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CIRCULARLY DISPOSED ANTENNA ARRAYS

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NRL REPORT NO. R-3213

CIRCULARLY DISPOSED ANTENNA ARRAYS

James H. Trexler

Approved by:

Mr. E. A. Speakman, Head, Countermeasures Section
Dr. L. A. Gebhard, Superintendent, Radio Division II

Problem No. 39R06-07 December 18, 1947

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CONTENTS

ABSTRACT

A radio intercept system combining properties of high sensitivity, precision direction finding and good intercept probability on signals of short duration is the subject of this preliminary report. A survey has been made of the properties of a circularly disposed antenna array known as the Wullenweber used by the German Navy during World War II. The results of this investigation are discussed, indicating a promising approach to intercept and direction finding problems. Primary emphasis has been placed on shore-based systems intended to work on a world-wide scale in the communication bands from 2 to 28 Mc. Systems with sensitivities equal to the best Rhombics and bearing accuracies five to ten times better than existing Adcock arrays seem to be within the realm of immediate possibility.

PROBLEM STATUS

This is an interim report on this problem: work is continuing.

AUTHORIZATION

The work reported on herein represents a comprehensive analysis of the general field of interception and direction finding. It is more specifically concerned with the universal intercept system covered by BuShips Problem S-1255.

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CIRCULARLY DISPOSED ANTENNA ARRAYS

INTRODUCTION

Circularly disposed antenna arrays reached their most advanced development in Germany during the recent war. Intelligence reports* reveal that over a period of several years the Germans operated such systems successfully for long-range direction finding where received signal strengths were below the noise level of the conventional Adcock arrays. Their submarines operating in the Atlantic were incapable of carrying antennas large enough to beam their signal on Germany to reduce interception, but the Wullenweber circularly disposed antenna array enabled fixes to be taken from low-powered radiations.

Unfortunately the German arrays were dismantled before a full evaluation of their merits could be made by the scientists of the occupying forces. It is believed that the circularly disposed antenna arrays possess potential usefulness to the U. S. Navy sufficiently great to warrant further exploration. The report is a survey of those potentialities with special emphasis on the technical aspects peculiar to naval application.

Recently, U. S. military activities have become interested in the properties of circularly disposed antenna arrays. The Air Forces have led the way by inaugurating a problem in the very high frequency band. In this case, the advantages of the antenna patterns produced by such arrays are to be utilized in producing a navigation aid for airport use that will allow direction finding operations on a multiplicity of signals at the same frequency. There are, however, no known active countermeasure applications of circularly disposed antenna arrays except by the Admiralty Signal Establishment of England and possibly investigation by the U.S.S.R. whose forces captured at least one Wullenweber system during the last war.

The immediate interest in circularly disposed antenna arrays is for use as a high-gain shore-based high frequency direction finder and intercept device. The bands at high frequency will certainly be used for a long time to come as means of military communications over great distances. As long as this condition exists it will be necessary to provide the best intercept equipment possible. The circularly disposed antenna array as described here is not the ultimate, but merely a step in what seems to be the right direction. Application of circularly disposed antenna arrays to other frequency ranges may prove profitable, but their greatest usefulness at the moment seems to be in the range from 2 to 28 Mc.

Several representatives from the Naval Communications Annex and the Bureau of Ships have consulted the author recently concerning the Wullenweber system. On 2 April 1947, a conference was held for the purpose of providing the Bureau of Ships with results of the Wullenweber investigation carried out by NRL. Twenty-four specially prepared drawings were presented and several hours were spent in discussion. Other conferences

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* Schlicke, <u>Electronics Research in the German Navy</u>, U. S. Division of Naval Intelligence, 15 September 1945

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on 16 July and 13 August were concerned with detailed discussions of the circularly disposed antenna array. Representatives from the Naval Communications Annex were present at all three meetings. This accumulated interest in the problem has encouraged the Radio Countermeasures Section to prepare a considerable amount of additional data on CDAA. Sixty graphs and drawings, all suitable for publication, were prepared along with 260 pages of notes (NRL Log Book No. 7023).

Because of the preliminary nature of this report, detailed drawings of the complex arrays and associated circuits of the circularly disposed antenna array were not prepared. Ten simplified sketches have been drawn, however, to summarize the more important analytical work carried out and to picture the physical array and the bearing indicators. Many of these sketches describe arrays which would be far too small for practical use but serve very well for examining such characteristics as beam width and side lobes. The Rhombic Rose and the Navy's Model DAJ Crossed-H Adcock direction finder systems are used as basis for comparison throughout this report, since they exemplify the high frequency intercept art in the United States today.

SYSTEM DESCRIPTION

Since the CDAA class of antenna is not well known, a brief description of its operating principles may be in order. In simple terms, a circularly disposed antenna array is one in which a group of simple antenna elements is arranged in a circle and connected in such a way that for one azimuth of signal arrival the r-f phases from each of the elements are the same. This arrangement will give a sharp directivity pattern since at all other azimuth angles a signal would not produce the proper phase matching for maximum output. The phase matching is done in a delay-line type of goniometer which allows the matching to be achieved at any desired azimuth by the simple rotation of a shaft. No brushes or other noise-producing devices are necessary, and the only modulation applied to the incoming signal is due to the directivity pattern of the array sweeping past the target angle during each rotation of the goniometer. In the Wullenweber system a circular screen is erected with each vertical, collecting element placed about one-quarter of a wavelength in front of it. The azimuthal directivity pattern of each element is then approximately a cosine-shaped curve through the first one hundred and eighty degrees. This is often called a tangent circle pattern. The vertical directivity pattern is a cosine curve through ninety degrees, that is, maximum on the horizon and decreasing to zero at the zenith. For any one direction of signal arrival only half of the elements in the circle will "see" the signal, due to the azimuthal directivity of the elements caused by the screen. The Wullenweber's goniometer utilizes at one time an antenna arc 90 degrees wide. The lower level elements at the edges of the array are not used. In some of the arrays designed at NRL, however, all the active elements are used and this results in a higher gain for a given side-lobe level. The side lobes are controlled by adjusting the amplitude as well as the phase in the goniometer. In some cases analysis has shown that it is possible to reduce side lobes to -26 db. This is considered very good for any type of directive antenna. The more complex arrays using tapering and wide-angle apertures have been called circularly disposed antenna arrays to distinguish them from the Wullenweber. The Wullenweber, however, is a special case of the family of circularly disposed antenna arrays.

Figure 1 shows a simplified top view of a small 18-element array. Such an array has too few elements to be practical, but the physical design principles can be seen. The circular screen is shown as a series of vertical wires supported by 80-foot telephone poles, while the 18-elements are modified, inverted pyramids, constructed of vertical wires strung between the poles of the screen and another ring of poles placed outside the screen. The elements have a peripheral spacing of

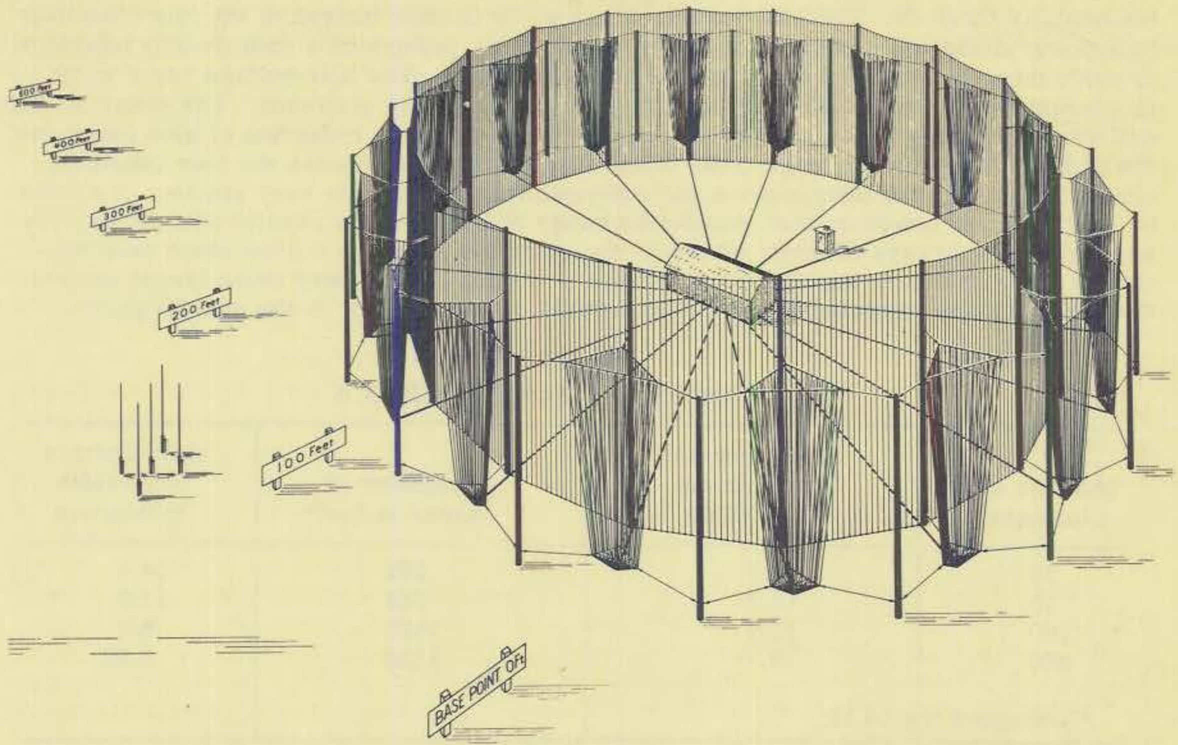

Fig. 1 - A Circularly Disposed Antenna Array of 18 Elements

one-half wavelength at the mean frequency of the array. There are many variations to the method of construction and the one shown is among the simplest capable of very broad band operation. Since each of the elements of a CDAA is identical, it is easy to visualize a system of as many elements as desired. A further discussion of some of the components of the system will be found later in the report. A sketch of the standard Navy DAJ Band-3 Adcock is included in Figure 1 for comparison with the CDAA. Both arrays have a mean frequency close to 10 Mc.

The subject of antenna pattern side lobe suppression is one of the most involved and interesting side issues of the CDAA problem. Much of the work carried out thus far by NRL has been concerned with this feature. An extremely interesting set of 23 graphs has just been prepared to show the relation between the array's angular aperture, the beam width and the side lobe level for tapered and non-tapered arrays. An even more ambitious program of calculations is planned, but it will not be completed for many months. The author feels that the side lobe theory evolved to date is an important contribution to the subject and could make future CDAA far superior to the original German systems.

