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AIRBORNE MEASUREMENTS OF THE THERMAL RADIATION FROM SUBMARINE WAKES IN THE GULF STREAM

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Optics Division

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AIRBORNE MEASUREMENTS OF THE THERMAL RADIATION FROM SUBMARINE WAKES IN THE GULF STREAM

INTRODUCTION

In the course of carrying out a basic investigation of the thermal radiation properties of submarine wakes, a series of measurements was conducted at night during the month of May 1950 over deep water approximately 150 miles east of Atlantic City, New Jersey. The results, which are described in another NRL report,[1] were excellent. With airborne radiation measuring equipment, submarine wakes generated from depths down to 150 feet were tracked up to 12,000 yards, the extent of the submarine's run. The radiation from such wakes as observed from an altitude of 2000 feet varied from 2.3 to 0.9 microwatts centimeters^{-2} steradians^{-1}, decreasing in magnitude with increasing submarine depth.

These measurements left a number of questions unanswered. One was whether similar results could be obtained in other localities such as the Key West area where earlier measurements[2] had been so unsuccessful. Another was whether the wakes could be tracked for greater distances had the submarines' runs been longer. Still another was whether rougher seas would markedly reduce the effectiveness of such gear.

To answer these questions, the measurements were repeated over the Gulf Stream south of Key West, Florida, during April 1951. Test conditions were similar except that the submarine runs were 20,000 yards or greater in length and the performance of the gear was improved twofold so that an operational noise level of 6.0×10^{-8} watts cm^{-2} steradians^{-1} was realized. This was equivalent to a temperature difference between the submarine's wake and adjacent surface water of $\pm 0.001^{\circ}$C assuming a 300°K sea and an atmospheric transmission of 30 percent.

The results of the second trials in the Key West area were also highly successful. Wakes generated at various depths down to 150 feet were tracked the entire length of the submarines' runs, 20,000 yards. Because of the stirring action of the currents in the Gulf Stream, which tended to produce isothermal conditions, signal magnitudes were approximately two times smaller than those observed under like conditions east of Atlantic City.

These measurements showed that submarine wakes could be observed in the rather unfavorable Key West waters but that the 8-10 knot currents present in the Gulf Stream tended to break up the tracks and limit their life to about $2\frac{1}{2}$ hours.

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[1] Clark, H. L., "Airborne Measurements of the Thermal Radiation from the Wake of the USS IREX." NRL Report 3783 (Secret), February 16, 1951

[2] Clark, H. L., "Airborne Measurements of Thermal Radiation from Submarine Wakes in the Key West Area." NRL Report 3606 (Secret), January 4, 1950

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The question of what effect rough seas have on the life span of submarine wakes was never answered during these trials. Although planned for, these measurements were not conducted because of the lack of submarine service. The six four-hour runs which were completed took approximately two months, at the end of which time, the trials were terminated at the request of the Naval Research Laboratory. It was felt that the efforts of the Laboratory personnel involved could be more advantageously expended on the development of better gear with which the desired measurement could be made at some later date.

EQUIPMENT

Except for minor improvements, the equipment employed over Key West waters is similar to that used earlier east of Atlantic City. It is designed to be flown in a blimp (Figure 1) at an altitude of 2000 feet at speeds of from 30 to 60 knots. The optical system scans at 30 rpm, the periphery of a 1000-yard diameter circle (Figure 2) which is transformed into a tight spiral by the forward motion of the airship. Projected upon the periphery are the two halves of the optical system's field of view, each measuring 250 feet wide by 300 feet high with a 500-foot separation between adjacent edges. As the optical system sweeps around the circle and crosses a wake, first one and then the other section of the field of view encounters the wake. If the temperature of the wake differs from the surrounding water by more than $\pm 0.003^\circ$C and the atmospheric transmission is 30 percent or greater, the difference in the radiated thermal energy at the optical system will produce an easily measurable signal therein. This signal consists of a positive- and negative-lobed voltage pulse which is amplified, partially differentiated, and then presented on an oscilloscope and two different types of recorders (Figures 3 and 4). Identity of the polarity of the signal is maintained throughout the system so that it is possible to determine whether the wake is hotter or colder than the surrounding water.

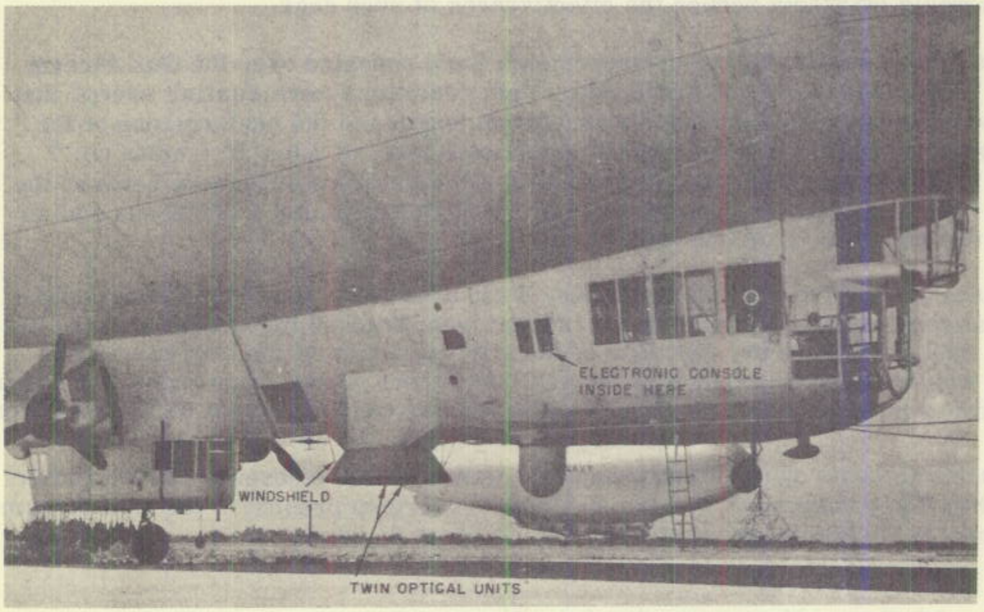

Figure 1 - Equipment installation in M-4 airships

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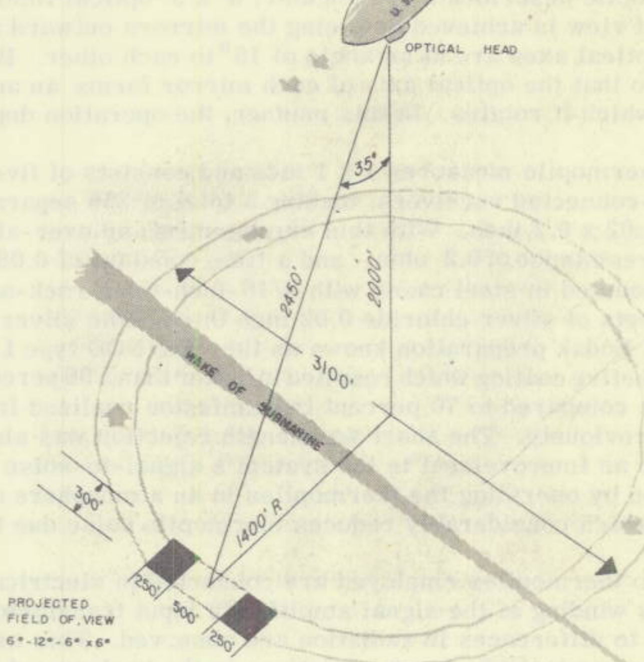

