necessary for the intensity to rise from 10% to 90% of its peak value and is an indication of the high-frequency components in the complex waveform of the light pulse.

To direct practically all of the light through the transmitter window, a parabolic reflector M is placed so that its optical axis coincides with the axis of the flashtube L,

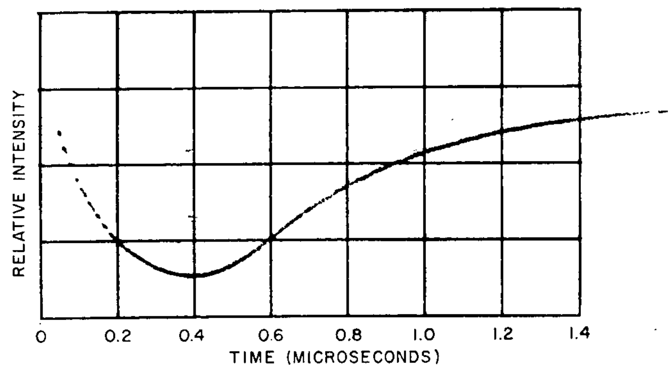

Fig. 6 - Relative intensity-time relationship of a light pulse from the transmitter: duration, 1.0 μsec; rise time, 0.2 μsec

as shown in Fig. 1b. Figure 7 is a cross-sectional drawing showing how selected rays of light from two points in the discharge column of the flashtube L are reflected at the inner surface of M outward through the window W. F is the focal point of the reflector, which is 9 inches in diameter and has a focal length of 1-3/8 inches. A small adjustment of the flashtube along its axis can be made, an arrangement whereby the emergent beamwidth can be changed to a small extent.

Spectral transmittance of the 1-inch-thick Pyrex glass window cover is shown to be 84% in the visible spectrum (Fig. 8). Transmittance falls off rapidly in the near-ultraviolet because of the great thickness which is necessary to withstand the high pressures encountered during deep submergence. To realize high transmittance below 400 mμ will require a different type of glass, but this type is not readily available in the size required for the transmitter.

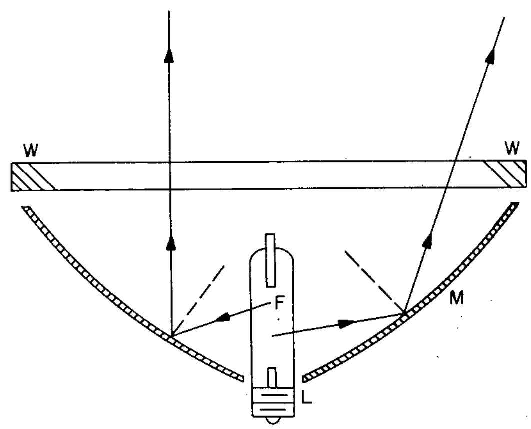

Fig. 7 - Reflection of two selected light rays from the discharge column of the LSD-2 flashtube L mounted coaxially in a parabolic reflector M. Practically all of the light is transmitted through the window W. F is the focal point of the reflector.

The arrangement of the optical components results in a high-intensity light-pulse beam of a narrow angular width. At the point of maximum flux density near the center of the beam, peak radiant intensity is 1.9×10^5 watts per steradian in the spectral region 330 to 680 mμ and peak luminous intensity is 1.8×10^7 candelas. Over this wavelength interval the spectral distribution of the light after passing through the 1-inch-thick Pyrex glass is shown in Fig. 9. Much of the radiation is continuum with a scattering of some high-intensity lines between 380 and 500 mμ where, incidentally, ocean water has good clarity. Greater advantage could be taken of the lines in the near-ultraviolet if the transmittance of the window cover glass were higher in this region.

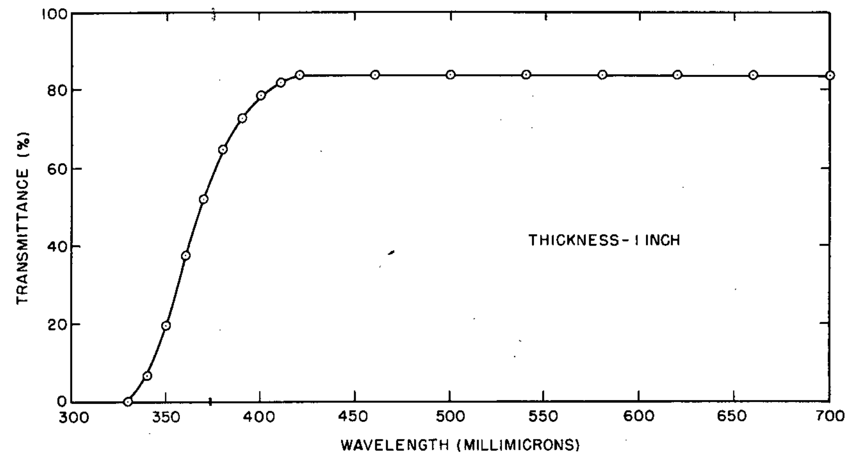

Fig. 8 - Spectral transmittance of the Pyrex glass placed over the transmitter window

