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NRL REPORT 3666

FR-3666

**A SUBMARINE DIRECTION FINDER
FOR RADAR INTERCEPT
THE AN/BPA-1(XN-1)**

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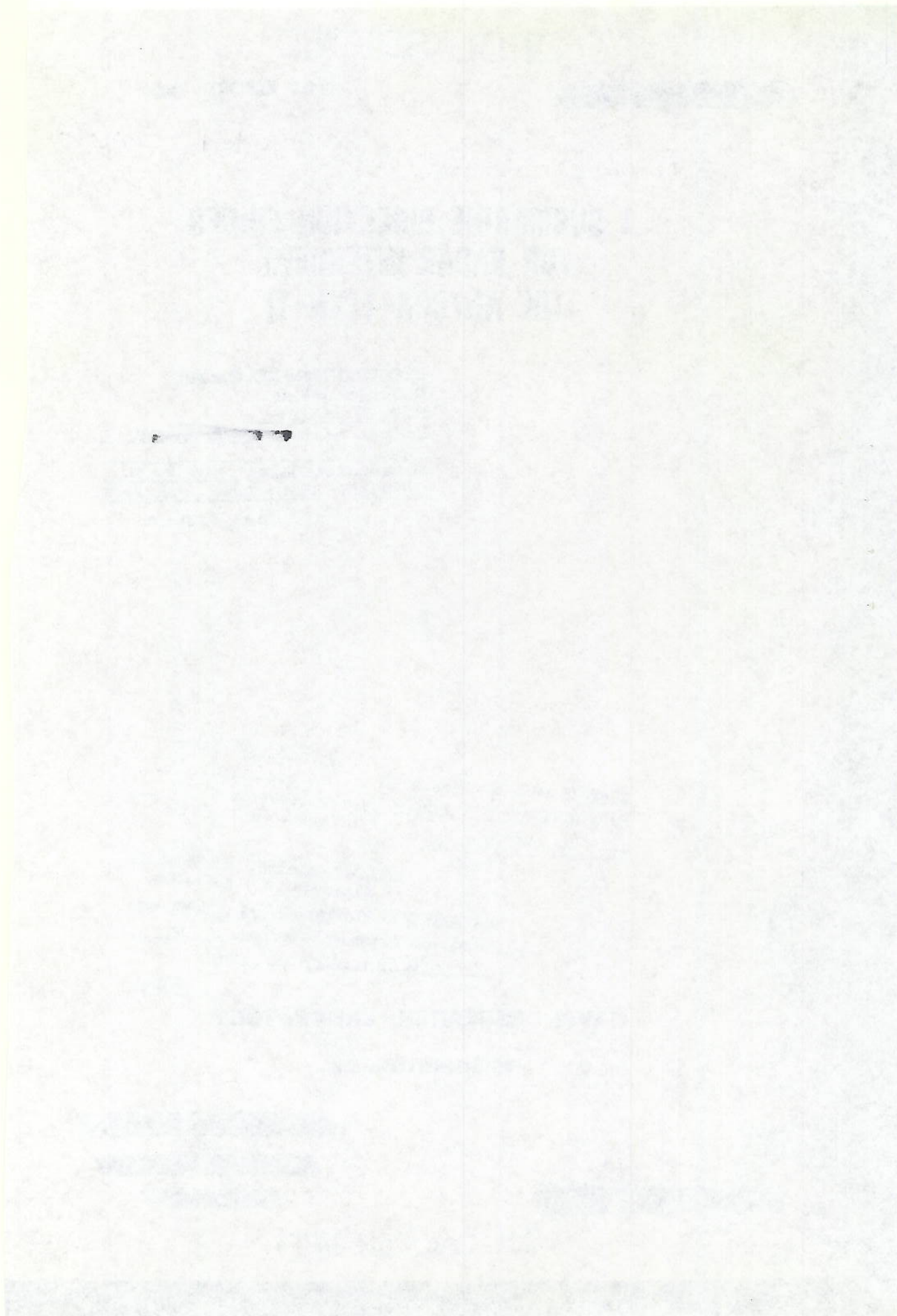
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A SUBMARINE DIRECTION FINDER FOR RADAR INTERCEPT THE AN/BPA-1(XN-1)

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May 16, 1950

Approved by:

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ABSTRACT

An experimental direction finder, AN/BPA-1(XN-1), has been developed for installation on submarines to serve primarily as a warning device against radar-equipped ships and planes. The direction finder employs a rotating, horn-type antenna system and covers the frequency range of 2300 to 10,600 Mc. The d-f antennas and drive unit are contained in a pressure-tight aluminum-alloy housing capped by a dielectric radome. Both radome and antenna housing are designed to withstand a submerged depth of 1000 feet. The antennas rotate at speeds up to 720 rpm and are capable of receiving either vertically or horizontally polarized signals. Bearings are presented automatically on a cathode-ray-tube indicator. Range tests of the direction finder against several shipborne radars indicate that it has an intercept range advantage of from 2-1/2 to 3 times the radar range against a surfaced submarine.

PROBLEM STATUS

This is a final report on this problem. Unless otherwise notified by the bureau, the Laboratory will consider the problem closed one month from the mailing date of this report.

AUTHORIZATION

NRL Problem R09-07D (BuShips Problem S-1354)
NE 070-123

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A SUBMARINE DIRECTION FINDER FOR RADAR INTERCEPT
THE AN/BPA-1(XN-1)

INTRODUCTION

Since about 1944 there has been an urgent need for a microwave direction finder, with automatic bearing indication, designed for installation on submarines. The primary purpose of such a direction finder is to detect and take bearings on radar-equipped ships and planes at distances well beyond the radar range. This requires that the d-f system have enough sensitivity and a high enough probability of intercept so that the submarine can detect the enemy radars at several times the radar range. In order to fulfill the requirements the d-f antenna must be mounted in a high unobstructed position on the submarine and must be capable of withstanding the same hydrostatic pressures as the submarine itself. The latter is a severe requirement because it presents a considerable number of mechanical design problems in addition to the electronic design problems.

The AN/BPA-1 direction finder, described in this report, not only provides bearing information on intercepted radars but also gives their frequencies and a rough estimate of their pulse-repetition and antenna-scanning rates. From this amount of information a large percentage of the intercepted radars can be identified. Thus, the AN/BPA-1 serves as a search and warning device as well as a direction finder.

In December 1949 the experimental AN/BPA-1 was installed aboard the USS IREX (SS 482) at the Portsmouth Naval Shipyard, Portsmouth, New Hampshire, and is now undergoing evaluation by the Operational Development Force of the United States Navy.

During the course of this AN/BPA-1 development several interim reports have been issued covering various phases of the project, including some test results. These reports are listed as References (2), (3), (4), and (5) on page 41

GENERAL DESCRIPTION AND PRINCIPLES OF OPERATION

The AN/BPA-1 is a rotating antenna type of direction finder which covers the frequency range of 2300 to 10,600 Mc. This d-f system consists of three principal parts: the collector unit, a microwave receiver, and a d-f indicator with automatic bearing presentation.

Figure 1 shows a photograph of the complete d-f system. The antenna-spinner housing is located at the right-hand side of the figure; the d-f indicator is on the top right-hand side of the small table which also holds several units of the AN/APR-9 receiver. The use of this receiver was dictated by the fact that it was the only type available for the frequency range of 2300 to 10,600 Mc. This frequency range is covered by two separate horn-type

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Figure 1 - Complete AN/BPA-1(XN-1) system

antennas; the low-band antenna covers from 2300 to 5000 Mc and the high-band horn from 5000 to 10,600 Mc.

A possible mounting location for the AN/BPA-1 collector unit is shown in Figure 2. Here the antenna is located high up on the forward side of the periscope fairwater. This is the type of installation which was made on the USS IREX. A much more desirable location for the d-f antenna would be on the top of an extensible mast such as the SV radar mast. This type of installation would permit the submarine to use its microwave direction finder while "snorkeling." Obviously the second installation offers many advantages and a considerably higher degree of protection to the submarine. These two types of installation will be discussed in more detail later.

The operation of the direction finder can best be explained by means of the block diagram in Figure 3. The radio-frequency signal is picked up by the rotating antenna and fed into the receiver through a mercury-contact rotating joint—a coaxial type of joint wherein the electrical contact between the rotating and stationary parts is made through a film of mercury, thereby eliminating any direct sliding contact. The signal is amplified and detected in the microwave receiver and the video output is fed into the pulse amplifier of the d-f indicator. Here the pulses are stretched and applied to the rotor of a 5G synchro located in the antenna housing and mechanically coupled so as to rotate at the same speed as the antenna. The stator windings of this synchro are connected by means of a cable to a similar 3-winding deflection coil placed around the neck of a cathode-ray tube. By means

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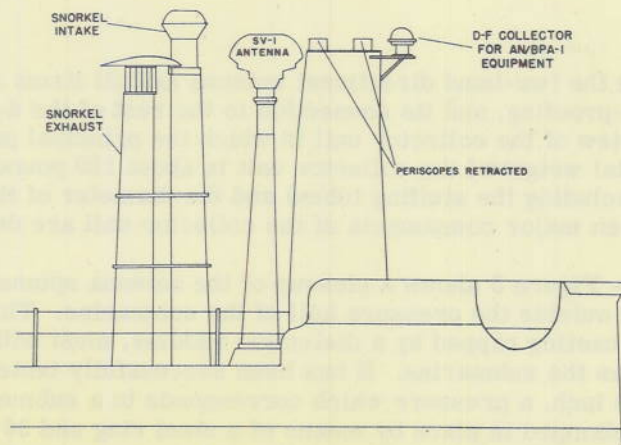


Figure 2 - Possible mounting location for d-f collector unit

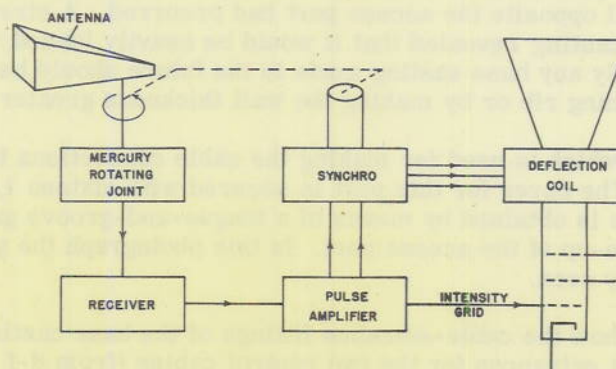


Figure 3 - Block diagram of AN/BPA-1(XN-1)

of this deflection circuit the pattern of the rotating d-f antenna is traced upon the cathode-ray tube and the bearing is obtained by bisecting this antenna pattern with a movable hair-line cursor. The bearing angle is read from the engraved azimuth scale which surrounds the face of the cathode-ray tube.

DESCRIPTION OF PRINCIPAL COMPONENTS

The three principal parts of this direction finder, as previously mentioned, are the collector unit, the microwave receiver, and the d-f indicator with automatic bearing

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presentation. These, with the exception of the receiver, were developed in the prosecution of this problem.

Collector Unit

This unit includes the two-band directional antenna and all items associated with its rotation, its pressure-proofing, and its connection to the rest of the d-f system. Figure 4 is a cross-sectional view of the collector unit in which the principal parts are labeled for identification. The total weight of the collector unit is about 120 pounds. The over-all height is 18 inches (excluding the stuffing tubes) and the diameter of the clamping flange is 17 inches. The seven major components of the collector unit are described below.

Antenna Housing - Figure 5 shows a closeup of the antenna spinner housing which is designed for mounting outside the pressure hull of the submarine. This unit, consisting of an aluminum-alloy casting capped by a dielectric radome, must withstand the same hydrostatic pressure as the submarine. It has been successfully tested at pressures up to 450 pounds per square inch, a pressure which corresponds to a submerged depth of 1000 feet. The radome is clamped in place by means of a steel ring and 36 one-half-inch bolts spaced every 10 degrees. Figure 4 shows how the radome is secured in place to provide a pressure-tight assembly with the base casting.

Both the base casting and the adapter ring are Navy Class 3 alloys containing 7 percent silicon. This particular alloy was chosen as a compromise between structural strength and corrosion resistance. The castings were stress-relieved and heat-treated after manufacture in order to achieve maximum strength. It was found after the base casting had been subjected to a hydrostatic pressure of 500 pounds per square inch (psi) that a slight deformation of the flat sidewall opposite the access port had occurred. A stress analysis of this particular part of the casting revealed that it would be heavily loaded when under 500 psi pressure. Consequently any base casting made in the future should be strengthened by the addition of a stiffening rib or by making the wall thickness greater at this surface.

The access port, which is used for making the cable connections to the antenna spinner, is seen in Figure 5. The cover for this port is secured with sixteen 1/4-20 machine bolts, and pressure tightness is obtained by means of a tongue-and-groove gasket arrangement. Figure 6 shows a close-up of the access port. In this photograph the groove for the neoprene gasket is readily seen.