In the table below are listed the gain, diameter and beam width of four different sizes of circularly disposed antenna arrays. The center design frequency is 10 Mc and the element spacing is taken as one-half wavelength. Notice that each listing in the table has twice the number of elements, and, consequently, twice the diameter of its predecessor. Since the outputs of the elements combine as power, the gain in doubling the number of elements is three db. The half-voltage beam width is used instead of the more familiar half-power designation because the appearance of the pattern on a cathode-ray indicator is more meaningly described by the half-voltage points. The half-voltage beam width is approximately equal to 610 divided by the total number of elements. The constant, 610, will vary according to the amount of tapering desired for the reduction of side lobes and the width of the aperture angle used. The simple relations between the four tabulated characteristics make interpolation and extrapolation of the table very simple. It should be kept in mind, however, that outside the range of the table the results will not be very accurate. For arrays of fewer elements the grain becomes too coarse since each element's contribution is too high a percentage of the total. For very much larger arrays the attenuation in interconnecting cables would become a factor in the overall gain.

TABLE OF CDAA CHARACTERISTICS

Number of elements	Gain over an Isotropic antenna in db	Diameter of Array in feet*	Half-Voltage beamwidth in degrees
25	9.7	392	24.4
50	12.7	784	12.2
100	15.7	1568	6.1
200	18.7	3136	3.05

* Designed for 10 Mc.

To give a simple and compact picture of the characteristics of large beamed arrays, Figure 2 was prepared. The German Wullenweber, the NRL CDAA and the Rhombic Rose are compared electrically and physically. The figure is self-explanatory but several features may need emphasis. First, the plan views of all three arrays are to the same scale as are the field patterns. The Wullenweber shown is similar to the German's Hjoerring, Denmark installation. The Tapered "55/120" Circularly Disposed Antenna Array is merely one of several arrays for which the characteristics have been computed. The "55/120" designation indicates that there are 55 active elements at any one instant, although the array has 120 elements in all. The Wullenweber, on the other hand, uses a lower percentage of active elements, and is, by the same designation, a "12/48" array, or 12 active elements in an array of 48 elements. The "tapered" designation indicates a tapering off of pickup on the edges of the array to reduce side lobes. The 4λ Rhombic Rose is similar to several search arrays now in operation in this country and was included in Figure 2 to give a basis for comparison. The number of elements in such Roses varies greatly, depending on the gain required and the space available. Some systems such as the one on Guam have 27 elements. It should be stressed that there is no rotating beam in the Rhombic system, but rather a multiplicity of fixed beams (two for each Rhombic element) which may be switched in and out for search or monitoring service. The gains of all three arrays are compared to an isotropic element. These gains are correct for all azimuths in the case of the first two systems; but between beams on the Rhombic Rose shown, the gain will drop about two db, or from 16.8 to 14.8.

The next section of this report will be devoted to a discussion of 12 outstanding advantages of the circularly disposed antenna arrays. An attempt will be made to point out which claims are taken from German documents and what work has been verified or originated by the author.

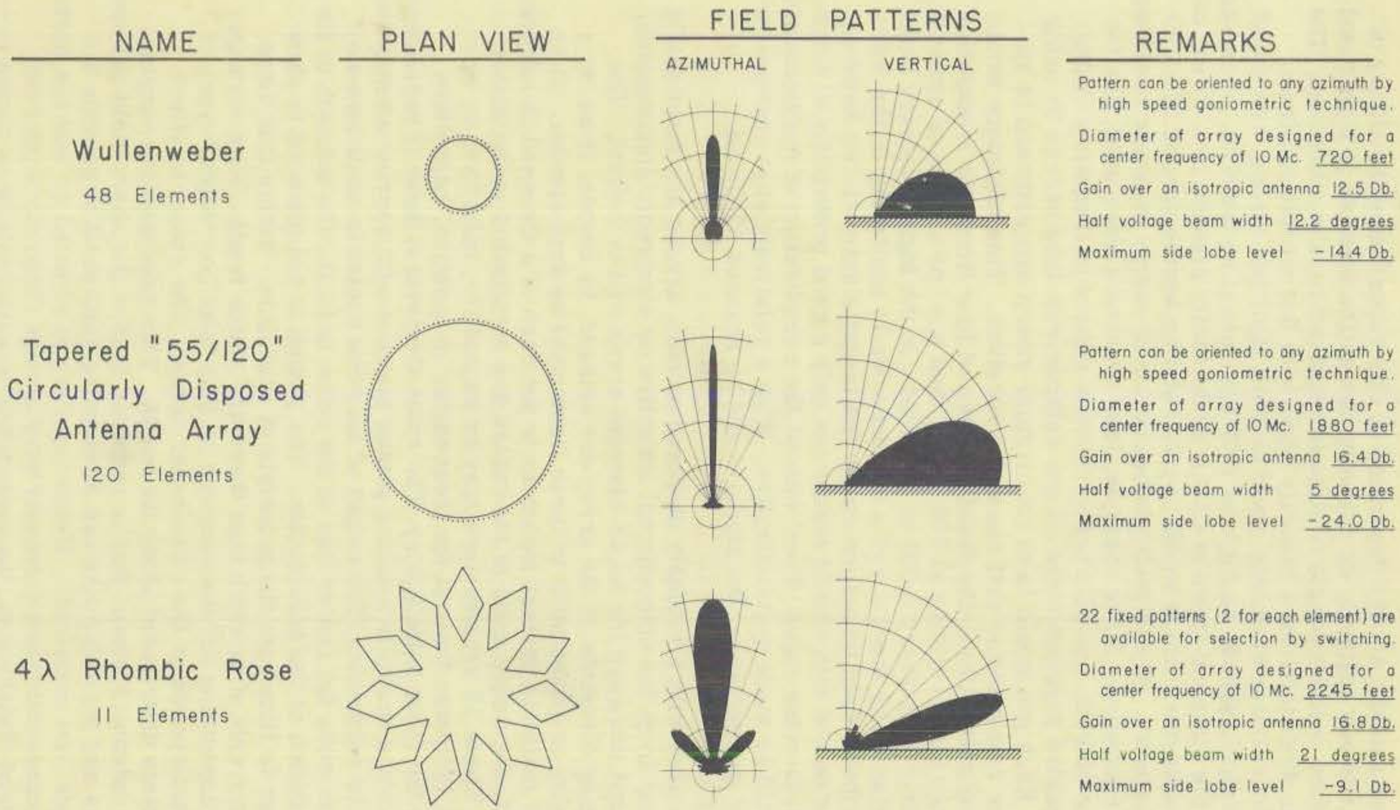

Fig. 2 - Comparison of Three Large Intercept Antenna Arrays

HIGH SPEED AZIMUTH SCANNING

The circularly disposed antenna arrays described in this report have the ability of "aiming" their beams towards any azimuth, or scanning the entire azimuth at high speed. As in all goniometric systems, a finite length of time is required to take a bearing. The goniometer assumed in this discussion is a capacity type, with the normal rotational speed limitations. Since the rotating elements could be built light and strong, and would, by their nature, be symmetrical, speeds as high as 7200 rpm would be feasible. A second consideration is that even the simplest types of CDAA could easily provide two, three, or four outputs from their goniometers which would supply rotating beams spaced 180, 120 or 90 degrees around the azimuth. These multiple beams could supply separate receivers at the same or different frequencies. If,for example, four receivers were used, one for each of the four goniometer outputs, and all receivers were ganged in frequency tuning, their outputs could be presented superimposed on one cathode-ray-tube screen by using a standard four-gun tube. Each gun would have its circular sweep synchronized in azimuth with the rotating beam connected to that channel's receiver. This technique would give four times the scanning rate without the disadvantages of four times the modulation frequency. If the goniometer were rotating at 7200 rpm, then any one section of azimuth would be swept approximately once every 0.002 of a second. In the high-frequency band the shortest usable transmission is about 0.4 of a second--due to scattering in the ionosphere. The system described would therefore sweep the target's azimuth two hundred times during the transmission and this should insure not only a good probability of intercept but also a good signal-to-noise ratio. Even without the complication of multichannel operation, the scanning could be made quite effective. With a relatively slow goniometer speed of 3600 rpm and only one receiver, the signal would be scanned 25 times.

Since the goniometers used with circularly disposed antenna arrays are electrically and physically very different from the conventional inductive or electronic goniometers, a description of a simple unit designed for an 18-element array will be helpful. The outputs from the 18 collecting elements of the array are brought, by coaxial lines, to a central point. The time delay or phase shift in these lines must be kept similar. It is not necessary, however, to maintain perfect match as in the case of a Crossed-H Adcock array. At the central point, the output ends of the cables are terminated in the stator elements of variometers. These 18 variometers may be capacitive, inductive, or electronic, but past experience indicates that, at the frequencies in question, capacitive coupling would prove to be the most satisfactory. The rotor elements of these 18 variometers lose their identity and become a multiple rotating pickup element with varying attenuation and phase delays between its segments. The output of the rotor varies in amplitude with rotation, having a maximum when the center line of the rotor is facing the azimuth of the target. Figure 3 shows a sketch of the goniometer. The sketch is not intended to show schematic details but rather to illustrate the principle of operation. Notice that there are more rotor elements per unit of azimuth than there are stator feeds. This arrangement is for the purpose of smoothing out the coupling so that "slot" or "tooth" types of modulation will not be superimposed on the goniometer output. The rotor, in effect, is a delay line with feed points distributed along its length. This produces the varying delay to the output of each antenna element that is required to give the sharp field pattern. Between the rotor elements and the delay line are attenuating pads used to provide the taper which reduces the side lobe amplitude. If this tapering is adjusted so that the useful effective heights of the antenna-collecting elements vary across the array's aperture according to a cosine-squared distribution, the goniometer's output will be as shown in Figure 4. This modulation envelope is drastically different from that of a conventional Bellini-Tosi system as used in the Model DAJ. The B-T goniometer produces a suppressed carrier type of spectrum while the CDAA goniometer's output resembles the "ideal pulse" in shape. The "ideal pulse" is defined as the pulse whose shape has the most easily

