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SOME PRELIMINARY MEASUREMENTS ON THE TRANSMISSION OF LIGHT SIGNALS FROM A SUBMARINE TO AN AIRCRAFT

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ABSTRACT

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Previous field work on the transmission of high-intensity, short-duration light pulses through sea water and from a submerged submarine to a surface ship led to the conclusion that signalling between a submerged submarine and an aircraft should be attempted. The horizontal ranges achieved and the conditions under which such signalling was performed are reported. In particular, the greatest detectable horizontal range measured was about 1.5 miles across the light-pulse beam from a transmitter submerged to a depth of 100 feet and for a receiver flown at a height of 2000 feet.

How refraction at the sea surface would affect the peripherally detected light rays and the light-pulse beam is shown. Had the sea been perfectly smooth, the peripherally detected rays emitted upward from the submerged transmitter would have been incident at the sea surface at an angle of about 41 degrees. This angle is very close to the critical angle of approximately 48 degrees for sea water where all the light would have been reflected back into the sea.

The procedure followed, and the difficulties encountered, in coordinating the movements of the submarine and the aircraft are discussed. Possible improvements of both the experimental procedure and the equipment are suggested. One major source of experimental error might be eliminated by having the position of the submerged submarine defined by a light so that positive visual location by the aircraft pilot could be assured.

PROBLEM STATUS

This is an interim report; work is continuing on the problem.

AUTHORIZATION

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SOME PRELIMINARY MEASUREMENTS ON THE TRANSMISSION OF LIGHT SIGNALS FROM A SUBMARINE TO AN AIRCRAFT

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INTRODUCTION

The possibility of optical signalling between a submarine and an approaching aircraft has been under consideration for some time. The work described herein is mainly an attempt to determine the feasibility of submarine-to-aircraft signalling by means of high-intensity, short-duration light pulses. As a result of this field work, it is anticipated that modifications and improvements in the equipment can be made to bring about more effective signalling ranges.

Previous investigations have shown that:

1. The ocean is sufficiently transparent to visible and to near-ultraviolet radiation to assure effective pulsed-light signalling ranges in the water of approximately 400 feet (1, 2).

2. Pulsed-light signalling between a submerged submarine and a surface craft is possible (3).

The nature of the present optical system is such that it is more adaptable to signalling between a submerged submarine and an aircraft in flight. Thus, the experiment was planned for a situation where the aircraft would be flown at an altitude of several thousand feet, while the submarine was submerged to a depth of several hundred feet.

The equipment used for the field work was specially built for this particular application. It underwent thorough testing and evaluation in the laboratory and in the field before it was used. The transmitter, which was mounted on the deck of the submarine, emitted a high-intensity, short-duration light pulse at a rate of three flashes per second. This light pulse was detected by a receiver, mounted in a P2V-7 aircraft, as the aircraft flew over the submerged submarine.

The chief objective of this experiment was to make measurements on the horizontal ranges over which the light pulses could be detected while the submarine was submerged. The data were accumulated by having the aircraft make runs directly over and parallel with the course of the submerged submarine. The greatest detectable horizontal range was approximately 1.5 miles when the aircraft flew at an altitude of 2000 feet, and the transmitter aboard the submarine was submerged 100 feet below the sea surface. This datum was taken from a run conducted over clear ocean water at night in a hazy atmosphere.

TRANSMITTER AND RECEIVER

The transmitter and its controls are described in detail in an earlier report (4). Briefly, the transmitter is a watertight cylinder weighing about 125 pounds and having in one end a pyrex window through which the light pulse is emitted. The light source is an argon-filled flashtube which is flashed by a triggered condenser discharge at a rate of three flashes per second. During each discharge, approximately 1.5 watt-seconds of energy are dissipated in the discharge circuit, resulting in a light pulse which has a radiant power of about 120,000 watts in the spectral region of 300 to 680 millimicrons. The length of the light pulse is 0.65 microseconds at the half-intensity points. The flash-tube is so mounted in front of a reflec[redacted] transmitter that the light pulses are emitted in a beam having a width at t[redacted]y points of 23 degrees. Holders are provided for inserting filters over the pyrex window in the transmitter if desired.

