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AIRBORNE MEASUREMENTS OF THERMAL RADIATION FROM SUBMARINE WAKES IN THE KEY WEST AREA

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AIRBORNE MEASUREMENTS OF THERMAL RADIATION FROM SUBMARINE WAKES IN THE KEY WEST AREA

Harry L. Clark

January 4, 1950

Approved by:

Dr. J. A. Sanderson, Superintendent, Optics Division



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CAPTAIN F. R. FURTH, USN, DIRECTOR
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ABSTRACT

Special airborne equipment was developed for measuring the thermal radiation from submarine wakes under various operating conditions. Flown in a blimp at 2000 feet at 30 knots, the equipment scanned a 2300-foot-diameter circle on the surface of the sea at 43 rpm. It employed a $4\frac{1}{2}$ -inch-diameter, f-0.5, spherical mirror and two halves of a compensated thermopile which described a $5^{\circ}-5^{\circ}-5^{\circ} \times \frac{1}{2}^{\circ}$ optical field-of-view. The field-of-view, when projected on the surface of the sea from an altitude of 2000 feet, consisted of two equal areas 200 feet wide by 23 feet high separated by 200 feet. Complete coverage of the sea was attained by the circular travel of these projected areas around the scanning circle and by the forward motion of the blimp which converted the circle into a tight spiral. In this manner, the field-of-view crossed the wake and permitted irradiation of the thermopile twice per complete circular scan. The resulting voltage pulses were amplified and presented on a polar coordinate oscilloscope, a facsimile recorder, and an ink recorder. An operational E. N. I. (Equivalent Noise Input) of 10^{-9} watts/cm² (1.3×10^{-7} watts) was realized from the equipment. The noise level was determined by the equipment and was due to vibration. No "optical noise" from the surface of the sea was observed. ?

Preliminary measurements made off the New Jersey coast at night showed that the thermal radiation from the wake of a submarine submerged to depths of from 75 to 200 feet was easily measurable up to 3 miles astern.

More extensive measurements were made at night in the Key West area with a Guppy-type submarine as a target. The thermal radiation from the wakes in this area was so small that only occasional detection was possible. Satisfactory measurements could not be carried out. Poor atmospheric transmission and low temperature contrast (0.05°C) between the wake and surrounding water were the determining causes.

It was concluded that the E. N. I. of the equipment was satisfactory if employed against wakes with a 1°C contrast but that an improvement in the E. N. I. of the equipment of at least 10 times is necessary if it is to be employed against wakes such as those encountered in the Key West area. The required improvement in the E. N. I. appears feasible.

PROBLEM STATUS

This is an interim report on the problem of measuring the thermal radiation from the wakes of submerged submarines. Work on this problem is continuing.

AUTHORIZATION

NRL Problem N03-19R (BuAer Project Number TED-NRL-EL-8-A-345 as established by BuAer ltr Aer-EL-84, Serial 0655, 26 January 1949).

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AIRBORNE MEASUREMENTS OF THERMAL RADIATION
FROM SUBMARINE WAKES IN THE KEY WEST AREA

INTRODUCTION

The feasibility of detecting the approximate position of a submerged submarine by observing the thermal radiation from its wake¹ with airborne detection equipment was demonstrated almost a year ago by a series of airborne measurements made at night in the New London-Block Island area.^{2,3} The results of these measurements were very encouraging. However, the work was carried out at only one geographical location under one set of weather conditions. In addition the makeshift equipment employed proved itself unsuitable for any airborne application of this type.

As a result a problem was established at this Laboratory by the Bureau of Aeronautics for the purpose of developing more suitable equipment and, with it, investigating the thermal radiation characteristics of submarine wakes. It was desired to determine the relationship between the magnitude of the thermal radiation from the wake and such variables as the submarine's depth and speed, the distance astern the submarine, the vertical temperature gradient in the water, sea states, and weather conditions.

New airborne equipment for measuring the thermal radiation from submarine wakes was developed to fulfill the requirements indicated by the earlier measurements with improvised gear. Designed to be flown at 2000 feet up to 30 knots, it was installed in a U. S. Navy blimp at Lakehurst, N. J., during the latter part of May 1949. After a number of "shakedown" flights were completed, formal measurements were made of the thermal radiation from the wake of a submerged Guppy-type submarine operating in the Gulf Stream off the coast of Key West, Florida.

This report describes the equipment employed and the results obtained therewith, a brief summary of which is given on the following page.

¹ The wake from a totally submerged submarine is a completely developed, narrow strip of water which has slowly risen to the surface at some distance astern the target and is produced by the action of the submarine's screws. It should not be confused with the much wider bow wake, periscope wake, or schnorkel wake produced by a partly submerged submarine. Nor should it be confused with the bubble formation which appears immediately astern a surfaced submarine.

² Harvey, G. L., "The Detection of Schnorkelling Submarines by Infrared," U. S. Navy Underwater Sound Laboratory Rpt. No. 101, September 30, 1948 (Confidential)

³ Clark, H. L., "Airborne Measurements of the Thermal Radiation from the Schnorkel and Wake of the U.S.S. Dogfish," Naval Research Laboratory Rpt. No. N-3386, November 22, 1948 (Confidential)

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- (a) The minimum detectable flux density of radiation was 10^{-9} watts/cm², or 1.3×10^{-7} watts focussed on the thermopile. Optical noise composed of random fluctuations in radiation from the sea produced signals smaller than the system could detect; hence, further increase in sensitivity in new designs of submarine detectors is possible before random signals from the sea become the limiting factor.
- (b) Over the Atlantic Ocean near Lakehurst, New Jersey, at latitude 40°N, at night, the wakes of submarines operating at depths of 75 to 200 feet were readily detectable from altitudes of 50 to 2000 feet. The wakes were detectable two or three miles astern of the submarine and could be followed in to the target. Direct-contact temperature measurements of the wake and the surrounding sea were not made. Earlier measurements in the New London area showed that a temperature difference of 1°C between wake and surrounding sea may occur.
- (c) Over the Straits of Florida near Key West and in the Gulf Stream, latitude 24° 30' N, at night, wakes of submarines of known position were barely detectable.

Contact water temperatures made during the tests by representatives of the Naval Air Development Center showed that wake temperatures were 0.05°C to 0.17°C colder than the surrounding sea. These numbers may be compared with a temperature difference of about 1°C encountered in the New London area in 1948 and thought to have existed during the Lakehurst tests. The vertical transmission of the atmosphere at Key West was low because of high humidity and low clouds. Observed infrared signals were in fair agreement with signals computed from the measured temperatures and estimated atmospheric transmission. ✓

These results lead to the conclusions that infrared detection equipment sensitive to signals of 1.3×10^{-7} watts would permit detection of submerged submarines in many areas of the seas where pronounced vertical temperature gradients exist. Furthermore, reduction in optical noise from the sea by the new scanning system indicates that the use of larger optical systems to increase sensitivity until optical noise again appears may permit detection of submerged submarines in areas of the seas where conditions like those encountered near Key West exist.

The effect of depth of target on detection has not been fully explored, and it is not yet known whether sunglints on the water can be sufficiently suppressed, even with the newest infrared filters, to permit daylight use of the equipment.

EQUIPMENT

Operating Principle

The complete equipment is shown in Figure 1, and its functions are depicted in the block diagram of Figure 2. It consists of an optical system in which is mounted a compensated thermopile, a low-signal-level amplifier, a facsimile recorder and its associated amplifier, a polar coordinate oscilloscope, and a two-channel ink recorder and its associated amplifier.

The optical system is mounted so that its optic axis is inclined at an angle of 30° to a vertical axis about which the system rotates. Designed to operate at an altitude of

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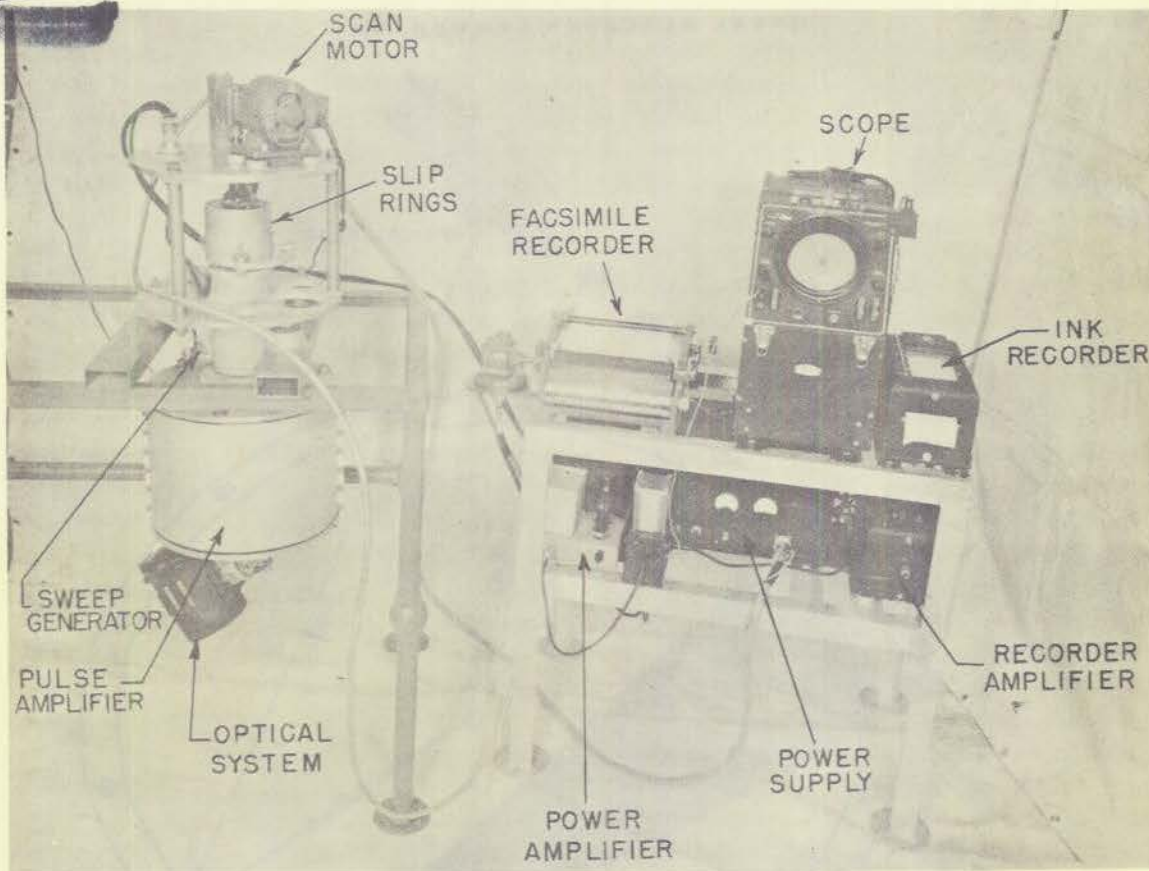