Figure 2 - Operating condition of detector

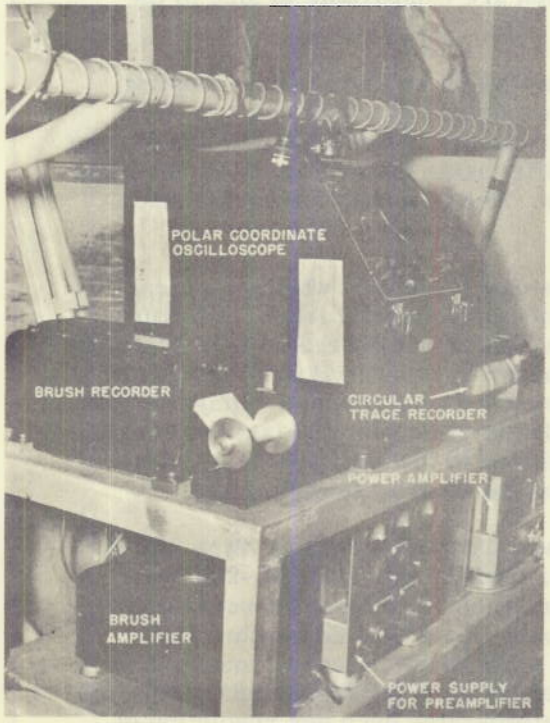

Figure 3 - Electronic units

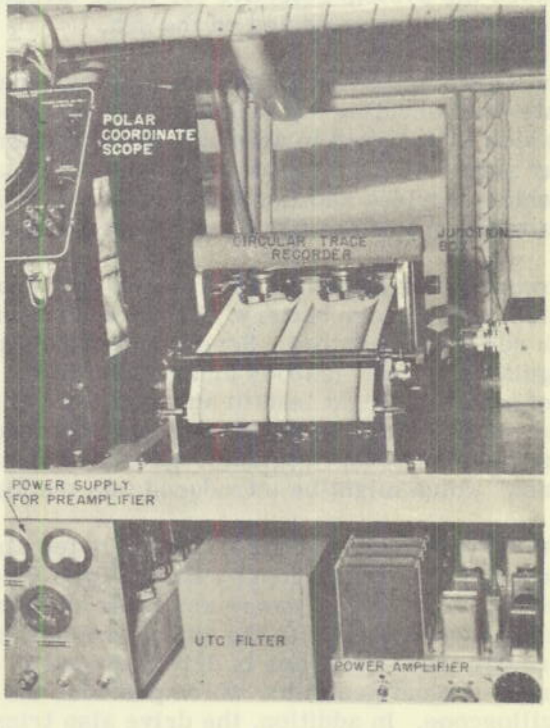

Figure 4 - Electronic units

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The optical system (Figure 5) consists of two 24-inch, f/0.4, stellite, parabolic mirrors, in the focal plane of which is mounted a special 1 x 1 inch Eppley thermopile. Each thermopile describes a rectangular, $5^{\circ} \times 5^{\circ}$ optical field of view. Separation of the two fields of view is achieved by toeing the mirrors outward away from each other so that their optical axes are at an angle of 15° to each other. Both mirrors are also tilted downward so that the optical axis of each mirror forms an angle of 35° with the vertical axis about which it rotates. In this manner, the operation depicted in Figure 2 is achieved.

Each thermopile measures 1 x 1 inch and consists of five series-connected banks of 50 parallel-connected receivers, making a total of 250 separate receivers. Each receiver measures 0.02 x 0.2 inch. With this arrangement, an over-all sensitivity of 0.0034 volts/watts, a dc resistance of 0.2 ohm, and a time constant of 0.08 second are attained. The units are mounted in steel cases with 3/16-inch-thick rock-salt windows over which are pressed sheets of silver chloride 0.02 inch thick. The silver chloride was treated with an Eastman Kodak preparation known as the "EK/NOD type I.R. Filter Coating" and a plastic protective coating which resulted in better than a 90 percent transmission for 9-13 micron radiation as compared to 70 percent transmission realized from the Harshaw coatings employed previously. The short wavelength rejection was also greater, all of which amounted to an improvement in the system's signal-to-noise ratio. Further improvement was realized by operating the thermopiles in an atmosphere of helium instead of air, a procedure which considerably reduces thermopile noise due to air swish.

The two thermopiles employed are connected in electrical series opposition across the primary winding of the signal amplifier's input transformer (Figure 5) so that only signals due to differences in radiation are observed. This arrangement minimizes the disturbances produced by mass variations in the background radiation from the sea and also makes the system selective for these targets which are comparable in size to the optical field of view projected on the sea.

The signal amplifier (Figure 6) is a four-stage unit which employs under-coupling and plate-load shunting for tuning purposes. Also incorporated is a 0.57 cps rejection filter which is designed to attenuate the fundamental frequency associated with the 34 rpm circular scan. Coupled to the output end of this amplifier is an m-derived, L-C, bandpass filter which provides additional attenuation at 0.57 cps. The frequency characteristics of the amplifier plus the filter are shown in Figure 7.

Power for the amplifier is provided by a separate unit (Figure 8) which operates from a 24-volt storage battery. Filament current is obtained directly from the battery through current regulators. Screen and plate supply voltages are generated by a dynamotor and regulated by both gaseous and vacuum tubes. In order to avoid feedback through the dynamotor, which might lead to an unwanted oscillatory condition, the high voltage for the first two stages of the amplifier is regulated independently of that for the last two stages. As an added precaution, regulator tubes are also employed in the amplifier to eliminate any "hash" which might be introduced into the high-voltage lines by the slip rings.

The filtered output of the amplifier is fed simultaneously to: a Dumont Type 275-A polar-coordinate oscilloscope; a Brush Type BL-905 amplifier and Type BL-202 two-channel recorder, and a power amplifier and circular-trace recorder. All recording units are synchronized with the optical scanner by means of a 50-speed synchro link. The circular trace recorder is driven directly. This same drive likewise rotates a permanent-magnet generator which provides the sweep voltages for the circular trace on the oscilloscope. In addition, the drive also trips a microswitch once per revolution of the optical scanner and thereby produces synchronizing marks on one channel of the two-channel Brush recorder.

