THE MARCONI REVIEW

Volume XXII *Number* 135 *Fourth Quarter* 1959

The Marconi Review is published four times a year
Annual subscription £1. Single copies 5s. Postage paid to any part of the world

EDITOR L. E. Q. WALKER A.R.C.S.

Marconi's Wireless Telegraph Company Limited, Baddow Research Laboratories
West Hanningfield Road, Great Baddow, Essex, England

Direction Finding

t one time the direction finder was the only navigational aid and was the bject of much applied research. Today it is one of many and not among ose generally chosen for urgent improvement. It has however a role of s own, which makes it a unique piece of radio apparatus, never likely to discarded entirely and, therefore, a fair amount of incentive for developent remains.

At the present time direction finding has two recognized roles which ll continue for a long time to come. One as a marine aid which takes its arings from shore beacons operating at timed intervals in the medium equency band, and the other as an airborne aid also operating from land sed beacons at medium frequencies. The marine direction finder is ually a simple device operated by hand and ear. Its aerial system is ther a single revolving loop or fixed crossed loops connected to a gonioeter. Automatic versions which display the bearing on a cathode ray be or circular-scale meter have begun to appear. The airborne direction nder is of necessity automatic. It is operated by a servo mechanism which arches for the bearing and displays it on a compass card—the equipment usually referred to as a radio compass.

At the relatively high field strengths and short distances around which ese equipments operate, the medium frequency wave front remains bstantially vertically polarized and becomes badly distorted only during riods of "night effect," and therefore, aerial systems with low polarizaon protection are reasonably satisfactory; indeed if this were not so, rection finding would not be practical on the confined spaces of ships d aeroplanes. In general the task of improving these types of direction nder is confined to circuit and mechanical design.

The difficult aspect of direction finder design appears at frequencies ove 1 Mc/s when ionospheric propagation produces an elliptically larized wave and often two or more signals arriving by different paths. hen it becomes necessary to construct aerial systems which have a very nall polarization error, that is to say, the designer must aim at aerials which will completely separate vertical and horizontal components. A simila problem arises from transmission between an aeroplane and the groun

In the case of the HF direction finder (a representative coverage i 2·5 Mc/s to 25 Mc/s) the most common aerial system is the Adcock whic comprises four vertical aerials, set in the corners of a square, from whic feeders are taken to a mechanical or an electronic goniometer. These fou horizontal feeders are the elements of the system most sensitive to it performance as a direction finder free from polarization erorrs and th practical treatment is to make them, as nearly as possible, alike and t bury them deeply in the ground. The conductivity of the ground i important, and cases have been known (e.g. deep sand) where the groun conductivity is so low that the installation is virtually useless. The choic of site is thus limited, and this disadvantage has led to alternatives, on notable example being the spaced loop. This is a symmetrical arrangemen of two similar vertical loops which are spaced apart parallel to each othe and joined by a horizontal feeder. The bearing is found by measuring th phase difference between the two loops, which becomes zero, when th loops are in line with the bearing, or alternatively when the horizontal feede is at right angles to the bearing. In a practical case the two loops are co nected in opposition and the system revolved until a null position is foun

The revolving spaced loop is not sensitive to ground conductivity an its polarization error is smaller than is achieved by the best Adcock. It admirable as a mobile direction finder but practical drawbacks limit it popularity on permanent sites. Not the least of these drawbacks is th mechanical inertia of the revolving structure which, if made easy t operate by hand can be done only by a reduction of the area or the spacin of the loops, both at the expense of sensitivity.

An important operational need in the HF direction finder is an automati presentation of the bearing. In fact the full operational need is complet remote control. The spaced loop is outclassed in this respect by th Adcock and by wide aperture applications of the fixed vertical aerial.

The wide aperture direction finder has been given much consideratio since the war. There are several experimental versions, all of them com prising a ring of vertical aerials of perhaps 100 feet in diameter an operated by sampling the phase difference of the EMF in adjacent aerials The advantage of wide aerial spacing—say, an order of magnitude greate than the conventional Adcock—is less error imposed by a distorted wav front, accompanied by low polarization error and less dependence on groun conductivity. It is potentially the best form of direction finder and has b no means reached the limit of development.

Direction finders in the VHF and UHF frequency bands are designe mainly for the control of aircraft and are operated in good numbers ove the world. The conventional aerial is the elevated Adcock which at thes equencies can be raised several wavelengths above the ground, thus aking a balanced vertical dipole a practical thing. The difficulties countered during design are similar to the HF case; avoidance of wanted resonances over a large frequency coverage, the reduction of rculating currents in the structure, the exact balance of four elements d so forth. Polarization error is doubly important and is made more acting by the reflected ground wave. The aircraft also presents difficulties the necessary compromise in the design and position of its aerial which ten results in a small ratio of wanted to unwanted component in the diated wave. Not enough is known about this failing. In spite of it, owever, very good performances are given by these direction finders, hich can be remotely controlled and spaced apart so that their bearings n be displayed on a map to give instantaneous position fixes of aircraft.

In almost any form of automatic direction finder the choice of method which the bearing is determined is controversial. The market is comratively small and it is necessary to design to a good all round specificaon containing compromises that are fully understood and revealed. No stem is absolutely free from faults which may be important to some operatnal purposes but insignificant to others. The bugbear of the designer is band idth, for the big wavelength coverages demanded by the users dictate eartbreaking compromises in aerial spacing and coupling circuits. The stem itself can be based on the twin-path amplifier and cathode ray tube, e spinning goniometer, or the servo operated search coil and meter. ne first of these is the classic concept, unbending and awkward to organize. Its bearings can be moved by an interfering signal, but it has e merit of being able to record bearings from extremely short transissions. The second is the handy method, more stable in operation and nding itself to both amplitude selection and phase comparison. Its worst ature is the modulation imposed on the signal by the repetition rate of e spinning search coil. The third method—well proved on aircraft—has cently shown itself to be satisfactory for marine use and, rather unpectedly, for HF use. In the latter case it has proved adaptable to the itomatic averaging of bearings, a feature which has considerably increased e operational facilities of the Adcock.

The immediate future of direction finding in the civil field is probably ot very bright. In the military field it must continue, for the position of the nknown transmitter will always be the object of military curiosity. rogress has not reached its limit, and if the ultimate forms of direction nder are to be attained, they are more likely to emerge from military eeds. We may therefore see the wide aperture direction finder more tensively developed, and mobile direction finders of all types studied rther. Also it seems certain that the direction finder will play a part in e coming use of satellites as mediums for communication. R. J. KEMP

SOME FACTORS IN THE DESIGN OF VHF AUTOMATIC DIRECTION FINDERS

By S. A. W. JOLLIFFE

The reasons for direction finding in the VHF band and the need for an au matic display of bearings are discussed. Basic systems are analysed and so of the more interesting design features of a preferred system are discussed detail. The performance of a typical automatic direction finder is stated.

INTRODUCTION

The purpose of radio in aviation is to perform two services both essent to regular and safe flight operation. The maintenance of rigid ti schedules depends to a very large extent on radio providing a relia communication service between the aircraft and the specified grou bases, and on radio navigational aids assisting the pilot.

At the outbreak of the Second World War the use of radio as an aid aviation was firmly established, the technique of direction finding bei the first radio navigation aid. Both services were generally located in t medium and high frequency bands, a part of the radio frequency spectr inherently unreliable because of the varying parameters of the eart atmosphere producing interruptions during violent atmospheric electri disturbances. As the speed of aircraft increased another type of disturba known as precipitation static became significant. This is caused by t passage of the aircraft through electrically charged clouds of rain, du sleet and snow.

At this period aviation gave a marked impetus to the application very high frequency techniques, the use of the VHF band for aeronauti communications being adopted almost universally for military and ci aviation during and after the war. Although the range obtained wi VHF is limited to approximately line of sight the following advanta are significant.

1. Improved intelligibility of speech between pilot and grou controller.
2. Ease of providing efficient aerials at both ground and airbo stations.
3. Adequate frequency channels are available.
4. Use by non-skilled personnel is practicable.
5. Virtual freedom from the effects of distant thunderstorm activit
6. Diminution of the effects of precipitation static.

The use of VHF for communications inevitably produced a demand for ground based direction finders, due solely to the fact that such equipments provide the most economic way of obtaining bearing and position information.

Manual instruments requiring a skilled operator were first developed by techniques similar to those used in the lower frequency bands. As the speed and density of air traffic increased the possibility of saturation of the manual instrument became apparent, and it was considered necessary to provide a VHF direction finding service commensurate with the speed of the modern aeroplane.

Fortunately, the stability of propagation, which is normally over an optical path, is such that an automatic system of bearing presentation is satisfactory. The natural development has been a presentation that can be used directly by air traffic control staff, thereby eliminating the Radio Officer on the ground, desirable for economic reasons.

This also means that remote presentation of the bearing is desirable since to obtain the greatest accuracy the direction finder is normally sited well away from hangars and buildings, while the bearing information is required in the Air Traffic Control room. The distance between the aerial site and remote presentation is only a few miles in this case, but there is also a demand for a VHF fixing service, for which the bearing must be presented at a plotting centre which might well be thirty to fifty miles from the aerial.

Provision must also be made for an output suitable for superimposing on the plan position indicator of a surveillance radar for the purpose of identifying certain radar targets. In the interest of flexibility and economy it is desirable that the bearing information should be capable of being transmitted on a standard telephone circuit or a simple radio link.

The speed of presentation of the bearing is very important when assisting aircraft which travel at speeds approaching 600 m.p.h. In considering this aspect it should be remembered that the real operational value of position information depends on two factors, the accuracy of the information and the time taken in obtaining it. The advent of the high speed aircraft places increasing emphasis on the time factor.

To ensure economy in equipment, multi-channel, multi-frequency operation from a single aerial is desirable, and to reduce operational costs full remote control of the aerial site from the operations centre should be possible.

The prime design objective of the modern VHF/DF is the economic achievement of maximum operational reliability with ease of servicing. It is now generally agreed that for aeronautical applications remotely operated equipments with automatic display of bearing are essential. This article discusses the more interesting design features of one type of equip ment intended for use in any part of the world as an aid to both militar and civil aircraft.

FACTORS INFLUENCING CHOICE OF BASIC SYSTEM

The nucleus of the direction finder is the aerial system, which mus possess a property by which the direction of arrival of RF energy at th aerial may be determined.

The characteristics of prime importance in the aerial design are azi muthal accuracy, sensitivity and protection against adverse polarization the latter assuming great significance in aeronautical applications wher the radiation of adverse polarization does not improve with the develop ment of the aircraft.

Many aerial systems were considered but, from experience, the elevate "H" Adcock configuration was considered the most promising for furthe development.

This basic "H" Adcock aerial can be applied to automatic directio finding in several ways.

(*a*) A single "H" pair of aerials may be continuously rotated.

(*b*) The rotor of a goniometer coupled to the four aerial elements o the fixed system may be continuously turned so that the direc tional characteristic is rotated in synchronism.

(*c*) The differential output of the two pairs of aerials may be con veyed to the receiver as separate signals on a single cable. Thi may be accomplished by means of balanced modulators house in the aerial head.

(*d*) The signals derived from the two pairs of aerials which are related b a tangent law may be amplified and applied to a bearing indicato

In methods *a*, *b* and *c*, the directional intelligence is conveyed as th modulation of the carrier and can be amplified by a single receiver. Metho *d* necessitates two receivers matched to close tolerance in gain and phas over the operational frequency spectrum, a requirement which impose limitations on the minimum overall receiver bandwidth employed Previous experience revealed the need for frequent and exacting balancin and it was considered extremely doubtful whether the system could b economically engineered for unattended operation.

Modulation by well-engineered mechanical methods was chosen rathe than electronic modulation because of cross modulation problems, and th probable inconvenience of frequent servicing resulting from the use o valves in the aerial head. Over the frequency band 100-156 Mc/s th rotation of an efficient aerial poses considerable mechanical problem which can be avoided by the use of a fixed aerial system and a moto rotated goniometer.

The principle of the preferred automatic direction finder is the comparison of the phase between two low frequency signals, the difference of phase being made to vary with the azimuthal angle of arrival of the signal whose direction it is required to determine. One signal has a phase independent of azimuth and is referred to as the reference phase, whilst the other signal varies in phase as the azimuth varies and is called the variable phase. The difference in phase between these two signals determines the azimuth of the transmitting source.

To produce the variable phase, the dipole elements of the preferred aerial system (Fig. 1) are coupled to a capacitance goniometer. The output voltage of the spinning rotor is an RF signal, 100% amplitude modulated by a rectified sine wave, with the RF phase constant during any half cycle but reversing at each zero point. If a sensing signal of constant amplitude and in phase with either half cycle of the envelope is added to the output of the rotor, the resultant is a sine wave modulated radio frequency signal. Its phase relative to the angle of rotation of the goniometer is the bearing of the received signal plus a correction depending on the spacing of aerial elements and the orientation of the aerial array.

The resultant voltage is amplified by the receiver, and a sine wave voltage with phase dependent on the received signal is extracted from the detector and applied to a phase discriminator. A voltage of preset phase is derived from a single phase generator driven by the goniometer drive motor, and applied to the phase discriminator. The phase discriminator converts the phase difference between the DF signal and reference voltages to two DC outputs one of which has a magnitude proportional to the sine and the other to the cosine of the phase difference.

These voltages are applied to a bearing display unit which may employ a cathode ray tube, but for some applications an electro-mechanical meter is preferred because of its greater reliability and flexibility.

Providing the phases of the reference and signal phase voltages are aligned at a defined azimuth, for example true north, the display will indicate the bearing of the signal source with respect to true north.

As the nominal frequency and voltage of power supplies vary considerably depending on location, the equipment should be designed to operate from single phase supplies of 40-60 c/s, and should include a regulator to accept nominal supply pressures of 100 to 255 volts $\pm$ 20%; these features ensuring compatability with world supplies. The frequency of the signals to be phase compared is one half the supply frequency and in practice may vary between 20-30 c/s.

There is an operational application for automatic direction finders in all parts of the world, and equipments produced to meet this need must be designed to satisfy a high degree of reliability. At the commencement of the development the worst environmental conditions which the

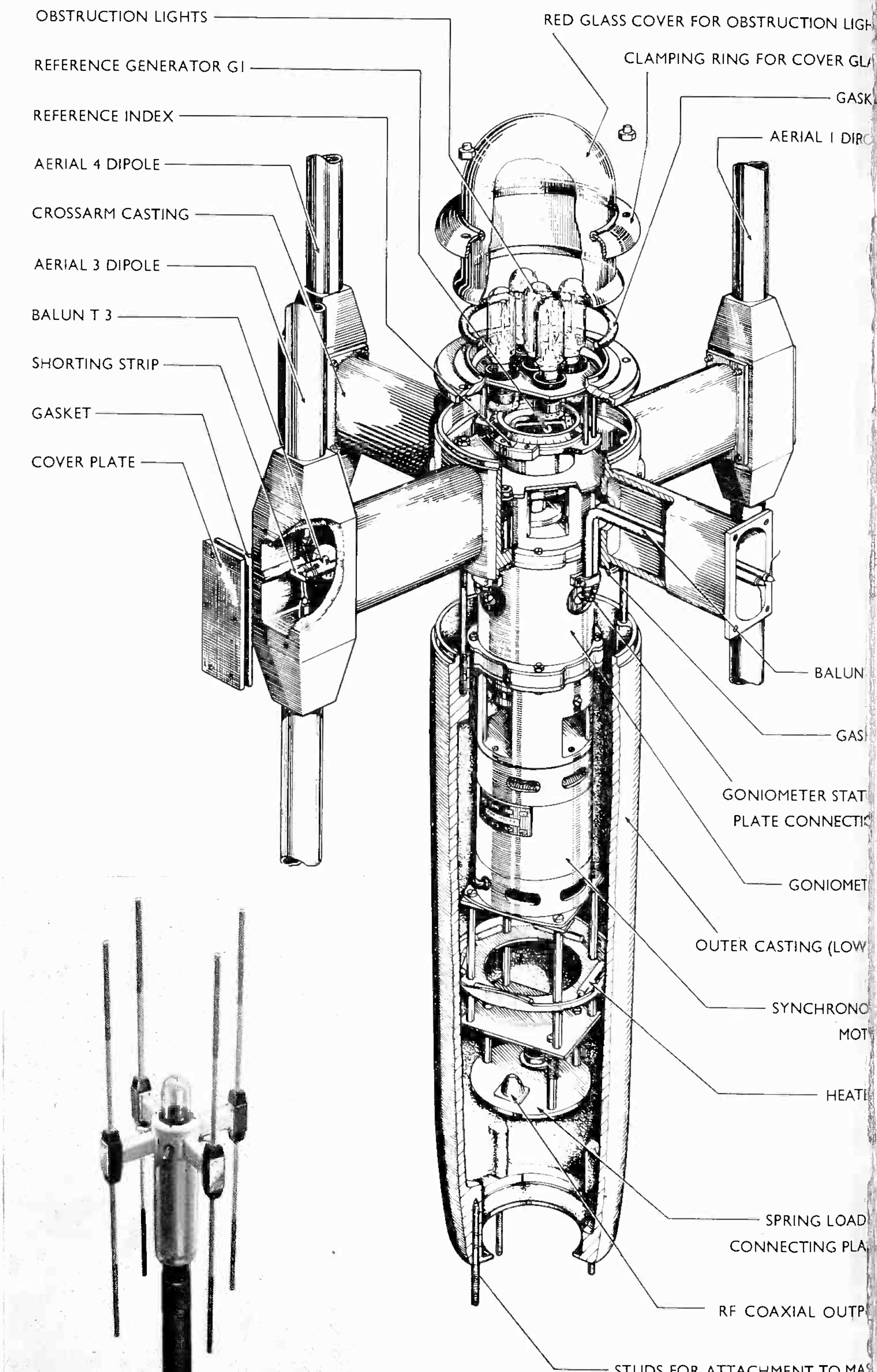


Fig.1. Elevated "H" Adcock aerial (frequency coverage 100-156 Mc/s)

ıvisaged equipment would be expected to suffer were considered to fall ithin the classification covered by Inter-Service Specification K 114/E, ıd the equipment was designed to conform with this specification. Such preferred system described above is shown in the block schematic agram, Fig. 2. Some of the more interesting design problems are now amined in detail.

ERIAL CONSIDERATIONS

he "H" Adcock aerial assembly consists of four spaced dipoles symetrically located around a central housing, inside which is a goniometer, reference generator and the common drive unit, a single phase synchroous motor (see Figs. 1 & 3).

The utility of the aerial depends on four principal characteristics:

(*a*) Reliable sensing.
(*b*) Azimuthal accuracy.
(*c*) Sensitivity.
(*d*) Protection offered against signals of unwanted polarization.

As a compromise between these parameters attempts were made to velop a mathematical analysis of the system, but it was found necessary make simplifying assumptions in order to render the system suitable r mathematical analysis. The simplification necessary distorted the oblem such that small but important circuit components were neglected. npirical methods were therefore, employed in optimizing the aerial stem design.

) RELIABLE SENSING

To obtain the sense voltage necessary for the production of an unamguous diagram, it has been common practice to employ a unipole aerial cated at the centre of the Adcock system. With this arrangement fficulties are experienced due to the different mode of operation of lcock and sense aerials, the latter being a unipole on an uncertain earth. ıe impedance and pick-up factors of the two aerials follow different ws with change of frequency and it is impracticable to maintain a finite phase and amplitude relationship over the required frequency nge of 100-156 Mc/s.

This difficulty is further emphasized as the angle of elevation of arrival of the signal increases. Signals at the output of the Adcock aerial vary cos $^2\phi$ and signals at the output of the sense aerial vary as cos ϕ. ıncellations due to the reflected wave occur for both signals and it is fficult to maintain a correct amplitude relationship between the two ltages.

Differences in the effective centres of the two aerials can cause violent ıase mistracks between the sense and directional aerials, sometimes sulting in bearing reversals.

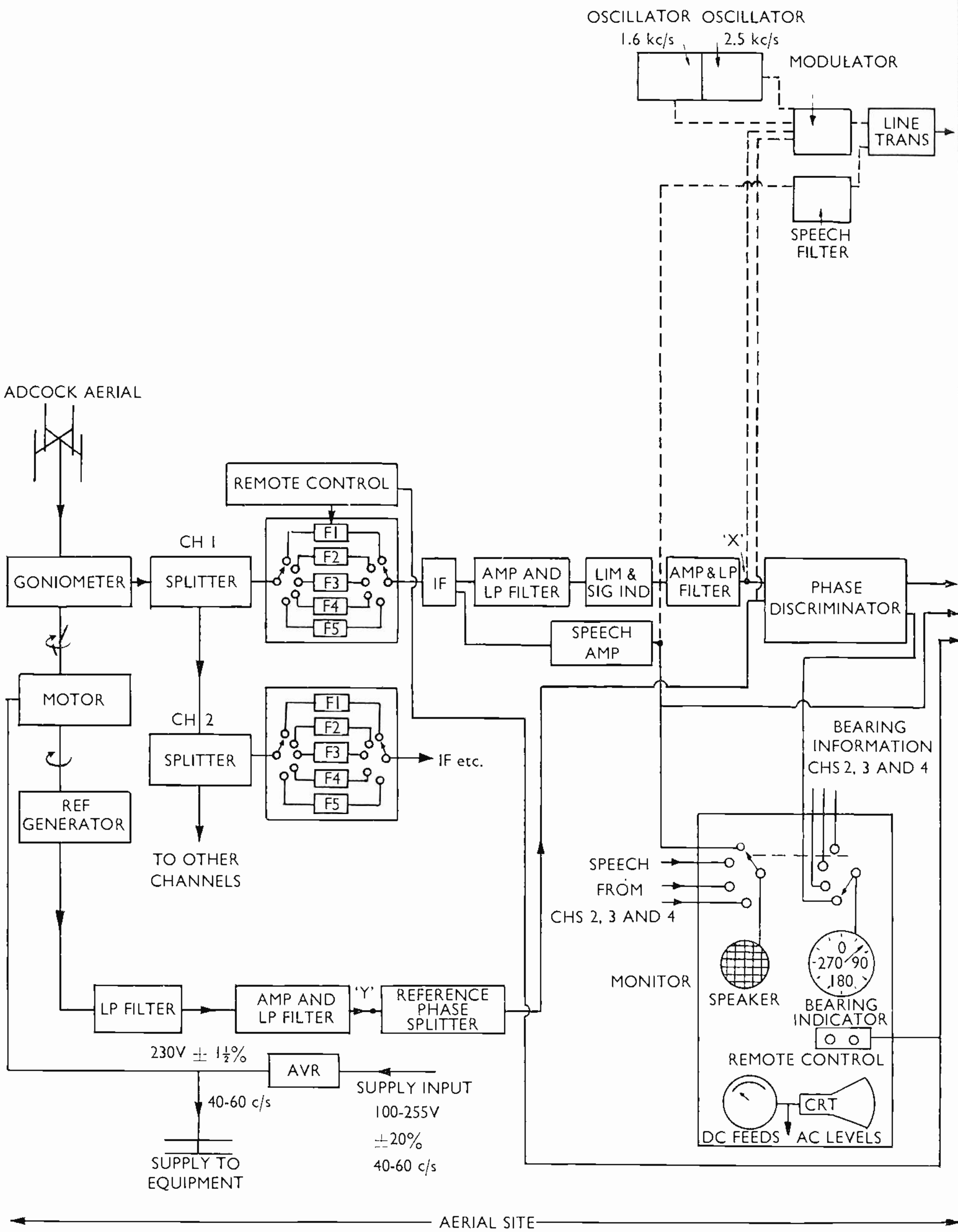
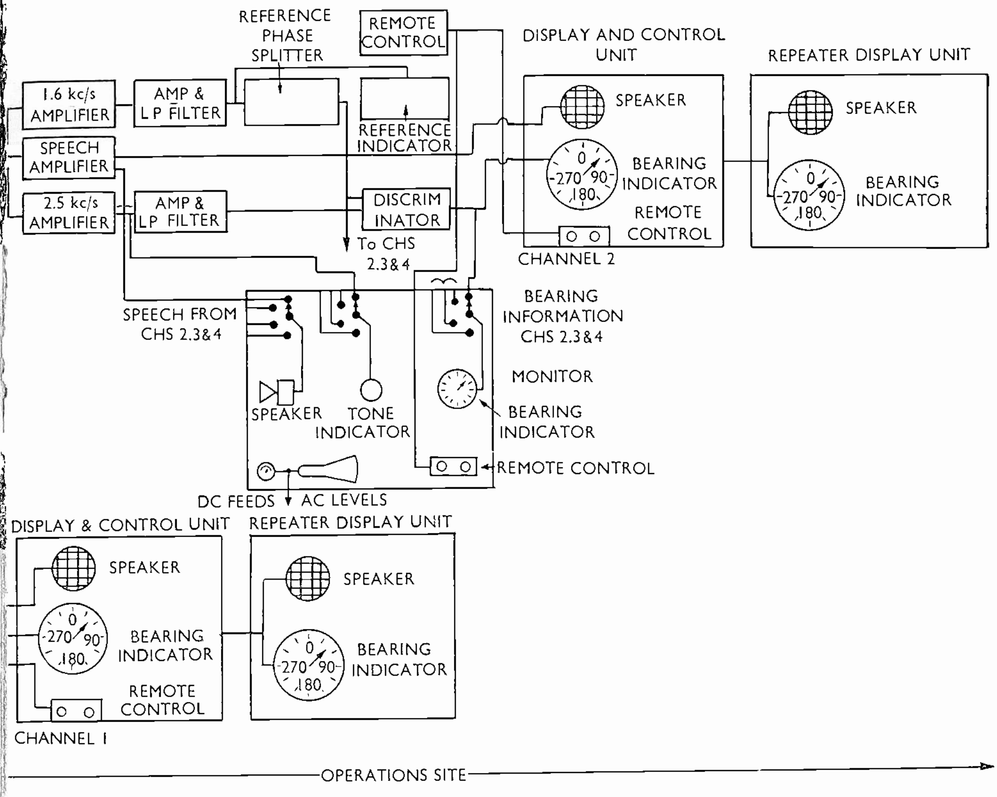


Fig. 2. Block schematic of automatic VHF/DF



There are two further difficulties. Firstly, currents could be induced in the aerial support mast, which is capacitance coupled to the sense aerial, and results in an induced voltage in the sense aerial which has incorrect phase relationship to the external field. Secondly, the field surrounding the sense aerial could be modified by currents flowing in the dipoles, this would produce considerable distortion of the sense aerial diagram, resulting in a sensing characteristic which is non-uniform in azimuth and frequency.

It has been found possible to resolve these difficulties and accomplish sensing in the goniometer. By taking an unbalanced output from the goniometer rotor, vector sum voltages are induced in the rotor and are combined with the figure of eight diagram, resulting in the required cardioid.

(*b*) *and* (*c*) AZIMUTHAL ACCURACY AND SENSITIVITY

The length of the dipoles and the separation between them are mainly governed by considerations of accuracy and sensitivity.