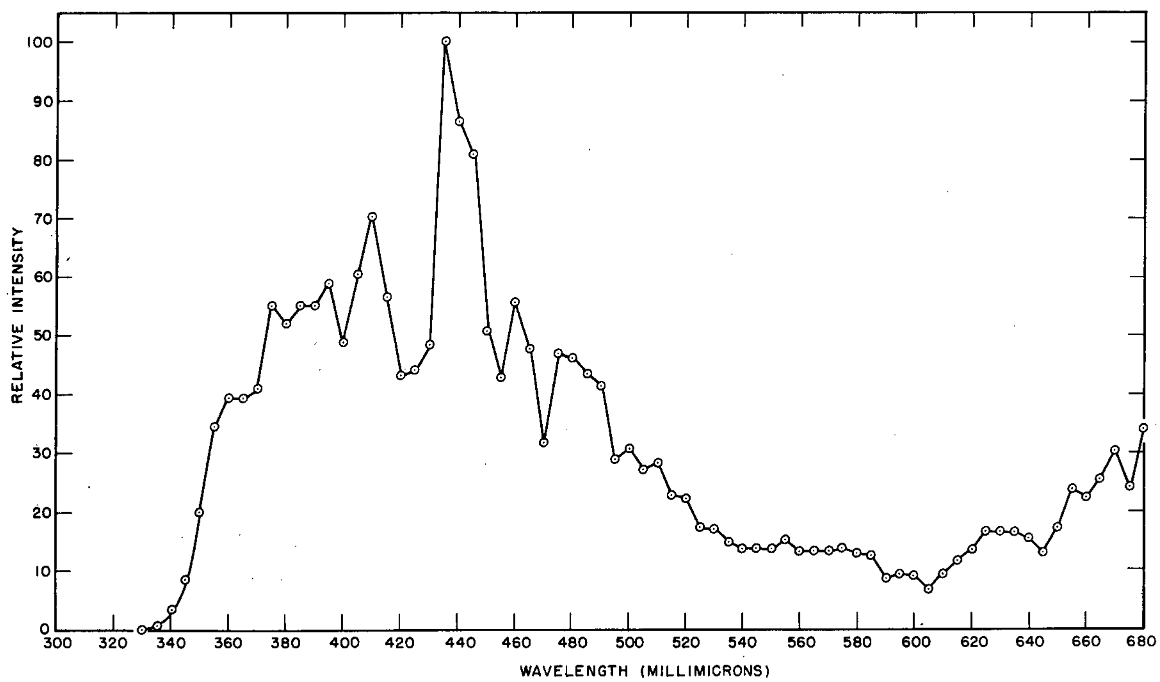

Fig. 9 - Average relative spectral peak intensity of light emitted by the transmitter after passing through the one-inch-thick plate of Pyrex glass

Beamwidth was a major consideration during the design stages of the transmitter because it was thought that light flux should be diverted from the central portion of the beam to its outer edges for most effective use. This is difficult to do in a simple optical system when the light source is extended, as in this case where it is 4 centimeters long. With the extended source in the parabolic reflector, the maximum amount of light is beamed outward by mounting the flashtube with its axis along the optical axis of the reflector. However, in such a mounting the beamwidth can be changed only very little by sliding the flashtube in or out along the reflector's optical axis. Space limitations within the transmitter prevent adjustment over a very wide range so that the discharge column always passes near the focal point, a circumstance which tends toward beam collimation. As a result, the average beamwidth, which is defined as the average angular spread of the beam at the half-maximum peak intensity points, is 9 degrees, Fig. 10a. These and all subsequent data on angular beam intensities were measured at a point 1040 feet from the transmitter. Since the maximum peak intensity is very high, the light at large angles from the beam center is still intense, but most of the flux is concentrated within the central portion. For example, the intensity at approximately 11 degrees from center is 1/10 maximum, and at 54 degrees it is 1/100 maximum.

