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A PARALLEL-CHANNEL SHIPBOARD DIRECTION FINDING SYSTEM.

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by

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UNITED STATES NAVAL POSTGRADUATE SCHOOL
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ABSTRACT:

Several parallel-channel receiver configurations are presented and analyzed. From this background a particular direction-finding system suitable for shipboard use is detailed. Use of three modes of operation of the defined system is shown to provide through 360° coarse and find indications of the bearings of each of several stations transmitting simultaneously. It is also shown that this system will provide measures of amplitude and, with some added circuitry, frequency of each of these received signals. It is shown that the gain characteristics of the antennas for each mode of operation are chosen in a manner which makes the parallel-channel receiving system immune to signals reflected from the ship and its rigging. Two different methods of obtaining independent measures of signal frequency and bearing are presented. A brief history of direction finding and an extensive bibliography are provided.

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SYMBOLS

α = angular width of blind sector

$\beta, \gamma, \phi_A, \phi_B, \psi$ = phase angles of sinusoids

θ = angle-of-arrival of radio wave

λ = wavelength in meters

ρ = voltage ratio

τ = delay in seconds

υ = velocity of propagation on transmission line

ϕ, r = polar display coordinates

ω = radian frequency

a = length of the ship

b = breadth of the ship

c = velocity of light = 3×10^8 meters per second

d = antenna separation in meters

f = frequency in Hertz

ℓ_1, ℓ_2, ℓ = lengths of transmission line in meters

m = constant

$p = \frac{d}{\lambda}$ = antenna separation in wavelengths

r, ϕ = polar display coordinates

s_1, s_2 = input sinusoidal signals

t = time in seconds

v_1, v_2, v_O, v_X, v_y = voltages

x, y = rectangular coordinates

z = differential distance along signal path

A, B, C, D = antenna designators

E_1, E_2, E = peak amplitudes of sinusoidal signals

L = length of line trace on CRO

L_S = length of slotted line

V_1, V_2, V_X, V_y = lengths of phasors

R_A, R_B = receiver designators

A PARALLEL-CHANNEL SHIPBOARD DIRECTION FINDING SYSTEM

1.0 Introduction and Background Material

1.1 Definition

The radio direction finder is a wireless receiving station which uses the properties of the electromagnetic wave radiating from a point source to find, relative to some standard (true North), the horizontal and/or vertical angle of incidence, of the signal received from this source. Upon reception the wave is usually assumed to be a plane wave. It is necessary to distinguish between direction-finding (DF) systems which are an aid to navigation and those systems which are intended to "intercept" unknown signals.

In navigation the DF station usually possesses a priori the frequency and the modulation of the received signal of interest as well as the geographical location of the transmitter. The DF station operators interpret the received signal in accordance with this a priori knowledge to "fix" the position of the station.

The "intercept" DF station attempts to assess the bearing (usually) of a received signal relative to the station geographic position. No knowledge about the number of incident signals nor about the parameters of any signal is assumed except that it must lie in the receiver frequency pass band and, perhaps, have a certain polarization to be received.

The ability to <u>locate</u> an unknown, earth-based transmitter requires a somewhat more complicated intercept DF ground station since location implies knowledge of range in addition to bearing.

1.2 Brief History of DF

Heinrich Hertz in 1886-87 gave a conclusive demonstration not only of the generation and detection of radio waves but of their reflection and refraction and in addition of one principle of radio direction finding as well (Ref. 1, Ref. 2, p. 67). He used a nearly closed loop of wire as a direction finder and determined that this gives best reception when its plane is in a plane containing the transmitting antenna and gives zero signal when these planes are at right angles.

As early as 1908, a suggestion was made to use Hertzian waves to determine the heading of a ship (navigation aid) (Ref. 3).

During the second and third decades of this century, considerable work of an experimental nature was done in the field of direction finding. Areas of interest included directive wireless telegraphy, location and tracking of thunderstorms (Ref. 2, 4), and the problems associated with DF from various platforms -- shipboard and airborne in addition to land-based (Ref. 5, 6). Born of this activity were varieties of direct-reading goniometers many of which used parallel receiving channels and, as a display device, a cathode-ray (Braun) tube (Ref. 7, 8).

The thirties nurtured sophisticated direction-finding. Sets were calibrated, errors calculated, polarization of high-frequency (HF) waves investigated, 'night effect' isolated and compensated, electrical properties of the soil determined, universal networks of stations for meteorological, nautical and aeronautical uses proposed, and innumerable varieties of techniques of DF recorded in the technical journals. Keen in his book Wireless Direction Finding (Ref. 9) considers these topics and provides a complete bibliography of DF through 1937. The articles by Smith-Rose on DF in general (Ref. 6) and by Tuska on application of DF to navigation in particular (Ref. 10) provide additional extensive lists of references on work done up to 1929 and 1939 respectively.

The technique of direction finding had many applications during World War II. The prime example is radar which functions to locate the source of a particular signal, i.e. one reflected from the target. As important and effective as that application is, DF was successfully extended to the high-frequency band

(HF DF) and deployed on board ship during the War to detect and locate German submarines. It was known by the acronym "Huff-Duff". The Naval historian, Samuel Eliot Morison, is purported to have claimed that HF DF was no less important to victory in the Battle of the Atlantic than was radar itself (Ref. 2, Chap. 25). Of course, DF was extensively used on aircraft and aboard ship as aids to navigation during this period.

All of these historical applications of DF exist today. In addition the art has been extended to the use and conquest of outer space. Not only is it important in tracking rockets and satellites (Minitrack, Ref. 11; Ref. 12), but DF has been applied to space-borne platforms to locate buoys, balloons, etc. (Ref. 13). A particular DF technique, interferometry, is of continual interest in astronomy as a means of locating and determining the size of radio stars (Ref. 14, 15).

A significant trend presently in land-based systems seems to be toward large and rather sophisticated DF networks. The Navy is responsible for at least two such systems: Bullseye which uses several "Wullenweber" installations to intercept signals (Ref. 15-18), and a space surveillance system (Spasur) to keep track of earth satellites (Ref. 19-24).

See Ref. 25 (pp. 10-2 to 10-5) for additional material of historical interest. A recent report by Bailey treats the state of the art on radio DF and source location (Ref. 25).

1.3 Contents of This Report

This report is concerned with shipboard direction finding in general and with the intercept problem in particular. To appreciate the relations among the various types of existing DF systems, it is necessary to classify the known techniques of DF. One such classification is the subject of Section 2 of this report.

Section 3 attempts to define the problem of shipboard DF and summarizes some of the present methods of DF aboard ship.

Section 4 first presents the basic properties of four different parallel channel systems which are considered practical for shipboard DF. These results are then applied to define a particular system. A block diagram, showing the antenna, receiver and display subsystems, is presented.

Appendices are used to present analyses supporting Section 4. An extensive bibliography is included as a part of this report.

2.0 Classification of DF Systems

Section 1.1 implied that DF systems were used only as aids to navigation or to determine the bearing of unknown RF signals. Not only is such a classification too gross to be of much value, it is also incomplete. In addition to the above, DF has been used to track meteorological balloons (Ref. 27), for surveying in inaccessible wooded terrains (Ref. 28), for mapping caves (Ref. 29), and to locate sources of interference in the radio and television frequency band (Ref. 30).

2.1 Classification Based on Application

Because of their vastly different platforms and operating environments, one might be tempted to think that land-based, shipborne, airborne, and space-borne DF systems represent four different technical disciplines. This classification is supported by the fact that an idea applied successfully in one system might border on the absurd when considered for another type of platform. The literature on this subject could be divided into roughly these four categories.

Although this classification according to use is convenient and popular, such a division does not indicate what is common, from a technical and analytical point of view, to the many and varied DF systems presented in the literature. When considering new systems and new ideas in light of the old, a classification according to techniques rather than application is desirable.

2.2 Classification Based on Techniques

L. A. deRosa reduces the DF problem to essentially one of determining the equiphase front of the received signal (Ref. 25). The bearing of the transmitter is then readily obtained since the equiphase front is usually normal to the direction of propagation. He classifies the various techniques of exploring the phase of the field vectors as follows:

A. Absolute or instantaneous methods of measurement of
    i. Amplitude
    ii. Phase
    iii. Delay

B. Sequential methods of measurement of
    i. Amplitude
    ii. Phase
    iii. Delay

Following this classification, deRosa discusses considerations determining the choice of any one of these six techniques. He also gives an example of systems which employ each technique.

3.0 Consideration of the Problems and Methods of DF Aboard Ship

Direction finding from a ship or aircraft presents at least four problems that are not shared by land-based systems. The existence of a rather large conducting mass distorts the electromagnetic field that describes the signal of interest. Secondly, the ship and its rigging reflect (scatter) the incident signal thereby further distorting the field at any point on or near the structure. In addition, the natural environmental conditions and the ship's vibration and swaying are hazards to equipment installation and calibration. Lastly, the severe space limitations (type and size of platform) restrict the kind of DF techniques that can be employed.

3.1 Effects of the Platform

Distortion of the electromagnetic field due to the conducting mass of the ship is generally ignored in the literature. This effect is, presumably, of minor importance. Further, this effect should be more consistent, and hence more easily compensated, than that due to reflections. The problem has not been completely overlooked, however. As early as 1932, an attempt was made to determine the resonant frequency of a ship and the consequent effect on a DF system of this structure which is situated at a surface separating two media of different dielectric constants (Ref. 31).

The effect of reflection from the hull, deck, and rigging of the ship is of considerably more consequence than any of the other problems mentioned. In the absence of reflections, a variety of DF techniques and equipments which satisfy present system requirements could be provided. With reflections, the field vector at any point in space consists of the incident signal plus components due to each reflection of the incident signal. Equiphase fronts are no longer of simple geometry, are time variable, and are no longer perpendicular to the direction of arrival of the incident signal. Consequently, exploration of the phase of the field vector gives at best a blurred indication of the bearing of the signal. Ross (Ref. 32) presents a rather good statement of the problem of DF when the r-f waves are not plane or when the waves consist of more than one component. Brooks (Ref. 33), shows that a three channel system can give an error-free bearing indication when the input signal consists of two components: the direct ray and one reflection.

Considerable effort has been spent analyzing, characterizing, and isolating the sources of interference (reflection) and in determining the effect these reflections have on various DF systems (Ref. 34, 41, 42). The results of these analyses are then interpreted to assess the effectiveness of various antennas and to determine the site of these suitably chosen antenna systems which would minimize the effect of the reflected signals (Ref. 43-48). Compensation of the antenna systems has also been tried (Ref. 41, 49).

This work has improved the performance of some DF equipment. In many cases, however, the return has not justified the investment. The nature and complexity of the problem was indicated early by Solt (Ref. 50) when he observed that although two vessels may be exactly the same and have identical rigging and mast arrangements, the difference in deviations between the DF readings on these two vessels may be considerable. Apparently any system which is sensitive to the signals reflected from the ship and its appurtenances is subject to erroneous or blurred indications of the direction of arrival of the incident signal.

3.2 Reception of Simultaneous Signals

Reception of simultaneous signals is yet another problem associated with radio direction finding. This is distinguished from the reflection problem by considering these signals to be of different frequency and, in most cases, of different origin (uncorrelated). When DF is used to provide navigational information, this problem is usually of no consequence since it is assumed the receiver knows the frequency of the signal of interest and hence can tune out all other signals. However, the intercept problem by its very nature requires monitoring a band of frequencies. This introduces the possibility of receiving many signals at a time. The field vector again consists of more than one component. Although now well defined, the equiphase fronts of the field are no longer normal to the direction of arrival of any one of the components of the composite field. As a result, a majority of the existing DF techniques and equipment give ambiguous if not erroneous indication of the number of signals and of the bearing of each.

This problem has received comparatively little attention. One theoretical solution has been advanced (Ref. 52). The practicability of systems based on this technique when operating on signals corrupted with noise is questionable since the signal bearings are represented by points of discontinuity or "breaks" in the plane figure displayed on the screen of a cathode-ray-tube. Noise tends to smooth these points and hence obliterates the bearing information. The problem of simultaneous signal reception will be considered again in the next section.

4.0 A Proposed Shipboard DF System

This section derives from practical and analytical considerations a particular shipboard DF system. The properties of four different parallel channel systems are considered in turn. This information is then used to detail the final system.

The configuration selected is intended to overcome the deleterious effects of reflections from the ship and its rigging. It will be shown that the system can be operated to provide coarse bearing information throughout most of 360 degrees at all times or to provide by sector coverage refined readings over 360 degrees. The system has the capability of providing bearing information on each of several cw or pulsed signals occurring simultaneously. An indication of the amplitudes of one or more received signals is provided by appropriate signal processing and display. At the expense of some additional equipment, the system is capable of determining the frequencies of each of several cw or pulsed signals occurring within a broad range of frequencies.

4.1 Design Considerations

4.1.1 Antenna Gain Characteristic

Fundamental to this development is the assumption that distortion in the r-f electromagnetic field is due primarily to reflections from the ship and to other field generators aboard ship; distortion of the field due to the presence of the ship itself is assumed to be negligible (Ref. 31, 35, 37, 42).

Under this assumption the effects of a distorted field can be overcome by using field sensors (antennas) which are sensitive (transparent) to signals traveling toward the ship (incident wave) and are immune (opaque) to radiation traveling away from the ship (reflected wave).

An alternate solution is to provide a receiver capable of balancing out the components of the field contributed by the reflections. This approach assumes the reflections can be described accurately. The experience of others indicates that balancing and compensation techniques are generally expensive and have met with limited and varied success (Ref. 38, 49). For this reason the choice was made to shape the antenna patterns to prevent reception of signals emanating from the ship.

Such a choice means each antenna of the system is blind to a portion of the 360° sector of coverage. It is usually desirable in any case to minimize this blind region of every antenna. This can be accomplished by separating the antennas and the reflecting source as much as practicable. From the geometry and rigging of most ships, this amounts to placing the antennas in an extreme forward or extreme aft position of the craft. (Keen (Ref. 9, p. 407) cites a virtue of fore and aft antennas in the 1938 edition of his book.)