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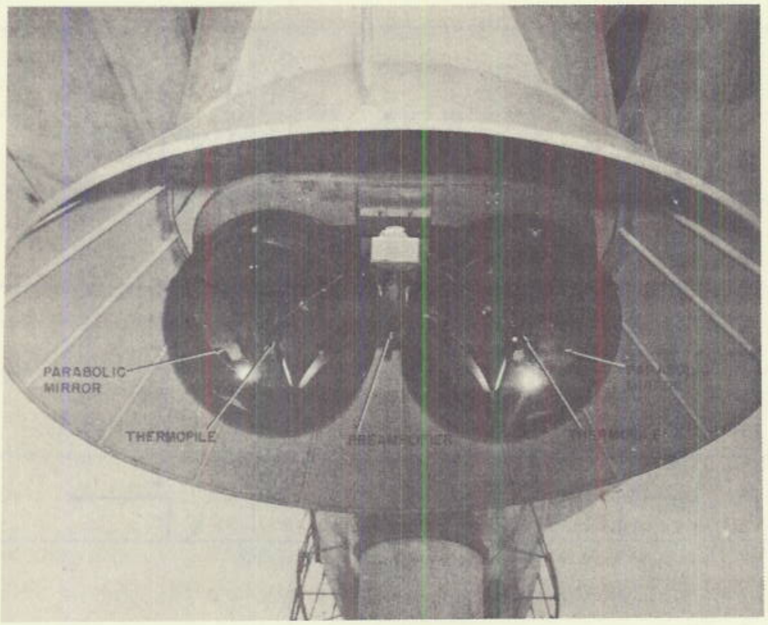

Figure 5 - Optical system

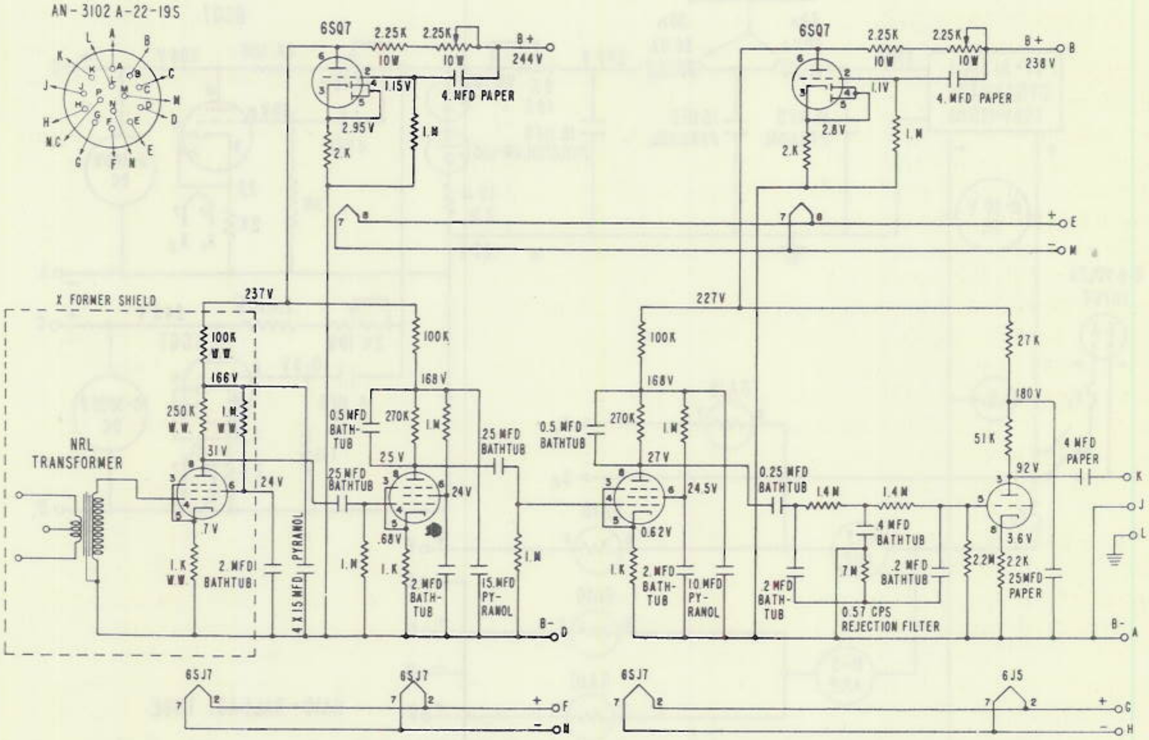

Figure 6 - Signal amplifier

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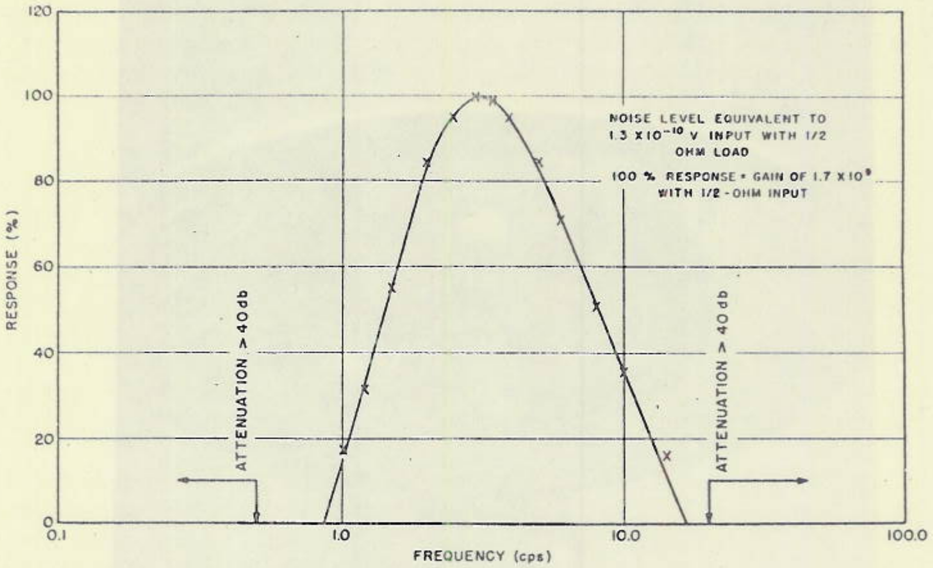