Besides the problem resulting from the length of the discharge column, there are two other peculiarities which are undesirable and detract from beam uniformity and reproducibility: crookedness of the discharge column and spatial jitter of the column from one flash to the next. Both cause the beam to fluctuate irregularly from a given direction on each flash, and although the angular fluctuation is not great, a small angular change is translated into a relatively large linear movement of the beam at long distances from the transmitter. The most successful method devised to offset these bad features is to diffuse the light at the flashtube by sand blasting its glass envelope. In effect, the envelope can be thought of as a large, uniformly radiating surface which does not change its position from one flash to the next. By so doing, the beamwidth is expanded to 11 degrees (Fig. 10b) at a sacrifice of 30% in maximum peak intensity near the center; along the sides the light flux is essentially unchanged. To date, a flashtube with a ground glass envelope has not been used in a transmitter tested at sea; therefore, all experimental range and optical data presented herein are for a flashtube with a clear envelope. Advantages of the ground glass in preventing beam fluctuation make it highly desirable that it be used in future field exercises.

Due to decreased transmittance and the breakage problem encountered when using thick glass to cover a large window, an experiment was performed to determine what effect smaller openings would have on maximum peak intensity and on the angular peak beam intensity pattern in the hope that a smaller opening covered by thinner glass would be satisfactory. Therefore, a black diaphragm having a 7-inch-diameter aperture and then a similar one having only a 5-inch aperture were centered over the 9-3/4-inch window; the resulting beam intensity patterns are shown in Figs. 10c and 10d, respectively. Beamwidth was increased slightly to 13 degrees for the 7-inch aperture and 14 degrees for the 5-inch aperture, and maximum peak intensity was reduced 53% and 68%, respectively. At large angles from the beam center, corresponding reductions in intensity occurred. All data were taken with and relate to the flashtube with a ground glass envelope as the transmitter light source. From the measurements it must be concluded that unless a sacrifice of intensity is allowable, the 9-3/4-inch window should be used with the present flashtube and parabolic reflector combination. Certainly underwater-to-air signalling is not an instance where any loss of light intensity can be tolerated. Without further studies it is impossible to ascertain the optimum angular intensity pattern for an underwater transmitter, and therefore only a general conclusion has been stated as to the use of smaller transmitter windows.

Field Operation

The submergible transmitter has been employed during one experiment at sea when it was mounted on the deck of a submarine. A watertight 1/2-inch-diameter cable, with 3 conductors to carry power, connected the transmitter to the control panel within the

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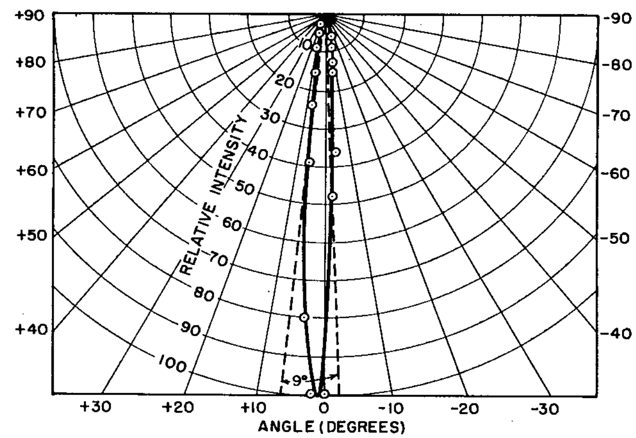
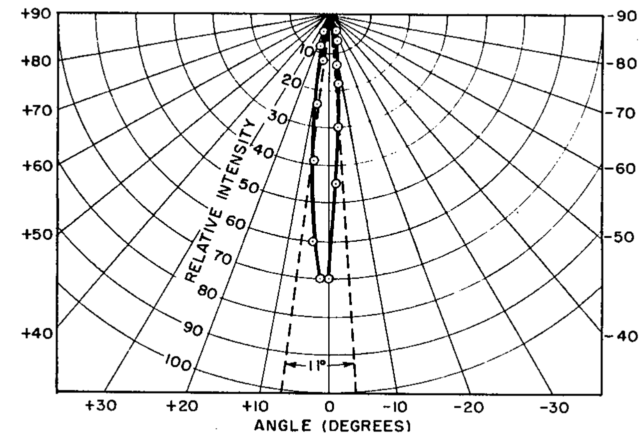
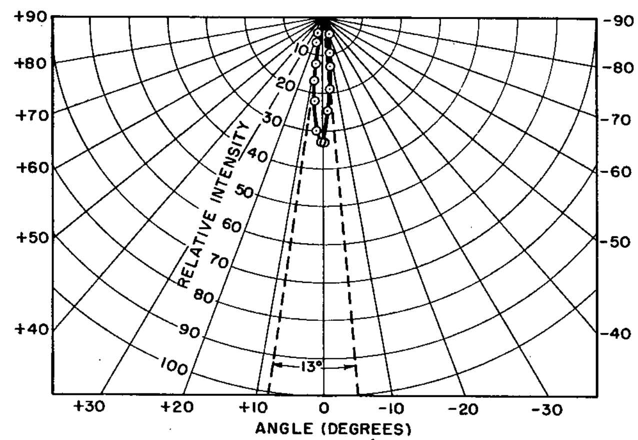