Fig. 4-1 shows an overhead plan of a ship and the geometry of a possible receiving station. Also shown are possible patterns for two antennas. To avoid reflections, each antenna must be blind to a sector of minimum width α where

$$\alpha = \tan^{-1} \frac{b}{a} \tag{4-0}$$

with a the length of the ship and b the breadth of the ship. Typically, a minimum value of α may vary from 6° for a cruiser or destroyer to 14° for a carrier (Ref. 52). Of course, directivity of the antenna system should be chosen, and the received signal processed, to minimize ambiguities and to enhance the accuracy and resolution of the DF system.

4.1.2 DF Measurement Technique

In terms of the classification of Section 2.2, only those systems which measure instantaneous amplitude or phase of the field vector will be considered. Measurement of delay will be considered for this application to be equivalent to measurement

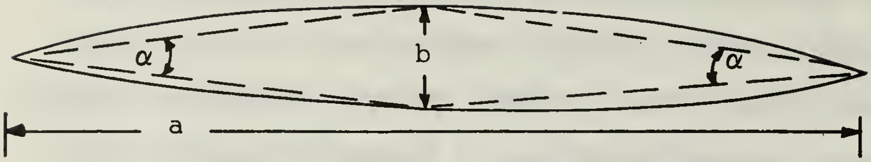


Fig. 4-1. Indication of the Blind Sector of Width α

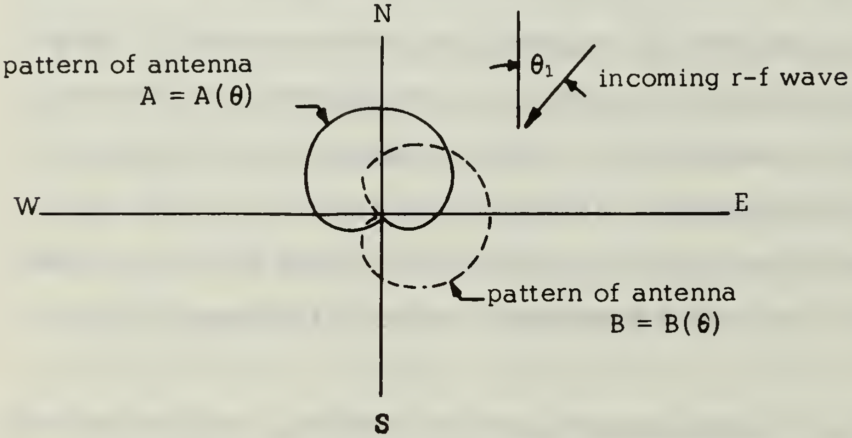


Fig. 4-2. Example of Spatially Different Antenna Patterns for Use with a Watson-Watt DF System

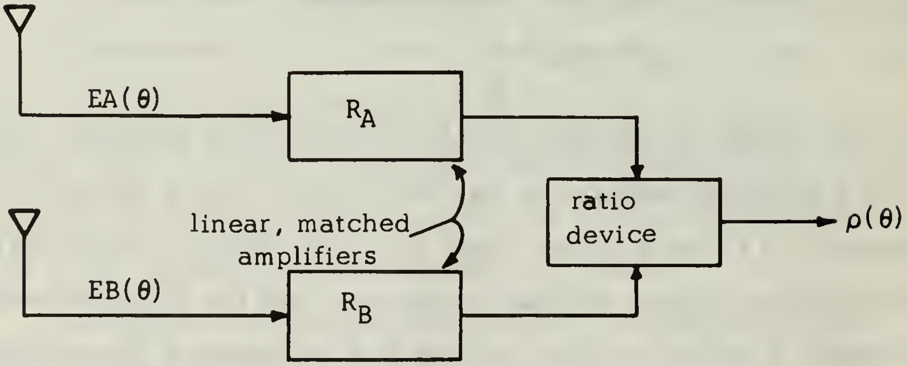


Fig. 4-3. Example of a Watson-Watt DF Receiver

of phase difference. It is felt that the application and platform rule out systems which measure sequentially the phase or amplitude of the field (arrays, rotatable antennas, variable or adjustable elements).

In all the systems to be considered, two channels will be used to balance out the effect of incident wave amplitude on the bearing indication. Amplitude information is, however, preserved and displayed as a separate parameter independent of bearing. Parallel-channel systems have been used repeatedly in the DF field because these systems can provide an instantaneous indication of signal bearing which is independent of signal amplitude and because they have an inherent simultaneous-signal capability (Ref. 7, Ref. 63-56).

The ways in which the amplitude data and the phase data can be collected, processed, and displayed will now be considered in turn. A summary of these methods is provided by Table 4-1 at the end of this section.

4.1.2.1 Measurement of Amplitude to Determine Bearing

The Watson-Watt cathode-ray direction finder is the earliest and perhaps the simplest implementation of a parallel channel system which relies on amplitude data to determine bearing (Ref. 7, Ref. 9, p. 682, Ref. 57). This system uses two spatially different antenna patterns as shown in Fig. 4-2. The receiving system is shown in Fig. 4-3. A wave of amplitude E arriving at an angle θ_1 produces a voltage proportional to $EA(\theta_1)$ in receiver R_A and to $EB(\theta_1)$ in R_B connected to antennas A and B respectively. If the ratio, ρ, of these voltages is formed, then

$$\rho = \frac{EA(\theta_1)}{EB(\theta_1)} \doteq \frac{A(\theta_1)}{B(\theta_1)} = \rho(\theta_1) \qquad (4-1)$$

and hence ρ is a measure of the angle of arrival, θ_1. Furthermore, ρ is independent of the amplitude E and hence the system is operable under conditions of fading.

The ratio of received signals can be formed, for example, by using an x-y cathode-ray oscilloscope (CRO). In this case, EA(θ) could be applied to the y - deflection plates and EB(θ) to the x - deflection plates. As shown in Fig. 4-4, the display will be a straight line (since x and y are r-f sinusoidal voltages) having an angle ϕ where

$$\phi = \tan^{-1}\frac{y}{x} = \tan^{-1}\frac{EA(\theta)}{EB(\theta)} = \tan^{-1}\rho(\theta) \tag{4-2}$$

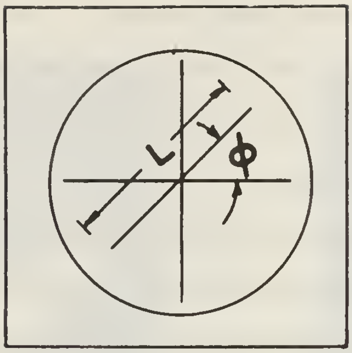
This expression links the angle of the display ϕ with the angle of the received signal θ. The length of the line trace is L where

$$L = 2\sqrt{x^2{}_{max} + y^2{}_{max}} = 2\sqrt{[EA(\theta)]^2 + [EB(\theta)]^2} = 2E\sqrt{A^2(\theta) + B^2(\theta)} \tag{4-3}$$

and hence the trace also provides a measure of received signal amplitude E. With appropriate antenna patterns a full 360° coverage is possible with no ambiguity in bearing measurement.

A usable (straight line) display for this system, which displays r-f voltage, requires that the x and y inputs to the oscilloscope be in phase. If these voltages are not in phase, it can be readily shown that the display is an ellipse whose eccentricity and major-axis slope is a function not only of this phase difference, but of the peak amplitude of x and of y as well. In general, then, an elliptical display is not a good indicator of bearing (Ref. 58, 59).

Rather than compensating for phase difference it is usually easier and more reliable to maintain an in-phase condition of the signals received on the two antennas and processed through the two receivers since this in-phase condition must be maintained over the range of input signal levels expected and over the band of frequencies of interest. Therefore, one



(a) Sketch

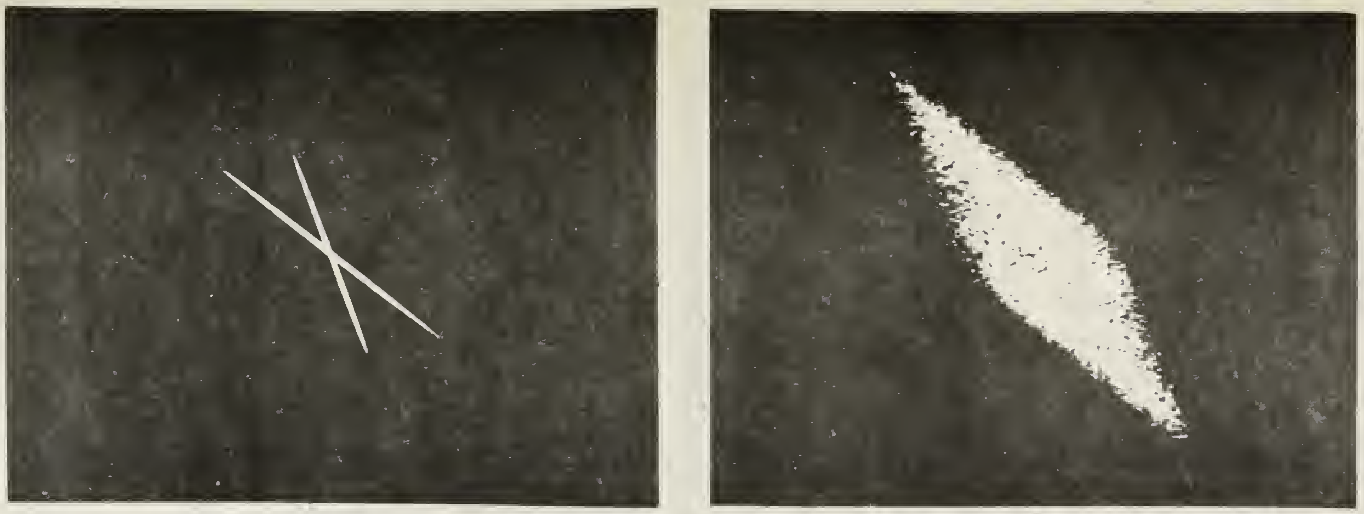
(b) Photograph of CRO Trace

Fig. 4-4. Typical Display for One Sinusoidal Signal specification of this type of system is that the two receiving antennas must be separated by no more than a small fraction of a wavelength of the lowest frequency signal to be received. A second specification is that the two receivers (amplifiers) of Fig. 4-3 must be matched in phase over a given dynamic range and a given band of frequencies.

Once this in-phase requirement is met, the system is capable of providing unambiguous bearing indication throughout 360° and over a range of frequencies. Signal amplitude data is preserved and displayed in terms of the length of the line trace.

It was observed by Watson-Watt that this type of direction finder has a simultaneous-signal resolution capability (Ref. 7). With n signals, the display is a parallelogram of 2n sides. The slope of each pair of sides indicates the bearing of one of the signals and their length is a measure of the amplitude of that signal. An example of such a display for two and three signals is shown in Fig. 4-5. (For signal frequencies beyond the range of conventional x-y oscilloscopes ($f > 30$ mHz), a sampling oscilloscope can be used as a display device. Commercial sampling x-y CRO's will display frequencies up to 6 GHz. A sampling CRO provided the traces of Fig. 4-5 (a) and (b).)

This type of system as originally conceived has two disadvantages. The requirement on phase matching has been mentioned. In addition, the sensitivity of the system is poor since the 360° range of bearings must be read from an effective 90° sector of the polar display (the line trace occurs in the first and third quadrants of the display). In terms of Fig. 4-4(a), sensitivity is defined here as $\frac{\partial \phi}{\partial \theta}$. Section 4.4 considers a method of improving sensitivity by a factor of two. Note that in general the display parameter ϕ will not be a linear function of the signal bearing θ. This requires that the screen of the CRO be calibrated



(a) Two Signals Occurring Individually; Sampling Oscilloscope Display

(b) Two Signals of (a) Occurring Simultaneously; Sampling Oscilloscope Display

(c) Two Signals Occurring Simultaneously; Conventional Oscilloscope Display (Not the same signals as in (b).

(d) Three Signals Occurring Simultaneously; Conventional Oscilloscope Display

Fig. 4-5. Typical Traces for Inputs of More Than One Signal to indicate bearing. The antenna patterns and amplifier gains can be chosen to provide linear indication over a range of bearing.

In cases where it is impractical to maintain phase match of the two channels of the receiver of Fig. 4-3, the envelope of the received signal can be used to provide a measure of bearing. This system assumes the form shown in Fig. 4-6. When the ratio and display device are a CRO, (4-2) holds except now x and y are video voltages and hence the trace is a dot instead of a line, as shown in Fig. 4-7. The polar coordinates of this dot are ϕ and $r = L/2$ as defined by (4-2) and (4-3).

This system using detectors will indicate bearing of cw or pulsed signals while removing the requirement on antenna location. Again, amplitude information is preserved and displayed. The simultaneous signal capability of this system is essentially lost however. It can be shown that for the case of two signals occurring simultaneously the trace is an ellipse having an origin approximately at the vector sum of the display formed by the signals occurring individually.* Such a display indicates the presence of multiple signals, but it is of little value in determining the exact number of signals being received or the bearing or amplitude of any particular signal.