Two transmitter units with their associated controls were installed aboard the submarine USS SARDA. One of these units was used as a standby in case of failure of the other. Figure 1(a) shows the two units mounted in the teardrop housing specially built for the purpose of reducing the resistance of the transmitters to the flow of water past them when submerged. The housing was bolted down to the forward deck of the submarine in the position shown in Fig. 1(b), where the keel depth of the submarine was 27 feet more than the transmitter depth. The position was such that there were no obstacles in the path of the light-pulse beam from the transmitter over a very large angle in all directions. Also, the units were lined up in such a way that the maximum light pulse beamwidth was in the vertical plane parallel to the hull of the submarine.

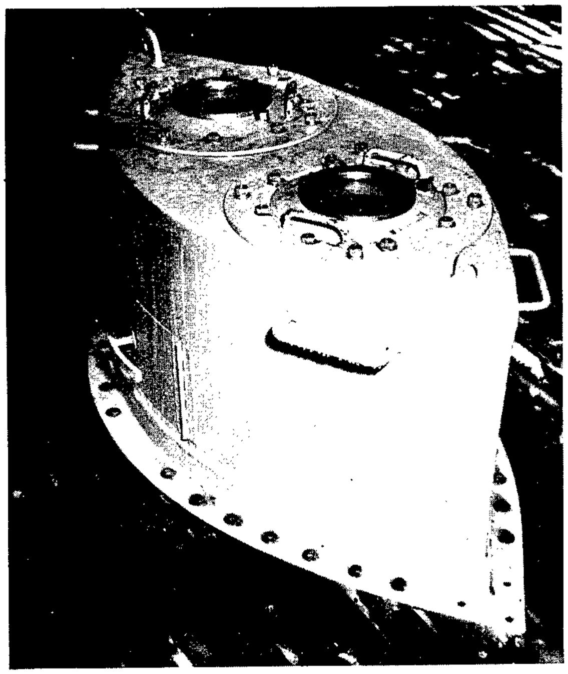
A 5/8-inch power cable was fed from the control panel within the submarine, through a stuffing box located in the submarine pressure hull nine feet aft of the transmitter housing, and thence through a special underwater-type connector in the transmitter. The access door, shown on the left side of the housing in Fig. 1(a), is for the purpose of facilitating the disconnecting and connecting of the power cable from one unit to the other in case of failure.

The receiver is the same as that used during previous field work (4) and will be described in detail in another report. The salient features of the receiver result from the conditions under which data were gathered in the field. It provides a convenient means of detecting light pulses of very short duration which vary considerably in peak intensity and which are separated in time by about 0.3 second. Briefly, the receiver converts the detected light pulse into an audible note to which the operator listens. The light pulse is detected by a phototube whose electrical output signal is amplified and then is used to trigger an audio oscillator. There are two detector units which may be incorporated in the receiver. One consists of a single phototube, and the other has two phototubes mounted at an angle to each other with a lens in front of each phototube. The advantage of the dual unit supposedly is that it has more gain in the desired directions. The video amplifier, which amplifies the signal output from the phototube, has its frequency bandwidth adjusted to maximize the signal-to-noise ratio.