Adequate sensitivity over the frequency band 100-156 Mc/s can be realized by optimizing the physical length of the dipoles and their separation. The dipoles are designed to be resonant at 90 Mc/s whilst the baluns

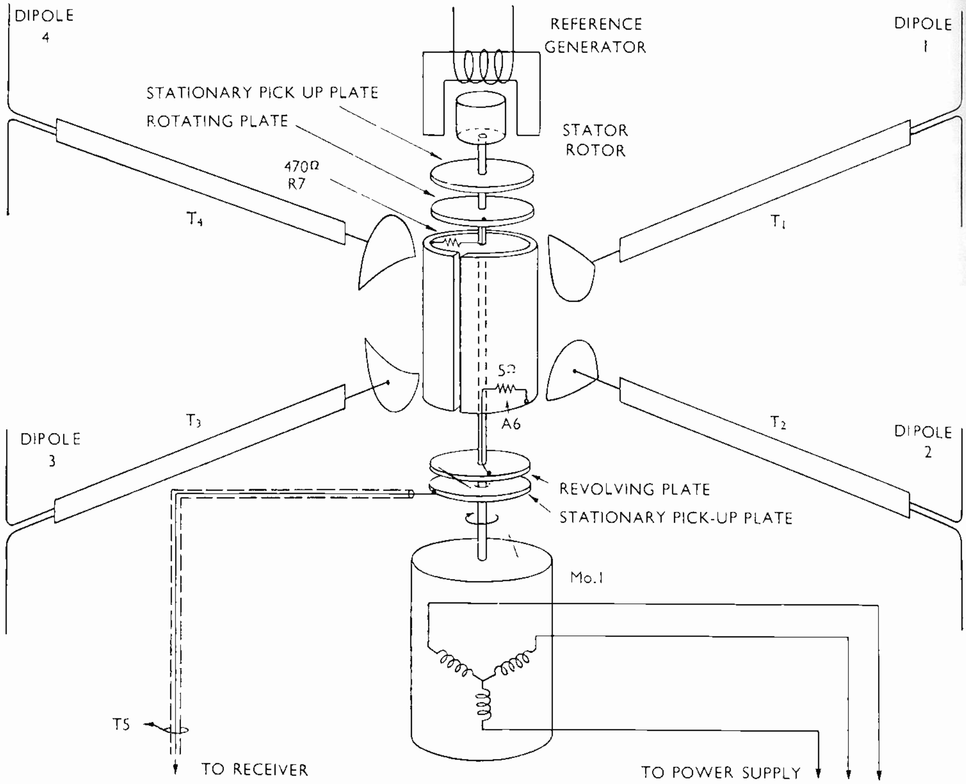


Fig. 3. Block schematic drawing of aerial head

connecting the dipoles to the stator plates of the goniometer are resonant just above 156 Mc/s. Sensitivity is also dependent on the impedance match of the aerial to the receiver. This problem is extremely complex when operation over a band of frequencies is considered, and the limitation of bandwidth of the system is enforced by the loss of sensitivity, and by unacceptable changes in the directional pattern with frequency. To obtain reasonable sensitivity with undistorted speech the modulation depth of the carrier should not be less than 35% and not greater than 80%.

A large source of aerial error is of octantal form and is dependent on the separation of the dipoles d/λ. With a spacing of $0{\cdot}27\lambda$ at 156 Mc/s, the octantal error is $\pm$ 1·75° at 156 Mc/s and $\pm$ 0·75° at 100 Mc/s. However, this error can be reduced to $\pm$ 0·5° by means of the phase comparator circuit described later. This is designed with an octantal error of $\pm$ 1·25° of opposite sign, resulting in partial cancellation of the aerial octantal, leaving a residue error of $\pm$ 0·5°.

The small aperture of the Adcock necessary to limit octantal error results in directional information being defined by extremely small phase differences between the aerials, so that small phase unbalances become significant. The aerial elements and associated baluns, therefore, quire extremely careful amplitude and phase matching. For example, t a frequency of 156 Mc/s the phase change in the Pyrotenax baluns is pproximately 10° per inch. Thus the lengths of the four baluns must be atched to a fraction of an inch.

Basic electrical stabilization is achieved by designing the system so hat the natural resonance of component parts is outside the operating equency band.

Errors in the system can be caused by mechanical asymmetry invariably roducing phase and amplitude unbalance, which result in errors of semi-rcular or quadrantal form. If the opposite pairs of dipoles, or the two ts of goniometer stator plates are not mutually perpendicular a quad-antal error results, while if the axis of the stator plates is not coincident ith the axis of the rotor plates, a semi-circular error is produced. Errors ue to purely electrical causes can result from the inhomogeneity of aterials, or from the coupling law of the goniometer differing from the quired law of $1 + \cos \theta$. This law is obtained by shaping the goniometer ator plates sinusoidally.

It must be stated that some doubt exists concerning the necessity of ator plates of sinusoidal shape as only the fundamental component of e modulation envelope is extracted and used for bearing determination. urther work is obviously necessary to resolve this point.

) POLARIZATION PROTECTION

he "H" Adcock aerial is intended to respond to a wave polarized in e vertical plane. If the incident wavefront at the direction finder aerial ntains a horizontally polarized component, errors can result since isting techniques in design and manufacture do not provide an infinite otection against the unwanted component. Polarization errors resulting om imperfections in the aerial may be due to physical asymmetry of the stem, inadequate earthing or bonding, or insufficient screening of the orizontal feeders (baluns) against the unwanted external fields. Such rors may seriously reduce the accuracy of the aircraft bearings observed hen the magnitude and phase of the resultant field at the direction finder rial may be adverse.

It is well known that when a dipole aerial system is elevated above the rth's surface the associated zenithal diagrams become lobed, and above e Brewster angle the response of the aerial to the two planes of polariza-on is "antiphased," so that for the arrival of a signal at certain zenithal gles the wanted to unwanted signal ratio may be adverse (Fig. 4). ne Brewster angle and the depth of the nulls depend on the electrical nstants of the earth in the immediate environment. The number of lobes epends on the height of the aerial above ground, and on the operational equency.

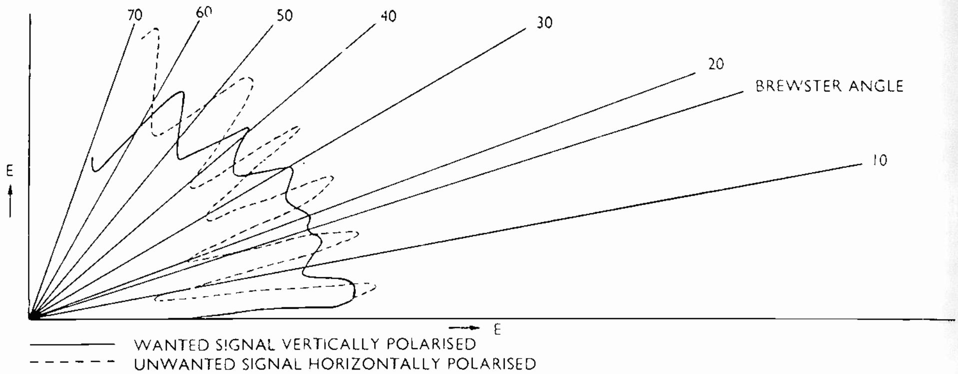


Fig. 4. Lobed zenithal diagram of aerial elevated 30′ above ground frequency 100 M/cs.

Polarization errors can be considerably reduced by the use of screened baluns which must be located with a high degree of symmetry in the aerial head. Great care must be exercised in the bonding of the baluns to the goniometer.

To achieve the aerial performance required under extreme climatic conditions, great care must be exercised in the choice of materials and components and in the manufacturing methods and tolerances permitted. The properties of the materials and components employed must be such that the standard of production reproducibility ensures operational interchangeability. As far as possible machine operations should be employed in the fabrication of materials and components and only high class workmanship employed.

Some features which exercise a major effect on the accuracy and polarization performance of this type of aerial are worthy of record.

(*a*) Where electrical bonding is important and a mechanical joint is necessary for reasons of assembly, brass is used. Light alloys were found to give inconsistent results due to oxidization producing indefinite surface contact. The goniometer housing and the junctions between the baluns and goniometer are constructed of brass.

(*b*) In order to reduce semi-circular errors in the goniometer the component parts are located by accurately turned spigots.

(*c*) The barrel on which the stator plates are located consists of Araldite loaded with chalk. Its use eliminates errors resulting from inhomogeneity of various other materials.

(*d*) The stator plates of sine wave form are jig pressed and located in the barrel with an accurate jig.

(*e*) Pyrotenax feeders with magnesium dioxide filling are used in the construction of the baluns. Their low velocity of wave propagation satisfied mechanical requirements and screening characteristics are good. The feeder is hygroscopic, but difficulties in sealing have been successfully overcome by the use of Araldite resin.

(*f*) Silicone rubber sleeving was used for insulating the copper bucket from the feeder and ensured reproducible results, since it is not affected by soldering methods used in assembly.

RECEIVER

[Th]e purpose of the receiver is to amplify the signal at the output of [th]e goniometer rotor to a level suitable for the efficient operation [of] the detector, from which is extracted the directional phase intelligence [of] the low frequency modulation and the associated speech.

Although the design of the receiver follows standard communication [pr]actice several characteristics require special attention. In order to [pr]eserve bearing accuracy the phase shift and distortion characteristics [of] all circuits preceding the phase discriminator must be rigidly controlled. [Th]is is generally achieved by careful design and the choice of stable [co]mponents.

In order to meet the requirement of multichannel operation from a [si]ngle aerial head, the receiver input consists of a "T" type splitter circuit [of] 75 ohms characteristic impedance, several of which may be cascaded, [ea]ch feeding one of five individual preset RF units. The splitter has a [un]iform response over the operating frequency range, cutting off sharply [ab]ove 156 Mc/s.

Transmitters employed in the aeronautical band must be frequency [st]able to 1 part in 10^4 and assigned communication frequencies are [se]parated by 100 kc/s. Receivers used must employ oscillator circuits of [hi]gh stability and several methods of channel selection are possible.

A conventional search receiver is possible, but the remote selection of [fr]equency channels and the attainment of the required receiver oscillator [st]ability would be very expensive. Another approach is to use a crystal [st]abilized receiver and to select, by means of a rotary switch, either the [pr]e-set components of each tuned circuit or complete pre-tuned RF units. [Th]e method preferred, an economic compromise, is to switch pre-set [co]mponents in the splitter circuit and to switch complete RF units [be]tween the splitter output and the intermediate frequency amplifier. [Th]e RF units are designed as plug-in assemblies, and the above approach [en]ables a quick change of frequency channel assuming spare units are [av]ailable.

The switching of pre-set elements or complete pre-set circuits ensures [m]aximum performance of each channel, since no tracking errors are [in]volved as in a conventional search receiver. Pre-set tuning of all circuits [is] achieved by variable capacitors in preference to variable inductances, [th]e advantages being greater stability, more uniform performance, and [le]ss cost.

In all systems bandwidth should be minimized in order to reduce noise and transmitter power, thus ensuring the most economic use of th frequency spectrum. The bandwidth necessary for the conveyance of certain intelligence is dependent solely on the rate of change of tha intelligence, a steady state waveform requiring zero bandwidth.

In the specific case of the automatic direction finder, the steady sta is only disturbed when the envelope of the carrier modulation is changin the bandwidth required being directly proportional to the change o azimuthal position of the transmitter from the direction finder. An aircra moving tangentially to the direction finder produces the maximum rat of change of the received carrier modulation. For example, consider a aircraft travelling tangentially to the direction finder at a speed o 360 m.p.h. and assume a change of bearing of 2° is significant. The band widths required to record a 2° change of azimuthal position at distance of 2 and 100 miles are 0·14 and 0·028 c/s respectively. This examp assumes that only a change of positional information is required. Howeve the safe operation of a direction finder requires the monitoring of th associated telephony, which necessitates an increase in bandwidth.

In practice, limitations in minimizing bandwidth are controlled b problems of producing oscillators of the required frequency stability, an bandwidths generally have to be much wider than required purely fro considerations of information rate.

Selectivity must be controlled so that interfering signals at eithe adjacent or image frequencies do not enter the receiver. Interferin signals as much as 35 dBs below the level of the wanted signal can caus a bearing error of 1° and circuits are used such that a protection of 90 dB against interfering signals is obtained. Two stages of RF amplificatio using four tuned circuits, provide sufficient gain to ensure no degradatio of the receiver sensitivity by mixer noise.

The choice of the intermediate frequency is a compromise between th ease of fulfilling image requirements and the practical difficulty of obtain ing circuits of sufficient Q to achieve the required selectivity. The solutio chosen was to use a high first intermediate frequency followed by a lo second intermediate frequency. Five pairs of circuits tuned to a secon intermediate frequency of 4·86 Mc/s provide an overall frequency respons of $\pm$ 22·5 kc/s at 6 dBs down and $\pm$ 80 kc/s at 90 dBs down.

Aircraft transmissions at 156 Mc/s may deviate from the assigne frequency by $\pm$ 15·6 kc/s. In order that the sensitivity is not degraded b more than 6 dBs, the receiver oscillator must be held within 7 kc/ (= 0·0045%) of the assigned frequency channel. BT cut crystals with total frequency spread of 0·0035% over a temperature range of + 3 to + 70°C are used, leaving 0·001% tolerance for circuit component drifts If operating conditions involve a wider range of ambient temperatur it is necessary to locate the crystal in a temperature controlled oven.

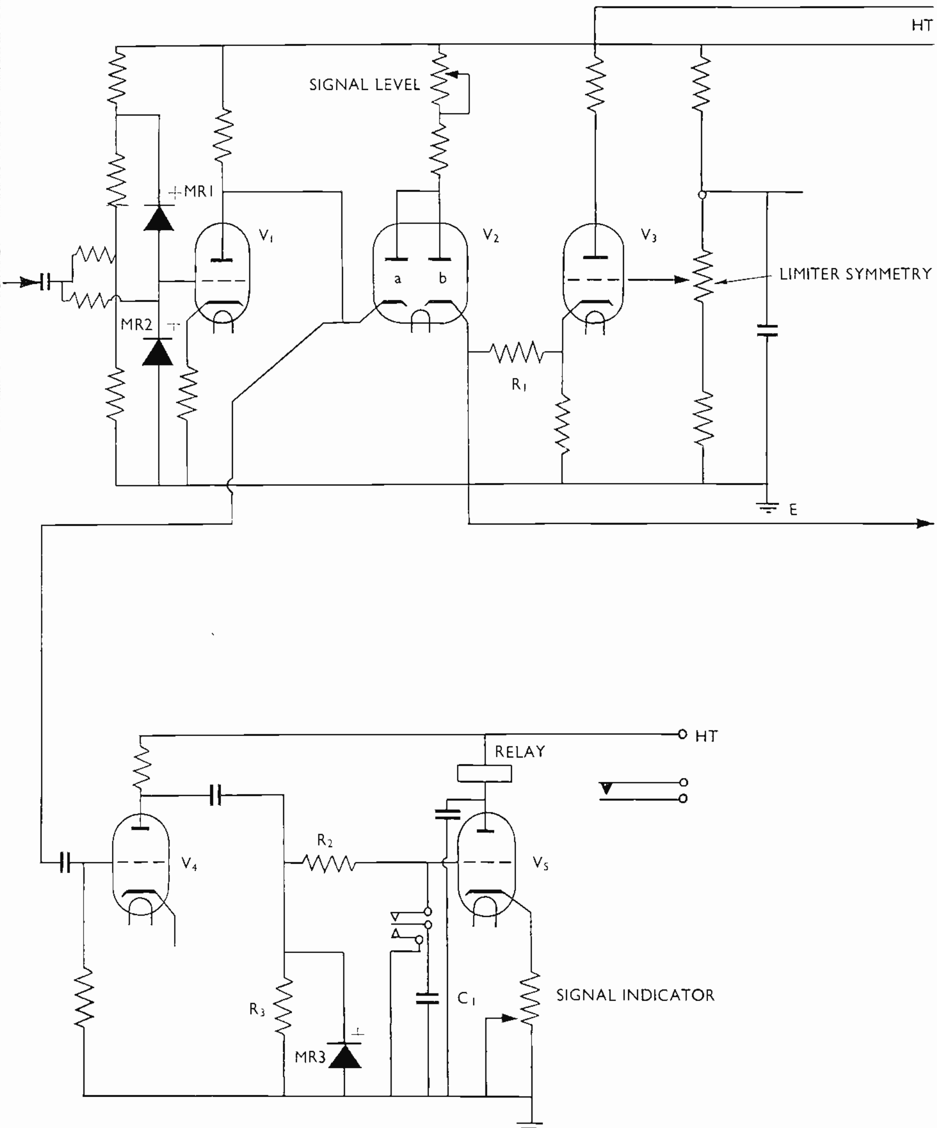


Fig. 5. Basic limiter and signal indicator circuit

The phase discriminator is sensitive to amplitude changes of the input ignal from the receiver, possibly resulting in bearing errors. Signal input evel must therefore be held constant to close limits. The levels at the eceiver input of most signals received from aircraft fall within the range f 3μV to 30 mV and a constant level of input to the discriminator is chieved by AGC control of the receiver augmented by a limiting action n the signal modulation.

Special consideration must be given to the AGC circuit of a receiver ised with direction finders of this kind, because of the necessity of

avoiding phase shift of the modulation conveyed by the IF signal. The effect of modulation ripple on the AGC voltage is to cause a variation of the bearing with signal strength since the controlled valves modulate the signal. The unwanted modulation has a different phase from the wanted and a depth which varies with the signal strength. The resultant phase at the receiver output, which is the vector sum of the wanted and unwanted modulations, will therefore vary with the received signal strength.

It is generally required that the modulation component in the AGC potential be removed, or sufficiently reduced in magnitude, to prevent the alteration of the modulation characteristics of the signal. However, the time the receiver takes to adjust itself to the level of the incoming signal is dependent on the time constant of the smoothing circuit employed. The use of critically damped inductance-capacitance filters would reduce the time constant, but because of the cost and the bulk involved, two stage resistance capacitance filters designed to discriminate against the modulation frequency are preferred.

By applying the AGC line to the three RF valves and first IF valve, signal input charges of 3μV to 30 mV produce receiver output changes not greater than 6 dBs. The lower level, which is the AGC threshold, depends on the noise present at the AGC detector and this is governed by the noise factor of the first RF valve and the bandwidth measured at the detector. The directional information is not appreciably impaired by noise when working near AGC threshold, because of the post detector selectivity which is discussed later. Between the receiver detector and the phase discriminator it is necessary to impose circuits to eliminate the small variations in signal amplitude, and to provide means for indicating that the signal level is sufficient for bearing observation.

Fig. 5 indicates the basic circuit developed to fulfil these requirements. The directional intelligence from the receiver detector is fed through a low pass filter discussed later, to the grid of V_1; rectifiers MR1 and MR2 limiting the signal and preventing the overload of this valve. The output of V_1 is DC coupled to V_2 which acts as a series limiter. When no signal is received, the anode of V_1 and the cathode of V_3 are at the same potential, with V_2 conducting. When a signal is received the negative half cycle causes the anode potential of V_1 to rise, the cathode potential of V_{2b} following, until V_{2a} cuts off. On the positive half cycle the action reverses and V_{2b} cuts off, as the potential cannot go negative relative to the cathode of V_3. The square wave output developed across R_1 is free from unwanted amplitude variations. It is taken from the cathode V_2 and fed to the discriminator via a low pass filter.

The output of V_1 is resistance-capacity coupled to the grid of V_4, rectified and clamped by MR3. During normal operating conditions V_5 conducts, energizing the relay, which connects the bearing intelligence nd associated telephony to both the monitoring panel and the operating entre.

The signal level at which the relay operates can be varied, but it is enerally set so that the relay operates on a signal which is just limiting, V_1 in conjunction with R_2 and R_3 providing a large time constant resulting n a delay at the grid of V_5 and preventing false operation due to noise mpulses and transient changes.

The speech frequencies necessary for monitoring the bearing are, of ourse, modulated by the rotating directional diagram, and in the case of he low frequency modulation implicit in the use of a mechanical modulaor, the intelligibility of the speech is impaired. By feeding to the speech mplifier a signal in antiphase to the wanted modulation but of the same requency and amplitude, demodulation of the speech waveform may be ccomplished.

The modulation depth of the RF carrier varies with carrier frequency, nd in practice this can be 80%, as indicated in Fig. 6a. Now, to demodulate his waveform, the gain at the trough has to be increased in the ratio 5 : 1 n order to raise it to the mean, and the gain at the crest must be reduced n the ratio 1·8 : 1 in order to decrease it to the mean. This can be accomlished by operating a valve at a point on its characteristic such that a

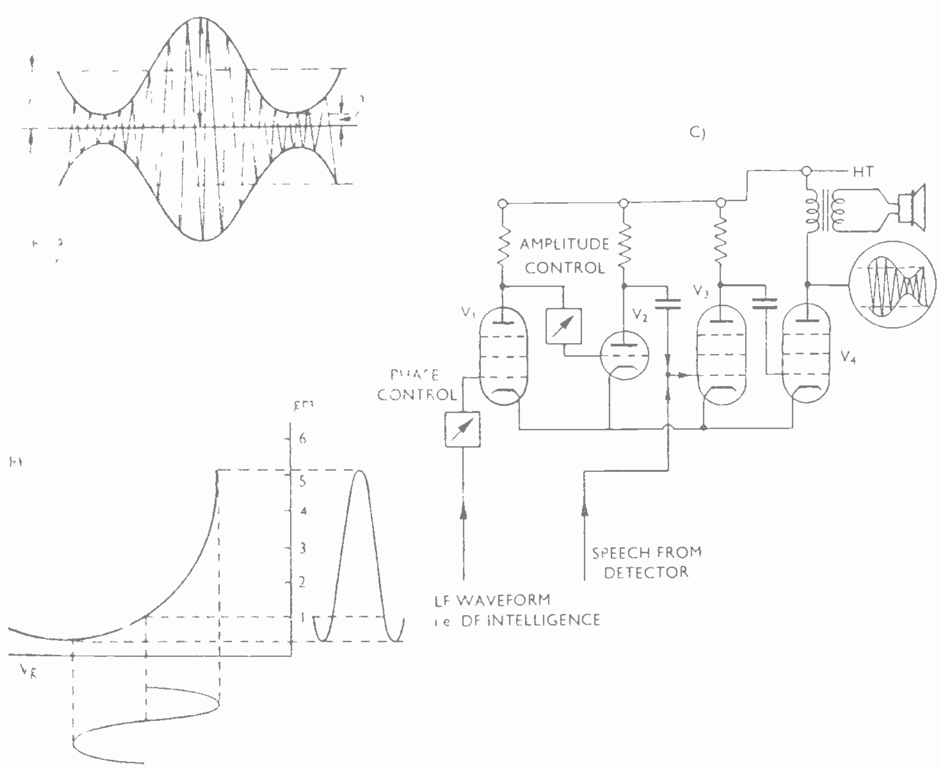


Fig. 6. Basic speech demodulation circuit

positive swing of the grid increases the gain 5 : 1 and for an equal negativ swing of the grid the gain is decreased 1·8 : 1 (Fig. 6b). Unfortunately, i was not possible to obtain an approved valve with sufficiently curve characteristic and in practice the required effect was obtained by usin two valves V_1 and V_3 indicated in the basic circuit Fig. 6c.

Speech from the receiver detector is applied at low level to V_3 so that i sweeps a substantially linear part of its characteristic and is undistorted The directional modulation output of the receiver fed to the discriminato is extracted prior to the limiter and applied to V_1, a non-linear amplifie The asymmetrical output waveform of V_1 is fed via the phase inverte V_2 to V_3 where it is mixed with the speech. The modulation output of V alters the gain of V_3 to the incoming speech waveform in such a manner a to remove from it the unwanted modulation imposed upon it by th rotating goniometer(1).

To facilitate initial adjustments it is necessary to provide means fo adjusting the amplitude and phase of the demodulating waveform. Th speech output is monitored by a servicing oscilloscope, this providing convenient method of adjusting the circuit.

The amplification of the receiver output to a level suitable for operatio of the discriminator is performed by special low frequency amplifiers These amplifiers are resistance-capacity coupled with cathode followe output valves feeding filters. The gains of the amplifiers are feedbac stabilized, the loop feedback circuit including a network for cutting th amplifier response at frequencies greater than 31·5 c/s.

The filters are designed with a low-pass characteristic, linearly passin frequencies of 19-31 c/s and rejecting harmonics by at least 30 dBs. Th filters are manufactured as hermetically sealed units, and productio units phase track within $\frac{1}{2}°$ for $\pm$ 5% variation of any frequency betwee 19 and $31\frac{1}{2}$ c/s. This phase stability is maintained even when the unit are subjected to temperatures of $-40°$C to $+70°$C and conditions o high relative humidity.

The action of the limiter in the signal chain results in the amplitude o the odd harmonics being insufficiently suppressed, but the filter followin the limiter rectifies this situation. In practice it has been found tha bearing errors resulting from circuit engineering can be kept below 1 providing the amplitude of the harmonics of the modulation waveform are at least -40 dBs relative to the fundamental at the input to th discriminator. Characteristics of the filters ensure that the secon harmonic amplitude is at least -48 dBs, the third harmonic at leas -40 dBs, and the amplitude of higher order harmonics at least -65 dB below the fundamental; assuming the harmonics at the output of th receiver are at least 10 dBs below the fundamental.

The directional intelligence of an automatic direction finder is conveye double-sideband amplitude modulation and when the receiver employs a linear detector the output signal to noise ratio will be found to be directly proportional to the strength of the modulated carrier only down to a certain carrier level. Below this value the output signal to noise ratio approaches proportionality to the square of the applied modulated carrier voltage. This effect is due to the phenomenon of "apparent demodulation" which occurs when the carrier to noise ratio at the input to a linear detector in the region of unity or less than unity(2).

When working near the AGC threshold, and receiving very weak signals, the carrier to noise ratio at the input to the final detector is unfortunately less than unity. However, even under such conditions, the post detection selectivity provided by the filters ensures that the direction finder still works satisfactorily and in practice reliable directional information can be obtained with field strengths insufficient to provide satisfactory telephony monitoring.

Identical low frequency amplification and selectivity is inserted between the reference phase generator and the reference phase splitter to ensure phase frequency characteristics identical with that of the variable phase path.

THE DISPLAY OF BEARINGS

At the output of the receiver and reference circuits (Points "X" and "Y" in Fig. 2) the bearing information appears as a phase difference between two sinusoidal voltages of low frequency, the angular phase difference being equal to the angle between the direction of arrival of the signal and a fixed datum line, usually true north.

In selecting the method of presenting the bearing information, due consideration must be given to the requirement of superimposing the bearing information on a radar PPI. The bearing information must be displayed in a clear and accurate manner, and may be accomplished by direct or indirect methods.

The direct method uses a dynamometer (i.e. selsyn) type of phase meter. The reference tone is fed into a phase splitting network giving two outputs in phase quadrature which are connected to the stator windings of the dynamometer. The variable phase output of the receiver chain is connected to the rotor coil of the dynamometer which aligns itself at the true bearing angle of arrival of the signal providing the reference and signal phase waveforms have been aligned at a defined azimuth.

Indirect methods involve a phase to amplitude converter in which the signal phase is combined in phase detectors with each of the outputs of the phase splitting network. Two DC voltages are obtained, one being proportional to the sine and the other to the cosine of the phase angle between the signal and reference voltages. Since the reference voltages

avoiding phase shift of the modulation conveyed by the IF signal. The effect of modulation ripple on the AGC voltage is to cause a variation of the bearing with signal strength since the controlled valves modulate the signal. The unwanted modulation has a different phase from the wanted and a depth which varies with the signal strength. The resultant phase at the receiver output, which is the vector sum of the wanted and unwanted modulations, will therefore vary with the received signal strength.

It is generally required that the modulation component in the AGC potential be removed, or sufficiently reduced in magnitude, to prevent the alteration of the modulation characteristics of the signal. However, the time the receiver takes to adjust itself to the level of the incoming signal is dependent on the time constant of the smoothing circuit employed. The use of critically damped inductance-capacitance filters would reduce the time constant, but because of the cost and the bulk involved, two stage resistance capacitance filters designed to discriminate against the modulation frequency are preferred.

By applying the AGC line to the three RF valves and first IF valve, signal input charges of 3μV to 30 mV produce receiver output changes not greater than 6 dBs. The lower level, which is the AGC threshold, depends on the noise present at the AGC detector and this is governed by the noise factor of the first RF valve and the bandwidth measured at the detector. The directional information is not appreciably impaired by noise when working near AGC threshold, because of the post detector selectivity which is discussed later. Between the receiver detector and the phase discriminator it is necessary to impose circuits to eliminate the small variations in signal amplitude, and to provide means for indicating that the signal level is sufficient for bearing observation.

Fig. 5 indicates the basic circuit developed to fulfil these requirements. The directional intelligence from the receiver detector is fed through a low pass filter discussed later, to the grid of V_1; rectifiers MR1 and MR2 limiting the signal and preventing the overload of this valve. The output of V_1 is DC coupled to V_2 which acts as a series limiter. When no signal is received, the anode of V_1 and the cathode of V_3 are at the same potential, with V_2 conducting. When a signal is received the negative half cycle causes the anode potential of V_1 to rise, the cathode potential of V_{2b} following, until V_{2a} cuts off. On the positive half cycle the action reverses and V_{2b} cuts off, as the potential cannot go negative relative to the cathode of V_3. The square wave output developed across R_1 is free from unwanted amplitude variations. It is taken from the cathode V_2 and fed to the discriminator via a low pass filter.