Figure 1 - Complete airborne equipment

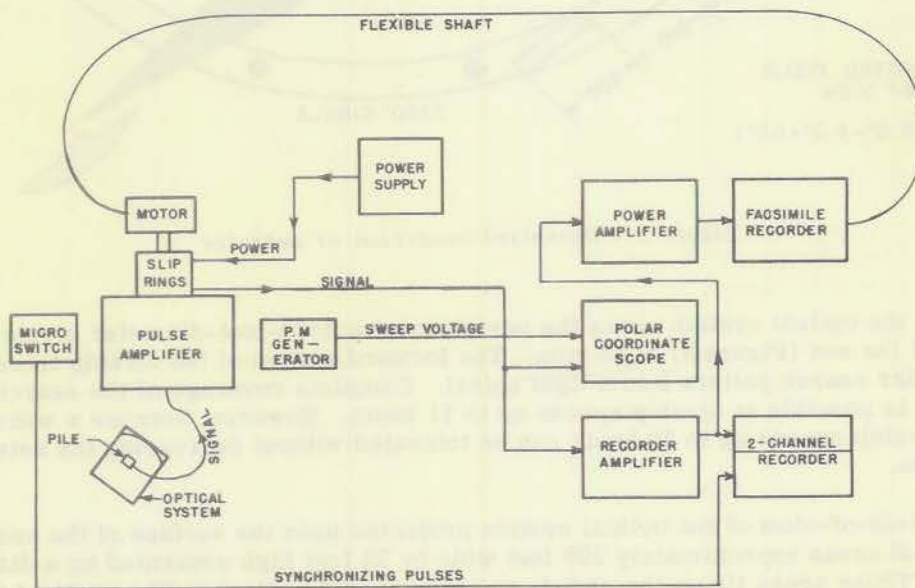


Figure 2 - Functional block diagram of equipment

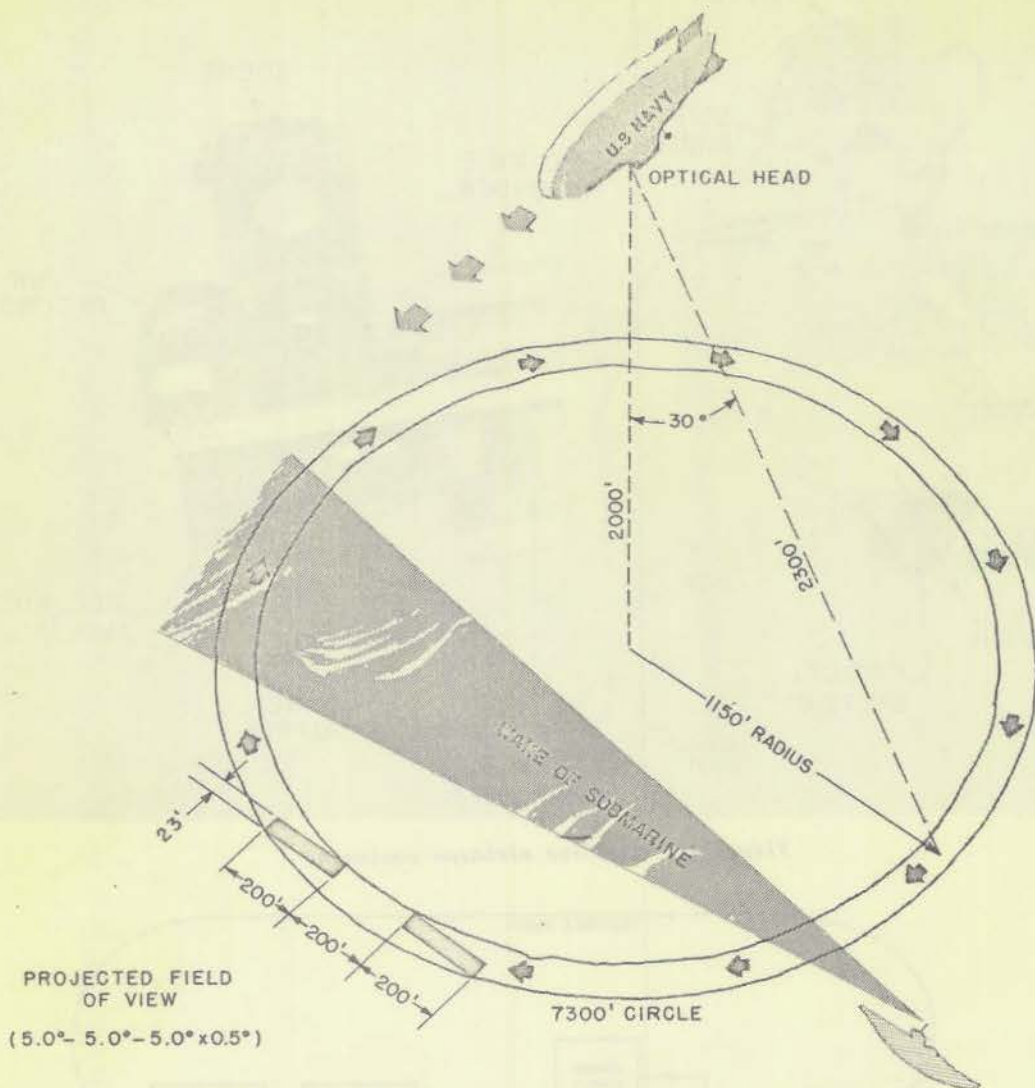


Figure 3 - Operating condition of detector

2000 feet, the optical system scans the periphery of a 2300-foot-diameter circle on the surface of the sea (Figure 3) at 43 rpm. The forward motion of the airship transforms this circular search pattern into a tight spiral. Complete coverage of the search area (no holes) is possible at airship speeds up to 11 knots. However, because a wake is a long target, airship speeds up to 30 knots can be tolerated without decreasing the detectability of the wake.

The field-of-view of the optical system projected upon the surface of the sea consists of two equal areas approximately 200 feet wide by 23 feet high separated by a distance of 200 feet. These areas lie on the periphery of the scanning circle. The width of the projected field-of-view is approximately equal to the width of a typical submarine wake 4000 to 6000 yards astern the submarine. The choice of field-of-view was influenced by the

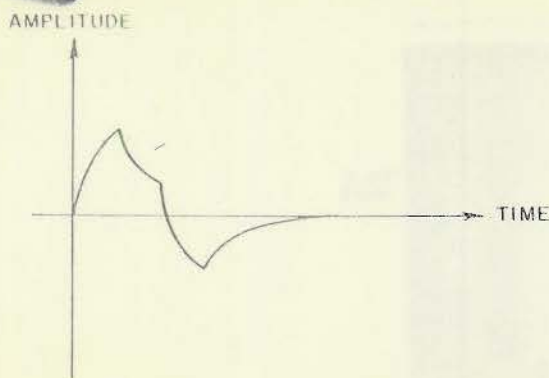


Figure 4a - Voltage pulse generated by thermopile when exposed to a cold wake

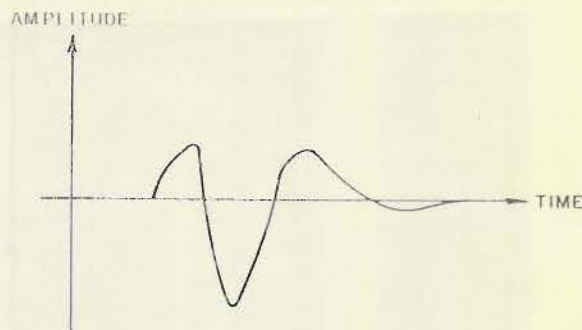


Figure 4b - Voltage pulse after amplification (cold wake)

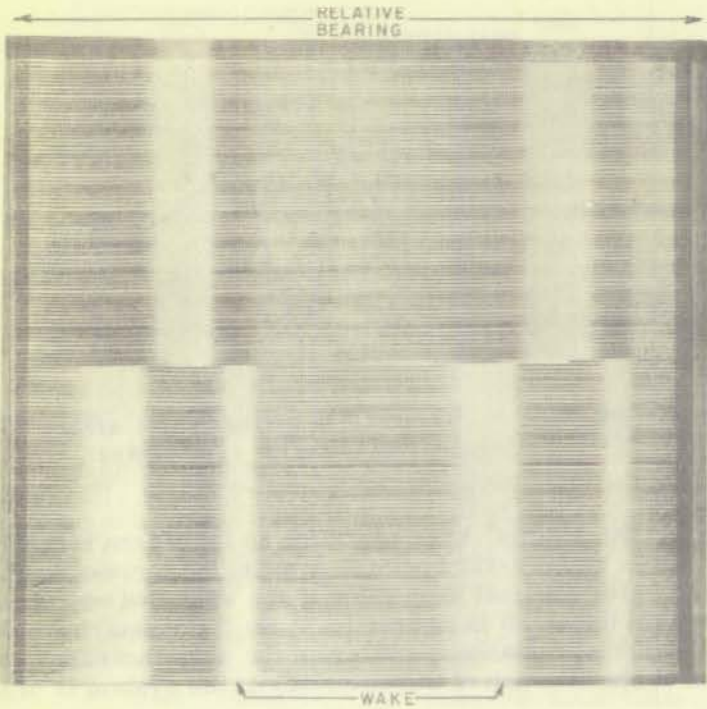
desire to maximize the efficiency of the system⁴ when operating as far astern the submarine as practicable. Beyond the 4000- or 6000-yard point in a wake, the thermal radiation signal is usually so small because of the physical dispersion of the wake that equipment designed to operate efficiently beyond this point is impractical. On the submarine side of the 4000- or 6000-yard point, the thermal radiation signal from the wake increases as the submarine is approached, and hence the question of the efficiency of the system is of less importance.

As the optical system sweeps around the periphery of the 2300-foot-diameter circle on the surface of the sea, first one half and then the other half of the optical field-of-view sweeps across the wake, thus allowing each half of the compensated thermopile mounted within the optical system to view the wake. As a result of this type of irradiation, the thermopile generates an isolated positive and negative lobed pulse (Figure 4a). Since the optical field-of-view usually crosses a wake twice per complete circular sweep of the optical system, two such voltage pulses are generated per complete scan. These voltage pulses are then amplified and assume the shape of a ram's head (Figure 4b). If the submarine's wake is colder than the surrounding water, the ram's head is right side up; if warmer, it is upside down.

The amplified voltage pulses are then presented on the facsimile recorder, the oscilloscope, and the two-channel ink recorder simultaneously. The pulses are fed directly to the oscilloscope (Figure 2) but undergo further amplification before being viewed on the recorders.