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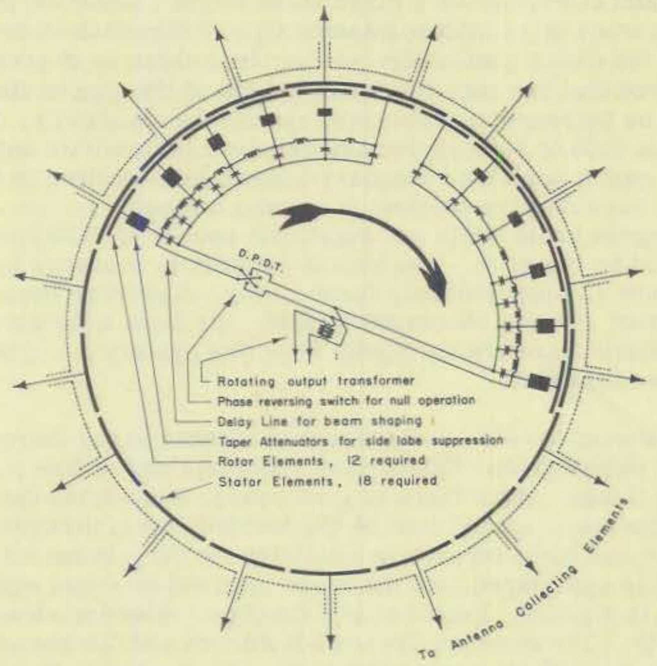

Fig. 3 - A "9/18" CDAA Tapered Goniometer

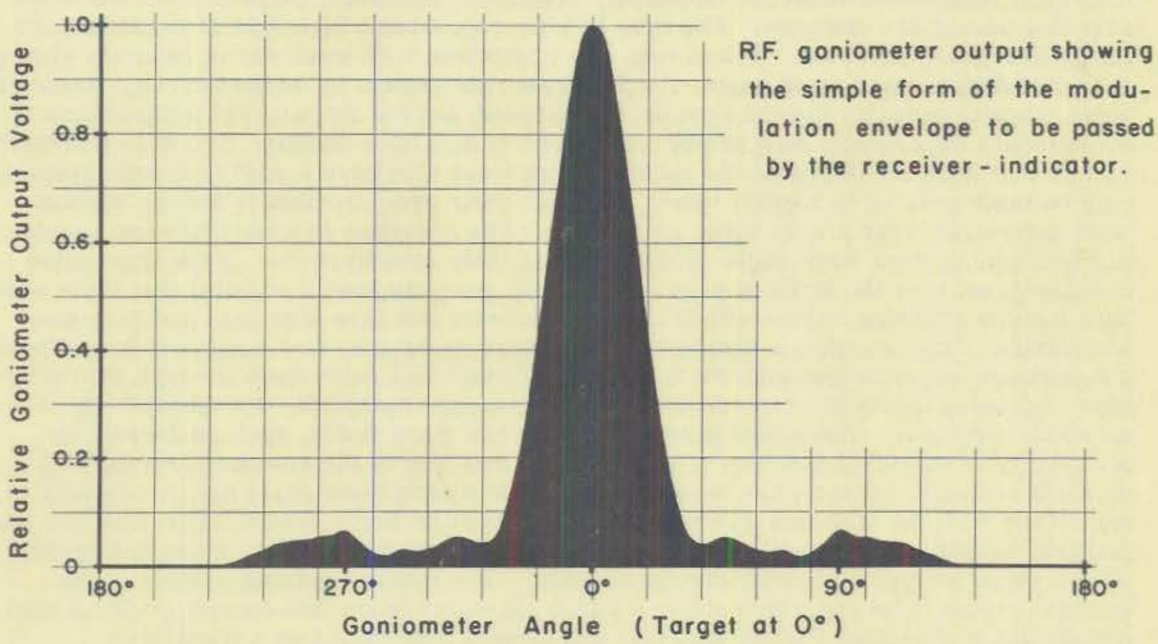

Fig. 4 - Modulation Envelope of a Tapered CDAA

transmitted side band spectrum for a given pulse length. Since the pulse length is a measure of the accuracy of a rotating-beamed type of direction finder, the fact that the pulse produced by the CDAA goniometer has an ideal shape is of great importance. It must be remembered that for high rotational speeds of the goniometer the bandwidth of the receiver must be increased and this will reduce the sensitivity. For most intercept work, bandwidths of 1000 to 3000 cycles are required to facilitate quick tuning. These bandwidths should easily pass the necessary components involved in the goniometer speeds described earlier, providing the number of antenna elements is low. For large arrays having only five-degree beam width and rotational speeds of 7200 rpm, however, a bandwidth of 30 kc would be required. The loss in sensitivity produced by this ten-to-one increase in bandwidth is approximately three to one. A greater loss might result due to the lack of selectivity, causing increased interference from adjacent signals. Hence, it would seem inadvisable to rotate the highly directive systems at speeds requiring a compromise in receiver bandwidth.

In the description of the circularly disposed antenna array there was no consideration of the fundamental philosophies of directional intercept and of how a scanning system fits into the scheme of things. Since there is good reason to question the advisability of scanning types of systems, a brief look at the possibilities of directional intercept may be in order. There are three techniques available for directional intercept if only the collecting element is considered, and the more involved terminal equipment which can take on infinite variety is omitted. The first and simplest collecting element is the wide-angle antenna or eye. The common Crossed-H Adcock and the human eye fall in this class. The second class of element is the narrow beam used in the circularly disposed antenna array, radars and telescopic equipment. These beam systems must sweep or scan to obtain wide-angle coverage. The compound-eye or multiple-beam collector is the third general class. This system requires the most complex terminal equipment but reaches the highest efficiency of directional intercept. It is interesting to note that nature has found, through evolutionary experience, that for high-efficiency, defensive intercept, omni-directional non-scanning coverage is required, while in offensive work scanning beams are adequate. The eyes of a fly represent a high type of instantaneous omni-directional coverage. These eyes are compound, with hundreds of separate elements, each covering a small solid angle. To duplicate this system in radio intercept would involve more complexity than has yet been attempted, but the fly, with its millenniums of evolutionary experience, may predict the future of direction finding. It is also interesting to note that such creatures as the rabbit, which must also have a good intercept system, rely on their hearing to a great extent, although their eyes are able to detect, without head movement, over a very large solid angle. The sacrifice in sensitivity and resolution inherent in such wide-angle systems limits their effectiveness. If the aggressive creatures, such as the birds of prey and the fox, are examined it is found that their eyes have narrow scanning angles without head movement, but have high gain and very good sensitivity. This provides a comparison with devices such as fire control radar. These comparisons seem to demonstrate that there are only two paths open for high gain intercept: scanning highly directive beams,or simultaneous reception on a multiplicity of fixed directive elements. The scanning beam system has many faults, such as decreased probability of intercept and loss of intelligence, both due to the scanning process. The multiple collector system, has been considered on a simplified scale but, to compete in sensitivity with the scanning technique, it would require more complication than has been justified to date. A description of a multi-element system using the CDAA as a multiplexed collector will be briefly discussed later. The most promising system at the moment seems to be one which scans a highly directive beam fast enough to obtain high probability of direction finding intercept and directs monitoring on a fixed beam.

It has been assumed in this discussion that instantaneous systems such as the Watson-Watt Crossed Adcock are fundamentally too insensitive to cope with the signal levels involved, or that interference, both natural and man-made, would so clutter the information that it would become useless. Schlicke summed up the whole question for goniometric Adcocks when he said that rotating, null-type, omnidirectional systems were "just plain stupid". Before condemning beam-scanning systems such as the circularly disposed antenna arrays because of their less than ideal principle, it should be remembered that beamed arrays have two advantages: first, the signal level is increased, and second, directional interference is suppressed. These two factors working together give a greater improvement in operation than the simple gain figure for the antenna might indicate.

The fundamental principles of scanning arrays by phase and amplitude control of the elements as is done in the circularly disposed antenna array is not new with the German Wullenweber. Arrays containing more than 200 elements were phase-shift scanned at high rates in some of the blind-bombing equipment developed by the United States during the war. Even though the scanning technique proposed for use with the CDAA is not ideal in all respects, it is far superior to any type of lobe switching that might be used with the Rhombic Rose which represents the art in the United States today. It is true that phased Rhombic arrays such as the Bell Laboratories' MUSA will give a certain degree of beam control, but the necessary complication to obtain high-speed, complete azimuth coverage does not seem justified in view of the many undesirable features of the resulting field patterns. If enough Rhombics could be installed to simulate the compound-eye technique, a fairly useful system might result, but again the undesirable field patterns produced by Rhombics would make the system less desirable than a multichannel CDAA.

AUTOMATIC BEARING INDICATION

The circularly disposed antenna array is ideally suited to automatic bearing indication (ABI). The shape of the array's field pattern is suitable for direct cathode-ray-tube presentation. As is the case with all maximum indicating systems, the gain of the receiving equipment must be adjusted to maintain the maximum of the pattern near the periphery of the screen. This is normally accomplished by manual control, but when the highest speed is required, automatic methods are desirable. Automatic gain control (AGC) is possible but will introduce considerable complication if it is to operate on all types of signals. The CDAA's property of low side lobes makes direct pattern display much cleaner and reduces the requirements on AGC. Figure 5 shows the relative appearance of automatic bearing indicators connected to three different direction finders, all operating at 10 Mc and at two different r-f field strengths. The first system is the Model DAJ, Band 3, Crossed-H Adcock. The second system is the German Wullenweber of 48 elements. The third system is the Tapered "55/120" Circularly Disposed Antenna Array which was described in Figure 2. The top three drawings represent the appearance of the three ABI's for a field strength just sufficient to give a 1-to-1 signal-to-noise ratio on the Model DAJ. This same field strength gives about a 4-to-1 signal-to-noise ratio on the Wullenweber and a 6-to-1 ratio on the larger 120-element CDAA. The three drawings at the bottom of the page show the appearance of the same three indicators when the field strength is raised six times, producing a 6-to-1 signal-to-noise ratio on the Model DAJ and ratios of 24-to-1 and 36-to-1 on the Wullenweber and 120-element CDAA respectively. From these sketches it can easily be seen why maximum indicating systems have advantages over null systems at low signal levels. To obtain a really "clean" pattern on the DAJ a signal-to-noise ratio of at least 30-to-1 is required. On the other hand, a 10-to-1 ratio will produce a good pattern on a circularly disposed antenna array's automatic bearing indicator which gives the CDAA another 10-db advantage over and beyond its antenna-gain figure. In other words, the "bearing sensitivity" of the 120-element CDAA discussed here should be 26 db better than the Band-3 DAJ. The additional advantages of the circularly disposed antenna array, which tend to enhance the bearing presentation, include the ability to resolve two or more interfering signals and to operate on modulated signals with higher resolution.