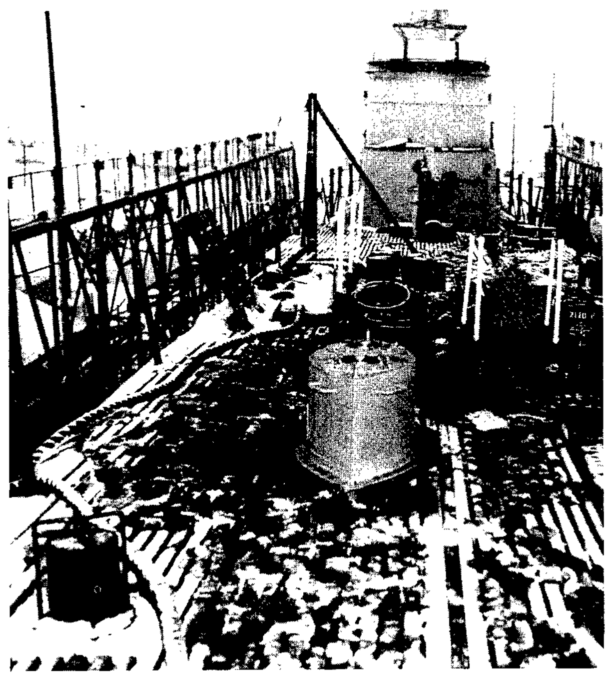
The phototube detector was installed in the photographer's hatch of a P2V-7 aircraft shown in Fig. 2. The field of view was downward and was unrestricted by any parts of the aircraft. The location of the detector was ideal except for the proximity of a running light of the aircraft, the light from which might have found its way into the detector. However, during this field work, tests showed that there was no interference from the blinking running light.

EXPERIMENTAL PROCEDURE

The general plan for successful completion of the experiment was originated in detail before any installation of equipment. However, due to the nature of the work, the general plan was flexible so that specific changes could be made in case of unforeseen developments.



(a) Construction features of and the mounting of the two transmitters in the teardrop housing



(b) Location of the transmitters on the forward deck of the submarine

Fig. 1 - Transmitters mounted aboard the submarine USS SARDA

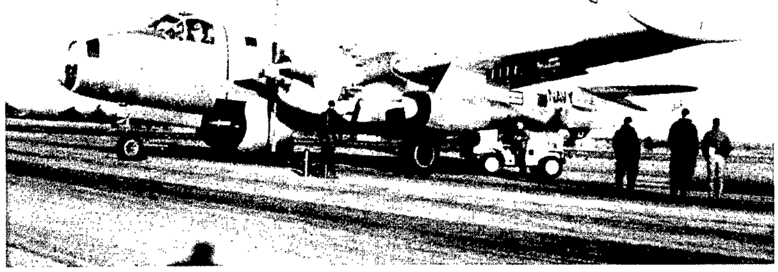


Fig. 2 - P2V-7 aircraft aboard which the receiver was mounted. The detector unit was fitted into the photographer's hatch near the tail section of the aircraft

The plan called for the submarine USS SARDA to be available for rendezvous in the areas and at the times given in Table 1. The aircraft was to leave its land base in sufficient time to effect rendezvous with the submarine. Once in the general area, the aircraft was to locate the submarine on radar until visual contact was established. Besides the running lights of the submarine, a vertical-beam light was mounted on the deck of the submarine in order to make easier its location and identification by the aircraft pilots. The light remained burning throughout the runs by the aircraft.

TABLE 1
Times and Places of Planned Rendezvous

Date (1957)	Time (EST)	Event	Area	Location	
				Latitude	Longitude
15 January	0300	ALFA	Narragansett	$39^{\circ}00'$N	$72^{\circ}05'$W
16 January	0200	BRAVO	Virginia Capes	$36^{\circ}00'$N	$74^{\circ}30'$W
18 January	0800	CHARLIE	Jacksonville	$29^{\circ}30'$N	$78^{\circ}50'$W
19 January	1900	DELTA	Jacksonville	$29^{\circ}30'$N	$76^{\circ}54'$W

The execution of the runs by the aircraft over the submerged submarine was carried out according to plan except for a few additions. The submarine captain outlined his course and speed to the aircraft pilot before submerging. Then, the submarine dove to a pre-selected depth and remained at that depth for one-half hour unless notified to come up to periscope depth for communication with the aircraft personnel. Such notification was given by dropping near the submarine three depth charges in rapid succession.