The facsimile recorder is driven from the rotating optical system assembly by means of a mechanical linkage. One lateral sweep on the recorder corresponds to one complete rotation of the optical system. The signal pulses appear as dark or light spots on a normally grey line (Figure 5a), the intensity of the spot being roughly proportional to the magnitude of the signal pulse. The recorder paper advances slowly thus allowing one complete trace to appear slightly below the previous trace. A series of such traces reproduces an approximate thermal radiation picture of the search area. Since the circular scan results in the crossing of the search area twice per scan, the resulting recorder pattern consists of two separate patterns (Figure 5a) corresponding to each half of the scanning circle. This type of signal reproduction is employed to show whether those hot or cold spots on the surface of the sea, which are responsible for the background "optical noise," possess any orderly arrangement which might lead to their being confused with an actual wake.

⁴ Clark, H. L. and Tucker, J. W., "The Dependence of Signal-to-Noise Ratio on Image Size in the Pulse-Type Compensated Thermal Detector," NRL Report N-3415, 11 February 1949



COLD WAKE

HOT WAKE

Figure 5a - Typical signal on facsimile recorder

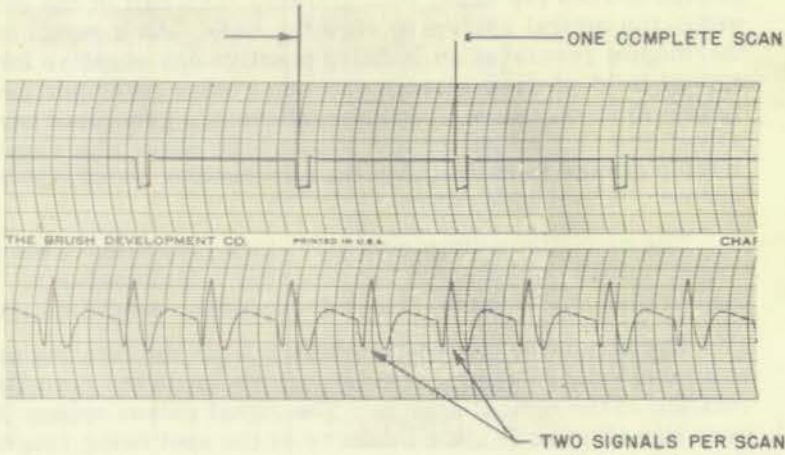


Figure 5b - Typical signal on two-channel ink recorder (artificial hot wake)

The two-channel ink recorder is driven independently from the optical system. Synchronization is achieved by means of a microswitch attached to the scanner which indicates the completion of one scan by momentarily applying voltage to one channel of the recorder. The resulting recorder deflection (Figure 5b) serves as an aid in evaluating the trace due to the signal pulses which appear in the second channel. This type of signal presentation is employed to provide a record of the magnitude and polarity (hot or cold) of the thermal radiation from the submarine's wake.

Figure 5c - Typical signal on oscilloscope employing radial deflection (hot wake)

WAKE PATTERN
NORMAL CIRCLE

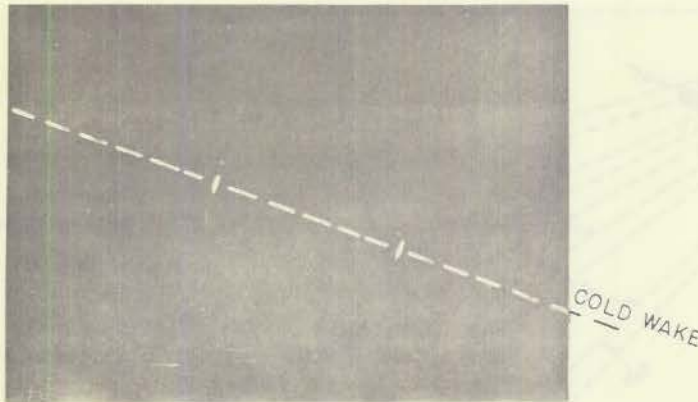
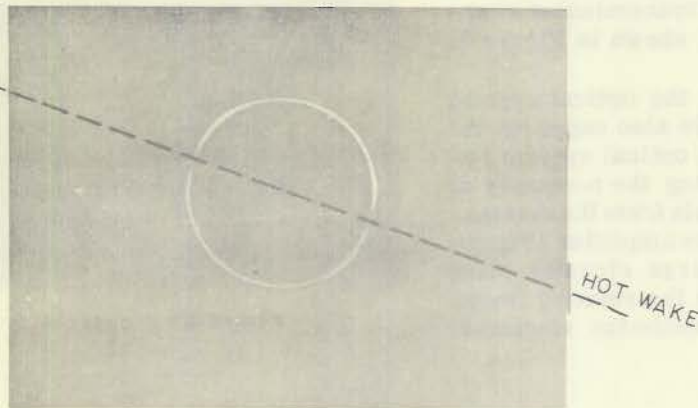
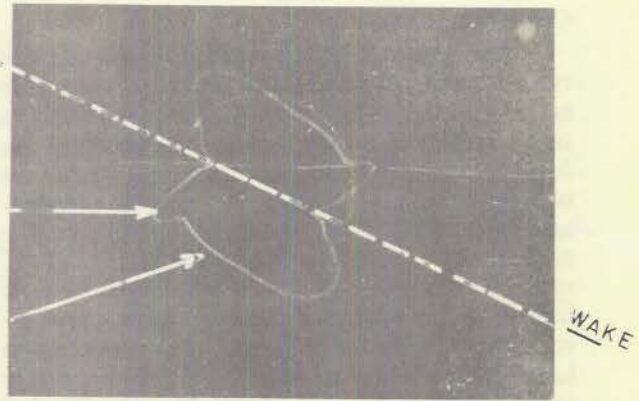


Figure 5d - Typical signals on oscilloscope employing intensity modulation

The oscilloscope serves as a monitor for both recorders. It employs a circular sweep synchronized with the scanner. In the absence of any signal, the trace which appears on the screen of the oscilloscope is a circle. The signal pulses appear as radial deflections from the circular trace (Figure 5c) or as variations in the intensity of the trace (Figure 5d), whichever is desired. The oscilloscope pattern is thus an exact reproduction of the circle being scanned on the surface of the sea. The angular positions of signal appearing on the oscilloscope correspond to the bearing or orientation of the wake relative to the airship.

Characteristics

The optical system (Figures 6a and 6b) consists of a spherical collecting mirror with an effective diameter of 4-1/2 inches and a focal length of 2-1/4 inches. Mounted in the focal plane of the mirror are the two halves of a compensated Eppley thermopile (resistance - 9 ohms, time constant - 0.1 secs, d-c sensitivity - 0.004 volt/watt/cm²). Each half of the thermopile is 0.2 inch wide by 0.02 inch high and generates a field-of-view approximately 5° wide by 1/2° high. The separation between halves is 0.2 inch or 5°. The system is closed off and made watertight with a treated AgCl (Clago) window, the transmission characteristics of which are shown in Figure 7.



Figure 6a - Optical system

The frame to which the optical system is attached at a 30° angle also supports the amplifier. Amplifier and optical system rotate together thus obviating the necessity of passing the low-level signals from the thermopile through slip rings. The amplifier (Figure 8) is constructed on a large circular plate suspended by springs from the rotating frame (Figure 9) in order to minimize vibration.

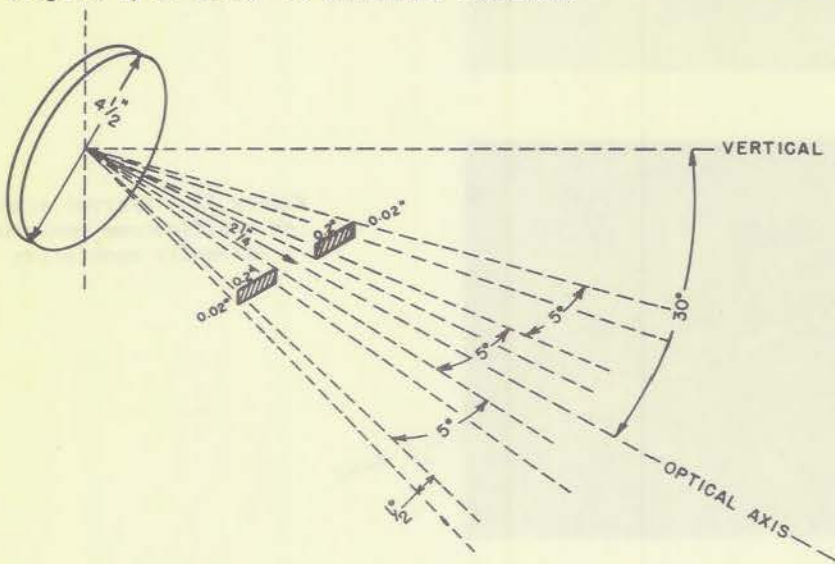
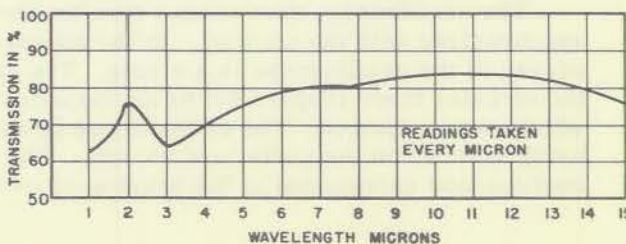


Figure 6b - Optical system parameters

Figure 7 - Transmission characteristics of AgCl (Clago) window



Additional precautions against interference from vibration include multiple magnetic shielding of the input transformer and careful selection of the input tube. The amplifier's response characteristics are shown in Figure 10. Tuning and selectivity are determined by the duration of signal pulses to be amplified, which in turn is determined by the 43-rpm scanning speed of the optical system.