Periphiral scanning can be used with CDAA systems if null-type indication is desirable. This kind of operation produces the highest type of bearing resolution, but at the sacrifice of gain and speed of operation. The advantage of satisfactory operation over very wide ranges of signal levels without the need for AGC may make this type of operation very desirable. The null mode of operation will be discussed in more detail later, but as far as automatic indication is concerned it would be very satisfactory.

The resolution of bearing information obtained by the CDAA will be inherently far finer than direction finders normally used with ABI. Further, this finer resolution justifies itself, since the system has higher accuracy. With meaningful bearing data in tenths of degrees, it will be necessary to improve the bearing indicators to obtain the full usefulness of the system. One simple and obvious method would be to have an auxiliary indicator with only a few degrees around its periphery. Push buttons spaced around the master indicator could select the sector for this vernier scan, or other switching devices could be worked out. Automatic selection of the vernier sector is not impossible and in some cases more than one vernier indicator might be justified.

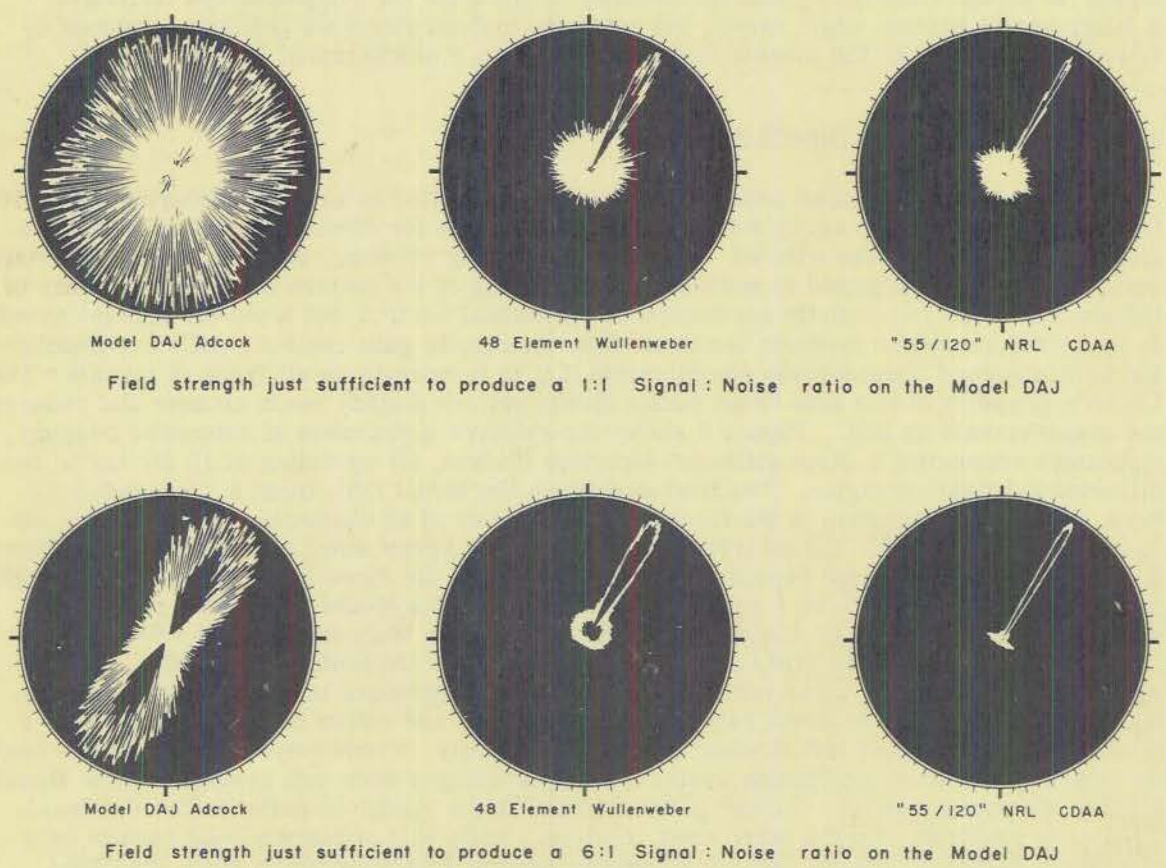

Fig. 5 - Comparison of Bearing Indicators

There are many types of directional displays which, in combination with the CDAA, might give very fine results. The B type of scan, displaying information in a Cartesian coordinate form, is ideal for restricted azimuth work and would serve nicely for the vernier system described above. The J type of scan, displaying information in a circular coordinate form, also has advantages, especially in a system with low side lobes. There is a rather new type of display which has been loosely called "television scan". In this system a long persistence screen is "painted in" radially with a high speed sweep, while the rotating scan is maintained in synchronism with the antenna beam. The intensity of the spot is controlled by the output of the receiver while the brightness increases with receiver output. This type of scan can also take the form of a television raster giving a B type of display. The receiver is adjusted so that the entire screen is dimly lit by background noise. When the antenna beam sweeps through a signal, the intensity rises and a wedge-shaped area appears on the scope, with the bearing of the signal the bisector of the wedge. Since the noise is completely random in nature and the signal is constant, an integrating action will take place. This action will make the screen much brighter where the signal is than where only the random noise is if the signal remains for several sweeps of the beam. The advantage in signal-to-noise ratio gained by this type of display can be as high as 15 db, making signals having a voltage level of only one-fifth of the noise show up very plainly. Such techniques require very sharp antenna patterns if the bearing information is to be usable. Patterns such as shown for the 120-element CDAA in Figure 2 would be ideal for this type of operation. Utilizing this televising type of display, the effective sensitivity of the 120-element CDAA would be 41 db better than the present DAJ. This means that if one-microvolt-per-meter signals are now detectable, the CDAA should allow detection of 0.01-microvolt-per-meter signals.

It should not be necessary to rely in any way on German techniques in developing the bearing indicating systems, since the United States has consistently led the field. The Radio Countermeasures Section has done a considerable amount of work on direction finder indicators and this work has led to the conclusion that CDAA indicating systems can be made both accurate and simple. In comparison, the Rhombic Rose shown in Figure 2 does not lend itself at all well to automatic bearing indication. Sector comparison methods and lobing techniques could be applied, but the only hopeful approach would be to use 22 amplitude-matched receivers, tracking in frequency and using a continuous sector-comparison display. Such a system would approach, in a crude way, the ideal compound-eye system of the fly, but would still be inferior to the CDAA multibeam system.

ANTENNA AZIMUTH PATTERN

The circularly disposed antenna array has a very narrow azimuthal beam width compared to most high frequency antennas of similar gain. This does not mean that the array is inefficient but rather that the shaping of its pattern has been so arranged that its narrowest dimension is in the azimuth plane, resulting in higher precision direction finding and greater interference suppression than would be obtained with wider beamed antennas with the same gain. Figure 2 shows a 120-element CDAA with almost identical gain to a 4λ Rhombic, although the beam width of the CDAA is only one-fourth as wide as the Rhombic's. If radio contact with the European Continent were desired, a relatively wide beam such as that supplied by the Rhombic would be ideal, since no movement of the antenna would be required to switch from Berlin to Rome. For direction finding use, however, the sharper beam of the CDAA is highly desirable. As pointed out earlier, the half-voltage beam width in degrees is approximately equal to 610 divided by the total number of elements in the array. This means that arrays of relatively small size have beam widths of less than ten degrees. Arrays as large as 360 elements seem feasible and would have beam widths of less than two degrees. Since the beam width of an array is, to a large measure, a designation of its value in determining bearings, the CDAA leads the science art of scannable direction finding antennas. The only array that comes close to the CDAA in azimuthal pattern performance is the broadside array. This array can be scanned in azimuth but the angular width of scan is limited because of pattern deterioration

It seems necessary to give the Germans credit for building the first practical CDAA, but experience in similar problems in this country eliminates all reasonable doubt concerning its practicality. All figures of CDAA beam width mentioned in this report have been arrived at by mathematical methods using certain simplifications that seemed justified. It would be extremely interesting to obtain measured beam width data on the German systems.

ANTENNA VERTICAL PATTERN

One of the important characteristics of the circularly disposed antenna array is its wide vertical beam width. This wide vertical beam gives, for all practical purposes, hemispherical coverage. Figure 2 compares the vertical beams of the Wullenweber, the 120-element CDAA and the Rhombic. Note that for the Rhombic system the downcoming angle of the intercepted signal must lie within a very few degrees of the vertical beam's center or it will suffer a considerable loss. For point-to-point communication work where the downcoming angle of signal arrival is well known, the Rhombic proves to be a simple effective device, but for intercept work where unknown transmitter distances are involved, the wide angle pattern of the CDAA holds a terrific advantage. A Rhombic large enough to produce a beam at ten degrees above the horizon is very expensive and impractical, but many signals arrive at angles even below ten degrees. The Rhombic's answer to this problem is use of the next higher hop mode--that is, reception of the component of the signal that has traveled through more reflections from ground to ionosphere. This technique works, but the signals at higher modes are usually weaker, since reflections at the ground and in the ionosphere are not perfect and considerable attenuation results. As the number of elements of the CDAA becomes large, the vertical beam sharpens to the point where correction is necessary. The 120-element CDAA shown on Figure 2 has had its vertical beam aimed about 12 degrees above the horizon. This is a practical and simple adjustment which sacrifices less than a decibel of overall gain. Considering the beam-shaping problem from the intercept point of view, the CDAA outclasses the Rhombic on every point. The vertical pattern of the CDAA is so much better than the Rhombic that for general work the gain of the former would effectively be several decibels better than the nominal gains of the two systems might predict.

The theory and practice of controlling the vertical patterns of an array are well known in the United States. There is no reason to expect difficulties in obtaining the desired results if antenna sites have reasonable conductivity and clearance.

