Improved V

Improved VOR Antenna Design Using the Image Ground Approach

by

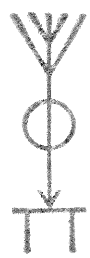
Jonathan B. Scott

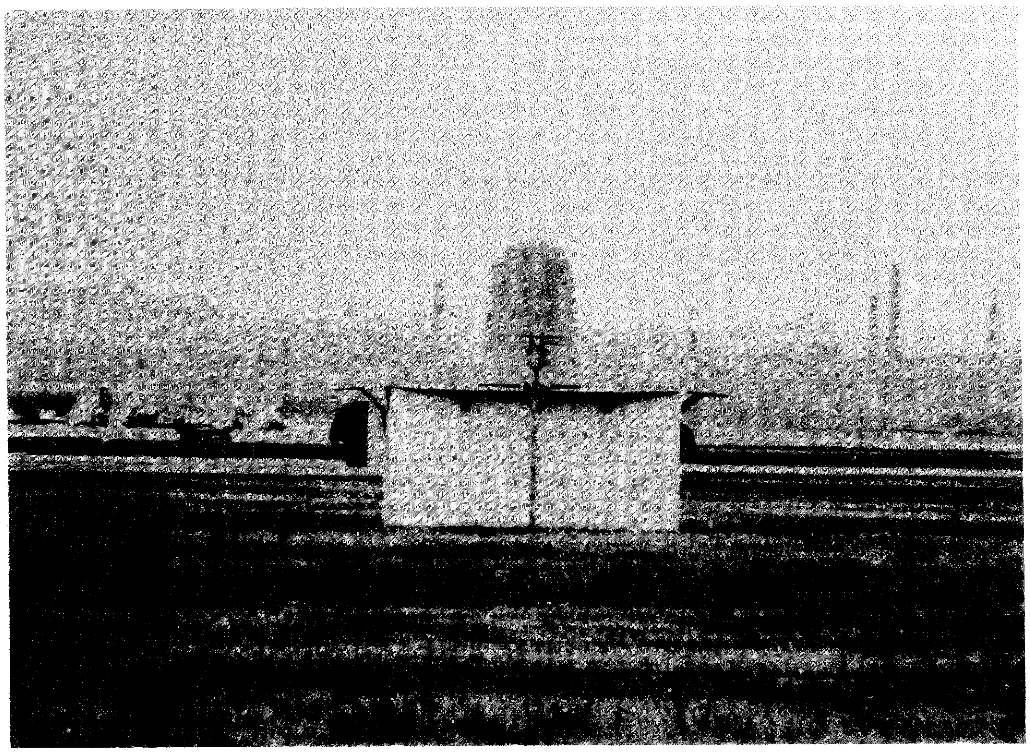
Submitted for

The Degree of

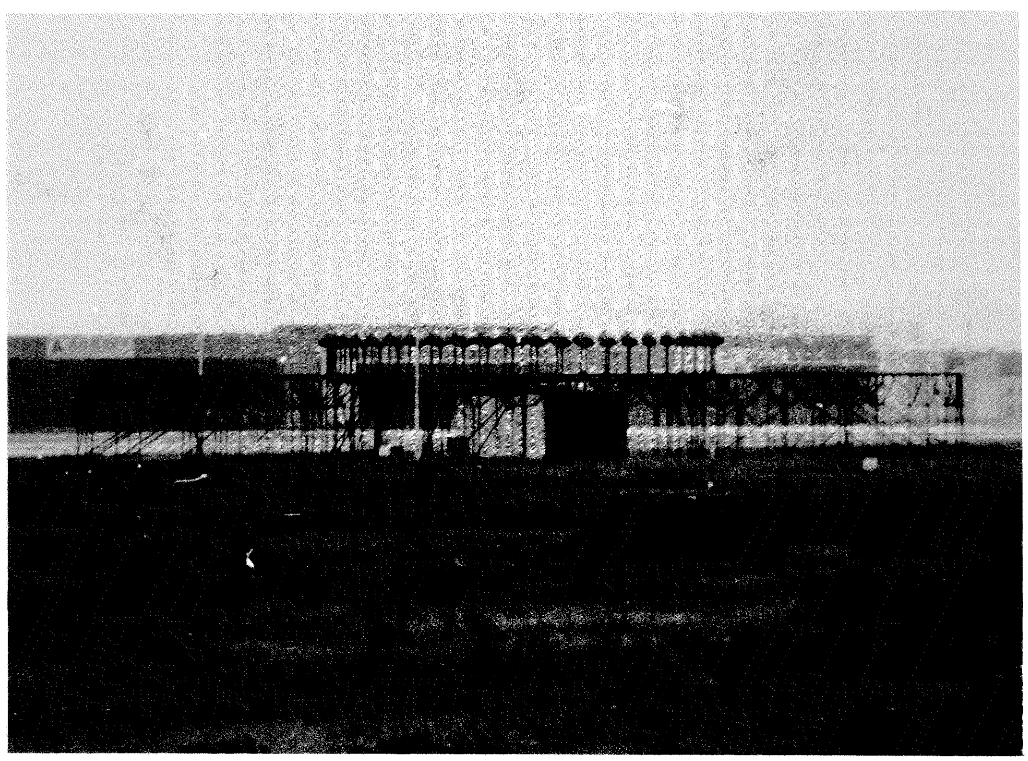
B. Eng. (Elec.) (Hons.)

November 1978





THE VOR AND DVOR AT MASCOT AIRPORT



IMPROVED V.O.R. ANTENNA DESIGN

USING THE IMAGE GROUND APPROACH

by

Jonathan Brereton Scott

Submitted for

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ABSTRACT

The operation of the VOR is outlined and the antenna systems which have been used at different times described. The main remaining error source is discussed and the current course of action taken in severe situations is reviewed. An alternate approach involving substantially less excess cost is available but work to date gives insufficient theory to allow a suitable antenna array to be selected. Furthermore, currently available methods cannot be used to predict array performance as they require approximations which are too coarse in this situation. A new theory for array selection is described and the improvement it affords demonstrated. Finally, the significance of the contribution to the far field from non-ideal ground currents in a small counterpoise is noted.

CONTENTS

ACKNOWLEDGEMENT

This work is fundamentally a reapplication of the ideas which led to the 3G and 4G I.L.S. arrays which were developed by Dr. J.G. Lucas and Mr. A.C. Young of the Air Navigation Group. On account of both this and their continued and valuable assistance I would like to thank both of the above. I would also like to thank all the A.N.L. members for their patience, help and good company, and also Mr. Eric Mills and Mr. Gordon Weiss for their technical assistance, Ming for his typing and proofreading, and Brazil for the coffee.

J.B.S.

November 1978

"... Let no-one else's work evade your eyes -
Remember why the Good Lord made your eyes,
So don't shade your eyes, but Plagiarise -
But always be sure to call it 'Research'."