The output of V_1 is resistance-capacity coupled to the grid of V_4 rectified and clamped by MR3. During normal operating conditions V_5 conducts, energizing the relay, which connects the bearing intelligence and associated telephony to both the monitoring panel and the operating centre.

The signal level at which the relay operates can be varied, but it is generally set so that the relay operates on a signal which is just limiting, C_1 in conjunction with R_2 and R_3 providing a large time constant resulting in a delay at the grid of V_5 and preventing false operation due to noise impulses and transient changes.

The speech frequencies necessary for monitoring the bearing are, of course, modulated by the rotating directional diagram, and in the case of the low frequency modulation implicit in the use of a mechanical modulator, the intelligibility of the speech is impaired. By feeding to the speech amplifier a signal in antiphase to the wanted modulation but of the same frequency and amplitude, demodulation of the speech waveform may be accomplished.

The modulation depth of the RF carrier varies with carrier frequency, and in practice this can be 80% as indicated in Fig. 6a. Now, to demodulate this waveform, the gain at the trough has to be increased in the ratio 5 : 1 in order to raise it to the mean, and the gain at the crest must be reduced in the ratio 1·8 : 1 in order to decrease it to the mean. This can be accomplished by operating a valve at a point on its characteristic such that a

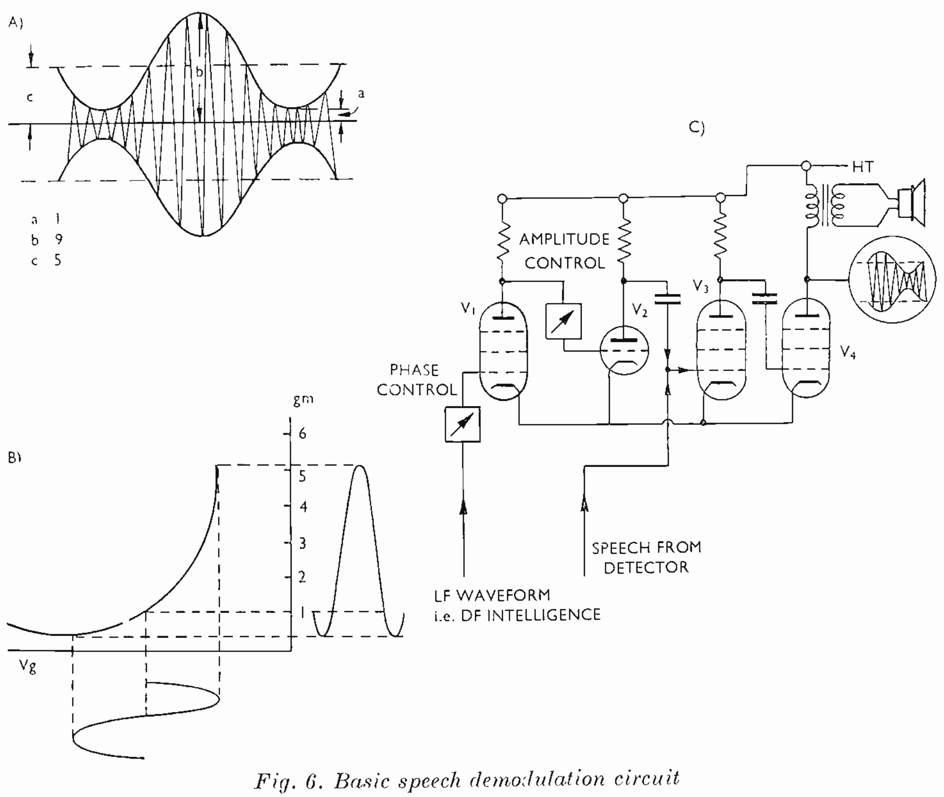


Fig. 6. Basic speech demodulation circuit

avoiding phase shift of the modulation conveyed by the IF signal. The effect of modulation ripple on the AGC voltage is to cause a variation of the bearing with signal strength since the controlled valves modulate the signal. The unwanted modulation has a different phase from the wanted and a depth which varies with the signal strength. The resultant phase at the receiver output, which is the vector sum of the wanted and unwanted modulations, will therefore vary with the received signal strength.

It is generally required that the modulation component in the AGC potential be removed, or sufficiently reduced in magnitude, to prevent the alteration of the modulation characteristics of the signal. However, the time the receiver takes to adjust itself to the level of the incoming signal is dependent on the time constant of the smoothing circuit employed. The use of critically damped inductance-capacitance filters would reduce the time constant, but because of the cost and the bulk involved, two stage resistance capacitance filters designed to discriminate against the modulation frequency are preferred.

By applying the AGC line to the three RF valves and first IF valve, signal input charges of 3μV to 30 mV produce receiver output changes not greater than 6 dBs. The lower level, which is the AGC threshold, depends on the noise present at the AGC detector and this is governed by the noise factor of the first RF valve and the bandwidth measured at the detector. The directional information is not appreciably impaired by noise when working near AGC threshold, because of the post detector selectivity which is discussed later. Between the receiver detector and the phase discriminator it is necessary to impose circuits to eliminate the small variations in signal amplitude, and to provide means for indicating that the signal level is sufficient for bearing observation.

Fig. 5 indicates the basic circuit developed to fulfil these requirements. The directional intelligence from the receiver detector is fed through a low pass filter discussed later, to the grid of V_1; rectifiers MR1 and MR2 limiting the signal and preventing the overload of this valve. The output of V_1 is DC coupled to V_2 which acts as a series limiter. When no signal is received, the anode of V_1 and the cathode of V_3 are at the same potential, with V_2 conducting. When a signal is received the negative half cycle causes the anode potential of V_1 to rise, the cathode potential of V_{2b} following, until V_{2a} cuts off. On the positive half cycle the action reverses and V_{2b} cuts off, as the potential cannot go negative relative to the cathode of V_3. The square wave output developed across R_1 is free from unwanted amplitude variations. It is taken from the cathode V_2 and fed to the discriminator via a low pass filter.

The output of V_1 is resistance-capacity coupled to the grid of V_4 rectified and clamped by MR3. During normal operating conditions V_5 conducts, energizing the relay, which connects the bearing intelligence and associated telephony to both the monitoring panel and the operating centre.

The signal level at which the relay operates can be varied, but it is generally set so that the relay operates on a signal which is just limiting, C_1 in conjunction with R_2 and R_3 providing a large time constant resulting in a delay at the grid of V_5 and preventing false operation due to noise impulses and transient changes.

The speech frequencies necessary for monitoring the bearing are, of course, modulated by the rotating directional diagram, and in the case of the low frequency modulation implicit in the use of a mechanical modulator, the intelligibility of the speech is impaired. By feeding to the speech amplifier a signal in antiphase to the wanted modulation but of the same frequency and amplitude, demodulation of the speech waveform may be accomplished.

The modulation depth of the RF carrier varies with carrier frequency, and in practice this can be 80% as indicated in Fig. 6a. Now, to demodulate this waveform, the gain at the trough has to be increased in the ratio 5 : 1 in order to raise it to the mean, and the gain at the crest must be reduced in the ratio 1·8 : 1 in order to decrease it to the mean. This can be accomplished by operating a valve at a point on its characteristic such that a

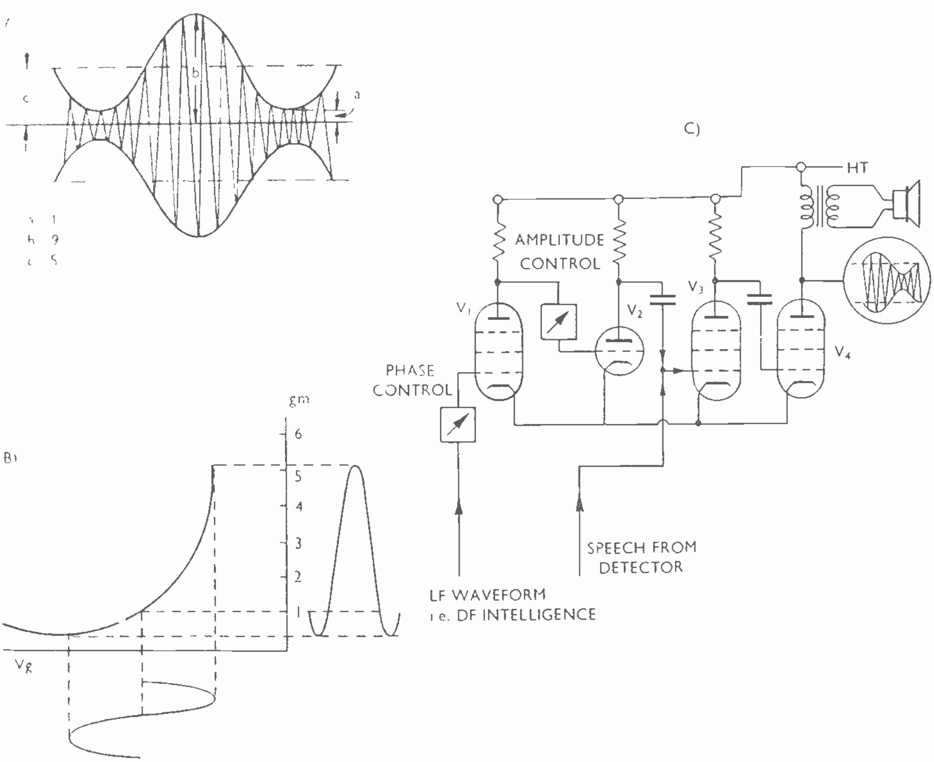


Fig. 6. Basic speech demodulation circuit

positive swing of the grid increases the gain 5 : 1 and for an equal negative swing of the grid the gain is decreased 1·8 : 1 (Fig. 6b). Unfortunately, it was not possible to obtain an approved valve with sufficiently curved characteristic and in practice the required effect was obtained by using two valves V_1 and V_3 indicated in the basic circuit Fig. 6c.

Speech from the receiver detector is applied at low level to V_3 so that it sweeps a substantially linear part of its characteristic and is undistorted. The directional modulation output of the receiver fed to the discriminator, is extracted prior to the limiter and applied to V_1, a non-linear amplifier. The asymmetrical output waveform of V_1 is fed via the phase inverter V_2 to V_3 where it is mixed with the speech. The modulation output of V_2 alters the gain of V_3 to the incoming speech waveform in such a manner as to remove from it the unwanted modulation imposed upon it by the rotating goniometer(1).

To facilitate initial adjustments it is necessary to provide means for adjusting the amplitude and phase of the demodulating waveform. The speech output is monitored by a servicing oscilloscope, this providing a convenient method of adjusting the circuit.

The amplification of the receiver output to a level suitable for operation of the discriminator is performed by special low frequency amplifiers. These amplifiers are resistance-capacity coupled with cathode follower output valves feeding filters. The gains of the amplifiers are feedback stabilized, the loop feedback circuit including a network for cutting the amplifier response at frequencies greater than 31·5 c/s.

The filters are designed with a low-pass characteristic, linearly passing frequencies of 19-31 c/s and rejecting harmonics by at least 30 dBs. The filters are manufactured as hermetically sealed units, and production units phase track within $\frac{1}{2}°$ for $\pm$ 5% variation of any frequency between 19 and $31\frac{1}{2}$ c/s. This phase stability is maintained even when the units are subjected to temperatures of $-40°$C to $+70°$C and conditions of high relative humidity.

The action of the limiter in the signal chain results in the amplitude of the odd harmonics being insufficiently suppressed, but the filter following the limiter rectifies this situation. In practice it has been found that bearing errors resulting from circuit engineering can be kept below 1° providing the amplitude of the harmonics of the modulation waveform are at least -40 dBs relative to the fundamental at the input to the discriminator. Characteristics of the filters ensure that the second harmonic amplitude is at least -48 dBs, the third harmonic at least -40 dBs, and the amplitude of higher order harmonics at least -65 dBs below the fundamental; assuming the harmonics at the output of the receiver are at least 10 dBs below the fundamental.

The directional intelligence of an automatic direction finder is conveyed as double-sideband amplitude modulation and when the receiver employs a linear detector the output signal to noise ratio will be found to be directly proportional to the strength of the modulated carrier only down to a certain carrier level. Below this value the output signal to noise ratio approaches proportionality to the square of the applied modulated carrier voltage. This effect is due to the phenomenon of "apparent demodulation" which occurs when the carrier to noise ratio at the input to a linear detector is in the region of unity or less than unity(2).

When working near the AGC threshold, and receiving very weak signals, the carrier to noise ratio at the input to the final detector is unfortunately less than unity. However, even under such conditions, the post detection selectivity provided by the filters ensures that the direction finder still works satisfactorily and in practice reliable directional information can be obtained with field strengths insufficient to provide satisfactory telephony monitoring.

Identical low frequency amplification and selectivity is inserted between the reference phase generator and the reference phase splitter to ensure phase frequency characteristics identical with that of the variable phase path.

THE DISPLAY OF BEARINGS

At the output of the receiver and reference circuits (Points "X" and "Y" in Fig. 2) the bearing information appears as a phase difference between two sinusoidal voltages of low frequency, the angular phase difference being equal to the angle between the direction of arrival of the signal and a fixed datum line, usually true north.

In selecting the method of presenting the bearing information, due consideration must be given to the requirement of superimposing the bearing information on a radar PPI. The bearing information must be displayed in a clear and accurate manner, and may be accomplished by direct or indirect methods.

The direct method uses a dynamometer (i.e. selsyn) type of phase meter. The reference tone is fed into a phase splitting network giving two outputs in phase quadrature which are connected to the stator windings of the dynamometer. The variable phase output of the receiver chain is connected to the rotor coil of the dynamometer which aligns itself at the true bearing angle of arrival of the signal providing the reference and signal phase waveforms have been aligned at a defined azimuth.

Indirect methods involve a phase to amplitude converter in which the signal phase is combined in phase detectors with each of the outputs of the phase splitting network. Two DC voltages are obtained, one being proportional to the sine and the other to the cosine of the phase angle between the signal and reference voltages. Since the reference voltages

positive swing of the grid increases the gain 5 : 1 and for an equal negative swing of the grid the gain is decreased 1·8 : 1 (Fig. 6b). Unfortunately, it was not possible to obtain an approved valve with sufficiently curved characteristic and in practice the required effect was obtained by using two valves V_1 and V_3 indicated in the basic circuit Fig. 6c.

Speech from the receiver detector is applied at low level to V_3 so that it sweeps a substantially linear part of its characteristic and is undistorted. The directional modulation output of the receiver fed to the discriminator, is extracted prior to the limiter and applied to V_1, a non-linear amplifier. The asymmetrical output waveform of V_1 is fed via the phase inverter V_2 to V_3 where it is mixed with the speech. The modulation output of V_2 alters the gain of V_3 to the incoming speech waveform in such a manner as to remove from it the unwanted modulation imposed upon it by the rotating goniometer(1).

To facilitate initial adjustments it is necessary to provide means for adjusting the amplitude and phase of the demodulating waveform. The speech output is monitored by a servicing oscilloscope, this providing a convenient method of adjusting the circuit.

The amplification of the receiver output to a level suitable for operation of the discriminator is performed by special low frequency amplifiers. These amplifiers are resistance-capacity coupled with cathode follower output valves feeding filters. The gains of the amplifiers are feedback stabilized, the loop feedback circuit including a network for cutting the amplifier response at frequencies greater than 31·5 c/s.

The filters are designed with a low-pass characteristic, linearly passing frequencies of 19-31 c/s and rejecting harmonics by at least 30 dBs. The filters are manufactured as hermetically sealed units, and production units phase track within $\frac{1}{2}°$ for $\pm$ 5% variation of any frequency between 19 and $31\frac{1}{2}$ c/s. This phase stability is maintained even when the units are subjected to temperatures of $-40°$C to $+70°$C and conditions of high relative humidity.

The action of the limiter in the signal chain results in the amplitude of the odd harmonics being insufficiently suppressed, but the filter following the limiter rectifies this situation. In practice it has been found that bearing errors resulting from circuit engineering can be kept below 1° providing the amplitude of the harmonics of the modulation waveform are at least -40 dBs relative to the fundamental at the input to the discriminator. Characteristics of the filters ensure that the second harmonic amplitude is at least -48 dBs, the third harmonic at least -40 dBs, and the amplitude of higher order harmonics at least -65 dBs below the fundamental; assuming the harmonics at the output of the receiver are at least 10 dBs below the fundamental.

The directional intelligence of an automatic direction finder is conveyed as double-sideband amplitude modulation and when the receiver employs a linear detector the output signal to noise ratio will be found to be directly proportional to the strength of the modulated carrier only down to a certain carrier level. Below this value the output signal to noise ratio approaches proportionality to the square of the applied modulated carrier voltage. This effect is due to the phenomenon of "apparent demodulation" which occurs when the carrier to noise ratio at the input to a linear detector is in the region of unity or less than unity(2).

When working near the AGC threshold, and receiving very weak signals, the carrier to noise ratio at the input to the final detector is unfortunately less than unity. However, even under such conditions, the post detection selectivity provided by the filters ensures that the direction finder still works satisfactorily and in practice reliable directional information can be obtained with field strengths insufficient to provide satisfactory telephony monitoring.

Identical low frequency amplification and selectivity is inserted between the reference phase generator and the reference phase splitter to ensure phase frequency characteristics identical with that of the variable phase path.

THE DISPLAY OF BEARINGS

At the output of the receiver and reference circuits (Points "X" and "Y" in Fig. 2) the bearing information appears as a phase difference between two sinusoidal voltages of low frequency, the angular phase difference being equal to the angle between the direction of arrival of the signal and a fixed datum line, usually true north.

In selecting the method of presenting the bearing information, due consideration must be given to the requirement of superimposing the bearing information on a radar PPI. The bearing information must be displayed in a clear and accurate manner, and may be accomplished by direct or indirect methods.

The direct method uses a dynamometer (i.e. selsyn) type of phase meter. The reference tone is fed into a phase splitting network giving two outputs in phase quadrature which are connected to the stator windings of the dynamometer. The variable phase output of the receiver chain is connected to the rotor coil of the dynamometer which aligns itself at the true bearing angle of arrival of the signal providing the reference and signal phase waveforms have been aligned at a defined azimuth.

Indirect methods involve a phase to amplitude converter in which the signal phase is combined in phase detectors with each of the outputs of the phase splitting network. Two DC voltages are obtained, one being proportional to the sine and the other to the cosine of the phase angle between the signal and reference voltages. Since the reference voltages

are in quadrature the outputs may be made to have approximately a sine and cosine relationship to the angle of arrival of the signal by suitable azimuthal orientation of the aerial. The voltages compared are of identical frequency resulting in the phase discriminator having the characteristics of a highly selective filter without the usual accompanying phase shift.

At the time of commencement of the development, low power dynamometers of the required accuracy were unobtainable and difficulties in remote bearing display, an essential requirement of the equipment, were anticipated. The indirect method of display was chosen because remote bearing display and the superimposing of the DF bearing on a radar PPI could be more economically achieved.

The sine-cosine information obtained from the phase discriminator may be applied to a DC ratiometer, or to a cathode ray oscilloscope, the bearing being indicated by the meter pointer or a radial line on the screen of the CRT. The DC outputs from the phase discriminator may be averaged by simple filtering, the limit being controlled by the required response time of the indicator.

The information is also suitable for application to the input circuitry of radar equipments with fixed coil displays. The application of the sine-cosine data to matched integrating circuits can be made to produce a saw-tooth sweep, resulting in a radial trace on the PPI.

The circuit of a typical phase discriminator is shown in Fig. 7. The stages are, phase splitting, amplifying, combining and rectifying. The phase-splitting networks in the reference path produce two components in phase quadrature. The design of the phase-splitting networks([3]) is such that the phase relationship at the output is maintained in spite of appreciable variations in frequency, e.g. $\pm$ 10%. The push-pull amplifiers have parallel fed transformers (T_1, T_2 and T_3) in their anode circuits. In order to reduce distortion the transformers, which have mu-metal cores, have a very high impedance. The secondaries are connected so as to combine the references and variable phase signals, as shown in Fig. 7. The resultant voltages are rectified by the four diodes and the differences between pairs of voltage are then approximately proportional to the sine and cosine of the phase difference.

The vector diagram of the voltages in the transformer secondaries is shown in Fig. 7. OA and OB represent the reference voltages in quadrature, A and B thus giving the potentials of the mid-points of the secondaries of transformer T_3. MN and M′N′ represent the voltage across these secondaries, so that OM, ON, OM′ and ON′, are the voltages applied to the diode anodes. The rectified voltages are proportional to these vectors, and the actuating voltages are ON-OM and ON′-OM′. These differences are approximately proportional to MN cos θ and M′N′ sin θ, if AM is small compared with OA.

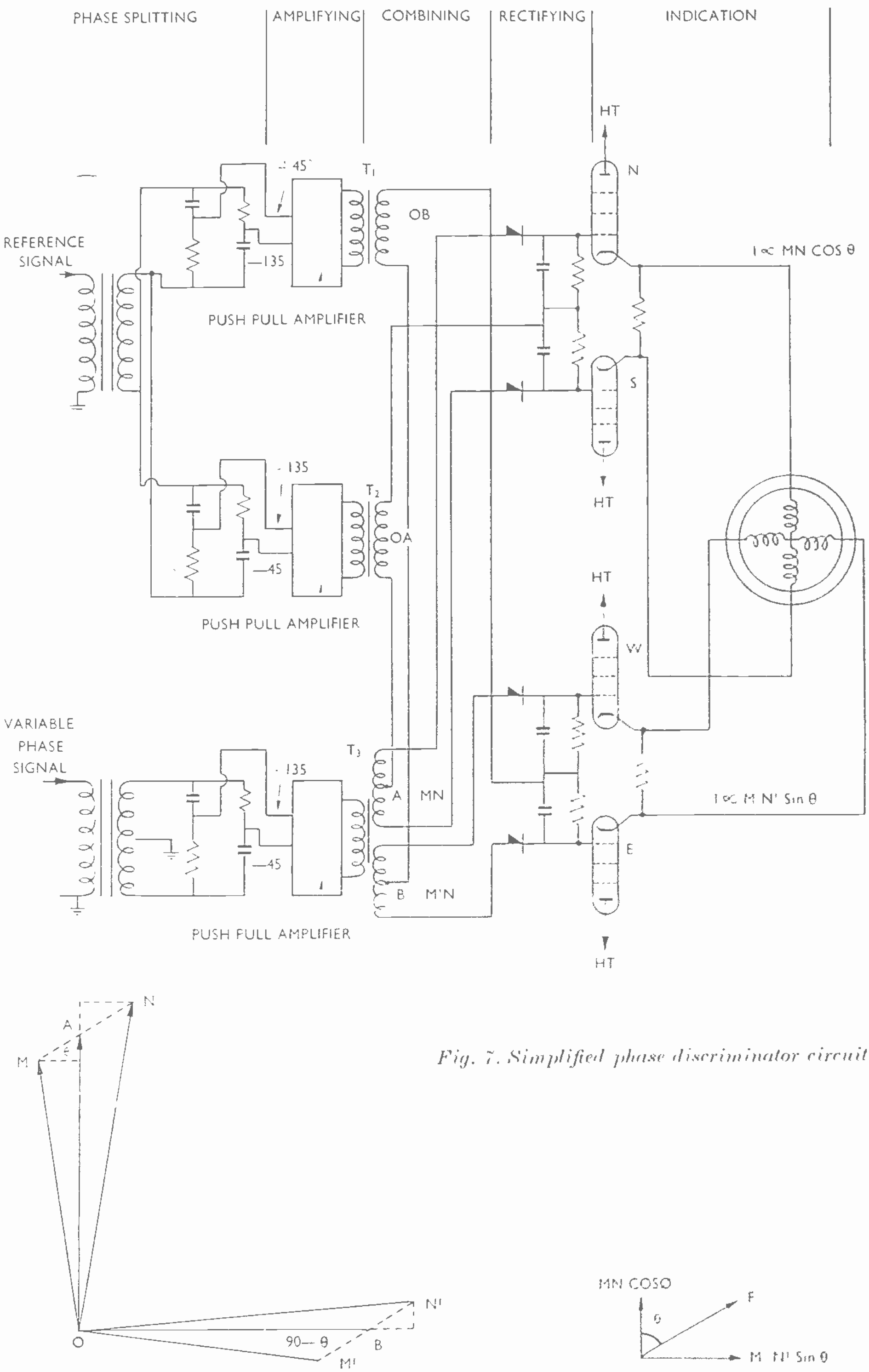


Fig. 7. Simplified phase discriminator circuit

The phase discriminator has a small basic error the magnitude of which depends on the ratio of AM to OA. The error, which is octantal in form, decreases in magnitude as the ratio increases and has been analysed by Shinn and Watson(4). The ratio was chosen to give an octantal error of 1·25° which is arranged at mid-band frequency to cancel the octantal error due to the spacing of the aerial dipoles. The phase between the detector error and the aerial octantal error may be easily changed by adjustment of the reference phase generator.

There are only two critical conditions required to maintain the accuracy of the display system assuming the indicating instrument obeys a true tangent law.

(1) MN must equal M′N′.

(2) OA and OB must be in exact phase quadrature.

If either of these two conditions is not met, a quadrantal error will be produced. Condition (1) is a function of transformer T_3 which is accurately constructed, means being provided for adjustment to equality of MN and M′N′. Condition (2) is met by using high stability close tolerance components for the phase splitting networks.

If the indicating device is for example a CRT using electrostatic deflection and has different deflection sensitivities on the two axes of deflection, this may be compensated by adjusting the relative amplitudes of MN and M′N′.

To reduce, to a negligible value, the effect of differing diode contact potentials, the average voltage level at the detector is higher than needed to operate the indicator. The diode loads are tapped down to about 60% to provide a suitable operating level.

If a CRT is used as an indicator the voltages derived from the phase discriminator will deflect the spot radially at an angle depending on the direction of arrival of the signal, and a radial distance proportional to the output level of the receiver. Such a presentation is not convenient and it is desirable that the bearing should be indicated by a radial line trace so that the bearing may be read off directly on a circular scale fixed on or close to the CRT face.

To produce this radial trace the DC outputs from the phase discriminator must be modulated by an approximately saw-tooth waveform. In one method the four voltages are periodically applied to integrating networks whose time constants are accurately matched. The resulting exponential rise in voltage or current is applied to the deflection system of the CRT. The speed of the radial sweep is not uniform, resulting in a brighter trace near the outer end at which the bearing is observed against an azimuth scale.

The type of bearing indicator employed depends on several factors;

type of aerial, type of signal, receiving and display circuit arrangement, and standard of maintenance facilities available.

The DF system described enables bearings to be presented on either a CRT or an electro-mechanical meter. The meter contains two coils whose axes are at right angles, and a small permanent magnet rotating in the centre of the coils on a spindle which has a pointer fixed to one end. When direct currents are passed through the coils, the magnet, and with it the pointer, turn to indicate an angle whose tangent is equal to the ratio of the two currents with an error of the order of $\pm$ 0·5°.

Indicators embodying features which do not require regular expert servicing in general yield a double dividend. Firstly the reliability factor is higher and secondly almost invariably the capital costs are lower.

A comparison between the meter and cathode ray tube indicators show the meter to have the following advantages:

(1) Indefinite life as compared with limited life of CRT.
(2) Initial and operating costs many times lower.
(3) Simplicity of circuit design and elimination of EHT supplies.
(4) Complete absence of setting up adjustments.
(5) No trace centring difficulties with attendant errors.
(6) With typical servicing the instrumental error is lower.
(7) Simple provision of repeater points.
(8) Easy daylight viewing.

However, there is no doubt that the CRT display is the only solution for observing bearings on very short transmissions, and when used with twin channel equipments it is capable of displaying more details of the characteristics of the received signal.

Laboratory tests show that under ideal conditions the two types of indicators have comparable errors of the order of $\pm$ 0·5°. When receiving operational signals of at least four seconds duration on equipments subject to ordinary servicing routine, the meter shows a gain, but when receiving very short duration signals, $<$ 1 second, the meter is unable to respond whilst the tube records a bearing.