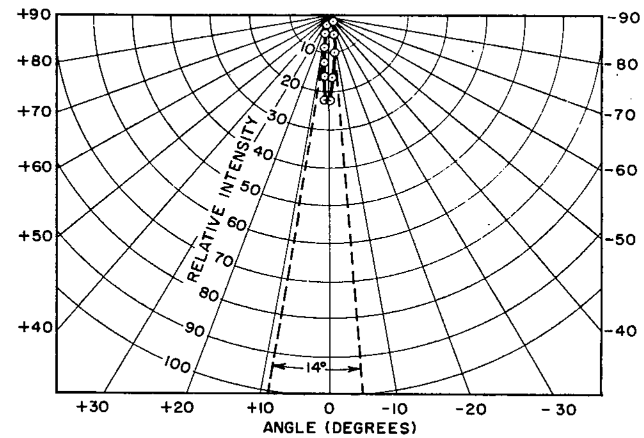
(a) Clear glass flashtube envelope, 9-3/4-inch-diameter transmitter window



(b) Ground glass flashtube envelope, 9-3/4-inch-diameter transmitter window



(c) Ground glass flashtube envelope, 7-inch-diameter aperture



(d) Ground glass flashtube envelope, 5-inch-diameter aperture

Fig. 10 - Average angular peak beam light intensity from the transmitter. Measured values of points on one curve are relative to those on other curves.

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submarine. It was stretched from a special underwater connector at the transmitter casing along the deck and through the pressure hull to the control panel in the forward torpedo compartment.

Operation of the transmitter controls is very simple; naval personnel aboard the submarine made all necessary adjustments after only a brief explanation previous to departing for the experiment at sea. Written instructions also given to them are stated below.

Operating Instructions for Transmitter

1. Start with Variac knob to left (counterclockwise).
2. Turn on toggle switch.
3. Wait two full minutes for warmup.
4. Turn Variac knob to right slowly until the flashing unit begins to operate. This is indicated by a severe dip in the ammeter.
5. Keep Variac turned up just enough to keep flash rate regular.
6. Turn back Variac before turning off main toggle switch.

COMPUTED UNDERWATER AND ATMOSPHERIC SIGNALLING RANGES

A detailed description of the transmitter is important, but its signalling capabilities are the main criteria by which its merits are judged. Therefore, based on the stated maximum peak intensity of the light beam from the submergible transmitter and the maximum peak response of a receiver described in another report (1), maximum nighttime signalling ranges in the sea and atmosphere were computed. The purpose of these calculations is to give briefly some idea of the ranges to be expected under favorable sea and atmospheric conditions, realizing of course that these conditions do not always prevail in reality. However, to make accurate calculations for poor conditions would be lengthy and would require a much more sophisticated theoretical development and understanding of the propagation of light beams through media of high scattering capacity.

Two cases of signalling were considered: (a) underwater to underwater, and (b) air to air. Signalling ranges were computed from published attenuation data for sea water and the atmosphere and the inverse square reduction of illuminance by using the following equation:

$$R = \left(\frac{I \times T^R}{E}\right)^{1/2}$$

where

R = maximum nighttime signalling range,

I = maximum peak beam luminous intensity of transmitter light pulse (1.8×10^7 candelas),

T^R = transmittance of medium over path length R, and

E = minimum peak illuminance capable of producing a signal in the receiver (0.005 microlumen/sq in.).

It was assumed that the most intense portion of the light beam is pointed directly at and is normal to the light-sensitive surface of the receiver. To simplify the calculations as much as possible, no consideration was given to scattering other than to the extent that it contributes to the attenuation of light.