- Thomas Lehrer -

GLOSSARY

The following terms occur frequently in air navigation antenna theory and are assumed to be understood in the text:

ARRAY: Set of aerials, frequently in a simple pattern (e.g. a straight line or square).

C.A.A. Civil Aeronautics Administration - the American body that sets aeronautical standards.

COUNTERPOISE: The metallic artificial groundplane placed below an antenna; usually the roof of the equipment hut in the case of a VOR.

DRIVE: This can mean either the actual hardware element or the complex number conveying amplitude and phase data about its current feed. Which of these is meant is usually clear from context.

GONIOMETER: Mechanical analog R.F. multipole distribution device analagous to the distributor in a car. It is used to derive the cyclically varying amplitude feeds for a VOR.

GROUNDPLANE: General term including counterpoise, surface of the earth etc. Again, meaning is usually clear from the context.

I.C.A.O.: The body that makes international Navaid performance specifications.

OMNIDIRECTIONAL RANGE: Device which can fixa craft's course at any azimuth angle rather than one which can only guide on a fixed set of courses (e.g. 2).

SCALLOPING: The cyclically varying error produced by multipath effects.

SCOOPING: Rapid reduction in field strength of the far field as one approaches some angle.

1.1 INTRODUCTION

A great deal of interest and enthusiasm has recently been seen with the introduction of the new Microwave Landing System (M.L.S.) and in particular the new Interscan System which has been adopted as the international standard. Such systems, it is hoped, will improve the quality of the information supplied to pilots to aid them in guiding the aeroplane. There are however many navigational aids in existence which were standardised some years ago. Though adequate in many situations, the technology available when they were adopted is now quite outdated. Over the years there have been many changes made to improve performance, yet still further improvement is desirable[4].

The Very High Frequency Omnidirectional Range (VOR) is one such system. Some 1700 VOR groundstations were operational in 1968, servicing over 100,000 airborne receiving sets, for small and large craft[1]. This work discusses the VOR and one serious remaining shortcoming, and investigates a design change which both improves performance and is relatively simple to implement. The proposed modification is developed from theoretical considerations and its effect verified by computation and experiment.

1.2 THE OPERATION OF THE V.O.R.

During the 1930's VHF frequencies were coming into more common use, and had been adopted for speech communication to aeroplanes, since the Line of Sight (LOS) range of this band was greatly increased by the high altitudes being used[1]. The Civil Aeronautics Administration (CAA) at this time felt that it would be desirable for navigation to be incorporated into this band and was also seeking an omnidirectional range to assist in coping with the growing amount of air traffic. An omnirange using the fundamental principle of the present VOR was first described by Luck[2] in 1939. The VOR was refined and adopted in its present form as the American Standard in 1946, and as the International Standard in 1949[1,4].

The standard VOR[1,3,5,6,7] operates between 108 and 118 megahertz, radiating a total signal which may, at the receiving end, be decoded to give the bearing (azimuth angle) of the receiver from the groundstation. In concept a simple antenna radiates an omnidirectional reference signal, as well as a beam which is arranged to rotate. The point in time at which the beam points towards the receiver is a function of the direction of the receiver from the base. This time is determined with respect to the reference signal (see Fig. 1.1).

The omnidirectional part carries an Amplitude Modulated (AM) signal identifying the station, as well as conveying any spoken message associated with the installation and finally a 9960 Hz Frequency Modulated (FM) audio reference subcarrier. The beamed signal appears at the receiver to be an AM signal whose phase varies with azimuth, and since the rotation speed is set at thirty revolutions per second, this produces a 30 Hz component in addition to those mentioned

VOR SIGNAL FIELD PATTERNS

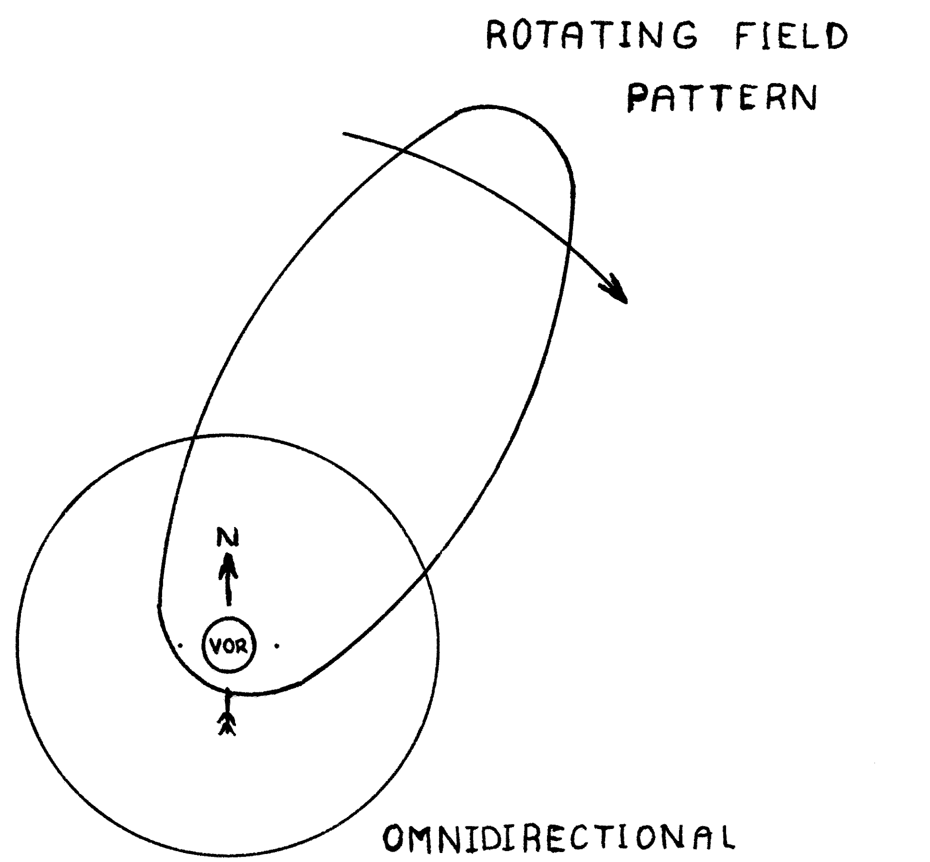


FIGURE 1.1

above. These components are seperated within the receiver to give firstly the information signal (speech) to the pilot, and secondly the two signals at 9960 and 30 Hz for the direction deciding circuitry. The FM 9960 Hz signal is passed through a discriminator and the phase of the 30 Hz signal thus obtained is compared to the AM 30 Hz signal to give azimuth bearing information.