4.1.2.2 Measurement of Phase to Determine Bearing

This technique uses two or more spatially separated antennas to obtain direction-of-arrival information. With reference to Fig. 4-8, assume that the signal received at antenna A is $E\cos\omega t$: that on B is

$$E\cos\omega(t-\tau) = E\cos(\omega t-\psi)$$

where $\psi = \omega\tau$. From the geometry of the antennas,

$$\sin\theta = \frac{z}{d}$$

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* Author's notes

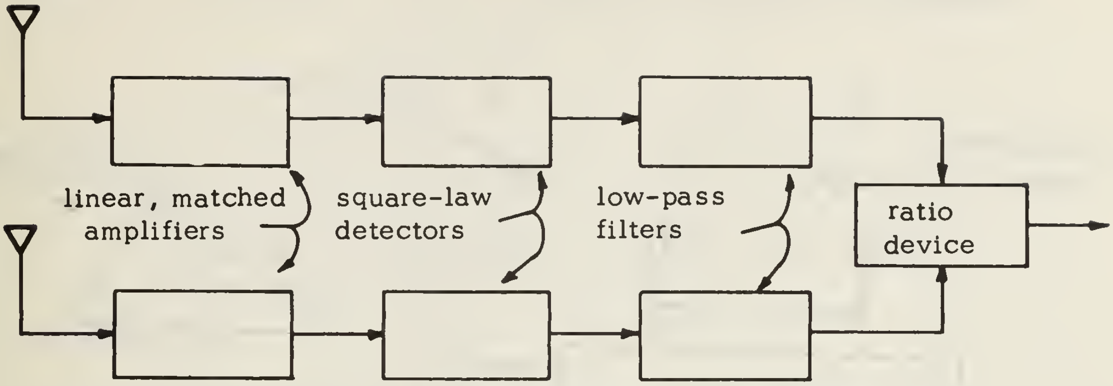


Fig. 4-6. A Parallel Channel System Which Displays the Envelope (Video) of the Received Signal

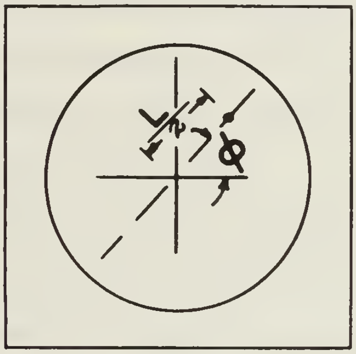


Fig. 4-7. CRO Display Formed by the System of Fig. 4-6 when the Input is One Sinusoidal Signal

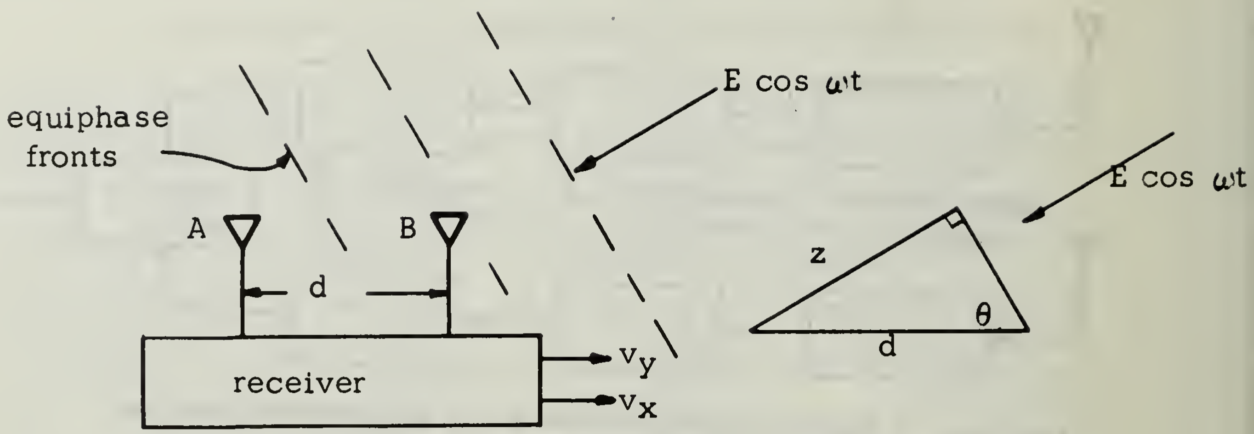


Fig. 4-8. Geometry of a Two Antenna System Which Measures Phase to Determine Signal Bearing.

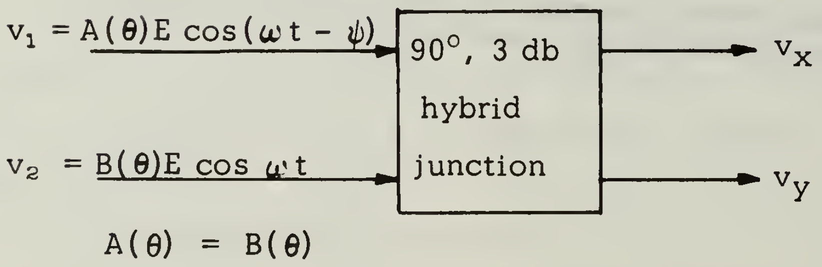


Fig. 4-9. A Receiver Which Measures the Difference in Phase of Two Equal Amplitude Signals.

where θ is, as before, the angle of arrival of the signal.

Also, $z = c\tau$ where $c = 3 \times 10^8$ meters per second. Therefore,

$$\sin \theta = \frac{c\tau}{d}$$

Rewriting,

$$\tau = \frac{d}{c} \sin \theta$$

and hence,

$$\psi = \omega\tau = \frac{\omega d}{c} \sin \theta = 2\pi \frac{d}{\lambda} \sin \theta = 2\pi p \sin \theta \tag{4-4}$$

where p is the antenna spacing measured in wavelengths. If ω is known, then ϕ, the phase difference in radians of the signals received on antennas A and B, is a function of θ, the bearing of the received signal. (Section 4-3 considers the case where ω and τ (or θ) are both unknown quantities.)

Methods of processing the data to extract $\sin \theta$ can be considered for the case of equal amplitude signals and for signals whose amplitudes are not the same.

i) Signals of equal amplitude.

If the signals received on the two antennas have equal amplitudes then the receiver shown in Fig. 4-9 will provide a suitable display. As shown in Appendix A, the r-f voltages v_x and v_y are in phase and have peak values given by

$$(v_y)_{max} = \sqrt{2}\, EA(\theta) \sin (\pi/4 + \psi/2)$$

$$(v_x)_{max} = \sqrt{2}\, EB(\theta) \cos (\pi/4 + \psi/2)$$

The trace will then be a line having slope ϕ and of length L where

$$\begin{aligned} \phi &= \pi/4 + \pi p \sin \theta \\ L &= 2\sqrt{2}\, E \sqrt{A^2(\theta) + B^2(\theta)} \end{aligned} \tag{4-5}$$

This is the same trace obtained previously (Fig. 4-4) using amplitude measurements and a linear receiver (no detectors). As in that system, a parallelogram display results when more than one signal is present at a time.

The display in this method is not limited to an effective 90° sector; the line trace can have positive as well as negative slope. In fact the sensitivity, $\frac{\partial \phi}{\partial \theta}$, is from (4-5) a function of the antenna separation:

$$\frac{\partial \phi}{\partial \theta} = 2\pi \frac{d}{\lambda} \cos \theta \tag{4-6}$$

There is then no theoretical limit to the accuracy of such a system. Increasing antenna separation beyond a wavelength does introduce ambiguities in measurement, a well-known property of all interferometer systems. By restricting coverage to particular sectors, good indications of bearing are possible without ambiguity.

To obtain the desired straight-line display, it is necessary to preserve signal amplitude throughout the system. Variations in amplitude between channels results in an elliptical trace. To avoid compensation in the receivers, the equal amplitude requirement means the two antennas must have identical gain characteristics in the plane of interest and any amplifiers in the receiver must have identical gains.

ii) Signals of unequal amplitude

The detection of phase difference between two signals of unequal amplitudes is difficult to accomplish practically. Appendix B indicates what is necessary to derive phase information. The nature of this problem suggests that in any practical DF system which relies on phase information, the antennas should have identical gain characteristics.

The salient features of these four methods of determining bearing are presented in Table 4-1. This will provide a useful reference for the next section which presents one practical combination of the methods of DF considered in this section.

TABLE 4-1

Method	Receiver characteristics	CRO Trace	Features
1	co-located antennas, different patterns, requires in-phase signals on the two channels	line	angle of line trace is a measure of bearing, length of line is a measure of signal amplitude, simultaneous signal capability, no ambiguity in measurement
2	signal phase not important, different antenna patterns, uses detectors	dot	angle of dot is a measure of signal bearing, radial coordinate of dot is a measure of signal amplitude, no simultaneous signal capability, no ambiguity in bearing measurement
3	separated antennas, identical patterns, requires equal amplitude signals	line	angle of line is a measure of bearing, length of line is a measure of signal amplitude, simultaneous signal capability, ambiguity in measurement if antenna separation exceeds one-half wavelength
4	separated antennas, patterns not critical	dot	considered impractical by comparison

4.2 Specification of a DF System

The material in the previous sections has suggested the following capability as desirable in a shipboard DF system:

i) Coverage throughout the 360° plane with no ambiguity in bearing; error in bearing indication to be a minimum .

ii) Operation over a band of frequencies with the bearing indication independent of signal frequency; knowledge of frequency is desirable.

iii) Operation over a range of signal levels with the bearing indication independent of signal amplitude; knowledge of signal amplitude is desirable.

iv) The ability to resolve simultaneous signals (cw or pulsed) and indicate the bearing, frequency, and amplitude of each.

Imposed on these operational requirements is the constraint to minimize the amount of equipment, particularly the size and number of antennas.

Section 4.1.1 considers the antenna pattern and placement requirements to avoid signal reflections, an assumed major source of error in bearing indication. Section 4.1.2 enumerates and discusses DF techniques of potential use for a shipboard system. This material is now considered in view of the assumed operational requirements to define a particular antenna, receiving, and display configuration.

4.2.1 An Elementary System and Its Properties

Before turning to the system proposed by this study, an alternate configuration will be briefly outlined. The approach taken in this digression is attractive because of its simplicity and because it provides an output voltage which is a nearly linear function of signal bearing. By contrast, the methods previously discussed gave measures which were sinusoidal or other non-linear functions of bearing.

The antenna pattern requirements stipulated in Section 4.1.1 are approximately satisfied by a cardiod characteristic. Admitting these patterns as candidates, it will now be shown that a simple DF system can be conceived using two antennas as shown in Fig. 4-10(a).

This system makes use of the following approximation

$$\sqrt{1 - \cos\theta} - \sqrt{1 + \cos\theta} \approx \begin{cases} +\theta, & 0 \le \theta \le 180^\circ \\ \sqrt{2} - \theta, & 180^\circ \le \theta \le 360^\circ \end{cases}$$

which is plotted as Fig. 4-10(b) (Ref. 60, p. 9). As shown in Ref. 60, departure from linearity is less than 2%. Since the cardiod antenna patterns of Fig. 4-10(a) are defined by the equations

$$A(\theta) = a(1 + \cos\theta)$$

$$B(\theta) = a(1 - \cos\theta)$$

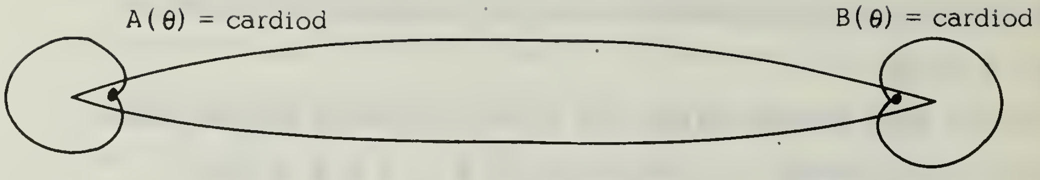
it is then necessary only to extract the square roots of the voltages received on the two antennas, form their difference and interpret the resulting voltage in terms of bearing. This difference voltage is, unfortunately, also a function of input signal level.

To eliminate this dependency without r-f limiting or automatic gain control, the ratio of the received voltages can be formed as shown in Fig. 4-11(a). The angle ϕ is again a non-linear function of bearing as shown. By adding square-root amplifiers to the receiver, a linear dependency of ϕ on θ can be achieved since, as shown in Fig. 4-11(b),

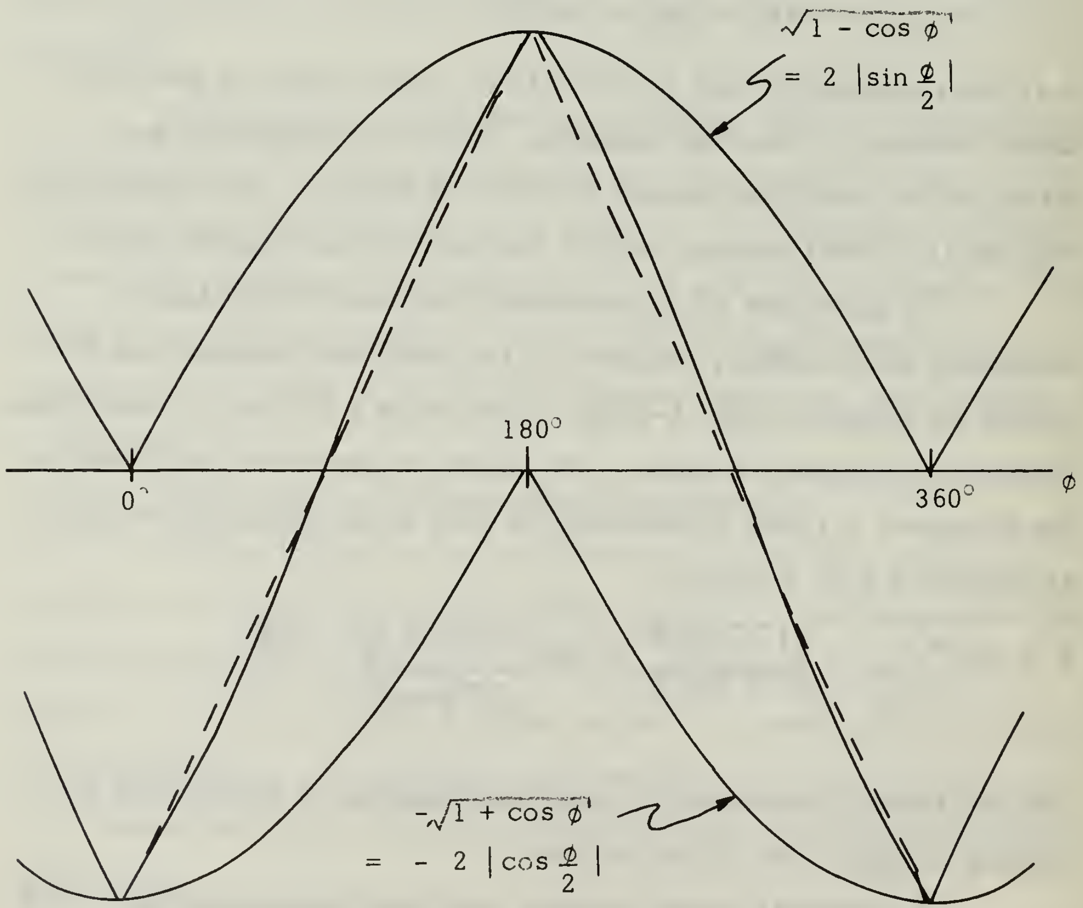
$$\phi = \tan^{-1}\frac{v_y}{v_x} = \frac{\sqrt{1 - \cos\theta}}{\sqrt{1 + \cos\theta}} = \tan^{-1}\frac{\sqrt{2}\left|\sin\frac{\theta}{2}\right|}{\sqrt{2}\left|\cos\frac{\theta}{2}\right|} = \frac{|\theta|}{2}$$

The dot trace is restricted to the first quadrant of the display resulting in some loss of sensitivity.