Figures 6 and 7 show the cable-entrance fittings of the base casting. These fittings provide pressure-tight entrances for the two control cables (from d-f indicator) and the r-f coaxial cable connecting the antennas to the receiver. The indicator control cables are brought through two aluminum-alloy stuffing tubes, one on each side of the coaxial cable fitting. These stuffing tubes are welded to the base casting and a pressure seal is obtained by tightening down the gland nut of each, thereby compressing the rubber gland (or grommet) which has previously been vulcanized to the cable sheath. Experiments with dummy stuffing tubes showed that the gland should preferably be made from natural rubber with the addition of some carbon black to bring the hardness to about 40 durometer. The clearances of the rubber gland and the cable with the inside of the stuffing tube are kept to a minimum in order to insure reliable sealing. The entrance fitting for the coaxial cable is machined from stainless steel and is drilled with a hole large enough to pass RG-9/U cable. This fitting is sealed to the base casting by means of a neoprene gasket and a torque-and-groove arrangement, all of which is secured by means of a locking nut located inside the casting (see Figure 6). This locking nut also compresses the neoprene gasket. In an actual installation of the antenna system aboard a submarine the coaxial

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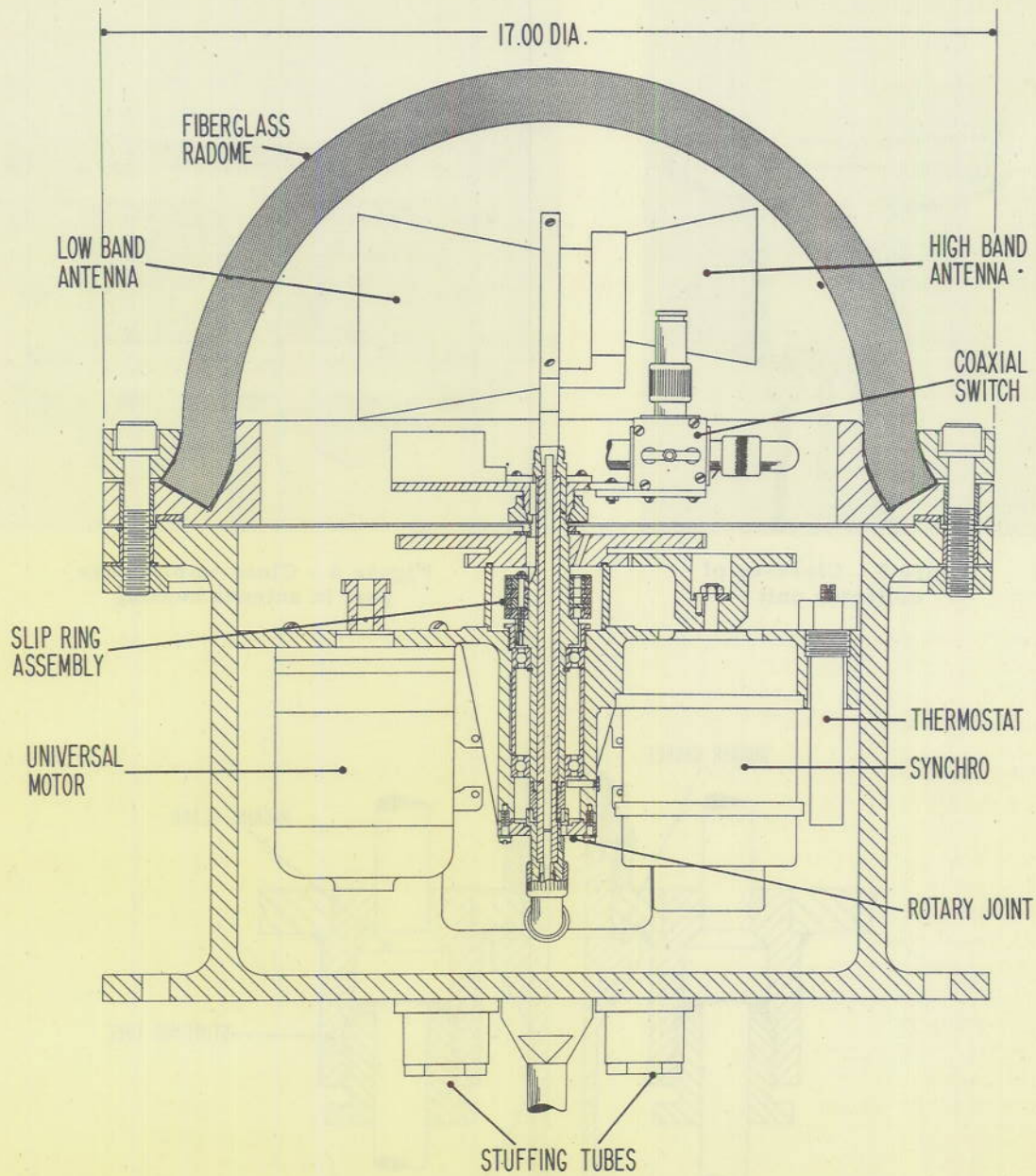


Figure 4 - Cross-sectional view of collector unit

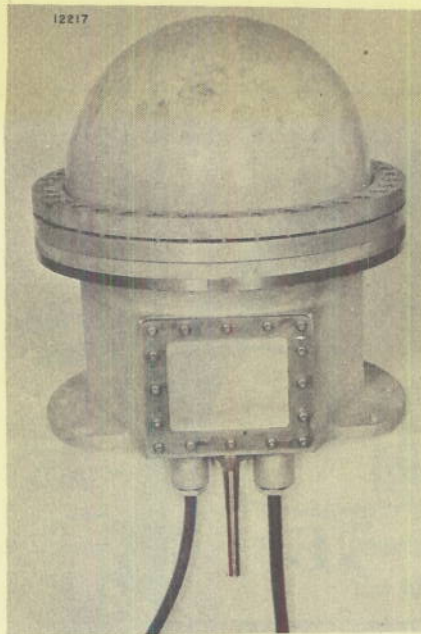


Figure 5 - Close-up of collector unit

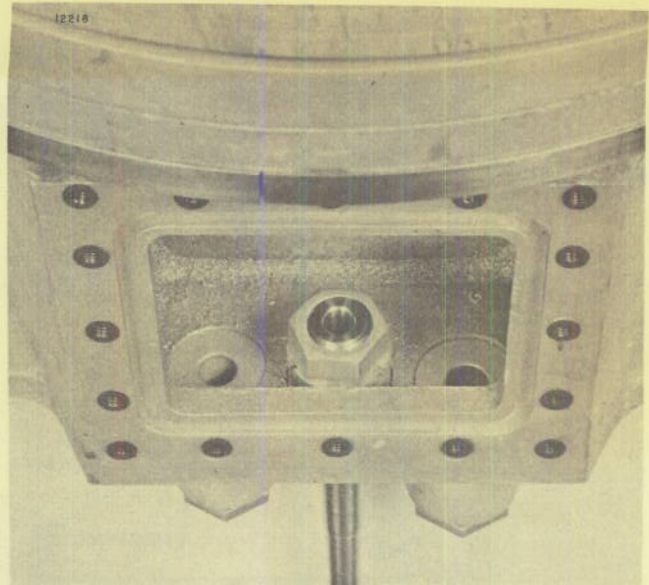


Figure 6 - Close-up of access port in antenna housing

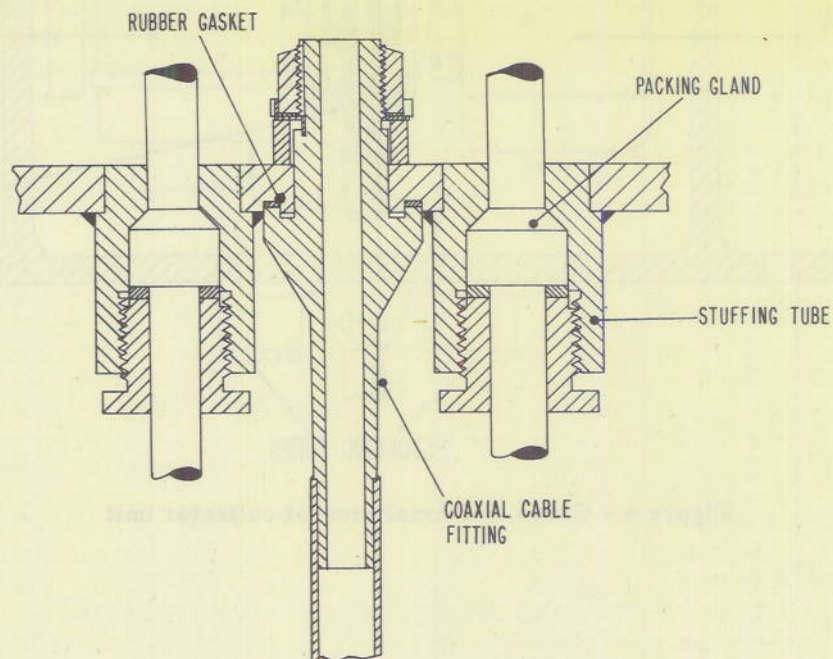


Figure 7 - Cross-sectional view of cable entrance fittings

r-f cable must be fully enclosed in 3/4-inch I.D. copper or steel tubing. One end of this tubing is welded to the stainless steel entrance fitting just described, and the other is welded to the pressure hull of the submarine. A shear valve is located at this point where the coaxial cable enters the pressure hull so that the copper tube can be closed off from the pressure hull in case a leak should develop in the antenna system. In a like manner the two power or control cables enter the pressure hull through separate stuffing tubes and shear valves. These two cables are not enclosed in tubing because they have heavy jackets of synthetic rubber which can be exposed to the external hydrostatic pressure. They are held in place outside the pressure hull by means of heavy cable clamps spaced about every 18 inches.

The antenna base casting was made of aluminum alloy in place of any other metal (such as bronze) in order to minimize its weight. It was realized that aluminum alloy was liable to severe corrosion under the type of service required of this equipment; so special precautions were taken to prevent serious corrosion. All aluminum parts were carefully anodized and the base casting was then given six coats of paint. The first coat was a wash primer, the next two were zinc chromate primers; then three coats of vinyl-base gray paint were applied. The latter type of paint has rather poor adhesive qualities and it is very important to prepare the casting surface properly and to apply the various coats carefully so that the resultant adhesion is as good as possible. The reason for using this vinyl-base type of paint is that it provides a very high degree of corrosion resistance to the painted surface.

Because of the high electrolytic potential between aluminum and steel when immersed in sea water, all the steel pieces—such as the radome clamping ring and the clamping bolts—were cadmium plated. This, in effect, greatly reduces the galvanic action between the dissimilar metals because the electrolytic potential between aluminum and cadmium is low. In order further to reduce corrosion, phenolic bushings were placed in all the holes of the aluminum adapter ring and the base casting, so that the steel radome clamping bolts would not be in direct contact with the aluminum. Similar bushings were also used in the holes of the access-port cover and these bushings can be seen in Figure 8, which is a view of the antenna spinner without the radome. Even the steel retaining ring which has 36 holes tapped to receive the 1/2-inch radome clamping bolts was insulated from the large clamping flange of the base casting by means of a 1/16-inch flat rubber sheet. In this manner it was possible to keep all the steel parts from coming into direct contact with the aluminum parts.

Radome - The rotating horn antennas are covered by a hemispherical dielectric radome shown in Figure 9. The white strip on the inside surface of the radome is the rubber gasket which seals the radome to the adapter ring. This radome is a thick polyester Fiberglas-cloth laminate which satisfies the requirements of high structural strength, low water permeability, low dielectric constant, and low electrical losses. The dielectric constant of this radome is about 4.0 and the wall thickness of one inch was chosen primarily so that the electrical thickness would be a half-wavelength at 3000 Mc and three half-wavelengths at 9000 Mc. This was done in order to minimize reflection losses due to the radome at both S- and X-bands. The manner in which this reflection loss varies with frequency is shown in Figure 10 which was taken from Reference (2). This curve was calculated to show the percent transmission through a flat sheet one inch thick and having a dielectric constant of 4.0; consequently it does not apply exactly to the spherical shape presented by the radome. The loss tangent of the radome material is low ($\tan \delta = 0.006$) and the calculated maximum attenuation of the r-f signal as it passes through the radome is less than 0.2 decibel. The actual transmission loss of the radome, including reflection and attenuation, has been measured for both horizontal and vertical polarization at frequencies of 2500, 3000, 4500, 6000, and 9500 Mc. The maximum loss encountered was



Figure 8 - Collector unit without radome

is termed the "diffusion" process (Reference (6)). The "diffusion" process, which results in a very nonporous radome material, consists of applying the resin to the glass-cloth filler under vacuum, thus eliminating entrapment of gases by the resin. These second three radomes, as well as the first three, had a physical shape as shown in Figure 11 with the exception that the last two were without any groove machined for the sealing gasket. This groove was eliminated and a large flat gasket was used in order to provide additional flange support.

Individual tests of these radomes were made by clamping them with 36 one-half inch bolts to a flat, solid steel plate, thereby compressing a rubber or asbestos gasket placed between the two. This assembly was then placed in a pressure tank to test the radome for porosity and mechanical strength under hydrostatic pressure. Although the laminate material of the fourth, fifth, and sixth radomes was nonporous these radomes still failed when subjected to pressure tests. The cause of this failure was a very high stress concentration set up at the flange-dome juncture. The combination of the small radius of curvature at this juncture, plus the type of clamping and loading applied to the radome, resulted in a cracking of the glass fibers and a gradual delamination. The radomes began to leak in about one or two hours after being placed under 500 psi pressure. The water leakage was very slow at first but gradually increased as the delamination of the radome progressed. A small section of one of these radomes is shown in Figure 12. In order to determine where the leakage was occurring, a dye

3 decibels, and it was found at some frequencies that the presence of the radome actually increased the output of the d-f antennas. This was apparently caused by an effective beam sharpening or lens action on the part of the radome.

The dielectric radome of Figure 9 was developed by the Plastics Division of the Naval Ordnance Laboratory under a contract with the Naval Research Laboratory. A full report on this development, by the Naval Ordnance Laboratory, describing the techniques used and some of the test results, is given in Reference (6).

During the course of this radome development a total of eight full-size radomes were manufactured from Selectron 5003 resin and a filler of Fiberglass-cloth layers. The first three of these radomes were unsatisfactory because they were found to be porous and leaked rapidly when subjected to a hydrostatic pressure test. The next three were made by what



Figure 9 - Fiberglass-laminate radome

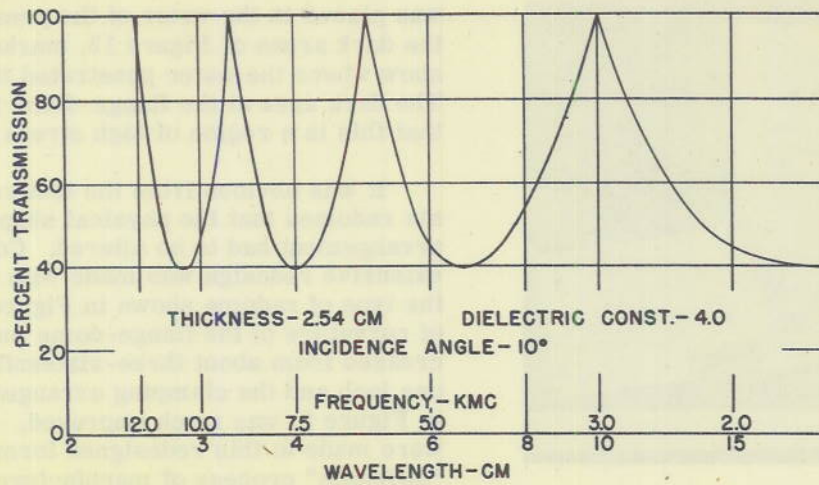


Figure 10 - Transmission characteristic of Fiberglass-laminate panel

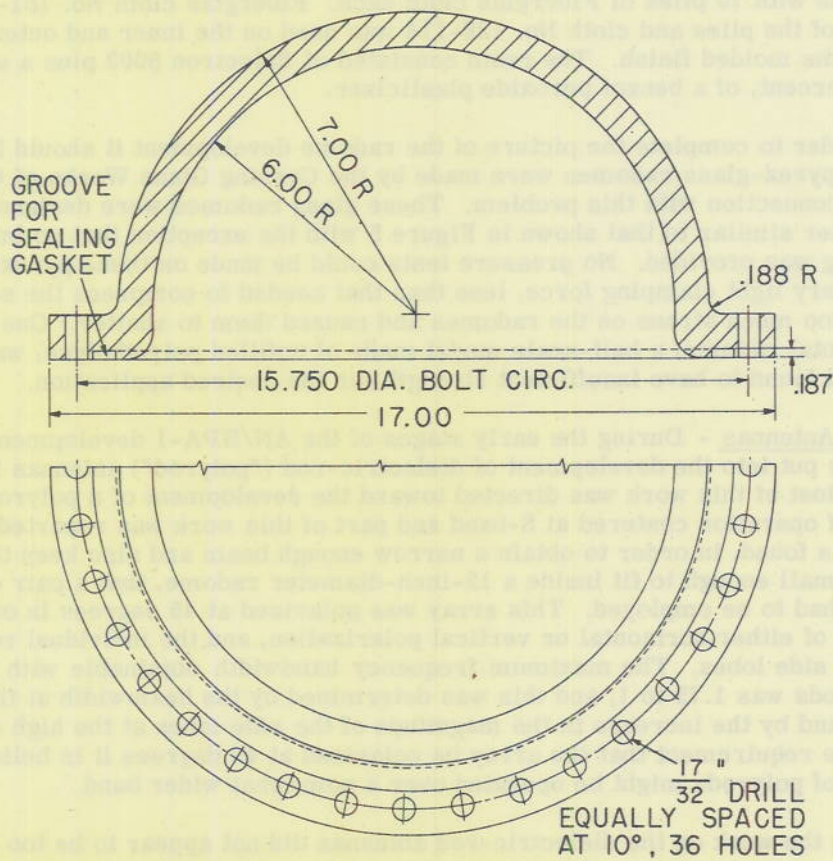


Figure 11 - Original Fiberglass-radome shape



Figure 12 - Small section of earlier type radome

was placed in the water of the pressure tank and the dark areas of Figure 12, marked by this dye, show where the water penetrated the radome wall. The dark area at the flange-dome juncture reveals that this is a region of high stress concentration.