Formally, the radiated reference signal may be written as the typical amplitude modulated signal:

$$E_r = \cos \omega_c t \, (1 + m\cos(\omega_r t + B \cos \omega_s t)) \qquad \ldots\ldots\ldots 1.1$$

where $\omega_c = 2\pi f_c$

f_c = Carrier frequency (typically 115 MHz)

$\omega_r = 2\pi f_r$

m = Subcarrier modulation depth (standardised to 0.3)

$\omega_s = 2\pi f_s$

f_s = Frequency of rotation (30 Hz)

B = Modulation index of sweep frequency on subcarrier (16 for 480 Hz deviation)

So also the variable phase AM signal can be written:

$$E_v = k.\cos \omega_c t.\cos(\omega_s t - \emptyset) \qquad \ldots\ldots\ldots\ldots 1.2$$

where k Establishes the ratio between variable and reference signal strengths

$\emptyset$ = Azimuth angle (from North)

Thus the total theoretical (desired) signal may be written:

$$E_r = \cos \omega_c t \left[1 + m.\cos(\omega_r t + B.\cos \omega_s t) + k.\cos(\omega_s t - \emptyset) \right] \qquad \ldots\ldots\ldots\ldots 1.3$$

The two major remaining factors limiting the accuracy of the information the pilot has available are the ability of the receiver to accurately determine the phase difference between received signals, and the susceptibility of the AM variable phase signal to errors produced by multipath effects. The latter of these is considerably more important as it is a property of the VOR and its fixed environment, while the former is a limitation of cost and complexity of any particular receiver.

Consider the situation where there is some reflecting object such as a hill or wooded area on which the signal from a VOR is incident (See Fig.1.2). There arises a second, reflected signal at the receiving position. The resultant "multipath" signal is the sum of direct and reflected signals. The reflected signal may be written as:

$$E_m = G.R.\cos(\omega_c t - d)\left[1 + m.\cos(\omega_r t + B.\cos\omega_s t) + k.\cos(\omega_s t - \theta)\right] \quad \ldots\ldots\ldots 1.4$$

where G = The fraction of the direct signal strength from the VOR to the receiver which is incident at the reflection point

R = The reflection coefficient of the reflecting object

d = Phase delay of the reflection path relative to the direct

θ = Azimuth angle to the reflecting obstruction

Now, if E_m arrives in phase quadrature to E_r it will phase modulate the signal; as the receiver is purely AM, this phase modulation will have negligible effect. However, if E_m arrives exactly in phase (or exactly 180 degrees out of phase) the signals will add (or subtract) (See Fig. 1.3). The worst case of d = 0 will be considered.

Let the receiver be at azimuth angle zero, and the reflector at azimuth angle θ. Then, the multipath signal E_{TM} will be given by:

$$E_{TM} = \cos\omega_c t\left\{(1 + G.R.)\left[1 + m.\cos(\omega_r t + B.\cos\omega_s t)\right] + k\left[\cos(\omega_s t) + G.R.\cos(\omega_s t - \theta)\right]\right\} \ldots 1.5$$

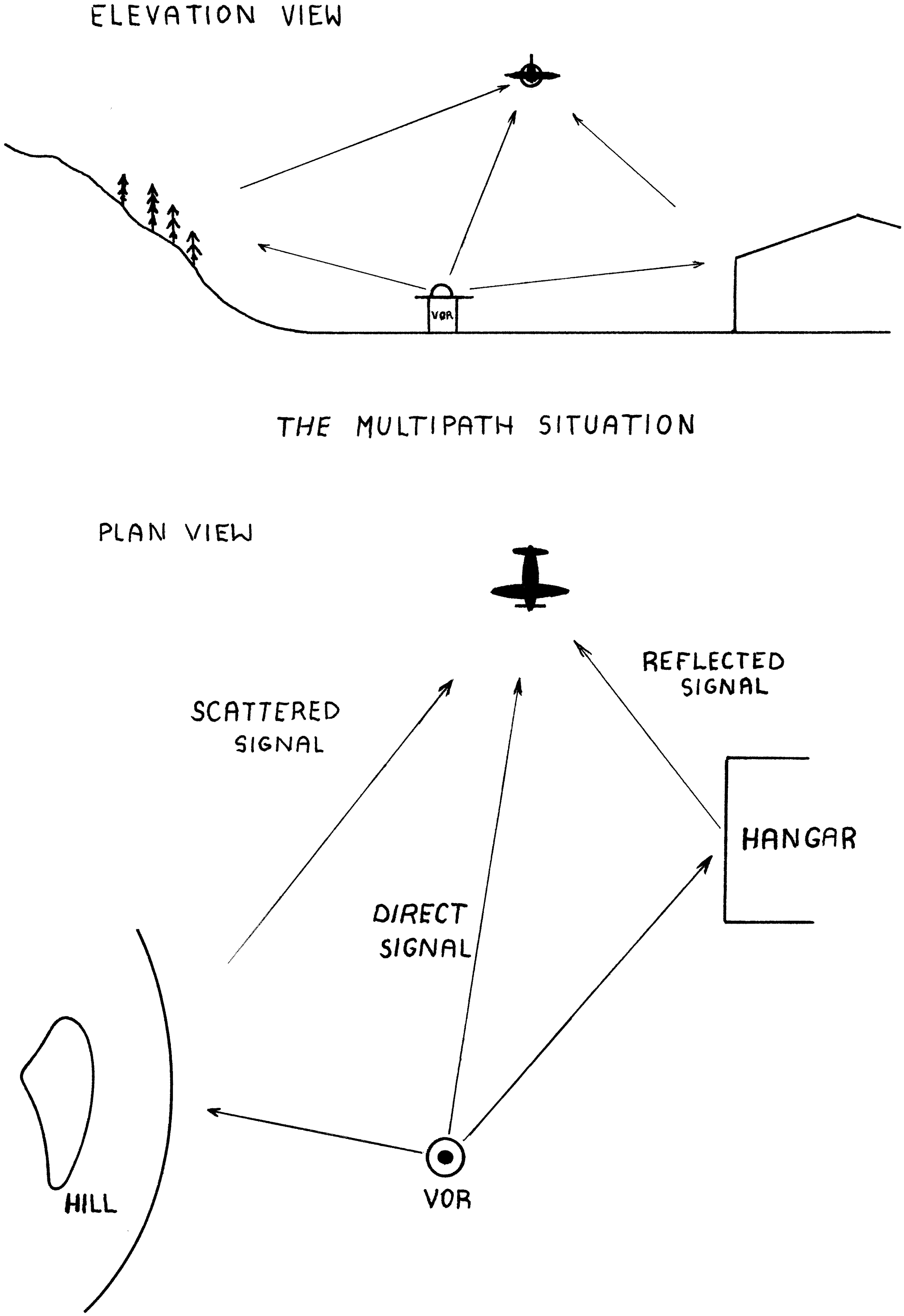
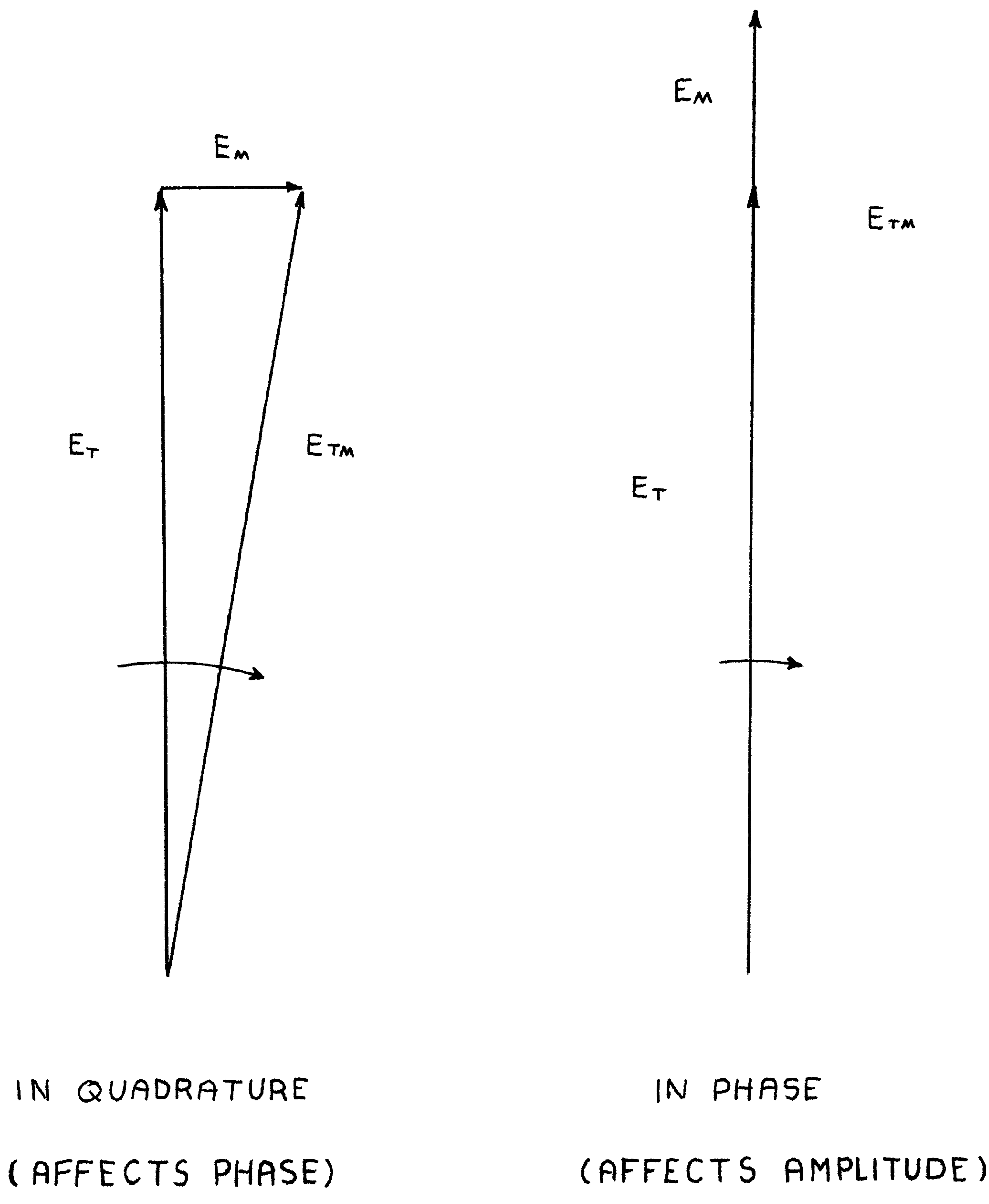