A practical system suffers from the following effects: the gain characteristics of the antennas should be nearly identical and the relative amplitudes of the received signals preserved in the

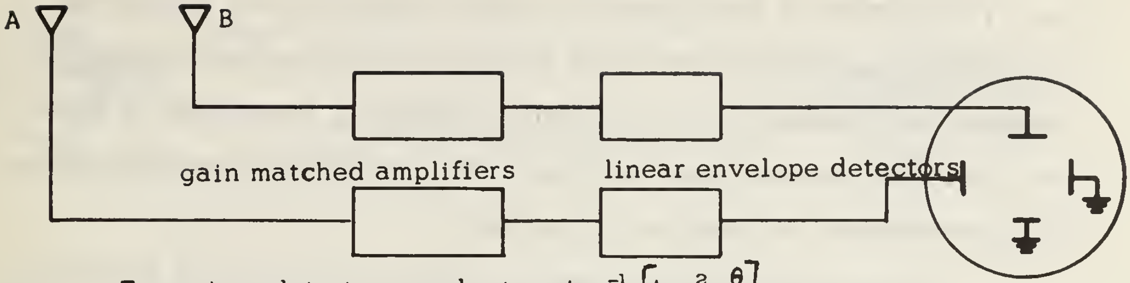


(a) Example of Cardiod Antenna Patterns



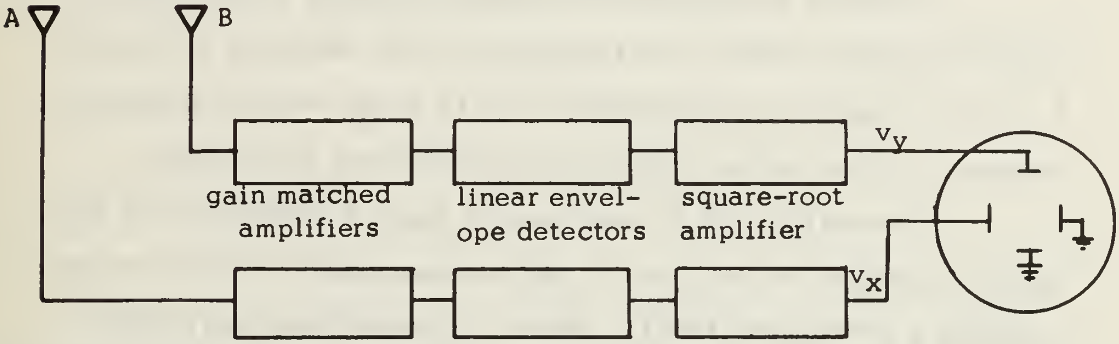
(b) Plot of $\sqrt{1 - \cos\phi}$ and $\sqrt{1 + \cos\phi}$

Fig. 4-10. Cardiod Pattern Characteristics



Trace is a dot at an angle $\phi = \tan^{-1}\left[\tan^2 \frac{\theta}{2}\right]$

(a) A Possible Receiver; Trace has Ambiguities and is a Nonlinear Measure of Bearing.



Trace is a dot at an angle $\phi = \left|\frac{\theta}{2}\right|$ where $-180^\circ \leq \theta \leq +180^\circ$

(b) An Alternate Receiver; Trace has Ambiguities but is a Linear Measure of Bearing.

Fig. 4-11. A DF System Which Uses Two Cardiod Antenna Patterns receiver; accurate, reliable, and matched square-root amplifiers may be difficult to produce (Ref. 60, p. 12 includes such a circuit); the system lacks a simultaneous signal capability; an ambiguity of 180° exists in the display which requires additional equipment to resolve; the display is compressed resulting in some loss of sensitivity. The system does provide with acceptable antenna patterns a linear measure of direction of arrival.

The next section proposes a more sophisticated equipment which overcomes some of the disadvantages of this simple system at the expense of equipment complexity (additional antennas).

4.2.2 A Recommended 'Three Mode' DF System

Without considering the many possible configurations which could be defined within the framework of the material of Section 4.1, the compromise determined by this study will be detailed. Reasons for the choice will be indicated where appropriate.

Basically, the system uses a pair of antennas fore and aft as identified in Fig. 4-12. All antennas have a blind sector of width α defined by (4-0). Hence, no antenna ever receives signals reflected from the ship or its rigging. The avoidance of these reflections necessitates use of antennas fore and aft for 360° coverage. As will be shown, additional benefits can be derived from such a configuration.

The signals received on antennas A and B of Fig. 4-12 are in phase; similarly for C and D. Therefore by appropriate choice of the gain patterns, each of these pairs can derive bearing information from the amplitude of the received signals (Method 1 of Table 4-1). Both pairs must be used to fill in the blind sector of any one pair. The system operating in this mode provides readings which are redundant over a sector of width $360 - \alpha$ degrees. This will be referred to as mode 1.

By virtue of their separation, signals received on antennas

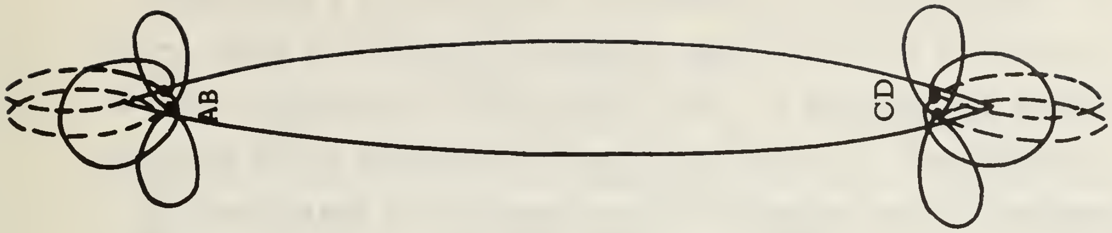


Fig. 4-12. An Example Showing Antenna Placement and Patterns.

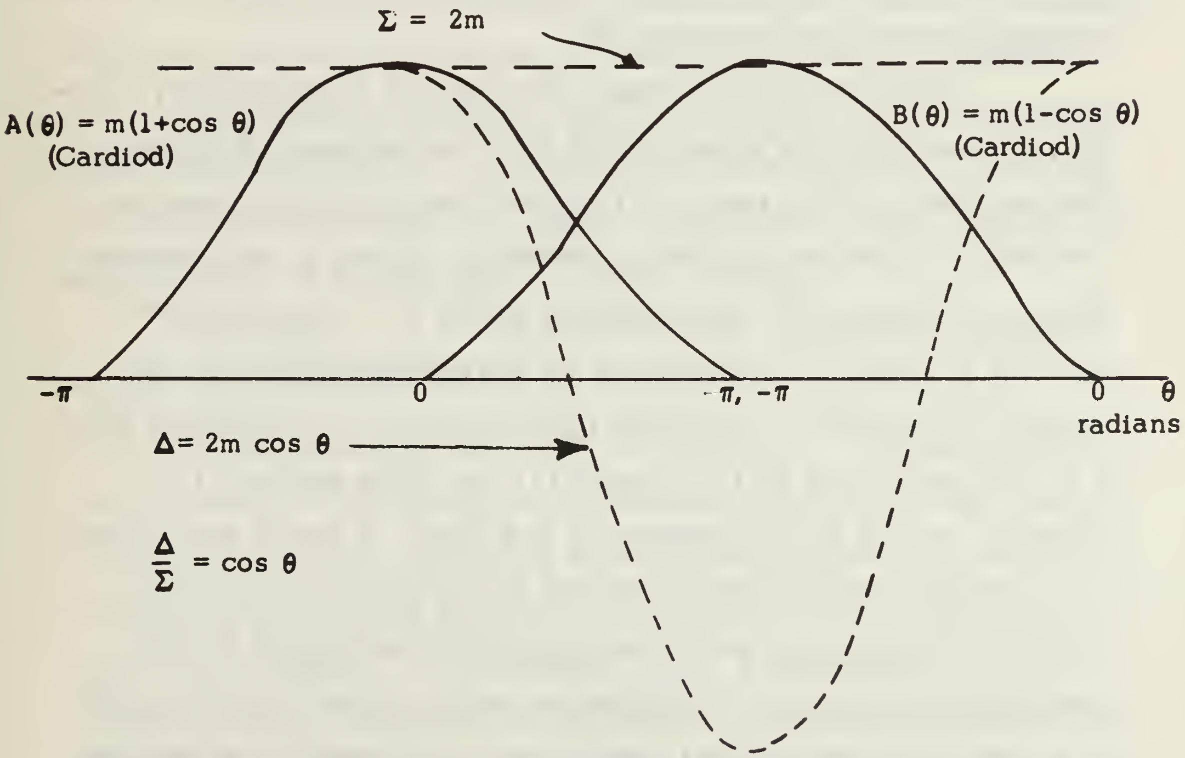


Fig. 4-13. Sum and Difference Patterns for Particular Gain Characteristics.

A and B are generally out of phase with those received on C and D. Therefore, A and C, for example, can be used as a pair (interferometer) to derive bearing information (method 3 of Table 4-1). Identify this as mode 2. This requires that the patterns of A and C be identical. For most ships and for operation in the HF band, operation in this manner introduces ambiguities (wavelength at 3 mHz is 328 ft. which is less than the length of most ships considered for this application). As shown in (4-5), sensitivity increases as $\frac{d}{\lambda}$ increases and so this method is capable of greater sensitivity than method 1 at the expense of ambiguities. However, methods 1 and 3 can provide information simultaneously; the result is that any ambiguities present in one indication can be resolved using the other.

For further discussion of HF interferometer DF systems, which are more elaborate than the system considered in this report, see reference 54. For a report on the errors due to two element interferometers, see reference 55.

In two sectors of total width 2α, the interferometry technique cannot be used since one or the other antenna of the pair has zero gain in this region. To obtain sensitivity in these sectors which is better than that provided by method 1, an alternate mode of operation can be introduced (mode 3). This consists of altering the feed of the antennas (or introducing additional elements, if practical) to increase the directivity of antennas A and B in one sector and that of C and D in the other sector. For example, with a ship's heading of true North, A and B would provide accurate bearing measurements on signals coming from a northerly direction; C and D would give the bearing of signals coming from the South. The antenna system shown for this mode of operation resembles that used in amplitude sensing monopulse systems. Rather than processing the amplitude data received on each channel to obtain signal bearing, monopulse seeks a null by sweeping the composite pattern until the signal source is aligned with the boresight axis (Ref. 62).

These pattern requirements of the four antennas are summarized in the form of an example in Fig. 4-12. The patterns of mode 3 are shown in dashed lines. Patterns shown are merely for purposes of illustration.

This system, then, has three possible modes of operation although two of these can coexist by providing separate processing circuitry. Each mode provides a simultaneous signal capability. (See Section 4.1.2) Each mode is insensitive to reflections from the ship. Together these three modes provide 360° coverage with coarse and fine indications of bearing available throughout most of this range.

4.2.2.1 Consideration of the Antenna Subsystem

This section provides additional detail of value in designing antenna patterns for the modes of operation presented in Section 4.2.2. No attempt is made to specify antennas which will produce these patterns although it is realized that the structures necessary to yield the defined gain and phase characteristics will determine in large measure the practicability of this system.

Section 4.1.2.1 derives for modes 1 and 3 the equations relating ϕ, the measure of bearing, to patterns $A(\theta)$ and $B(\theta)$. It was observed in that section that the display is a line confined to the first and third quadrants of the scope screen. To permit use of the entire screen which results in increased sensitivity, the sum and difference of these patterns can be formed as shown in Fig. 4-13. Applying the difference to the y deflection plates and the sum to the x deflection plates results in a line trace which can assume any value of positive or negative slope. The trace is a line instead of an ellipse since it is assumed the original signals are in phase and hence their sum and difference are in phase. The angle of the trace is given by

$$\phi = \tan^{-1} \rho = \tan^{-1} \left[\frac{A(\theta) - B(\theta)}{A(\theta) + B(\theta)} \right] \tag{4-7}$$

For a given $A(\theta)$ and $B(\theta)$, the sensitivity of measurement is given by $\frac{d\phi}{d\theta} = \frac{A'B - AB'}{A^2 + B^2}$ where the prime denotes differentiation. The general case of ϕ not equal θ implies that some bearings can be read more accurately than others.

In general, ϕ is not a linear function of θ. For a given system, then, the screen of the CRO will have to be calibrated to obtain true bearing. To make ϕ a linear function of θ requires from (4-7) that

$$A(\theta) - B(\theta) = \sin \theta$$

$$A(\theta) + B(\theta) = \cos \theta$$

In this mode of operation, the primary antenna pattern design requirements remain as follows: selection of $A(\theta)$, $B(\theta)$, $C(\theta)$ and $D(\theta)$ to be blind to a sector of width α; selection of A and B, and similarly C and D, such that unambiguous displays, over sectors of width $360 - \alpha$ degrees, result. Linearity of ϕ vs θ and particular values of sensitivity, both in restricted sectors, are of secondary importance in mode 1. Mode 3 allows greater freedom in design since the coverage in this mode is restricted.

When phase is used to determine bearing (mode 2), the relation of ϕ to θ and the sensitivity $\frac{\partial \phi}{\partial \theta}$ are given by (4-5) and (4-6). For a given installation, d is fixed; sensitivity then is a function of λ and θ, neither of which is known in practice.

Bearing indication and sensitivity are independent of antenna directivity. It is desirable, however, to provide uniform antenna gain in all except the blind regions. This results in a uniform probability of intercept in these areas. As indicated previously, to simplify phase detection it is required that $A(\theta) = C(\theta)$ for A and C the interferometer pair.

Fig. 4-12 is an example of antenna patterns which may be candidates for an actual system. Work on antennas of interest here has been reported in the literature (Ref. 62-65).