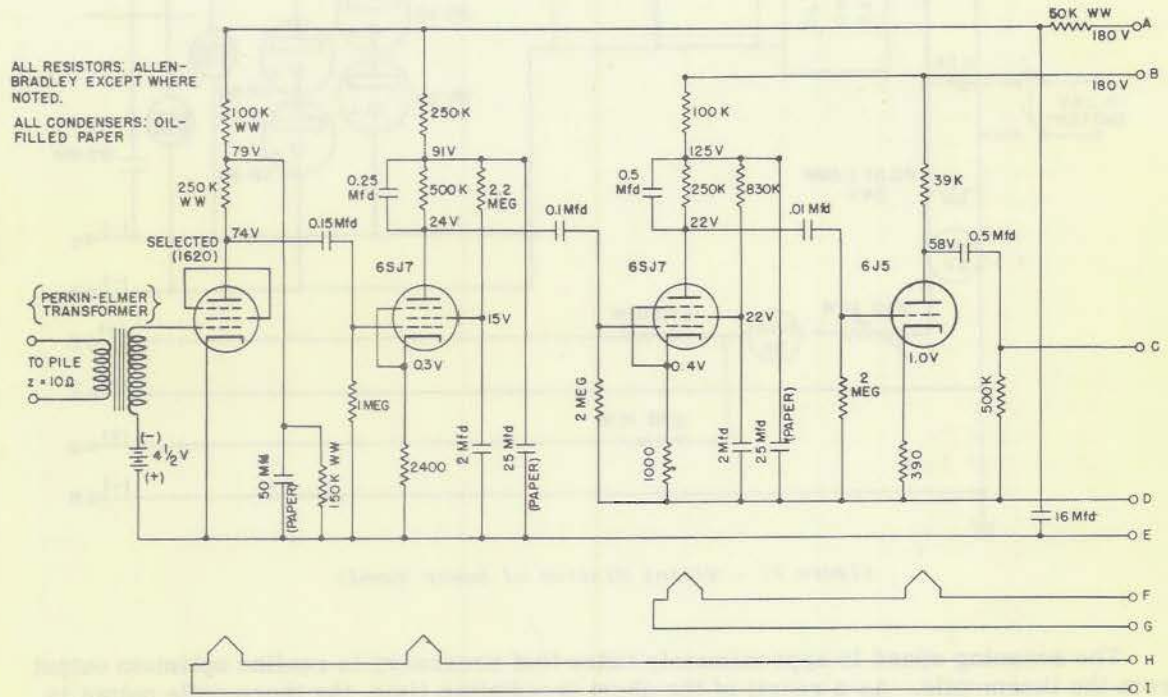


Figure 8 - Wiring diagram of pulse amplifier

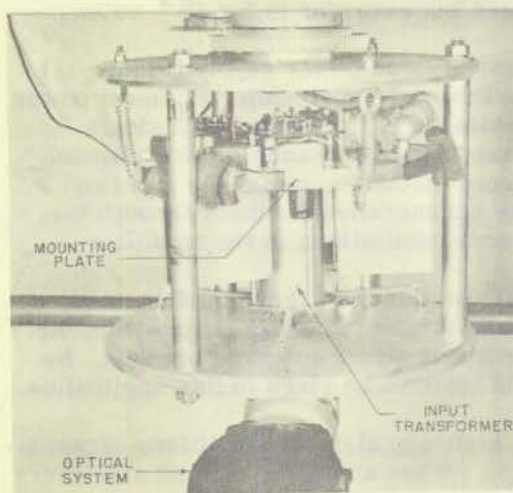


Figure 9 - Pulse amplifier

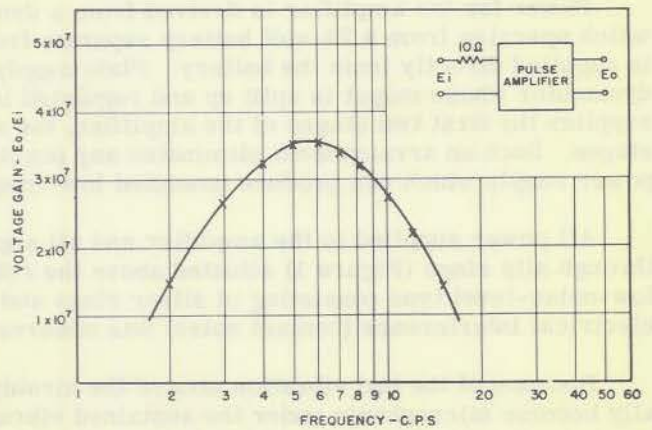


Figure 10 - Response of pulse amplifier

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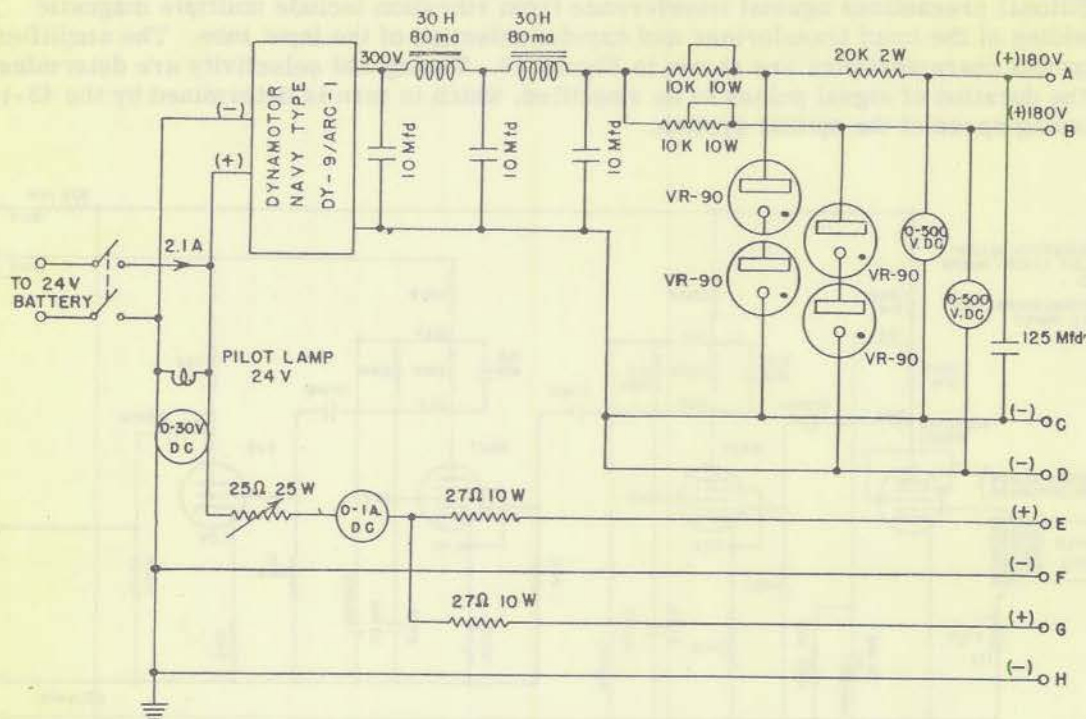


Figure 11 - Wiring diagram of power supply

The scanning speed is approximately twice that necessary to realize optimum output from the thermopile. As a result of the short irradiation time, the thermopile output is considerably reduced. However the pulse duration is shorter, thus making it possible to operate the amplifier at higher frequencies where the flicker noise from the input tube is considerably less. An actual improvement in signal-to-noise ratio is realized in this manner in spite of the loss in thermopile output. The measured noise level of the amplifier operating from a 9-ohm thermopile into the high-speed ink recorder is 2×10^{-9} volts.

Power for the amplifier is derived from a dynamotor-type power supply (Figure 11) which operates from a 24-volt battery separate from those of the airship. Filament power is supplied directly from the battery. Plate supply voltages are produced by a single dynamotor whose output is split up and regulated in two separate channels. One channel supplies the first two stages of the amplifier, the second channel supplies the last two stages. Such an arrangement eliminates any possible regenerative feedback through the power supply which can produce unwanted low-frequency oscillations in the amplifier.

All power supplied to the amplifier and all signals produced by the amplifier pass through slip rings (Figure 1) situated above the rotating frame. The slip rings are of the low-noise-level type consisting of silver rings and multiple silver-graphite brushes. No electrical interference (contact noise) was observable from these rings in this application.

Because of the bad vibration aboard the airship, high-signal-level amplifiers occasionally become microphonic under the sustained vibration. When a number of such amplifiers are cascaded, the problem of locating and eliminating the source of trouble becomes difficult. For this reason, the output of the pulse amplifier is presented on a Dumont type 275-A polar coordinate oscilloscope before undergoing further amplification for recorder

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presentation. The oscilloscope not only acts as a monitor but also serves as a means for signal presentation when the components which follow fail. The normal synchronous circular sweep employed in this oscilloscope is generated by a two-phase permanent magnet generator geared to the scanning mechanism. External terminals on the instrument permit presentation of the signal pulses as intensification of the circular sweep pattern or as radial deflections from the circular pattern.

After being monitored, the signal pulses are amplified further by a Brush type BL-905 low-frequency amplifier and are presented on one channel of a two-channel Brush type BL-202 ink recorder. The frequency response of amplifier-recorder combination is flat from $\frac{1}{2}$ cps to 80 cps and hence does not modify the frequency characteristics of the system. Tape speeds up to 5 inches/sec allow a spreading of the time base so that the shape of the signal pulses can be examined in detail. The synchronizing markers which appear on the second channel of the recorder once every complete revolution of the optical system further facilitate the evaluation of data. For example, unless two signal pulses appear for every one synchronizing marker, it is fairly certain that a wake is not producing them. Furthermore, unless at least twenty-five sets of signal pulses appear in succession (resulting from a 30-knot right-angle wake crossing at 2000 feet), it is also fairly certain that a wake is not the producing agent. This, of course, assumes that the wake is continuous for at least 1000 yards and does not have sections "washed out" of it, as may be the case occasionally.

Further amplification of the signal pulses for presentation on the facsimile recorder are provided by a two-stage power amplifier (Figures 1 and 12). A cathode-follower output stage of high transconductance is employed to mark the recorder paper and accommodate the large variations in paper impedance produced by the varying signal level. Switching at the input to the power amplifier permits the ram's-head-like signal to appear on the recorder either as light-dark-light trace or as a dark-light-dark trace. The recorder tape is 8-inch Alfax type 511A-693 electrolytic paper and is employed with a monel helix

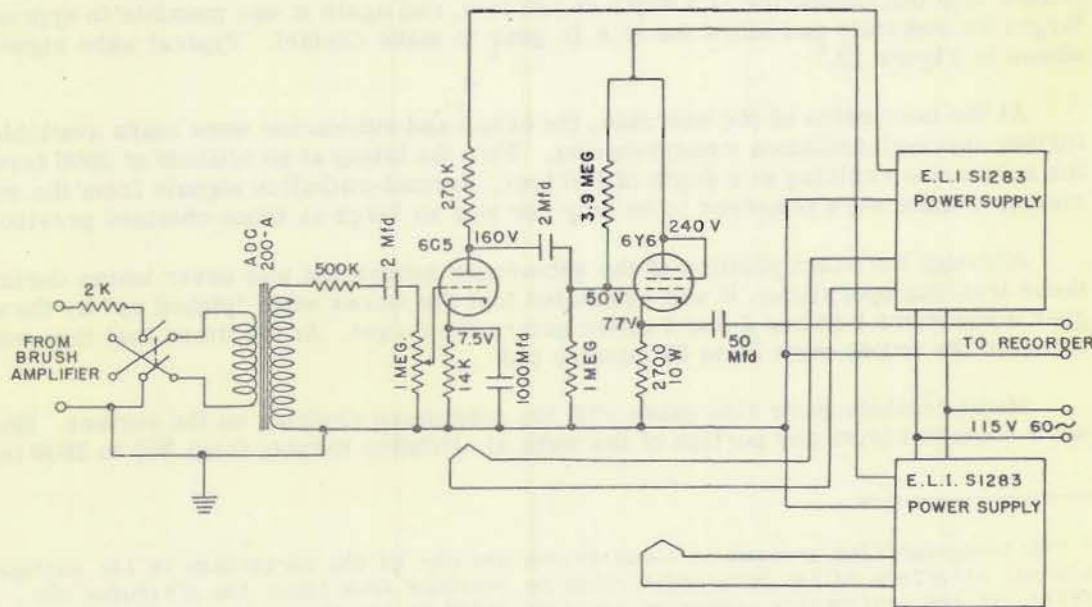


Figure 12 - Wiring diagram of power amplifier

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wire and platinum-iridium printer bar. Gearing between the paper drive mechanism and the helix allows the paper to advance 1/32 inch for each revolution of the helix, which in turn is driven in synchronism with the optical system by means of a flexible shaft.