The transmissions from aircraft are generally of short duration and the air traffic controller has many duties with the resultant possibility that a bearing may be missed. Cathode ray tubes with afterglow screens, and circuits whereby the pointer of the meter indicator is locked, are used to ensure the display of bearings after the cessation of transmissions. On the reception of a new signal the previous bearing information is cancelled.

REMOTE DISPLAY OF BEARINGS AND REMOTE CONTROL OF EQUIPMENT

In order to obtain the greatest accuracy the direction finder is normally sited well away from the Control Centre where the bearing information is required. It is thus necessary for the bearing information, as defined at the aerial site, to be faithfully reproduced at the centre and for the controller to have complete control of the equipment.

The distance over which a bearing can be transmitted and over which remote control can be exercised depends on the characteristics of the transmission circuits used.

Over distances up to approximately 10 miles the sine-cosine unidirectional voltages at the output of the discriminator are conveyed over a DC circuit, and remote control is effected by transmitting polarized direct current pulses in the reverse direction.

Over a wide range of separations between the direction finder and the control, the bearing information in the form of low frequency signal and reference phase components are conveyed as the modulations of two voice frequency carrier tones. Remote control of the aerial site is exercised by transmitting from the control centre to the aerial site pulses of a further two voice-frequency tones.

When a control function is initiated the transmission circuit is borrowed by the control equipment for approximately three seconds, and bearing intelligence is interrupted for this brief period. A uniselector switch at the operations centre is stepped round by a pulsing relay and as the contacts rotate they connect to the transmission circuit polarized pulses or pulses of 600 c/s and 750 c/s tone, in a code which is determined by the function selected. When control is exercised by signalling tones the aerial site equipment includes a selective receiver which selects and rectifies the pulses of the two frequencies. These pulses, or the polarized pulses transmitted over DC transmission circuits, are fed to a control unit which decodes the pulses and operates the appropriate relays which complete the desired function.

Normal line engineering techniques are used and protection against false operation is provided by the design of the selective receiver and control units, which ensures that only pulses of the correct frequency and lengths will be accepted. Thus random pulses of these frequencies contained in the speech transmitted over the line will not cause false operation.

On DC circuits the line resistance limits the practical separation to about 10 miles. When VF transmission and signalling is employed, attenuation at the operative frequencies is the limiting factor.

Narrow band channelling equipment used in line and radio link telephone circuits to CCIR specifications have a low pass frequency characteristic cutting sharply at 2·7 kc/s. Hence the carrier and signalling frequencies employed are below this frequency. Signalling pulses of 600 and 750 c/s are used and bearing intelligence is conveyed on carriers of 1·6 and 2·5 kc/s.

Fig. 2 shows the additional apparatus necessary at the aerial and operations site when the separation is too great for the employment of

DC circuits. At the aerial site the 1·6 and 2·5 kc/s carrier tones are generated by 5° X cut crystals and maintained by valve circuits which include a limiter to provide a constant output. The two tones are fed to modulators where they are modulated with the reference and signal low frequency components, the depth of the modulation being adjusted to approximately 50%. The audio output from the receiver is fed through a filter which attenuates frequencies of 1·6 kc/s ± 75 c/s and 2·5 kc/s ± 75 c/s by at least 50 dBs, and frequencies greater than 2·575 kc/s by at least 40 dBs relative to the response over the band 0-750 c/s.

The signal transmitted to the operations site consists of the speech intelligence from a received signal, plus the bearing information carried on the tones of 1·6 and 2·5 kc/s.

At the operations centre the incoming signal is applied through filters to the inputs of three circuits, the signal, reference, and audio chains.

The filters preceding the signal and reference chains have band pass characteristics, each filter accepting one tone and rejecting the other tone by at least 50 dBs relative to the level in the pass band. The rejection characteristics are necessary to eliminate unwanted mixing of the two tones in the first valves of the following amplifiers, where after amplification the two tones are demodulated, further amplified and fed to the phase discriminator through selective circuits identical to those used in the aerial site equipment and previously described.

The filter preceding the audio-amplifier rejects the tone frequencies and the beat frequency between the two tones. Failure to remove the 900 c/s beat results in a note of this frequency impairing the speech at the operational point.

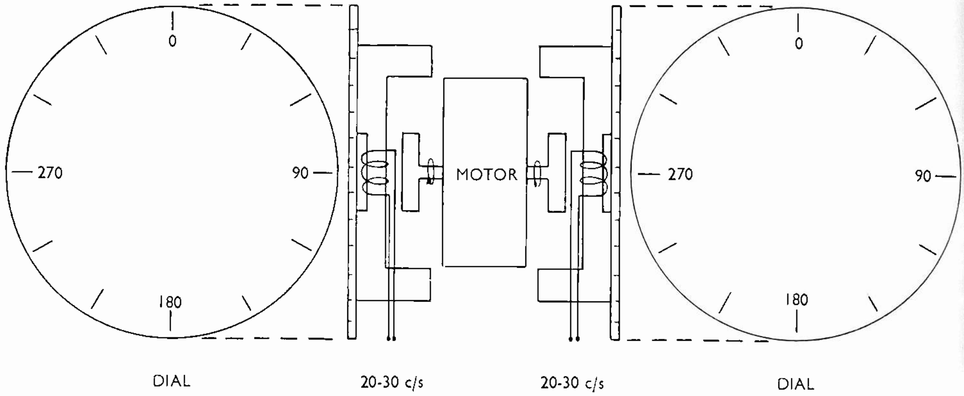
Because of the non-linear phase-frequency characteristic of a telephone line, a phase shift between the two low-frequency modulations may be produced. Correction is obtained by a combination of phase-shift networks which enable the phase of the low-frequency signal modulation to be varied at both aerial and remote sites.

Adequate decoupling of the modulator and associated transmission circuits is necessary to prevent unwanted crosstalk between the two low frequency bearing components, and between direction-finding channels.

SERVICING FACILITIES

Previous experience has focused attention on the variable standard of ability of servicing personnel, and the need for speedy location of faults.

Thus the equipment was designed so that individual chassis were withdrawable from their cabinets, each chassis consisting of a vertically mounted sub-assembly, hinged where necessary to allow accessibility to all parts of the circuit without interfering with normal operation. Circuit selector switches enable the amplitude and waveform of the signal to be



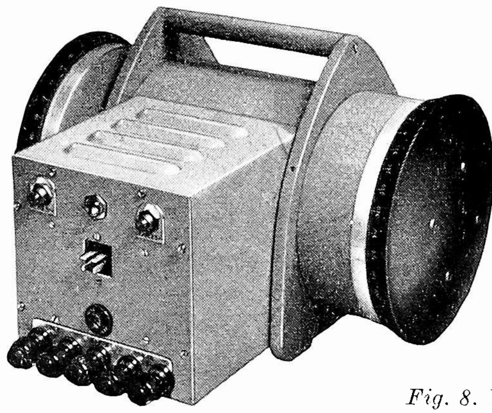


Fig. 8. Variable phase generator

checked by means of a monitor oscilloscope at the input and output of all sub-units; and the feed of all valves to be checked. Thus faults can be quickly located to a particular sub-unit or valve circuit.

A crystal-controlled oscillator installed approximately 100 yards from the direction finder, and at a known bearing relative to it, is a suitable transmitting source for adjusting the overall operating parameters of the circuits and for indicating major changes in the overall accuracy of the equipment. The equipment therefore includes an oscillator capable of radiating on any one of five frequencies, the selection being by means of the remote control system previously discussed.

It is desirable to be able to check at regular intervals the accuracy of the phase comparison circuits and the bearing indicator. The use of a calibrated source provides a method, independent of a radiated transmission, for checking the phase comparison circuits.

The instrument developed for this purpose is known as a variable phase generator and one version is shown in Fig. 8. It comprises a single phase synchronous motor with a double ended shaft, to each end of which are rigidly fixed the armatures of small generators. The stators associated with these generators are mounted on bearings and are rotatable. To the stators are attached dials linearly calibrated 0-360°. The motor runs synchronous with power supply inputs of 40 to 60 c/s, the shaft speeds being 1,200 and 1,800 r.p.m. respectively. At a shaft speed of 1,500 r.p.m. the nominal output is 14 V r.m.s. at a frequency of 25 c/s. The Magnidur rotors of the generators have been shaped to reduce the harmonic content of the outputs, the amplitude of the third harmonic predominates but has been reduced to the order 30 dBs below the fundamental.

When servicing an equipment the output of one generator is connected to the signal phase chain and the output of the other generator to the reference chain. One dial is set to 0° and the other rotated until the bearing indicator of the circuits under test records 0°. Subsequent rotation in small steps of the first dial, enables an error curve to be plotted, this dial recording directly the number of degrees phase change between the two outputs for a given angular rotation. The inherent accuracy of the variable-phase generator is controlled entirely by the mechanical accuracy of construction. With dials accurately engraved, the only possible source of error is due to eccentricity of the component parts and in practice the instrument is accurate to $\pm\frac{1}{8}°$.

THE PERFORMANCE OF VHF AUTOMATIC DIRECTION FINDERS

ACCURACY

Errors in VHF direction finding are generally due to either instrumental non-uniformity or to the installation of the equipment on an unsuitable site.

The overall systematic instrumental error of an equipment may be determined by comparing over the operational frequency range the true and observed bearings of a source located on a site substantially free from disturbances due to reflections. Error curves are obtained by rotating the aerial system through 360° in small steps, using as a signal source a local oscillator radiating vertically polarized waves situated some 100 yards from the direction finder. The operational accuracy is invariably modified from that obtained under the ideal conditions stated above. Additional errors are produced by distortions of the signal wavefront due to imperfect siting and an incident field of mixed polarization.

Existing commercial direction finders are designed to respond to a wave polarized in a single plane, generally vertical, but existing techniques do not provide infinite protection against the unwanted mode.

The three major factors, influencing the magnitude of the errors introduced are:

(1) The solid radiation diagrams of the aircraft for both wanted and unwanted polarization.

(2) The protection provided by the direction finder aerial against unwanted polarization.

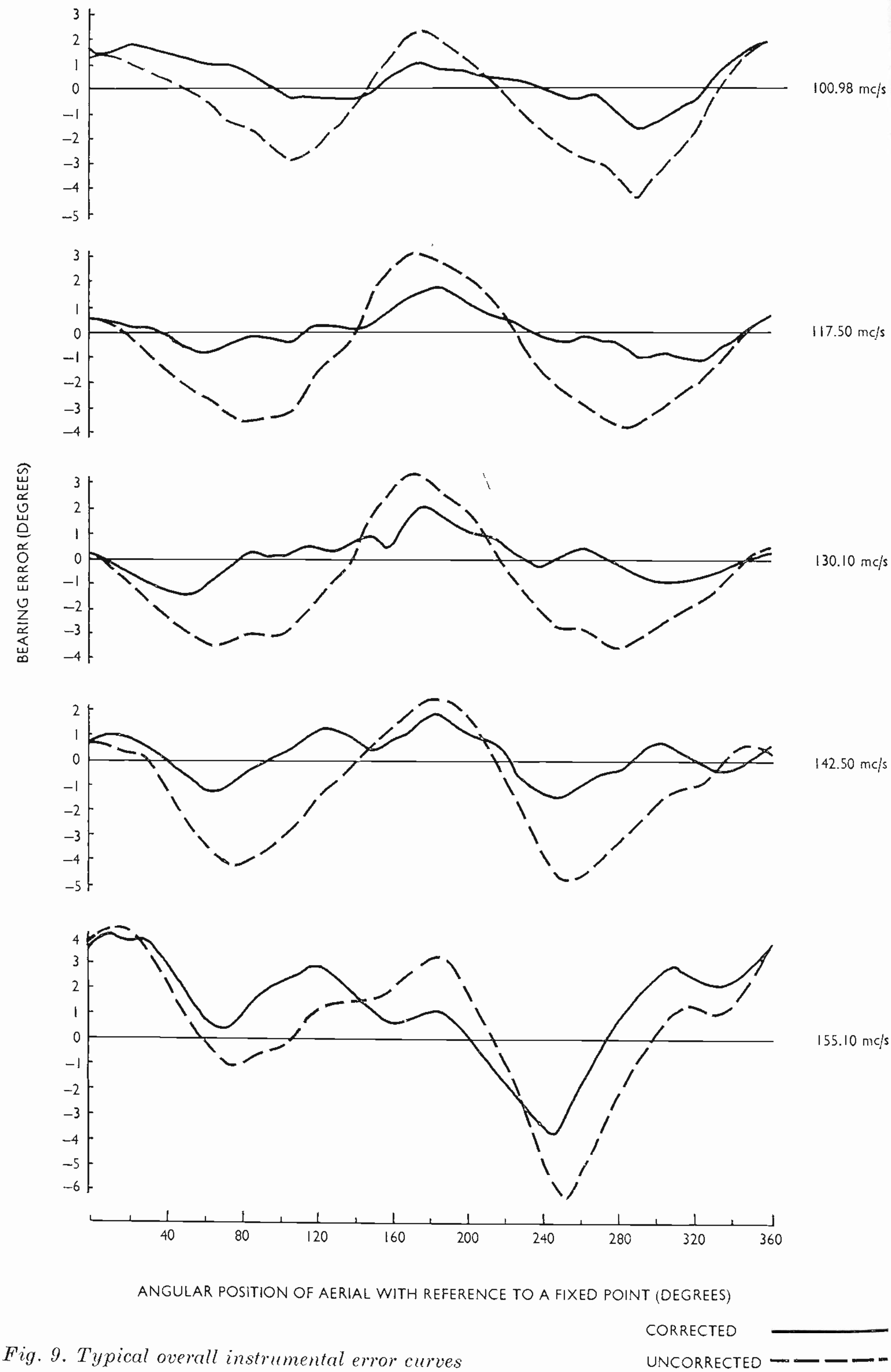


Fig. 9. Typical overall instrumental error curves

(3) The polarization, magnitude and phase of the resultant field at the direction finder aerial.

The polarization of a ray incident at the direction finder aerial is not enerally the same as the polarization at the source, particularly if the ngle of arrival is steep(5).

In practice this means that there is a possibility of unreliable bearings the signal arrives at a large zenithal angle, conditions encountered when ie transmitting aircraft is close to the direction finder. The controller is ade aware of such conditions by the erratic behaviour of the bearing ointer.

Fig. 9 shows a family of overall uncorrected systematic error curves of typical automatic direction finder. The errors, partly the result of roduction inequalities, can be substantially reduced by the adjustment circuit parameters.

The secondaries of the transformer T_3 (Fig. 7) are multi-tapped, the osition of the centre tap and the total number of turns may be varied. he receiver is tuned to the approximate mid-band frequency (130·1 Mc/s) ıd the aerial is rotated to each cardinal point and the bearing recorded. Centre tap "A" is adjusted to make northerly and southerly bearings pposite, and centre tap "B" adjusted to make easterly and westerly earings opposite. The result of such an adjustment might for example e bearings of 001°, 089°, 181° and 269°. A second adjustment involves tering the value of the resistors in the phase splitting networks to roduce accurate cardinal bearings. The sub-cardinal points are then camined and, in a typical example, may be 043°, 163°, 223° and 316°. he total number of turns of the secondaries are adjusted to give minimum rors at sub-cardinal points. In practice errors are seldom completely iminated at cardinal and sub-cardinal points, but over a frequency band

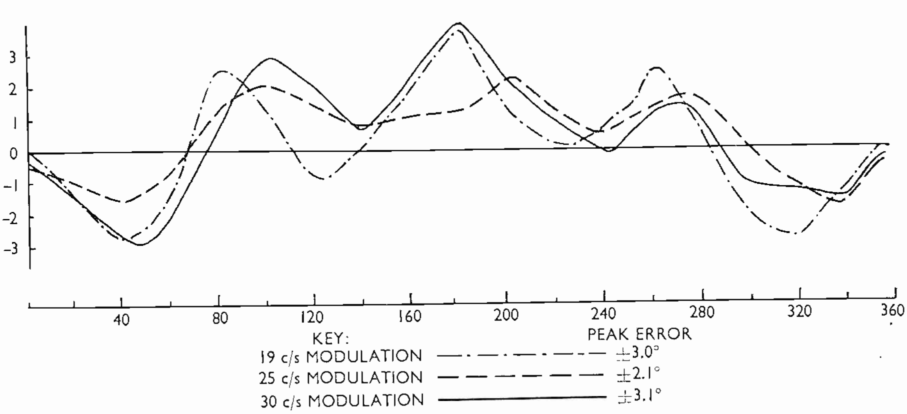


Fig. 10. Variation of systematic error with change of modulation frequency

of 100-156 Mc/s, a substantial reduction in errors is obtained. The table below shows the improvement in accuracy obtained by applying this technique to the direction finder whose error curves are shown in Fig. 9.

Frequency in Mc/s	Uncorrected		Corrected		Peak Error Reduction %	Root-Mean Square Error Reduction %
	Peak Errors	Root-Mean-Square Error	Peak Errors	Root-Mean-Square Error		
100·98	± 3·45°	2·03°	± 1·85°	1·11°	46	46
117·50	± 3·50°	2·16°	± 1·50°	0·86°	57	60
130·10	± 3·40°	2·09°	± 1·65°	0·99°	51	53
142·5	± 3·55°	2·13°	± 1·55°	0·93°	56	56
155·10	± 5·25°	2·86°	± 4·1°	2·09°	22	26

Fig. 10 shows the change of overall systematic error curves which occur when the frequency of the supply to the synchronous motor is changed. The curves were produced from bearing observations on a typical automatic direction finder tuned to a radio frequency of 130·1 Mc/s and on which no error correcting procedure had been applied. The maximum change of error at any azimuth is 3° and the spread of maximum errors is only 1°.

The operational performance of a VHF direction finder is sometimes checked by means of an aircraft flying an orbit of approximately 20 miles radius.

At intervals of approximately 5° bearings are observed, and the navigator simultaneously ascertains his position by visual pinpointing or by reference to another aid of known performance.

The error curve obtained by this means is generally only valid for a calibrating aircraft, flying at a stated height, range, and direction. Error corrections suggested by the single flight calibration have not been found to improve the overall operational accuracy, due to the dependence to some degree of overall error on, type, aspect, altitude, range and the solid polar diagrams of each aircraft.

It should be noted however, that limited flight checking does indicate particular sectors in which large errors are liable to occur.

Experience indicates that 90% of the bearings received by a well sited modern direction finder, covering the frequency band 100-156 Mc/s, will be less than 5° in error. If the frequency band is restricted to 100-140 Mc/s, 90% of the bearings will have errors of less than 2·5°.

The sensitivity is measured in terms of the minimum field strength required to give a reliable bearing, and is arbitrarily defined as one in which random noise causes an indicator pointer fluctuations of ± 5° or less.

A transmitter radiating vertical polarization is situated approximately 100 yards from the direction finder aerial. The level of the radiated signal is adjusted so that the peak wander of the indicator pointer does not exceed ± 5°, conditions representing the commencement of operation of the amplitude limiter. A tuned dipole is substituted for the direction finder aerial and the receiver detector current noted. A signal generator is then substituted for the dipole and the level adjusted to produce the same receiver detector current. Knowing the effective height of the aerial, and the generator microvolts, the field strengths required to display a reliable bearing may be calculated.

The sensitivity of a typical production equipment is tabulated below.

Frequency in Mc/s	Field Strength in μV per Metre Required to Display Bearing with Maximum Angular Fluctuation of ± 5°
101·0	3·1
118·5	3·6
127·5	1·5
140·1	1·4
156·1	1·2

FUTURE DEVELOPMENTS

Considerations of the cause of the inaccuracies in equipments at present in use suggest means of obtaining more accurate instruments. From the discussion on polarization errors it is apparent that any improvement in overall accuracy must invoke equipments with improved polarization protection, since there is little doubt that polarization error is the main factor limiting the accuracy of existing narrow aperture well sited direction finders.

Advancement of the art of direction finding therefore, necessitates improved aerial systems. Two systems have been suggested, omni-polarized and wide aperture.

Omni-Polarized Aerials

An omni-polarized aerial consists of elements designed to respond to both planes of polarization. Means are provided such that the elements in the plane of polarization of greatest signal strength are used to determine the bearing. Practical systems would use either polarization diversity or time sharing techniques. In the first case two separate receivers are employed, one connected to each set of polarized aerial elements, the output of the two receivers being combined to drive the indicator circuits. In the second case a single receiver is automatically connected to the polarized elements with the stronger signal, a given polarization being used for the period of time it is the stronger signal.

Wide Aperture Aerials

When the wavefront of the signal is disturbed by a reflecting object, the phase front becomes rippled, due to the secondary radiation generating an interference pattern. A narrow aperture aerial indicates a tangent to the rippled phase in the immediate vicinity of the observing point, and the normal to this tangent can differ considerably from the direction of the true signal source. A wide aperture aerial system explores the phase front some distance either side of the observing point, and indicates a direction that on the average is normal to the phase front. If the aerial is several wavelengths in aperture, the effect of the individual ripples tend to average out, and a bearing very close to that of the true signal source is indicated.

It will thus be apparent that the use of wide aperture aerial systems could result in an acceptable direction finder service on a site regarded as inadequate for installation of narrow aperture systems.

However, when a site approaching the ideal is involved, the limiting factor is the polarization performance of the equipment, and although in this respect the wide aperture aerial system is considerably better than a single polarized narrow aperture aerial, it would appear that with any single polarized aerial, it is possible to receive unwanted signals of such an amplitude and phase as to cause large bearing errors or loss of signal. Thus it seems probable that future direction finders will employ wide aperture omni-polarized aerials resulting in a general improvement in accuracy of the navigational systems of which they form a part.

REFERENCES

1 British Patent Application No. 13356/57.

2 H. Busignies and M. Dishal: "Some Relations Between Speed of Indication, Bandwidth and S/N Ratio in Radio Navigation and Direction Finding." *Elect. Comm.*, Vol. 26, No. 3, p. 228 (September 1949).

3 British Patent Specification No. 543, 222 (1942).

4 *The Marconi Review*, 3rd Quarter 1953, Vol. XVI, No. 110, p. 121.

5 *The Marconi Review*, 3rd Quarter, 1953, Vol. XVI, No. 110, p. 128.

OPERATIONAL APPLICATIONS OF VHF DIRECTION FINDERS

By S. A. W. JOLLIFFE

The practical application of the modern ground based VHF direction finder as an aid to aircraft navigation is considered. Factors limiting the accuracy are discussed and, where possible, systems are compared in terms of technical performance and capital and operating costs, factors in which the user is vitally interested.

INTRODUCTION

In areas of high traffic density self-help aids are an operational necessity and, with the exception of the emergency fixing services direction finding is relegated to the status of a secondary aid to be used only when the primary aid has failed. This status is due to direction finding being a saturable system capable only of handling a small number of aircraft during a given period of time.

However, at the many hundreds of airports and airstrips with limited funds, and handling only a few flights daily, the VHF direction finder is the primary and indeed often the only aid available. Feeder line routes to such airports are generally operated by the smaller aircraft carrying only a VHF communication set. To the operators of these aircraft who are primarily interested in the maximum payload compatible with safety, the ground based VHF/DF has a strong appeal, since it is the most economic and reliable way of providing bearing and position information to these aircraft.

OPERATIONAL PERFORMANCE LIMITATIONS

PROPAGATION

The direction finding problem at VHF is very different from that at the lower frequencies where the operational accuracy on short duration signals has, to the first order, been limited by Nature. VHF propagation is substantially free from ionospheric effects, resulting in direction finding systems capable of providing bearings with a high degree of accuracy.

Whereas lower frequency waves are subject to ionospheric effects producing deviations from the great circle route, VHF waves travel in straight lines. The range obtainable depends primarily on the height of the aircraft and is generally about 1·4 times the optical range, assuming average radiated power, e.g., 5 watts. Extremely long ranges from low flying aircraft during anomalous propagation conditions are, however, possible. This effect is most noticeable over sea and near the equator and is the result of the formation of a duct due to a temperature inversion occurring at a low altitude.

SITING

The overall operational accuracy of a direction finder is dependent to some degree on the site on which it is erected, the important parameters of the site depending on the operational frequency band.

In the VHF band the conductivity of the soil and, within limits, the flatness of the site are usually negligible factors, but objects capable of causing radiation from the transmitter to reach the direction finder by indirect paths are important.

Indirect radiation can reach the direction finder aerial by three main ways:

By Reflection

The commonest cause of error is due to reflection from objects displaced from the line joining the transmitter and the direction finder, the mechanism being illustrated in Fig. 1a. If the laws of optical reflection are applied it will be observed that radiation from the aircraft can reach the direction finder via two paths, the direct TR and the reflected TOR. Bearing errors greater than the angle contained by the transmitter and reflector at the direction finder are possible, the magnitude being dependent on the physical size and shape of the reflector, and its distance from the direction finder. A reflecting object placed near the ground with the direction finder aerial many feet above has minor effect because the aerial is in a much stronger field.

By Radiation

Vertical metallic objects having dimensions in the plane of polarization which are multiples of a quarter wavelength can be serious sources of re-radiation resulting in degradation of accuracy.

Horizontal conductors can be energized by a transmitter elevated at an appreciable zenithal angle, the re-radiated vertically polarized field being greatest when the re-radiator, the transmitter and the direction finder all lie in the same vertical plane.

Re-radiation is seldom of importance because generally the conductors encountered are close to the ground (e.g. fencing stakes) and the associated unwanted field decays rapidly with distance from the direction finder.

By Diffraction

Errors due to diffraction are rare and only likely to occur in mountainous terrain. A mountain on the line of the direct path can result in two or more diffracted waves of comparable magnitude arriving at the direction

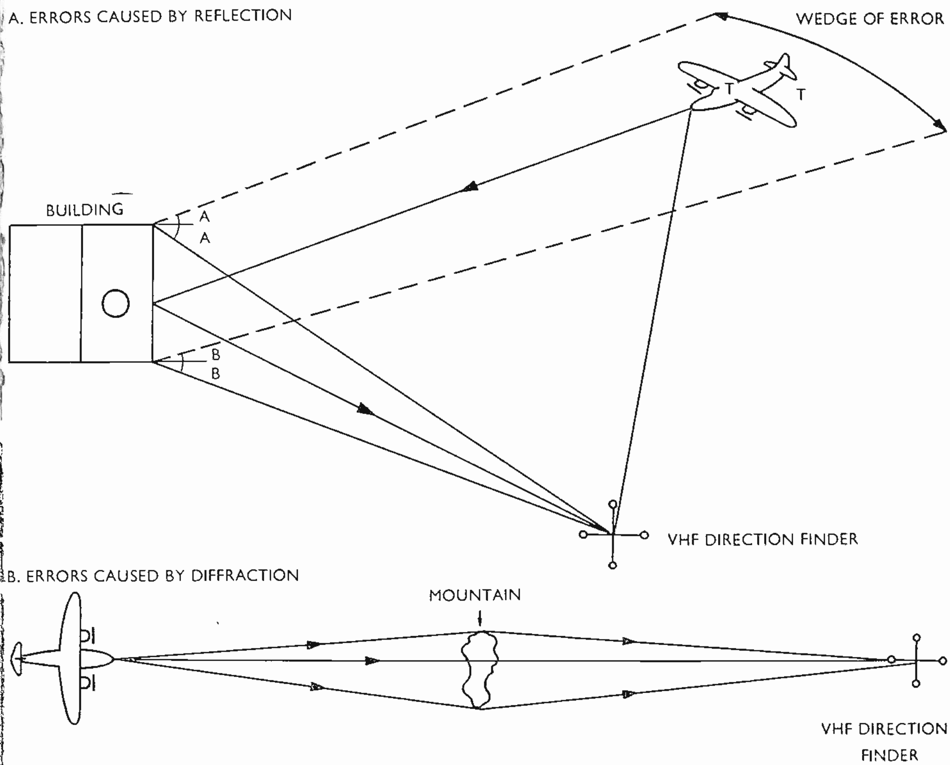


Fig. 1a and 1b

finder (Fig. 1b). One wave might be diffracted directly over the mountain, but the other error producing components are diffracted round the mountain. This effect cannot be eliminated, but it will operate only over a limited arc.