4.2.2.2 Consideration of the Receiver Subsystem

The material of Section 4.1.2 can now be applied to design the receiving portion of the system which is shown as Fig. 4-14. Mode 1 requires a pair of amplifiers, matched in phase over the frequency range of interest, driving a sum and difference (SAD) network. The SAD output connects directly to the x - y oscilloscope display. Appendix C presents the realization of a SAD network which is independent of frequency.

The mode 3 receiver is identical to that of mode 1; the two are distinguished by their differing antenna gain characteristics. In Fig. 4-14 the mode of operation is determined by the setting of switch S.

Mode 2 operates in parallel with mode 1 and requires a somewhat simpler receiver as shown; e.g. gain matched amplifiers may be less of a problem than phase matched; the 90° hybrid is a component of the SAD network. The mode 2 display indicates the difference in phase between the signal on antenna A and that on C. As indicated in (4-4), to convert this reading to signal bearing requires knowledge of signal frequency. This can be provided by a tuned receiver. Alternatively the mode 2 receiver could be modified to provide independent readings of signal frequency and signal bearing, as discussed in the next section.

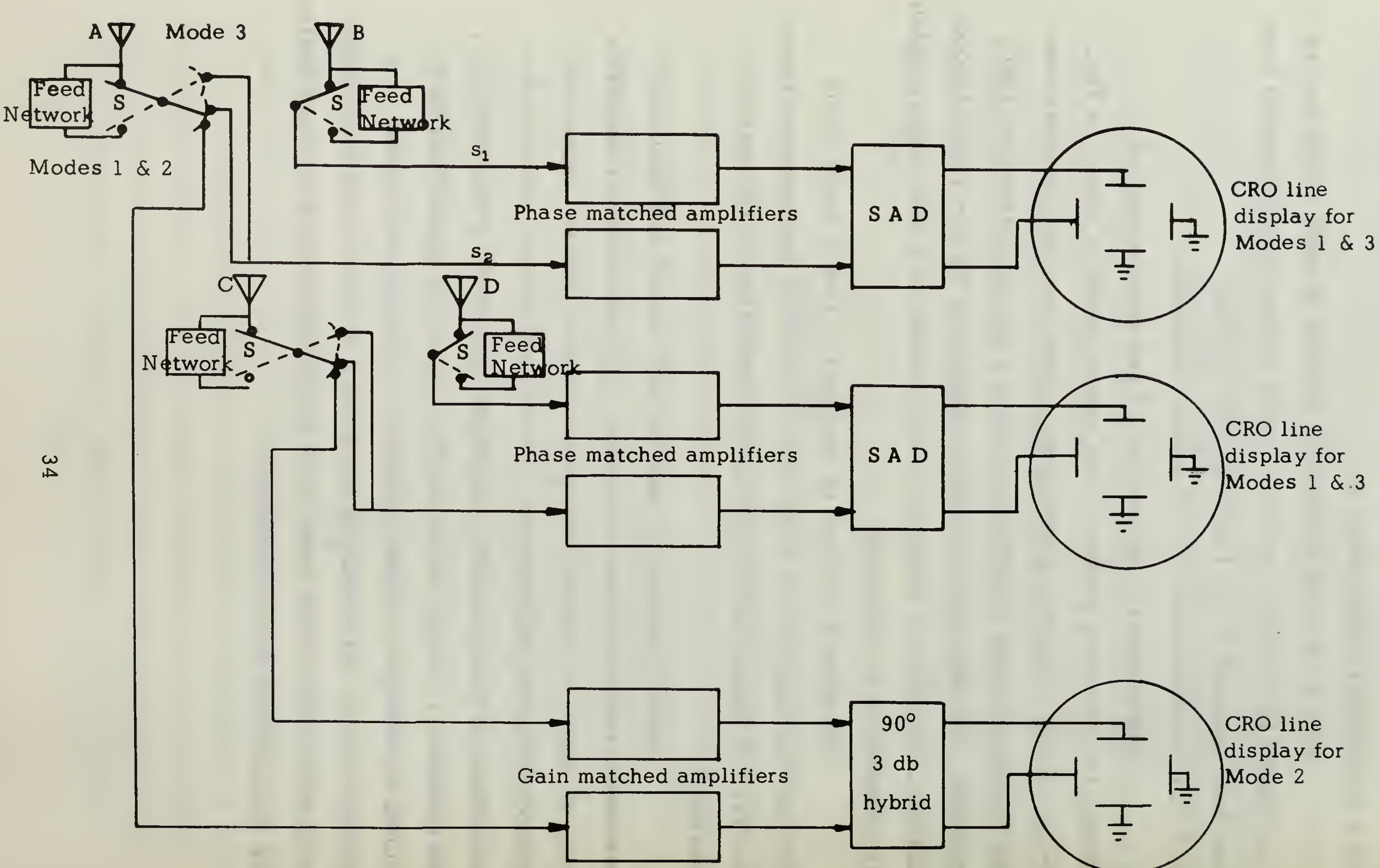


Fig. 4-14. Receiver-Display Block Diagram Showing the Three Operating Modes

4.3 Consideration of the Measurement of Frequency*

As indicated in Section 4.1.2.2, the mode 2 parallel-channel receiver shown in Fig. 4-14 is essentially a phase discriminator.* Equ. 4-4 shows that ψ , the phase difference between the signals on the two channels, is a function of signal frequency, ω , and signal bearing, θ . This section presents two different methods of resolving ψ into components which are independent measures of ω and θ .

The first method essentially uses two phase discriminators, one to measure ψ and the other to measure ω . If the voltages out of these discriminators are v_1 and v_2 where

$$v_1 = k_1 \omega \tag{4-8}$$

$$v_2 = k_2 \psi = k_2 \frac{\omega d}{c} \sin \theta$$

then v_1 is a direct measure of frequency independent of bearing and the ratio

$$\frac{v_2}{v_1} = k_3 \frac{d}{c} \sin \theta \tag{4-9}$$

is a measure of bearing independent of frequency. The k's are constants.

Fig. 4-15 is a block diagram of an instantaneous frequency discriminator. Except for the delay τ in one channel, this device is identical to the mode 2 receiver (phase detector) of Fig. 4-9. The delay τ introduces a phase difference equal to $\omega \tau$ between the signal of channel a and that of channel b. As before

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* The techniques presented in this section were outlined at the Applied Electronics Laboratory, Stanford University, Stanford, California. Work in this particular area and more generally work on a variety of parallel-channel phase and frequency meters is continuing at Stanford's Applied Electronics Laboratory.

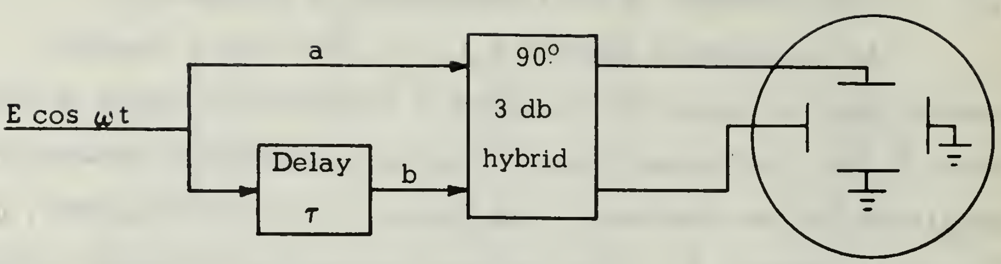


Fig. 4-15. An Instantaneous Frequency Measuring System Which Displays r-f Voltage

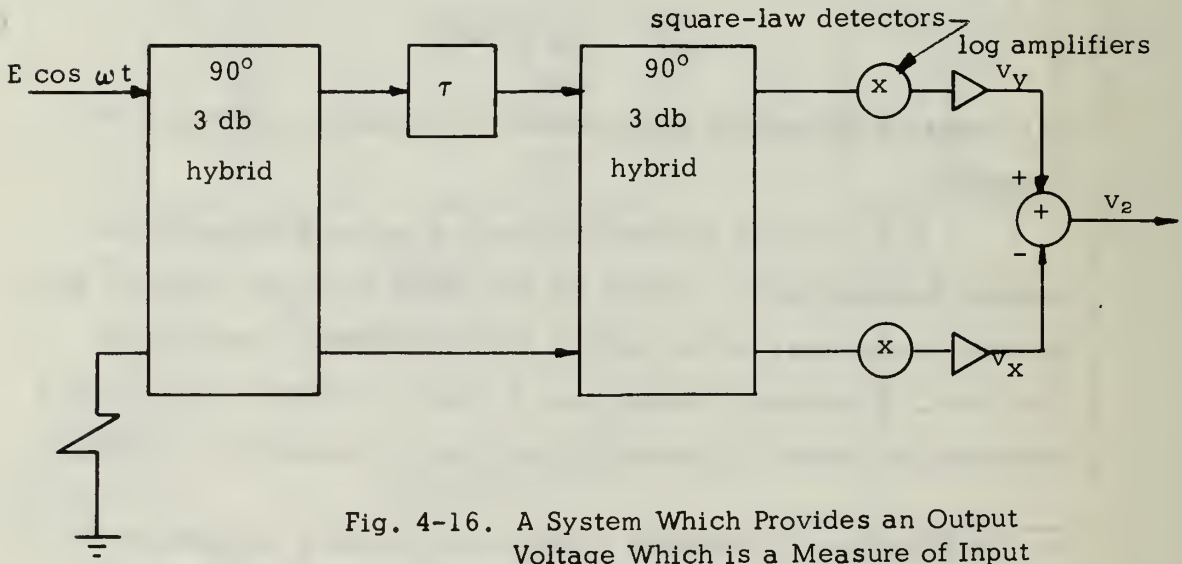


Fig. 4-16. A System Which Provides an Output Voltage Which is a Measure of Input Signal Frequency

(equ. 4-4 and 4-5 and Appendix A), the display is a line at an angle ϕ where

$$\phi = \pi/4 + \frac{\omega \tau}{2}$$

For a fixed, known delay, ϕ indicates signal frequency directly. Increasing τ increases measurement sensitivity, $\frac{d\phi}{df}$, but also introduces additional ambiguity in a frequency band.

To obtain a voltage that is a measure of frequency, the circuit of Fig. 4-15 can be modified as shown in Fig. 4-16. Here the ratio is formed by taking the difference of the logarithms of the two quantities. The output voltage, v_2 is then

$$v_2 = \log \frac{v_y}{v_x} = \log \quad \tan \frac{\omega \tau}{2}$$

To make the voltage a linear function of frequency as required by (4-8), the circuit of Fig. 4-16 can be modified as shown in Fig. 4-17 which shows the complete receiving system. The introduction of the 6db of attenuation linearizes the v_o vs ω curve; it also decreases the slope of this function which thus reduces measurement sensitivity. Since the video is used to measure phase in this circuit, the simultaneous signal capability is sacrificed. The ratio of (4-9) is meaningful, though, only when one signal is present at a time.

An alternate phase discriminator which has a nearly linear output voltage vs input phase difference is shown in Fig. 4-18. This is the same system discussed in Section 4.2.1. Reference 60 presents a more complete discussion of this type of phase discriminator.