The flight path of the aircraft was determined by the course of the submarine. The aircraft pilot, knowing the submarine's approximate location, course, and speed flew a track parallel to the submarine so that he passed as nearly as possible directly over the submerged ship. A run consisted of setting the aircraft on course at a given altitude from

[redacted]

about five miles astern of the submarine and maintaining that course until notice came from the scientific personnel aboard that the run had been completed. Then, the aircraft was brought around to commence another run over the submerged submarine on a reciprocal course from the previous one. During these runs, it was possible to gather information on the detectable horizontal ranges.

Some difficulties were encountered and dealt with in the best way possible at the time, but they were never eliminated. To fly the aircraft very closely parallel to and directly over the submerged submarine was impossible. The two main reasons for this were (1) the position and course of the submarine were not visible to the aircraft pilot, and (2) crosswinds were continually blowing the aircraft off course. To offset the former, the pilots laid out the course of the submarine by dropping smoke pots along the path fore and aft of the submarine. In dealing with the crosswind situation, the captain of the submarine was requested to steer a course with or against the wind to reduce the crosswind on the aircraft to a minimum.

DETECTABLE HORIZONTAL RANGES

All events except BRAVO were executed according to the schedule given in Table 1. BRAVO was cancelled because of poor weather conditions; reports indicated that snow was falling heavily in the area of the intended rendezvous. More specific information regarding the length of time over and the location of each actual rendezvous point is given in Table 2.

TABLE 2
Times and Places of Actual Rendezvous

Date (1957)	Time (EST)		Event	Area	Location	
	Beginning	Ending			Latitude	Longitude
15 January	0308	0332	ALFA	Narragansett	39°00′N	72°06′W
18 January	0826	0854	CHARLIE	Jacksonville	29°30′N	79°07′W
18 January	1904	2012	DELTA	Jacksonville	29°30′N	76°54′W

TABLE 3
Atmospheric and Sea Conditions at Rendezvous Sites

Event	Atmospheric Clarity	Cloud Cover	Sea State
ALFA	Hazy, intermittent snow, sea fog	Ceiling - 2000 ft, 100% overcast	2
CHARLIE	Thin fog	Ceiling - 2500 ft, 100% overcast	3
DELTA	Hazy	Ceiling - 2500 ft, 90% overcast	4

[redacted]

In general the operating conditions were good to very poor. As already noted, one event had to be called off because of inclement weather. The other three events were executed with the atmospheric and sea conditions prevailing as shown in Table 3. During event ALFA, there was considerable sea fog, usually encountered only over regions much farther to the north. However, during the period of this field work, the eastern portion of the United States was subjected to a very low temperature cold wave which it was believed accounted for the presence of the sea fog. On the remaining events all the runs were made in a rather hazy atmosphere having a medium ceiling and an almost completely overcast sky. The moon was in its full phase during all events, but was not visible through the clouds. The intermittent snow and sea fog greatly increased the difficulties of experimentation. The sea was rough on all occasions, particularly during event DELTA off the coast of Florida, when whitecaps were very numerous and the waves were continuously sweeping across the bow of the submarine.

Table 4 contains the data on the detectable horizontal ranges attained during the various events along with other pertinent information. The last column of Table 4 states for each run the total horizontal distance flown by the aircraft while positive detectable light pulses were being received from the transmitter below. During three runs positive detection of the light-pulse signals occurred. On Run 5 of event CHARLIE, the first light-pulse signal was detected during daylight about eight thirty in the morning when the submarine was surfaced, the detectable horizontal range being 2300 feet. The purpose of this run was to ascertain whether or not the equipment was functioning properly since no signal had been detected at as shallow a transmitter depth as 25 feet during the previous run. The greatest ranges were recorded during the first and second runs of event DELTA at night, these being 7600 and 8600 feet respectively. The submarine was submerged to a transmitter depth of 100 feet, corresponding to a submarine keel depth of 127 feet. Subsequently, the transmitter was taken down to 150 feet, but no signal was detectable on two more runs.