ELEVATION VIEW
VØR
THE MULTIPATH SITUATION
PLAN VIEW
SCATTERED
SIGNAL
REFLECTED
SIGNAL
DIRECT
SIGNAL
HANGAR
HILL
VOR

FIGURE 1.2



E_M
E_T
E_{TM}
E_M
E_{TM}
E_T
IN QUADRATURE
(AFFECTS PHASE)
IN PHASE
(AFFECTS AMPLITUDE)

FIGURE 1.3

It may be seen that the amplitude of the subcarrier has been changed marginally but that its phase is unaltered, owing to its omnidirectional radiation (which results in both receiver and reflector seeing the same phase of modulation). This is not true of the variable component, however. Now, the interfering signal contains different phase data, since the reflector is on another bearing from the VOR and thus introduces an error:

$$\cos \omega_s t + G.R.\cos(\omega_s t - \theta)$$

$$= \cos \omega_s t\,(1 + G.R.\cos\theta) + G.R.\sin\omega_s t.\sin\theta$$

$$= \text{constant} \times \cos(\omega_s t - e)$$

where e = Phase error

$$= \arctan\left(\frac{G.R.\sin\theta}{1 + G.R.\cos\theta}\right) \qquad \ldots\ldots\ldots 1.6$$

It may be shown that e is maximal when

$$\theta = \arccos(-G.R.) \qquad \ldots\ldots\ldots 1.7$$

R is first estimated as 0.2. As will be shown shortly G might typically be **a half**. With these values the error is a maximum of $5\frac{3}{4}$ degrees when θ = 96 degrees (See Fig. 1.4). This is called scalloping error. Scalloping error of more than two or three degrees is unacceptable, and some reduction would be demanded. This might be achieved by clearing the site of the offending obstruction, if it can be identified, or by installation of a higher accuracy and more reflection-immune 'wide aperture' VOR ground station. Alternately, this reflection error could be dealt with by controlling the signal intensity incident upon the reflector. This method of dealing with siting errors has certain advantages, and is the approach with which this work is concerned.