ANTENNA-PATTERN SIDE LOBES

The most noticeable feature of the circularly disposed antenna array's patterns is the low level of side lobes obtainable. Compared with long-wire antennas such as the Rhombic shown in Figure 2, the CDAA is far better in side lobe suppression. All long-wire antennas have high-amplitude side lobes with values running from -12 to -8 db compared to the main lobe. Since the Rhombic is a special class of such long-wire systems, suppression of its side lobes is impossible without extensive modification. For communication work side lobes are not too annoying and with fixed antennas they can often be shifted to eliminate troublesome interference. For direction finding and high sensitivity intercept, however, such lobes are a severe handicap. The simple Wullenweber has side lobes between 12 and 16 db below the main lobe, while more complicated arrays similar to the Tapered "55/120" CDAA shown in Figure 2 have their side lobes reduced to -24 db or lower. The extent to which this refinement of pattern shape is carried depends to a large extent on the type of bearing presentation being used. Automatic cathode-ray-tube displays are much cleaner and operate effectively over wider ranges of signal strengths when the pattern does not have large secondary lobes. As yet, no lower limit to the side lobe level has been found in practical systems having -40 db ratios in sight. For a given size array there is a rather complex relation between azimuthal beam width and side lobe level. Gain and beam width must be sacrificed for side lobe suppression and this results in the necessity for specifying the desirable pattern refinement, with the bearing accuracy and sensitivity holding the balance.

As it has been pointed out, the side lobes are controlled by adjusting the amplitude as well as the phase of each element before combination. The simplest example of this side-lobe suppression technique is its use in the broadside array. If a very long straight line array of antenna elements were all connected together in phase, there would be a sharp pattern perpendicular to the array. Side lobes would exist, however, since at other angles of signal arrival besides the perpendicular there would be conditions that would cause a somewhat additive effect. It can be shown that if the ratio of pickup from the different elements of the array follows certain laws, the side lobes will disappear entirely; the disadvantage of the technique is that some of the elements contribute so little that the overall gain suffers markedly. Dr. Dolph, recently of NRL, has presented a very excellent report describing the best tapering curves for any given side-lobe suppression. An attempt was made to carry this theory over into CDAA's but some very subtle difficulties arise which have yet to be solved. The result is that trial and error methods must be used to determine the tapering law, but very satisfactory results have been obtained.

Figure 6 shows two antenna field patterns, the first for a simple Wullenweber of 18 elements and the second for a tapered 18-element array. The use of larger aperture angles, when the tapering technique is employed, results in little or no loss compared to the Wullenweber. In the case shown, however, the side lobes have been reduced, as a result of the tapering, by about 8 db. The voltage tapering across the aperture of the array closely follows a cosine-squared relation. Other relations can be used, but in general the lower the side lobes, the lower the gain. As it has been pointed out, the 18-element CDAA is too small to be practical, but it is used here for examples because of the relative simplicity of calculations and drawings.

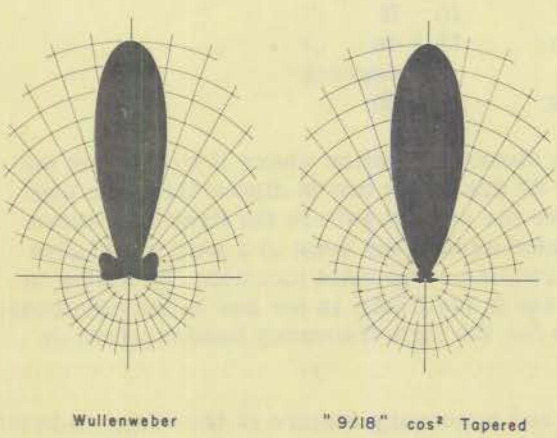

Fig. 6 - Effect of Tapering on Side Lobes

A CDAA side lobe phenomenon not previously discussed is the fact that there are no nulls between side lobes as there are in the Rhombic and other systems. The side lobes are more like little serrations in the pattern, varying only two or three db from one maximum to the next minimum. This situation prevents mistaking a side lobe for a different signal or mistaking a minimum between lobes for a null in the null type of reception sometimes used. The whole subject of side-lobe suppression in the CDAA has been worked out independently, since there are no known references in German or other literature.

PHYSICAL DIMENSIONS

The design principles of the circularly disposed antenna array are valid over the whole radio spectrum and the dimensional parameters are reasonable from about 100 kc to possibly 100 KMc. Charts have been prepared which show the relations between frequency, gain, diameter and number of elements for CDAA's with design center frequencies from 10 kc to 100 KMc. The disadvantage of using the system at low and medium frequencies lies in the large spacing required. For these lower frequencies the design could be simplified by using a set of two or three towers for each element, with the towers connected in such a way that a cardioid azimuth pattern would be formed with its minimum facing the center of the array's circle. It is difficult to estimate at what frequencies this technique would give way to the monopole-in-front-of-a-screen technique at higher frequencies.

An example of the characteristics of a medium-frequency array is shown in the following tabulation:

Center frequency	550 kc
Number of elements	18
Diameter	1 mi
Gain above an isotropic antenna	7 db
Half-voltage beam width	32 degrees
Side lobe level with $\cos^2$ tapering	- 24 db

An example of an ultra-high-frequency array is shown next:

Center frequency	1000 Mc
Number of elements	64
Diameter	10 ft
Gain above an isotropic antenna	13.5 db
Half-voltage beam width	9.5 degrees
Side lobe level with $\cos^2$ tapering	- 26 db

If this 1000 megacycle system were used in an elevated position where it would look out over the sea, the gain would be increased by 9 db due to the use of dipole elements and the reflection from the water. This would make the overall gain in the first lobe above the horizon about 23 db. Such an antenna mounted around the mast of a ship would give good intercept direction finding and would not require a top mast location. As stated in the first part of this report, the primary interest in the CDAA is for use in the communication bands. A table of array characteristics for the high-frequency band is given on page 4.

Since the reflecting screen is a desirable and necessary feature of the CDAA, a brief discussion may be of interest. The physical nature of the antenna elements will be covered in the next section. A reflector for radio frequencies need only consist of a grid of wires running in the direction of the r-f field's electric lines of force and spaced about one-twentieth of a wavelength apart. Measurements have shown that such reflectors have 98 percent efficiency, which makes them entirely adequate for CDAA use. If ten Mc is the frequency of a high-frequency array, then the wire forming the screen would be about two feet apart to operate effectively up to 15 or 18 Mc. For the 48-element Wullenweber shown in Figure 2, this would mean that about 1200 vertical wires would be required to form the screen. The height of the screen need not be more than one-eighth of a wavelength above the elements, so that in the case under discussion 80-ft telephone poles could be used to support the screen. In Figure 1 such a screen is shown. The bottom of the screen should be grounded and might require a ground mat if the soil conductivity is low.

The array design has been taken, in a large measure, from the work done in Germany. Verification of screen design has been done here and in England. No serious questions seem to arise concerning the physical feasibility of the system.

BANDWIDTH

The circularly disposed antenna array can be designed to operate efficiently over frequency ranges of three or four to one. This means that operation from five to twenty Mc would be possible with a system having a design center frequency of ten Mc. The broader the bandwidth required in an array, the more expensive it would be from both a design and construction point of view. In comparison, simple Rhombics cover only a two-to-one frequency range, while the more complex multiwire Rhombics have been designed with good matching characteristics over a range of four to one in frequency. The Rhombic, however, changes its vertical pattern rather fast with frequency making it difficult to obtain efficient operation at frequencies far removed from the design value. The CDAA, on the other hand, has a very slow azimuth pattern change with frequency and practically no vertical pattern change.

The broad banding of the CDAA is almost entirely a matter of collecting-element design. Schematically each element is a vertical monopole above an infinite ground plane. A thin vertical monopole, however, presents to its load a very difficult matching problem. Even with the greatest care it is difficult to obtain an efficient, phase-conscious and amplitude-stable transformer. The greatest hope is to design a collecting element having impedance characteristics that are stable, flat and close to the transmission line's characteristics. Antenna elements of the "fat" type can be built to fulfill these requirements. Such broad-band elements need not be made up as sheet metal cylinders or cones as in centimeter wave work, but can be designed as wire "baskets" with tapering, toploading or any other features required. Elements of this type have been worked on recently with very satisfactory results. About the only limitation on bandwidth for such elements is their pattern stability. Four-to-one bandwidths with good pattern stability and with less than three-to-one standing-wave ratios seem to be possible using open wire "basket" elements. The elements pictured in Figure 1 are not as elaborate as some of the German Wullenweber collectors but they are shown to give a general idea of the physical nature of the array.

In discussing the elements it might be well to point out that the polarization of the normal CDAA is vertical. This differs from the Rhombic, which is primarily horizontally polarized. As far as receiving distant transmission is concerned, vertically polarized antennas are inherently better, since the vertical patterns are more desirable. In the immediate vicinity of electrical disturbances, such as ignition noise, however, the horizontal Rhombic is quieter than the vertical CDAA. Since a search array like the CDAA requires a large, flat, open space for installation, the disadvantage of higher noise level for local interference does not seem to be important.

The broad-banding theory and practice necessary in designing a CDAA are well known in this country and little of importance to them has been contributed by the Germans. Only minor difficulty would be expected in developing broad-band arrays if advantage could be taken of preliminary model work. Impedance measurements of German installations would greatly expedite any contemplated development.

INSTALLATION ADVANTAGES

From an operations point of view, one of the best features of the circularly disposed antenna array is its large, centrally located area isolated from the receiving elements. Since the screen gives the elements a very high front-to-back ratio on their patterns, the center of the circular screened-in area is very free from interaction with the array. In installations of the DAJ and other standard shore-type direction finders it has been necessary to expend considerable effort in clearing the site of all reradiators such as cables and metallic structures. For example, all the r-f cables had to be buried in deep trenches, with no wiring more than three feet off the floor in operating huts, no communication antennas in the immediate vicinity, etc. The CDAA, on the other hand, can have almost any type of equipment and structures inside the screen. It would not be necessary to bury the cables, and multistory operating buildings could be placed in the enclosure. It might even be possible to have the entire establishment, including communications equipment, offices, and barracks, installed within the array. A 20-by-40-foot operating house, r-f cables and other facilities are shown inside the comparatively small CDAA pictured in Figure 1. The area outside the array must be reasonably clear and flat, but extreme requirements like those for the DAJ are not necessary.

It is not known how much use the Germans made of the center area of their arrays, but simple tests could quickly determine how far the use of this area could be carried.

