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PERISCOPE DETECTION WITH A HIGH-RESOLUTION RADAR

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ABSTRACT

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A ten-nanosecond-pulse, rapid-scan, X-band radar was designed, built, and installed aboard the USS MALOY (EDE 791). The capability of this radar for submarine periscope detection was investigated. It was found that the high range resolution and rapid-scan features permitted resolution of individual waves and showed their growth, movement, and decay. Periscope detection and tracking capability were found to be superior to that of conventional search radars because of the ability to distinguish periscope radar return from that of the sea background. However, antenna configuration and low average power in the experimental radar limited tracking range to about 6000 yd.

PROBLEM STATUS

This is a final report on one phase of the problem; work continues on other phases.

AUTHORIZATION

NRL Problem R02-34
Projects RF 001-02-41-4008
and SF 001-06-01-1500

Manuscript submitted August 10, 1961.

PERISCOPE DETECTION WITH A HIGH-RESOLUTION RADAR
[Unclassified Title]

INTRODUCTION

Usually, the radar cross section of a submarine periscope is of the order of one square meter. It is difficult to detect such a small target with a conventional low-resolution radar because the target is usually obscured by a strong background of sea clutter. Experiments conducted by NRL (1-4) using a ten-nanosecond-pulse radar at a land site overlooking the ocean indicated that periscope detection with a high-resolution radar might be feasible. First, the area of the ocean illuminated is reduced so that the target-to-clutter ratio will be increased. Second, the high resolution breaks up the sea clutter, as presented on the display, into wave-like patterns which should easily be distinguishable from the point-target return of the submarine periscope. These considerations led to the decision to build and install an experimental radar system on shipboard for tests against periscopes at sea where operating conditions would be realistic. The installation and tests were conducted aboard the USS MALOY (EDE 791) during 1958.

DESCRIPTION OF THE EQUIPMENT AND INSTALLATION

The major radar specifications are shown in the following list,

RADAR SPECIFICATIONS

| | |
|-----------------------|--|
| Frequency | 9375 Mc |
| Pulse length | 10 μ sec (10^{-8} sec) |
| Recurrence rate | 4550 pps |
| Transmitter power | 160 kw peak (7 watts avg) |
| Antenna beamwidths | 3.0 degrees horizontal 5.4 degrees vertical |
| Antenna scan rate | 20 rps (1200 rpm) |
| Receiver noise figure | 10 db |
| Receiver bandwidth | 200 Mc |
| Presentation | Delayed-B type |
| Vertical sweeps | 1000, 3000, and 10,000 yd |
| Horizontal sweep | 345 degrees of antenna scan |

The choice of X-band as the operating frequency represents a compromise. At a lower frequency it would be difficult to obtain a narrow-beam antenna from a structure of reasonable size. At a higher frequency the obtainable rf power would have to be sacrificed. There was also the practical consideration that many of the components and much of the design work were available at X-band.

A ten-nanosecond pulse was used in the system. This gives a range resolution of about five feet, which is several times shorter than the distance between ocean-wave

crests and consequently permits their resolution. Because it is difficult to generate a pulse of this short duration by direct modulation of a magnetron, indirect methods had to be used (Fig. 1). An RCA A1092C developmental magnetron was modulated using a thyatron to produce a 0.1- μ sec pulse. This pulse was fed through a ferrite circulator to a special gas cell inserted through the X-band waveguide. Since the gas in the cell was initially un-ionized, the pulse passed through the cell unimpeded until ionization occurred, which was approximately ten nanoseconds after the leading edge of the pulse. Ionization caused the last 90 nanoseconds of the pulse to be reflected back to the circulator, where it was absorbed in the load R. After passing through a second ferrite circulator, used to separate transmitted and received pulses, the ten-nanosecond unattenuated part of the original 0.1- μ sec pulse was fed to the antenna and radiated.

Admittedly, this is an inefficient method of pulse generation, but efficiency was not the prime consideration. This method gave the highest peak power of any available at that time. At the present time, pulse compression could be used to increase both the efficiency and power.