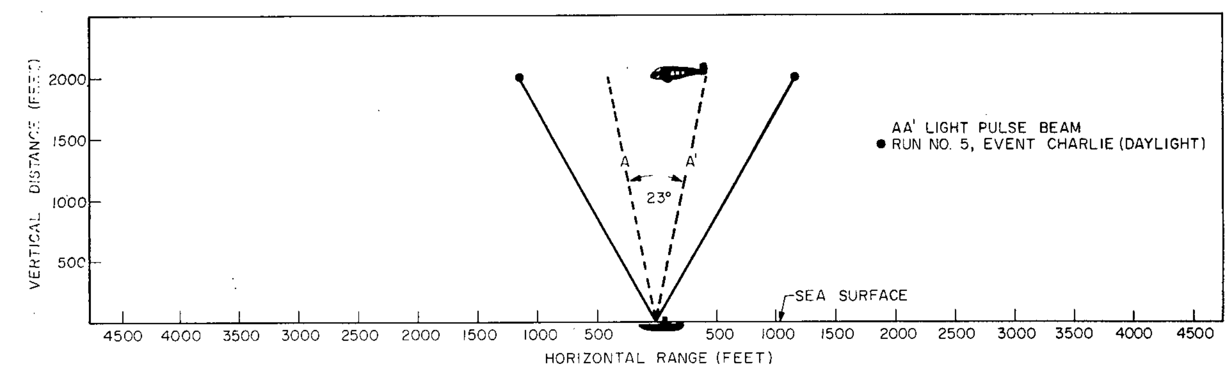
TABLE 4
Detectable Horizontal Ranges Over the Light Pulses from the Transmitter

Event	Run Number	Detector Unit	Aircraft Altitude (ft)	Transmitter Depth (ft)	Submarine Keel Depth (ft)	Detectable Horizontal Range (ft)
ALFA	1	dual	2000	50	77	0
	2	dual	2000	50	77	0
	3	dual	2000	50	77	0
	4	dual	2000	50	77	0
CHARLIE	1	single	2000	50	77	0
	2	single	2000	50	77	0
	3	single	2000	50	77	0
	4	single	2000	25	52	0
	5	single	2000	surface	surface	2300
DELTA	1	single	2000	100	127	7600
	2	single	2000	100	127	8600
	3	single	2000	150	177	0
	4	single	2000	150	177	0

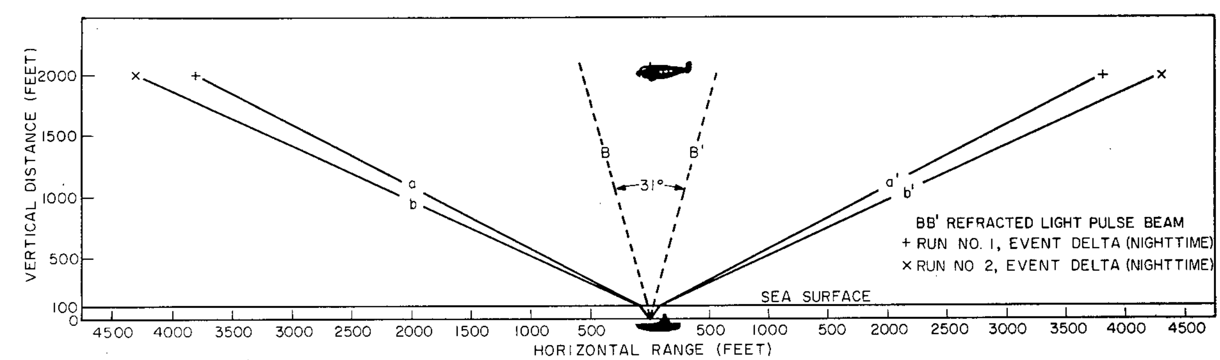
A graphical presentation of the detectable horizontal ranges for the three runs is shown in Fig. 3. The plotted points are taken from the data in the last column of Table 4. No signal was picked up outside the plotted points for any particular run, but inside these points the light pulses were always detectable as the aircraft flew a straight course crossing the light-pulse beam. The peak intensities of the light pulses detected when the aircraft was vertically over the transmitter were much higher than those at the peripheries.