It was obvious from the test results on the first six radomes that the physical shape and clamping arrangement had to be altered. Consequently, an extensive redesign was made with the result being the type of radome shown in Figure 9. The radius of curvature of the flange-dome juncture was increased from about three-sixteenths of an inch to one inch and the clamping arrangement, as shown in Figure 5, was much improved. Two radomes were made to this redesigned form utilizing the "diffusion" process of manufacture. One of them was subjected to a pressure of 500 psi for a total of about 20 hours including six cycles of pressure between zero and 500 psi. No leakage or deterioration of the radome was observed during or after these tests. These last two radomes were made with 79 plies of Fiberglas cloth each. Fiberglas cloth No. 181-114 was used for most of the plies and cloth No. 128-114 was used on the inner and outer surfaces to improve the molded finish. The resin consisted of Selectron 5003 plus a small amount, about 1 percent, of a benzol peroxide plasticizer.

In order to complete the picture of the radome development it should be mentioned that four pyrex-glass radomes were made by the Corning Glass Works of Corning, New York, in connection with this problem. These glass radomes were designed to be clamped in a manner similar to that shown in Figure 5 with the exception that no internal support or backing was provided. No pressure tests could be made on these pyrex radomes because a very light clamping force, less than that needed to compress the sealing gasket, imposed too much stress on the radomes and caused them to shatter. One other type of experimental radome, a half-scale model made of unfilled polyethylene, was pressure tested and found to have insufficient strength for the desired application.

D-F Antennas - During the early stages of the AN/BPA-1 development considerable effort was put into the development of dielectric-rod ("polyrod") antennas for this direction finder. Most of this work was directed toward the development of a polyrod antenna with a range of operation centered at S-band and part of this work was reported on in Reference (2). It was found, in order to obtain a narrow enough beam and also keep the size of the antenna small enough to fit inside a 12-inch-diameter radome, that a pair of cophased polyrods had to be employed. This array was polarized at 45 degrees in order to permit reception of either horizontal or vertical polarization, and the individual rods were tapered to reduce side lobes. The maximum frequency bandwidth obtainable with this array of two polyrods was 1.75 to 1, and this was determined by the beamwidth at the low end of the band and by the increase in the magnitude of the side lobes at the high end. If it were not for the requirement that the array be polarized at 45 degrees it is believed that such an array of polyrods might be operated over a somewhat wider band.

Since the work on the dielectric-rod antennas did not appear to be too promising, this work was stopped in favor of an investigation of horn-type antennas. This line of investigation was found to be considerably more fruitful and resulted in the development of horn antennas which cover a greater bandwidth than two to one. It was found that, by properly

Since the work on the dielectric-rod antennas did not appear to be too promising, this work was stopped in favor of an investigation of horn-type antennas. This line of investigation was found to be considerably more fruitful and resulted in the development of horn antennas which cover a greater bandwidth than two to one. It was found that, by properly

choosing the operating-frequency bands, two antennas could be designed to cover not only S- and X-bands but also all the frequencies lying between these bands. The AN/BPA-1 antennas covering the frequency range of 2300 to 10,600 Mc are shown in Figure 13. The two larger horns on the left side of the figure are fed in phase as an array and cover the band from 2300 to 5000 Mc. The single small horn covers the frequency band from 5000 to 10,600 Mc. Both these antennas are oriented at 45 degrees so that they will receive both vertically and horizontally polarized signals.

It should be pointed out that the low-band antenna was made as an array of two horns instead of as a single horn because of beamwidth requirements and space limitations. It would have been considerably easier to design a single horn to cover the frequency range of 2300 to 5000 Mc with the same beam width, but the physical shape and size of such a horn would have made it very difficult to locate both it and the high-band horn under the 12-inch-diameter radome. By using the pair of horns as the low-band array it was possible to nestle the high-band horn between the low-band pair and thus obtain efficient utilization of the available space.

The three individual horns for these antennas are fabricated from sheet copper with silver-soldered seams and the finished horns are silver plated to provide surfaces of high conductivity. A cross-sectional view of a low-band horn is seen in Figure 14. Each of the horns of this low-band array was designed to have an impedance of 100 ohms at its feed point; consequently, the rigid coaxial line from each of these horns to the common feed point (or junction) has a characteristic impedance of 100 ohms. The resultant impedance at the common feed point, where the two horns are in parallel is thus 50 ohms. As seen in Figure 14, the cavity which forms the back end of each low-band horn is, in reality, a

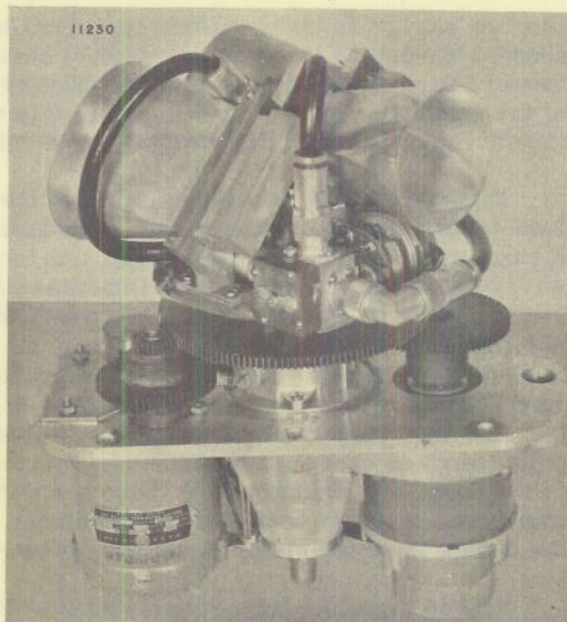


Figure 13 - D-F antennas and drive unit

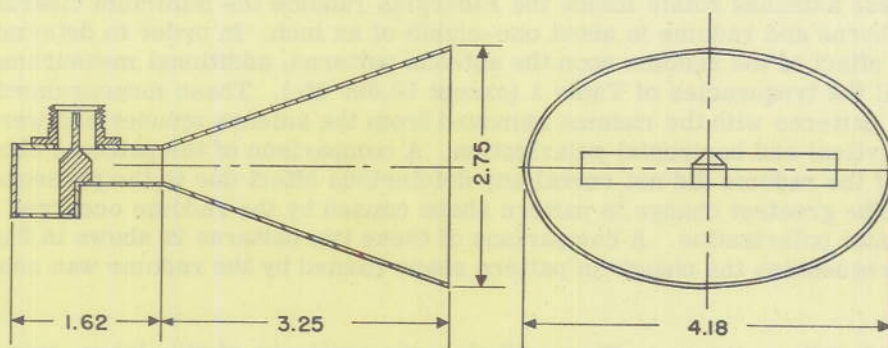


Figure 14 - Cross-sectional view of low-band horn element

shorted waveguide transmission line, the impedance of which shunts the feed point. This shorted waveguide line was designed to have a higher characteristic impedance than the forward part of the horn so that its shunting effect would not limit the operating bandwidth of the antenna. The effective length of this waveguide section, including the susceptance introduced by the step discontinuity, is a quarter wavelength long at about 3700 Mc.

Figure 15 shows a sectional view of the high-band horn. This horn has a waveguide feed section whose characteristic impedance is 100 ohms. This impedance is transformed to match the 50-ohm coaxial line by means of a quarter-wavelength section of ridge waveguide whose characteristic impedance is about 60 ohms. Actually, the ridge-waveguide section has a much lower cutoff frequency than the rest of the horn feed; consequently its electrical length does not approach zero as the cutoff wavelength of the rest of the waveguide is approached. This aids in making the matching section of ridge waveguide a wide-band transformer. One other desirable feature of the ridge-waveguide transformer is the fact that the discontinuity susceptance introduced by it, when referred to the coaxial feed point, tends to cancel part of the susceptance shunted across the feed point by the back end of the horn. By making use of these properties the horn can be designed to provide a good impedance match to a 50-ohm transmission line over a wide frequency range. Much of the design information for these horn feeds was obtained from Reference (7).

The voltage-standing-wave-ratio characteristics of these two d-f antennas are plotted in Figure 16. The data for these curves were obtained on a 50-ohm slotted coaxial line fitted with a UG-21B/U, type N connector which mated with the antenna connector.

Horizontal-plane response patterns of the AN/BPA-1 antennas have been measured with the automatic pattern plotter of the Radio Countermeasures Branch. This pattern plotter plots the antenna response logarithmically on a polar chart. Since a decibel-type plot is not desirable in presenting these d-f patterns, the data were transcribed and re-plotted on a voltage basis. Figure 17 shows the low-band antenna response to vertically and horizontally polarized signals. Figure 18 shows the high-band antenna patterns when receiving vertically and horizontally polarized signals. All of these patterns were measured with the antennas mounted on the AN/BPA-1 spinner and covered with the Fiberglas radome, thereby duplicating actual operating conditions. The half-power beamwidths of these antennas at various frequencies in the operating range are given in Table 1. Table 1 also gives the computed values of antenna gain relative to an isotropic radiator. These values of gain are for operation on vertically or horizontally polarized signals and are actually 3 decibels below what would be obtained if the antenna feed were polarized in the same plane as the signal.

As these antennas rotate inside the Fiberglas radome the minimum clearance between the horns and radome is about one-eighth of an inch. In order to determine the proximity effect of the radome upon the antenna patterns, additional measurements were made at all the frequencies of Table 1 (except 10,600 Mc). These measurements consisted of antenna patterns with the radome removed from the antenna spinner and were obtained for both vertical and horizontal polarization. A comparison of the patterns obtained with and without the radome did not reveal any deleterious effect due to the presence of the radome. The greatest change in pattern shape caused by the radome occurred at 5000 Mc for horizontal polarization. A comparison of these two patterns is shown in Figure 19. At other frequencies the change in pattern shape caused by the radome was considerably less.

Several of the patterns in Figure 17 show the existence of side lobes only 7 decibels below the strength of the main lobe. For the type of direction finder being described this level of side lobes can be tolerated, especially when it is considered that the nonlinearity

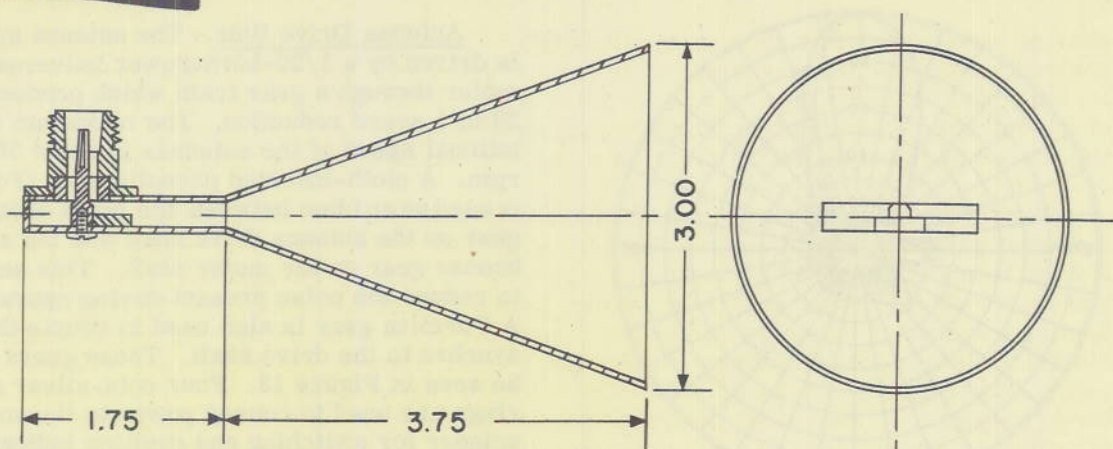


Figure 15 - Cross-sectional view of high-band antenna

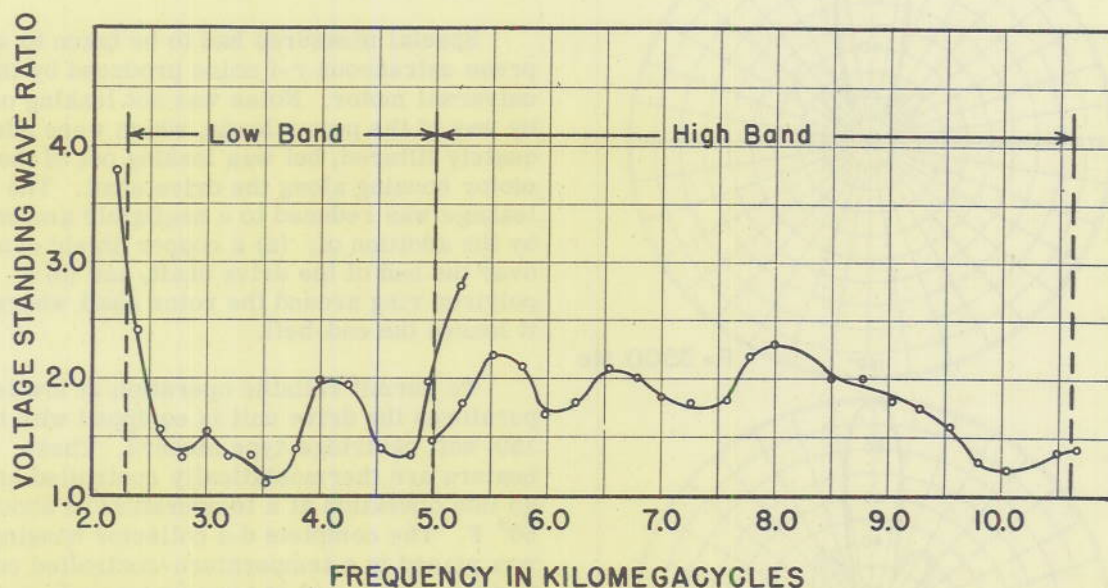


Figure 16 - Voltage-standing-wave-ratio characteristic of AN/BPA-1(XN-1) antennas

of the deflection amplifiers in the d-f indicator can be utilized to reduce these side lobes to a much lesser value. With the indicator circuits utilized in the AN/BPA-1 the effective side lobes of the antenna pattern, as it appears on the cathode-ray tube, are down about 12 decibels or more below the main lobe. The deflection amplifier response characteristics are shown in Figure 26 and are discussed later. As a note of caution it should be pointed out that the deflection amplifiers must not be made too nonlinear since this might cause excessive narrowing of the d-f indicator pattern.