The radar system was physically divided into two main parts (Figs. 1,2). This was necessary because the radar antenna had to be mounted near the top of the ship's mast, about 75 ft above the water line. In order to avoid prohibitive loss in transmitted power and degradation of the receiver noise figure, the radar transmitter and the first two amplifier stages of the receiver were also mounted with the antenna on the ship's mast (Fig. 3). Radar and control signals were fed between the transmitter and the part of the receiver mounted on the mast (Fig. 4) and the main unit located below deck (Figs. 5,6).

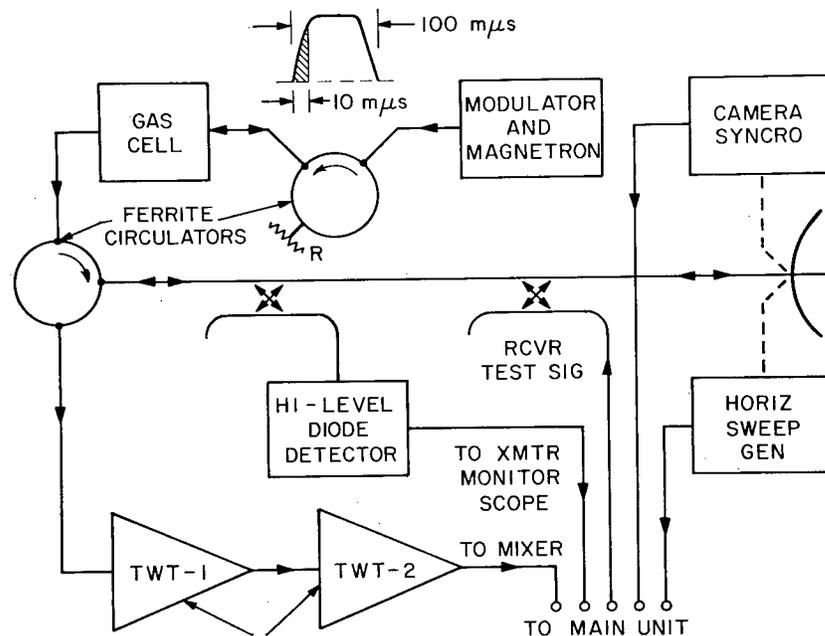


Fig. 1 - Block diagram of mast installation, with method of transmitter pulse generation illustrated