The measured signal-to-noise ratio of the entire system varies with the method of signal presentation. The best signal-to-noise ratio is obtained with the facsimile recorder. That for the polar coordinate oscilloscope is approximately two times poorer and that for the ink recorder four to six times poorer. However, since it is the purpose of this problem to measure and record the magnitude of thermal radiation from the wake under various conditions rather than merely to detect the wake signals, only the signal-to-noise ratio of that portion of the system which includes the ink recorder is of interest. The E.N.I. (Equivalent Noise Input for a signal-to-noise ratio of unity) of the ink recorder portion measures 4.0×10^{-10} watts/cm² or 4.2×10^{-8} watts in the laboratory. This value increased two to three times in the presence of airship vibration.

SHAKEDOWN TESTS AT LAKEHURST

The equipment was installed in the K-113 (ZL-7), a U.S. Navy blimp, at Lakehurst, New Jersey, in May 1949, and a number of flights were made at night off the New Jersey shore. Most of the flight time was utilized in getting the "bugs" out of the apparatus using the wakes from passing surface ships as targets.

Upon one occasion however, a submarine was made available. Although the test with the submarine was intended primarily as an operational exercise with the M.A.D (Magnetic Airborne Detector) gear, it was possible to employ the thermal-radiation measuring equipment also. The first run involved evasive tactics by the submarine at a depth of 75 feet while the blimp searched the area at altitudes varying from 50 to 100 feet. The thermal radiation gear picked up the submarine's wake immediately and permitted a direct approach to the target where the M.A.D. gear made contact. The same maneuver was repeated with the submarine at a depth of 125 feet, and again it was possible to approach the target immediately and allow the M.A.D. gear to make contact. Typical wake signals are shown in Figure 13.⁵

At the conclusion of the exercise, the blimp and submarine were made available for further thermal-radiation measurements. With the blimp at an altitude of 2000 feet and the submarine cruising at a depth of 200 feet, thermal-radiation signals from the submarine's wake were observed to be only one half as large as those obtained previously.

Although the exact position of the submerged submarine was never known during these tracking operations, it was estimated that the wakes were "picked up" by the airborne gear somewhere between 2 and 3 miles astern the target. At the times that they were detected the wakes were 25 to 35 minutes old.

Measurements were also made with the submarine cruising on the surface. No signals were observed from any portion of the wake at altitudes varying from 200 to 2000 feet.

⁵ The irregularities present in these traces are due to the variations in the surface thermal structure of the wake which could be resolved from these low altitudes (50 - 100 feet). At the equipment's operating altitude (2000 feet), the projected field-of-view of the optical system is large enough to "average out" these variations.

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SUB: 125'
 BLIMP: 100'
 SENSITIVITY: 6×10^{-10} W/cm² = 1 DIV
 TIME: 1830
 DATE: 5-31-49

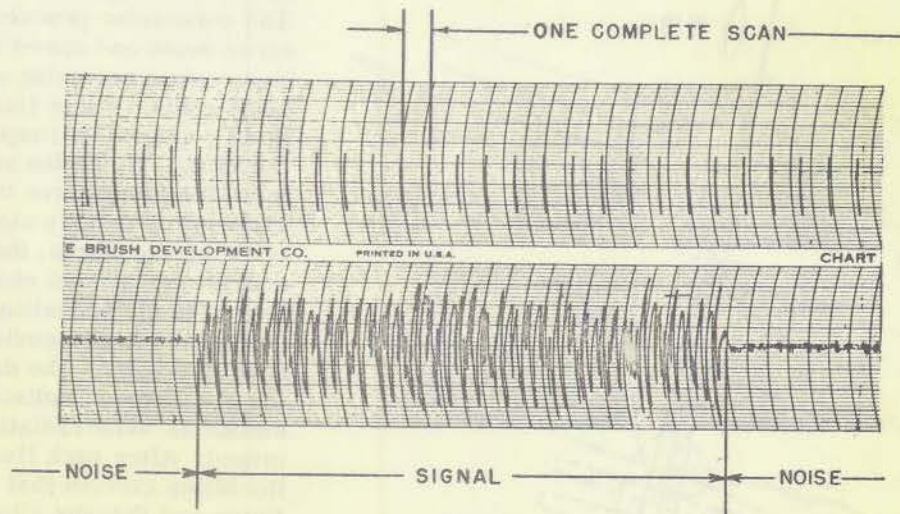


Figure 13 - Typical submarine wake signals obtained off Lakehurst, New Jersey, 31 May 1949

It is believed that the vertical temperature gradient of the water in which the submarine was operating was such that the water churned to the surface by the submarine's screws was colder than the surface water only if it came from a depth of 75 feet or greater. Water brought up by the surfaced submarine was the same temperature as the normal surface water and hence could not be detected thermally.

Upon completion of these measurements, the blimp headed toward shore. Approximately 45 miles from the New Jersey coast and 5 miles from the operational area, strong wake signals were again observed. A few moments later the M.A.D. gear made a contact. No targets other than the submarine with which the exercise had been conducted were visible. It was concluded that another submarine was in the area. *And they*

MEASUREMENTS AT KEY WEST

Airborne Radiation Measurements

Formal airborne measurements were conducted in the Gulf Stream east of Key West during the nights of 16, 17, and 21 June 1949. A Guppy-type submarine, the U.S.S. Cutlass, was employed as a target operating at various depths and speeds. Airborne measurements of the thermal radiation from the resulting wakes were made from the airship by the NRL group. Simultaneous measurements of the actual water temperature in and around the wakes were made from aboard a surface craft, the U.S.S. EPCS-1431, by ASW Development Branch personnel from the U.S. Naval Air Development Center. The results of the surface-temperature measurements are reported elsewhere.⁶

⁶ West, H. L., "Surface Measurements Taken on Thermal Wakes Generated by Submarines," USNADC Report No. ADC-50-50, 8 November 1949

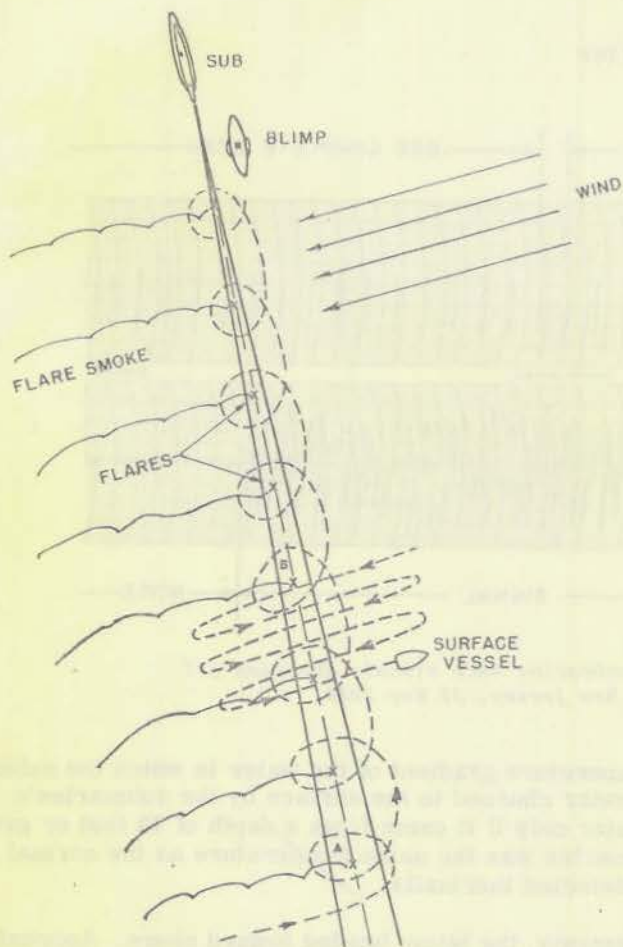


Figure 14 - Tactics employed during measurements at Key West

The tactics employed are depicted in Figure 14. The submarine started its run from point A, which was marked by a flare dropped from the blimp. The submarine proceeded at the desired depth and speed on a straight-line course releasing a flare every 1000 yards. These flares were immediately replaced by longer-life flares from the blimp. Since the smoke and fumes from the flares gave indications on the airborne gear very similar to those given by the wakes, the submarine's course was always chosen to be at right angles to the prevailing wind so that the smoke and fumes could be blown away from the wake. The danger of identifying the thermal radiation from the flare smoke as wake radiation was thus minimized. After each flare was dropped, the blimp circled that flare several times and thereby allowed a number of radiation measurements to be taken at that point on the wake. During these maneuvers, it was possible to locate the position of the wake very accurately by merely "lining up" the flares visually.

After the submarine had reached the midpoint of its run (point B of Figure 14), the surface craft, which up until now had been lying to, commenced a zig-zag run back and forth across the submarine's wake heading toward the starting point of the run (point A of Figure 14). Water-temperature measurements were made during this run.

Meanwhile, additional airborne radiation measurements were made further up the wake behind the submarine. In this manner, almost simultaneous measurements from the air and from the surface were made without interference with each other.

When the submarine had completed its run, it proceeded to a new operating area where the same procedure was repeated. The use of a new operating area for each run helped insure a fresh water surface unmarked by the older wakes from the submarine and surface craft.

Of the hundred or so passes made across the wake by the blimp during the three-day trials, none produced airborne measurements⁷ of any value. The wake could be detected

⁷ These measurements were concerned with the self-radiation from the completely developed wake of a submerged submarine and were made in total darkness. They should not be confused with the measurement of radiation reflected from the turbulent waters immediately astern a surface submarine such as have been described in an Eastman Kodak report, "Submarine Radiation Survey with DOVE EYE at Key West, June 27-29, 1949" (Contract NOrd 9979). The reflected radiation from bubbles immediately aft a surfaced submarine may be 10 to 100 times greater than the self-radiation from the wake of a totally submerged submarine. Such bubbles are not present in the wake of a completely submerged submarine.

occasionally, but the signals were never of sufficient magnitude to be of good measurable quality. The biggest signals obtained, shown in Figures 15, 16, 17 and 18, varied between 1.0×10^{-9} w/cm² (Figures 15 and 16) and 2.5×10^{-9} w/cm² (Figures 17 and 18). In no case was the signal-to-noise ratio greater than two.