Figure 7 - Frequency characteristics of amplifier plus L-C filter

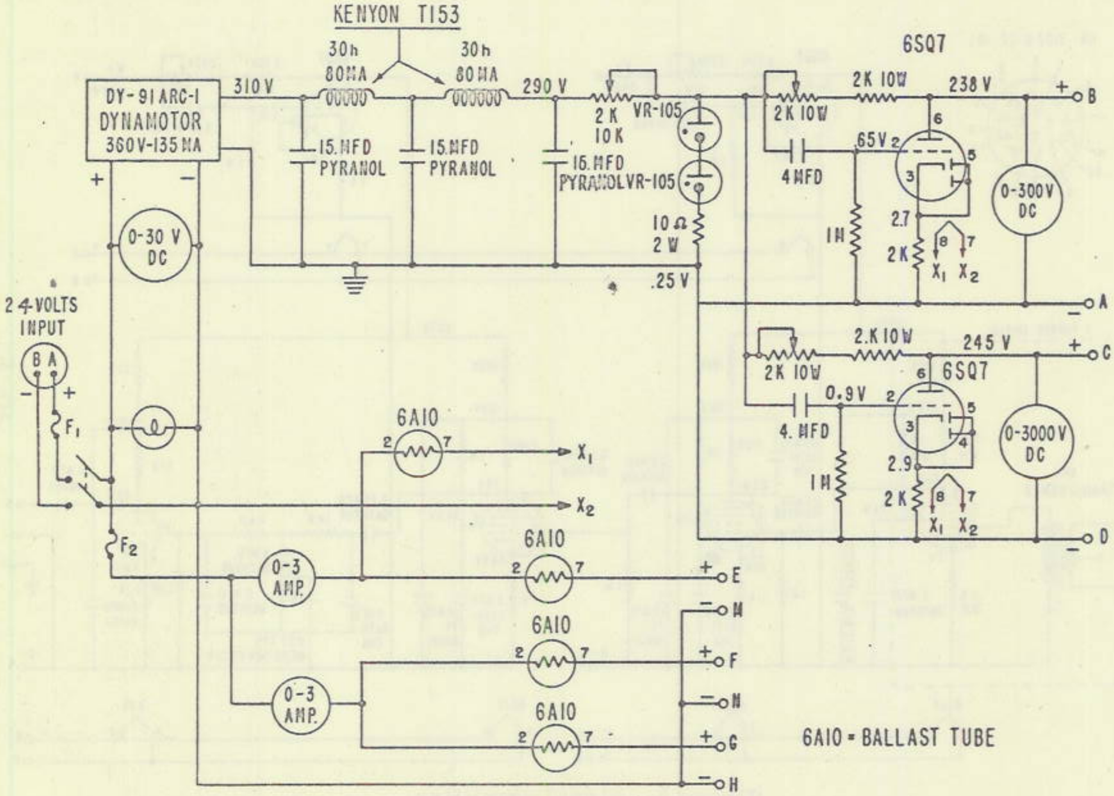

Figure 8 - Power supply

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Signals appear on the Brush recorder as amplitude deflections from which the magnitude of the wake radiation can be deduced. As explained in an earlier report,[3] the signal assumes the shape of a ram's head due to the differentiating action of the amplifier. If the ram's head is right side up, the wake is colder than the surrounding water; if up side down, warmer.

The circular-trace recorder presents the signals as variations in intensity of a gray line spiral printed on chemically-activated paper. The recorder (Figure 4) is designed so that its various moving parts simulate the actual search procedure generated by the circular scan of the optical system and the forward motion of the airship. Thus, the continuous advance of the paper through the recorder represents the forward flight of the airship; and the circular motion of the printing stylus, which is synchronized with the scan, represents the optical search. The diameter of the printed circle and the linear speed of the paper are scaled down proportionally so that distortion in the printed thermal map of the area under the airship is held at a minimum.

Two rotating styli are employed to print two thermal maps simultaneously. On one map, cold wakes appear with maximum contrast and, on the other, hot wakes appear with the greatest contrast. In the past, attempts to present hot and cold wakes on a single map have been only partially successful. For example, the system could be set up so that a cold wake appeared as a dark trace on a light background. As a result, a hot wake, because of its opposite polarity, appeared as a light trace on a dark background and hence exhibited very poor visual contrast. Oftentimes, hot wakes went undetected because of this method of printing. On the other hand, had the polarity been reversed, the signals would have been easily readable. This difficulty has been overcome by employing the two styli and feeding them separately from a two-channel power amplifier (Figure 9). A phase inverter in one of these channels inverts the signal so that it is printed in just the opposite manner from that of the other channel. Thus the stylus, which is fed from the channel containing the inverter, prints hot-wake signals best while the other channel takes care of cold-wake signals.

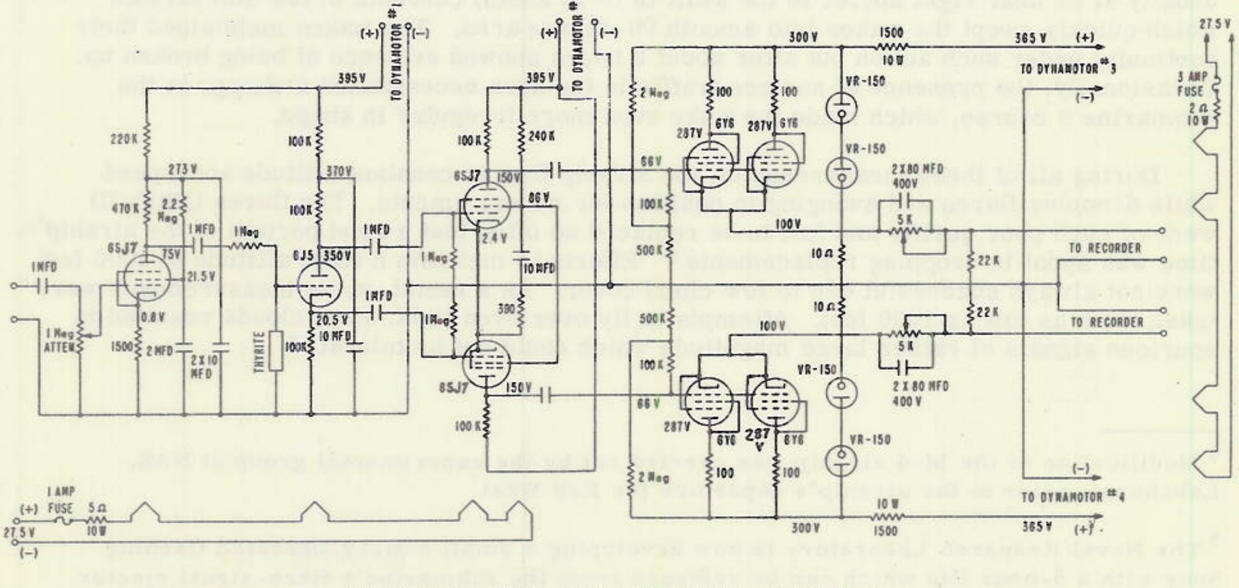

Figure 9 - Two-channel power amplifier

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[3] Ibid.

It is difficult to estimate the improvement in signal-to-noise ratio realized from the the circular-trace recorder. For the detection of signals which are well down in the noise, it is superior to either the Brush recorder or the Dumont polar-coordinate oscilloscope. Because of the difficulty in estimating the system's signal-to-noise ratio when employing the circular-trace recorder and because the system is intended for the measurement and not the detection of signals, the signal-to-noise ratio as observed with the Brush recorder is used as a criterion of the system's performance.