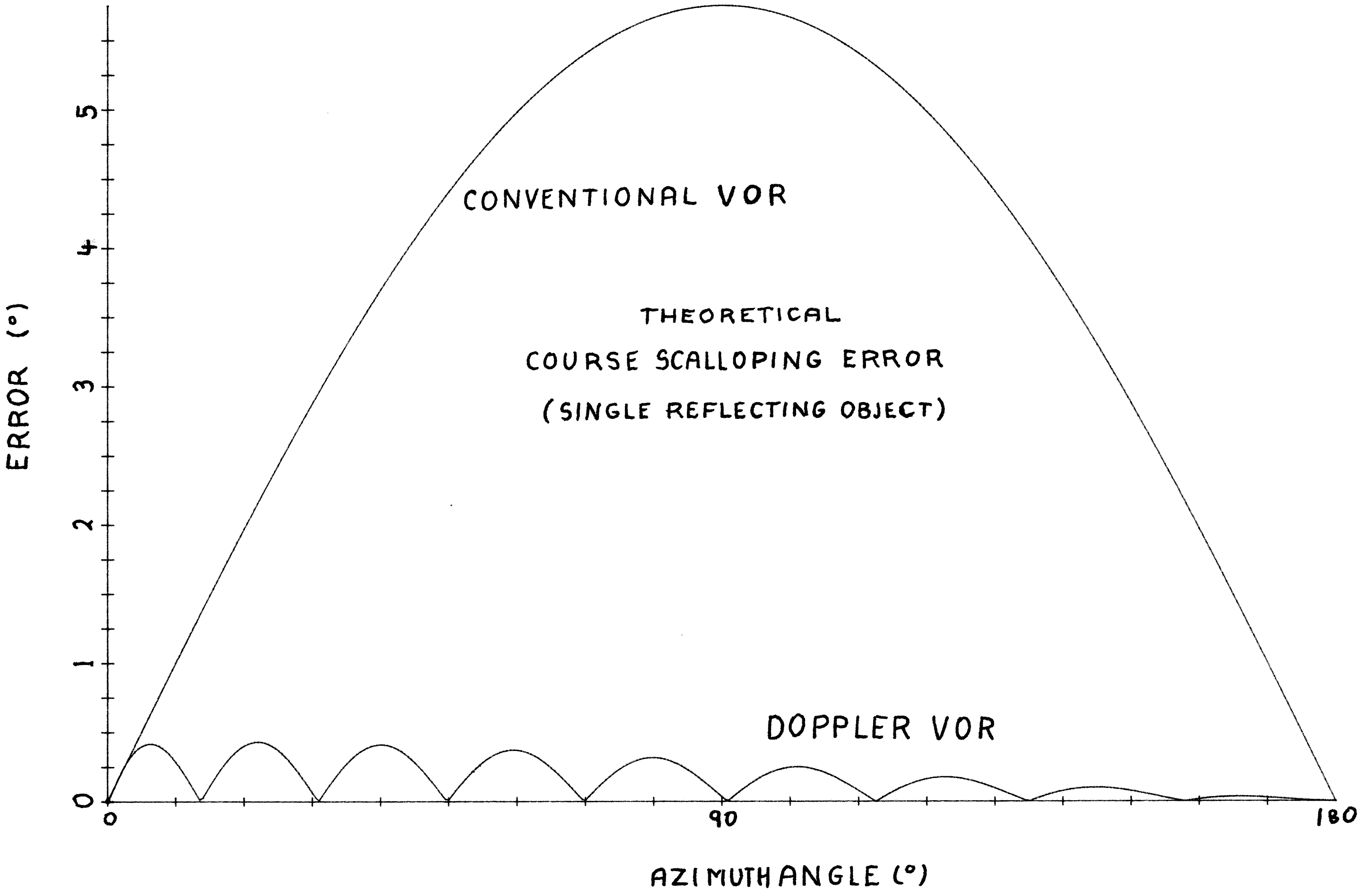

CONVENTIONAL VOR
THEORETICAL
COURSE SCALLOPING ERROR
(SINGLE REFLECTING OBJECT)
DOPPLER VOR
ERROR (°)
0
1
2
3
4
5
0
90
180
AZIMUTH ANGLE (°)

FIGURE 1.4

1.3 THE VOR ANTENNA[3,6,13,16]

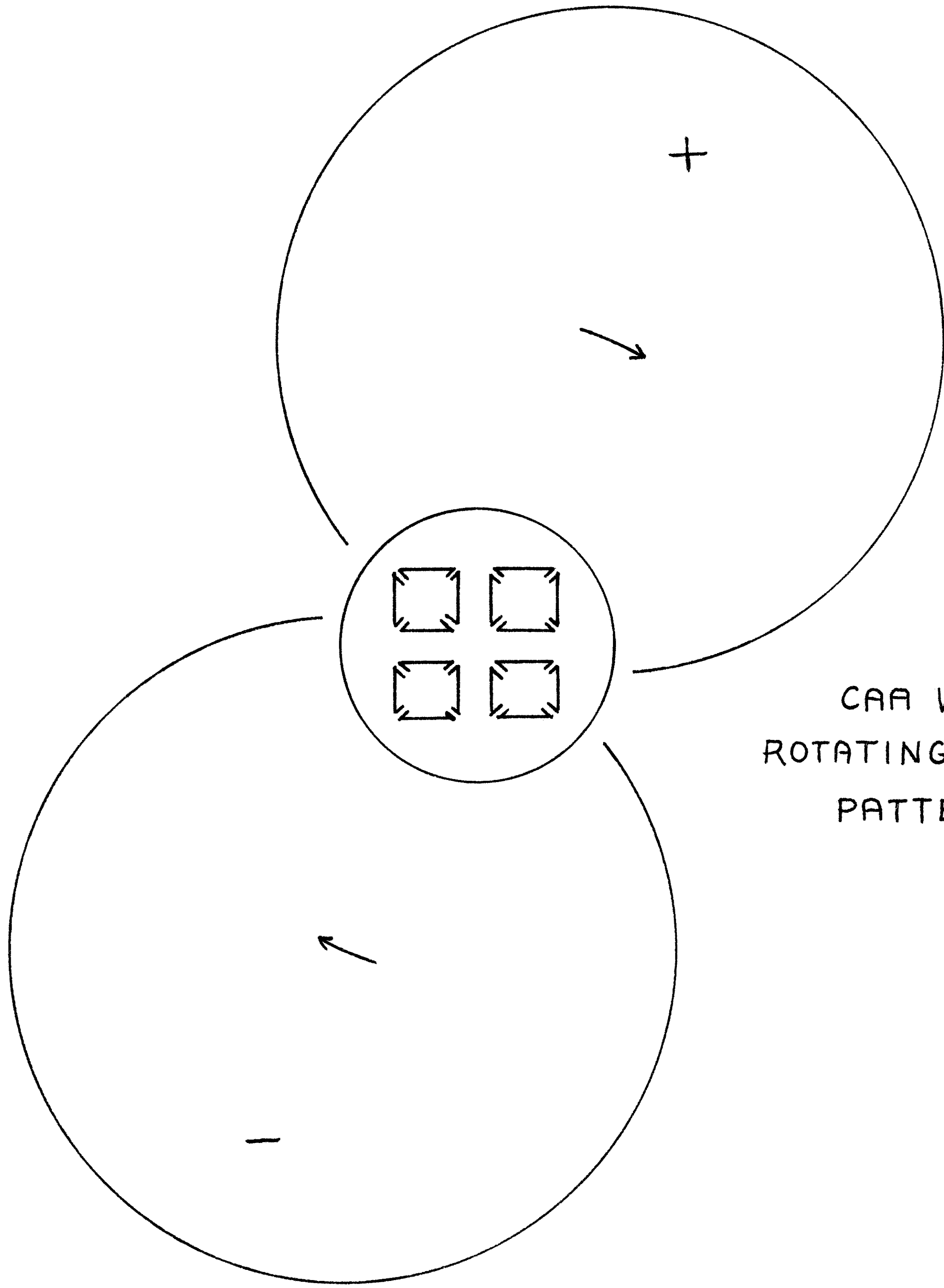
There are three basically different forms of VOR aerial system. It can be shown[16] that four omnidirectional aerials placed at the corner of a square are able to produce a rotating beam when fed by the appropriately varying amplitude signals. The beam adds to an omnidirectional signal in the forward direction, and subtracts in the reverse. The original CAA standard used Alford Loop antennas as the omnidirectional radiating elements, and employed one to radiate the reference signal, and four to achieve electrical rotation of the directional beam (See Fig. 1.5). The four small squares represent the Alford Loop antennas, which will be discussed in more detail in a later chapter. They may be taken[15] as small circular wires carrying uniform currents. It was soon observed that if fed in a suitable manner, the fifth omnidirectional antenna was redundant, as the four could carry its function as well as the beam producing signals.