Since signal-to-noise ratios of at least 5 and preferably 10 are required for reliable measurements, and since it became increasingly evident as the trials progressed that such signal-to-noise ratios were not going to be realized in the Key West area,⁸ termination of the measurements was effected after the third flight.

Correlation of Airborne and Surface Measurements

In order to correlate the contact temperature measurements of the wake and surrounding water, which were made from the surface vessel, with the thermal-radiation measurements, which were made from the blimp, it is necessary to make the following simplifying assumptions:

- (1) The wake and surrounding water are black bodies.
- (2) The wake and surrounding water have emitting surfaces of uniform temperature.
- (3) The radiation from the wake obeys Lambert's cosine law in the plane at 90° to the wake but the optical system always lies in the plane of the wake.⁹ ?
- (4) The linear dimensions of each half of the field-of-view of the airborne optical system projected upon the surface of the water do not exceed the dimensions of the wake.
- (5) The optical system scans across the wake at right angles at a rate commensurate with the speed of response of the entire airborne system (determined in this case by the time constant of the thermopile).
- (6) The entire system measures the difference between the thermal radiation from a cross-sectional slice of wake and the thermal radiation from an equal area of adjacent water.

⁸ These results were not entirely unexpected. Earlier measurements of the microthermal structure of the water in the Key West area (reported in Urlick, R. J. and Searfoss, C. W., "Microthermal Structure of the Ocean Near Key West, Florida, Part I - Description," NRL Report S-3392, December 1948) clearly indicated that large vertical temperature gradients near the surface of the water, which are necessary for easy wake detection by thermal-radiation means, seldom exist in the Gulf Stream. Poor atmospheric transmission, which was deducible from available wet- and dry-bulb thermometer readings taken in that area, was also expected.

⁹ The assumption that the optical system lies in the plane of the wake obviates the necessity of considering the variation in target signal due to the cosine law in the perpendicular plane as modified by the bearing of the optical system with respect to the wake. In such an assumption the maximum error, which occurs when the optical system actually lies in the perpendicular plane, is only equal to $1 - \cos 30^\circ$ or 13%. *Bob!*

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SUB: SCHNORKELLING, 60', 11 kts.
 BLIMP: 2000', 1000 yds. ASTERN
 SENSITIVITY: 6×10^{-10} W/cm² = 1 DIV.
 TIME: 2100
 DATE: 6-16-49
 HUMIDITY: 72%/76°

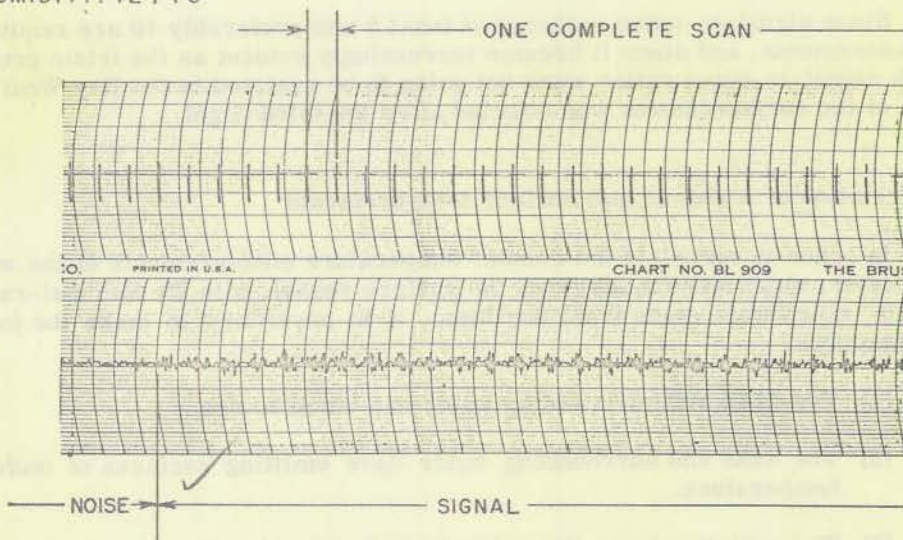


Figure 15 - Radiation from wake of schnorkelling submarine (6-16-49)

SUB: 85', 8 kts.
 BLIMP: 2000', 500 yds. ASTERN
 SENSITIVITY: 6×10^{-10} W/cm² = 1 DIV
 TIME: 2330
 DATE: 6-16-49
 HUMIDITY: 72%/76°

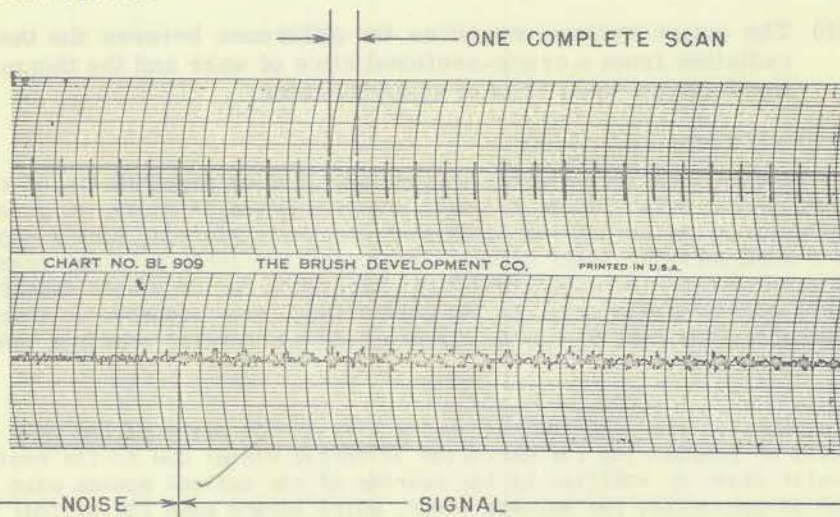


Figure 16 - Radiation from wake of submarine at 85 feet (6-16-49)

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SUB: SCHNORKELLING, 60', 11 kts. *Height?*
 BLIMP: 500 yds. ASTERN
 SENSITIVITY: 3×10^{-10} W/cm² = 1 DIV.
 TIME: 2215
 DATE: 6-17-49
 HUMIDITY: 77°/81.5°

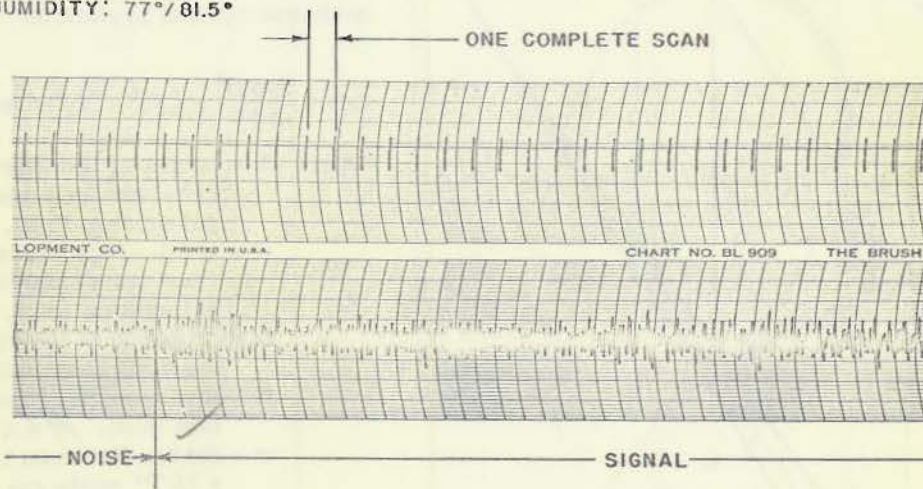


Figure 17 - Radiation from wake of schnorkelling submarine (6-17-49)

SUB: 60', 8 kts.
 BLIMP: 1000', 1000yds. ASTERN
 SENSITIVITY: 3×10^{-10} W/cm² = 1 DIV.
 TIME: 2100
 DATE: 6-21-49
 HUMIDITY: 72.5°/74.5°

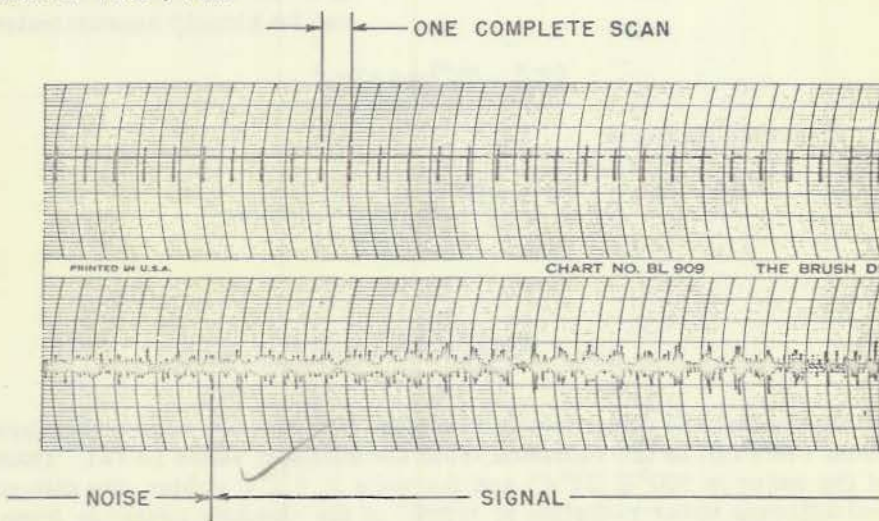


Figure 18 - Radiation from wake of submarine at 60 feet (6-21-49)