In order to compare the detectable horizontal ranges with the diameter of the cross section of the light-pulse beam from the transmitter, the angular spread of the beam is shown in Fig. 3. The angular beamwidth is defined as the angle inside of which the peak intensities of the light pulses are more than one half of the maximum value. A relative angular, peak-radiant-intensity plot of the light-pulse beam shows that the peak intensities of the light pulses are a maximum near the center of the beam and fall off rapidly on all sides of the center, so that the beamwidth at the half-intensity points is 23 degrees (4).

The light-pulse beam is represented by the lines A and A′ in Fig. 3(a), for the situation where the submarine was surfaced during Run 5 of event CHARLIE. During Runs 1 and 2 of event DELTA, Fig. 3(b), the transmitter was submerged to a depth of 100 feet so that refraction and scattering at the sea surface became phenomena which must be considered



(a) Altitude of aircraft is 2000 feet and transmitter is at sea surface



(b) Altitude of aircraft is 2000 feet and transmitter is 100 feet below sea surface

Fig. 3 - Detectable horizontal ranges across the light-pulse beam from the transmitter at and below the sea surface

[redacted]

in extending the light-pulse beam from the sea into the air. In the extraordinary situation when the sea is perfectly calm, refraction will be the dominant factor contributing to the spreading of the light-pulse beam, and it is on this basis that lines B and B′ have been drawn to represent the refracted beam. They include an angle of 31 degrees.

It can be seen from Fig. 3(a) and Fig. 3(b) that signals were always detected well outside the light-pulse beams where the peak light intensities were of extremely low values compared with those inside the beams. This is especially true of Runs 1 and 2 of event DELTA in Fig. 3(b), where presumably the light pulses from the transmitter were refracted and scattered at the sea surface.

The visibility of the light pulse from the submerged transmitter to observers in the aircraft was not exceedingly good although there were no filters placed over the source. The pilot reported that it was difficult to fly the aircraft over the position of the submerged transmitter although the light pulses were visible to him over a considerable distance. As the aircraft approached the transmitter, the pilot's view was blocked by the aircraft. An observer stationed in the bow lookout position was very effective in guiding the pilot over the transmitter.

During all of the runs, the aircraft was flown just under the clouds, at an altitude of about 2000 feet. It was decided to try both the dual and single detector units. However, previous measurements proved that the single unit was the more sensitive detector, and for this reason it was used throughout events CHARLIE and DELTA. Between these two events the equipment was given a thorough check, and it was considered advisable to connect another stage of amplification into the receiver video amplifier.

DISCUSSION

Of primary concern during this field work has been the detectable horizontal ranges which could be attained when flying through the light-pulse beam of the transmitter submerged below the sea surface. It seems rather evident that the refraction at the sea surface and the sea state, if not also the scattering taking place in the sea, will affect the ranges. However, it is not the purpose of this report to speculate on the relative importance of the effects which the aforementioned phenomena have on signalling ranges. As progress is made toward the development of an optimum system of signalling between a submerged submarine and an aircraft by means of pulsed light, they must be investigated throughly. The path of the light as it travels from the transmitter to the receiver and the reasons for its deviations should be determined.

It is interesting to consider what effect refraction would have had on the light incident on the detector during Runs 1 and 2 of event DELTA had the sea surface been perfectly smooth. (Refraction will be taken as the main cause for the bending of the light rays at the sea surface.) The bending of a light ray striking the boundary between two transparent media is expressed by Snell's law of refraction,

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

where

n = refractive index of the medium containing the incident ray,
ϕ = angle of incidence of the incident ray,
n' = refractive index of the medium containing the refracted ray, and
ϕ' = angle of refraction of the refracted ray.