In actual flight, a signal-to-noise ratio of unity on the Brush recorder, which is equivalent to 6×10^{-8} watts cm^{-2} $steradian^{-1}$ at the mirror of the optical system is realized. If a sea temperature of 300°K and an atmospheric transmission of 30 percent are assumed, the unity signal-to-noise ratio corresponds to a temperature difference between a wake and surrounding water of ± 0.001°C. This, of course, also assumes that the wake is at least as wide as the optical field of view projected on the surface of the water; that the wake is of uniform temperature; and that it is a black body.

FORMAL MEASUREMENTS

The task of assisting the Naval Research Laboratory in carrying out the formal measurements in the Key West area was assigned to Airship Development Squadron 11 (ZX-11) at Boca Chica, Florida. With this squadron's cooperation, the thermal radiation equipment was installed in the M-4 airship[4] and flown against the submarines USS CLAMAGORE, USS MANTA, and USS CUTLASS on six separate nights. The operational areas, all of which are in the Gulf Stream south of Key West, were those designated as: Nan-3,4; Oboe-1, 2, 3, 4; Roger-1, 2; and Sugar-1, 2. All runs started in the evening after it was completely dark and lasted from 3 to 4 hours. The submarines' courses were straight lines at right angles to the prevailing winds so that smoke from the flares, which were employed to mark the tracks, was blown away from the area. As a result, the runs were usually at or near right angles to the swift (8 to 10 knots) currents in the Gulf Stream which quickly swept the wakes into smooth 90-degree arcs. The wakes maintained their continuity under such action but after about 2 hours showed evidence of being broken up. Occasionally, the presence of surface traffic in the area necessitated a change in the submarine's course, which made the wake even more irregular in shape.

During all of these measurements, the airship flew at constant altitude and speed while dropping flares and swinging in position for measurements. The flares (Mark II) were of such poor quality and had to be replaced so often that a good portion of the airship's time was spent in dropping replacements.[5] Efforts to maintain a fixed altitude of 2000 feet were not always successful due to low cloud cover. As a result, some measurements were taken from as low as 1000 feet. Attempts to fly over even light, wispy clouds resulted in spurious signals of rather large magnitude which could not be tolerated.

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[4] Modification of the M-4 airship was carried out by the experimental group at NAS, Lakehurst, prior to the airship's departure for Key West.

[5] The Naval Research Laboratory is now developing a small battery-operated flashing buoy with a 5-hour life which can be released from the submarine's flare-signal ejector and thus relieve the airship of these duties.

RESULTS

The results obtained during five of the six nights are tabulated in Table 1. The maximum, minimum, and average wake signals in microwatts per square centimeter of mirror surface and steradian of field of view are given. Also given are the corresponding temperature differences between the wakes and surrounding water which have been calculated by assuming a uniform rectangular temperature distribution across the wake, a water emissivity of unity, a water temperature of 20°C, and a total atmospheric transmission of 30 percent.

TABLE 1
Results of Exercises 2,3,4,5, and 6

Exercise	2	3	4	5	6
Date	5 April '51	11 April '51	26 April '51	17 April '51	19 April '51
Time (Hours)	1945-2237	2037-2304	2002-2232	2124-2320	1950-2223
Operating Area	Oboe-1,2,3,4	Oboe-3,4 Sugar-1,2	Oboe-3,4 Sugar-1,2	Nan-3,4 Roger-1,2	Roger-1
Submarine	CLAMAGORE	MANTA	CUTLASS	CUTLASS	MANTA
Screw Depth (Feet)	60	60	60	60	150
Speed (Knots)	6	4	4	2	4
Condition	Schnorkelling	Periscope Only Up	Schnorkelling	Periscope Only Up	Buttoned Up
Run (Yards)	22,000	20,000	20,000	16,000	20,000
Airship	M-4	M-4	M-4	M-4	M-4
Altitude (Feet)	2000	1800	1000 1500	2000	1500 2000
Ground Speed (Knots)	48	45	45-50	50	50
Sea State	1 White Caps	1 Calm	2 White Caps	1 Calm	1 White Caps
Surface Temperature	20.0°C	20.0°C	20.5°C	20.2°C	20.0°C
Vertical Gradient	Isothermal	Isothermal	Isothermal	Isothermal	Isothermal
Sky	Overcast	Hazy Clouds 1000′	Slight Rain Clouds 1600′	Hazy Moon Out	Moon Out Clouds 1800′
Wind (Knots)	5	0	12-15	0	8
Wet (Dry Bulb)	64°-70°F	73°-75°F	68°-71°F	69°-72°F	73°-76°F
Cm H_20/2000 yd	2.5	3.7	3.1	3.2	3.7
(μw cm^{-2} steradians^{-1}) Maximum Signal	1.48	0.89	2.20	1.33	1.62
(μw cm^{-2} steradians^{-1}) Minimum Signal	0.59	0.29	0.81	0.44	0.44
(μw cm^{-2} steradians^{-1}) Average Signal	0.94	0.52	1.48	0.83	1.04
Maximum Temperature Difference	0.026°C	0.016°C	0.040°C	0.024°C	0.029°C
Minimum Temperature Difference	0.011°C	0.005°C	0.015°C	0.008°C	0.008°C
Average Temperature Difference	0.017°C	0.009°C	0.027°C	0.015°C	0.019°C

A comparison of the average values of wake radiation observed during these measurements and those obtained earlier east of Atlantic City is made in Table 2. In general, the Key West values are smaller by a factor of two. This condition is probably brought about by the turbulence in the Gulf Stream and the resulting isothermal conditions. Exceptions to this behavior can be attributed to physical conditions at the edges of the Stream.

TABLE 2
Comparison of Atlantic City and Key West Results

Screw Depth (Feet)	Speed (Knots)	Operating Conditions	Average Wake Radiation (μ w cm^{-2} steradians^{-1})	
			Atlantic City	Key West
60	6	Schnorkelling	2.3	0.9
60	4	Schnorkelling	1.7	1.5
60	4	Periscope Only Up	1.1	0.5
60	2	Periscope Only Up	1.0	0.8
150	4	Buttoned Up	0.9	1.0

Submarine Surfaced and Underway at 3½ Knots

The first exercise was carried out with the CLAMAGORE and was employed to familiarize the NRL group with all phases of the test procedure. Unlike the earlier trials off the New Jersey coast, these measurements were carried out under conditions which were far from ideal. The curvature imparted to the wake by the current in the Gulf Stream, the intrusion of surface traffic into the operating area, the failure of the flares which made it necessary for the airship to fly a "helter-skelter" course dropping replacements, all made the taking of data most difficult.