In all three cases the azimuthal error recorded depends on the relative amplitudes and phases of the wanted and unwanted signals and on the type of direction finder used, manual or automatic.

The VHF band, although not affected by distant thunderstorm activity, is subject to interference from man-made noise, motor-car ignition and electrical machinery radiation.

The ideal site would be an elevated plateau giving an area clear for a radius of at least 800 yards from such obstacles as wire fences, buildings, telephone lines and trees. A site at which the summits of hills and obstacles subtend a zenithal angle greater than $2\frac{1}{2}°$ should, if possible, be avoided. Should the operational role of the direction finder demand the observation of bearings on high flying aircraft in proximity to the direction finder, the site in the immediate environment of the aerial is of primary importance as the wanted signal is small, and in order to avoid errors the ground reflected signal must be regular and not scattered.

OPERATIONAL PERFORMANCE

The operational accuracy of a VHF direction finder depends on the following factors.

(*a*) The overall systematic instrumental error.
(*b*) The siting of the direction finder aerial.
(*c*) The protection provided by the direction finder aerial to adverse polarization.

Analysis of the results obtained by a large number of direction finders operating over the frequency band 100-156 Mc/s shows that 90% of the observed bearings will be less than 5° in error.

REMOTE DISPLAY AND CONTROL

In order to satisfy the siting requirements specified on page 201, the site chosen for a direction finder is invariably some distance from where the controller in communication with the aircraft is situated.

In the case of a single direction finder the aerial site may be half to three miles from the control, and in the case of a DF fixer service the controller may be fifty miles from one or more of the individual direction finders forming the network.

In both cases it is necessary for the bearing information to be faithfully indicated at the control centre, and for the controller to have complete control of the equipment located at the aerial sites. This is accomplished by either telephone line or radio link transmission.

OPERATIONAL APPLICATIONS OF VHF DIRECTION FINDER

Over paths where lines are available and reliable the choice is generally decided by comparing operating with capital costs; the rental of a hired line compared with the capital cost of installing a private line or radio link system. In difficult terrain a radio link will invariably be used due to the difficulty of installing and maintaining wired circuits.

When radio links are employed it will normally be necessary to erect towers of 100 feet height in order to obtain economical hops. The towers should, if possible, be wooden structures and situated at least 800 yards from the direction finder.

In the case of the short hop considered for a homer service, it should be possible to operate the direction finding end of the link close to the ground and thus arrange for the link terminal to be closer to the direction finder.

The maximum separation possible between the aerial site and the control centre depends on the characteristics of the signal transmitted and on the characteristics of the transmission circuit used. Attenuation of the operative signals and distortion are usually the limiting factors.

The remoting of bearing information over a well engineered transmission system does not result in an additional bearing error of greater than $\pm 1°$.

APPLICATIONS OF VHF DIRECTION FINDERS

THE SINGLE DIRECTION FINDER

Civil Aviation

In the United Kingdom VHF/DF installations are operated by the Ministry of Aviation on a request basis. A procedure for aircraft requesting bearings has been internationally agreed upon. This procedure based on the requirements of a manual direction finder, requires the aircraft, after acknowledgment from the ground, to transmit for ten second periods concluding with the aircraft call sign. When an automatic equipment is used a rapid assessment of the mean bearing by the controller enables the transmission time to be reduced to two or three seconds.

Aircraft request bearings for two purposes, firstly to maintain a homing track, and secondly to establish position by reference to two or more direction finders.

The homing service can be provided from extreme optical range, but in practice is usually required for approximately the final twenty-five miles to the airport. Bearings passed to the aircraft are magnetic headings (QDM).

En route aircraft request bearings in order to check their position. The bearings passed to the aircraft are usually the bearing of the aircraft with reference to true north (QTE). In addition VHF/DF is used to aid the control staff on the ground.

Military Aviation

During the Second World War VHF/DF was used to track our fighters and to "home" individual aircraft to base after the squadron had been separated in combat. In the latter stages of the war it assisted crippled aircraft of our offensive squadrons, whose primary aids had become unserviceable. A valuable fixing service was also provided for allied aircraft about to force land in the sea.

Air-ground communication for service aircraft is now mainly located in the UHF band 225-400 Mc/s, and ground based direction finders are already in operational use. UHF direction finders will no doubt provide services identical to that provided by their VHF counterparts, the mobile unit figuring prominently in the operations of a tactical air force.

Aircraft Industry

The aircraft manufacturers of the United Kingdom have installed VHF direction finders to aid their test pilots. This approach has the advantage

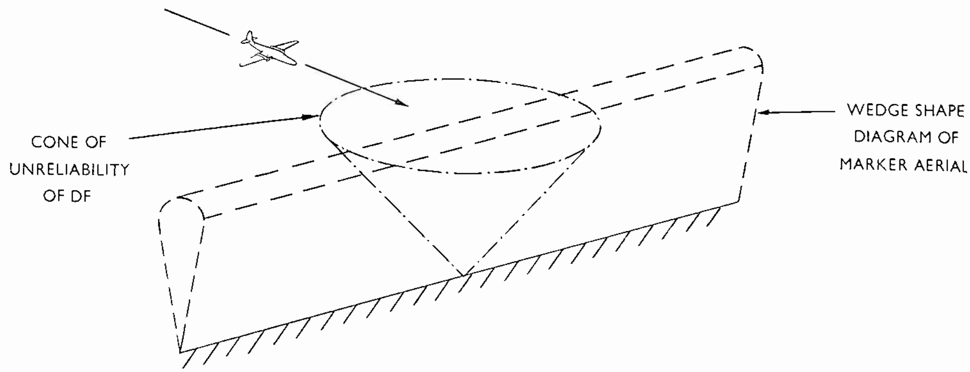


Fig. 2

that the pilot is relieved of navigation problems, the aircraft radio equipment needed is the basic minimum, and in the event of an emergency the approximate position of the aircraft is known for rescue purposes.

Standard Approach Procedure

One of the standard approach procedures practised at the smaller airfields is known as the "ZZ" method, and involves the use of a direction finder to direct the aircraft to a position in line with the duty runway.

The aircraft is homed by magnetic headings and the position "overhead" of the airfield is indicated. A standard pattern is then flown aided by the direction finder; and height is reduced at a prescribed rate to a minimum known as the "break off" height based on surrounding topography. If at the break off height the runway is visible, the landing is completed.

Accurate knowledge of overhead is necessary to determine the position from which the standard pattern is commenced. Due to their zenithal diagrams no direction finders at present in use are capable of defining to the required degree of accuracy when high flying aircraft are overhead.

One means of improving overhead identification is to provide a marker beam in this cone (Fig. 2). The marker aerial, the beam of which is either conical or wedge shaped, has a width small compared with 60°, and is switched to the DF receiver when the cone of unreliable bearings is entered by the aircraft. When the aircraft transmission is heard via the marker aerial, the aircraft is known to be overhead and is informed accordingly.

POSITION FINDING

At both civil and military control centres, it is important that the position of aircraft operating in areas under their jurisdiction should be known.

In areas of high traffic density, position fixing is normally accomplished by means of primary aids, in some cases augmented by a direction finding service. Nevertheless, an important fixer service is provided in the United

Kingdom by a network of direction finders tuned to the International Emergency frequency of 121·5 Mc/s.

In the less highly developed regions of the world economic considerations alone will be responsible for the application of plotting systems of which direction finding equipments are a major component.

The position of an aircraft with respect to the ground can be defined by the measurement of bearing, of range, or of both bearing and range; the method used depending on the type of ground equipment employed. If at three or more widely separated ground installations range or bearing is measured, all positions of the aircraft can be defined. In circumstances where only a single site is available it is necessary to observe both bearing and range, the equipments employed being referred to as Rho-Theta (ρ/θ) system.

The solution to the problem is in practice governed by many factors such as capital expenditure, service area required, traffic density involved, complexity of equipment, and bulk and weight of equipment permissible in the aircraft.

It is evident that the required information could be provided by radar capable of operating at large elevations. To obtain a true plan position indication of high flying aircraft close to the radar, height finding facilities would be necessary and the problem of identification must be solved.

Position information free from the difficulties of identification and interpretation of primary radar may be obtained by plotting on an appropriate map the bearing lines defined by two or more direction finders. In some ρ/θ systems a direction finder defines the bearing line, distance along this line being measured by auxiliary apparatus.

MANUAL DIRECTION FINDERS

When manual direction finders are employed, the bearings from each are conveyed by landline or radio link in speech or morse code to the control centre. At the control centre, the bearings are laid off on a map by means of strings which have as their origin the geographical position at which the ground stations are situated. This is a comparatively slow process.

AUTOMATIC DIRECTION FINDERS

The advent of the automatic direction finder has made it possible to display instantaneously at the control centre precisely the same information obtained at the remote direction finding sites. Three or more automatic direction finders are tuned to a common frequency and information from each is transmitted to the control centre where the bearing lines are automatically displayed on a translucent map of the service area, the position of intersection of the lines being read off by the controller.

Automatic fix displays used with automatic direction finder networks are basically of two types. In one case a single display indicator is time

Fig. 3

shared between each direction finder in the network, whilst in the other type the projected images of individual indicators, one for each direction finder, are displayed on a translucent screen.

TIME SHARED AUTOMATIC DIRECTION FINDING FIXER

This system employs a 17 inch cathode ray tube and associated circuits perform two functions. First the origin of the tube spot is shifted sequentially at a high repetition rate to positions corresponding to the geographical locations of each of the direction finders. Secondly the spot is shifted along a radial from each origin in a direction corresponding to the bearing obtained by a particular station. The cathode ray tube has long afterglow characteristics which causes the display to appear as three lines whose intersection indicates the aircraft position.

The sequential switching can be accomplished either mechanically or ectrically, a rate of twelve cycles per second associated with afterglow eing sufficient to produce a substantially flicker-free picture.

Provision is made to accommodate up to eight stations, capable of eing divided into two networks of four stations each. Both networks can e viewed–on the one display, the bearing lines of one network being hatched" for identification. A particular use of these facilities is where vin channel direction finders are installed at each site, allowing the osition fixes of two aircraft to be displayed simultaneously.

A control enables the origin of a marker trace to be located on an rcraft fix, and a further control allows the rotation of this trace to dicate the course an aircraft must fly to reach a stated destination. This x display can be built into an airport control desk (see Fig. 3).

ROJECTED IMAGE FIXER DISPLAY

The display of a projected image equipment is on a translucent screen bout 5 feet square mounted at some convenient viewing angle. The rger display is extremely valuable when several controllers are interested the aircraft movements, a situation which may exist in a fighter or civil rways area control centre.

rojected Image Cathode Ray Tube Display

he bearing information from each direction finder is applied to a projecon tube via circuits which produce a radial line on the tube. The cathode ay tubes mounted behind the screen are so aligned that the origin of each ace coincides with the position of the corresponding direction finder on e map. The radial lines are projected on to the map to produce a fix. uring quiescent conditions the origins are marked by a small cross of ght which facilitates alignment.

rojected Image Meter Display

mages of the electro-mechanical bearing meters previously mentioned ay be projected on the screen by the episcope or diascope principle (see ig. 4).

OMPARISON BETWEEN, AND ACCURACY OF, DIRECTION FINDER IXER SYSTEMS

he time shared display is preferred for all duties where viewing is by a ingle controller. It is the only usable system in conditions of high ambient ght encountered in the modern control tower. All other systems must be iewed in subdued lighting conditions, generally resulting in controller atigue.

The salient feature of the single time shared display is simplicity, perational research suggesting that the addition of such frills as video apping and anti-parallax devices would serve no useful purpose.

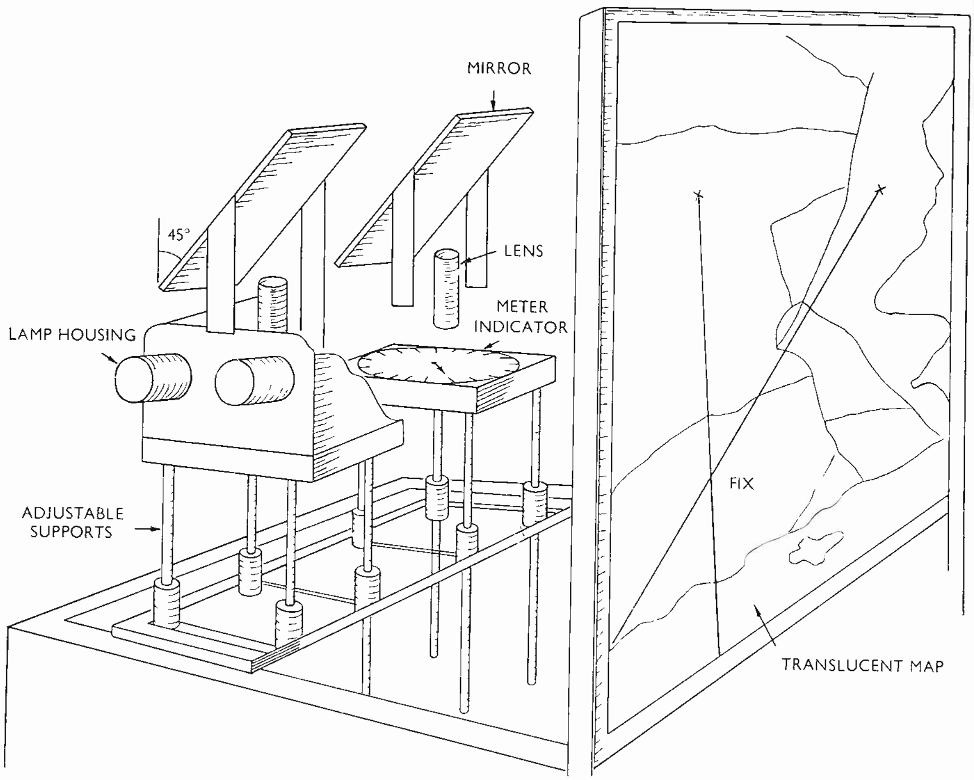


Fig. 4

Displays using cathode ray tubes suffer from effects such as zero drift, high tension problems in conditions of high humidity, tube replacement, etc., but are nevertheless preferred because they produce approximately correct plots even with signals of very short duration (< 1 sec.). When the signal duration is two seconds or more, the instrumental accuracy of all the fix displays are similar, the maximum error of each bearing component contributing to the fix being approximately 1° greater than at the parent direction finder.

The fix display enables the individual bearings to be quickly weighted according to their reliability. Weight is a statistical approach to the evaluation of several bearings of different reliability, a function which during the last war improved plotting by a considerable factor. For example if one contributing bearing was swinging erratically its contribution to the fix would be considered less than a steady bearing.

Weighting together with the ability of the controller to guess the centre of gravity of the fix area results in operational fix errors considerably less than calculations indicate. Limited operational trials have indicated a probable error of not greater than two miles for positions inside the service area.

LIMITED FIX SYSTEM

The typical homing procedure described on page 204, limits the traffic handling capacity of a terminal and involves exacting instrument flying.

The system detailed in Fig. 5 provides the pilot during the approach with reasonably accurate range information in addition to QDM bearings. Height adjustment can be made at the correct points en route, thereby relieving the pilot of instrument flight, speeding up aircraft traffic flow, and reducing the uneconomic and potentially dangerous practice of stacking.

In the example the approach course to the airfield is C-A, a QDM of 190°. A pilot destined to land at A would align his aircraft on QDM 190°

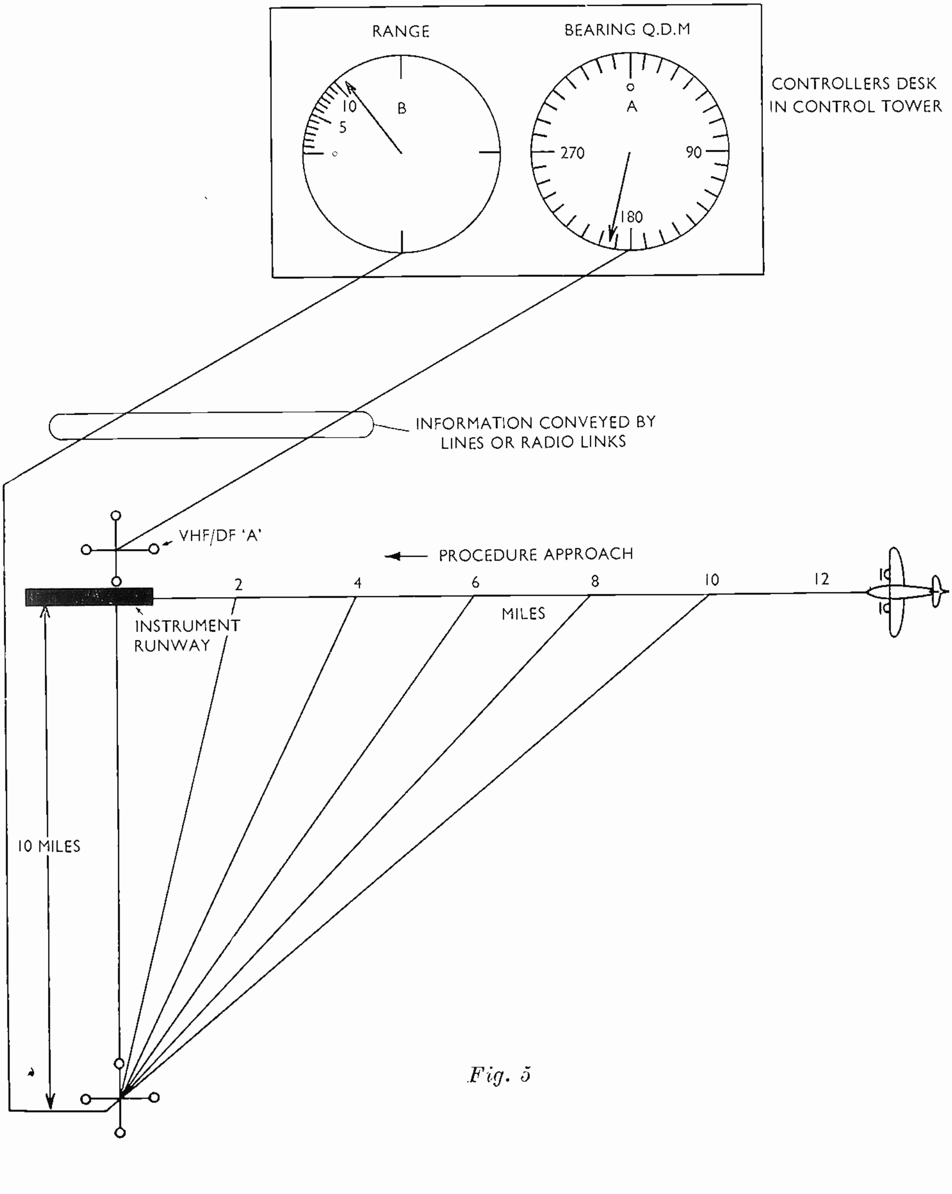


Fig. 5

by means of requested bearings obtained from an automatic direction finder "A" suitably sited adjacent to the runway. The directional intelligence of "A" is remoted to the control tower where it is presented on a bearing indicator. A second automatic direction finder is sited at "B" and the directional intelligence is remoted to the control tower, where it is presented on indicator "B" alongside indicator "A". It will be evident that as the aircraft proceeds from C to A the bearing displayed by indicator "B" will be changing in the following manner.

Bearing at "B"	*Range from "A"*
315°	10 miles
309°	8 ,,
301°	6 ,,
292°	4 ,,
281°	2 ,,
276°	1 ,,

It is thus possible to calibrate indicator "B" direct in range. At the request of the aircraft the controller can provide instantaneous bearing and range information, enabling the pilot to hold his course and make the necessary height reduction at the correct range.

If the probable error of the direction finder at "B" is assumed to be $\pm$ 3° the errors in range would vary between $\pm$ 2·2 miles at 10 miles to $\pm$ 0·52 miles at 1 mile. Small deviations of the aircraft from the correct QDM approach would not result in any appreciable additional error in range.

The system is effectively a two station position finder requiring no plotting for the application described. Indicator "B" can also be calibrated in bearing thus providing with indicator "A" an area fixing system enabling the controller to assist the pilot in finding the standard approach course.

The geometry of the system can be varied to suit particular approach problems. The principle is used by Dutch Civil Aviation.

A possible extension of the system to greater automaticity has been proposed(1). A plurality of flight information is verbally recorded on 35 millimetre film. When a pilot calls the airfield for range and bearing information the signals received at direction finders A and B operate circuits which automatically select the appropriate pre-recorded verbal statements of the present range of the aircraft and the bearing it must fly in order to reach the airfield. The selected verbal announcement is made to modulate the appropriate ground-air communication channel, and thus automatically answers the pilots request for positional information. The controller can monitor the system and break in for essential instructions.

RHO-THETA SYSTEMS

Range measurement in conjunction with ground based automatic direction finders offers in special circumstances considerable advantages to both military and civil users.

It is impossible to provide a fixer network for an aircraft carrier, or for the advanced-landing strip of a tactical air force. Likewise in undeveloped areas and at island air terminals fixer networks would be impracticable due to economic or geographical factors.

The well known ρ/θ system illustrated in Fig. 6 utilizes the principle of phase measurement for the determination of range in conjunction with an automatic direction finder(2). The transmitter TX and the direction finder are located close together, the actual spacing used being determined solely by consideration of DF site error. The ρ/θ information can be remoted to a control tower or centre many miles distant. The standard VHF aircraft communication equipment is modified to receive and transmit on two channels simultaneously. The aircraft receives from the ground station a carrier f_1 amplitude modulated at a frequency of approximately 900 c/s and simultaneously retransmits the modulation as an amplitude modulation on carrier f_2.

Signals radiated from the aircraft are received by the ground based

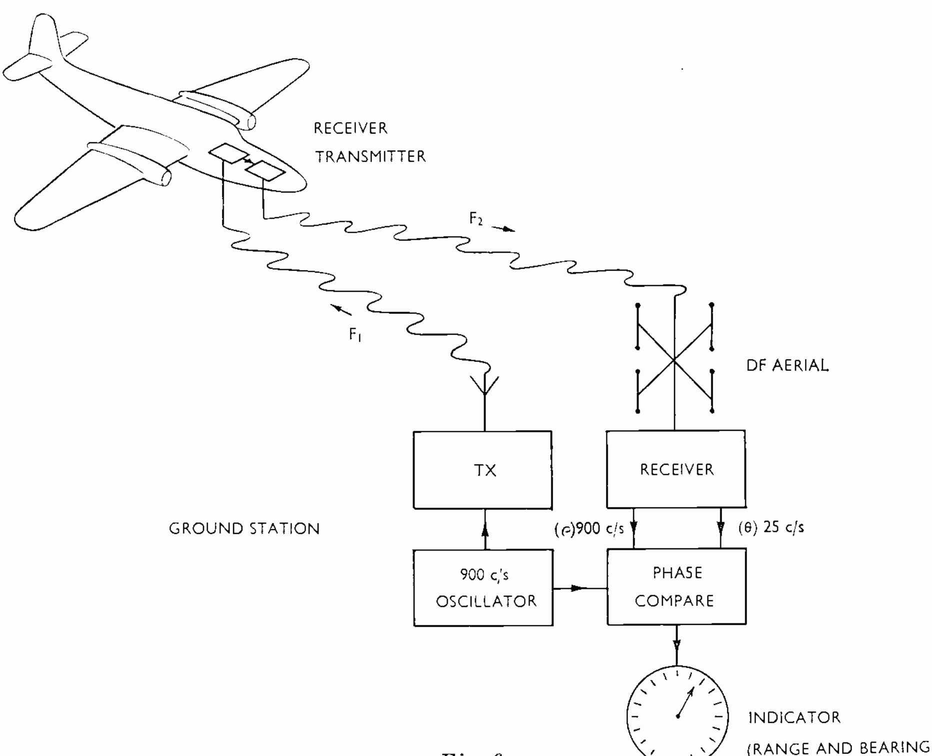


Fig. 6

direction finder tuned to frequency f_2, and the bearing is displayed on the cathode ray tube as a radial trace.

The phase of the modulation signal extracted from f_2 is compared with the phase of the outgoing signal used to modulate f_1, the aircraft range being displayed as a blip on the radial trace.

The choice of modulation frequency is a compromise between freedom from ambiguities and accuracy. High accuracy at short ranges is particularly valuable and is obtained by using a higher modulation frequency, the lower modulation frequency being retained to resolve ambiguities. Phase shifts in the circuits are compensated for by a preset adjustment, which can be quickly checked by the ground controller.

The above system although workable in certain areas has the serious disadvantage that it requires simultaneous transmission and reception in both directions which involves the use of two carrier frequencies.

A modified system in which one carrier frequency is time shared between the "go" and "return" paths of the continuous wave range finder has been successfully operated ([3]). Electronic switching at the ground and airborne stations are synchronized to ensure that when the ground transmitter and the airborne receiver are operating, the ground receiver and the airborne transmitter are quiescent, and vice versa.

SIMPLE GROUND CONTROL APPROACH AID

A further system providing limited ρ/θ information is a simplified ground control approach aid designed for operation by one man. It is achieved by combining a simple radar installation with a simple direction finder. The equipment is available as a mobile unit, which enables it to be quickly sited in the most advantageous position relative to the landing strips in use.

In one commercial design ([4]) a radar dish and a direction finder aerial are mounted on a common rotatable shaft such that the axis of the radar beam is at right angles to the plane of simple elevated "H" aerial of the manual direction finder. The elevation of the radar dish can be independently controlled. The dish which has a conical beam 3° wide is coupled to a transmitter operating in the "X" band and delivering 10 kW peak output power. A simple "A" scope presentation of range is provided and two further scales indicate the azimuthal angle of the dish and direction finder aerial and the elevation of the dish. A meter provides a visual indication of the direction finder null.

The ground control drill is simple but effective. The aircraft is homed to within radar contact by established direction finding procedure, an operation which automatically aligns the radar dish in azimuth. During this homing procedure the dish is scanned in elevation until a "blip" is seen on the "A" scope. The aircraft is now under radar control, the azimuth and elevation of the dish being adjusted to obtain maximum radar response on the "A" scope, which indicates the distance of the aircraft from the aid.

Identification of the blip with the aircraft seeking assistance is resolved in the established way by instructing the pilot to turn the aircraft.

This aid enables the aircraft to be talked down on a pre-set approach pattern to the local obstruction clearance limit, indicators warning the controller when the aircraft has deviated either in azimuth or glide angle from the limits of a prescribed course.

The system provides fix information at close range where it is of greatest value to the pilot and the air traffic controller. In a typical flight of an aircraft approaching an airport at 10,000 feet altitude, the direction finder would provide the pilot with homing bearings from approximately 100 miles, and full radar position information would be available from a range of approximately 15 miles.

The system which has been designed for the customer with limited funds is suitable for installation at the smaller airports, one operator providing considerable assistance to a few aircraft. The major disadvantage of the aid is that effort is concentrated on the single aircraft and collision possibilities can occur due to the presence of unmonitored aircraft in the approach area.

A modified system using an automatic direction finder and a simple sector scan radar would speed up the direction finding procedure and reduce the collision hazard.

AID TO PRIMARY RADAR IDENTIFICATION

Although primary radar gives an indication of all aircraft within range it does not positively identify a particular aircraft.

Radar identification is at present achieved by controlled flight movements directed from the ground, by responder techniques, or by securing the co-operation of a suitable ground based direction finder. It is recognized that ground controlled identification movements occupy valuable time, whilst the use of secondary radar is unpopular with the aircraft operator because it necessitates carrying responder apparatus in the aircraft.

An aircraft without aids other than VHF communication can be located and identified with a limited degree of certainty by means of a primary radar and a co-operating direction finder. In existing systems using fixed coil radars, it is arranged that the bearing line is displayed every *n*th trace of the PPI scan. Due to the probable error of the bearing line, the use of a single direction finder as a means of positive identification is doubtful, but it does assist the traffic controller in a variety of ways. For example, in the event of echo masking by clutter, the direction finder does tell the controller the azimuth to watch.

The position information obtained from the fixer systems previously discussed can be displayed on a radar PPI. Information from two or more direction finders can be periodically applied to the radar and a "cocked hat" displayed, or position established by the ρ/θ (see page 211) can be exhibited as a bright spot at the end of a bearing line. These methods considerably reduce the possibilities of error in identification and might be acceptable to all parties.