[redacted]

When applied to the cases where a ray of light travels from the transmitter in the sea, through the sea-air boundary, and into the air, n is 1.34 for the first medium, seawater (5), and n′ for the second medium, air, is 1.00. For the specific case of Run 1 (100 feet depth) we find by Snell's law that the angle of incidence of the peripheral rays at the sea surface would be about 41 degrees. For Run 2, the rays would be incident at an angle of about 42 degrees. These rays are shown graphically in Fig. 4 along with the light-pulse beam. a and a′ represent the rays detected by the receiver at the peripheries of Run 1, and b and b′ represent the same for Run 2. These are the same rays shown in Fig. 3(b). Incidentally, the critical angle for seawater, that is, the angle of incidence at which all the light is reflected back into the sea, is about 48 degrees.

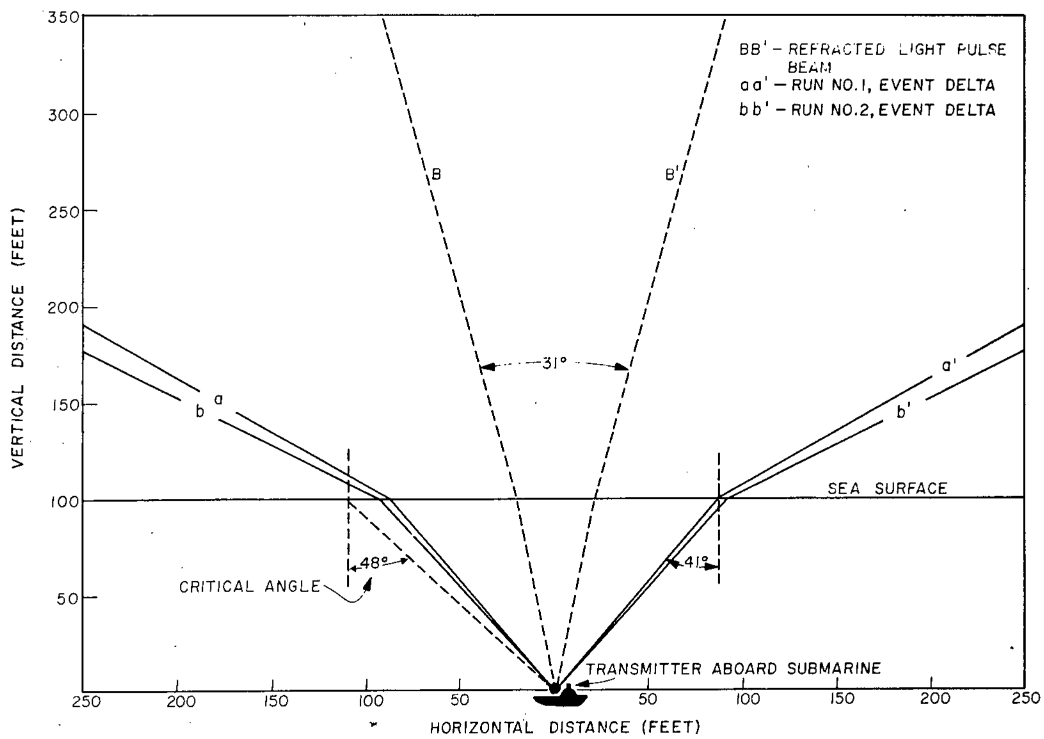


Fig. 4 - Refraction of light pulse at a smooth sea surface from submerged transmitter

Indications are that rays a, a′, b, and b′ are of very low intensity by the time they arrive at the receiver. Angular intensity measurements of the light from the transmitter (4) show that when the transmitter is directed vertically upward, the intensity of the light which would be incident on the sea surface at an angle of about 41 degrees is down by a factor of ten or more compared with that light incident at small angles. The pathlength through the sea for a light ray emitted from a transmitter 100 feet below the sea surface is 133 feet. Thus, the light incident at the sea surface at 41 degrees must traverse 33 more feet of water than a vertical light ray; as a result, its intensity will be attenuated by a factor of the order of between two and one hundred depending upon the transmission characteristics of the sea. Event DELTA was performed in seawater of high transparency, and it is suspected that the extra pathlength of the ray incident at 41 degrees did not contribute to its attenuation by more than a factor of about five.