To overcome these obstacles, a repeater oscilloscope with an NRL operator was placed in the pilot's compartment. A separate communication system between the forward operator and the people operating the bulk of the NRL gear in the aft compartment was also installed. With this arrangement, the forward operator could talk the airship into position over the wake and, at the same time, relay information regarding the airship's position to the aft operators. Operationally, these difficulties proved that a repeater type indicator, located in the pilot's compartment so that it can be viewed by the pilot and copilot, is a prime requirement for the successful tracking of a submerged submarine.

Submarine Submerged to 60 Feet and Schnorkelling at 6 Knots

On the following night, the CLAMAGORE made a schnorkelling run at a screw depth of 60 feet and a speed of 6 knots in the same area. The resulting wake appeared to be warmer than the surrounding water. Variations in signal magnitude of more than two to one were observed along the length of the wake. These variations bore no relationship to the age of the wake and appeared to be randomly distributed.

Submarine with Periscope Up, Submerged to 60 Feet,
and Underway at 4 Knots

A week later, the MANTA made a similar run in the same area at 4 knots with only her periscope extended above the surface of the water. As had been observed in previous measurements, retraction of the schnorkel resulted in a reduction in the wake signal. Since the MANTA's speed was 2 knots less than the CLAMAGORE's, part of this reduction in signal can possibly be attributed to the reduction in speed. Like the earlier wakes, the MANTA's wake also appeared warmer than the surrounding water. During these measurements, the airship had to fly at an altitude of 1800 feet in order to stay below existing cloud cover, a common requirement during these and earlier measurements in this area.

Submarine Submerged to 60 Feet and Schnorkelling at 4 Knots

To date, opportunities to make measurements in foul weather have not presented themselves. During these trials, the closest approach to such conditions was realized with the CUTLASS during a 4-knot schnorkelling run at 60 feet. A light rain, driven by 12 to 15 knot wind, was falling and a state 2 sea was running. For some unknown reason, the largest signals yet observed in the Key West area were recorded. All indicated a warm wake. Perhaps, the falling rain, which was colder than the surface of the sea, spread a cold blanket over the water and the mechanism, which was responsible for the wake's persistence, caused the wake to break through this layer. The result was a relatively greater contrast between the wake and surrounding waters, and therefore, greater signal strength from the entire length of the wake.

Submarine with Periscope Up, Submerged to 60 Feet,
and Underway at 2 Knots

The CUTLASS also made a periscope run at a screw-depth of 60 feet. Conditions were similiar to the MANTA's run earlier except that the CUTLASS' speed was 2 knots, one half the MANTA's speed. Yet signals from the CUTLASS' wake were almost twice as great as those observed from the MANTA's wake, which is quite the reverse of what is normally expected with a decrease in speed. Since the operating areas in which the runs were made were different in each case, it is possible that water conditions were responsible for these unexpected results.

Submarine Buttoned Up, Submerged to 150 Feet,
and Underway at 4 Knots

One completely submerged run was made by the MANTA at a screw-depth of 150 feet and a speed of 4 knots. The length of the run was 20,000 yards. At the beginning of the track, the wake signals were quite large, being comparable to those from the wake of a 6-knot schnorkelling submarine. For the first and only time during the entire test the wake appeared colder than the surrounding water. Then, approximately 5000 yards from the diving point, the wake became warm and continued that way for the remainder of the track. A decrease in signal magnitude of from three to four times accompained the change in the polarity of the signal. One explanation has been advanced for this behavior. If it is assumed that the run started near the edge of the Gulf Stream, it is possible that the submarine traveled through some of the cold "fingers of water" which sometimes extend into the stream at a considerable depth and thereby brought cold water to the surface. Once the submarine got out of these "fingers," the resulting wake appeared normal.

Sections of the thermal map obtained during this run are shown in Figures 10,11, and 12. These recordings were made by flying along the length of the wake after the submarine had completed its 20,000 yard run. In an effort to stay over the wake, the airship was forced to fly a shallow zig-zag course which resulted in a sampling procedure rather than in a continuous accumulation of data. A typical sample is shown in Figure 10 and is the result of an angular crossing of the wake, between 10,000 and 12,000 yards astern the submarine. The wake in this case was warmer than the surrounding water. Figure 11 shows a sample which is the result of making a very shallow turn over the wake between 12,000 and 14,000 yards astern. Here too, the wake was warmer than the surrounding water. A portion of the cold section of this wake is shown in Figure 12. This portion extends from 17,000 to 19,000 yards astern the submarine and is located near the diving point at the start of the run. This record and those of Figures 10 and 11 were all made on the "hot side" of the circular trace recorder which prints black against white for hot wakes. Hence, the cold wake of Figure 12 shows up as white against black, just the reverse of the previous two. From Figure 12 it appears as though the wake were starting to break up near the 19,000-yard point. Since the submarine's speed was 4 knots, this places the age of the wake at $2\frac{1}{2}$ hours.

An examination of these and other recordings obtained during this run exhibit signals with multiple overshoots indicating that the width of the wake was much greater than the width of the airborne optical system's field of view projected on the water. This was verified later in the Laboratory by constructing a photoelectric wake-signal simulator and feeding voltage signals from it into the signal amplifier in an effort to reproduce the recordings obtained in flight. In order to obtain the desired signal shapes, the "wake slit" in the simulator had to be widened so that it was at least three times wider than the field-of-view slit. This meant that the wake generated at a depth of 150 feet appeared at the surface with a width approximately three times greater than the width of the projected field of view of the airborne optical system. Reference to the NADC report[6] shows that the width of a mature wake originating at a depth of 150 feet may be expected to vary from 400 to 800 feet depending on its surface age. The airborne measurements indicated an average width of about 700 feet which is in agreement with NADC's surface observations.

OPTICAL NOISE

Extraneous signals from a number of sources other than wakes were also observed and recorded. Although the airborne system is designed to operate with maximum efficiency on wakes which are 250 feet or less in width, much of this discrimination is lost when the two optical systems become unbalanced. For example, on one occasion during the Key West trials, a light deposit of coral dust on one of the mirrors was sufficient to unbalance the system so that optical noise from the surface of sea was observed. A return to the airfield was made; the mirror was cleaned; and the flight was resumed. As a result the optical noise was no longer observable.

It is estimated that, with all components in top condition, the two optical systems were matched and balanced within 4 percent. In some cases, even this amount of unbalance proved to be too much. During one flight, the airship flew between two thunderstorms. Lightning flashed and the entire area around and under the airship was illuminated for brief intervals. Each flash resulted in a spurious signal indication which proved to be of an optical origin.[7] Since the magnitude of the interference was independent of the azimuth position

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[6] West, H. L., "Surface Measurements Taken on Thermal Wakes Generated by Submarines." NADC Report No. ADC EL-50-50 (Confidential), November 8, 1949

[7] The optical origin of the interference was demonstrated by closing the shutters over the thermopiles and observing no signal.

of the optical systems, it was concluded that the nonuniform radiation distribution on the surface of the sea was not an influencing factor, but that it was the unbalance between the two optical systems which was responsible for most of the interference.