The second form of VOR aerial system used a mechanically rotated dipole to simplify feed arrangements and to reduce unwanted vertical polarisation. This latter point was achieved by enclosing the now much less bulky aerial in a cage structure[6]. Discs forming part of the cage structure doubled as radiators of the omnidirectional reference signal. This form did not become common as the advantages of simplified feed did not outweigh the complications of rotation and in addition vertical polarisation problems were brought to an acceptable level in the alternate antenna designs.

The third form uses electrical rotation, and hence has need of the more complex varying amplitude signals derived from a goniometer assembly; however, it uses radiating slots in a cylindrical structure rather than Alford Loops (See Fig. 1.6). The omnidirectional signals are radiated from a separate pair of Alford Loops. This approach has several advantages. Firstly it is more compact and manageable, being tall, thin and substantially one single unit rather than a set of units requiring careful positioning. Secondly the unwanted vertically polarised signal is inherently smaller than in the loop design. The preference for this final form is evidenced by the existence of two companies manufacturing it and by its adoption as the standard here in Australia.

Now one aspect of the design has been neglected in all of the above systems, that is, the effect of counterpoise dimensions. The original Alford Loop design specification did not demand a particular counterpoise radius, though it discussed the effects of the height of this counterpoise from the ground, and specified the aerial placement above the centre of the counterpoise[3]. It was designed empirically (such parameters as polarisation being chosen by testing the alternatives), and it was pushed through quickly to try and make up for the time lost due to the Second World War. Counterpoise radius was chosen without great thought, and size dimensions of 1 to 3 wavelengths (3 to 8 metres) were settled upon. The height of the antennas above the counterpoise was chosen to produce a signal null directly above the VOR and to minimise the width of this signal null (See Fig. 1.7). This zone is referred to as the 'cone of confusion' since a craft loses meaningful signal when directly overhead; it is clearly desirable to have as small an ambiguous region as is practical.

The slot design was developed with almost as little consideration for the elevation pattern. Manufacturers' specifications quote suggested counterpoise radii of 1 to 2 wave-