NULL MODE OF OPERATION

A feature of the circularly disposed antenna array that has not been stressed in this report is its ability to operate on the null principle in taking bearings. This is accomplished by dividing the outputs from the antenna elements into two groups, one for each side of the center line of the array and then "bucking" the combined outputs of each side. The center line of the array at any instant is the line passing through the azimuth angle of goniometer symmetry or the azimuth angle at which maximum gain would occur if the system were operating normally. The modification necessary to produce this null type of operation is very simple. In the goniometer, after the phase and amplitude adjustments have been made, the output derived from one-half of the array is reversed 180-degrees in phase and combined with the output from the other half. The phase reversing is only a matter of interchanging transmission line leads by a switching operation. This switch is shown in Figure 3 next to the rotating output transformer. The simplicity of the change makes it feasible to use both maximum and null types of operation in one equipment. The more sensitive maximum indication would be used for search and rough direction finding, with the null system switched in for high-precision bearing work when time was available. The null produced by a CDAA is very sharp compared with the normal B-T goniometer or loop. A null with wall slopes 100 times steeper than a loop would not be unusual. This null type of operation makes possible the simple realization of the high precision and accuracy obtainable with CDAA. The Germans used the null mode of operation almost entirely, but they were using hand operation and not automatic bearing indicators. Figure 7 shows indicator patterns that might be obtained with this null type of operation. The first drawing, (A), shows the field pattern of the null mode of an 18-element CDAA as it would be traced out on an indicator using radial deflection. Considerable difficulty would be experienced in trying to utilize this display, since the bearing is poorly defined, with the null at the center of the indicator. The second drawing, (B), shows the same information but it is displayed in a reciprocal manner. Zero signal is made to trace a large circle and the pattern is "driven" towards the center in the same manner the first pattern was "driven" out. Now, as in the case of the Model DAJ's ABI, the null is displayed as a sharp point giving higher resolution than might be obtained with a lobe pattern. Notice that opposite the null there is a large rounded lobe caused by the absence of signal at the back and sides of the array. If other signals existed at these azimuths the system would give multiple bearings without serious interaction. Probably the most outstanding feature of this peripheral type of display is its ability to work over large changes of signal level without requiring adjustments in the gain of the receiver. Drawings (C) and (D) show the same pattern displayed in drawing (B) but with -10 and +10 db change in field strength. The big disadvantage to the null mode of operation is its loss in system sensitivity due to the lower gain of the array (about 6 decibels) and the indicator loss as shown in Figure 5.

The side lobes of the CDAA are only small serrations and do not have deep minimums. This keeps the operator from accidentally mistaking a minimum between side lobes for the true null. The Germans felt that this feature was very important since it completely relieved the operator of the added work of making large azimuth swings to check for ambiguity.

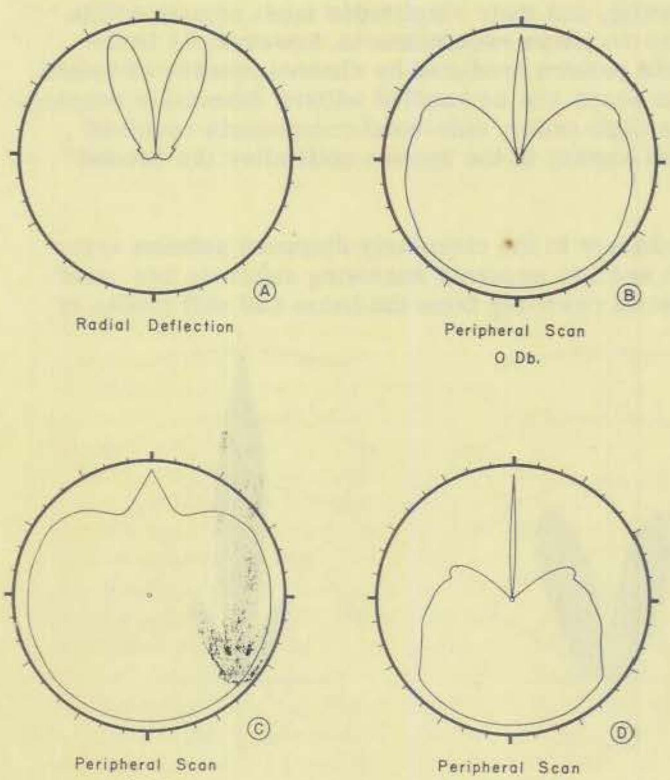

Fig. 7 - Null Types of Bearing Indication

The technique of shifting a beamed array to a null type array has been well investigated at NRL. The RCA UHF direction finder tested in the Radio Countermeasures Section had the same principle of operation. No difficulty should be experienced in building a goniometer that would make the null type operation possible. Since there are tactically many countermeasure uses for null type monitoring systems it would seem advisable to consider the possibility of including this feature in any future development of CDAA. One of these countermeasure uses for null operation is in antijamming work where a "blanket" is being laid down by a transmitter close to the desired source. The CDAA would be able to suppress such a jammer and provide reasonable reception of the protected station.

SIMULTANEOUS LOBING

The circularly disposed antenna array is well suited to the application of simultaneous lobing. Such techniques greatly enhance the precision of indication without reducing the probability of intercept that results from simple lobing procedures. Simultaneous lobing has had sporadic use in direction finding for about ten years, but a description of its principles may help to show how it may be applied to the CDAA.

To explain simultaneous lobing a simple crossed loop and sense element can be used as the antenna equipment, with a two-channel receiver connected to this antenna in the following manner. Loop number one is connected through receiving channel number one with the output at the second detector having the normal cusped form with a null every 180 degrees. Loop number two and the sense antenna are connected together and the resulting cardioid output fed through receiving channel number two. The output at the detector of the second channel will be a sine wave plus a d-c component equal to one-half the sine wave's peak-to-peak voltage. Or in other terms, the output of channel two does not have cusps but broad minimums which give the pattern a sine-wave shape. There is only one minimum every 360 degrees of antenna rotation for channel number two. Now, since the two loops of the antenna are spaced 90 degrees apart, the maximum of channel number two will occur at the same antenna azimuth setting as one of the nulls of the first channel. This means that as we rotate the antenna array, the outputs of the two channels will vary so that when channel number one is on the true null, channel number two is on maximum. When channel number one is on the reciprocal null, however, channel number two is at a minimum. The next step is to combine the two detector outputs in such a way that the output of channel one is subtracted from the output of channel two. The procedure will give a very sharp maximum at the azimuth angle of the true bearing and very reduced output for all other azimuths. A few interesting points should be emphasized. First, the two receiving channels must track in their tuning, and their amplitudes must remain within about 25 percent of each other. There are no phase requirements, however, as in the Watson-Watt system. Second, the cardioid pattern produced by channel number two need not be perfect. Considerable tolerance in shape can be handled without detectable bearing-shift or pattern deterioration. Third, the high-order, side-band components required to pass the sharp pulse-like pattern do not appear in the system until after the second detectors of the receiving channels.

To apply the simultaneous lobing technique to the circularly disposed antenna array is quite simple. Two goniometer outputs and two separate receiving channels are used as before. Figure 8 shows the field patterns resulting from the beam and null modes of

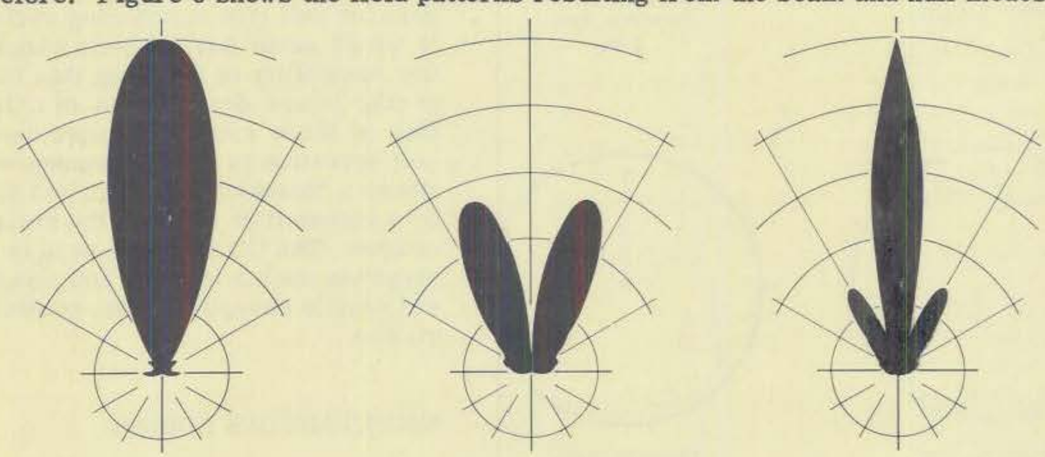

Fig. 8 - Simultaneous Lobing

goniometer operation. Notice that the gain for the null mode is almost six db below that of the beam mode. The outputs of the second detectors of the two receivers are combined so that the absolute value of the null mode is subtracted from the absolute value of the beam mode. This operation tends to "shave off" the sides of the beam mode's pattern, giving it the very sharp characteristic of the reciprocal null pattern described in the previous section. The sharpened pattern is shown in Figure 8 and should be carefully distinguished from the patterns of Figure 7. The pattern produced by the simultaneous lobing technique is in effect a sharpened beam and not an inverted null. The relatively large side lobes produced in the example shown can be reduced by properly shaping the primary beams. Since the normal pattern of the CDAA is fairly sharp, and there are no sense problems to be solved as in the first example, it may seem that simultaneous lobing is unjustified. The real usefulness of this lobing technique would arise in indication systems that use the directional information to form bright areas or spots on a screen, instead of a traced antenna pattern. The "television" scan described in the section on automatic bearing indication is a good example of such a system. If it is desirable to obtain a "pip" from the directional information, a sharp point is ideal since simple differentiating circuits will produce the desired wave form without introducing bearing error. The null type output will, of course, lend itself to these differentiating techniques, but for weak signals the noise quickly reduces its effectiveness.

The biggest field for simultaneous lobing lies with panoramic direction finding (PDF) and its associated azimuth frequency indicators (AFI). These systems must crowd large amounts of data onto small screens requiring the highest type of resolution for good results. The multiplexed circularly disposed antenna array described at the end of this report would require simultaneous lobing techniques to realize the inherent possibilities of bearing and frequency resolution.