The second method of obtaining bearing measurements

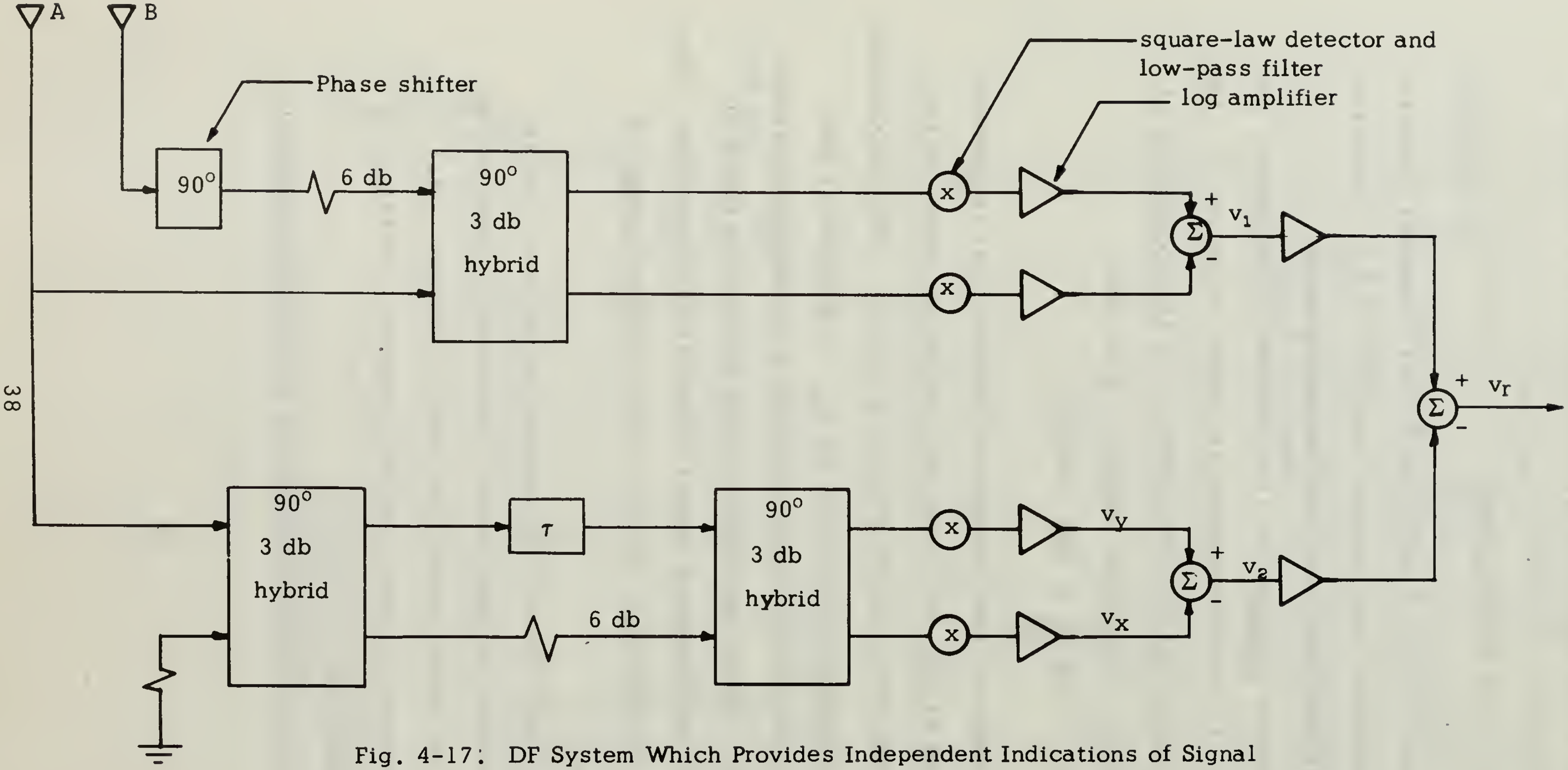
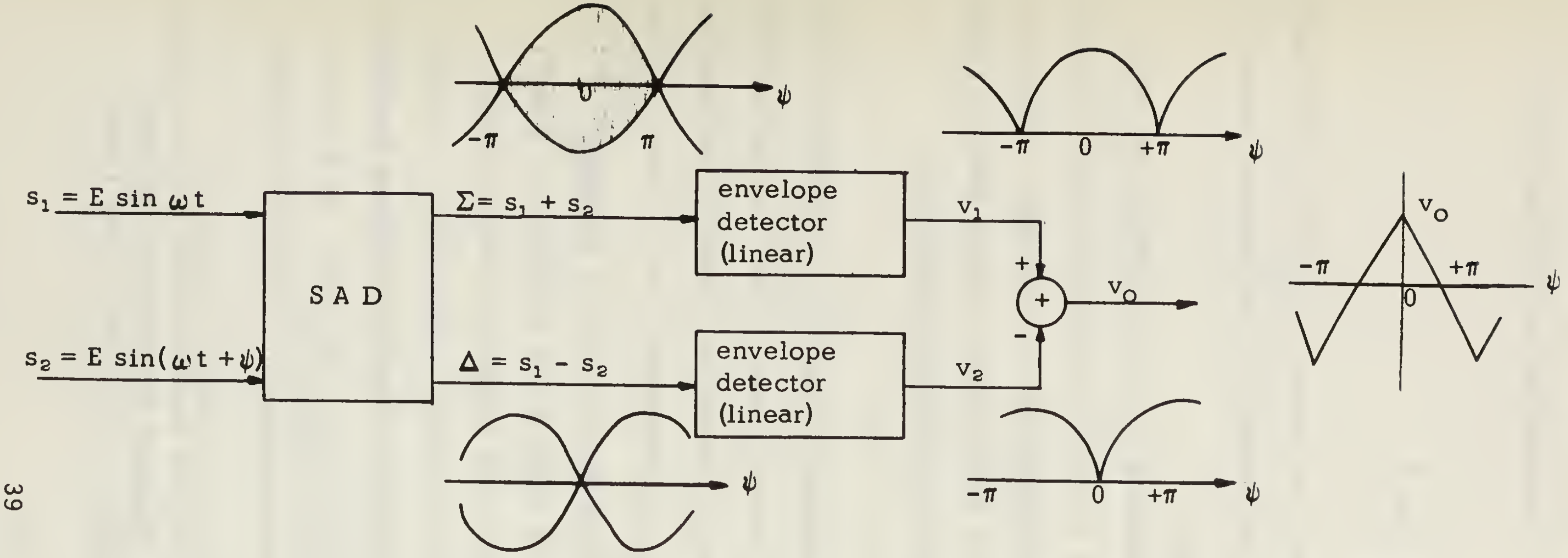


Fig. 4-17: DF System Which Provides Independent Indications of Signal Frequency and Bearing.



a) Circuit

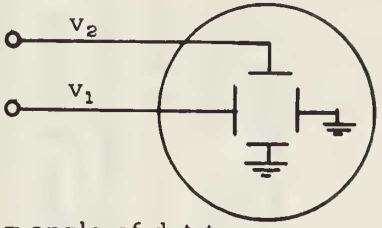
$$\Sigma = \sqrt{2}\, E\sqrt{1 + \cos\psi}\, \sin(\omega t + \psi/2)$$

$$\Delta = \sqrt{2}\, E\sqrt{1 - \cos\psi}\, \sin(\omega t + \psi/2 - \pi/2)$$

$$v_1 = \sqrt{2}\, E\sqrt{1 + \cos\psi} = 2E\,|\cos\psi/2\,|$$

$$v_2 = \sqrt{2}\, E\sqrt{1 - \cos\psi} = 2E\,|\sin\psi/2\,|$$

b) Equations



ϕ = angle of dot trace
$\phi = |\psi/2|\quad 0 \le \phi \le \pi/2$

c) Alternate Measure of Phase Difference

Fig. 4-18. A Phase Detector Which Uses a SAD Network and Linear Envelope Detectors.

independent of signal frequency is presented in Fig. 4-19.* The analysis of Appendix D shows that ℓ_1 the position of one null in the standing wave on the line, is independent of frequency and varies according to

$$\ell_1 = \frac{L_S}{2} - \frac{d}{2} \sin \theta$$

The position of this first null from the center of the line is then given by $\frac{d}{2} \sin \theta$. (This assumes υ, the velocity of propagation along ℓ, is equal to c, the speed of light.)

A probe could be moved along the line to detect the null; alternatively, a series of probes could be positioned along the line and their outputs inspected to estimate the null position. The last method lends itself to digital data processing. Raabe (Ref. 67) discusses this technique as a means of measuring frequency.

4.4 Effects of Noise

In nearly all visual displays of the type considered in this report, noise when added to the signal tends to blur the scope trace. A dot trace becomes a spot having illumination intensity decreasing as radius increases. A line trace is broadened into a "trail." The general effect is that a trace which is the locus of a point in the absence of noise is the locus of a spot in the presence of noise.

The statistics of x and y, the outputs of twin-channel receivers (phase discriminators) have been determined. In 1949, de Walden and Swallow considered the amplitude density functions of these voltages for gaussian noise input (Ref. 68). In a more recent report, Tsvetnov considers the phase correlation properties

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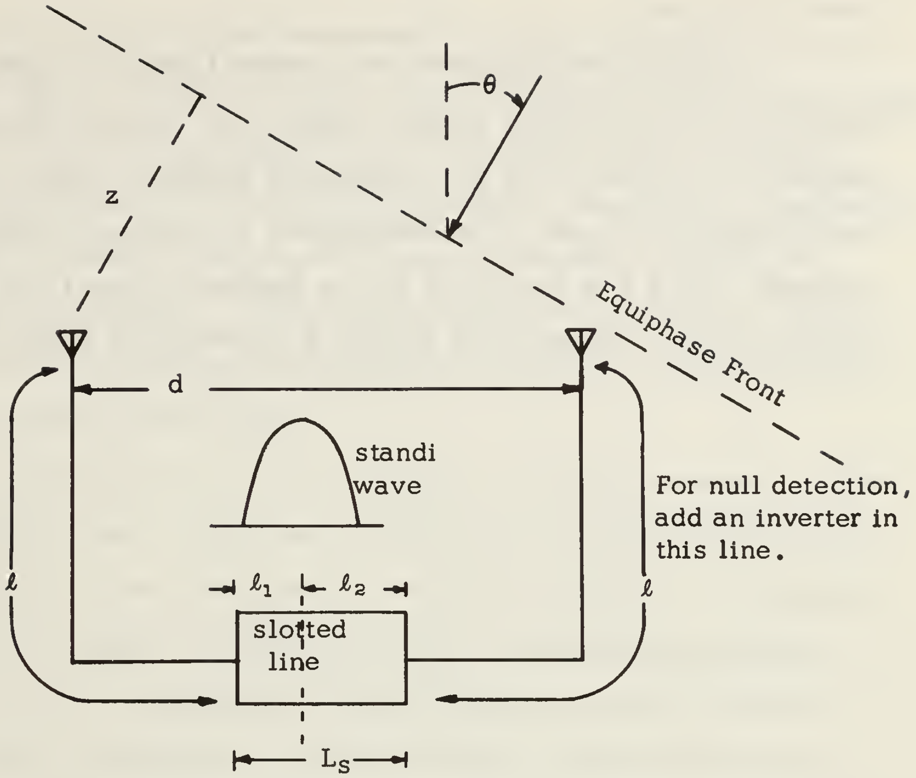
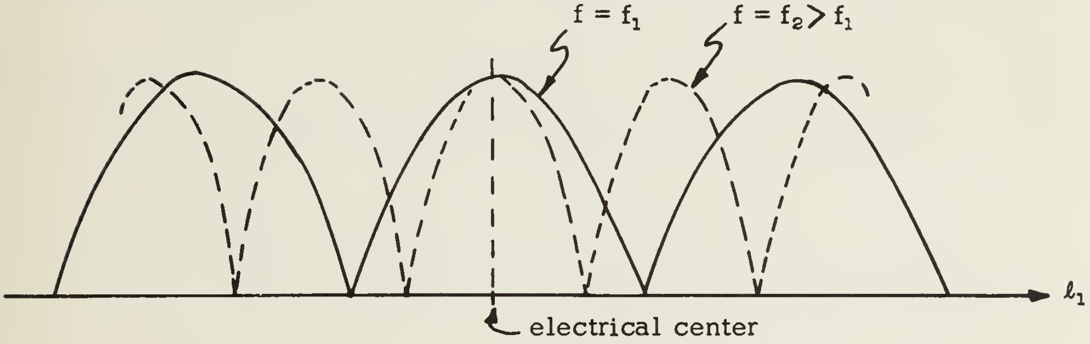
* This "symmetrical ring" system was suggested by R. M. Kochis, Applied Electronics Laboratory, Stanford University, Stanford, California. The principle is similar to one used in the Fredif System (Ref. 66).



(a) Geometry



(b) Standing wave pattern on the slotted line

Fig. 4-19. Symmetrical Ring DF System

of signals and gaussian interference in two-channel phase systems (Ref. 69).

Reference 70 considers a general class of parallel channel receivers which display a video signal and derives the mean and variance of x and y and the covariance between these voltages for gaussian noise input. The normalized covariance of these random variable x and y is the slope of the line which best fits (in a minimum mean square error sense) a blurred line trace (Ref. 71).

5.0 Conclusions and Future Work

A DF system which operates in three modes has been considered in detail (Section 4.2.2). As presented this receiving system is capable of providing data, on an intercepted signal, such as bearing, amplitude and, with some additional equipment, frequency. The system provides these data on each of several signals received simultaneously. The signals can be cw or pulsed. Hence no deterioration in system performance is expected when operating in a dense signal environment.

No attempt was made to specify physical antenna systems or to estimate what is involved in achieving design requirements. Obtaining appropriate gain characteristics over a range of frequencies may be a difficult design problem. This subject certainly warrants careful consideration before this or a similar system is pursued further, particularly in the HF band. This study also neglected to consider the effects of a nonstationary platform. To obtain an absolute measure of signal bearing, the equations must be appropriately expanded to include the platform coordinates.

SELECTED BIBLIOGRAPHY

1. J. Blanchard, "Hertz, the Discoverer of Electric Waves," Proceedings of the Institute of Radio Engineers, Volume 26, No. 5, pp. 505-15, May, 1938.

2. R. Watson-Watt, The Pulse of Radar, The Dial Press, New York, 1959.

3. A. Blondel, "On the Determination of the Direction of Ships by Means of Hertizian Waves", Jahrb. d. Draht, 2:190, 1908.

4. R. A. Watson-Watt, "Directional Observations of Atmospherics -- 1916-1920", Philosophical Magazine, 45:1010-26, 1923.

5. F. E. Smith, "Modern Navigation Devices", Engineering, 117: 299-300, Mar. 7, 1924.

6. R. L. Smith-Rose, "Radio Direction-Finding by Transmission and Reception", Proceedings of the Institute of Radio Engineers, Vol. 17, No. 3, pp. 425-78, Mar. 1929.

7. R. A. Watson-Watt, J. F. Herd, "An Instantaneous Direct-Reading Radiogoniometer", Journal of the Institution of Electrical Engineers, 64:611-22, 1926.

8. H. T. Friis, "Oscillographic Observations on the Direction of Propagation and Fading of Short Waves", Proceedings of the Institute of Radio Engineers, 16:658-65, May, 1928.

9. R. Keen, Wireless Direction Finding, Iliffe & Sons Limited, Dorset House, Stamford Street, London S. E. 1, 1938, Third Edition.

10. C. D. Tuska, "Radio in Navigation", Journal of the Franklin Institute, Vol. 228, pp. 433-443, Oct., and pp. 581-603, Nov. 1939.

11. M. Spafford, R. Wiack, R. Woodman, "The Rocket Interferometer Tracking (RIT) System", Goddard Space Flight Center, Greenbelt, Md. NASA TN D-2682.

12. O. E. Kerr, W. J. Kearns, J. F. McIlvenna, G. E. Reynolds, L. F. Shodin, "Satellite-Tracking", Electromagnetic Radiation Lab., Electronics Research Directorate, AFCRL, USAF, Bedford, Mass. AFCRL 1102, Dec. 1961.

13. M. H. Blitz, N. J. Saber, "Satellite Based Systems for Locating Drifting Sensor Platforms", IEEE Transactions on Aerospace, AS-2:116-24, No. 2, April 1964.

14. H. Hecksher, G. O. Reynolds, "Relative Advantages of Interferometer over Telescope for Measuring Source Sizes", Technical Operations Research, AFCRL-65-179.

15. M. Ryle, "A New Radio Interferometer and Its Application to the Observation of Weak Radio Stars", Proceedings of the Royal Society, Series A, 211:351-75, 6 Mar 1952.

16. (a) Reports on Project Bullseye, Naval Research Laboratory, K. E. Gustafson, 1962, 1963.

    (b) Bullseye Technical Notes, Radio Corporation of America, Defense Electronic Products, 1962, 1963.

17. W. C. Bain, "The Theoretical Design of Direction-Finding Systems for High Frequencies", Proceedings of the Institution of Electrical Engineers, 103B:113-19, Jan. 1956.

18. R. C. Benoit, Jr. and M. W. Furlow, "Design for Wide-Aperture Direction Finders", Tele-Tech, Vol. 14, No. 9, pp. 60-2, 104-8, Sept. 1955.