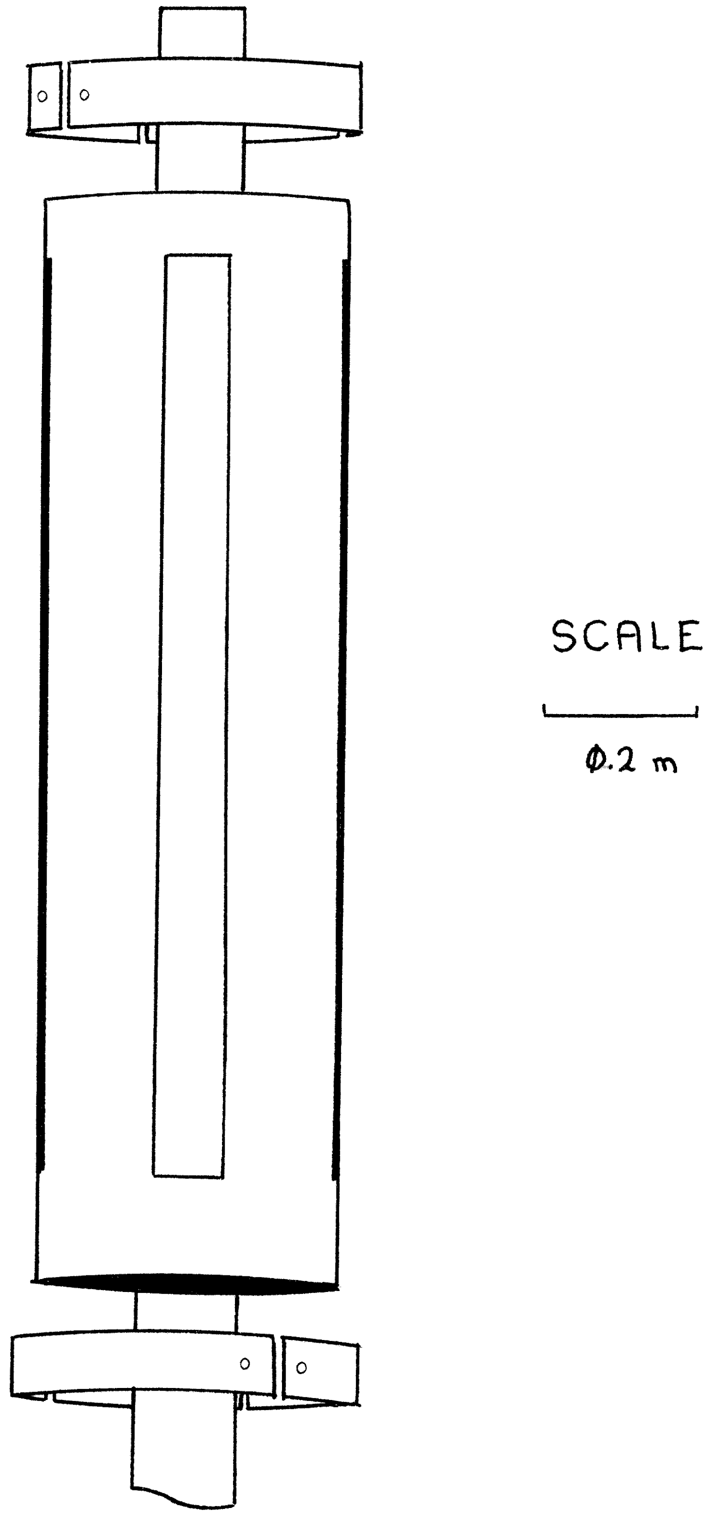


CAA VOR
ROTATING FIELD
PATTERN

TYPICAL SCALE

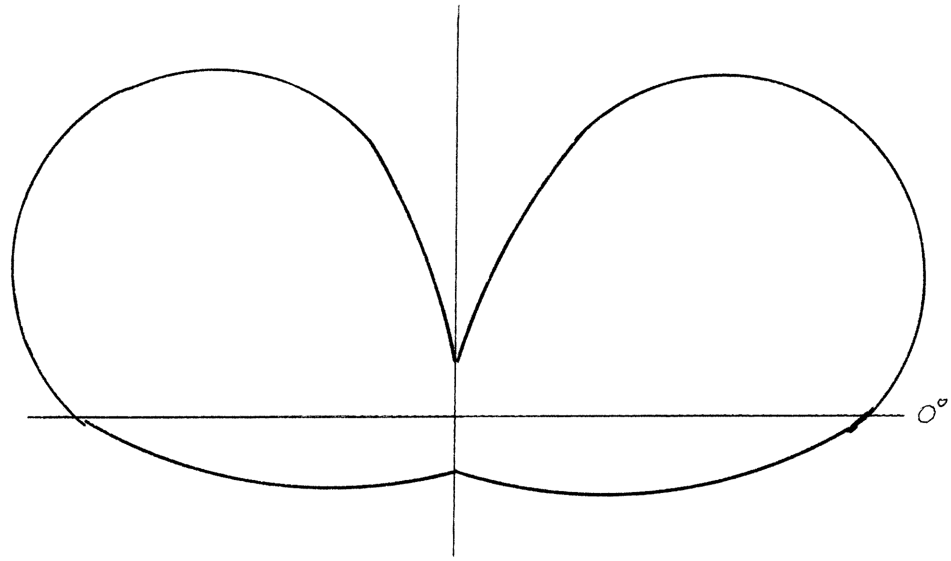
1.5 m

FIGURE 1.5



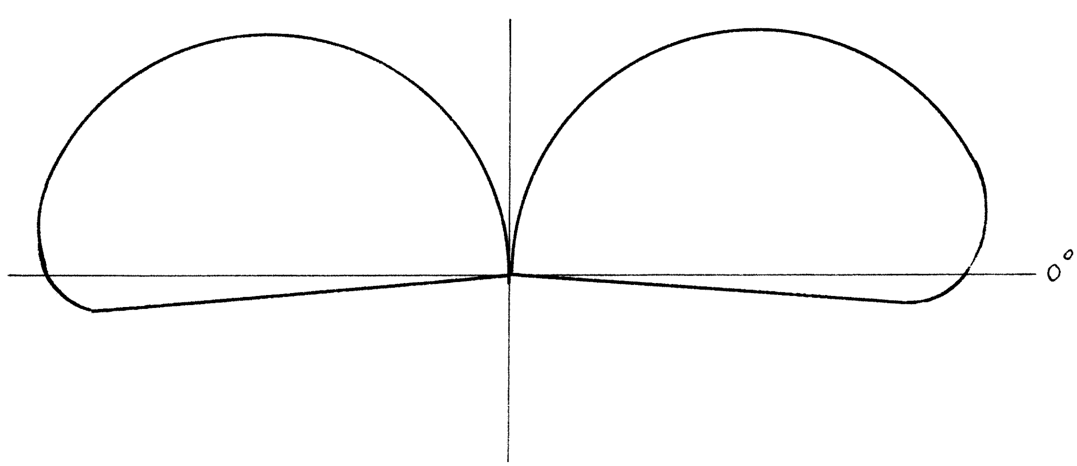
VOR CYLINDRICAL SLOT AERIAL

FIGURE 1.6



FORM OF TYPICAL VOR ELEVATION PATTERN

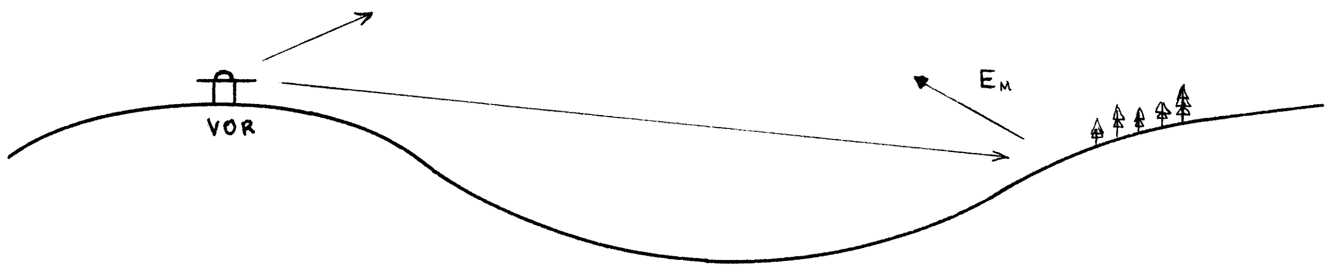
FIGURE 1.7



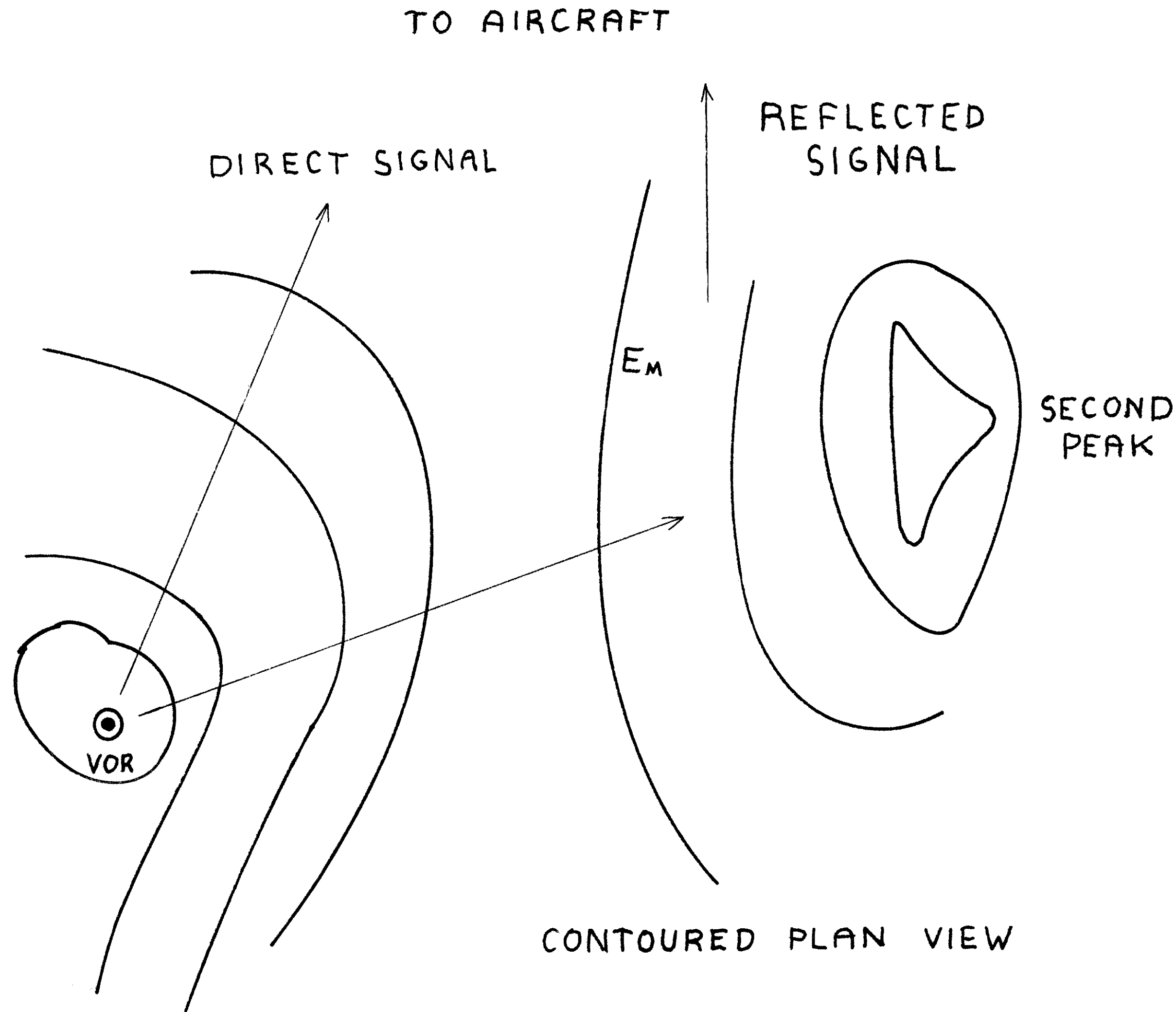
A DESIRABLE VOR ELEVATION PATTERN

FIGURE 1.8

lengths, once again determined by the cone-of-confusion considerations, and with little concern for the amount of signal transmitted with large angles of declination[13]. Such arrangements fell seriously short[10] of the ideal radiation pattern of a VOR, which resembles more the pattern of a horizontally polarised antenna above an infinite ground plane[17] save that it has some signal just below zero degrees, to illuminate a craft immediately above the horizon (See Fig. 1.8). As a result a significant amount of the radiated power is beamed in a direction where it can be of no use, and where it may give rise to multipath effects. Such situations are not uncommon, particularly with en-route VOR installations not located near an airport, or with VOR systems positioned away from and possibly above the cleared area associated with runways. A site such as that depicted in Fig. 1.9 has severe multipath problems arising from signal radiated well below the horizontal. Such a site is presently dealt with by abandoning the standard VOR and installing a Doppler VOR (since clearing the obstruction is out of the question). This alternative is now reviewed.