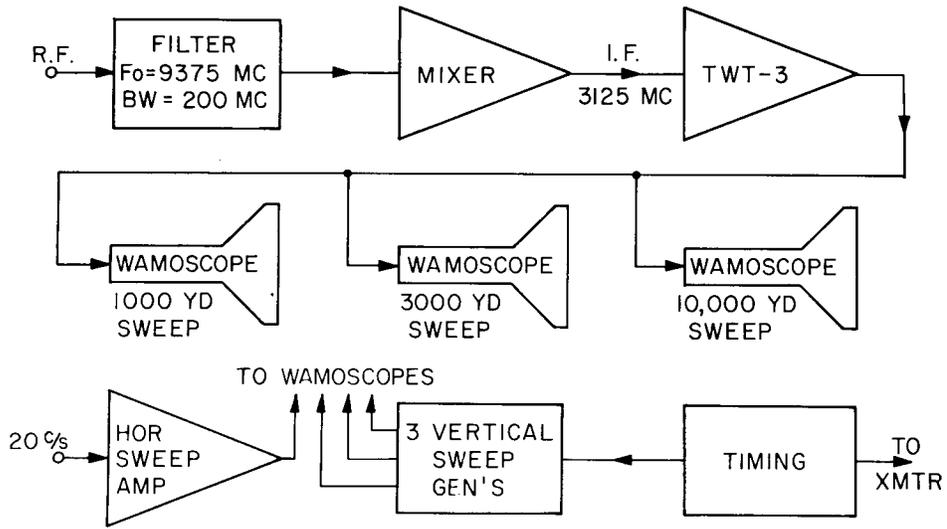


Fig. 2 - Block diagram of the below-deck installation

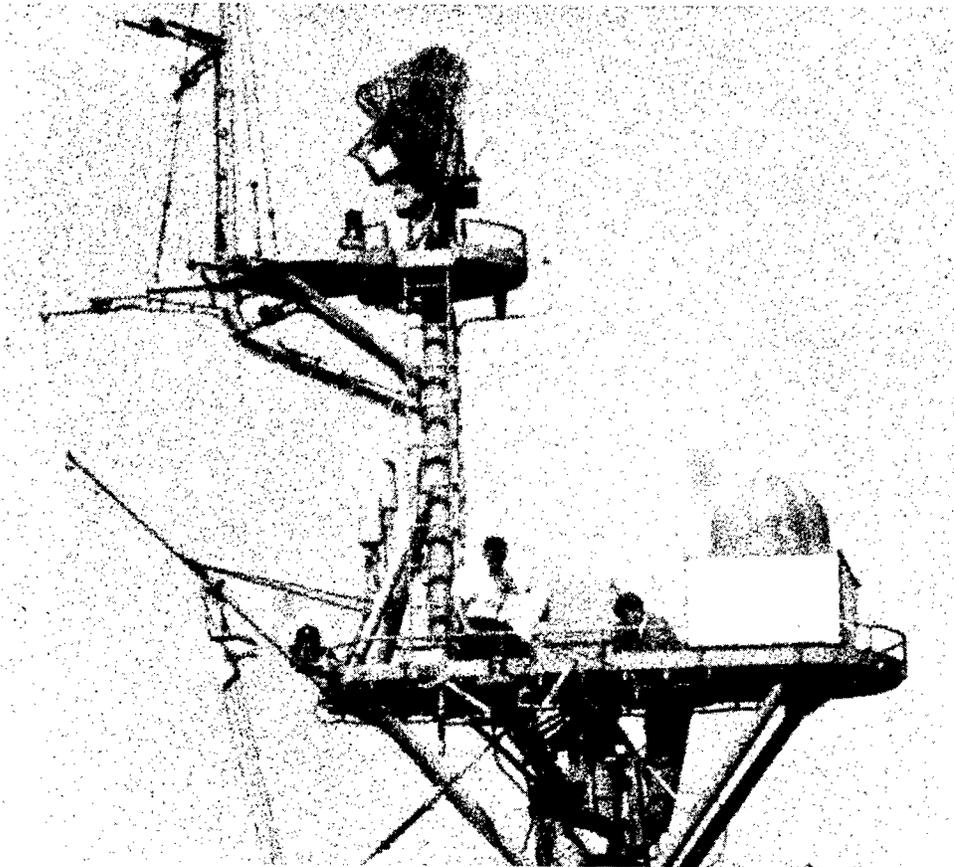


Fig. 3 - Mast installation

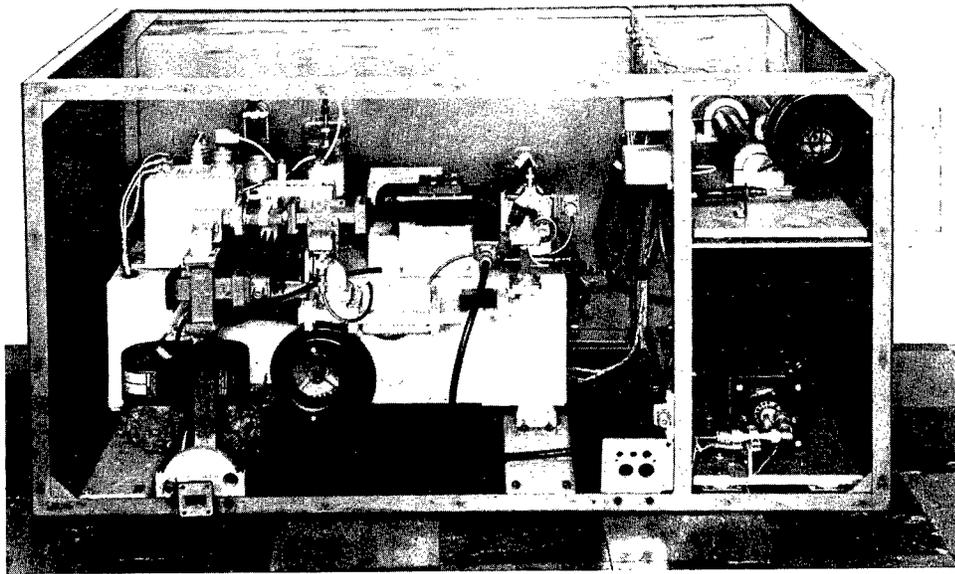


Fig. 4 - Photograph of transmitter and the part of the receiver mounted on the mast (top and side were removed)

The radar antenna was a 20-in.-high by 30-in.-wide paraboloid spun at 20 revolutions per second and mounted in a radome to reduce air resistance (Fig. 7). This extremely high scan rate gave a steady, essentially flickerless display which, as will be described later, proved to be a great advantage in detecting the periscope in a background of sea clutter.

In order to accommodate the wide rf bandwidth required by a ten-nanosecond pulse, traveling-wave amplifiers were used throughout the receiver. Wamoscope display tubes (5) were used because of their great bandwidth and extreme sensitivity. However, since these were S-band devices, frequency conversion from X-band to S-band was required. The conversion was accomplished in a crystal mixer.

The Wamoscope performs the functions of amplification, detection, and display in one envelope. Velocity modulations are produced on the electron beam passing through the helix by S-band signals applied to the traveling-wave-tube amplifier section. A retarding electric field at the output end of the helix allows only the faster electrons to pass through an aperture in the gate electrode, after which they are accelerated and focused on to a fluorescent screen (Fig. 8). The amount of screen current is roughly proportional to the input rf power. By applying suitable sweeps, an intensity-modulated display is produced on the Wamoscope screen (Fig. 9).