Calculations show that the maximum underwater-to-underwater signalling ranges in most sea water vary between 2530 and 990 feet depending upon the clarity at various places and times. The first range is for clearest sea water having a transmissivity of 99.4% per foot and the second for more turbid water having a transmissivity of 98.3% per foot. With only a few exceptions, optical measurements made by Jerlov (2) in tropical and subtropical areas of the Atlantic, Pacific, and Indian Oceans and in the Caribbean, Red, and Mediterranean Seas showed transmissivities in the upper 10-meter stratum of water to be between these two limiting values. Arctic waters are likely to exhibit more turbidity. During NRL experiments (3), a transmissivity of 98.3% was measured at a wavelength of 474 mμ over a vertical water path from the surface down to 432 feet near the Gulf Stream 155 miles east of the Florida coast. Closer to shore, that is, in coastal water, signalling ranges would be greatly reduced due to large amounts of suspended matter which cause scattering to be the major factor in attenuating light. How beams of light are affected thereby is not well known experimentally, and thus ranges calculated for water of high scattering capacity might be very inaccurate; therefore, only typical ranges for clear sea water are given.

Air-to-air signalling in the lower atmosphere presents a somewhat analogous situation in that scattering becomes an indeterminable factor under certain poor conditions. However, if an extremely clear atmosphere (4) is selected where the transmissivity is 92.1% per mile, corresponding to a daylight visual range of approximately 30 miles, the maximum signalling range is calculated to be 65 miles. This might be looked upon as an upper limit to signalling ranges with this equipment in the lower atmosphere.

Daylight visual ranges are often less than 30 miles; for example, 2.5 miles is typical in hazy weather, and on foggy and smoky days especially around industrial areas visual ranges can be much lower, in a thick fog they might be as low as 165 feet. Calculated signalling ranges for such adverse atmospheric conditions would be of little significance because of scattering effects and the receiver's wide field of view. Large errors in a computed range are introduced by the nonhomogeneous nature of the atmosphere as to both time and place, a situation which makes it difficult to measure atmospheric transmissivity accurately. For instance, near the earth's surface fog, smoke, dust, rain, snow, and sea spray are constantly changing atmospheric clarity while at higher altitudes clouds of different densities act in the same way. At extreme distances from the earth where the air would be very thin and there would be practically no light absorption or scattering, maximum signalling ranges might approach 950 miles, a range calculated for vacuum conditions.

Discretion should be exercised in applying these maximum signalling ranges because they are calculated for total darkness and favorable sea and atmospheric conditions. At most, a feeling for the signalling capabilities of this equipment should be gained from the computed ranges; and if these ranges indicate that the equipment might serve a useful purpose, it can be experimentally tested.

MEASURED SUBMARINE-TO-AIRCRAFT SIGNALLING RANGES IN COASTAL WATER

Submarine-to-aircraft optical signalling ranges were measured on September 18, 1957 during a series of daylight-to-nighttime runs east of Block Island off the coast of Rhode Island beginning at a point approximately 41°10'N, 71°10'W (5). The submergible transmitter was mounted vertically in a streamlined housing on the forward deck of the submarine USS TUSK, and the receiver (1) was fastened into the after photographic hatch of a P2V-5 aircraft. According to a prearranged schedule, the aircraft flew at various altitudes across the light-pulse beam emitted by the transmitter aboard the submarine, which dove to different depths in the water. During these flights, measurements were made of the time necessary for the aircraft to cross the beam at a given altitude from the edge where the light was first detected to the similar opposite edge. By multiplying this time by the aircraft's ground speed, horizontal air ranges were calculated. Then, knowing the transmitter depth and receiver altitude, slant ranges were computed; that is, the distance between the submerged transmitter and the receiver when it was at the limit of light-pulse detection.

A total of seventeen runs were completed and the results are reported in Table 1. Using full receiver gain, horizontal air ranges were 3.9 and 1.9 miles when the transmitter was 13 and 63 feet, respectively, below the sea surface and the receiver was at an altitude of 1000 feet. The sky was cloudless and visibility was good; the sea was green and turbid with scattered whitecaps.

TABLE 1
Submarine-to-Aircraft Signalling Ranges Using Light Pulses from the Submergible Transmitter

Run No.	Time at Start of Run* (EST)	Relative Receiver Gain	Transmitter Depth† (feet)	Receiver Altitude (feet)	Horizontal Air Range (miles)	Slant Range (miles)
1	1700	1	13	500	0	0
2	1710	1	13	500	0	0
3	1720	1	--	500	0	0
4	--	1	13	200	Aircraft off	course
5	1833	40	43	1000	1.09	0.58
6	1853	40	43	1000	1.28	0.67
7	1912	40	43	1000	0.76	0.43
8	1933	40	43	500	Aircraft off	course
9	1950	240	43	500	0.40	0.23
10‡	2007	240	43 to 13	500	1.5	0.76
11	2028	240	13	500	3.3	1.65
12	2043	240	13	1000	3.9	1.96
13	2102	240	13	1000	2.8	1.42
14‡	2125	240	13 to 63	1000	3.3	1.65
15	2145	240	63	1000	1.25	0.66
16	2201	240	63	1000	1.9	0.97
17	2223	240	63	1500	1.0	0.58

*Sunset - 1749; end of evening astronomical twilight - 1921.
†Submarine keel depth equals transmitter depth + 27 feet.
‡Data taken while submarine was changing depth.