19. "Satellite Tracking Net Established in Southern U. S. ", Aviation Week, p. 104, May 11, 1959.

20. P. J. Klass, "Spasur Net Giving Vital Norad Coverage", Aviation Week and Space Technology, pp. 52-63, Nov. 26, 1962.

21. M. G. Kaufman, "A Phase-channel Combiner, Mod. I, for the NRL Space Surveillance System", IEEE Transactions on Instrumentation & Measurements, IM-12:106-19, No. 3, Dec. 1963.

22. M. G. Kaufman, "Post-detection in the Navy Space Surveillance System", IEEE Transactions on Aerospace, AS-2:151-9, No. 2, April 1964.

23. M. G. Kaufman, "Radio Interferometry Techniques Used by the U. S. Naval Space Surveillance System", Proceedings of the Institute of Electrical and Electronics Engineers, 52:421-3, No. 4, April 1964.

24. P. J. Klass, "Navy Improves Accuracy, Detection Range of Space Surveillance Chain", Aviation Week & Space Technology, pp. 56-61, Aug. 16, 1965.

25. Electronic Countermeasures, Institute of Science and Technology, University of Michigan, 1961, Secret.

26. A. D. Bailey, "State of the Art on Radio Direction Finding and Source Location", Stanford University, Stanford, California, Sept. 1962, Secret.

27. W. R. Blair, H. M. Lewis, "Radio Tracking of Meteorological Balloons", Proceedings of the Institute of Radio Engineers, Vol. 19, No. 9, pp. 1531-60, Sept. 1931.

28. P. Neidhardt, "Calculation of an Amplitude-Sensitive Directional System and its Application for Surveying Purposes", Nachrichtentechnik, 3:295-301, July 1953.

29. E. R. Roeschlein, "Mapping Caves Magnetically", Electronics, Vol. 33, No. 39, p. 61, Sept. 23, 1960.

30. E. Meister, "The New Vehicle for Tracking Radio-Electric Interference with Radio and Television Services", Technische Mitteilungen P.T.T., 41:184-96, No. 5, 1963.

31. H. Ruprecht, "Resonant Frequency of a Ship", Hochfrequenztechn. u. Elektroakustik, 39:59-66, Feb. 1932.

32. W. Ross, "Fundamental Problems in Radio Direction-Finding at High Frequencies (3-30 Mc/s)", The Journal of the Institution of Electrical Engineers, Vol. 94, Pt. IIIA, pp. 164-65, 1947.

33. F. E. Brooks, Jr., "Ratio Operation of the Brooks Antenna System", EE Research Lab, The U. of Texas, Report No. 8-04, 30 Mar 1956.

34. W. M. Sherrill, D. N. Travers, "Shipboard Siting of Direction Finders for the 3 to 30 Mc Range", Interim Development Report for 1 Dec. 1964 - 28 Feb. 1965, Southwest Research Institute, San Antonio, Texas, April 1965.

35. G. Ziehm, "Fundamentals of a General Theory of the Direction-finding Error on Ships", Pt. I: Frequenz, 16:281-93, No. 8, Aug. 1962; Pt. II: Frequenz, 16:431-2, No. 11, Nov. 1962; Pt. III: Frequenz, 16:502-10, No. 12, Dec. 1962.

36. C. W. McLeish and R. S. Roger, "An Investigation of High-Frequency Direction-Finding Errors Caused by Nearby Vertical Reradiators", Proceedings of the Institution of Electrical Engineers, 106B:58-60, Jan. 1959.

37. H. Gabler, G. Gresky and M. Wachtler, "The Analysis of Radio Navigational Bearings When Rotary Fields Arise", Arch. elekt. Ubertragung, Vol. 10, No. 9, pp. 383-91, Sept. 1956.

38. G. Ziehm, "Explanation of the Difficulty of Direction-finding with Short-and Boundary-Waves on Board Ship", Frequenz, Vol. 9, No. 9, pp. 310-18, Sept. 1955.

39. A. Troost, "Problems of Long-wave Direction Finding in Ships", Telefunken Zig, 27:149-55, Sept. 1954.

40. H. Gabler, G. Gresky and W. Runge, "Experimental Comparison of Frame-coil and Stretched-wire Loop Aerials for Ship Direction Finders", Telefunken Zig, 25:5-11, March 1952.

41. G. J. Burtt and R. T. P. Shipple, "Medium-frequency Direction Finding in H. M. Ships", The Journal of the Institution of Electrical Engineers, Pt. IIIA, Vol. 94, No. 15, pp. 838-56, 1947.

42. C. Crampton, R. T. P. Whipple and A. H. Mugridge, "The Errors in Bearings of a High-frequency Direction-finder Caused by Reradiation from a Nearby Vertical Mast", The Journal of the Institution of Electrical Engineers, Pt. IIIA, Vol. 94, No. 15, pp. 815-22, 1947.

43. D. N. Travers, J. D. Moore, W. M. Sherrill, "Multiloop Antenna Arrays for High-frequency Shipboard Direction Finding", IEEE Transactions on Antennas and Propagation, AP-13:665-671, No. 5, Sept. 1965.

44. H. Rattei, H. Sauer, "A New Direction-Finding Aerial for the Long, Critical and Short Wave Bands", Telefunken Zeitung, 37:56-61, No. 1, 1964.

45. C. Crampton, W. Stryszynski, S. de Walden and P. G. Redgment, "Some Principles Underlying the Design of Aerial Systems for High-frequency Radio Direction-finders in H. M. Ships", The Journal of the Institution of Electrical Engineers, Pt. III, Vol. 95, pp. 437-48, Nov. 1948.

46. R. M. Griffith and W. Rosinski, "The Extension of Wireless Direction-finding Techniques to Very High Frequencies for Naval Use", The Journal of the Institution of Electrical Engineers, Pt. IIIA, Vol. 94, No. 15, pp. 727-40, 1947.

47. C. Crampton, W. Struszynski, J. H. Marshall and J. C. Woolley, "The Performance of High-frequency Direction-finders in Various Types of H. M. Ships", The Journal of the Institution of Electrical Engineers, Pt. IIIA, Vol. 94, No. 15, pp. 798-808, 1947.

48. C. Crampton, W. Struszynski, R. T. P. Whipple, "High-frequency Direction Finding in H. M. Ships, Secondary Radiation from a Ship's Superstructure, and Factors Controlling the Selection of the Most Suitable Position for H/F D/F Aerials in Ships", Great Britain A. S. E., Dec. 1941, Secret.

49. L. Buchholz, Elektrotek, T., "Tuning Conditions and Maximum Sensitivity of Bellini-Tosi Radio Direction Finders", Vol. 69, No. 5, pp. 49-54, Feb. 15, 1956.

50. C. T. Solt, "The Development and Application of Marine Radio Direction Finding Equipment by the U. S. Coast Guard", Proceedings of the Institute of Radio Engineers, Vol. 20, No. 2, pp. 228-60, Feb., 1932.

51. W. M. Sherrill, D. N. Travers, "Single-Channel Direction Finding in a Multicomponent Field", IRE Transactions on Antennas and Propagation, pp. 521-6, Nov. 1961.

52. R. V. B. Blackman, Jane's Fighting Ships, Sampson Low, Marston and Co. Ltd., Potter Row, Great Missenden, Bucks, England, 1965-66.

53. "A Short-Wave Cathode-Ray Direction Finding Receiver", The Wireless Engineer, pp. 432-9, Aug. 1938.

54. S. de Walden, A. F. L. Rocke, J. O. G. Barrett and W. J. Pitts, "The Development of a High-frequency Cathode-ray Direction-finder for Naval Use", The Journal of the Institution of Electrical Engineers, Pt. IIIA, Vol. 94, No. 15, pp. 823-37, 1947.

55. C. W. McLeish, N. Burtnyk, "The Application of the Interferometer to H-F D-F", Proceedings of the Institution of Electrical Engineers, Pt. B, pp. 495-9, 1961.

56. A. D. Bailey, W. D. McClurg, "A Sum-and-Difference Interferometer System for HF Radio Direction Finding", IEEE Transactions on Aerospace and Navigational Electronics, pp. 65-72, March, 1963.

57. W. J. Kessler, H. L. Knowles, "Direction-Finder for Locating Storms", Electronics, Feb. 1946, pp. 212, 214; April 1946, pp. 224, 226, 228; May 1948, pp. 106-110.

58. Y. A. Erukhimovich, "Some Problems of Direction Finding of Interfering Radio Waves", Radiotekhnika, 15:62-6, No. 6, June, 1960.

59. P. Miram, "Night Effect in Radio Direction Finding", Elektronische Rundschau, 10:163-6, No. 6, June, 1956.

60. C. J. Shoens, "Preliminary Investigation of a Microwave Phase Detector", TR No. 551-1, May 27, 1957, Stanford Electronics Laboratories, Stanford University, Stanford, California.

61. D. R. Rhodes, <u>Introduction to Monopulse</u>, McGraw-Hill Book Company, New York, 1959.

62. R. C. Honey, E. M. T. Jones, "A Versatile Multiport Biconical Antenna", Proceedings of the Institute of Radio Engineers, 45: 1374-83, Oct. 1957.

63. E. McCann and H. H. Hibbs, "Electrically Small D. F. Antenna", IRE National Convention Record, Vol. 7, Pt. 1, pp. 64-73, 1959.

64. J. D. Dyson, E. C. Hayden, "Studies and Investigations Leading to the Design of a Radio Direction Finder System for the MF-HF-VHF Range", Final Report 1 July 1961-30 June 1963, Engineering Experiment Station, Illinois University, Urbana, Illinois.

65. D. N. Travers, "High Frequency Direction Finding Research for Shipboard Use", Interim Development Report 1 June-31 Aug. 1964, Southwest Research Institute, San Antonio, Texas, Sept. 1964.

66. Monthly Technical Progress Reports on Fredif Detector, (QRC-213CT dated 15 Dec 1963), Systems Laboratories, A Division of Electronic Specialty Co., 5121 San Fernando Road, Los Angeles 39, California.

67. H. P. Raabe, "Measurement of Instantaneous Frequency with a Microwave Interferometer", Proceedings of the Institute of Radio Engineers, 45:30-38, Jan. 1957.

68. S. de Walden, J. C. Swallow, "The Relative Merits of Presentation of Bearings by Aural-Null and Twin-Channel Cathode-ray Direction-Finders", Proceedings of the Institute of Electrical Engineers, Vol. 96, Pt. III, pp. 307-20, July, 1949.

69. V. V. Tsvetnov, "Phase Correlation Properties of Signals and Gaussian Interference in Two-channel Phase Systems", Radiotekhnika, 13:53-62, No. 4, 1958.

70. B. B. May, "An Analysis of a General Class of Frequency Discriminators with Application to Broadband Microwave Discriminators", Technical Report No. 1962/66-1, March 1966, Stanford Electronics Laboratory, Stanford University, Stanford, California.

71. W. B. Davenport, Jr., W. L. Root, An Introduction to the Theory of Random Signals and Noise, 1958, McGraw-Hill Book Co., Inc., New York.

Appendix A

Use of a Hybrid Junction to Determine the Difference in Phase Between Two Equal Amplitude Sinusoids

Consider the system of Fig. A-1. For inputs v_1 and v_2 to the hybrid junction,

$$v_y = \frac{v_1 + \hat{v}_2}{\sqrt{2}} \tag{A-1}$$

$$v_x = \frac{v_2 + \hat{v}_1}{\sqrt{2}} \tag{A-2}$$

where $\hat{v}_j$ is v_j delayed $\frac{\pi}{2}$ radians ($j = 1, 2$). Fig. A-2 shows the phasor construction of v_x and v_y which, as shown there, are in phase providing v_x and v_y have identical amplitudes. (Upper case letters denote phasors.)

The Phase lag of v_1 referenced to v_2 is ψ where, from (4-4),

$$\psi = 2\pi p \sin\theta \tag{A-3}$$

Displaying v_x and v_y on a CRO gives a trace of slope θ where

$$\phi = \tan^{-1}\frac{v_y}{v_x} = \tan^{-1}\frac{|V_y|}{|V_x|} \tag{A-4}$$

The last equality holds since v_x and v_y are in phase and hence the trace is a straight line.