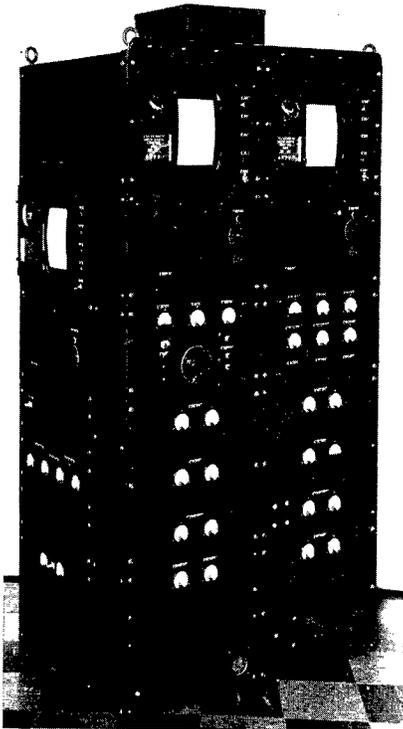


Fig. 5 - Below-deck unit

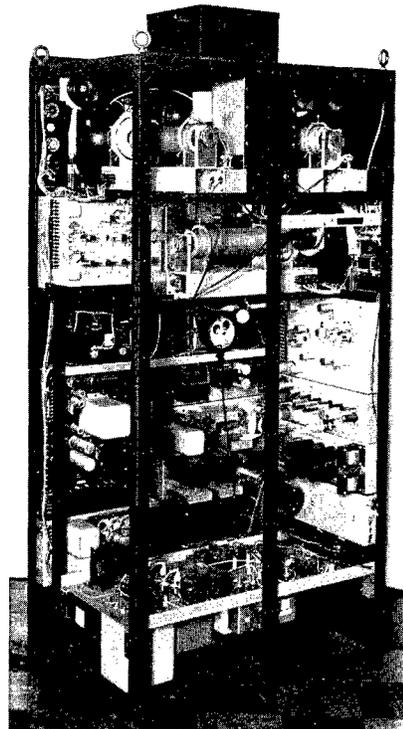


Fig. 6 - Below-deck unit with back and side panels removed

Because it makes efficient use of the screen area, a delayed B-scan presentation was employed. The relationship between actual geometry and display for this scan is illustrated in Fig. 10. As can be seen, the wide angular sector encompassed can make the visual display appear quite different from the geometry. However, once this type of display is understood and becomes familiar, it will be found to be well adapted for periscope detection.

Three separate Wamoscope display tubes were employed, with vertical sweep lengths of 1000, 3000, and 10,000 yd respectively. The purpose of the multiple display was to determine optimum sweep length for periscope detection. Each display station was fitted with facilities for taking motion pictures. The radar was provided with the usual devices for testing and calibrating system operation.

TEST RESULTS AND DISCUSSION

Tests using the ten-nanosecond radar, made over a period of six months, involved seven separate trips to sea. Operation in conjunction with submarines was often shared

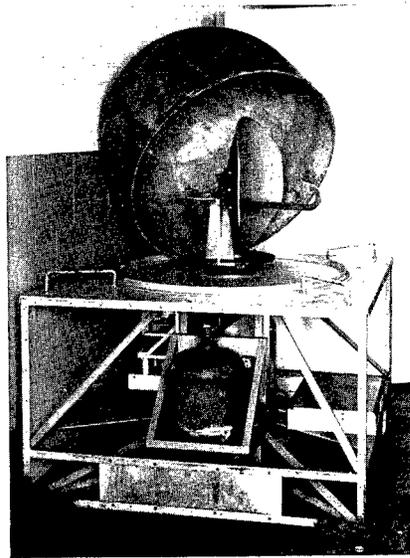


Fig. 7 - High-speed antenna and drive with radome removed

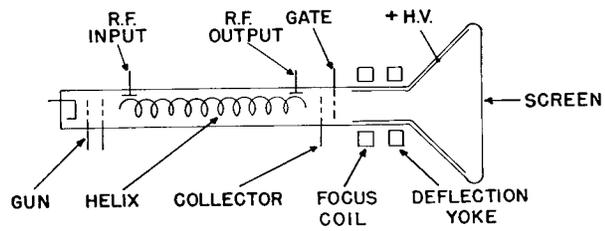


Fig. 8 - Schematic diagram of the Wamoscope

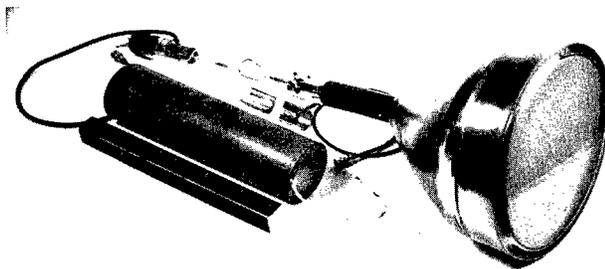


Fig. 9 - Photograph of the Wamoscope with one of the rf couplers and the focusing solenoid removed

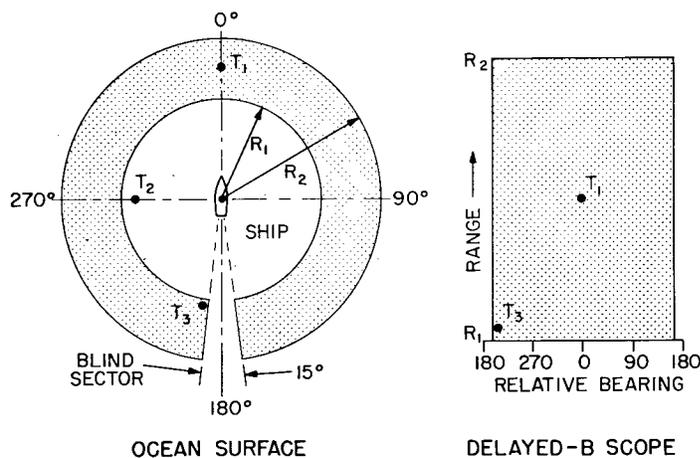


Fig. 10 - Relationship between actual geometry and display as it appears on the Wamoscope screen