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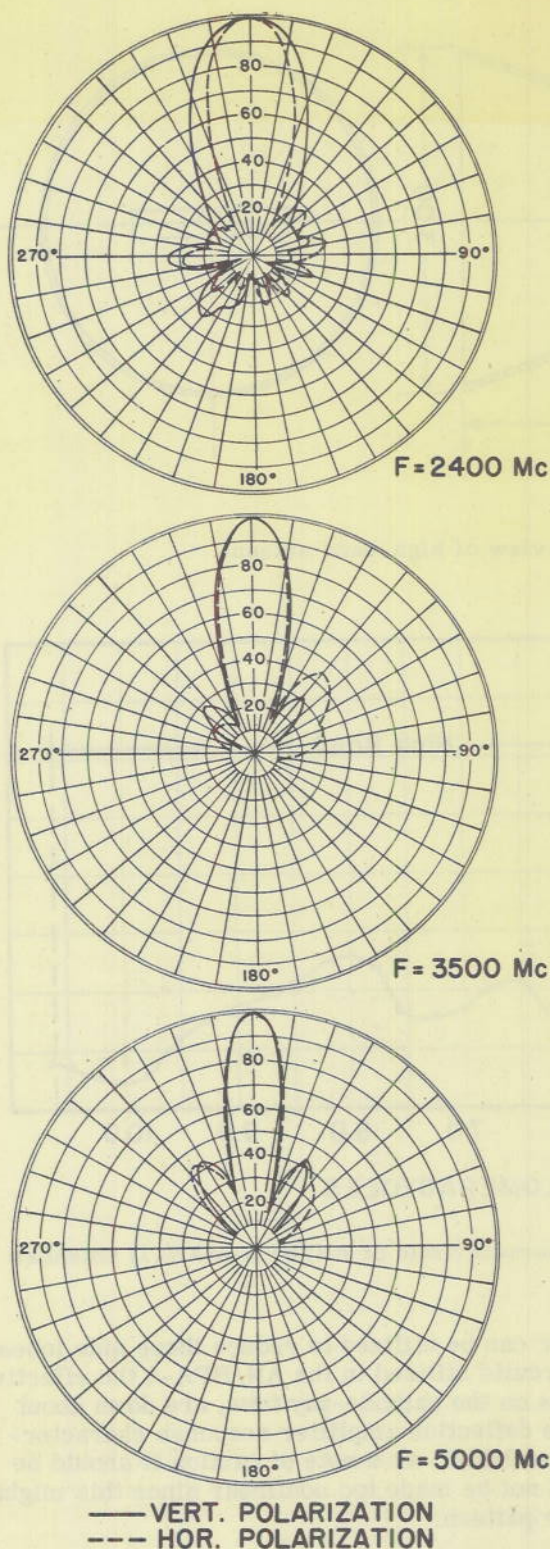


Figure 17 - Low-band antenna patterns

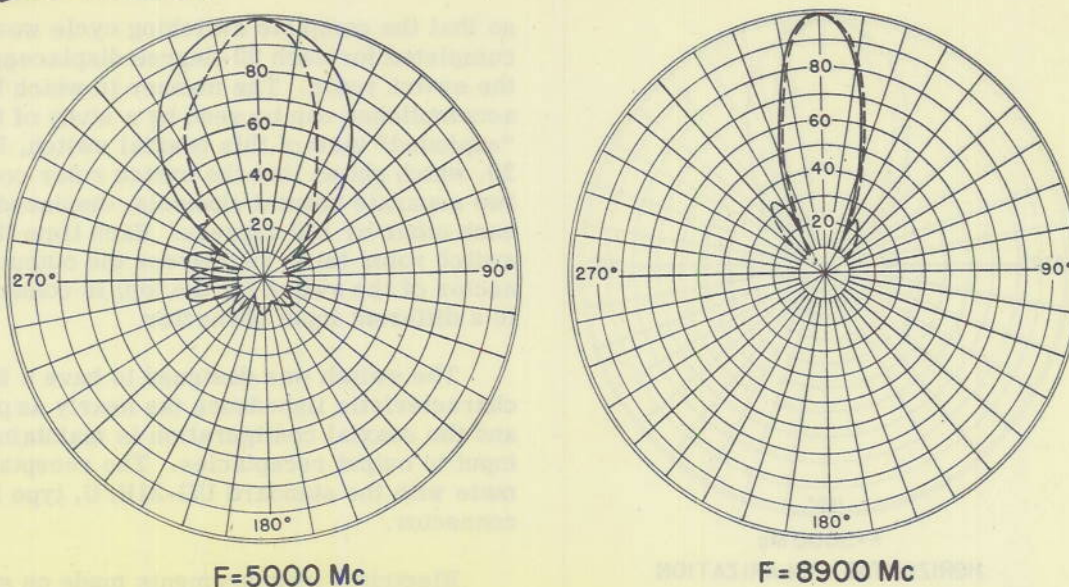
Antenna Drive Unit - The antenna spinner is driven by a 1/20-horsepower universal motor through a gear train which produces a 20 to 1 speed reduction. The maximum rotational speed of the antennas is about 700 rpm. A cloth-inserted phenolic gear (Formica) is used as an idler between the large oilite gear on the antenna drive shaft and the small bronze gear on the motor shaft. This serves to reduce the noise present during operation. A Formica gear is also used to couple the synchro to the drive shaft. These gears can be seen in Figure 13. Four coin-silver slip rings are used to convey power to the antenna spinner for switching and position indicating purposes. They are enclosed with an aluminum-alloy shield which also serves as a support for the slip-ring brushes. For the brushes, a silver-graphite alloy was found to be more suitable than pure silver.

Special measures had to be taken to suppress extraneous r-f noise produced by the universal motor. Noise was not leaking out by way of the power leads, which were adequately filtered, but was leaking out of the motor housing along the drive shaft. The leakage was reduced to a negligible amount by the addition of: (a) a copper shield can over the end of the drive shaft, and (b) a polyiron ring around the rotor shaft where it leaves the end-bell.

To permit reliable operation at low temperatures the drive unit is equipped with two 150-watt cartridge-type heaters. These heaters are thermostatically controlled and go into operation at a temperature of about 50° F. The complete d-f collector housing was placed in a temperature-controlled cold-test box and tested at temperatures down to -4° F. (-20° C). By using thermocouples to indicate the temperatures inside the antenna housing it was found that the heaters maintained the temperature of the drive unit at a minimum of 50° F. With the cold-box temperature at -4° F the heaters had only to operate one-third of the time (duty cycle = 33%) in order to maintain this drive unit temperature of 50° F. Since the low limit of the cold-box was -4° F, tests could not be carried out at any lower temperatures.

Coaxial Switch - A coaxial switch is used to select the high- or low-band antenna and

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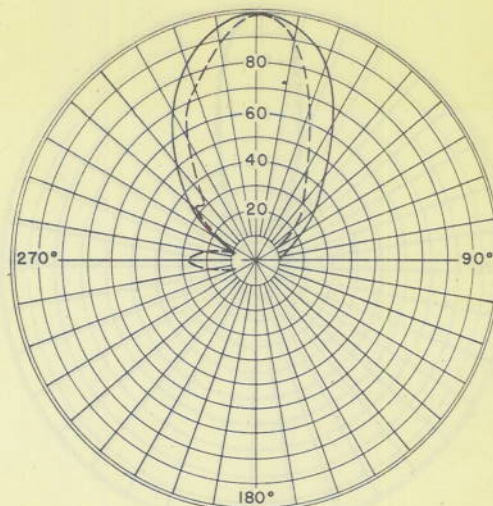
— VERT. POLARIZATION
 --- HOR. POLARIZATION

Figure 18 - High-band antenna patterns

TABLE 1
 Beamwidth and Gain Data on AN/BPA-1 Antennas

Antenna	Freq. Mc.	H.P. Beamwidth (Degrees)		Decibels Gain Over an Isotropic Radiator
		H. Pol.	V. Pol.	
Low-Band	2400	30	41	8.0
Low-Band	3500	25	26	10.4
Low-Band	5000	19	19	12.4
High-Band	5000	41	67	9.3
High-Band	8900	27	27	14.4
High-Band	10600	--	--	15.9

connect its output through the rotating joint to the receiver. This switch is mounted on the antenna spinner (Figure 13) and is actuated by a No. 5 Ledex rotary solenoid. The operation of the antenna switch is controlled by a push button on the front panel of the d-f indicator. Each time the push button is depressed the rotary solenoid throws the coaxial switch rotor through 90 degrees. This disconnects one antenna and connects the other to the receiver. The coaxial switch was specially designed with a two-channel type of rotor



F=5000 Mc

HORIZONTAL POLARIZATION

— WITHOUT RADOME
 --- WITH RADOME

Figure 19 - Comparison of antenna patterns measured with and without radome

so that the complete switching cycle would be completed for each 90-degree displacement of the switch rotor. The manner in which this is accomplished can be seen by a study of the "exploded" view of this coaxial switch, Figure 20, which shows that the switch rotor contains two separate coaxial channels, displaced from each other by 180 degrees. Each time the switch rotor turns 90 degrees the output connector of the switch (at the top) is connected to a different input connector.

The switch was designed to have a 50-ohm characteristic impedance (as nearly as possible) and the coaxial configuration is maintained from input to output receptacles. The receptacles mate with the standard UG-21B/U, type N connector.

Electrical measurements made on similar coaxial switches showed a voltage standing-wave ratio of about 1.5 at around 10,000 Mc (considerably less at lower frequencies), and a minimum crosstalk* between channels of 38 decibels. In the two-channel switch of Figure 20 a special effort was made to improve the crosstalk characteristic by employing a ring of beryllium-copper wiping fingers

between the switch housing and the rotor. Previous experiments showed that the crosstalk characteristic could be improved by means of such a set of wiping fingers and by maintaining very small clearances between the rotor and its housing.

It should be mentioned that a coaxial switch with a single-channel rotor could be used for the necessary antenna switching. In this case the actuator would have to throw the switch rotor in alternate steps of 90 and 270 degrees. This has the advantage of requiring a longer switching time for the 270-degree throw than for the 90-degree throw. The single channel coaxial switch would, however, be cheaper to manufacture. A commercial model of such a switch is now available and could probably be used with slight modifications.

Mercury Joint - As seen in Figure 3, a rotating joint is needed to connect the spinning antennas to their transmission line. The development of the mercury-contact coaxial joint was undertaken for the purpose of obtaining a type of broad-band rotary joint which could be operated at high rotational speeds, would require less frequent servicing, and would produce less electrical noise than the conventional contacting rotary joint.

Previous experience with conventional finger-type coaxial joints revealed that they have a serious shortcoming; r-f noise is produced by the fine metal particles which result from the rubbing contact between the moving and stationary parts of the joint. At low rotational speeds this wearing is not very rapid but at high rotational rates the wearing and production of metal particles can occur with great rapidity. This situation can be tolerated only by demanding periodic maintenance of the rotating joint so that no serious r-f noise

*Crosstalk is defined as the signal attenuation produced when the switch is opened.

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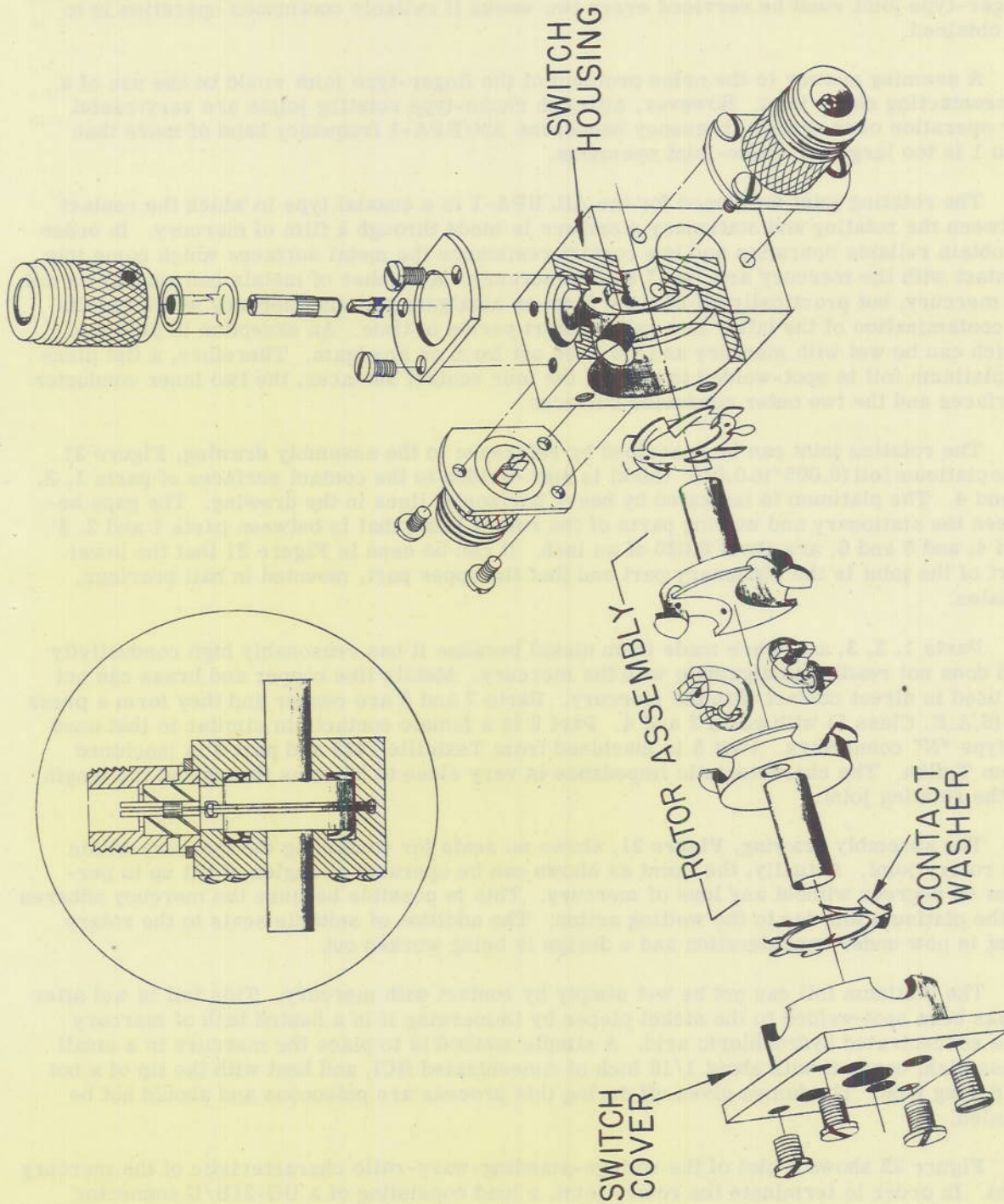


Figure 20 - Exploded view of coaxial antenna switch

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develops. In the DBM-1 direction finder (maximum rotational speed, 250 rpm) the rotating finger-type joint must be serviced every two weeks if reliable continuous operation is to be obtained.