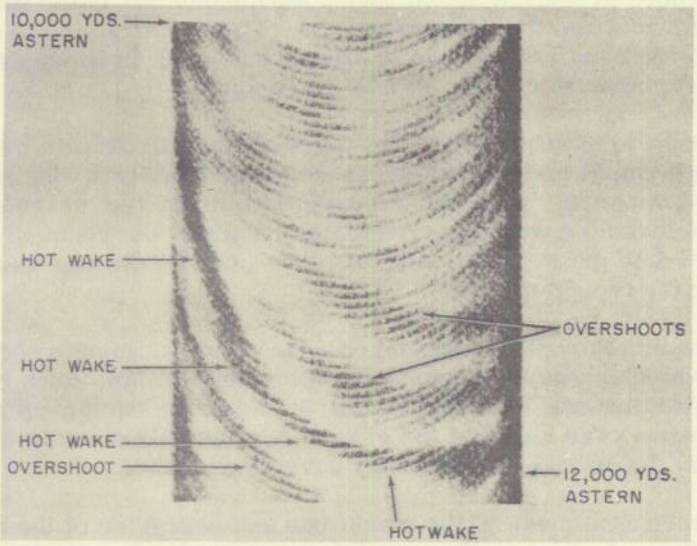

Figure 10 - Section of completely laid wake extending from 10,000 yards to 12,000 yards astern

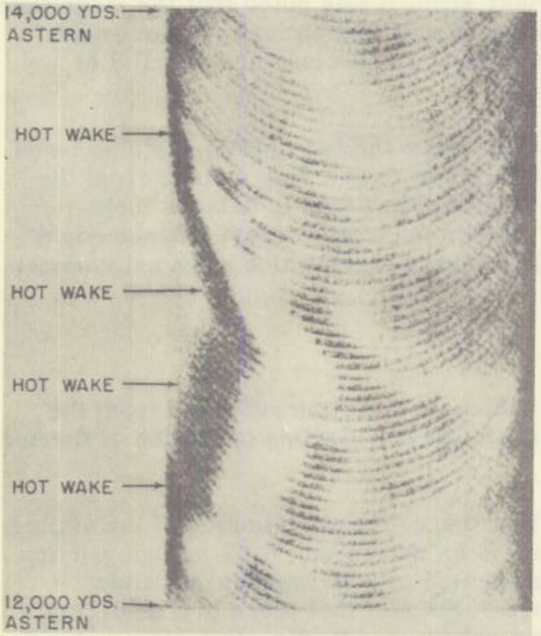

Figure 11 - Section of completely laid wake extending from 12,000 yards to 14.000 yards astern

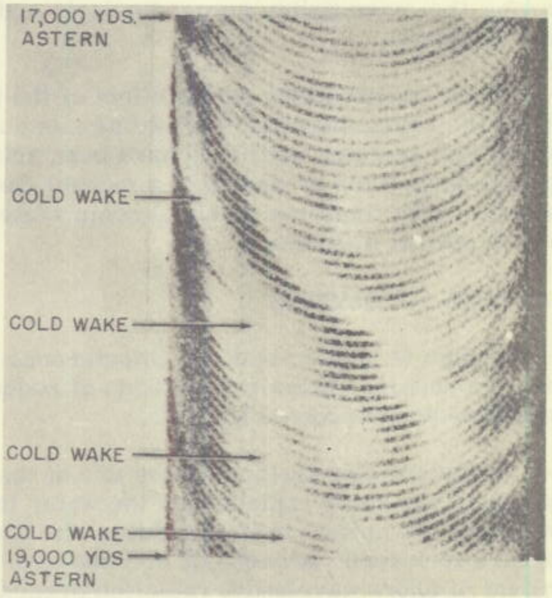

Figure 12 - Section of completely laid wake extending from 17,000 yards to 19,000 yards astern

In many cases, even a perfect balance between the opposing optical systems will not completely eliminate undesirable interference. Usually the interference is reduced but not eliminated. Thus a scan across the moon's path on the water produced a small but observable signal due to the fact that, although it is considerably wider than the optimum width of 250 feet, it does produce a signal whose harmonics fall in the passband of the equipment's amplifier and are therefore observed. The same applies to scans across the sun's path. The interference in this case is almost one hundred times greater than that from the moon's path; otherwise, the problem is the same.

No attempt was made to scan across the edges of the Gulf Stream because of the difficulty in locating them at night in the presence of the equally strong freighter wakes which criss-crossed the area. Time did not permit an extensive search. Had the airborne system not included the width discriminatory feature, the edges of the Gulf Stream would have appeared with greater intensity than they actually did and would have been easily recognizable among the freighter wakes.

The balance between the optical systems seemed to discriminate somewhat against light wispy clouds which appeared occasionally below the airship. Such clouds produced noise which was approximately 20 times the self-noise of the equipment and exhibited no orderly characteristics. The fact that the clouds were usually close to the airship and were out of focus for the optical systems may have helped also.

Observations were also made of the magnitude and character of the noise produced by sun glints on the water. As long as the wavelets were randomly orientated physically, the resulting noise had a random character. But when the wavelets lined up in the breeze to form discrete wavetrains, the resulting noise became more orderly. Under such conditions the magnitude of the noise was dependent on the azimuth orientation of the optical system. For example, in the course of each complete circular scan, it was noted that the magnitude of the noise fluctuated by a factor of two, being greatest when the optical system swept across the wave trains perpendicularly and least when it swept along and parallel to the wavetrains.

These observations on the effect of the balance between the two optical systems leads one to the conclusion that it would be more advantageous to isolate the outputs from the two optical systems until they have been suitably amplified and then to balance them against each other by means of a manual control. In this manner an exact balance could be obtained in flight and would accommodate any inherent changes which were not common to both optical systems.

DAYTIME OPERATION

Enough is known about the interference from the sun's radiation reflected from the water to consider practical methods of reducing it, so that the daytime operation of thermal wake detectors becomes feasible.

One promising method makes use of the fact that the spatial distribution of the visible portion of the sun's radiation on the water is the same as that of the 8-13 micron portion. Hence, as the optical system rotates, the time distribution of both wavelength bands appears identical. Because of this and also because of the fact that there is a negligible amount of short wavelength radiation present in the wake's output, discrimination against both the sun's and moon's radiation, which is reflected from the water, is possible. The procedure is to add to the present optical system, a receiver, such as a photocell, which is selective to short wavelength radiation, and to buck its output against the output from the thermopile. Thoretically, if a proper balance is achieved, the effects from all of the

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reflected radiation can be eliminated without detriment to the wake's radiation. Of course, the photocell receiver must "see" exactly the same portion of the sea as the thermopile and at precisely the same time. Also, the amplification between each receiver and its portion of the balance network must be achieved with like frequency and phase characteristics. In addition, the difference in time constants between the photocell and thermopile must be compensated for.