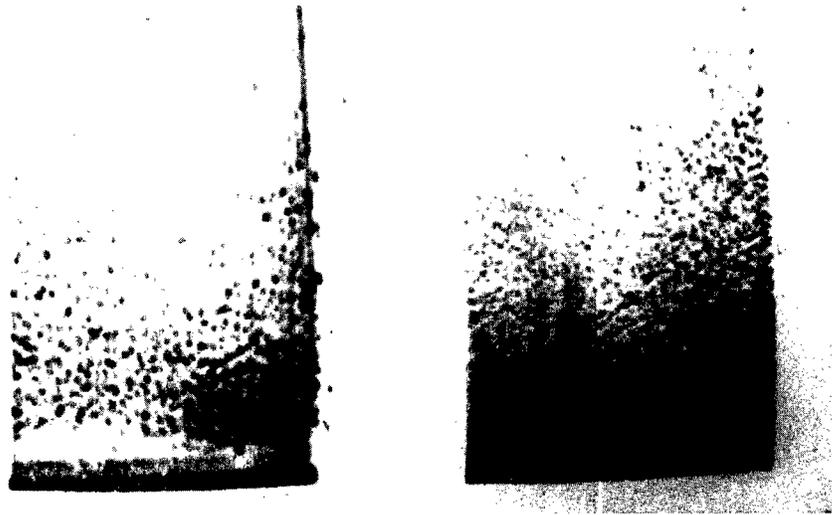
with sonar experiments and simulated torpedo attacks, so the time at sea available for controlled radar tests was rather limited. All controlled tests were of one type. The submarine was operated on a straight course at periscope depth, and at a specified speed. The destroyer escort on which the radar was installed then ran a zig-zag pattern so as to close and open ranges alternately with the submarine. Minimum range was usually about 1000 yd, and the maximum was beyond periscope-detection range. Courses were varied in order to observe the effect of wind and wave direction. Sea states encountered during the tests ranged from very calm to very rough, with wave heights of ten or twelve feet. During periods when the submarine was unavailable, data on sea return and clutter were obtained. Although not a part of the tests, it was found that the high-resolution radar system was an excellent aid for navigation in close quarters.

Motion pictures were taken of the indicator presentations. Only every third of the 20 complete pictures formed every second on an indicator was taken; the time during the two unphotographed presentations was used to advance the film in the camera. Since the normal film projection rate is 16 frames per second, the motion-picture presentation is speeded up by a factor of 2.4 in time. This does not change the character of the presentation, however.

The advantage of a high-resolution system over ordinary radar systems for periscope detection is most easily appreciated by viewing the films taken of the indicator presentations. Unfortunately, this is not possible for the reader to do. He should bear in mind that the still photographs of the presentation included herein do not really do the high-resolution system full justice, and he will be obliged to depend mostly on the verbal description which follows to provide him with a visualization of the sequence of events shown on indicators.

Sea clutter as seen by the short-pulse, fast-scan radar differs from the sea clutter as seen on a conventional search radar in two major respects:

1. The equivalent length of a ten-nanosecond pulse on the surface of the ocean is about five feet. As a result, individual waves can be resolved on the presentation.



(a) Three- to four-foot waves

(b) Ten- to twelve-foot waves
with rain

Fig. 11 - Sea return as displayed on the Wamoscope screen

Figures 11(a) and 11(b) show sea returns for three- to four-foot wave heights and ten- to twelve-foot wave heights respectively. These pictures are enlargements of motion-picture positives taken of the Wamoscope screen. Much detail is lost in the reproduction process.