A seeming answer to the noise problem of the finger-type joint would be the use of a noncontacting choke joint. However, although choke-type rotating joints are very useful for operation over narrow frequency bands, the AN/BPA-1 frequency band of more than 4 to 1 is too large for choke-joint operation.

The rotating joint developed for the AN/BPA-1 is a coaxial type in which the contact between the rotating and stationary members is made through a film of mercury. In order to obtain reliable operation and low contact resistance the metal surfaces which come into contact with the mercury are "wet" by the mercury. A number of metals can readily be wet by mercury, but practically all of them form an amalgam with the mercury which results in contamination of the latter in a rather short period of time. An exception is platinum which can be wet with mercury and yet does not form an amalgam. Therefore, a flat piece of platinum foil is spot-welded to each of the four contact surfaces, the two inner conductor surfaces and the two outer conductor surfaces.

The rotating joint can be described by reference to the assembly drawing, Figure 21. The platinum foil (0.005" to 0.010" thick) is spot-welded to the contact surfaces of parts 1, 2, 3, and 4. The platinum is indicated by heavy horizontal lines in the drawing. The gaps between the stationary and moving parts of the rotary joint, that is between parts 1 and 2, 3 and 4, and 5 and 6, are about 0.020 of an inch. It can be seen in Figure 21 that the lower part of the joint is the stationary part and that the upper part, mounted in ball bearings, rotates.

Parts 1, 2, 3, and 4 are made from nickel because it has reasonably high conductivity and does not readily amalgamate with the mercury. Metals like copper and brass can not be used in direct contact with the mercury. Parts 7 and 8 are copper and they form a press fit (S.A.E. Class 5) with parts 2 and 4. Part 9 is a female contact pin similar to that used in type "N" connectors. Part 5 is machined from Textolite 1422 and part 6 is machined from Teflon. The characteristic impedance is very close to 50 ohms throughout the length of the rotating joint.

The assembly drawing, Figure 21, shows no seals for containing the mercury within the rotary joint. Actually, the joint as shown can be operated at angles of tilt up to perhaps 45 degrees without any loss of mercury. This is possible because the mercury adheres to the platinum foil due to the wetting action. The addition of suitable seals to the rotary joint is now under consideration and a design is being worked out.

The platinum foil can not be wet simply by contact with mercury. This foil is wet after it has been spot-welded to the nickel pieces by immersing it in a heated bath of mercury plus concentrated hydrochloric acid. A simple method is to place the mercury in a small glass dish, cover it with about 1/16 inch of concentrated HCl, and heat with the tip of a hot soldering iron. The fumes given off during this process are poisonous and should not be inhaled.

Figure 22 shows a plot of the voltage-standing-wave-ratio characteristic of the mercury joint. In order to terminate the rotary joint, a load consisting of a UG-21B/U connector and 260 feet of RG-8/U cable was used. The dashed line shows the voltage standing-wave ratio of this load. Although the standing-wave ratio of the mercury joint appears somewhat high at some frequencies it must be realized that this curve includes the effects of the mercury joint proper, of the terminating load, and also of a mated pair of type N connectors which were necessary to connect the rotary joint to the slotted measuring line.

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Although no actual life tests of the mercury joint have been conducted, it is believed that the rotating joint should perform satisfactorily for periods of several months (perhaps four to six) without any maintenance. This belief is based upon intermittent operation of a mercury joint for a period of one year. The only maintenance required during this period was a re-wetting of the contact pieces to make up for the gradual loss in wetting which occurs with time. This re-wetting was performed about every four or five months.

Collector Unit Circuits - A diagrammatic representation of the circuitry inside the collector housing is given in Figure 23. The seven-conductor control cable from the d-f indicator connects to the receptacle AN-3102-18-9P, which is located just inside the access port of the antenna housing. The other receptacle, AN-3102-16S-8P, is located adjacent to the first and receives the synchro-control cable. As seen from Figure 23, the seven-conductor cable carries the a-c power for the drive motor and heaters and also the d-c power for operation of the coaxial-switch actuator. This same d-c voltage is used, in conjunction with an extra wafer on the actuator shaft, to indicate the position of the coaxial-switch rotor. A total of four conductors, two for d-c power and two for position indication, are connected to the antenna spinner by means of the four slip rings. All the circuitry to the right of the slip rings and above the synchro shown in Figure 23 is located on the spinner itself. A terminal strip is located on the antenna spinner so that the four slip-ring wires can readily be disconnected and the spinner removed from the drive unit without the necessity for unsoldering any leads. This provides greater ease in assembly and disassembly

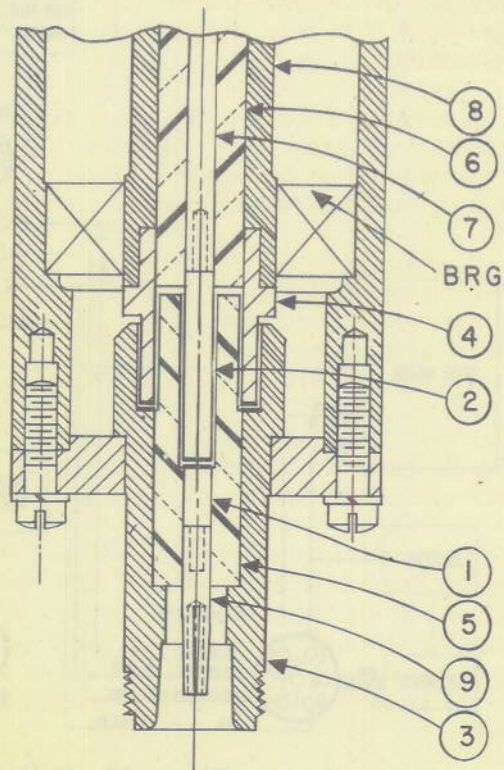


Figure 21 - Mercury contact coaxial rotary joint

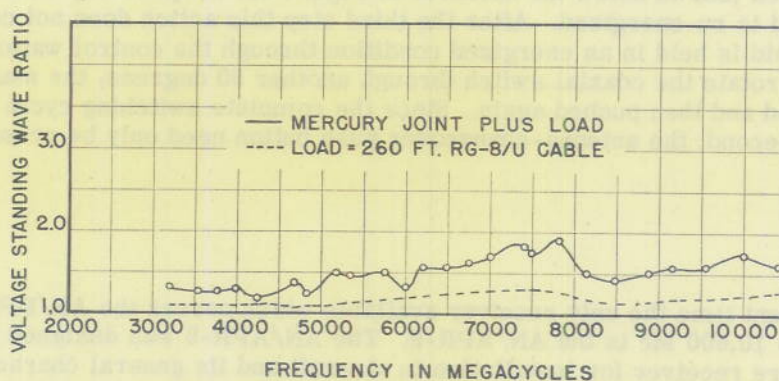
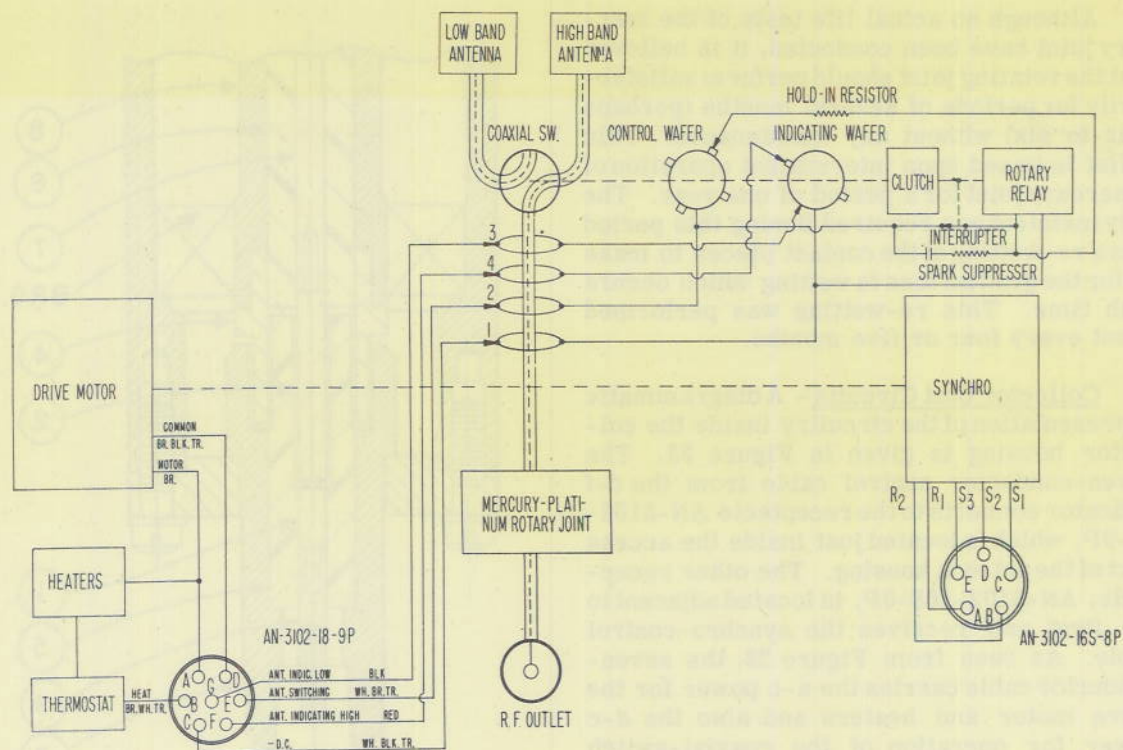


Figure 22 - Voltage-standing-wave-ratio characteristic of mercury joint



of the antenna spinner with less likelihood of an incorrect connection, since the wires going to the terminal strip are labeled.

To energize the rotary solenoid which actuates the coaxial switch, 90 volts dc is obtained from a bridge-connected selenium rectifier located in the d-f indicator. This d-c voltage is applied to the solenoid by means of the antenna-changeover push button on the indicator panel. In actual operation, each time the push button is depressed, the rotary solenoid throws 90 degrees in three 30-degree steps. After each 30-degree step, the interrupter switch (shown below the solenoid in Figure 23) is opened by cam action, and then the solenoid is re-energized. After the third step this action does not continue because the solenoid is held in an energized condition through the control wafer and holding resistance. To rotate the coaxial switch through another 90 degrees, the main push button must be released and then pushed again. Since the complete switching cycle requires only a fraction of a second, the antenna-changeover push button need only be pressed for this length of time.

Receiver

At the present time the only receiver available which covers the AN/BPA-1 frequency range of 2300 to 10,600 Mc is the AN/APR-9. The AN/APR-9 was designed primarily as a countermeasure receiver for installation in aircraft and its general characteristics make it quite suitable for use with the AN/BPA-1 type of d-f system. The principal

characteristics of this receiver which make it useful for intercept d-f work are:

1. A superheterodyne circuit with r-f preselection.
2. Automatic sector tuning over a predeterminable frequency band.
3. A 20-Mc i-f bandwidth.
4. A 4-Mc video bandwidth.
5. A 20-Mc panoramic oscilloscope presentation.

The chief disadvantage in trying to use this receiver in a shipboard installation is its power requirement of 28 volts dc and 115 volts ac at 400 or 800 cycles per second. This is a serious disadvantage since it necessitates the installation and use of auxiliary power sources which often prove unreliable in operation. The difficulties already experienced in trying to utilize auxiliary power sources for this AN/APR-9 receiver point out the urgent need for a countermeasure receiver of this type which operates on 115-volt 60-cycle power.

Another disadvantage occurs in using the AN/APR-9 to cover the complete frequency range of 2300 to 10,600 Mc. Three separate tuning heads are needed to cover the above band and no provision is made for switching from one head to another. The tuning heads can be changed only by changing cables from one head to another and this requires a considerable amount of time.

D-F Indicator

The AN/BPA-1 indicator, completely contained in a single ATR size cabinet, is shown with its dust cover removed in Figure 24. The indicator measures 10 x 8 x 20 inches and its total weight is about 40 pounds. The d-f indicator is powered with 115 volts, 60 cycles, and requires about 40 watts exclusive of the antenna spinner and drive unit. The d-f bearing is presented on a 5-inch cathode-ray tube, the face of which is covered by an alidade with a movable hairline cursor. The azimuth scale of this alidade is illuminated by three 6-volt panel lamps whose intensity can be controlled from a front-panel rheostat.

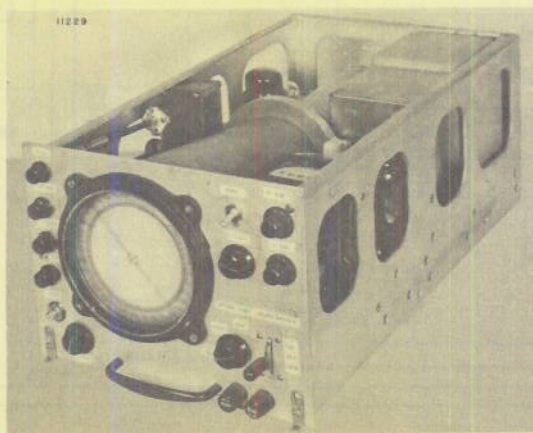


Figure 24 - D-F indicator

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amplifier is fed by the wide-band video output of the microwave receiver. From this 6AK5 the signal is applied to the 6AL5, which acts as a pulse stretcher. The output of the pulse stretcher consists of pulses stretched to greater than 200 microseconds in duration. These pulses are then amplified by a 6AK5 followed by a 6C4. The 6C4 is used to drive the 6L6 grid through an "ouncer" transformer. In addition to feeding the synchro rotor, a part of the 6L6 output is applied to the intensity grid of the cathode-ray tube to provide intensity modulation of the trace. Intensity modulation is essential for successful operation of this type of indicator which displays the individual pulses on the cathode-ray tube.

The reason for providing so much pulse stretching in the deflection amplifier is to make the pulses compatible with the low-pass response of the iron-core deflection circuit. This iron-core circuit has a frequency response of only several thousand cycles which is determined principally by the 60-cycle synchro through which the pulses must be passed. Some idea of this low-pass frequency response can be seen by examination of the spot-deflection versus input curves of Figure 26. These deflection response curves were obtained for a five-microsecond video pulse input to the deflection amplifier at pulse-repetition frequencies of 1000, 2500, and 3000 cycles per second. The amplifier was set at maximum gain for these curves. The nonlinearity at the lower input levels accounts for the apparent suppression of antenna-pattern side lobes. This was mentioned previously when the antenna patterns were being discussed. The nonlinearity at the higher input levels is an amplifier-limiting or saturation effect which is desirable when the direction finder is operating against signals of rapidly varying amplitude. This high-level limiting is desirable because it tends to keep the rapidly fluctuating pattern on the face of the cathode-ray tube for a greater percentage of the time than it would remain without the limiting. In other words it acts as a type of automatic gain control (AGC). This automatic limiting effect could have been exploited to a greater degree by locating the deflection-amplifier gain control near the last stage of the amplifier. Then by a proper adjustment of the receiver gain and the deflection-amplifier gain it would be possible to bring this limiting effect into action for signals of almost any pulse repetition frequency. It should be pointed out, however, that a large part of the nonlinearity seen in the curves of Figure 26 is caused by magnetic saturation of the iron-core deflection circuit itself and this is a fixed effect which cannot be changed except by a redesign of the magnetic circuit.