Run number 1 started at 1700 EST, 49 minutes before sunset (1749 at sea level), when the sun was approximately 9 degrees above the horizon. Reflected glare of sunlight from the sea surface created so much noise in the receiver during the first four runs that the gain could not be turned up high enough to detect light pulses from the submerged transmitter. On run number 5, which started 44 minutes after sunset, ambient illumination had diminished sufficiently so that advancing receiver gain by a factor of 40, it became possible to detect the light pulses for the first time. During the period from runs number 5 to number 8 ambient illumination decreased gradually until at approximately 1921 evening astronomical twilight ended for that day; that is, the sun was 18 degrees below the horizon and complete darkness had set in. Thereafter, illuminance remained constant at approximately 0.00008 foot-candle, which is the nighttime illumination associated with no moonlight. Receiver gain was held constant from run number 5 until number 9 when once again it was increased by 6 times and kept at that level until the completion of the experiment. As the receiver gain was increased, horizontal air ranges also increased as can be discerned by comparing the ranges for run numbers 1 and 2 with run 11, on each occasion transmitter depth was 13 feet and receiver altitude was 500 feet. Whereas during run numbers 1 and 2 no light pulses could be detected, the horizontal air range for run number 11 was 3.3 miles after receiver gain had been increased by a factor of 240.

Two major difficulties were encountered in coordinating the efforts of submarine and aircraft personnel, who did not have continuous communication between them because of the submerged condition of the submarine. In the first place, in executing the runs according to the procedure which was prearranged, the aircraft made a run during the same period that the submarine changed depth on two occasions, run numbers 10 and 14. During the former run the transmitter depth decreased from 43 to 13 feet, and then during the latter it increased from 13 to 63 feet. To assign an average depth to the transmitter during run number 10 could not be done accurately, but due to the similarity of the horizontal air range of run number 14 to those of numbers 11, 12, and 13 and its dissimilarity to those of numbers 15, 16, and 17 one might conclude that the transmitter depth was close to 13 feet over the major portion of this run.

A second difficulty was experienced in attempting to fly the aircraft across the light beam on a straight path so that it would pass directly over the submerged submarine. Two reasons for this difficulty were: (a) the wind consistently blew the aircraft off course although corrections for this were attempted, and (b) an accurate estimate of the submarine's exact position at all times was impossible especially since it was proceeding at a low speed underwater and was invisible to aircraft personnel at night. The aircraft crossed closer to the submarine on some runs than on others so that on runs where similar conditions prevailed, those horizontal air ranges which are greatest are likely to be close to although still not as great as the true maximum ranges. As an example, between run numbers 12 and 13 when receiver gain and altitude and transmitter depth were the same, the greater range of 3.9 miles for run number 12 would indicate it to be closer to the true maximum range for the given conditions. During run numbers 4 and 8, the aircraft was far off course.

Data from five selected runs were taken from Table 1 and are plotted in Fig. 11 to show graphically how ranges varied. The ordinate gives the vertical distance (altitude of the receiver plus depth of the transmitter) and the letters (A, A', B, B', etc.) indicate the limits of light-pulse detection, or stated another way AA', BB', etc. are horizontal air ranges as given on the abscissa. Lines representing slant paths are drawn downward from the limits of detection to the underwater transmitter, which was at different depths on various runs. Each abscissa division represents a horizontal distance somewhat more than 10 times the vertical distance shown by one ordinate division, and therefore, the length of a line representing a slant path is not the distance of the slant range. If the abscissa were to the same scale as the ordinate, points A, A', B, B', etc. would be far off the graph at both sides and lines representing slant paths would be much longer and inclined from the vertical at much greater angles than shown.