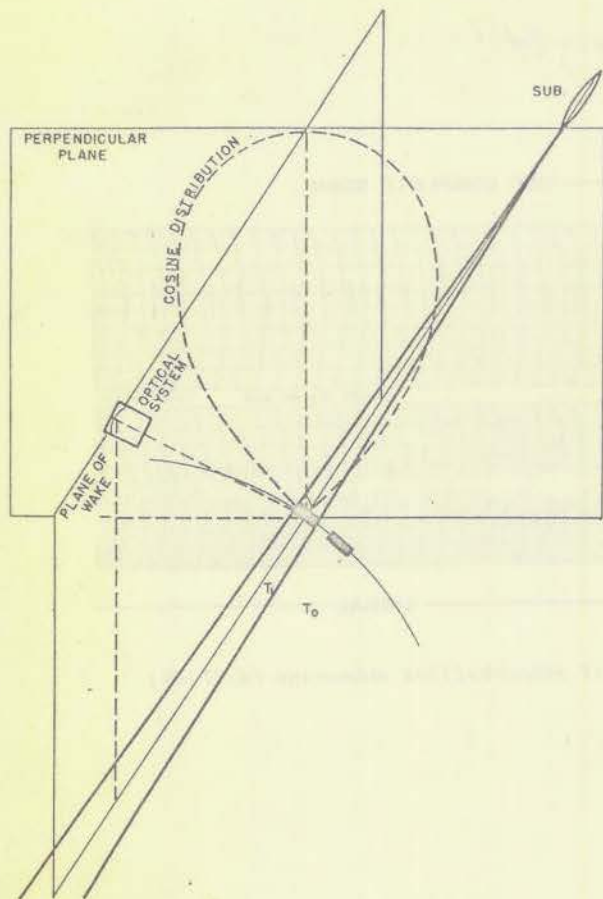


Figure 19 - Simplified conditions of measurements

With these assumptions and reference to Figure 19, one can express the difference between the wake and adjacent water radiation which is available at the airborne optical system as

$$\Delta\phi = \frac{hwD^2}{4F^2} \sigma (T_1^4 - T_0^4) \tau \text{ watts} \quad (1)$$

- where h = height of the thermal element receiver employed in the optical system (cm),
- w = width of the thermal element receiver employed in the optical system (cm),
- D = diameter of the aperture of the optical system (cm),
- F = focal length of the optical system (cm),
- σ = Stefan-Boltzman constant (5.72×10^{-12} watts cm^{-2} deg^{-4}),
- T_1 = temperature of the surface of the wake (degrees Kelvin),
- T_0 = temperature of the surface of the adjacent water (degrees Kelvin),
- τ = total transmission of the atmosphere over the optical path between the wake and the optical system (percent).

If the difference in temperature between the wake and adjacent water, ΔT , is 2° or less, the radical in equation (1) can be closely approximated by

$$(T_1^4 - T_0^4) \approx 4\Delta T T_0^3 \quad (2)$$

Equation (1) therefore becomes

$$\Delta\phi = \frac{hwD^2}{F^2} \sigma \Delta T T_0^3 \tau \text{ watts} \quad (3)$$

or

$$\Delta\phi = \frac{hwD^2}{F^2} \left(\frac{\Delta T}{T_0} \right) (\sigma T_0^4) \tau \text{ watts} \quad (4)$$

Equation (4) states that the difference in radiation between the wake and adjacent water is some fraction, $(\Delta T/T_0)$, of the radiation from the adjacent water (σT_0^4) . Thus if the temperature of the water is 300°K (27°C) and the wake is 0.1°C colder, the difference between the wake and adjacent water radiation is $1/3000$ of the absolute radiation from the adjacent water. For ease in calculation, the function (σT_0^4) has been calculated and plotted in Figure 20 for the range of water temperatures normally encountered in practice.

Equation (4) may be written in a more useable form by expressing the linear dimensions of the sensitive receiving element, h and w , and the focal length, F , of the optical system in terms of the vertical and horizontal angular dimensions of the optical field-of-view, α and β . From Figure 21a, the following relationships hold

$$\alpha = \frac{h}{F} \text{ radians} \quad \alpha \leq 5^\circ \quad (5)$$

$$\beta = \frac{w}{F} \text{ radians} \quad \beta \leq 5^\circ \quad (6)$$

Thus

$$\Delta\phi = \alpha\beta D^2 \left(\frac{\Delta T}{T_0} \right) (\sigma T_0^4) \tau \text{ watts.} \quad (7)$$

For the equipment employed at Key West,

$$\begin{aligned} \alpha &= \frac{1}{2}^\circ = 0.0087 \text{ radian} \\ \beta &= 5^\circ = 0.087 \text{ radian} \\ D &= 4\frac{1}{2}'' = 11.5 \text{ cm.} \end{aligned}$$

Hence equation (7) becomes

$$\Delta\phi = 0.1 \left(\frac{\Delta T}{T_0} \right) (\sigma T_0^4) \tau \text{ watts.} \quad (8)$$

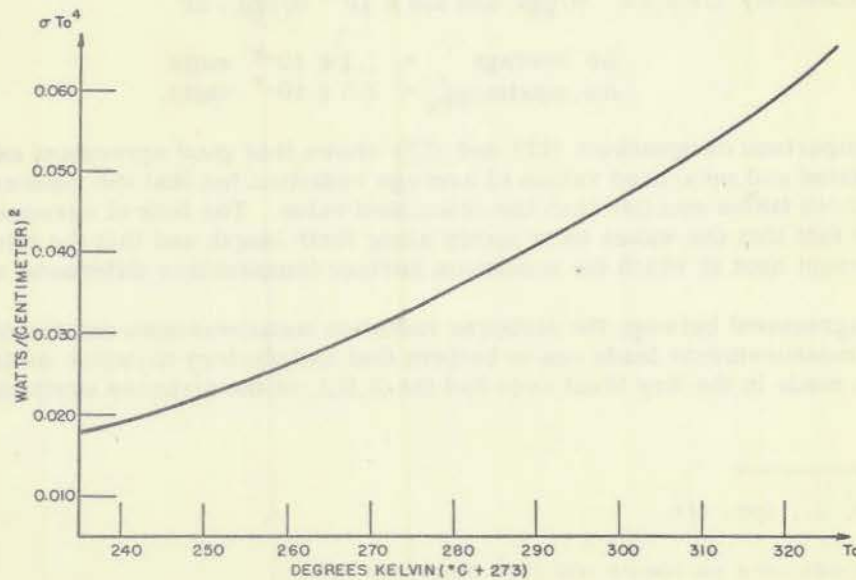


Figure 20 - Portion of blackbody radiation curve applicable at sea temperatures

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The surface contact temperature measurements¹⁰ showed that the difference in temperature between the wake and adjacent water averaged approximately 0.05°C and never exceeded 0.17°C. If it is assumed that the temperature of the water is 300°K (27°C), then

$$\left(\frac{\Delta T}{T_0}\right)_{\text{average}} = 1.67 \times 10^{-4} \tag{9}$$

$$\left(\frac{\Delta T}{T_0}\right)_{\text{maximum}} = 5.7 \times 10^{-4}$$

and from Figure 20

$$(\sigma T_0^4) = 4.7 \times 10^{-2} \text{ watts/cm}^2. \tag{10}$$

Thus

$$\begin{aligned} \Delta\phi \text{ average} &= 7.9 \times 10^{-7} \tau \text{ watts} \\ \Delta\phi \text{ maximum} &= 2.6 \times 10^{-6} \tau \text{ watts.} \end{aligned} \tag{11}$$

During the airborne measurements the absolute humidity varied between 3.4 and 4.1 cm of precipitable water per sea mile (2000 yds). For the optical path lengths employed, this amounts to a total atmospheric transmission of from 30% to 40%. In addition, considerable haze was present at all times in the optical path. Occasionally low-hanging clouds were also present, although an effort was made to keep below them.¹¹ It is therefore estimated that the total atmospheric transmission for the optical path lengths employed varied between 10% and 30% with an average of 20%. Thus

$\frac{2.6}{5} = 0.52$

$$\begin{aligned} \Delta\phi \text{ average} &= 1.6 \times 10^{-7} \text{ watts} \\ \Delta\phi \text{ maximum} &= 7.8 \times 10^{-7} \text{ watts.} \end{aligned} \tag{12}$$

The results obtained directly from the air and shown in Figures 15, 16, 17, and 18 are approximately $1.0 \times 10^{-9} \text{ w/cm}^2$ and $2.5 \times 10^{-9} \text{ w/cm}^2$, or

$$\begin{aligned} \Delta\phi \text{ average} &= 1.3 \times 10^{-9} \text{ watts} \\ \Delta\phi \text{ maximum} &= 2.6 \times 10^{-7} \text{ watts.} \end{aligned} \tag{13}$$

A comparison of equations (12) and (13) shows that good agreement exists between the calculated and measured values of average radiation but that the measured maximum value is three times smaller than the calculated value. The lack of agreement is probably due to the fact that the wakes were spotty along their length and that the blimp never flew over the exact spot at which the maximum surface temperature difference was observed.

The agreement between the airborne radiation measurements and the surface temperature measurements leads one to believe that satisfactory airborne measurements could have been made in the Key West area had the E.N.I. of the airborne equipment been smaller.

¹⁰ West, H. L., loc. cit.

¹¹ Some clouds were as low as 500 feet above sea level.

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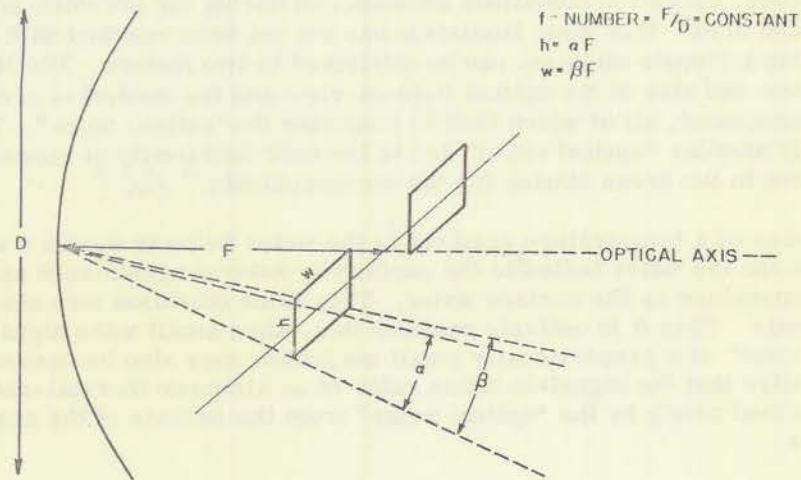


Figure 21a - Generalized parameters of optical system

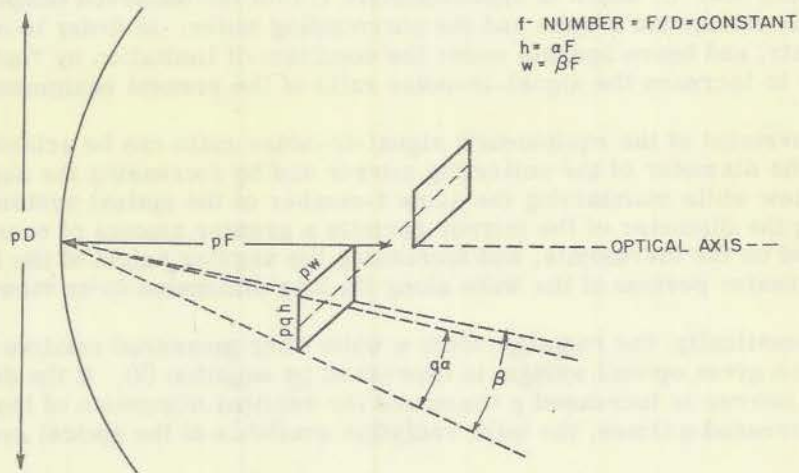


Figure 21b - Parameters of improved optical system

OPTICAL NOISE LIMITATIONS

At no time during the tests at Lakehurst or during the measurements in the Key West area was it possible to observe "optical noise" from the surface of the sea. The noise level in the gear was due primarily to microphonics in the input stage of the amplifier and was produced by the vibration of the airship. Therefore by simply increasing the "gain" of the optical system the signal-to-noise ratio of the equipment can be improved up to the point where the "optical noise" predominates. Once the "optical noise" level has been reached, further major improvements in the over-all signal-to-noise ratio of the system are not possible. In other words the "optical noise" from the surface of the sea presents a basic limitation to this method of detection.