From Fig. A-2 and from the properties of parallelograms,

$$|\sqrt{2}\,V_y| = 2\,|\hat{V}_1|\cos\alpha$$

$$|\sqrt{2}\,V_x| = 2\,|\hat{V}_2|\cos(\alpha + \psi)$$

$$2\alpha + \psi = \pi/2$$

Therefore,

$$\alpha = \frac{\pi}{4} - \frac{\psi}{2}$$

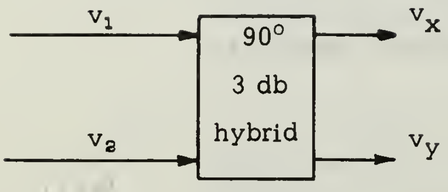


Fig. A-1. Phase Detector

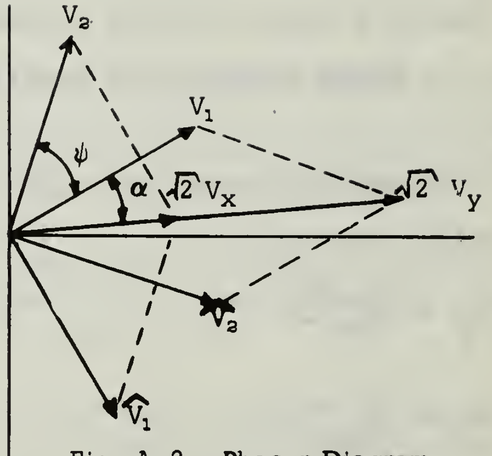


Fig. A-2. Phasor Diagram

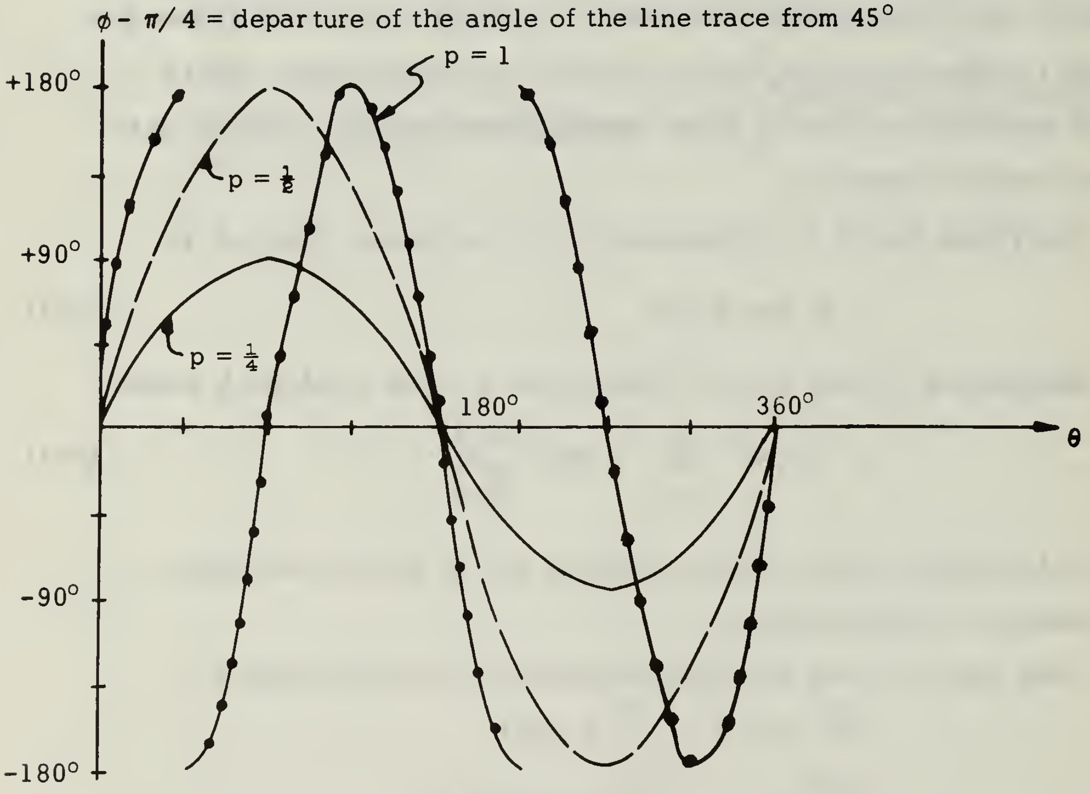


Fig. A-3. Variation of ϕ, Angle of the Line Trace, with θ, Signal Bearing, for Various Values of Antenna Separation.

and

$$\alpha + \psi = \frac{\pi}{2} - \alpha = \frac{\pi}{4} + \frac{\psi}{2}$$

from which

$$|V_y| = \sqrt{2}\,|\hat{V}_1|\cos(\pi/4 - \frac{\psi}{2})$$

$$= \sqrt{2}\,|V_1|\sin(\pi/4 + \frac{\psi}{2}) \qquad \text{(A-5)}$$

and

$$|V_x| = \sqrt{2}\,|\hat{V}_2|\cos(\pi/4 + \frac{\psi}{2}) \qquad \text{(A-6)}$$

Equations A-5 and A-6 with A-3 show the variation of $|V_y|$ and $|V_x|$ and hence v_y and v_x with bearing. Using (A-5) and (A-6) in (A-4) gives

$$\phi = \pi/4 + \psi/2$$

which from (A-3) can be written

$$\phi = \pi/4 + 2\pi p \sin\theta \qquad \text{(A-7)}$$

Therefore the slope of the line trace is a sinusoidal function of received signal bearing. Equation A-7 is plotted in Fig. A-3 for three values of p, antenna separation in wavelengths.

Appendix B

Determination of the Difference in Phase of Two Equal Frequency, Unequal Amplitude Sinusoids

Given two signals s_1 and s_2 where

$$s_1(t) = E_1 \cos(wt + \beta)$$

$$s_2(t) = E_2 \cos(wt + \gamma)$$

it is desired to obtain a voltage proportional to $\beta - \gamma$, the phase difference of these two signals. If $E_1 = E_2$, various well-known techniques can be used (see Appendix A for one simple circuit realization).

If $E_1 \neq E_2$, the problem is more difficult since the output of conventional phase detectors is now dependent on signal amplitudes E_1 and E_2. To eliminate this dependence, circuits which form products and quotients are generally required as shown below.

Figure B-1 indicates how a voltage v_1 equal to $4A_1A_2 \cos(\beta - \gamma)$ can be formed by using a mixer or multiplier and a low-pass filter. By making one input to the mixer much larger than the other (local oscillator action), v_1 can be made independent of the amplitude of one signal. However, in phase-measuring DF systems, E_1 and E_2 are of comparable amplitudes. By forming the product $v_2 = E_1E_2$ and taking the ratio $\frac{v_1}{v_2}$ there results a voltage v_3 dependent only on phase:

$$v_3 = 4 \cos(\beta - \gamma)$$

Figure B-2 indicates a mixer or multiplier circuit having output v_1. The sum and difference of the input signals is formed. Straightforward trigonometry verifies that $v_1 = 4E_1E_2 \cos(\beta - \gamma)$.

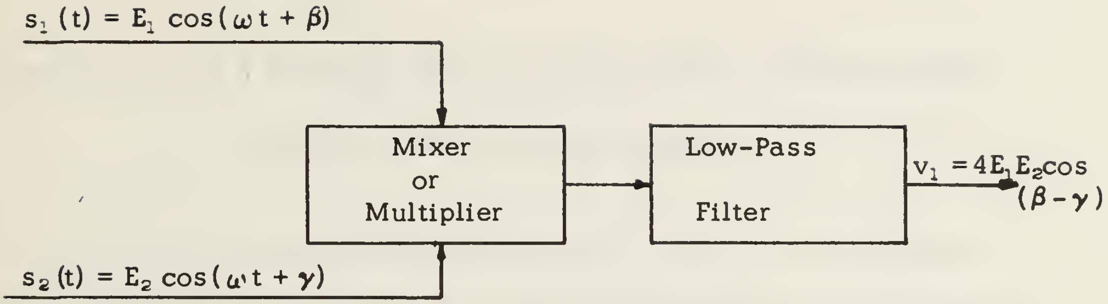


Fig. B-1. A Simplified Phase Detector; Output is Dependent on Signal Amplitude.

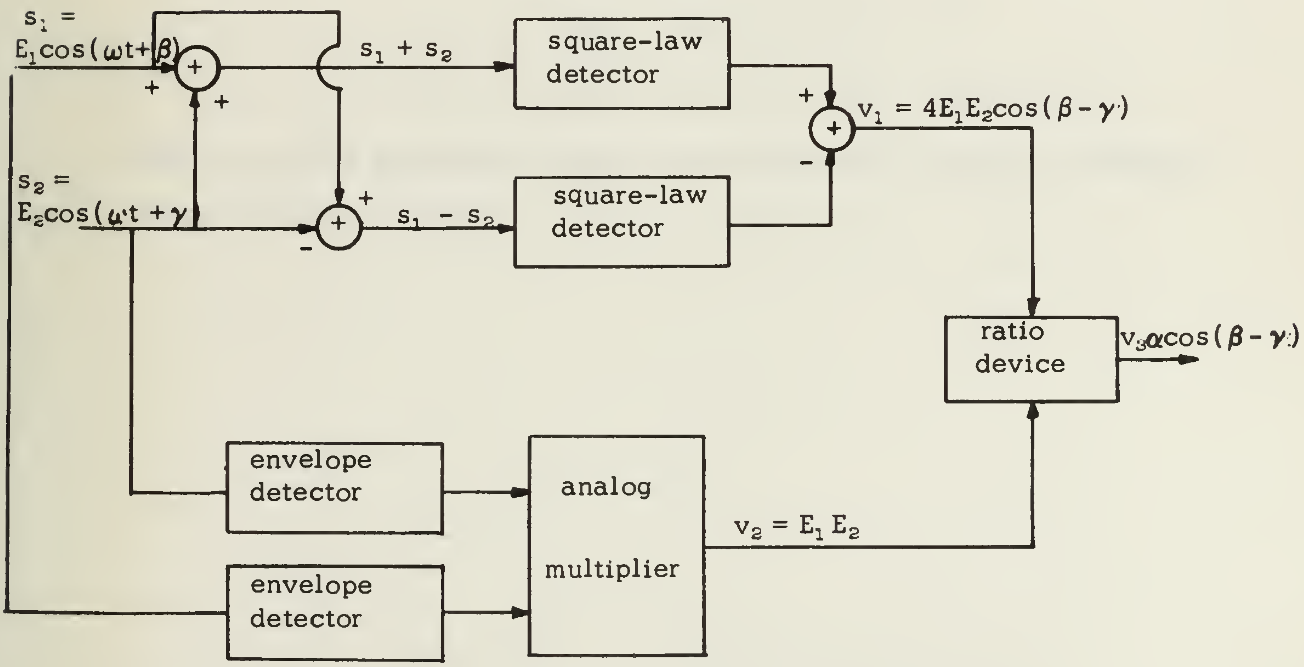


Fig. B-2. A Phase Detector Whose Output is Independent of Input Signal Amplitude.

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Appendix C

Realization of a Network Which Forms the Sum and Difference of Two In-Phase Input Signals

It will be shown here that the circuit of Fig. C-1 forms the sum, Σ, and the difference, Δ, of the input signals s_1 and s_2 where s_1 and s_2 are assumed to be in phase. Let

$$s_1(t) = E_1 \cos \beta$$

$$s_2(t) = E_2 \cos \beta$$

The inputs to the hybrid are s_1 and $\hat{s}_2$ where $\hat{s}_2$ lags s_2 by 90°. The outputs of the hybrid are

$$v_1 = \hat{s}_1 + \hat{s}_2 = (E_1 + E_2) \sin \beta = \Sigma$$

$$v_2 = s_1 + \hat{\hat{s}}_2 = s_1 - s_2 = (E_1 - E_2) \cos \beta = \Delta$$

These sum and difference signals can be placed in phase by adding a phase shifter as shown.

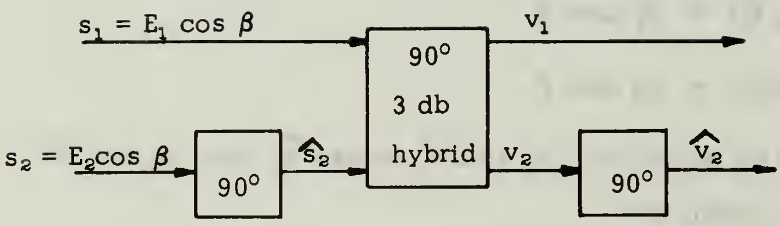

Fig. C-1. Sum-and-Difference Network

Appendix D

A Symmetrical - Ring DF System

Consider the system of Fig. 4-19(a) where identical antennas A and B separated a distance d are connected by transmission lines of equal length ℓ to a slotted line of overall length L_s. A signal arriving at an angle θ is delayed τ seconds in arriving at A compared to B. This delay is

$$\tau = \frac{z}{c} \tag{D-1}$$

where the velocity of propagation in air is $c = 3 \times 10^8$ meters/sec. From the figure,

$$z = d \sin \theta \tag{D-2}$$

so that using (D-1)

$$\tau = \frac{d \sin \theta}{c} \tag{D-3}$$

At some position ℓ_1 in the slotted line, the phase of the signal received on antenna A, ϕ_A, equals that received on antenna B, ϕ_B, and a maximum of the standing-wave on the line occurs. To solve for the dependency of ℓ_1 on θ, find ϕ_A and ϕ_B and equate.

From the figure,

$$\phi_A = \omega\tau + \frac{2\pi(\ell_1 + \ell)}{\lambda}$$

$$\phi_B = \frac{2\pi(\ell_2 + \ell)}{\lambda}$$

where

$\omega = 2\pi f$ = signal frequency in radians per second

$\lambda = \frac{\nu}{f}$ = signal wavelength in meters

ν = velocity of propagation on the lines

Setting $\phi_A = \phi_B$ gives with (D-3)

$$\frac{\omega d \sin\theta}{c} + \frac{2\pi(\ell_1 + \ell)}{\lambda} = \frac{2\pi(\ell_2 + \ell)}{\lambda}$$

Using the relations

$$\ell_2 = L_S - \ell_1$$

$$\frac{2\pi}{\lambda} = \frac{\omega}{c}$$

and collecting terms gives

$$\ell_1 = \frac{L_S}{2} - \frac{d\nu}{2c} \sin\theta \qquad \text{(D-4)}$$

where $\frac{L_S}{2}$ is the electrical center of the system known as a symmetrical ring.

It is interesting to note that the position of this central maximum is independent of input signal frequency ω. The spacing between adjacent maxima and minima does change with frequency: spacing decreases as frequency increases. This is illustrated in Fig. 4-19(b).

To obtain a measure of θ, a probe could be moved along the line to determine ℓ_1 from which, according to (D-4),

$$\theta = \arcsin\left[\left(\frac{L_S}{2} - \ell_1\right) \frac{2c}{d\nu}\right]$$

Alternatively, a series of probes could be attached to the line and their outputs commutated and interpolated to obtain an estimate of ℓ_1. This approach lends itself readily to processing the data by digital means.

For sinusoidal waveforms, null points can generally be determined more accurately than extrema since the function experiences its greatest rate of change at the null points. Therefore, rather than searching for a maximum, it is desirable to define a null which is independent of frequency. Inverting the signal on one path has the effect of substituting maxima of the standing wave for minima and vice-versa. The position of these extrema is determined as before. Therefore, in a practical system, Fig. 4-19(a) would be modified to include a signal inverter in one path.

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13. ABSTRACT

Several parallel-channel receiver configurations are presented and analyzed. From this background a particular direction-finding system suitable for shipboard use is detailed. Use of three modes of operation of the defined system is shown to provide through 360° coarse and find indications of the bearings of each of several stations transmitting simultaneously. It is also shown that this system will provide measures of amplitude and, with some added circuitry, frequency of each of these received signals. It is shown that the gain characteristics of the antennas for each mode of operation are chosen in a manner which makes the parallel-channel receiving system immune to signals reflected from the ship and its rigging. Two different methods of obtaining independent measures of signal frequency and bearing are presented. A brief history of direction finding and an extensive bibliography are provided.

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