COMPARISON BETWEEN FIXER SYSTEMS

Of the fixer methods discussed, the systems using only ground based direction finders and the simple ground control approach aid are the most attractive to the aircraft operator, as they require within the aircraft only the mandatory communication equipment.

ρ/θ fixer systems using CW and pulse ranging techniques have the advantage that they can be operated in areas where triangulation methods are uneconomic. Such circumstances can arise where air routes cross water or undeveloped country and it is impossible to arrange direction finders with overlapping service areas. Economy in sites, lines, equipment, and staff, is obtained at the expense of non-standard equipment in the aircraft.

The most attractive system for the airport with a low traffic density is the simple ground control approach aid. At extreme range a homing service is provided, whilst at close range where it is most required, fixing and talk down facilities are available. The superimposition of bearing information from a direction finder on the PPI of a primary radar establishes identified position. A simple primary radar retaining the salient features of the simple ground control approach aid and providing means of assessing collision possibilities is undoubtedly the most valuable and the most economic aid.

REFERENCES

1 Patent Specification 701, 592.
2 *Journal I.E.E.*, Vol. 94, Part IIIA, N.16, pp. 984-989.
3 Patent Specification 793, 198.
4 *Journal of Guild of Air Traffic Control*, April 1957.

THE MARCONI AUTOMATIC PLOTTER

By D. W. G. BYATT, B.Sc, A.Inst.P.

The logical sequence to a network of radio direction finders is to provide for the automatic plotting of fixes. The common working frequencies used in aircraft communications, particularly in the VHF and the UHF bands, leads to a relatively simple system which is described in the following article.

The ability to present a number of position lines as a fix increases very considerably the usefulness of direction finding as a navigational aid. However, it must be borne in mind that direction finders are, at the present time, at any rate, considered secondary navigational aids, and consequently, simplicity, consistent with speedy reliable operation, is the main consideration.

As the main application of the device to be described below is for use with VHF and UHF aircraft communication, a self-contained unit in the form of a desk, as shown in Fig. 1, was chosen as most suitable for use in aerodrome control towers. However, it may be worth noting that with the advent of VHF ship-to-shore communication for harbour approach, a fixer system such as this may be of use in the maritime world.

GENERAL DESCRIPTION

The Marconi AD200 and AD210 series VHF direction finders are typical direction finders that can be used with this plotter, and they function very briefly as follows.

An Adcock type aerial system, containing a capacity goniometer, is used to provide the bearing information, as shown in Fig. 2. The goniometer is rotated at 25 c/s by means of the motor M. As the polar diagram of the aerial system is of the cardioid type, when the goniometer is rotated a 25 c/s modulation is superimposed upon any signal being received. This is passed through the receiver system and selective filters, to eliminate all but the original 25 c/s signal modulation. Also attached to the motor shaft is an a.c generator. This produces a 25 cycle a.c voltage of fixed reference phase.

The signal 25 c/s voltage is arranged to be exactly in phase with the reference voltage when the received signal originates due north of the direction finder aerial. As the direction of the received signal changes, so also does the phase of the modulation superimposed upon the received RF by the goniometer. The two 25 c/s voltages are then passed to a phase comparator, or discriminator. The output of the discriminator is in the form of two balanced d.c voltages, shown as the NS pair and the EW pair.

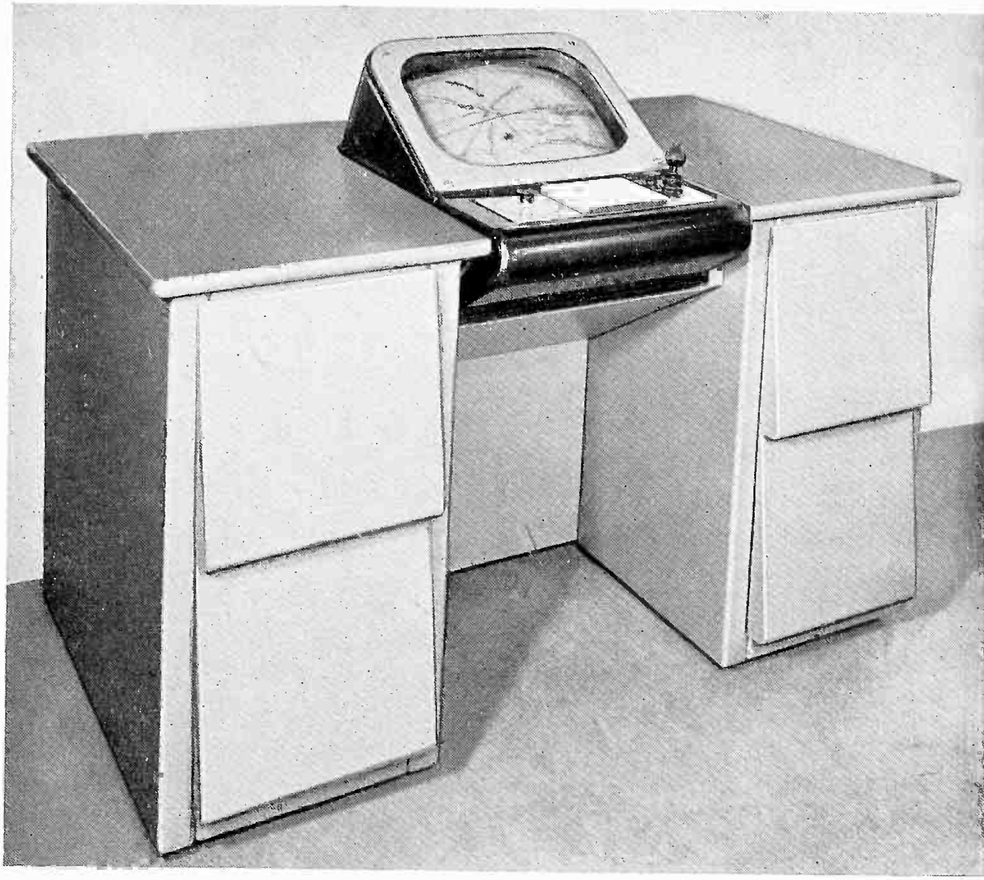


Fig. 1

These voltages vary in sine and cosine fashion depending upon the bearing of the received transmission.

For use with a fixer system, it is necessary to transmit the information from the direction finders some distance—say sixty miles. This may be done by means of carriers, over telephone lines or radio links.

The 25 c/s signal and reference voltages are used (as shown in Fig. 2) to modulate two tones of 1·6 kc/s and 2·5 kc/s (or 3 kc/s). This enables both 25 c/s voltages to be carried over one pair of lines or over one link.

At the remote end of the system, the tones are separated, demodulated and then fed into a phase discriminator as before. It is the sine/cosine d.c voltages that are used by the plotting table.

A typical complete installation is shown in Fig. 3. It has been assumed that the aircraft pilot has requested a course to steer to reach Rochester. The position of an aircraft transmitting on its communication channel is shown in the fundamental manner on a map as intersecting lines originating from the indicated locations of the direction finders. The lines are

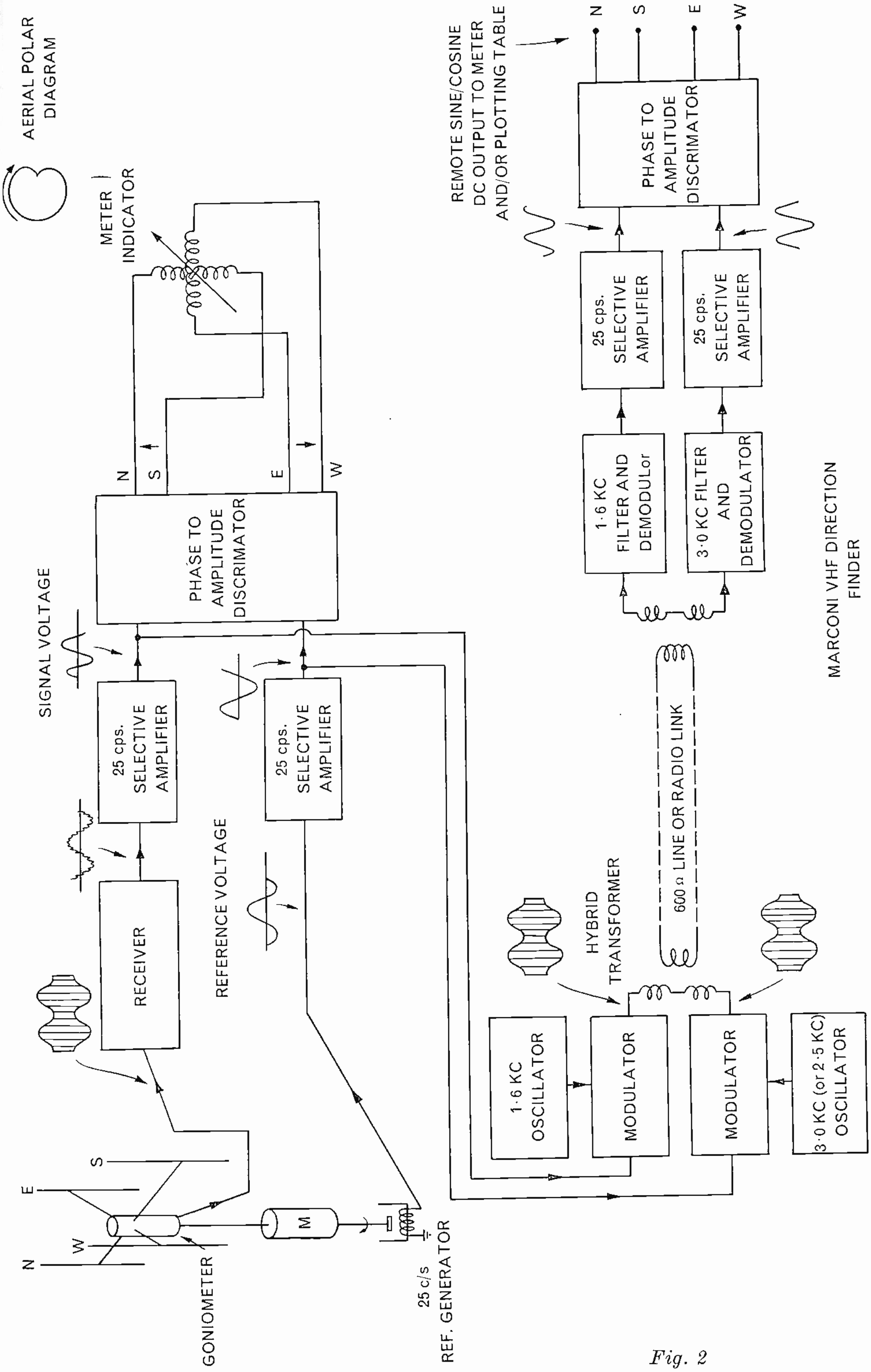

AERIAL POLAR DIAGRAM
METER INDICATOR
SIGNAL VOLTAGE
REFERENCE VOLTAGE
RECEIVER
25 cps. SELECTIVE AMPLIFIER
25 cps. SELECTIVE AMPLIFIER
PHASE TO AMPLITUDE DISCRIMINATOR
N
S
E
W
GONIOMETER
M
25 c/s REF. GENERATOR
1·6 KC OSCILLATOR
MODULATOR
MODULATOR
3·0 KC (or 2·5 KC) OSCILLATOR
HYBRID TRANSFORMER
600 Ω LINE OR RADIO LINK
1·6 KC FILTER AND DEMODULATOR
3·0 KC FILTER AND DEMODULATOR
25 cps. SELECTIVE AMPLIFIER
25 cps. SELECTIVE AMPLIFIER
PHASE TO AMPLITUDE DISCRIMINATOR
REMOTE SINE/COSINE DC OUTPUT TO METER AND/OR PLOTTING TABLE
MARCONI VHF DIRECTION FINDER

Fig. 2

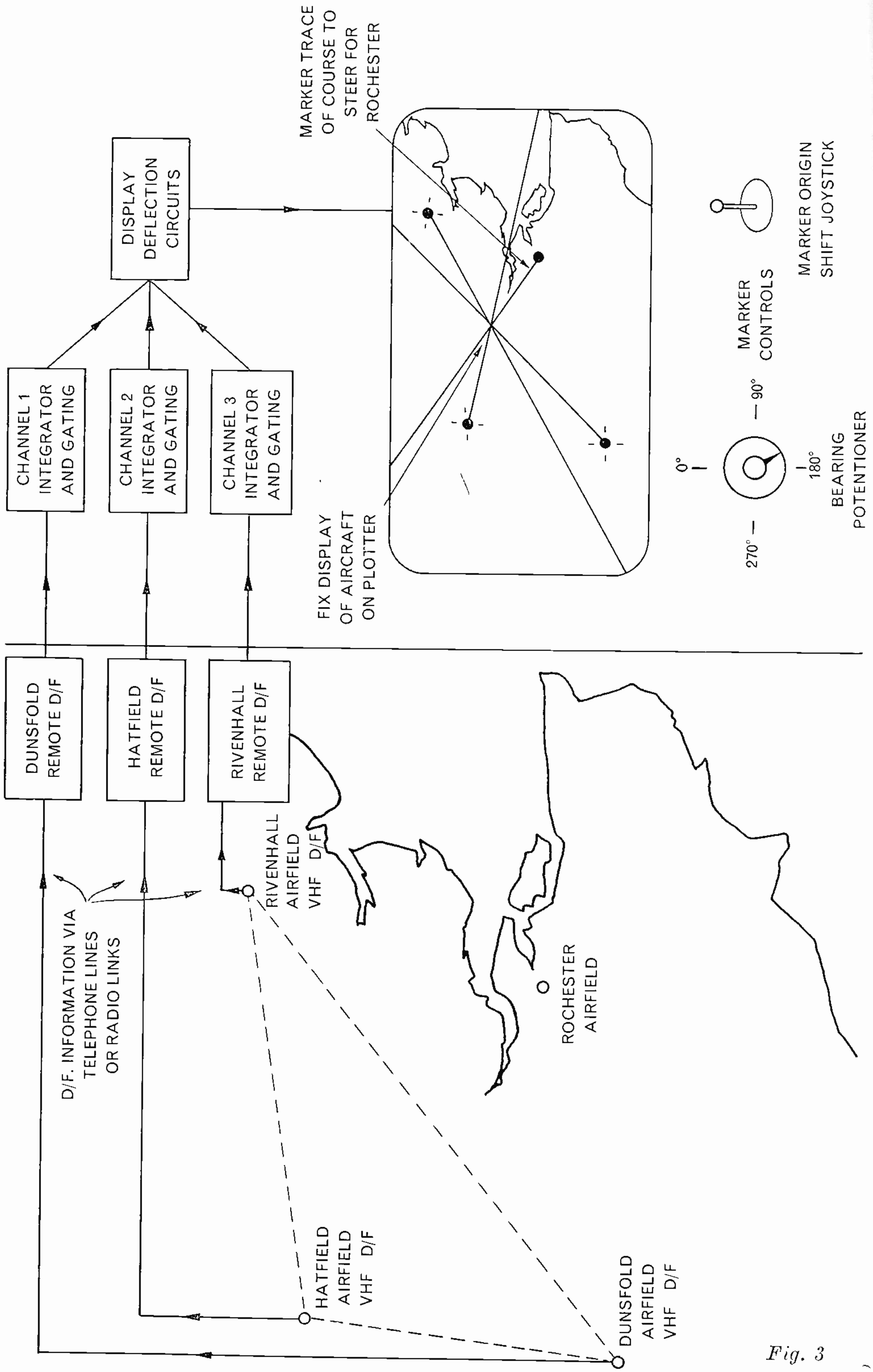

MARKER TRACE OF COURSE TO STEER FOR ROCHESTER
DISPLAY DEFLECTION CIRCUITS
CHANNEL 1 INTEGRATOR AND GATING
CHANNEL 2 INTEGRATOR AND GATING
CHANNEL 3 INTEGRATOR AND GATING
FIX DISPLAY OF AIRCRAFT ON PLOTTER
0°
90°
180°
270°
BEARING POTENTIONER
MARKER CONTROLS
MARKER ORIGIN SHIFT JOYSTICK
DUNSFOLD REMOTE D/F
HATFIELD REMOTE D/F
RIVENHALL REMOTE D/F
D/F. INFORMATION VIA TELEPHONE LINES OR RADIO LINKS
RIVENHALL AIRFIELD VHF D/F
ROCHESTER AIRFIELD
HATFIELD AIRFIELD VHF D/F
DUNSFOLD AIRFIELD VHF D/F

Fig. 3

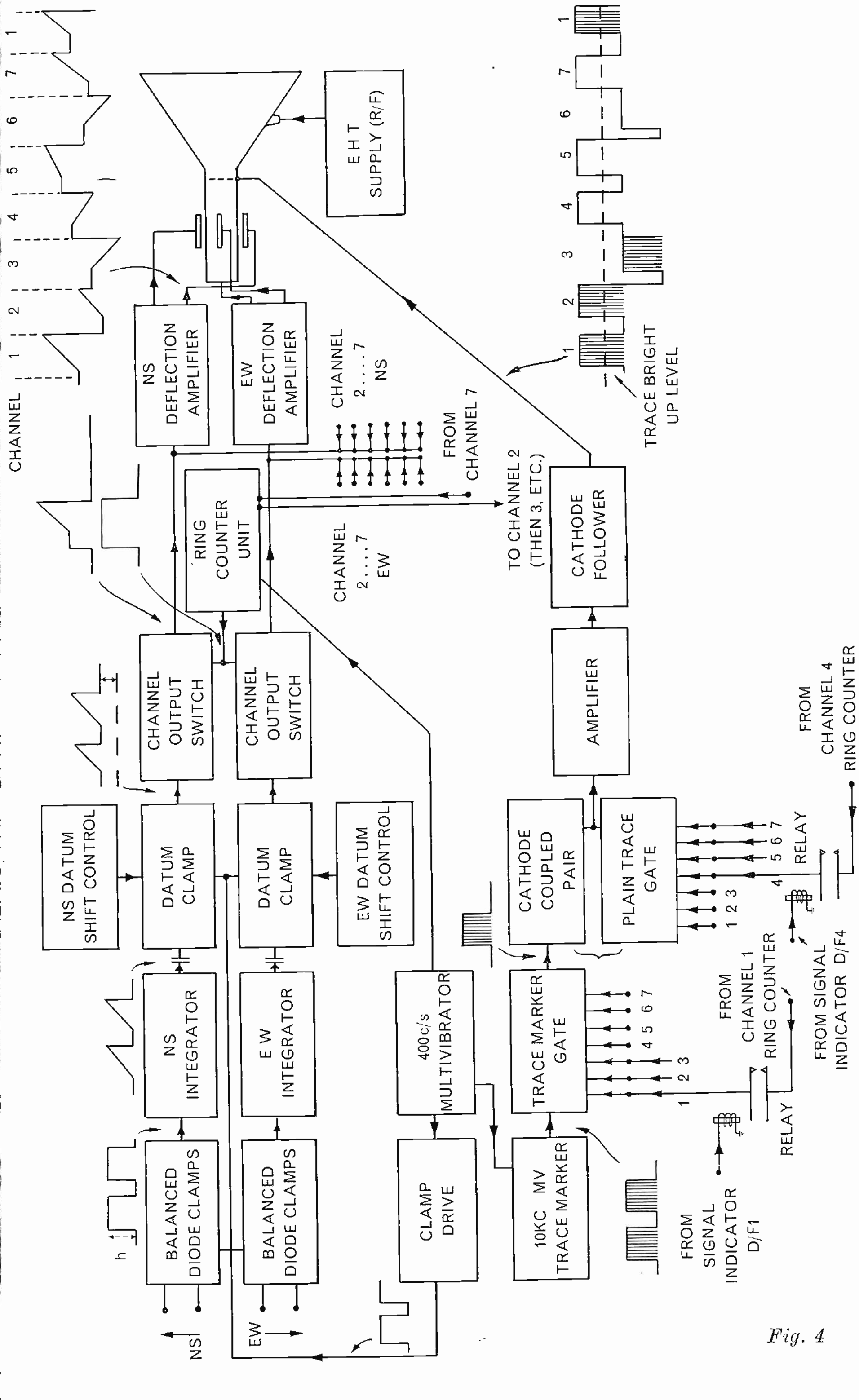

CHANNEL
1 2 3 4 5 6 7 1
NS DEFLECTION AMPLIFIER
EW DEFLECTION AMPLIFIER
E H T SUPPLY (R/F)
CHANNEL 2 . . . . 7 NS
FROM CHANNEL 7
RING COUNTER UNIT
TO CHANNEL 2 (THEN 3, ETC.)
CHANNEL 2 . . . . 7 EW
CATHODE FOLLOWER
TRACE BRIGHT UP LEVEL
CHANNEL OUTPUT SWITCH
CHANNEL OUTPUT SWITCH
AMPLIFIER
FROM CHANNEL 4 RING COUNTER
NS DATUM SHIFT CONTROL
DATUM CLAMP
DATUM CLAMP
EW DATUM SHIFT CONTROL
CATHODE COUPLED PAIR
PLAIN TRACE GATE
RELAY
NS INTEGRATOR
E W INTEGRATOR
400c/s MULTIVIBRATOR
TRACE MARKER GATE
FROM CHANNEL 1 RING COUNTER
FROM SIGNAL INDICATOR D/F4
BALANCED DIODE CLAMPS
BALANCED DIODE CLAMPS
CLAMP DRIVE
10KC MV TRACE MARKER
RELAY
FROM SIGNAL INDICATOR D/F1
h
NS
EW

Fig. 4

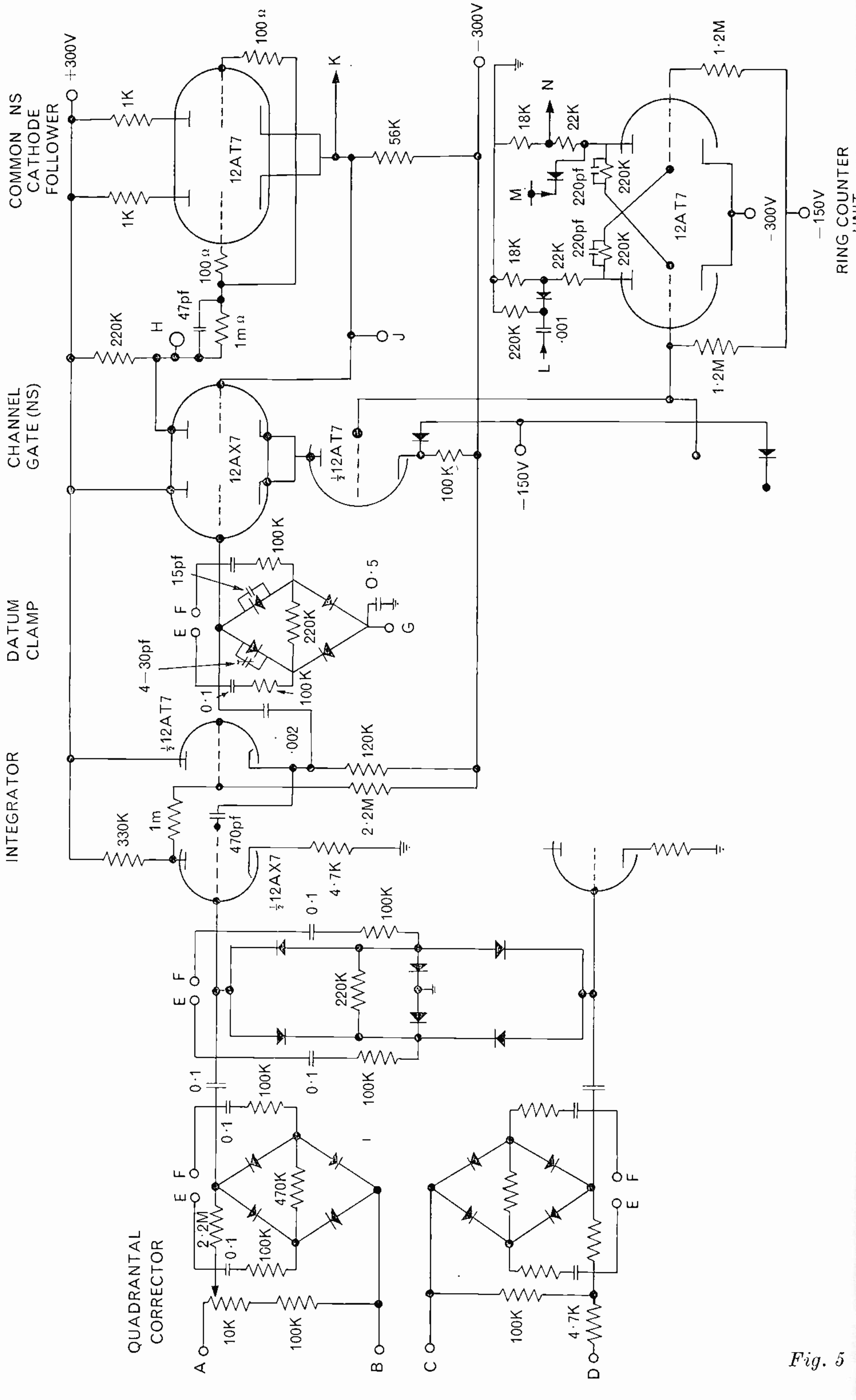

COMMON NS CATHODE FOLLOWER
CHANNEL GATE (NS)
DATUM CLAMP
INTEGRATOR
QUADRANTAL CORRECTOR
RING COUNTER UNIT
12AT7
12AX7
½12AT7
½12AX7
+300V
−300V
−150V

Fig. 5

Fig. 5. One Integrator Unit
Note. NS chain only shown completely. EW chain identical

A, *B* } *NS input from direction finder*
C, *D* } *EW input from direction finder*
E, *F* } *Diode clamp drive*
G *NS datum shift*
H *Common connection to all other channel NS switch valves (anodes)*
J *Common connection to all other channel NS switch valves (grids)*
K *Channel output to NS deflection amplifier*
L *"Switch-on" voltage from preceding ring counter flip/flop*
M *"Switch-off" voltage from common input line*
N *"Switch-on" voltage to following ring counter flip/flop*

Fig. 6. Trace Dotting and Blanking Unit

A *400 cps multivibrator locking pulses*
B *Inputs from ring counters of channel to be "dotted"*
C *Inputs from ring counters of channels "plain"*
D *Output to CRT Grid*

traces on a 17 inch cathode ray tube, suitable for daylight viewing. The skeleton map is applied to the inside surface of the perspex implosion screen, closely covering the tube face, by a photographic process.

There is provision for up to six bearing traces in the equipment, which may come from up to six direction finders on one frequency, or from three direction finders operating simultaneously on two frequencies. Identification between the two frequencies is shown by using plain traces for one frequency and dotted traces for the other.

A seventh trace is also available when required and is controlled by a "joystick" and a knob and pointer calibrated 0-360°. The joystick moves the origin to any place on the map, for example an emergency aerodrome, and the pointer rotates the trace about the origin. Effectively, the marker trace enables the operator to give an aircraft pilot a course to steer to any position on the map.

The accuracy of the fixes naturally depends on the accuracy of the direction finders, and the position of the aircraft. This aspect has been fully dealt with in a paper by R. G. Stansfield*.

THE BEARING CONVERSION SYSTEM

For each trace, the plotter has one integrator chassis. Thus, the complete plotter contains seven similar chassis. One of these is shown in the block diagram of Fig. 4, and in more detail in Fig. 5. The d.c outputs from the NS and EW pairs of the DF for different bearings are approximately as follows:

*"Statistical Theory of DF Fixing" by R. G. Stansfield, M.A, B.Sc, *Journal I.E.E.*, Vol. 94, part IIIA, 1947.

NS Pair		*EW Pair*
N	+ 40 V	0
NE	+ 28 V	+ 28 V
E	0	+ 40 V
SE	− 28 V	+ 28 V
S	− 40 V	0
SW	− 28 V	− 28 V
W	0	− 40 V
NW	+ 28 V	− 28 V

i.e., the NS output varies as a cosine and the EW output varies as a sine.