2. The fast-scan antenna presents a continuously changing radar picture of the sea surface, so that the growth, movement, and decay of individual waves can easily be seen. A long-pulse, slow-scan system presents a very slow succession of clutter pictures with no readily apparent correlation between scans. The result of being able to see continuously changing, highly resolved clutter patterns makes periscope detection considerably easier, particularly in conditions of heavy clutter.

Differences in wave height, wind velocity, and direction of viewing relative to the wave structure produce pronounced differences in the clutter pattern as displayed on the indicator. For low sea states with wave heights less than a foot and with no whitecaps, the clutter appeared on the indicator as fast-changing random groups of spots with no wave structure apparent, much like the glint of sunlight reflected from the surface of water having small ripples. With the particular power, antenna gain, etc., of the experimental system, the maximum at which such clutter could be seen was about 1500 yd and was independent of azimuth direction.

At higher sea states, the clutter return increased in amplitude and could be seen out to ranges of 6000 yd for wave heights of ten or twelve feet. Maximum clutter range was azimuth dependent. Looking upwind, in the direction from which the waves came, the clutter was seen to be greater in amplitude and extending to a greater range than it did in the opposite, or downwind, direction. Clutter often extended twice as far in the upwind direction as in the downwind direction. The higher the sea state the more pronounced became the wave structure, as shown on the indicator, and the longer was the duration of the return from individual waves. These wave returns might last a large fraction of a minute for wave heights in excess of several feet.

Wave-structure detail, as presented on the indicators, was range dependent. The five-foot range resolution was independent of range. Since angular resolution was fixed, azimuth resolution was proportional to range, and for this system was about ten yards at one-third of a mile. Consequently, the resolving power was sufficient to present the individual waves well at only the shorter ranges; at longer ranges the presentation of the wave return was smeared and showed the wave structure less clearly. A wider antenna would have improved this situation, but the fast-scan requirement would complicate its use. If a higher frequency were used, better angular resolution could be obtained with a small antenna.

The periscope-detection capability of the radar was, of course, greatly affected by sea state. In a fairly calm sea the periscope return was very much greater than that of the surrounding sea clutter (Fig. 12). The periscope echo was continuous, and detection and tracking were very easy. At higher sea states, sea return increased, the signal-to-clutter ratio was lower, detection and tracking were more difficult, and there were short periods when the periscope echo would vanish, probably due to physical shielding by high waves.

No pictures are shown of periscope radar return in heavy seas because of the loss in detail in the blow-up of single motion-picture frames. As has been stated, a proper appreciation of the high-resolution radar's capabilities for periscope detection is best obtained by viewing a complete motion-picture sequence.

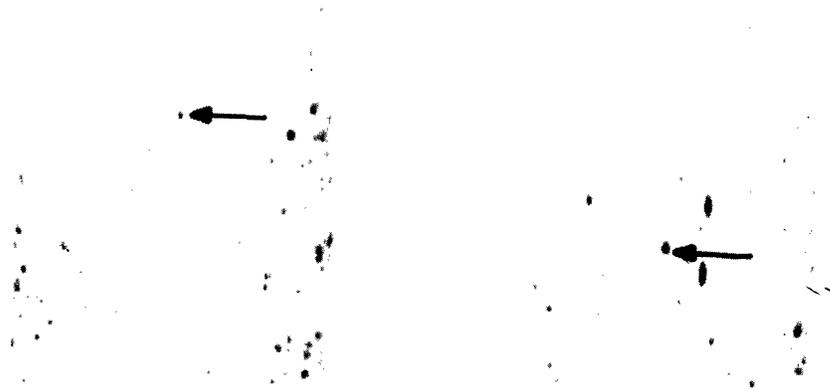
In Fig. 13 an echo is shown from a submarine only partially submerged. Here it presents a target sufficiently large to be easily distinguishable from the high sea background, even on a still picture.