[redacted]

The maneuvers of the aircraft will affect the design of an acceptable signalling system considerably. It has been agreed generally that an optical system should be developed with the idea of attaining the maximum detectable horizontal ranges. However, these horizontal ranges are dependent upon the altitude at which the aircraft will fly while signalling occurs. Previous plans for equipment were made on the basis of aircraft altitudes of about 5000 feet. Now it has been suggested that the equipment be operable over a detectable horizontal range of 6000 feet at an aircraft altitude of 500 feet and a submarine depth of 200 feet. It is clear that new equipment is in order for such drastic changes in operating conditions.

The transmitter and receiver remained in good operating condition throughout this field work. A total of approximately two and one half operating hours was logged on both. The transmitter endured a week on and under the sea without any indication of failure either electronically or mechanically. The receiver continued free from vibration-produced noise and failure throughout the trip. The addition of another stage of amplification between event CHARLIE and event DELTA was routine since the equipment was designed so that this change could be made readily.

The procedure for conducting the runs did not work nearly as well as was anticipated. As pointed out previously, several extemporaneous decisions had to be made to insure that the aircraft flew as parallel to the course and as directly over the submarine as was possible under the prevailing conditions. Outlining the course of the submarine with smoke pots was not very successful, but requesting the submarine to proceed on a course with or against the wind was very effective in keeping the aircraft on a given course. With regard to the latter idea, it should be pointed out that in order to obtain more accurate data, one means of reducing the ground speed of the aircraft is to fly it against the wind. Thus, a longer interval of time is spent over the detectable light pulse, and the errors in the peripheral measurements are reduced.

Even with the above improvements in tracking the submarine, the pilots were very handicapped in locating the underwater position of the submarine at night especially after they had made several runs over it. Therefore, it is unlikely that the present data are a true indication of the maximum detectable horizontal ranges across the light-pulse beam from the submerged transmitter. Rather the data are probably for the detectable ranges across chords of the cross section of the light-pulse beam and as such do not represent the maximum values which would be found by traversing diameters. It is evident that if runs are conducted at low altitudes of about 500 feet rather than higher altitudes of about 5000 feet, the deviation of those ranges actually detected from the maximum horizontal ranges will be considerably enhanced by an aircraft flying off course by a given amount.

For the above reason, improvements in the procedure for making the measurements is imperative if accurate data are to be recorded. A suggestion is to have the submarine hover at a certain location which would be marked by a light or flare directly over the submarine. This would give the aircraft pilot a positive visual identification of the point over which he must fly. Also, a slower moving and more maneuverable type of aircraft, such as a helicopter, would be more suitable for the lower-altitude experiments. This is especially true if it were decided to make field-intensity measurements over the light-pulse beam.

FUTURE PLANS

What are the paths of the light rays emitted by the submerged transmitter and detected at the receiver? The refraction and scattering effects at the sea surface on the light-pulse beam for different states of the sea have a very important bearing on this question. Thus, an experimental and theoretical investigation into these effects should be undertaken. At this time more experimental data need to be gathered for various sea-surface conditions.

Besides the study of the natural physical phenomena, work is continuing on the development of more intense and durable sources of pulsed light and more effective detectors. Several new commercial flashtubes have been acquired for evaluation. Also, several special flashtubes, designed and built at the U. S. Naval Research Laboratory especially to fit the needs of this problem, are awaiting testing.

A new transmitter is being built to better satisfy the requirements imposed by signalling from a submerged submarine to a low-flying aircraft. Concerning the receiver, it would seem that the dual detector unit would have great potentialities; so improvements on it are planned.

ACKNOWLEDGMENTS

Thanks are due to Mr. C. M. Whitfield, Jr. of the U. S. Naval Research Laboratory for his efforts in overseeing the installation of the transmitter aboard the submarine and for his assistance during the field work. Also, we are particularly grateful for the cooperation given by the Commanding Officer of Submarine Division 31, CDR H. J. Smith, Jr., the Captain of the submarine USS SARDA, Lt. R. D. Thompson, and the Commanding Officer and pilots of the aircraft from Patrol Squadron VP-11.

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