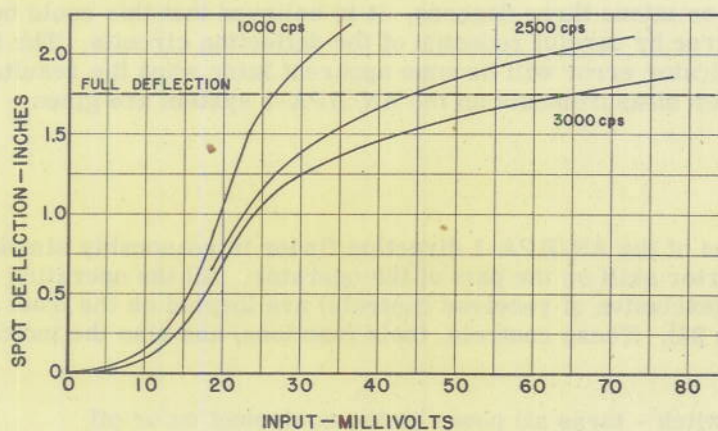


Figure 26 - Deflection characteristics of indicator

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The two most serious disadvantages of the d-f indicator in its present form are caused by the poor high-frequency response of the deflection circuits. These two disadvantages, poor deflection sensitivity for high-pulse repetition rates and low-level illumination of the cathode-ray tube screen, could be eliminated by either redesigning the deflection circuits or by using a different type of deflection circuit. The present deflection circuit could be redesigned to eliminate its poor high-frequency response by using a high-quality two-phase resolver in place of the present 5G synchro and by replacing the present 3-winding deflection coil with a new 2-winding magnetic deflection yoke of greater deflection power and greater frequency response. As an alternative to using the magnetic deflection yoke about the neck of the cathode-ray tube, the deflection could be produced electrostatically by feeding the two outputs of the two-phase resolver to a set of deflection amplifiers which would drive the horizontal and vertical deflection plates of the tube. It should be pointed out that this latter circuit does not possess the same simplicity of operation which is characteristic of the original magnetic deflection circuit because the two deflection amplifiers must have provision for gain and output balance. The absence of any balance controls in the magnetic deflection circuit is its chief advantage.

The low-level screen illumination in the present d-f indicator is a result of using a maximum accelerating voltage of only 2000 volts. However, this restriction was imposed by the necessity for maintaining the deflection sensitivity of the cathode-ray tube high. In other words, the poor high-frequency response of the magnetic deflection circuit made it necessary to accept rather low accelerating potential in the cathode-ray tube. If the deflection circuits were redesigned for better high-frequency response and greater sensitivity, then the accelerating voltage could be increased and a tube with either a P-1 or P-2 phosphor could be employed. From previous experience with the use of P-1 and P-2 phosphors for this type of d-f indicator it is believed that the P-2 phosphor is more desirable, particularly under conditions where the ambient light level might be fairly high. The longer persistence of the P-2 type screen would also make it easier to see and to obtain bearings on signals of short duration which are common when working against scanning radar transmitters. For a more complete discussion of the choice of the proper screen persistence under different conditions of operations, see Reference (8).

A redesign of the deflection circuits might also improve the d-f indicator in one other respect. The use of a standard 5G synchro in the present d-f deflection circuit results in a fairly large instrumental error which could be reduced by the use of a carefully designed resolver. The instrumental bearing-error characteristic of the AN/BPA-1 indicator is plotted in Figure 27. As shown by this curve the maximum instrumental error of the indicator is plus or minus three degrees. It is believed that this could be reduced to plus or minus one degree by careful redesign of the deflection circuits. The importance of reducing this indicator error will become apparent later when the results of the over-all instrumental error measurements on the AN/BPA-1 system are given.

OPERATION

The operation of the AN/BPA-1 direction finder is reasonably simple and does not require any superior skill on the part of the operator. All the operating controls of the direction finder (exclusive of receiver controls) are located on the front panel of the d-f indicator (Figure 24). These controls, their functions, and also the indicating lamps are listed below:

- a. Power Switch - turns all power to the equipment on or off
- b. Lights Control - controls the brilliance of the alidade lamps

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- c. Hi-Band Indicator - lights when the high-band antenna is in operation
- d. Lo-Band Indicator - lights when the low-band antenna is in operation
- e. Antenna Speed - selects the rotational speed of the antenna spinner
- f. Antenna Rotation - energizes the antenna drive motor
- g. Gain - controls the gain of the deflection amplifier
- h. Antenna Switch - controls the coaxial switch which connects either the low-band or high-band antenna to the rotary joint
- i. Intensity - adjusts the brightness of the cathode-ray tube trace
- j. Position (2 controls) - adjusts the position of the undeflected spot on the cathode-ray tube
- k. Focus - adjusts the focus of the trace on the cathode-ray tube.

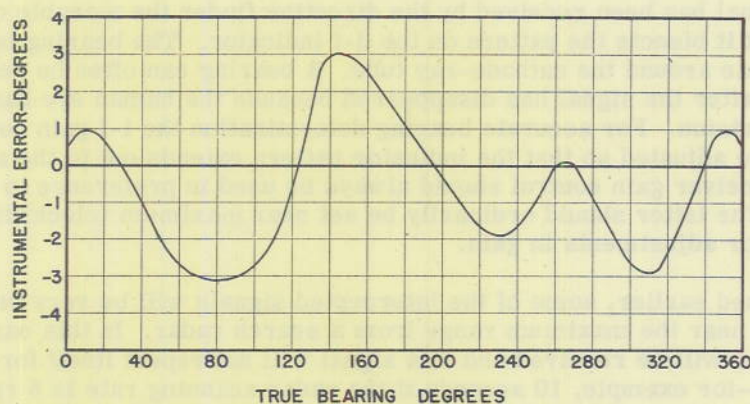


Figure 27 - Instrumental error of indicator

The first requirement for operation is to see that the d-f indicator and receiver are supplied with suitable power sources. If the AN/APR-9 receiver is used, it must be supplied with 28 volts dc and 115 volts ac at 400 or 800 cycles. After the proper tuning head is connected to the rest of the receiver circuit, the equipment is put into operation by throwing the main power switches of the receiver and d-f indicator. Next, depending upon what frequency band of operation is desired, the proper d-f antenna is selected by means of the antenna switch on the d-f indicator. This selection is checked by noting which of the two indicating lamps is lighted. After a short warm-up period for the receiver the gain control of the deflection amplifier should be adjusted for nearly maximum gain, and the receiver gain should be adjusted until the receiver noise gives a radial deflection of about 1/2 or 3/4 inch on the d-f indicator. Since intensity modulation is employed in the cathode-ray tube circuit, the intensity of the spot at the center of the tube is adjusted until it is just barely discernible. The antenna-rotation switch can next be thrown to the "run" position and the desired rotational speed is determined by the position of the antenna

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speed selector switch. This antenna speed selector should be placed in the slow position (300 rpm) only if it is anticipated or known that the pulse-repetition frequency of the radar signal is less than about 500 pulses per second. At other times it is desirable to operate the antenna spinner at high speed (700 rpm) in order to improve the probability of obtaining an interception.* The antenna rotational speed can be cycled between about 400 and 700 rpm by putting the selector switch in the "cycle" position. This cycling, which is performed automatically, will prevent any direct synchronization between the d-f antenna speed and any multiple of the radar antenna rotational rate. The importance of using high antenna rotational rates, whenever possible, will be pointed out later when the d-f performance is discussed.

In searching for signals with the AN/BPA-1 system, headphones should be utilized since they are an aid in picking up brief signals. Any signal heard in the headphones should give an indication on the d-f indicator provided the gain controls are properly adjusted. The AN/APR-9 receiver should always be operated with the wide-narrow switch in the wide-band position. Otherwise the chances of intercepting a brief signal will be very poor. The cathode-ray tube of the d-f indicator should always be used in preference to the panoramic indicator of the AN/APR-9 receiver when searching. The reason for this is that all received signals will appear on the d-f indicator, but not necessarily on the panoramic scope because the latter does not instantaneously display all of the i-f passband.

Once a signal has been received by the direction finder the movable cursor should be adjusted so that it bisects the pattern on the d-f indicator. The bearing is then read from the azimuth scale around the cathode-ray tube. A bearing can often be read with reasonable accuracy even after the signal has disappeared because the human eye has considerable persistence of vision. For accurate bearing determination the i-f gain control of the receiver should be adjusted so that the indicator pattern extends out to the azimuth scale circle. The receiver gain control should always be used in preference to the indicator gain control. The latter should ordinarily be set near maximum (clockwise) and used mainly for minor adjustments in gain.

As mentioned earlier, some of the intercepted signals will be very brief, especially when operating near the maximum range from a search radar. In this case only the main lobe of the radar will be received and this signal will not repeat itself for an appreciable length of time—for example, 10 seconds if the radar scanning rate is 6 rpm. This points out the need for maintaining close scrutiny of the d-f indicator when the receiver is sector scanning so that the receiver tuning can be stopped as soon as a signal is seen. It is fairly obvious that, when searching for long periods of time, this requirement for close observation of the d-f indicator will impose a severe strain on the operator and that his efficiency will naturally decrease with time. Fortunately this situation can be improved considerably by the use of an automatic "lock-on" circuit developed by the Radio Countermeasures Branch of the Naval Research Laboratory. This "lock-on" circuit, the C-719 (XB-1)/APR-9, is designed for use with automatic sector-tuning type receivers such as the AN/APR-9, and its purpose is to stop the tuning motor whenever a radar signal is received. The lock-on circuit is operated by the video output of the receiver and this video signal is used to trigger a control relay which stops the tuning motor in about one one-hundredth of a second. After a bearing is obtained on the received signal, the tuning motor can again be started simply by pressing a push-button on the control panel. The use of the lock-on

* The reason that the pulse-repetition frequency of the radar limits the maximum usable rotational speed of the d-f antenna is that a certain minimum number of pulses are needed to outline the antenna pattern on the indicator. For a given radar prf, the d-f antenna should not be rotated faster than that speed at which one pulse is received every 8 or 10 degrees of rotation (See Reference (8)).

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circuit, which has been tested under actual operating conditions, greatly reduces the effects of operator inattentiveness and fatigue.

PERFORMANCE

Instrumental Bearing Accuracy

The instrumental bearing accuracy of the complete AN/BPA-1 direction finder was measured at frequencies of 3000 Mc, 4420 Mc, and 9470 Mc. These measurements were made with the d-f collector unit mounted on the top of the antenna pattern-plotting pedestal on the roof of Laboratory Building 29. The test signal emanated from a horn antenna in the horizontal plane of the d-f collector, and the d-f indicator was located in the operating room below the pedestal position. The d-f antennas were rotated continuously during these measurements. The test antenna was fixed in position, the d-f collector unit was rotated on the pedestal, and readings were taken for each 10 degrees of rotation of the pedestal. These readings were the angular position of the pedestal and the actual bearing obtained from the cathode-ray tube of the d-f indicator. Data were obtained for both vertical and horizontal polarization of the test signal. The results of these measurements are given in Figure 28 for the three test frequencies. The maximum instrumental error obtained was 5.5 degrees at a frequency of 4420 Mc. The general similarity in shape of all the error curves is significant. This is so because the d-f indicator error is such a large percentage of the total system error. This is readily seen by comparing the error curves of the d-f indicator, Figure 27, with those curves of Figure 28. From the results shown in Figure 27 and 28 it can be deduced that the error contributed by the Fiberglas radome and the d-f antennas is not large (about $\pm 2\frac{1}{2}$ degrees). The system error shown in Figure 28 is not considered too high for the type of service for which the AN/BPA-1 was designed. However, an appreciable reduction in the over-all instrumental error could be obtained by an improvement in the d-f indicator circuits.

Sensitivity and Range Tests

The sensitivity of a microwave direction finder of this type is important because it determines the maximum operating range of the equipment against radar signals. Assuming free-space propagation conditions (i.e., that the direction finder and radar antennas are within line-of-sight distance), the maximum operating range of the direction finder against a radar can readily be found. This maximum range

$$R = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r}{P_r}} \quad \text{meters} \quad (\text{Reference (9)}) \quad [1]$$

where P_t = power transmitted in watts,

P_r = d-f receiver sensitivity in watts,

G_t = power gain of transmitting antenna over an isotropic radiator,

G_r = power gain of d-f antenna over an isotropic radiator,

λ = wavelength in meters.

However, because the average radar transmitter has high power and high antenna gain, the maximum calculated range ordinarily turns out to be greater than the line of sight distance; consequently the above formula is not very useful.

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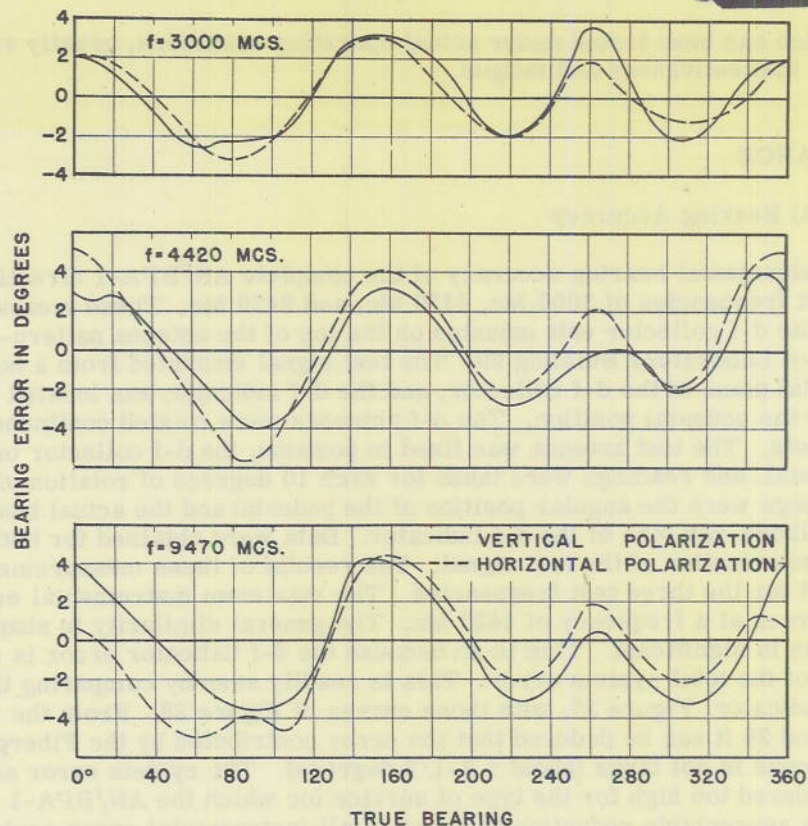


Figure 28 - Instrumental bearing error of AN/BPA-1(XN-1) system

A more useful equation for calculating the direction finder sensitivity is one which gives the rms field strength required for a given signal-to-noise ratio at the receiver output. This equation is derived in Appendix I and has the form,

$$E_{\text{eff}} = \sqrt{\frac{P_r Z_s^4}{G_r \lambda^2}} \text{ volts/meter} \quad [2]$$

where E_{eff} = the required rms field strength in volts/meter,

P_r = receiver sensitivity in watts for a given signal-to-noise ratio output,

G_r = power gain of d-f antenna over an isotropic radiator,

Z_s = impedance of free space ($Z_s = 120\pi$ ohms),

λ = wavelength in meters.