Since clutter varied with bearing, periscope detection and tracking in heavy seas were easiest in the downwind direction, where the clutter was least, and more difficult in the upwind direction, where the clutter was the heaviest. However, once detected the periscope was not difficult to track in the upwind direction.

A good sensitivity-time control would be highly desirable in order to optimize the presentation in clutter regions, but this might be difficult to incorporate, since the clutter is bearing dependent in most cases. Any sensitivity-time control would have to compensate itself for varying conditions of clutter with angle.

Although the submarine was operated at various speeds between two and six knots, controlled tests were too few and sea conditions encountered were too many to come to definite conclusions as to the effect of submarine speed on signal-to-clutter ratio. There was some indication that increased submarine speed results in greater signal return, and this seems likely, since a faster-moving submarine would create a larger water plume, or wake, behind its periscope.

On the controlled runs maximum periscope-detection range on closing and maximum tracking range on opening were observed. In all cases both were beyond the clutter range. On closing the average range of first detection was 5700 yd, and on opening the periscope tracking range averaged 6000 yd. These averages were computed for several sea states, although the variation in sea state was not very great. Admittedly these ranges are rather short, but they are in fair agreement with calculated ranges based on system parameters. They do emphasize the need for higher peak power and possibly the use of a greater pulse-recurrence rate to obtain greater range in the system.



(a) Initial contact

(b) 29 seconds later

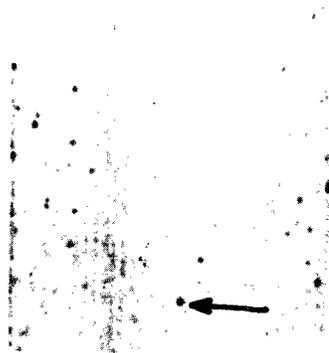
(b) 45 seconds after
initial contact

Fig. 12 - Successive positions of periscope (arrow points to periscope return). A 1000-yd sweep delayed 3000 yd is used.

Fig. 13 - Submarine return in rough seas



A major problem connected with the use of a very short pulse and a narrow beam-width is that the area of ocean viewable on an indicator of a given screen resolving power is small. It was found that a 3000-yd range interval was about optimum for a ten-nanosecond pulse. A shorter sweep length does not present any more detail in the radar picture, and a longer one causes information to be lost due to insufficient resolution of the indicator screen.

A defect in the experimental system was lack of antenna stabilization. Rolling of the ship in heavy seas caused the antenna beam to swing periodically well above the surface of the water in a given direction. During these periods radar return was either entirely lost or greatly reduced. A practical system would therefore have to incorporate antenna stabilization.

SUMMARY

A short-pulse, fast-scan system makes it possible to see radar return from individual waves resolved on the indicator screen, and to see them grow, move, and decay.

Clutter return increases with sea state and is greater when viewing upwind than downwind, especially for high sea states.

Since the minimum resolvable area increases directly with range, the wave patterns are less clear at the longer ranges.

Periscope-signal-to-clutter ratio for a low sea state is very high, and detection and tracking of periscopes is relatively easy. Detection and tracking difficulty increase with sea state.

For waves higher than five or six feet, detection and tracking are easier downwind, where the clutter is less. Detection upwind is generally more difficult, but tracking difficulty does not increase to the same degree.

The operating range of the experimental radar was limited by lack of sufficient transmitted power and not by fundamental considerations. Considerable improvement in range appears possible and feasible.

Even with its present low power, the short-pulse, rapid-scan radar is much superior to conventional long-pulse, slow-scan search radars for periscope detection in heavy clutter.

ACKNOWLEDGMENTS

The work described in this report is largely that of Clark C. Watterson, formerly an employee of NRL. He was aided in the construction and testing of the radar system by P. M. Thiebaud, F. A. Kittredge, Jr., and D. L. Drake, as well as others in the High Resolution Branch at NRL. The aid and cooperation of LCDR P. Roth and his crew on the USS MALOY during the sea tests is gratefully acknowledged.

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