However, unlike the conditions encountered during the previous measurements in the New London area¹² this basic limitation has not yet been reached with the present equipment. This fortunate situation can be attributed to two factors. The first is the choice of the shape and size of the optical field-of-view and the method of scan employed by the present equipment, all of which tend to minimize the "optical noise". The second is the apparently smaller "optical noise" due to the near uniformity of temperature of the surface waters in the areas chosen for the measurements.¹³ Oh!

Absence of a temperature gradient in the water helps to insure a uniform radiating surface since the water boiled to the surface by natural agents such as the wind is of the same temperature as the surface water. This same condition may also bring about small wake signals. Thus it is entirely possible that, when small wake signals are encountered, "optical noise" of a proportionally small magnitude may also be encountered. Hence it is imperative that the signal-to-noise ratio of an airborne thermal-radiation detector be determined solely by the "optical noise" from the surface of the sea under all weather conditions.

Surface temperature measurements in the Key West area revealed that the surface of the sea was covered with randomly positioned hot and cold spots approximately 20 feet in diameter. The temperature of these spots never differed from the surrounding water by more than 0.01 °C, which is approximately 1/10th the observed temperature difference between the submarine's wake and the surrounding water. In order to observe these spots from the air, and hence operate under the condition of limitation by "optical noise," it is necessary to increase the signal-to-noise ratio of the present equipment at least ten times.

Improvement of the equipment's signal-to-noise ratio can be achieved easily by increasing the diameter of the collecting mirror and by increasing the angular height of the field-of-view while maintaining the same f-number of the optical system. Physically, increasing the diameter of the mirror permits a greater amount of energy to be collected and focused on the thermopile, and increasing the angular height of the field-of-view allows a greater portion of the wake along its long dimension to be viewed.

Mathematically, the radiation from a wake when measured relative to the surrounding water with a given optical system is expressed by equation (7). If the diameter of the collecting mirror is increased p times and the vertical dimension of the angular field-of-view is increased q times, the wake radiation available at the optical system becomes

$$\Delta\phi' = (q\alpha) \beta (pD)^2 \left(\frac{\Delta T}{T_0}\right) (\sigma T_0^4) \tau \text{ watts.} \quad (14)$$

If the f-number, f, of the system is kept constant (f = 0.5), equation (14) becomes

$$\Delta\phi' = (qp\alpha) (p\beta) \left(\frac{F}{f}\right)^2 \left(\frac{\Delta T}{T_0}\right) (\sigma T_0^4) \tau \text{ watts,} \quad (15)$$

or

$$\Delta\phi' = (qph) (pw) \left(\frac{1}{f}\right)^2 \left(\frac{\Delta T}{T_0}\right) (\sigma T_0^4) \tau \text{ watts.} \quad (16)$$

¹² Clark, H. L., *loc. cit.*

¹³ Sea states up to 4 were encountered at Key West.

But, in order to generate the desired angular field-of-view, the dimensions of the thermopile (Figure 21b) must be increased to

$$H = p q h \text{ cm} \quad (17)$$

and

$$W = p w \text{ cm.} \quad (18)$$

Thus

$$\Delta\phi' = HW \left(\frac{1}{f}\right)^2 \left(\frac{\Delta T}{T_0}\right) (\sigma T_0^4) \tau \text{ watts,} \quad (19)$$

which is another form of equation (4). Equation (19) states an important basic fact: the flux density, ψ , in the focal plane of the optical system depends only on the f-number of the optical system, or

$$\psi = \frac{\Delta\phi'}{HW} = \left(\frac{1}{f}\right)^2 \left(\frac{\Delta T}{T_0}\right) (\sigma T_0^4) \tau \text{ watts/cm}^2. \quad (20) \checkmark$$

The flux density, ψ , in the focal plane is a maximum when the f-number is a minimum ($f = 0.5$). Thus if the f-number is held at a minimum (constant), the flux density in the focal plane remains constant when the diameter of the collecting mirror and the height of the field-of-view are changed. *width*

If the new thermopile of dimensions H and W is made up of a multiplicity of receivers of dimensions h and w, the total radiation falling on each small receiver is equal to ($\psi h w$) watts. If the d-c sensitivity of one small receiver is s volts/watt and its resistance is r ohms, and if n small receivers are connected in parallel and m such groups are connected in series, the voltage output, V' , of the large thermopile is

$$V' = m s (\psi h w), \quad (21) \checkmark$$

and its resistance, R, is

$$R = \frac{m}{n} r. \quad (22) \checkmark$$

The Johnson noise, N' , due to the resistance, R, is

$$N' = k \sqrt{R} = k \sqrt{\frac{m}{n} r}, \quad (23)$$

where k is a constant of proportionality. Thus the signal-to-noise ratio is

$$\frac{V'}{N'} = \frac{s (\psi h w) \sqrt{mn}}{k \sqrt{r}}. \quad (24)$$

But (mn) is the total number of small receivers employed. This number is also given by $p^2 q$. Thus

$$mn = p^2 q. \quad (25)$$

Hence

$$\frac{V'}{N'} = \frac{s (\psi h w) p \sqrt{q}}{k \sqrt{r}} \quad (26)$$

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A similar expression can be written for the signal-to-noise ratio of one small receiver:

$$\frac{V}{N} = \frac{s (\psi h w)}{k \sqrt{r}} \quad (27)$$

Thus the improvement in signal-to-noise ratio is

$$\frac{V'/N'}{V/N} = p \sqrt{q} \quad (28) \quad \checkmark$$

Equation (28) holds as long as the "optical noise" is considerably less than the Johnson noise. When the optical noise becomes comparable to the Johnson noise, a second term must be added to equation (23) to take into account the increase in optical noise due to an increase in the angular dimensions of the field-of-view (at constant altitude). However, until that point is reached in practice and until more is learned about the behavior of "optical noise," it is not worth considering.

Equations (20), (26), and (28) together state three basic facts. The first is that the f-number of the optical system should be as small as possible for maximum signal-to-noise ratio. This condition is satisfied in the present system with an f-number of 0.5. The second fact is that the signal-to-noise ratio increases as the first power of the diameter of the mirror. Thirdly, the signal-to-noise ratio increases as the half power of the vertical dimension of the angular field-of-view. These three conditions hold when the altitude of the optical system is kept constant and the horizontal dimension of the vertical field-of-view is just large enough to cover the width of the wake.

As an example of the possible improvement in the signal-to-noise ratio of the present system, assume that the diameter of the collecting mirror is increased from $4\frac{1}{2}$ to 24 inches and that the vertical angular dimension of the field-of-view is increased from $\frac{1}{2}^\circ$ to 5° . Thus $p = 5.3$ and $q = 10$ and

$$\frac{V'/N'}{V/N} \approx 17. \quad (29)$$

Hence an improvement in signal-to-noise ratio of 17 times can be realized with optics of practical size. However, equations (17) and (18) indicate that the dimensions of the thermopile would be approximately 1 inch x 1 inch, which is rather large but not impractical. The number of small elements included in such a large area would be approximately 280.

It therefore appears quite feasible to improve the signal-to-noise ratio of the present system so that the equipment can operate under conditions limited by "optical noise," in areas such as around Key West. With such equipment the characteristics of both wakes and "optical noise" can be investigated. From this information, it should be possible to establish criteria for the design of detection gear to operate under optimum conditions in the presence of "optical noise." ✓

SUMMARY AND CONCLUSIONS

- (1) The detection of submarine wakes with airborne thermal radiation gear appears to be very promising.
- (2) The measurement of the thermal-radiation characteristics of wakes requires equipment with a much greater signal-to-noise ratio than that of detection gear.

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- (3) The radiation from submarine wakes in the Lakehurst area was great enough to be easily measurable, but the radiation from wakes in the Key West area was too small to be measured properly with the available equipment.
- (4) The small wake radiation in the Key West area was due to the small difference in temperature between the wakes and surrounding water, which in turn was due to the small vertical temperature gradient in the water.
- (5) The failure to measure properly the radiation from wakes in the Key West area was due to the equipment itself and was not due to the physical properties of the wakes being investigated.
- (6) "Optical noise" from the surface of the sea was not the limiting factor in the determination of the signal-to-noise ratio of the equipment employed.
- (7) A reduction in the E.N.I. of the present equipment of at least ten times appears necessary before the "optical noise" becomes a limiting factor in the signal-to-noise ratio.
- (8) Preliminary considerations indicate that the E.N.I. of the present equipment can be reduced at least ten times by redesigning the optical system. *x This is not precisely stated.*
- (9) With the improved equipment, measurements of the characteristics of both submarine wakes and "optical noise" should be possible in areas similar to those around Key West.

RECOMMENDATIONS

On the basis of the results obtained with the present equipment and the conclusions drawn therefrom, it is recommended that:

- (1) Further measurements with the present equipment not be undertaken.
- (2) The equipment be modified so as to realize an improvement in signal-to-noise ratio of at least ten times with a resulting E.N.I. of approximately 5×10^{-9} watts/cm².
- (3) Extensive measurements of both "optical noise" and submarine wake radiation be conducted off the New Jersey coast prior to any measurements elsewhere.
- (4) If the measurements in the New Jersey area so indicate, the measurements in the Key West area be repeated. *to*

ACKNOWLEDGMENTS

This Laboratory wishes to express its gratitude to ComFairShipWing 1 at Lakehurst, to the BlimpRon of AsDevRon 1 at Key West, and to SurAsDevDet at Key West for the splendid cooperation given the NRL personnel. Normally these groups are concerned only with completely developed equipments ready for fleet evaluation and are not concerned with exploratory measurements of such basic nature as those which have just been undertaken. The efforts of these groups were certainly outstanding.

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Miss Dorothy Estes of the Radiometry Branch of this Laboratory is to be commended for her part in measuring the transmission characteristics of the optical window. Mr. Linwood Ethridge and Mr. C. T. Jeffrey of the Applied Optics Branch did a good job of constructing the optical, mechanical, and electronic portions of the complete equipment.