There are a number of practical ways of satisfying all of these conditions. Since none of these methods has yet been tried, a considerable amount of experimental work is necessary before the feasibility of daylight operation at the present time can be determined.

SIGNAL-TO-NOISE RATIO CONSIDERATIONS

The trials at Key West and the earlier ones east of Atlantic City have both shown that a unity signal-to-noise ratio corresponding to 6.0×10^{-8} watts cm^{-2} steradians^{-1} is insufficient for any but marginal operation in these areas. If the performance of this gear is considered in terms of fleet operation by fleet personnel, it is wholly inadequate.

It is not difficult to show that the signal-to-noise ratio for any type of thermal wake detection gear, which is flown at a fixed altitude, is given by:

$$S/N \backsim DT\sqrt{\alpha,\beta} \quad (f = \text{constant})$$

where

D = diameter of limiting aperture in optical system (in this case, it is the diameter of the parabolic collecting mirror);

T = on-target time or length of time that each thermopile "sees" wake (it is made equal to the build-up and decay time constant of thermopile);

α,β = vertical and horizontal angular dimensions of the optical field of view which are assumed to be equal to or less than the corresponding angles subtended by the wake at the optical system; and

f = f/number or ratio of focal length to diameter of the optical system (it must be a practical minimum for maximum signal-to-noise ratio).

This is a fundamental equation. It applies to all types of wake detectors which employ thermal radiation sensitive receivers such as thermister bolometers, low-resistance bolometers, and thermopiles. Additional terms must be included in this expression if trick circuitry or long persistent indicators, which provide post integration, are employed.

The gain realizable from an increase in the size of the collecting mirror is limited by the practical weight capacity of the airship in which it is flown. At the present time, a 100-inch diameter aperture appears to be the maximum for use in an M-ship. This means that the quantity, D, and hence the signal-to-noise ratio can be increased only 4 times more by this method.

The 30 rpm scanning speed of the present equipment provides for an on-target time, T, of approximately 0.1 second when employed against a wake which is 250 feet wide. It

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is highly desirable to make this time much longer. However, the difficulties associated with the electronic amplificatiion of the low-frequencies harmonics in the resulting signal pulses, makes such an increase impractical at the present time.

Further improvement in the signal-to-noise ratio must therefore come about by maximizing the angular dimensions, α and β, of the optical field of view. In other words, the optical system should "see" as much of the wake as possible during a single crossing. To go beyond this point and make the projected field of view greater than the wake is fruitless. Further enlargement would not increase the wake signal but would increase the inherent electrical noise of the system and would also increase the optical noise from the water if the sensitivity of the system were great enough.

The present system with its 250 x 300 foot rectangular field of view is designed for the wake from a submarine at a keel depth of 60 feet. The equipment performs moderately well on wakes generated at a depth of 150 feet but could do much better if the field of view were properly matched with the wake. Under such conditions, the angular dimensions, α and β, of the field of view would have to be 3 times greater than they are now. This increase would mean a corresponding increase of 3 times in the over-all signal-to-noise ratio of the system. The same reasoning applies to the wider wakes generated at greater depths.

It is therefore important that the width of the wake as a function of submarine depth be accurately determined. The NADC data, which were obtained by measuring temperature differences directly with a thermister immersed in the water, is good for wakes generated at depth of less than 150 feet. The temperature differences associated with wakes generated at greater depth are, in most cases, too small to be observed with this type of equipment. Wake width determinations must therefore be made from the air with the more sensitive thermal-radiation gear.

There are sufficient data to show that once a wake has reached the surface, the total radiation from a cross sectional slice of fixed breadth and of variable width equal to the width of the slowly expanding wake is almost constant. Thus, as the width of the wake increases and its body temperature approaches that of the surrounding water, they do so at practically the same rate which results in almost constant radiated output from a cross sectional slice.

There are also strong indications, that in some cases, the same thing happens as the wake rises to the surface. During the ascension, the temperature difference between the wake waters and surrounding medium decreases at almost the same rate at which the width of the wake increases. Upon reaching the surface, the total radiated output from a cross sectional slice appears to be independent of the depth of generation. It has not been possible to demonstrate this effect with the airborne gear because its field of view has not been wide enough to view entire cross sectional slices of wakes generated at depths greater than 60 feet. However, calculations based on the NADC data support this theory.

Thus it is very important that the width of the wakes generated at various depths and of various ages be accurately known so that the airborne thermal-radiation gear can be designed intelligently.

SUMMARY AND CONCLUSIONS

Successful airborne measurements of the thermal radiation from the wakes of submarines operating at depths down to 150 feet were first made over deep water 150 miles east of Atlantic City, N. J. These measurements were followed by equally successful

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measurements over the Gulf Stream south of Key West, Florida. During both trials, it was possible to track the wakes over the entire length of the submarines' runs; 14,000 yards in the first instance, 20,000 yards in the second. In turbulent waters, such as the Gulf Stream, under sea conditions of 1 or 2, wakes attained an age of approximately $2\frac{1}{2}$ hours before being broken up or diluted. Longer lifetimes are to be expected in quieter waters.

The results of these measurements are promising, but the work has not been carried to conclusion because of the lack of target submarines with which to operate, despite the splendid assistance offered by the lighter-than-air and submarine groups of OpDevFor. At the present time, there exists an insufficient amount of empirical data for the intelligent design and development of airborne wake-detection equipment for fleet use. In the hands of laboratory personnel present equipment, is, at best, only marginal in performance because of an inherently poor signal-to-noise ratio. Fortunately, the limitations are man-made and can be overcome eventually.

The nighttime operation of properly designed equipment is now limited by self-noise or electrical noise in the receiving channels and is not limited by outside interference of natural origin such as optical noise from the surface of the sea. Thus the signal-to-noise ratio of the system can most easily be increased by:

a. Increasing the diameter of the collecting mirrors.
b. Lengthening the on-target time.
c. Enlarging the angular dimensions of the optical field of view to make them commensurate with the dimensions of the wake.

Some gains can be realized from the first two approaches but these are limited by the operational difficulties associated with heavy, bulky equipment and slow rates of search. Most promising is the third approach, provided that the necessary information concerning the width of wakes as a function of age and submarine depth is determined.

The daylight operation of airborne wake detection gear, something not yet successfully accomplished, looks hopeful. However, considerable basic laboratory and field work is required before the feasibility of operating in broad daylight can be determined.

To carry on these investigations the Naval Research Laboratory has almost completed an improved airborne measuring device. Employing a 100-inch diameter optical system and 4 x 4 inch thermopiles, it will have an equivalent noise input of approximately 10^{-8} watts cm^{-2} steradians^{-1} which is equvalent to a temperature difference of 0.0002°C at the surface of the sea. It is planned to complete installation of this equipment in the M-4 airship by 1 July 1952 and to commence the measurements at that time.

ACKNOWLEDGMENTS

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