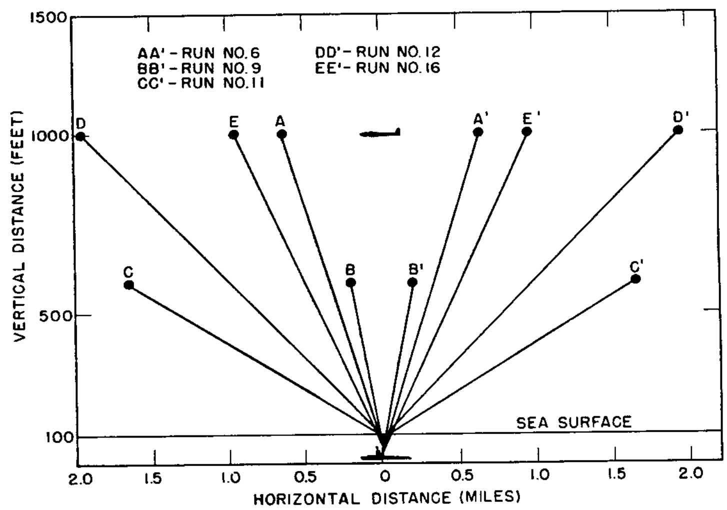

Fig. 11 - Five selected optical ranges measured when signalling from a submerged submarine to an aircraft. Horizontal air ranges are given by the horizontal distances AA', BB', etc. Slant paths are indicated by lines from A, A', B, B', etc., but slant range is not given by line length.

Figure 12 shows the lower portion of the slant paths of Fig. 11 and the transmitter light beam, taken from Fig. 10a, on a graph where the coordinates have the same scale. Here the effect of refraction on light rays both along slant paths (a, a', b, b', etc.) and at the light-beam edges (dotted lines) can be seen more clearly. The angular change at the sea/air interface was computed by using Snell's law of refraction which states:

$$n \sin \phi = n' \sin \phi'$$

where

n = refractive index of the medium containing the incident ray ($n = 1.34$ for sea water),

ϕ = angle of incidence of the incident ray,

n' = refractive index of the medium containing the refracted ray ($n' = 1.00$ for air), and

ϕ' = angle of refraction of the refracted ray.

To make it possible to use this law, the sea surface was assumed to be perfectly smooth and flat. Furthermore, in extending the lines representing slant paths and the light beam, scattering which would occur in reality in the sea and air was disregarded. These assumptions were made because the exact path along which light was propagated from transmitter to receiver is not known, thus the graphical presentation of Fig. 12 shows what the light path would be under special conditions.

Precise parameter values plotted in Fig. 12 are stated in Table 2. Angles between slant paths and the normal to the sea surface (angles of refraction, ϕ') were computed

[redacted]

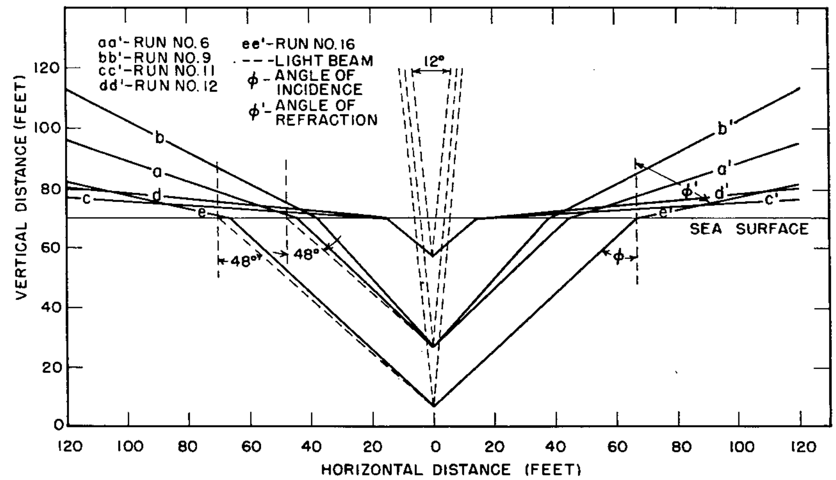

Fig. 12 - Refraction of light rays along slant paths and in the light-beam edge at a smooth sea surface. Forty-eight degrees is the critical angle, and 12 degrees is the angular width of the light beam after being refracted at the sea surface.

TABLE 2
Incident and Refractive Angles for Slant Path Light Rays at a Smooth Sea Surface and the Corresponding Light Path Lengths Through Water for Five Selected Runs

Run No.	Transmitter Depth (feet)	Angle of Incidence, ϕ (degrees)	Angle of Refraction, ϕ' (degrees)	Water Path Length (feet)
6	43	46	73	62
9	43	42	63	58
11	13	47	86	19
12	13	47	84	19
16	63	47	78	92

from data on horizontal air ranges, transmitter depths, and receiver altitudes, and then using Snell's law angles of incidence, ϕ, were found. Also given in the table are distances traveled in water by slant path light rays, these being calculated from the angles of incidence and the transmitter depths.