Referring to Fig. 4, the bearing indicated by the arrows at the inputs of the integrator unit is approximately NW. Taking the NS chain of the channel (the operation of the EW chain is the same), the d.c input is converted into square waves of about 400 pulses per second by diode ring clamps. These clamps are operated by a 400 c/s multivibrator, with a mark space ratio of about 5 : 1. The height h of the square waves formed by the clamps is proportional to the magnitude of the d.c input, and the polarity is the same.

Each square wave is integrated by a Miller integrator to produce a saw-tooth wave, with a slope proportional to the input. A second ring clamp is used to clamp the saw-tooth to the required d.c shift necessary to move the origin of the trace to the position of the DF station on the cathode ray tube face. For the marker trace, the d.c input is provided by a sine/cosine potentiometer, and for the datum shift, the two potentiometers on the joystick.

Immediately an aircraft calls on the R/T, each direction finder on the correct frequency takes a bearing. Thus each channel of the plotter connected to these DF's produces the saw-teeth simultaneously.

The traces, however, are put on to the cathode ray tube sequentially by means of a seven-ring counter. The ring counter is driven by the 400 c/s multivibrator, and by means of channel output gates passes the NS and EW saw-teeth sequentially to the deflection amplifiers. Thus, each trace appears for 400/7 secs. The deflection amplifiers (one for NS and one for EW deflection) are conventional push-pull d.c feedback amplifiers.

The remaining functions are to provide identification of two different frequencies by trace dotting, and to ensure that traces only appear when an aircraft calls. This is also shown in Fig. 4, and in more detail in Fig. 6. A 10 kc/s multivibrator, locked to the 400 c/s master multivibrator, is fed into a trace marker gate. This gate can only be opened when a ring counter square wave is passed to it. Any trace can be dotted, provided its associated ring counter is connected to the trace marker gate. Between the ring counter and the gate is interposed a relay which is closed by information

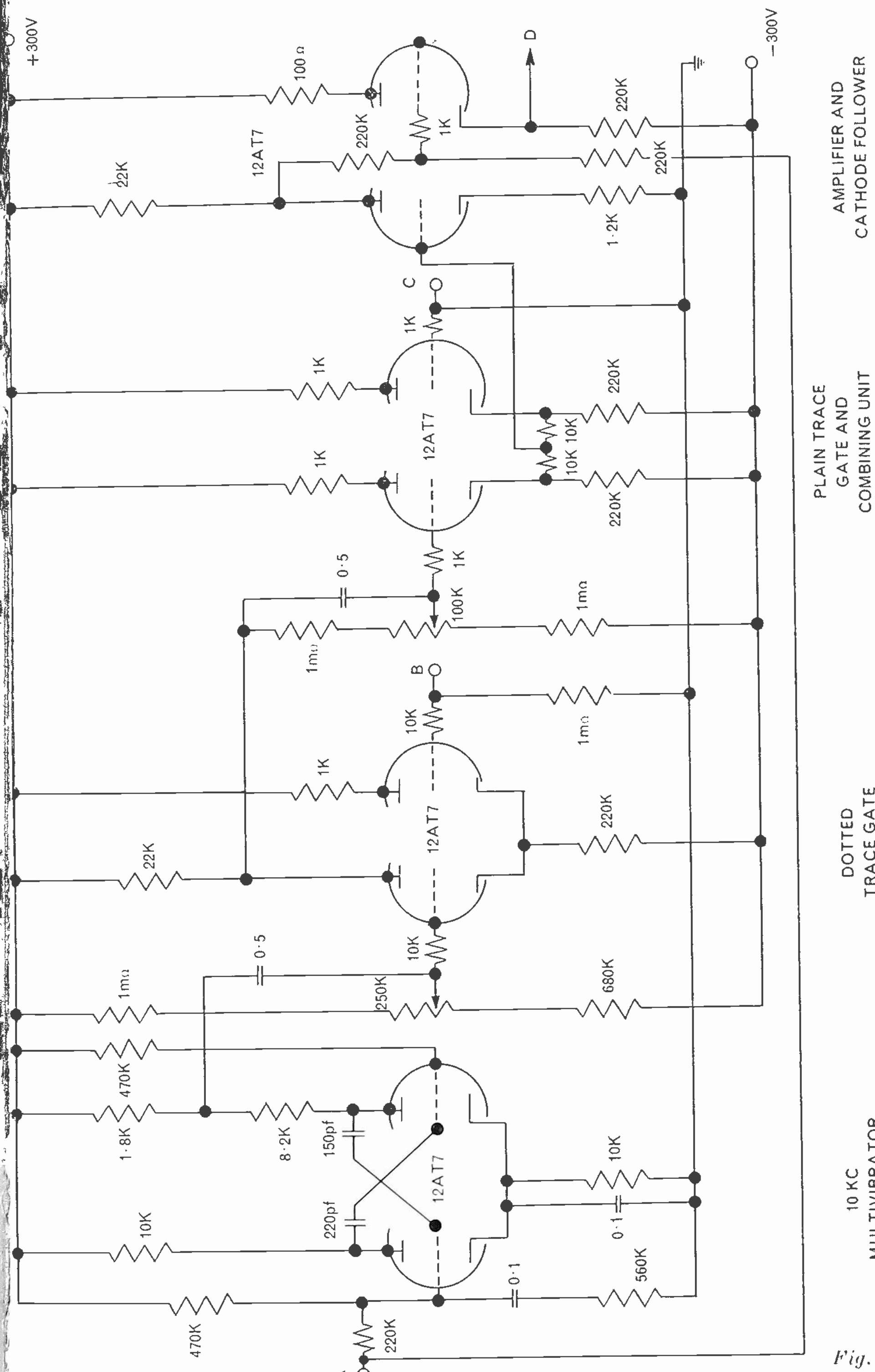

+300V
−300V
D
C
B
A
12AT7
AMPLIFIER AND CATHODE FOLLOWER
PLAIN TRACE GATE AND COMBINING UNIT
DOTTED TRACE GATE
10 KC MULTIVIBRATOR

Fig. 6

from the appropriate direction finder only when the signal strength from the aircraft is sufficiently strong to give a reliable bearing. For a plain trace, the appropriate ring counter is connected to the plane trace gate, and this gate is not provided with 10 kc/s square waves.

The two gates are combined in a cathode coupled pair of valves, the output amplified and fed to the grid of the cathode ray tube. A brilliance control is also incorporated in this circuit. The oscillogram of the trace "bright-up" signal given in Fig. 4 shows channel 1 and 2 dotted, channel 3 blanked, channel 4 and 5 plain, channel 6 blanked and channel 7 plain. Channel 7 is usually the marker trace and its relay is controlled by a switch on the display panel.

RADAR SUPERIMPOSITION

By exactly the same process as outlined above, direction finder traces can be made available on fixed coil radar display tubes. The method used is to allocate every tenth trace to the DF. Thus, if the PRF of the radar is 600, the DF trace is put up 60 times per second. Never more than one in ten of the traces are given, so that if three DF's are used each is displayed 20 times per second.

The effect on the radar intelligibility is negligible, especially as the tenth trace is only given to the DF (a) when the aircraft transmits, and (b) when the radar operator selects the facility.

Radar superimposition is a method of positively identifying a particular aircraft on the radar screen, without providing special responder equipment in the aircraft. The normal R/T transmitter, in effect, takes the place of the responder. Ideally, there should be three suitably placed direction finders, to eliminate ambiguity when two aircraft are on the same bearing.

CONCLUSION

The location of aircraft by means of direction finders has one main advantage. The aircraft need only possess normal communication equipment. Whenever the aircraft transmits, its position can be recorded. The fact that only one aircraft at a time can be accommodated on one frequency is rarely a disadvantage, as this is also true of the communication itself.

ACKNOWLEDGEMENT

The author wishes to thank the Engineer-in-Chief, Marconi's Wireless Telegraph Co. Ltd, for permission to publish this article. Acknowledgement is also given to Mr. K. A. Harrod, who carried out the initial work on the integrator units and display, and to the members of Ground Navigations Aids, who contributed to the design.

BEARING ERRORS IN MEDIUM FREQUENCY AUTOMATIC DIRECTION FINDERS

By R. W. SHARPLES, B.Sc. Tech, Hons, A.M.I.E.E.

number of publications have discussed Direction Finder errors caused by ropagation effects on aerial design. These errors are common to both auto-atic and manual systems. This article analyses a number of causes of error Automatic Direction Finders caused by receiver circuitry and design.

An automatic direction finding system is briefly described below and errors herent in its design discussed under two headings.

The first type of error is that caused by motor torque being produced at the op null position, when the loop should be at rest.

Several different causes of spurious motor input are discussed, with rticular attention to spurious coupling with the loop amplifier stage.

Secondly, errors due to lack of sensitivity in the servo system are analysed d finally the effect of loop input phasing is discussed.

HE AUTOMATIC DIRECTION FINDING SYSTEM

he abbreviation ADF is used in the remainder of this article for the utomatic Direction Finder.

It is necessary before dealing with ADF errors to outline the basic ystem, a block diagram of which is shown in Fig. 1. The system shown mploys an omni-directional vertical aerial and a rotatable loop aerial eared to a two-phase motor.

The basic idea of the ADF is that the signal received by the loop aerial modulated and amplified in the receiver and after detection the modula-on is fed to the loop drive motor. This motor then turns the loop until he latter receives no signal and hence the motor receives no input. This is arried out as follows:

Assuming the loop to be at an angle other than either zero signal osition and to be receiving a CW signal. The signal is amplified in the op amplifier stage and changed in phase by 90° to bring it either in phase r antiphase with the "vertical" or "sense" aerial signal. The signal from he loop amplifier is then passed to an electronic reversing circuit, which used to reverse the phase of the loop at a low audio frequency. The witching frequency could be, say, 100 c/s and in this case the loop signal ould be reversed every half cycle, that is every 1/200th second. The eversing circuit is referred to as the balanced modulator.

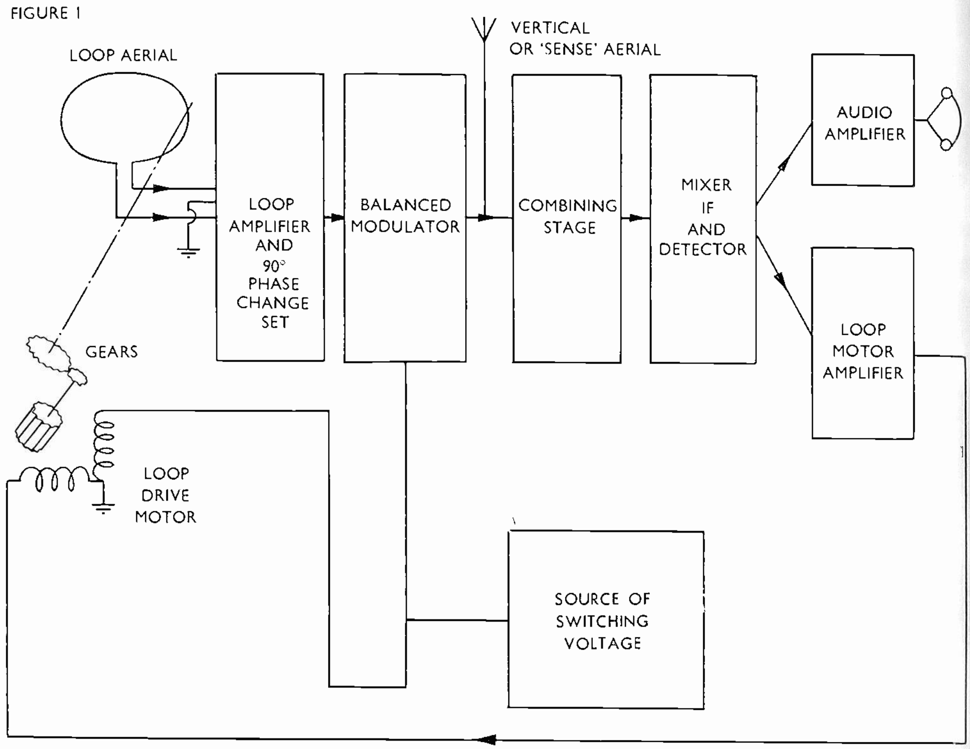
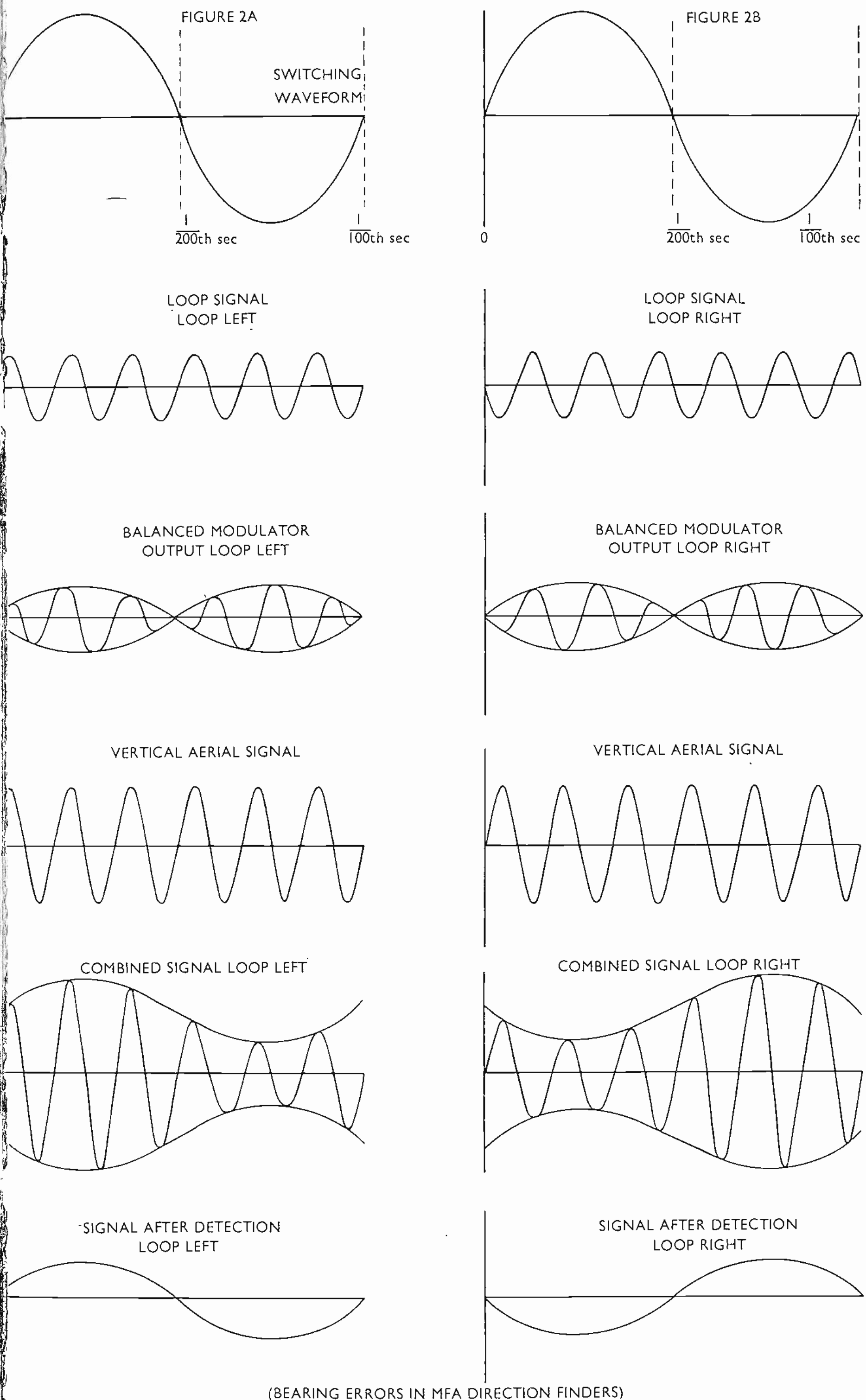


Fig. 1.

The signal from the balanced modulator is now added to the sense aerial signal. This is an unprocessed CW signal and the modulated loop signal will alternately add to it and subtract from it. The result is a carrier at signal frequency modulated at 100 c/s to a depth dependent on the relative amplitude of the loop and sense aerial signals, as shown in Fig. 2a. This signal then passes through the RF, IF and the detection stages of the receiver. The detector output is a 100 c/s signal and is fed to the low frequency amplifier. The output of the 100 c/s amplifier feeds one phase of the two phase motor the other phase of which is supplied via a phase shifting network from the 100 c/s source. The phase shifting network is used to obtain the 90° phase difference necessary between the motor phase currents.

The two inputs to the motor cause it to drive the loop until the loop signal and hence the amplifier output, fall to zero.

If the loop is off the null in the other direction, it will be receiving an RF signal in opposite phase, and as is shown in Fig. 2b, the motor amplifier output will be reversed in phase. Hence, the motor always drives the loop towards one null and away from the other.



Figs. 2a and 2b.

At the null, the signal from the sense aerial remains, but it is unmodulated and will not drive the motor. Speech or other modulation originating at the transmitter may be present, but this has no effect as there is not normally any steady component of the required frequency and phase.

TYPES OF ERROR TO BE EXPECTED

At the loop position where the axis of the loop is in line with the path of the signal being received, the loop, neglecting spurious effects, will be receiving no signal. The loop drive motor should have no input to its signal phase and hence produce no torque.

If, for any reason, the motor does produce torque at the loop null position, the loop will be turned off the null to a position where sufficient opposing torque is produced to cancel the spurious torque and a wrong bearing will be indicated. A second possible cause of error is a lack of ADF sensitivity which causes the motor torque to fall to a level too low to drive the loop before the null position is reached.

All the errors to be discussed fall into one of these two categories.

Consider first the case where the motor is receiving a spurious input to the signal phase with the loop at the null position. The spurious input can be introduced at any point in the chain from the motor amplifier to the loop itself.

SPURIOUS COUPLING INTO THE MOTOR AMPLIFIER

The ADF signal in the motor amplifier is at the low frequency modulation frequency, that is, 100 c/s in the equipment considered above.

The fixed phase of the motor is fed continually from an oscillator at this frequency, so there is a possible source of feed into the amplifier circuits, if any stray coupling is present.

At 100 c/s the impedance of stray capacities is very high and unless the two circuits are very close together, the only source of trouble normally encountered is caused by the common impedance of the HT supply.

The motor fixed phase is often fed from a valve, and as a power of about one watt is required, the HT power pack must have a very low impedance at 100 c/s, if the output valve is not to impose ripple on the HT line.

At 100 c/s an 8μF condenser has a reactance of approximately 200 ohms and, by itself, would be quite inadequate to maintain the ripple at a low enough level to avoid introducing appreciable error voltages in the early stages of the motor amplifier.

Very high capacity electrolytics are one answer to the problem, but it is more economic in space and weight to obtain the separation of the two motor phase circuits by using separate HT smoothing circuits.

PURIOUS COUPLING INTO THE IF AND RF STAGES

Iere trouble can be caused by the modulation of the RF signal by 100 c/s ipple from the fixed phase circuits on the HT line.

Very low depths of modulation can produce appreciable errors. For xample, in an equipment where the loop maximum signal in the RF ircuit is equal to that of the sense aerial, the modulation depth required o produce a 1° error would be (sin 1°) × 100% or 1·75%. This is assuming he worst case, where the unwanted modulation was in phase with the nodulation due to the loop signal.

The precautions already taken to reduce 100 c/s ripple from the fixed hase circuits may be insufficient to reduce this effect to a negligible level nd further filtering of the RF and IF high tension supplies may be ecessary.

PURIOUS SIGNALS IN THE LOOP AMPLIFIER STAGE

his type of spurious signal presents the greatest problem in the design of DF receivers and merits detailed consideration. In a manual Direction inder, precautions are taken to balance the loop aerial in such a way as o prevent it from receiving any signals at its nulls by acting as a normal ertical aerial. Providing this is done and the loop circuits are screened, is only necessary in the manual Direction Finder to have the vertical erial isolated by an effective switch when the bearing is being taken. he sources of coupling into the loop stage are then removed.

In the ADF the sense aerial is connected all the time and all the circuits om the vertical combining circuit to the mixer stage are energised with gnal frequency.

If any of this signal is coupled back into the loop or loop input stage, it ill be present when the loop is at a null, and will cause an error.

Considering again the ADF whose loop maximum signal is equal to hat of the vertical aerial, to maintain the error due to this cause to less han $\frac{1}{2}°$ the isolation between the combining tuned circuit and the loop input ircuit must be more than $\frac{A}{\sin \frac{1}{2}}$ or $\frac{A}{0 \cdot 0087}$ times where A = gain between he two tuned circuits. If, at a particular frequency, $A = 10$, the figure equired is 1150 times. Assuming that the tuned circuits have the same ynamic impedance, this equals 61·5 dBs.

If there is a gain of 30 dBs from the combining circuit to the mixer grid rcuit then the reverse gain between the mixer and loop circuits must e less than −90 dBs to produce an error of less than $\frac{1}{2}°$.

Normal screening does not give this order of protection and to obtain all the forms of coupling known to occur must be studied and reduced eparately to low levels.

Spurious signal can be introduced into the loop amplifier valve along the HT line or the heater chain. The former can be prevented by decoupling and the latter by arranging the heater circuits, so that one side of the loop amplifier heater is earthed.

Circuits where both sides of the loop amplifier valve heater are above earth or earthed at a remote point are unsuitable, as condensers from the heater pins to earth are not of sufficiently low impedance to be effective.

Direct coupling between the later tuned circuits and the loop input tuned circuit is more difficult to prevent. Any one of three forms of coupling can be encountered:

(*a*) MUTUAL INDUCTANCE COUPLING

The amount of mutual inductance coupling present is a function of the spacing and screening of the coils. With miniature coils in cans on a metal chassis, mutual inductance only gives trouble when the spacing of the cans is very close.

(*b*) TOP CAPACITY COUPLING (see Fig. 3a)

This occurs due to stray capacity between parts of the tuned circuits at relatively high RF potentials.

(*c*) COMMON INDUCTANCE COUPLING (see Fig. 3b)

This occurs usually due to the finite impedance of the earth path in the chassis or common earth connections.

Consider the top capacity and bottom inductance cases in more detail.

It was shown above that the separation between the loop and mixer circuits must be of the order of 90 dBs for errors of less than $\frac{1}{2}°$. Allowing a small safety factor for variations from set to set, let us say that 100 dBs is desirable.

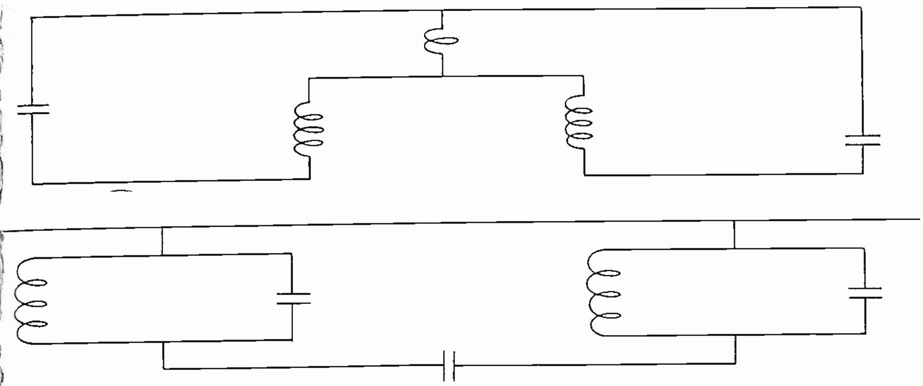
If the Q of the coil is 50, then, since KQ is small, the voltage transfer

$$\frac{E_0}{E_1} \doteqdot KQ = \frac{1}{10^5} \text{ and } K = \frac{1}{50 \times 10^5}$$ where K is the coupling coefficient

between the two tuned circuits. If the tuning condenser is 100 pFs, the stray coupling between the two parts of the two circuits must be less than

$$\frac{100}{50 \times 10^5} \text{ or less than } \frac{2}{10^5} \text{ pFs.}$$

A similar calculation for the bottom inductance case shows that the common inductance must be reduced to one five millionth part of the tuning inductance. In general the capacity coupling can be reduced to the required level by spacing and screening; where incomplete screening boxes are used the size of screen required is easily found by experiment.



Figs. 3a and 3b.

The bottom inductance coupling by common chassis impedances is ficult to deal with experimentally, and here the separation of the circuits ıst be achieved by attention to layout and earthing arrangements.

The ideal arrangement would be to have the tuned circuit complete th their condensers in screening boxes, and only one earth, say at the lve base, so that the valve input capacity which carries some of the nal current, would return to the same earthing point.

In a conventional condenser tuned receiver, the ganged condenser otor is earthed at the condenser, and further all the sets of moving vanes e connected together by the spindle. so that any impedance to earth om the spindle is common to all the tuned circuits.

It is possible to use an insulated spindle or even insulated rotors but r mechanical reasons these solutions are not acceptable.

A compromise has to be adopted, and the most practical is to earth the indle of the condenser at each section by double sets of high pressure ushes to reduce the impedance to earth, then to isolate the coil cans om earth, taking their earth back to the tuning condenser.

If the condenser minimum value is not allowed to be too low, the valve pacitance current will be too small to give a measurable error provided at the arrangement is such that the chassis path from the valve to ndenser gang is short. In a permeability tuned receiver the problem is eatly simplified since the tuned circuit can be a compact assembly, rthed at one point, say the valve base.

The carriage carrying the tuning cores is a common element, but the ores themselves can be insulated from this without difficulty. The wave-ıange switch spindle is common to all the stages, and there is capacitance etween it and the switched line ends of the coils. The capacitances are nall, but errors occur unless the switch spindle is earthed by a low npedance path.

Another type of error signal which produces torque at the loop null osition, can be caused by the effect of an unbalance in the balanced modulator on the receiver noise. This type of error is present only at low field strength, and is characterized by an ADF giving errors which increase or where the signal is reduced until at zero input, the loop revolves continually.

At the balanced modulator the bandwidth is several kc/s and as the ADF bandwidth of motor is extremely narrow the ADF will still function when the signal at the balanced modulator is very small compared to the random noise.

If the balance is good, the noise is modulated but the envelope of the modulated noise is at the second harmonic of the switching frequency and does not have any effect on the loop drive motor. If the balance of the modulator is imperfect, the noise modulation envelope has a component at the fundamental switching frequency. After detection, this will tend to drive the loop motor. The remedy is to use a modulator whose balance does not depend on active elements, but can be set up to a sufficiently accurate balance by fixed high stability resistors.

ERRORS CAUSED BY AN INSUFFICIENTLY SENSITIVE SERVO SYSTEM

If the servo system is to function correctly, it is not only necessary that the gain be adequate, but also that the phase relationships between the AF signals at the servo motor are correct. Considering first the switching frequency signals at the servo motor, the condition for maximum torque from the motor is that the signals on the two phases shall be in quadrature. Phase is not extremely critical, but torque begins to fall measurably when the phase error exceeds about 30°.

This is not a very tight specification to hold, but there are many networks involved, and the phase shift in these depends on the switching frequency. This must be closely controlled, particularly if a narrow band filter is used in the low frequency amplifier.

It can be shown that, when a modulated signal is passed through a series of tuned circuits, the phase of the modulation is retarded. In a typical ADF this retardation may be as much as 60°. This can be taken into account when the bandwidth is fixed, but where variable selectivity is employed either the change in retardation must be compensated or the phase tolerance used to allow a compromise setting to be chosen.

In the combining circuit the phase condition to be met is that the loop and sense aerial signals shall be in phase. From the point of view of servo system sensitivity, the phase criterion here is similar to that in the switching frequency circuits and phase errors up to 30° can be tolerated without noticeable effect. The phase relationship at the combining circuit is important for another reason; a phase error here can, under certain conditions cause an input to the loop drive motor to be produced at the op null position and hence create an error of the type discussed earlier. he error signal is derived from the residual signal present at the loop null e generally to re-radiation of the incoming signal from objects near the op.

Residual signal at the loop null is essentially in phase quadrature to e main signal as the loop is always rotated to the point of zero signal r the component in the correct phase. If the phase relationship at the mbining circuit is correct, the quadrature signal will, after balanced odulation, remain balanced when the vertical signal is added to it.

If the phase relationship is not correct, or if the balance modulator is t well balanced, the quadrature signal will produce at the combining rcuit, a signal with some fundamental modulation, and hence an error.