There are no known references to simultaneous lobing techniques in the German literature and the discussion given here is based on U. S. techniques. The important thing is that the null technique, the lobing system and all the various bearing indicators described so far are only simple terminal modifications of the CDAA and may be applied at any time after the array is in existence.

SPACE-DIVERSITY ACTION

The most useful direction finding property of the circularly disposed antenna array is its space-diversity action, which greatly improves bearing accuracy. This takes the CDAA far out of the Adcock and Spaced Loop class of direction finding and should open whole new fields of intercept activity. As an example of the Germans' results with CDAA it was claimed that high-frequency transmitters operating in the United States were "spotted" within plus or minus fifteen miles of their true position by Wullenwebers operating on the European continent. A circle with a diameter of 30 miles centered in Washington subtends an arc of about 31 minutes at the closest Wullenweber, in Hjoerring, Denmark. This means that the bearings would have to be accurate to 15 minutes of arc to obtain the azimuth information necessary for the "spotting" carried out. It might be well to point out that triangulation from a group of direction finders was not used to obtain a fix, but instead a method of computing the distance to the transmitter was used which, together with the highly accurate direction finding, made the remarkable "spotting" work possible. The method of distance determination will be touched on later in this report.

Methods of diversity direction finding have been tried in this country but the techniques used were ill-advised. In most cases an attempt was made to average out the bearings obtained at several Adcock installations separated by a few wavelengths.

The difficulty here lies in the fact that the averaged results in such attempts are not a measure of the average of a randomly varying direction of arrival of the signal, but rather an average of the phase fronts existing at several isolated points in a complex interference pattern. To study the difficulties of diversity direction finding and to show how the CDAA overcomes some of these, a simple discussion of the interference phenomena may help. Assume that two wave trains, both from the same transmitter, are arriving at a direction finder but due to ionospheric disturbances are arriving at slightly different angles. If the field strength at the receiving site could be mapped it would be found that it varies over wide limits and is in a constant state of flux. This condition is caused by the interference between the two arriving wave trains, each of which may be varying in amplitude, elevation and azimuth. The simple diversity receiver operates on the principle that one of its several antennas will be in an area of high field strength most of the time. The Adcock and other direction finders, on the other hand, operate on the phase front of the wave which may be quite detached from the amplitude. With the undulating field pattern moving across the direction finder site, the phase front across the small array (less than a wavelength) will swing violently through wide angles. It is true that the largest swings in phase front are associated with weaker spots in the interference pattern. Bearing errors of 90 degrees are possible, however, even with a good Adcock and with real direction of arrival of the interfering signals no more than a small part of a degree removed from the great circle path to the transmitter.*

Figure 9 shows a simplified plan of the field intensity and phase conditions in a region where two rays interfere with each other. The direction of arrival of the rays is indicated by the large arrows marked Ray 1 and Ray 2. The field intensity, which is a standing-wave phenomenon, is indicated by the small circles. The size of these small circles is directly proportional to the field strength as it would be measured by a field intensity meter. At the very top and left edges of the figure there is no interference between the rays, and hence the field intensity is uniform. For the purposes of the drawing, Ray 1 was given as two db stronger than Ray 2. This condition will give variations in the field intensity in the interference zone of about 19 db. The angular separation of the rays is five degrees, and it is assumed that the true direction to the transmitter is along the bisector of the rays. The lines running from lower left to upper right in the drawing are lines of instantaneously equal phase, with one line shown for every 360 degrees of phase. In the afore-mentioned regions of no interference these isophase lines are straight, but in the interference zone they are quite irregular, showing their maximum variation in the regions of lowest field intensity. At right angles to the direction to the transmitter a row of 11 circles with a dot in each of their centers is shown. The circles are approximately the size of an Adcock Direction Finder that would operate on the frequency of Ray 1 and Ray 2; that is, they are slightly over one-quarter of a wavelength in diameter. Such direction finders would indicate the bearing to the transmitter as shown. In the regions of low field strength the bearings are in error by as much as 20 degrees. At regions of high field strength the error is zero. The fact that all erros are positive further adds to the confusion in trying to take a bearing, since the swing of any one direction finder would always be in the same direction. It is interesting to note that, for this particular example, the average bearing error for the 11 direction finders is greater than the error of the rays. The average error is 3.1 degrees while the rays are only 2.5 degrees removed from the true path. If to each bearing a weighing factor is assigned equal to the relative field strength at the place of measurement and the bearings are averaged again an error of only 1.3 degrees is obtained. The circularly disposed antenna array has a long enough base line to achieve effectively the requirement of collecting energy from a large area of the interference field. The system used in the CDAA for obtaining the bearing of the signal automatically weighs the output from each collector and gives the most attention to the signals of greatest intensity.

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* Heiligtag, T., Causes of Errors in Direction Finding, Jahr. d. Draht, Vol. 21, p 77, 1923.

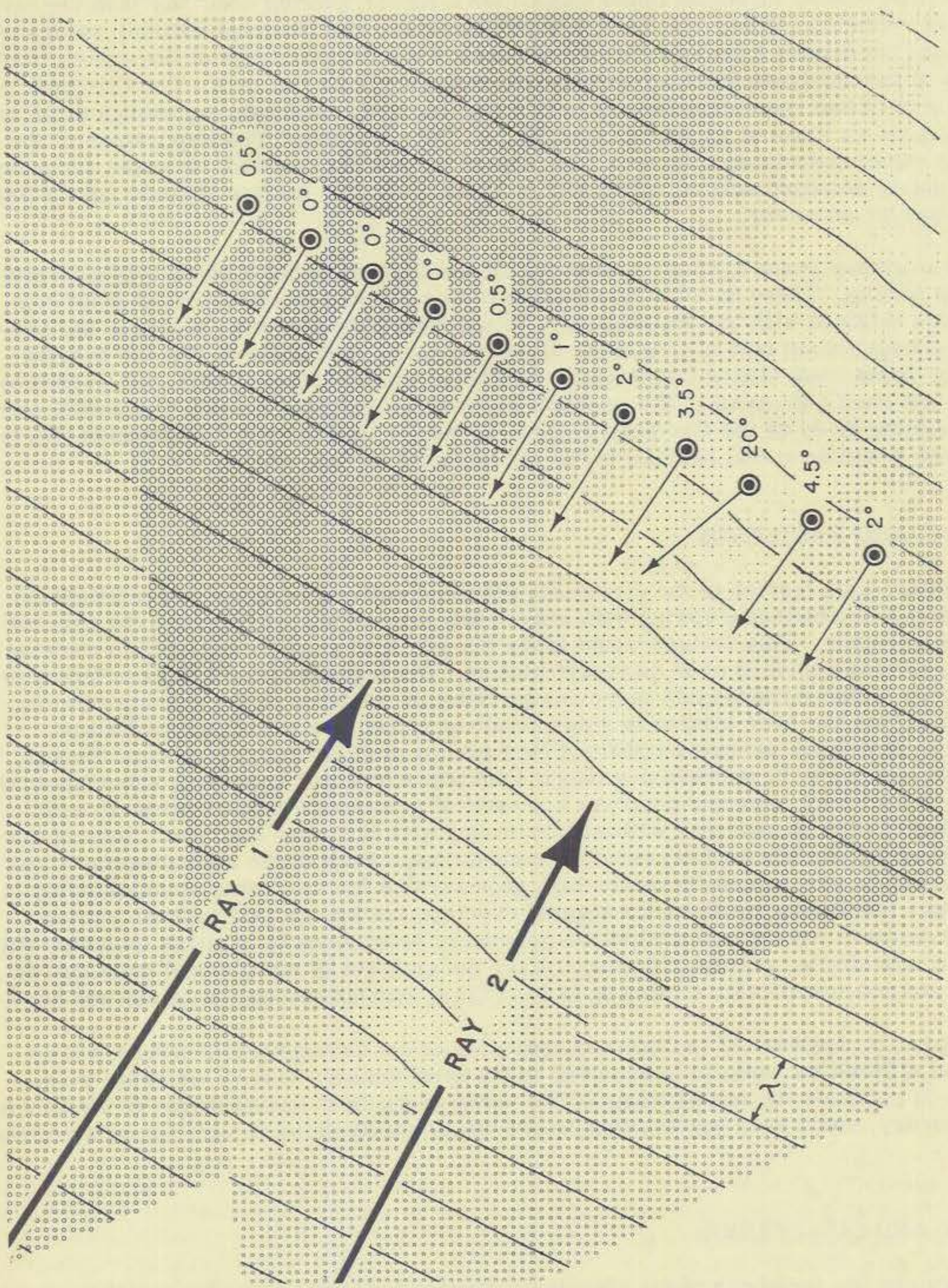


Fig. 9 - Ray Interference Showing Isophase Irregularities

It is true that no direction finder can obtain a higher bearing accuracy than the arriving signal indicates. It has long been thought, however, that the large bearing swings of the Adcock and the Spaced Loop were true measures of the arrival angle of the signal, but in the light of the foregoing discussion this does not seem to be the case. The Germans were able to obtain consistent results over very long paths with bearing swings about one-tenth as large as those of an Adcock installed on the same site. The importance of the diversity effect associated with the CDAA cannot be overemphasized. It would seem that if the circularly disposed antenna array had no other desirable feature it could justify itself by its superior accuracy.

The Germans seem to have carried out all the productive work on diversity effects in direction finding. There is little information in this country that verifies or disproves the results obtained with the Wullenweber. If sufficient interest were shown in the problem, a simple Guben type of long-wire array could be constructed to test the bearing shift over some fixed transmission path. Facilities are available at NRL and Cheltenham to carry out such a program. The problem is being investigated at NRL in a model form and the claims made by the Germans seem reasonable. A thorough investigation into the phenomena would be a real service to the art of direction finding.