A number of facts are evident from the diagram of Fig. 12 concerning slant paths. One is that the limits of detection, which determine slant paths, are far outside the most intense portion of the light beam. At the half-intensity points of the light beam the angular width is 9 degrees, and after being refracted at an assumed smooth sea surface, the beam opens up to 12 degrees. Such a beam has a small cross section in comparison with horizontal air ranges for transmitter depths of 13, 43, and 63 feet.

[redacted]

A second fact is that all slant paths are inclined at small angles to the sea surface and some, notably c, c', d, and d', are grazing along the surface. Because of this the angles of incidence vary from 42 to 47 degrees, values very close to 48 degrees which is the critical angle for sea water. All light incident at the sea/air interface at angles greater than the critical angle would be totally reflected back into the sea.

Thirdly, it should be noted that the angle of incidence is equal to the angle between the light-beam axis and the direction of emission of light along a slant path. Because angles of incidence are relatively large and therefore angles of emission are large also, the peak intensities of light emitted along slant paths are only approximately 1/50 of the maximum intensity near the beam center.

Finally, the distance which light must travel in the water along a slant path is considerably more than the vertical depth of the transmitter. These distances (Table 2) vary from 19 to 92 feet depending almost exclusively on transmitter depth because the angle of emission in all cases is nearly the same.

By inspecting the circumstances under which each of the five selected runs were made and on the basis of calculations made from Snell's law by assuming a smooth sea surface, some logical qualitative explanations for the differences in horizontal air signalling ranges can be given. One exception presents itself immediately in that run number 6 has a greater range, 1.28 miles, than run number 9 (0.40 mile) although receiver gain had been increased for the latter by a factor of 6. Had there not been an increase in receiver gain, the horizontal air range for run number 6 might be expected to be slightly greater because at the increased receiver altitude the light-beam cross section would be wider. In the absence of a medium having a high capacity for light scattering and using the same receiver gain, the line to A, Fig. 11, should not be inclined from the vertical by a greater angle than the line to B. One explanation for the discrepancy between the ranges of these two runs is that the aircraft may have been off course during run number 9, but this was not mentioned by the pilot. On all subsequent runs receiver gain was held constant so that no effect can be attributed hereafter to increased sensitivity.

Between run numbers 9 and 11 transmitter depth decreased from 43 to 13 feet, and as might be expected horizontal air range increased greatly from 0.40 mile to 3.3 miles due to the diminished attenuation of the light by the shorter water path length, 19 feet for run number 11 versus 58 feet for run number 9. Then, the aircraft climbed to 1000 feet for run number 12, and because the receiver altitude was greater, the horizontal air range increased slightly to 3.9 miles. Finally, the range decreased again to 1.9 miles for run number 16 when the transmitter was taken down to a depth of 63 feet and the increased water path length of 92 feet attenuated the signal greatly.

FACTORS AFFECTING SUBMARINE-AIRCRAFT OPTICAL SIGNALLING

One fact which becomes obvious after working with underwater light signalling devices for a period of time is the real lack of basic information concerning the optics of the sea. The submergible transmitter described herein and the airborne receiver (1) are by no means optimum designs simply because very little experimental data are available to be used in specifying this equipment. Many comprehensive theoretical and laboratory experimental investigations have resulted in exact determinations of the optical properties of water, these included a large cross section of many types of natural water. However, much of the information is not applicable to this work since it deals with a signalling system to be used at sea under conditions which are not controllable as is the case in most laboratory experiments. There is not available much of the type of information which is needed — that measured in situ on and in the open sea. Therefore, more basic research on the optical properties of the sea is a necessary prerequisite to the design of underwater light signalling equipment that can be used by the Navy under everyday operating conditions.

With the present equipment it has been proven that signalling with high-intensity light pulses from a submerged submarine to an aircraft is feasible in darkness, but the ranges are short. Nothing can be stated explicitly at the present time about how the equipment should be optimized to realize best operation under a variety of natural conditions. Time of day; type, depth, and location of water; sea state; atmospheric clarity; cloud height, type, and cover; and moonlight are all independent naturally occurring parameters which affect the performance of a submarine-to-aircraft optical signalling system. A program for the study of these parameters as they affect system performance is of the utmost importance in order to be able to specify in more detail the characteristics of component equipment for best operation. Also, investigations of high-intensity light sources and very sensitive receivers are necessary. Not only should it be possible to extend operating capabilities of the present equipment, but it may be possible to realize positive operation not feasible now under certain conditions, as for example during daylight.

ACKNOWLEDGMENT

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