Since all the quantities on the right-hand side of the above equation are known, or can be found, the value of the d-f sensitivity can easily be calculated at various wavelengths. The results of such a set of calculations are given in Table 2. For these calculations the d-f antenna gain was obtained from Table 1 and the receiver sensitivity was assumed to be 106 decibels below one watt for a signal-to-noise ratio of two. The AN/BPA-1 indicator requires a minimum signal-to-noise ratio of about two for readable bearings, and the

above figure of 106 decibels below one watt is a reasonable average sensitivity for the AN/APR-9 receiver. Column 3 gives the required field strength calculated directly from Equation [2] while column 5 gives the required field strength when losses are included for the coaxial cable connecting the collector unit to the receiver. It is significant to note the reduction in sensitivity caused by only 25 feet of the RG-9/U coaxial cable. This problem of transmission-line loss will be discussed in a subsequent section of the report.

TABLE 2
Field Strength Required to Produce a Signal-to-Noise Ratio
of 6 Decibels at AN/BPA-1 Indicator

Freq. Mc	Antenna	Field Strength Required* (microvolts/meter)	Cable Loss (decibels) 25 feet RG-9/U	Field Strength** Required
2400	Lo-Band	1100	3.7	1680
3500	Lo-Band	1210	4.7	2080
5000	Lo-Band	1380	6.0	2760
5000	Hi-Band	1970	6.0	3940
8900	Hi-Band	1940	9.0	5450

*Assuming no coaxial cable loss

**Including coaxial cable loss (25 feet RG-9/U)

Engineers who are familiar with sensitivity figures of only a few microvolts per meter in the medium- and high-frequency bands may be surprised at the magnitude of the figures given in Table 2. The reasons for the magnitude of these figures are: (a) the very small effective apertures of the d-f antennas, and (b) the comparatively low sensitivity of microwave search receivers with wide over-all bandwidths. It must be remembered that the effective aperture (or absorbing cross section) of an antenna is proportional to wavelength squared, and this factor becomes rather small in the microwave region.

The value of the sensitivity data in Table 2 is seen when estimating the maximum intercept range of the d-f system against a given radar transmitter. Provided that the field strength curve of the radar is available, the maximum range of the AN/BPA-1 can be found by reading this range directly from this curve using the d-f sensitivity figure from Table 2. As an example, Figure 29 gives the field strength curve of an SG-3 radar at 3500 Mc with a radar antenna height of 130 feet and a receiving antenna height of 12 feet. This curve was calculated by the method of reference 10 and was checked in part by a second method. By using the sensitivity figure of the AN/BPA-1 at 3500 Mc from Table 2 ($E = 2080 \mu\text{V/m}$) the maximum range is found to be 37 nautical miles. This same method can be employed to estimate the direction-finder range against other radar transmitters, but each estimate is of necessity a rather special case depending upon the radar characteristics and the two antenna heights as well as upon the d-f sensitivity.

To show that the above method of estimating d-f range is accurate, however, the results of actual range tests will be given. Range tests of the AN/BPA-1 were made in May and July of 1949 in the Chesapeake Bay Area (Reference (3)). The direction finder was mounted on a landing craft (LCM) and operated against four different radar transmitters located at the Chesapeake Bay Annex of the Naval Research Laboratory. These radars, which were the SP, SG-1, and SG-3 at S-Band, and the SU-2 at X-Band, had antenna

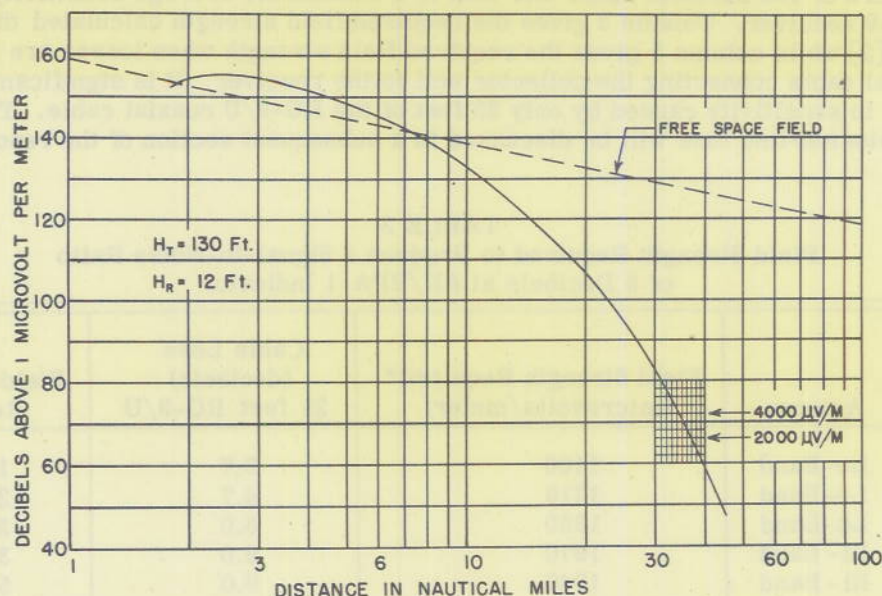


Figure 29 - Field strength versus distance for an SG-3 radar

elevations of about 130 feet. The d-f antenna was mounted at an elevation of 12 feet on the landing craft and was connected to the receiver with about 25 feet of RG-9/U cable. The landing craft was taken to a maximum range of 31 nautical miles, at which range three of the radars were still being received with signal-to-noise ratios of about 12 decibels or more. With these data and the field strength curves of the radars it is fairly simple to estimate the maximum range of the AN/BPA-1 against each radar. For example, by following the curve for the SG-3 radar (Figure 29) until the field strength has decreased 6 decibels below its value at 31 miles the maximum d-f range against the SG-3 is found to be about 34 nautical miles for a signal-to-noise ratio of 6 decibels. At this distance the SG-3 field strength is somewhat over 4000 microvolts per meter, which is about 6 decibels above the value calculated in Table 2 for the AN/BPA-1 sensitivity at 3500 Mc. This difference, however, between the calculated and measured values of d-f sensitivity is a result of having poorer receiver sensitivity during the range tests than the value of sensitivity assumed in the calculations of Table 2. In fact, the receiver sensitivity measured just prior to the range tests was about 6 decibels poorer than the value assumed in calculating Table 2. Thus the actual agreement between the range test results and the calculated d-f sensitivity is rather good.

On the basis of the results of the range tests conducted in the Chesapeake Bay a comparison is made of the AN/BPA-1 intercept range and the radar range in Figure 30. The radar range shown for each radar is the maximum reliable range against a surfaced submarine and the d-f range is the maximum intercept range as obtained in the actual range tests. Against these surface-search radars the AN/BPA-1 range is from 2-1/2 to 3 times the radar range against a surfaced submarine. Against a partially submerged or snorkeling submarine the radar range would be considerably less; consequently the direction finder advantage over the radar would be even greater than 2-1/2 to 3 times.

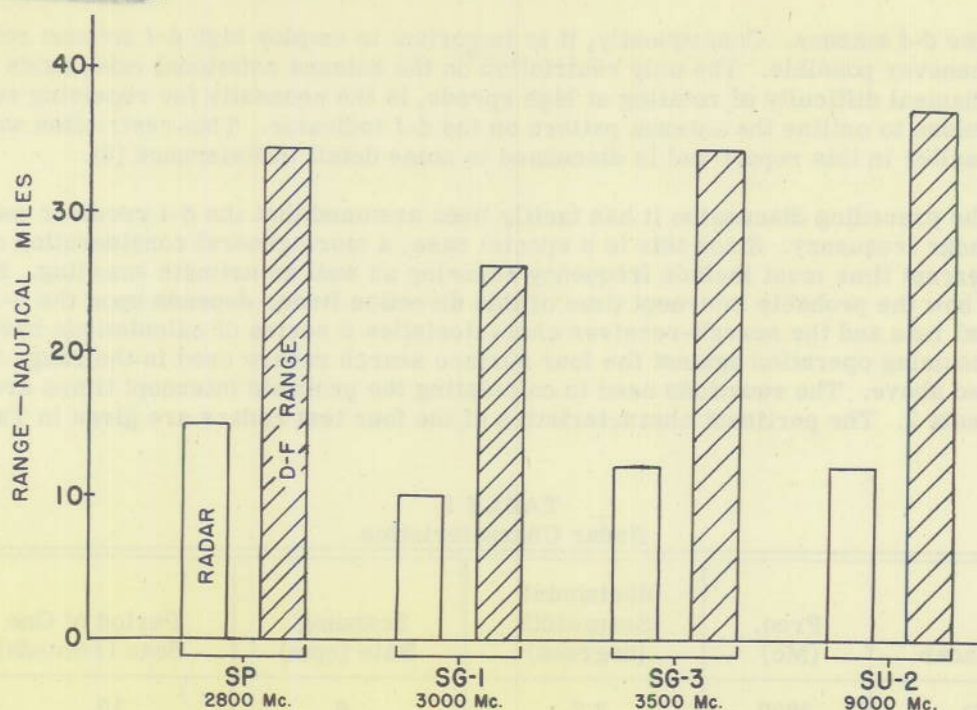


Figure 30 - Comparison of radar range and d-f intercept range

Since no tests of the AN/BPA-1 were made against an airborne radar, little can be said about its performance against such radars. It can be pointed out, however, that the maximum d-f intercept ranges against airborne radars will in general be considerably greater than those against surface radars because the line-of-sight distance from an airborne radar is large, depending upon its altitude. Thus, the field strength of the airborne radar is such that the direction finder can intercept it at much greater ranges than is possible against surface radars.

Probability of Intercept

A direction finder designed for countermeasure work must satisfy several important requirements such as accuracy, ease of operation, long trouble-free service, and high usable sensitivity. A fifth requirement, no less important than those just mentioned, is high probability of intercept. A microwave direction finder, such as the AN/BPA-1, is designed for operation against scanning-radar transmitters and cannot have certainty of intercept for any period of time less than that required for one rotation of the radar antenna. (This is on the assumption that the direction finder is within intercept range of the radar.) Since the AN/BPA-1 employs a rotating directional antenna the direction finder will have certainty of intercepting the radar during one sweep of the latter if the d-f antenna makes one complete rotation (360 degrees) while the radar beam is passing by the d-f position. If the d-f antenna makes only a fraction of one complete rotation during the time that the radar beam illuminates the d-f position, then the probability of intercept during one radar sweep will no longer be 100 percent. The above situation can be restated in the following manner: The probable time required to intercept a scanning radar transmitter with a rotating-antenna direction finder is inversely proportional to the rotational

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rate of the d-f antenna. Consequently, it is important to employ high d-f antenna rotational rates whenever possible. The only restriction on the antenna rotational rate, aside from the mechanical difficulty of rotating at high speeds, is the necessity for receiving sufficient signal pulses to outline the antenna pattern on the d-f indicator. This restriction was mentioned earlier in this report and is discussed in some detail in Reference (8).

In the preceding discussion it has tacitly been assumed that the d-f receiver was tuned to the radar frequency. Since this is a special case, a more general consideration of probable intercept time must include frequency scanning as well as azimuth scanning. In order to show how the probable intercept time of this direction finder depends upon the d-f antenna rotational rate and the search-receiver characteristics a series of calculations have been made assuming operation against the four surface search radars used in the range tests described above. The equations used in calculating the probable intercept times are given in Appendix 2. The pertinent characteristics of the four test radars are given in Table 3.

TABLE 3
Radar Characteristics

Radar	Freq. (Mc)	Horizontal Beamwidth (degrees)	Scanning Rate (rpm)	Period of One Scan (seconds)
SP	2800	2.7	6	10
SG-1	3000	5.6	12	5
SG-3	3500	3.0	5	12
SU-2	9000	1.8	6	10

It is seen that the half-power beamwidth of the SU-2 is considerably less than the beamwidths of the S-Band radars, and also that the amount of time the receiving position is illuminated by the radar beam, per scan, is less for the X-Band radar than for the S-Band radars.

Table 4 gives the probable time required to obtain an interception of the main beam of the four test radars by the d-f antenna when the AN/APR-9 receiver is tuned to the signal frequency and the direction finder is rotating at 300 rpm and at its maximum speed of 720 rpm. None of these radars have a pulse repetition frequency low enough to actually restrict the rotational rate of the d-f antenna to less than 720 rpm.

TABLE 4
Probable Time Required to Obtain a D-F Interception When the
AN/APR-9 is Tuned to the Radar Frequency

Radar	Probable Time Required for D-F Interception	
	$\omega_{d-f} = 300 \text{ rpm}$ (seconds)	$\omega_{d-f} = 720 \text{ rpm}$ (seconds)
SP	21.7	10.2
SG-1	10.6	4.9
SG-3	20.6	9.4
SU-2	29.9	14.6

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Table 5 shows the probable time required to obtain an interception of the main beam of the various radars when it is assumed that an omnidirectional receiving antenna is employed, and that the AN/APR-9 receiver is automatically searching over a frequency band of 537 Mc. (537 Mc is equal to 25 percent of the TN-129 (S-Band head) range and is equal to 14.5 percent of the TN-131 (X-Band head) range.) It is also assumed that the signal lies within this band being searched.

TABLE 5
Probable Time Required to Intercept Radar Signal Using Omnidirectional Antenna with AN/APR-9 Searching a 537-Mc Band

Radar	Probable Time Required for Interception (seconds)
SP	228
SG-1	113
SG-3	261
SU-2	237

Table 6 gives the probable time required to intercept the various radar signals when using both the d-f antenna rotating at 300 rpm and 720 rpm and the AN/APR-9 receiver searching over a frequency band of 537 Mc. It is again assumed that the signal lies within the frequency band being searched.

TABLE 6
Probable Time Required to Intercept Radar Signal With Rotating D-F Antenna and AN/APR-9 Receiver Searching a 537-Mc Band

Radar	Probable Time Required for D-F Interception	
	$\omega_{d-f} = 300 \text{ rpm}$ (seconds)	$\omega_{d-f} = 720 \text{ rpm}$ (seconds)
SP	568	269
SG-1	275	130
SG-3	535	261
SU-2	776	386

A comparison of the results given in Tables 4, 5, and 6 leads to the following conclusions:

- (1) The probable time required to obtain an interception with the AN/BPA-1 is considerably less when the d-f antenna rotates at maximum speed (720 rpm) than when it rotates at slow speed (300 rpm).
- (2) The probability that the AN/BPA-1 direction-finder antenna, when rotating at maximum speed, will obtain an interception of the main radar beam for each rotation of the S-Band radar antennas is high (above 90%).
- (3) The probability that the AN/BPA-1 antenna, rotating at maximum speed, will obtain an intercept of the X-Band radar during one rotation is only about 68 percent because of the narrow beamwidth of the SU-2.
- (4) The probable time required for a d-f antenna interception (Table 4) is considerably less than the probable intercept time for the AN/APR-9 receiver operated over a 537-Mc band with an omnidirectional antenna (Table 5).