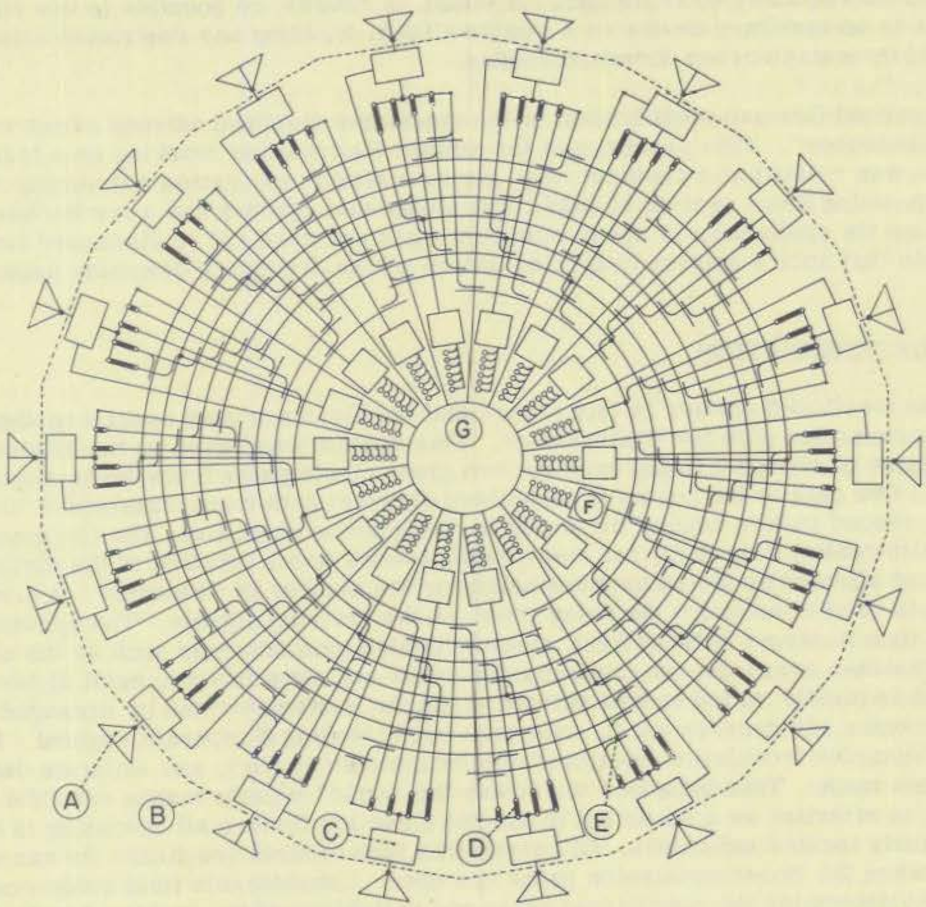
MULTIPLEXED FACILITIES

An interesting feature of the circularly disposed antenna array is that multiplexed operation can be obtained allowing both search and monitoring operations to be carried out simultaneously. This feature would allow the CDAA to supply most of the receiving antenna services required at an intercept station. The biggest disadvantage of this type of operation is that considerably more complication is required in the antenna circuits. One system that has been studied in some detail is shown in block-diagram form in Figure 10. Individual antenna amplifiers feed groups of delay lines, combined through directional couplers, to multiplexing output amplifiers to which receivers are connected. Parallel to the delay lines and couplers are several goniometers which allow direction finding facilities to be operated without interfering with the other features. Each of the multiplexing outputs has several receiver connections. Each of the multiplexers "looks" toward a narrow azimuth and provides high gain service for recording or monitoring. The antenna amplifiers would be the biggest development job for this system, but the Germans claim to have accomplished the necessary requirements of phase matching and bandwidth in a similar problem (Guben). Since the problem of multiplexed operation is complex and not specifically a function of the CDAA, further discussion is omitted here.

There is no evidence of multiplexed operation of the German Wullenweber, but no particular difficulties seem to be involved in its development. It does not seem wise, however, to consider the multiplexing of the array in the first embodiments of the CDAA in this country, since the complications would considerably delay completion of a working system.

BROMMY AND GOLDWEBER

There are two members of the circularly disposed antenna array family whose operation is unlike those discussed so far and probably should be mentioned to preclude confusion. The first, and most important of such systems is the German Brommy. This system uses the Wullenweber antenna array, but achieves instantaneous direction finding by the application of the Watson-Watt sum-difference technique. The CDAA is divided into groups of elements, each group producing a beam. Adjacent beams overlap considerably so that signals arriving



ITEM	NAME	NUMBER REQUIRED
A	Vertical Antenna Collecting Element	18
B	Antenna Reflecting Screen	1
C	Broad Band Antenna Isolation Amplifier	18
D	Delay Lines (four different delay times)	72
E	Broad Band Directional Coupler (not electronic)	162
F	Antenna Multiplexer (six or more outputs for monitoring)	18
G	Direction Finding Goniometer (outputs for search receivers)	1 or more

Figure 10 - Block Diagram of Multiplexed CDAA

on the axis of one beam will still be adequately received on the second beam. The outputs from two adjacent beams are fed through twin receiving channels which must be matched in phase but need not be matched in gain. The outputs of the last intermediate frequency stages are combined in two separate circuits. In the first circuit the sum is obtained and applied to one set of deflecting plates of a cathode-ray tube. The second circuit obtains the difference of the two outputs and applies it to the second set of cathode-ray-tube deflecting plates. The resulting pattern on the screen is a line whose angle to the deflecting plates is a function of the angle of arrival of the signal. Automatic circuits can be provided to correct for frequency and spacing errors, leaving the trace on the tube only a function of the angle of signal arrival. The number of receiving positions required to cover the entire azimuth depends on the sharpness of each beam, and consequently upon the gain. It would, of course, be possible to use the Brommy technique as an auxiliary device on a simple CDAA, enabling any restricted azimuth to be monitored by instantaneous direction finding.

The second German modification of the circularly disposed antenna array was known as the "Goldweber". This system was the simple Wullenweber working as a transmitter. The beam was rotated at a constant rate, giving a simple navigation aid similar to the Marconi Rotating Beam system of 1926. The Goldweber system has a few backers in this country, but its application is not in intercept work and need not be discussed further. It is possible that such a system could find use as a high-frequency-jamming antenna.

RANGE DETERMINATION

It was mentioned earlier in this report that the Germans used special methods of distance determination with the Wullenweber. This system was based on the difference in arrival times of signals coming over the two great circle paths from the transmitter to the receiver. One path is the normally visualized shortest path from transmitter to receiver, while the second path is around the world in the opposite direction. The Germans showed that the differential time delay for long-distance work was a function of the distance only and was not affected by the ionosphere height or the number of "bounces". A Loran-type indicator is used to measure the delay times of the arriving signals. The system is more practical than it seems to be at first, since with high gain antennas such as the circularly disposed antenna array the two transmission paths are often found to exist at the same time. The CDAA is ideally suited to this service since the goniometer can be arranged to produce two beams 180 degrees apart, with each beam feeding a separate channel. In this way very complex modulation envelopes can be matched in time, and accurate determination of distances made. This technique of "round-the-world" signals makes one CDAA installation as effective as a whole net of simple direction finders all operating in synchronism with centrally located indicators. Of course this type of direction finder fix can only be achieved when the two transmission paths are open. Considerable field study would be required to determine the operational value and reliability of the system, but its investigation seems desirable.

PANORAMIC DIRECTION FINDING (PDF)

By combining multiplexing and panoramic techniques with the output of a circularly disposed antenna array it would be possible to achieve a high definition type of azimuth frequency indication (AFI). A system of scanning receivers, working at each of a multiplicity of azimuths and presenting their information as bright spots on a large screen, so arranged that frequency is one coordinate and azimuth is the other, would produce very valuable intercept information. A considerable amount of work along these lines has been done at NRL but a detailed description will not be given here since this also is only a terminal equipment and would follow work on the array.

INVERSE LORAN

A system of direction finding which is making a bid for high speed intercept work is the Time of Arrival of Inverse Loran system. Great hopes have been held out for this principle but the complications of high-gain antennas and multiple indication would give the system questionable operational value. For restricted azimuth work where Rhombics could be used at each of the several receiving stations the Inverse Loran system might prove very valuable. To produce the 15-minute azimuthal accuracy claimed for the CDAA, the Inverse Loran, with a 200-mile base line, would have to compare times of arrival with plus or minus two and one-half microseconds accuracy. This would require extremely well designed receiving and intercommunication equipment and might well be beyond the limits of resolution, due to the deterioration of the leading edges of the pulses traveling via the ionosphere.

LONG-RANGE RADAR

Recently there has been considerable interest in long-range radars capable of guided-missile detection at more than 1500 miles. The use of frequencies in the high-frequency band are contemplated to take advantage of ionospheric propagation. The use of Rhombic antennas for transmitting and receiving has been proposed, but it would seem that the circularly disposed antenna array might offer considerable advantage in both services. The azimuthal selectivity and ease of scanning of the CDAA would greatly facilitate any such radar project.

PROPOSED PROGRAM

In the whole field of direction finding there seem to be no systems which can compare in simplicity of design, accuracy of results and sensitivity with the circularly disposed antenna array. The size of the system is not an indication of its complexity, because each element is identical to its neighbor. The goniometer is not complicated and installation problems are mainly mechanical. If support for a program to develop a circularly disposed antenna array is obtained, the following outline of problem programming with the necessary man power and expenditure is proposed:

First, a survey of all German and English documents concerned with the Wullenweber would be made, followed by an interim report giving the results of the survey and the results of the work carried out to date. This phase of the project would take one man about three months.

The next step would be a visit by one or two men to the Wullenweber project at the Admiralty Signal Establishment in England to obtain firsthand data on design and operation. This would be followed by a second interim report which could probably predict with some certainty the expected result. Three to four months would be required for this phase of the project.

Next, scale model work on antenna elements and possibly full-scale work on five or six elements could be carried out at NRL's Blue Plains Field Site. This would take two or three men about 18 months and the result would be a complete system design.

Finally a complete system would be built at a new NRL field site or a shore station such as Skaggs Island. This would require the services of two or three NRL men and construction crews. The size of the system constructed would determine the cost. The present feeling is that a 72-element array having 33 active elements is the optimum size for the first attempt. Such a system would cost close to $1,000,000 if present rough estimates are correct. Construction should not require more than one year, during which the final goniometer would be built and tested at NRL.

The completion of the goniometer and the array would be merely the beginning of a CDAA project, since an almost unlimited number of tests and terminal equipment developments could be carried out with the pilot system. It should be possible to take the first bearings about four years after the project was started. With the world situation as it is today this may be too long a time. More man power would, of course, speed up some of the development work. If a large field site close to NRL could be procured for the development a real saving in time would be realized, since the entire design would not have to be completed before construction work was started. The estimates indicate that this project is definitely of a peacetime nature since no future war will be protracted enough to allow such time-consuming research.

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