To avoid this, it is necessary to maintain the loop input circuit tracking d the 90° phase shifting circuit in the loop amplifier as closely as ssible at all frequencies covered by the receiver.

BOOK REVIEW

LEVISION SERVICING *by A. Levy and M. Frankel*

Graw-Hill. Price 43s.

e authors of this book are well fitted to te a book on television servicing. One is ocational high school instructor and the er is an engineer in an electronic main- ance corporation. They have set out to vide a logical approach to their subject considering each section of the receiver turn, outlining the elementary theory t, then basic circuits, and finally the vicing procedure. This method is sound, l the authors have succeeded in compiling ext book which will doubtless appeal to new-comer to the industry in the ited States.

n many instances the publication in this ntry of American text books is a com- ndable practice, and there are a number such books which are standard on both es of the Atlantic. The volume under iew is unlikely to fall within this egory. The instruction is essentially for the nerican student, and is necessarily based the United States television standards ich are quite different from ours. These ferences are so great that the instruction almost valueless to a British student, if leed not seriously misleading.

n the opening chapter, for example, the dent is informed that the distance from e gun to the screen of a cathode ray tube is in. or more, which is certainly not correct with the wide angle tubes (some are less than 9 in. long) now so popular with British television receiver manufacturers. Likewise a block schematic of the picture and sound channels is very misleading, showing as it does the intercarrier system commonly used in the United States but not here. In this system the sound signal is frequency modulated and is passed through the common IF amplifier to the detector. Only at this point does the sound channel start its individual existence. Consequential on the text being based on the intercarrier method and on the use of negative modu- lation, the waveforms given in association with the various diagrams throughout the book are confusing to a British reader. Many of the instructions for servicing are similarly mis-directed in this country. As an example, the statement that a break in the picture chain also stops sound, because the sound picked off is well along the channel, is incorrect. On the contrary, the sound signal in British sets is usually picked off the mixer or, less frequently, the first IF amplifier.

The final chapter on aerials only serves to emphasise the differences between United States and British practice : their aerials must receive horizontally polarized signals whereas we use mainly vertical polarization.

A METHOD OF PROVIDING TEST SIGNALS OF CALCULABLE STRENGTH FOR AIRBORNE RADIO DIRECTION FINDERS

By R. W. SHARPLES, B.Sc.Tech.Hons, A.M.I.E.E.

In this article possible methods of providing signal inputs of known strength for testing medium and low frequency Direction Finders are discussed.

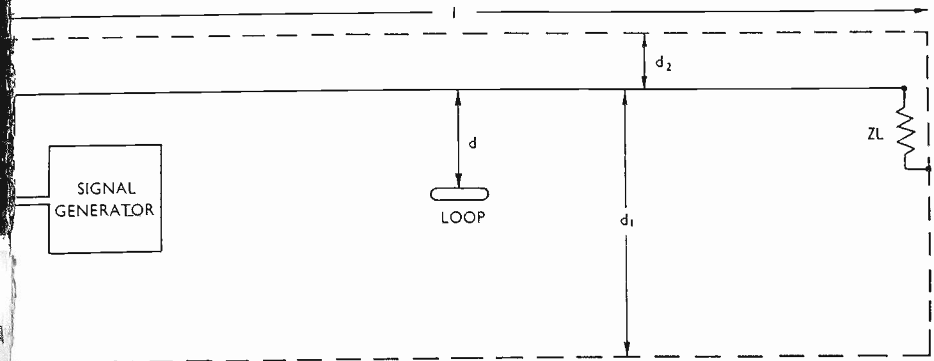
The input to the loop aerial is shown to present the main problem and a method is described in which the loop itself is placed in a magnetic field of known strength. A transmission line carrying a known current is used to provide the magnetic field, the line being mounted inside a screened enclosure.

A formula is derived for the magnetic field strength taking into account all the significant dimensions of the screened enclosure.

Practical results are given which show that the screened volume can be reduced to a size suitable for portable use without appreciable loss of accuracy.

The medium frequency Direction Finder requires two aerial inputs, one to the "sense" aerial terminals and one to the loop aerial terminals. The sense aerial is a capacitative source with an effective height which is constant at all frequencies. This can be represented for test purposes by a capacity potentiometer across the terminals of a signal generator. The output capacity of the potentiometer is arranged to be equal to the capacity of the aerial to be simulated.

The input to the loop aerial must fulfil more conditions if the performance of the loop itself is to be reproduced. The effective height of a loop aerial is proportional to the frequency being received and the polar diagram is a figure of eight pattern with the two lobes of opposite phase. The loop must also be simulated, as a balanced inductive source. Dummy loops consisting of attenuators, transformers and other networks usually referred to as test boxes can be used to simulate the performance of the loop, but are generally secondary instruments calibrated by some more fundamental method. To provide, in a test box, all the facilities required for testing a present day automatic direction finding system would require an elaborate piece of apparatus. Such apparatus would itself be liable to error in the event of a component failure and the fault might not be obvious.



SCREENED ROOM AND TRANSMISSION LINE

Fig. 1.

A method providing a signal at the loop terminals without the above jections is to energize the loop aerial itself by means of a magnetic field known strength. The field near a long wire carrying a current i amps given by the simple formula $H = \frac{i}{2\pi d}$, where H is the field strength in ps/metre and d is the distance from the line in metres.*

This suggests a possible method of providing a field of known strength t a long wire in free space is not readily realizable and it is desirable to form the receiver tests in a screened room to avoid interference from tside fields. A practical arrangement is to make the wire carrying the rrent of the same length as the screened room, and to terminate it in characteristic impedance to avoid standing waves. For convenience e line is placed above head height as shown in Fig. 1.

The current in the line is $i = \frac{V}{Z_L}$ amps where V is the generator voltage d Z_L is the terminating resistor. To calculate the field due directly to e line, taking into account its finite length, Ampere's rule forms a rting point. This gives the field strength due to an element of the line at a point distance r metres from the element as:

$$\delta H = \frac{i\,\delta l \sin\phi}{4\pi r^2} \text{ amps/metre}$$

rom Fig. 2

$$\delta l \sin\phi = r\,\delta\phi$$

erefore

$$\delta H = \frac{i r \delta\phi}{4\pi r^2}$$

$$= \frac{i\delta\phi}{4\pi r} \text{ amps/metre}$$

* MKS rationalized units are used for all calculations in this article.

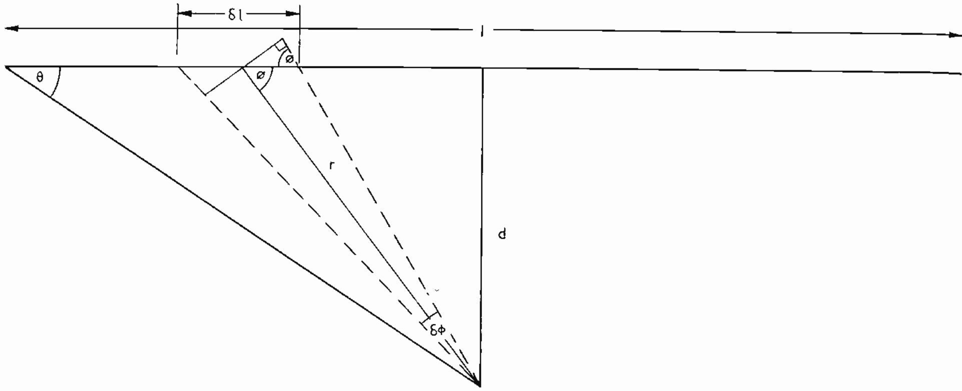


Fig. 2.

Also from Fig. 2, $r \sin \phi = d$

therefore

$$r = \frac{d}{\sin \phi}$$

and

$$\delta H = \frac{i \sin \phi \, \delta\phi}{4\pi d}$$

integrating from $\phi = 0$ to $\phi = \frac{\pi}{2}$ and doubling

$$H = 2 \int_0^{\frac{\pi}{2}} \frac{i \sin \phi}{4\pi d} \, d\phi$$

$$= -\frac{i}{2\pi d} \Big[\cos \phi\Big]_0^{\frac{\pi}{2}}$$

$$= \frac{i}{2\pi d} \cos \theta \text{ amps/metre}$$

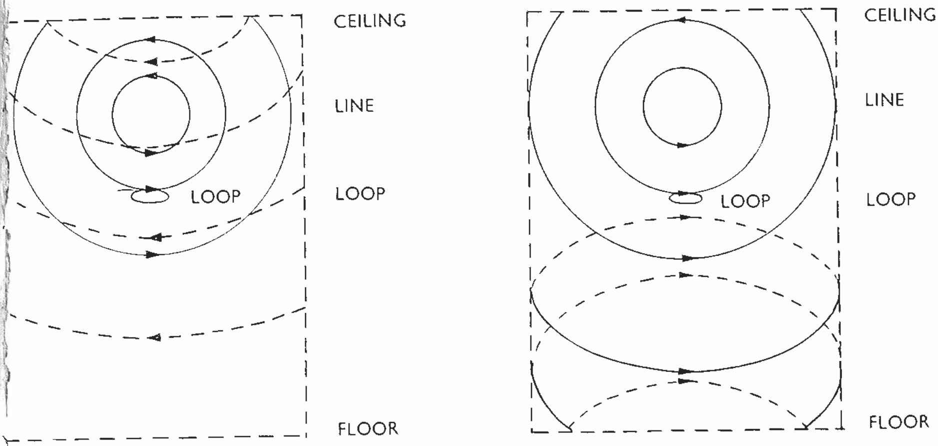
where $\theta = \tan^{-1} \frac{2d}{l}$

This gives the strength of the magnetic field at the loop.

An electromagnetic wave is being simulated and it is usual to quote the field strength in terms of the electric field, that is to say in volts/metre. In free space

$$\frac{\varepsilon}{H} = 120\,\pi \text{ ohms}$$

where ε is the electric field in volts/metre
and H is the magnetic field in amps/metre



Figs. 3a and 3b.

he equivalent field ε is

$$\varepsilon = 120\,\pi \times \frac{i}{2\pi d} \cos \theta \text{ volts/metre}$$

$$= 60 \frac{i}{d} \cos \theta \text{ volts/metre}$$

nd, since $i = V/Z_L$

$$\varepsilon = \frac{60 V \cos \theta}{Z_L\, d} \text{ volts/metre}$$

In addition to the direct field, the field will be reflected from the floor nd ceiling and there will be repeated reflections giving rise to a series of erms in the expression for the field strength at any point.

Fig. 3a shows that the field reflected from the ceiling will oppose the irect field below the transmission line while Fig. 3b shows that the field eflected from the floor will add to it.

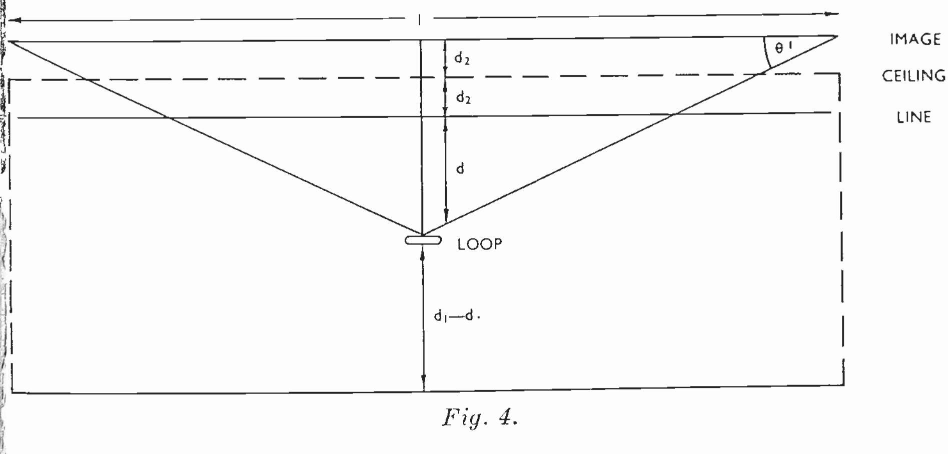


Fig. 4.

Fig 4 shows the image of the line caused by the first ceiling reflection. The field at the loop due to this image will be opposite to that due to the direct field and is therefore

$$\varepsilon' = -\frac{60V}{Z_L}\frac{1}{d+2d_2}\cos\theta'$$

$$\text{where } \theta' = \tan^{-1}\frac{2(d+2d_2)}{l}$$

After reflection at the floor, the same field will produce a second term

$$\varepsilon'' = -\frac{60V}{Z_L}\frac{1}{d+2d_2+2(d_1-d)}\cos\theta''$$

$$= -\frac{60V}{Z_L}\frac{1}{2d_2+2d_1-d}\cos\theta''$$

The series for repeated reflections of this field is

$$\varepsilon_1 = \frac{60V}{Z_L}\left\{-\frac{1}{d+2d_2}\cos\theta' - \frac{1}{2d_2+2d_1-d}\cos\theta'' + \frac{1}{4d_2+2d_1+d}\cos\theta''' + \ldots\right\}$$

If the denominator of the nth term is D_n, then $\theta_n = \tan^{-1}\frac{2D_n}{l}$

A similar series of terms is produced by the field that first left the line downwards. This series is:

$$\varepsilon_2 = \frac{60V}{Z_L}\left\{\frac{1}{d}\cos\theta + \frac{1}{2d_1-d}\cos\theta_1 - \frac{1}{2d_1+2d_2-d}\cos\theta_2 - \frac{1}{4d_1+2d_2-d}\cos\theta_3 + \ldots\right\}$$

Both the $1/d$ and $\cos\theta$ factors are diminishing as the series progresses so that the series are rapidly convergent and in practical cases only the direct term and the first two reflected terms of each series need to be considered.

The resultant expression for the field strength at the loop is

$$\varepsilon = \frac{60V}{Z_l}\left\{\frac{1}{d}\cos\theta + \frac{1}{2d_1-d}\cos\theta_a - \frac{1}{2d_2+d}\cos\theta_b - \frac{1}{2d_1+2d_2+d}\cos\theta_c - \frac{1}{2d_1+2d_2-d}\cos\theta_d\right\}$$

where $\theta_x = \tan^{-1}\frac{2D}{l}$ and D is the denominator of the term.

In order to test the above expression, the calculation was performed for veral screened rooms of different dimensions. In each case the signal nerator output was adjusted to give 1 volt at the line and a square loop low inductance whose effective height could be calculated was placed the correct position. The voltage at the terminals of the loop was then easured directly, using a previously calculated sensitive valve-voltmeter ted with a low capacity probe. Transmission lines of lengths ranging m 2 to 4 metres were used and distances of the loop to the line ranged m $\frac{1}{3}$ to $1\frac{1}{3}$ metres. No measurable error was found in any case, the curacy of the measurements being better than $\pm \frac{1}{2}$ dB.

As a further check, a portable test rig was constructed in which the hole screened room was scaled down to the size of a suitcase. A small ir of Bellini Tosi loops 2 inches from the transmission line were used, d the signal generator placed outside the screening case. As the field so ar the line was curved, the loops were constructed to be of only a few llimetres length. Again the measurement was in agreement with the culated result to within $\frac{1}{2}$ dB.

The portable test rig gave complete facilities for testing Bellini Tosi tomatic direction finding equipments in the medium/low frequency nge except, of course, the testing of full size loop aerials. The width of screened box was not taken into account in the above calculations, cause reflection from the walls cancel if the loop is placed centrally tween the walls. Experiments were carried out to determine the effect reducing the width but no effect was observed so long as the width was t allowed to approach the dimensions of the loop itself.

Memorial to Mr. T. L. Eckersley

A bronze bust of her late husband, Mr. T. L. Eckersley, F.R.S, B.A, B.Sc, M.I.E.E, F.I.R.E, who died in February last, has been presented to the Marconi Company by Mrs. E. Eckersley.

T. L. Eckersley, one of the most brilliant physicists and mathematicians of this century in the field of radio wave propagation, carried out much of his work at the Marconi Research and Development Laboratories at Great Baddow, Essex, where the bust now stands.

At the recent unveiling ceremony, which was carried out by Mrs. Eckersley, the Marconi Company was represented by Mr. F. N. Sutherland (Managing Director), Dr. E. Eastwood (Chief of Research), and by many other senior officials.

The photograph shows Mrs. Eckersley performing the ceremony. Also in the picture are three of Mr. Eckersley's old colleagues, (L. to R.) Mr. G. A. Isted, Chief of Propagation Research Group (Field Studies), Mr. R. J. Kemp (Deputy Engineer-in-Chief) and Mr. G. Millington, Chief of Propagation Research Group (Theoretical Studies).

The bronze was executed by the late Kathleen Scott (Lady Kennett).

September 30th, 1959.

BOOK REVIEWS

SIC ELECTRICITY – IN FIVE VOLUMES The Technical Press Ltd. 12s. 6d. each

ese books cover the groundwork of an nentary course in electricity and have n compiled by a firm of management sultants and graphological engineers for ning the lower grades for the United tes Navy. The course represents an empt to overcome the difficulty of train- men with very little education to carry , with some interest, such work as oper- ng and maintaining electrical equipment.

The general arrangement consists of senting in the most simple language, ential and rudimentary facts about ic electrical concepts and equipment. nultaneously, these are copiously illus- ed by cartoon type drawings. This hod of teaching – doubtless suggested by strip cartoon – is claimed to halve the e normally required for training.

The profusion of drawings is such that suspects the authors were more grapho- cal than technological. Many times oughout the text drawings are repeated h but a trace of reason. For example, in . 1.88, which purports to show four types voltmeter, four identical meters are strated, the only difference being the e beneath each. The student is told that nsformers are used in most electronic and ctrical equipment but instead of showing ew different types of transformer, two- rds of a page are occupied by drawings of five cases of equipment using trans- formers, ranging from an oscillograph to a torpedo. This style of teaching may well be confusing.

In an elementary training manual, it is particularly important that errors or mis- leading statements do not occur. Yet several of the drawings depicting experimental equipment connected to demonstrate some of the elementary laws of electro-technology, show meter readings that do not correspond with the related problems given in the text. The poor student will be left in a quandary as to which answer is the correct one. In Fig. 2.57 the resistance of an electric iron is shown as being more than twice that of a vacuum cleaner and only slightly less than that of a small table radio receiver.

Testing of electrical equipment is des- cribed and many of the instructions will undoubtedly be of value to the tyro. But why advise the testing of transformers with a voltmeter even for a complete short circuit? The authors should try this method themselves when the transformer in question is joined to the mains!

It is difficult to visualize the technician who would profit more by this method of teaching than the conventional method. If he exists – and it would seem that he does – the reviewer doubts whether he would fit into a commercial establishment.

ALYSIS OF LINEAR SYSTEMS *by David K. Cheng*

dision-Wesley Publishing Co. Inc, Reading, Massachusetts, U.S.A,

d 10-15 Chitty Street, London, W.1. Price £3 4s.

is is an excellent book; it can be recom- nded among many which have appeared recent years as a well thought out and nned elementary introduction to the hniques of linear analysis. The author is are of the danger of introducing Laplace nsforms formally, for this often leads to er-reliance on tables of transforms. Hence, book opens with a thorough revision of "classical" methods of solution of linear ferential equations; this provides for an gineer or a physicist a sufficient and familiar background to the more modern techniques which follow. The next two chapters deal with lumped element electrical and with analogous mechanical systems. The principle of electro-mechanical analogy is exemplified on the dual nature of Kirchhoff's laws and the d'Alembert prin- ciple. The chapter on Fourier Series (con- taining a very useful discussion on the symmetry properties) leads to the treatment of Laplace transforms in the following three chapters. The complex Laplace Inversion

Integral is derived from the Fourier integral, but evaluation of Inverse Laplace Transforms is not attempted by contour integration in the complex plane; instead, Heaviside's Expansion Theorem is used. Such simplified treatment is quite sufficient for an elementary textbook.

A valuable introduction to feedback systems includes a clear and original explanation of the use of block and flow diagrams and of their transformations. The Routh-Hurwitz and the Nyquist stability criteria are also included. Sampled data systems are discussed in the next chapter. Here the z-transform and its modified form are introduced in association with linear-difference equations. This is a very use and unique addition to an introduct textbook. The book closes with a sh discussion of systems with distribut parameters.

The tutorial value of this book is grea enhanced by numerous problems students, all of which are provided (a this is surely a welcome novelty) wi answers at the end of the book. It shou prove a useful addition to a college o lecturer's library, while the great divers of problems discussed in the text and offer as examples will make this textbook serviceable vade-mecum for an engineer physicist.

THE CATHODE RAY TUBE AND ITS APPLICATIONS *by G. Parr and O. H. Davie*

3rd Edition. Chapman and Hall, London. Price 50s.

It is hardly surprising that this edition, the third of a book which started life in 1937 as *The Low Voltage Cathode Ray Tube*, has expanded from a small volume into a tome of 433 pages. The advent of broadcast television and radar, with consequential development in techniques relating to the cathode ray tube, have made necessary major additions to the text. As the last edition was published at the beginning of the war, the author was unable to include much information which has since become generally available.

No effort seems to have been spared in preparing the new edition and the revision of material has been drastic. The joint authors have maintained the original object of the book: to present a guide to the use of the cathode ray tube in oscillography. The treatment is almost non-mathematical although a few algebraic equations have been used to aid some of the descriptions. Starting with a chapter on history and development (which seems hardly necessary in a book of this type) the text covers the general constructions and performance of the cathode ray tube, power supplies and amplifiers. The application of the tube to television reception is included, and an outline of the generation of EHT supply from the line time base is given. Energy recovery circuits are not mentioned which is rather a pity because these circuits are now almost universally used in television receivers.

The important subject of time bases dealt with in four chapters, totalling 1 pages, and mechanical bases are describe These chapters are particularly good a comprehensive, and comprise a most eff tive introduction to first principles operation of time bases before passing on description of a wide range of circuits a time base amplifiers. Most of the war-ti developments for radar and allied purpo are outlined. Notes are not given on t Blumlein feedback circuit commonly used television receivers for overcoming t influence, on linearity of scanning, the inductance of the scanning coils, or t leakage inductance of the transformer, in t case of transformer coupling to the amplifi valve.

The last six chapters deal with vario applications. These cover mechanic electrical, radio, television, nuclear physi and miscellaneous applications, and are t least satisfying part of the book. Howeve these notes are probably only intended indicate the versatility of the cathode ra tube as a measuring device rather than t constitute a text for the use of the tube those applications.

The authors are to be congratulated o this new edition; it is well written a illustrated and is recommended with enth siasm to both engineers and students as valuable guide to principles and circuit associated with the cathode ray tube.

NSCHWINGVORGÄNGE IN DER NACHRICHTENTECHNIK

ANSIENT RESPONSE IN COMMUNICATION TECHNIQUE) *by Dr. V. Fetzer*

ta Verlag, München, also Verlag Technik, Berlin, 1958.

; book deals with mathematical teches for the analysis and synthesis of e shaping networks.

he author makes use of the latest netk theories as well as developing the er techniques to make them applicable he stringent demands of modern systems.

book contains 350 pages including an nsive appendix, useful tables and some graphs and sketches and several illustra- examples with practical solutions.

he approach to each problem is supted often by the brief and concise vation of formulae from fundamental ciples, a treatment which should be h appreciated by those students and neers who have but little acquaintance ı Laplace transforms and Fourier sforms. Fundamental theorems concern- Fourier and Laplace transforms, integral niques, Bode's method of using Hilbert ion between real and imaginary comnts of network functions, are briefly particularly well presented in a clear ner.

his book opens with a discussion of rier analysis and synthesis, and the ler will immediately appreciate the hematical and electrical treatment of cepts relating to spectrum analysis, contion integral and the superposition ciple.

he following section on the application hese mathematical tools is demonstrated various well-chosen examples of response icial, transient, delay, amplitude and se) of networks to different electrical ulses. These are shown diagrammatically explain very well the associated matheical formulae.

The practical part of the book starts with simple low pass and high pass structures and proceeds with more complex equalizers, resistance-capacitance amplifier stages and long line behaviour, all of which are treated in a very clear and concise manner. The mathematical theory concerning indicial and transient response is supplemented by a description of the Samulon method based on the response of ideal filters. The practical application of the method is treated rather briefly, but some design charts are provided.

The treatment of phase or delay characteristics is based mainly on the Bode relation between phase and amplitude functions. Though well illustrated by graphs, tables and formulae, it seems that too little space is given to the practical limitation of the Bode method. However, the details can be seen in the worked examples; a particularly useful example is that of the vestigial filter, the design of which is briefly treated. This example illustrates particularly well the approximate effects of in-phase and the envelope components, which is treated in some detail in the section concerning amplitude modulated system.

Throughout the book the author's emphasis is rather on the design of amplifiers and staggered tuned circuits with variable Q-factors, and their transient response, and the large number of examples makes the book particularly valuable for students.

The author is well known as a specialist in network synthesis and has contributed much in the field of filter design and transient response; the contents of his book, though concise, reflect long theoretical and practical experience in this important subject.

TAL RECTIFIER ENGINEERING

E. A. Richards. Sir Isaac Pitman and Sons Ltd. (209 pages). Price 37s. 6d.

; book sets out to provide an introduc- to metal rectifiers which are playing an increasing role in the electrical and tronic industries. Although it is based elenium rectifiers, most of the contents be applied to any metal rectifier such as copper oxide, copper sulphide, gernium and silicon rectifiers, whose construction and characteristics are discussed. It is a pity that only 3% of the book deals specifically with germanium and silicon rectifiers and that there are few direct comparisons between the various types.

There are chapters dealing with the construction and characteristics of rectifiers, basic rectifier calculations, electrical and mechanical design of stacks, transformers for use with rectifiers, design of rectifier equipment, rectifier harmonics and smoothing, with a final chapter on special applications which include spark quenching and the charging of capacitors from either a single or three phase supply.

Unfortunately, the author died before finishing this work and his son should be commended for his efforts in arranging for its publication. There are, however, parts which lack the finished touch and the reader will find it annoying to be given cross references without being given either the page number or a suitable index; it was tedious to have to search for tables 1, 2 and 7.

References would have been very useful, especially after such remarks as ". . . results have been published . . ." (page 68) and "No attempt is made in this work to describe the complicated physical pheno ena of rectification, for which the reade referred to more competent authoriti (pages 3 and 4).

A glossary of definitions and symbols the beginning would have been help because a number of the formulae are self explanatory. The use of comparativ such as "higher" and "greater" with indicating the degree, should be avoid Fig. 1.1 (page 2) is almost meaning without having scales on its axes.

Although this is not the only book wh has been written on metallic rectifiers, should prove useful to those who interested in their practical application. is hoped that, in a second edition, pa numbers on cross references as well as m information on germanium and sili rectifiers will be included.

ANALYTICAL TRANSIENTS *by T. C. Gordon Wagner*

Chapman and Hall Ltd. Price 70s.

Prof. Wagner's book could be successfully used as a sequel or the next stepping stone in the study of linear systems, following an initial course on elementary techniques. The author states that it represents the means of acquiring the more advanced mathematical knowledge necessary for greater understanding of network analysis, Fourier series and Laplace transformation; an elementary acquaintance with all these subjects is presumed. The choice of topics for more advanced treatment betrays a well-tested teaching experience; although the subject matter looks at the first sight rather like a personal anthology, a closer study will show that it includes most of the more difficult, but essential, topics.

Thus the chapter on Fourier series includes a lucid explanation of the Gibb's phenomenon as a consequence of a particular optimization process, convergence problems and sampling theorems. Fourier integral provides a logical introduction to the Laplace transformation where the initial transient behaviour and disconti ities in driving functions are treated detail. Chapters on network anal include many interesting problems, wh stability theorems are clearly formula with the help of the Cauchy's principle the argument. It is a pity that the aut does not introduce the z-transforms plicitly, in view of the well-established c vention in the technical literature; "step" notation used in the book is cumb some and even misleading.

The final chapter gives enough of complex variable theory to understand Laplace inversion integral and transient transmission lines.

The problems set as exercises are v original and carefully chosen. This sm book (200 pages) should provide a stimul ing reading for more mathematically min engineers and physicists, especially th who are not satisfied with incomplete log arguments and dislike holes in mathemati proofs. It is a pity that the price is so hi