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- (5) When both the rotating d-f antenna and the frequency scanning AN/APR-9 are used, the probable time required to intercept the principal radar beam is considerably longer at X-Band than at S-Band.

It should be pointed out that one reason the "probable intercept times" given in Tables 4, 5, and 6 are rather large is because the assumption was made that only the main lobe of the radar was available for interception. This is a reasonable assumption because it is important to know the probability of intercept which obtains when the radar first comes within range of the direction finder. As the range between the radar and direction finder gets smaller, eventually the radar side lobes will be received and the interception of the radar will then become much easier.

Improvement in Over-All Sensitivity

It was illustrated in Table 2 that the attenuation of the coaxial cable connecting the collector unit to the receiver degrades the over-all system sensitivity. As can be seen in the table, this cable attenuation increases with frequency. In the present installation of the AN/BPA-1 aboard the USS IREX, with the receiver tuning heads located in the conning tower, about 30 feet of RG-9/U cable is needed to connect the collector unit to the tuning heads. This length of cable has an attenuation of about 11 decibels at 9000 Mc. If the AN/BPA-1 collector unit were mounted on the top of the SV radar mast instead of on the periscope fairwater, a minimum of about 50 feet of transmission line would be needed. This emphasizes the need for some type of low-loss transmission line to connect the d-f antennas to the receiver. The logical answer to this situation is waveguide because of its low attenuation per unit length. A difficulty arises in using rectangular waveguide, however, when trying to cover a bandwidth of more than 4 to 1 (2300 to 10,600 Mc) with a single size of waveguide. A standard rectangular waveguide of given size covers a nominal bandwidth of less than 1.7 to 1.0 and ordinarily is not operated above the cutoff frequency for the second lowest mode (TE_{20}) because of the difficulties involved in trying to excite a waveguide when only a single mode in the existence of higher-order modes is possible.

Although some recent work (Reference (11)) indicates that it should be possible to operate a rectangular waveguide above the cutoff frequencies of higher-order modes, a somewhat different approach was undertaken. This was the development and test of a section of single-ridge waveguide to cover the frequency band of the AN/BPA-1. A cross-sectional view of this experimental ridge waveguide is shown in Figure 31. It is made up of a piece of standard UG-50/U (1-1/2 x 3/4) rectangular waveguide in which is placed a solid brass ridge measuring 3/4 x 1/2 x 36 inches. At each end of the waveguide section is a broad-band waveguide-to-coaxial-line transition. In order to facilitate the measurement of standing-wave ratios and attenuation per unit length, a probe slot was milled into the center of the broad waveguide wall opposite the ridge. A probe carriage was then mounted as shown in Figure 32. The standing-wave ratio of the coaxial-to-waveguide transition was measured by terminating one end of the ridge waveguide with resistance-strip material and measuring the input voltage-standing-wave ratio with a slotted line. The results of these measurements are shown in Figure 33. Although the standing-wave ratio rises at the low frequency end of the range it is believed that this could be improved by a change of the ridge dimensions, since the ones used are not considered optimum.

The measured attenuation of the ridge waveguide is shown in Figure 34 which also shows the attenuation of RG-9/U coaxial cable. The difference in attenuation between the two transmission lines shows the considerable improvement in sensitivity which can be effected by using the waveguide in place of the coaxial cable.

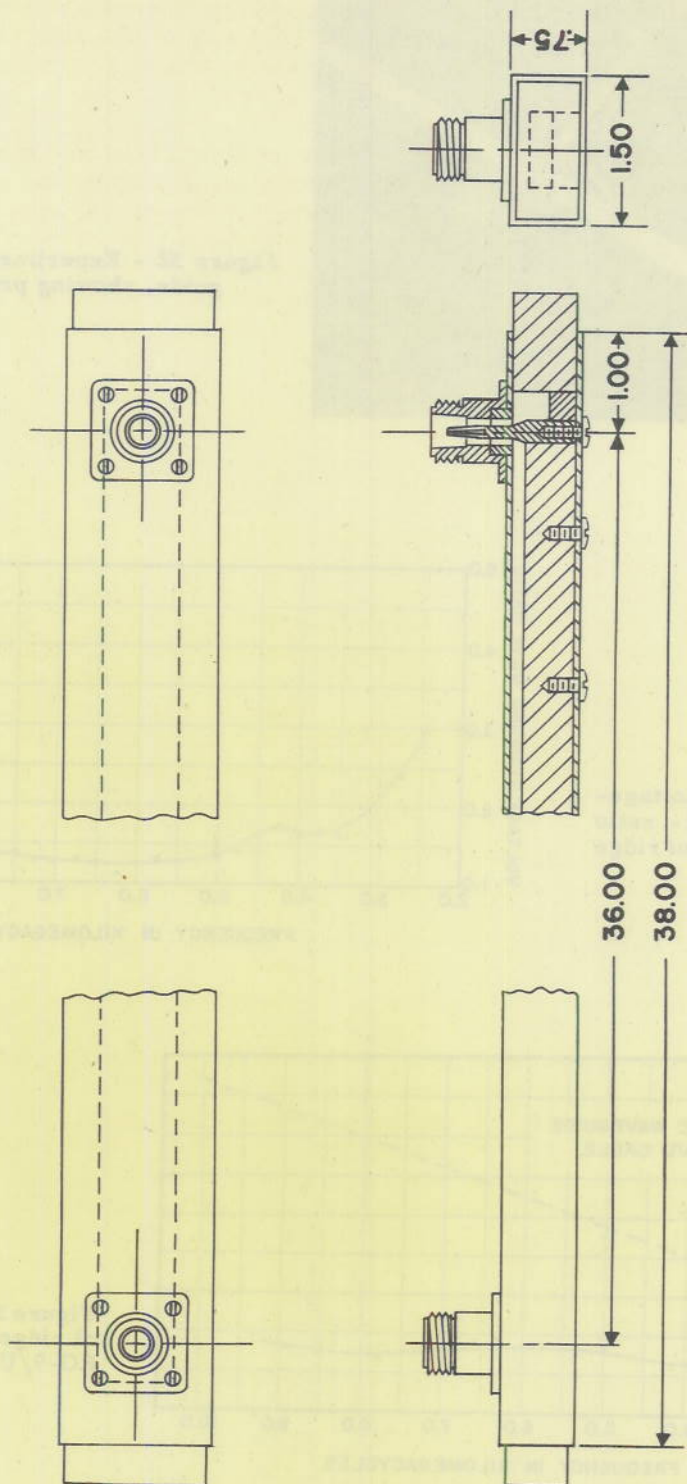


Figure 31 - Cross-sectional view of experimental ridge waveguide

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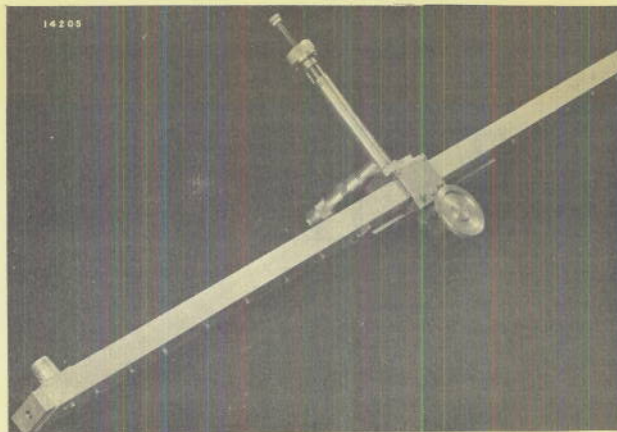


Figure 32 - Experimental ridge waveguide, showing probe detector

Figure 33 - Voltage-standing-wave-ratio characteristic of ridge waveguide

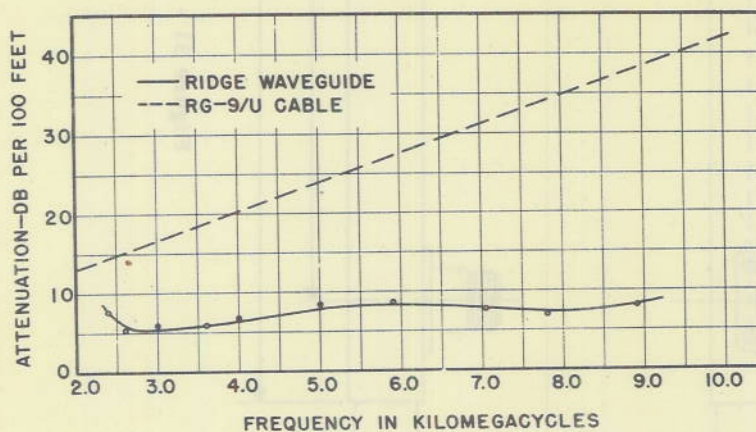
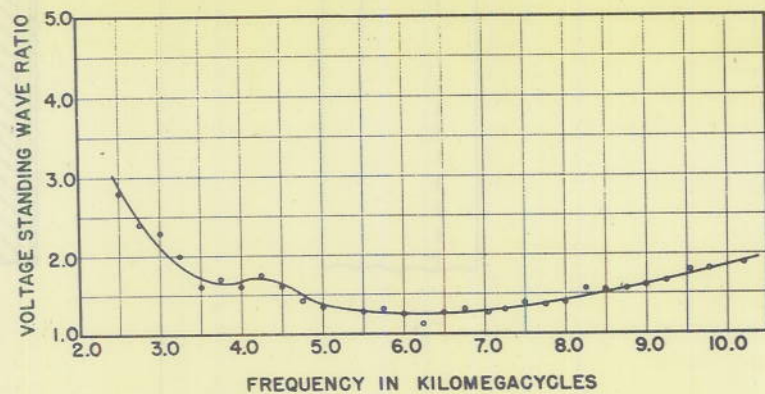


Figure 34 - Attenuation of ridge waveguide and RG-9/U coaxial cable

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The best method of fabricating the ridge waveguide has not been determined, but it is believed that electroforming, or some form of precision drawing, would be desirable because the guide made by this method would have low weight per unit length. A solid brass ridge is not desirable, of course, because of its large weight per unit length. It should be pointed out that the broadband-ridge waveguide described above may not be suitable for use in installations which require anything more complicated than an E-Plane bend. For installation in an extensible mast similar to that of the SV radar, only a straight run would be required.

CONCLUSIONS

The development of the AN/BPA-1 submarine direction finder illustrates the solution of a number of problems which result from: (a) the countermeasure nature of the equipment, (b) the broadband microwave coverage required of the equipment, and (c) the design of the equipment for installation on submarines. The direction finder described in this report has been designed to have high probability of intercept, better than average sensitivity, suitable bearing accuracy, and simplicity of operation. A continuous frequency coverage is provided from 2300 to 10,600 Mc which is considerably greater than was asked for in the original problem request. Range tests of the equipment have been made which show its appreciable advantage in range over a number of shipborne radars. A number of possible improvements have been pointed out which would enhance the performance of the direction finder, particularly with regard to increased bearing accuracy and sensitivity.

ACKNOWLEDGMENTS

Acknowledgment is hereby made to Mr. F. Harris, who guided the work on this problem until he left the Laboratory in 1948; to Mr. M. J. Sheets for the development of the d-f indicator and for his contributions to the design of the mercury rotating joint; and to Mr. C. R. Miller, who assisted in all phases of the development and testing of the direction finder.

As mentioned previously, credit for the development of the Fiberglass radome is due mainly to the staff of the Plastics Division of the Naval Ordnance Laboratory.

* * *

U N C L A S S I F I E D

APPENDIX I

Calculation of the Field Strength Required to Give a Particular Signal-to-Noise Ratio

Assuming a plane wave with the E and H vectors having the following form:

$$E = E_0 e^{j(\omega t - k n \cdot R)}$$

$$H = \frac{j}{\omega \mu} \nabla \times E = \sqrt{\frac{\epsilon}{\mu}} (n \times E) = \sqrt{\frac{\epsilon}{\mu}} (n \times E_0) e^{j(\omega t - k n \cdot R)}$$

where

E_0 = amplitude of E,

n = unit vector in direction of propagation,

R = position vector from origin to field point,

$k = 2\pi/\lambda$,

$\sqrt{\frac{\mu}{\epsilon}} = Z_S = 120 \pi$ ohms, impedance of free space.

With the d-f antenna situated in the above field, the power received will be

$$P_R = S_0 A_R \text{ watts}$$

where

S_0 = average Poynting vector,

A_R = absorption cross section of receiving antenna.

Now,

$$S_0 = \frac{1}{2} \text{Re} (E \times H^*) = \frac{1}{2} \sqrt{\frac{\epsilon}{\mu}} |E_0|^2$$

or

$$S_0 = \frac{E^2_{\text{eff}}}{Z_S}$$

Also,

$$A_R = \frac{G_R \lambda^2}{4 \pi}$$

where G_R = power gain of receiving antenna over that of an isotropic antenna. Therefore, the received power

$$P_R = \frac{E^2_{\text{eff}}}{Z_S} \cdot \frac{G_R \lambda^2}{4 \pi}$$

or

$$E^2_{\text{eff}} = \frac{P_R Z_S 4 \pi}{G_R \lambda^2}$$

$$E_{\text{eff}} = \frac{2 \pi}{\lambda} \sqrt{\frac{120 P_R}{G_R}} \text{ volts/meter.}$$

Thus, the required rms field strength, E_{eff} , can be determined if the receiver sensitivity P_R , for a given signal-to-noise ratio, and the receiving antenna gain G_R are known.

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APPENDIX II

Formulas Used to Calculate the Values of Probable Time Required
for Intercept Given in Tables 3, 4, and 5

These following formulas were obtained from the Appendix of Reference (12). The following symbols are used:

T = period of rotation,
 t = duty period of antenna beam in a given direction.

The subscripts 1 and 2 refer to the radar and d-f antennas respectively. For the search receiver:

T_3 = period of cyclic frequency coverage,
 t_3 = duty period on one frequency.

1. Consider the radar and d-f antennas only, that is, for the search receiver tuned to the radar frequency. For this case the probable time required for an intercept,

$$T_{12} = \frac{T_1 T_2}{t_1 + t_2}.$$

2. Consider the search receiver with an omnidirectional receiving antenna operating against a scanning radar transmitter. In this case the probable time required for intercept,

$$T_{13} = \frac{T_1 T_3}{t_1 + t_3}.$$

3. Consider the rotating antenna direction finder with frequency scanning receiver operating against a scanning radar transmitter. For this case the probable time required for intercept,

$$T_{123} = \frac{T_1 T_2 T_3}{t_2 t_3 + t_3 t_1 + t_1 t_2}.$$

In the above formulas the probable time of intercept is defined as the time interval during which an average of one intercept can be expected on a long-term search.

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