TYPICAL SEVERE VOR SITE



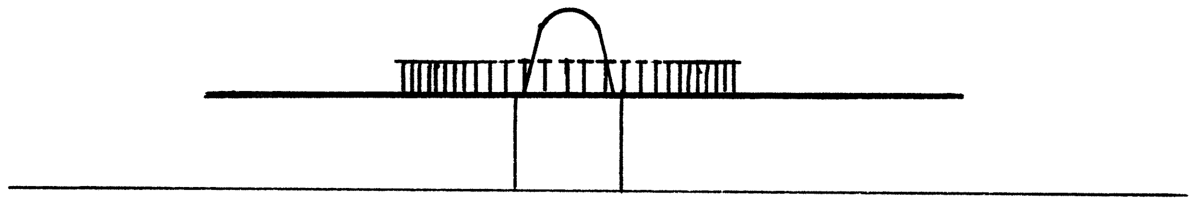
CONTOURED PLAN VIEW

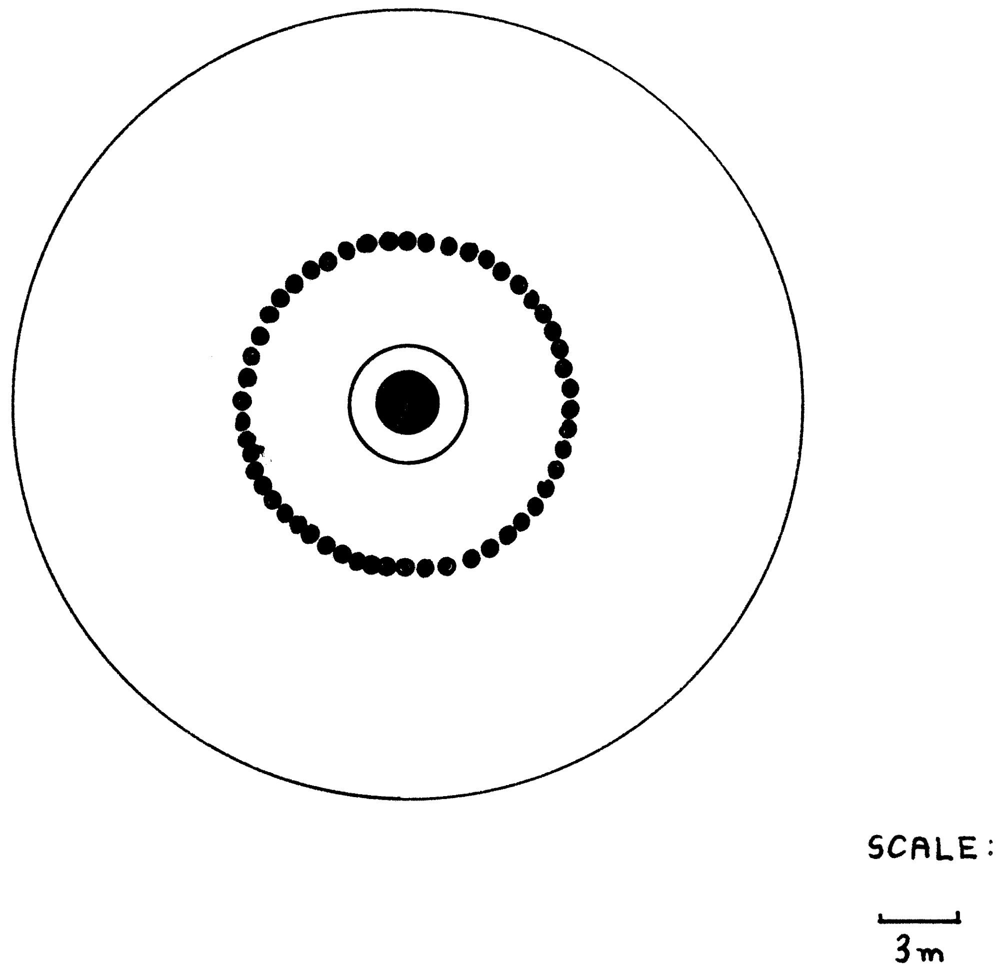
FIGURE 1.9

1.4 THE DOPPLER VOR[7,8,9]

The DVOR avoids the problem of susceptibility to multipath errors by encoding the variable azimuth data not in the 30 Hz amplitude variation but in the subcarrier frequency modulation. Subsequent phase modification which in the conventional VOR is directly related to apparent azimuth is now only evident as phase modulation of an FM signal, and has consequently greatly reduced significance to the receiver[9] (See Fig. 1.4). The reference signal is now transmitted as omnidirectional AM at 30 Hz, allowing the DVOR total signal to be indistinguishable from the conventional VOR signal: thus the two are compatible. The method by which this role reversal is achieved depends, as the name suggests, on the well-known Doppler Effect. An antenna is rotated about a central point in order to provide a moving radiator. The frequency produced by the rotating element as measured by a distant observer varies cyclically. Moreover, the point in the cycle where the frequency is a maximum is a function of when the antenna is approaching the observer, and is thus a function also of the azimuth angle from the antenna to the observer.

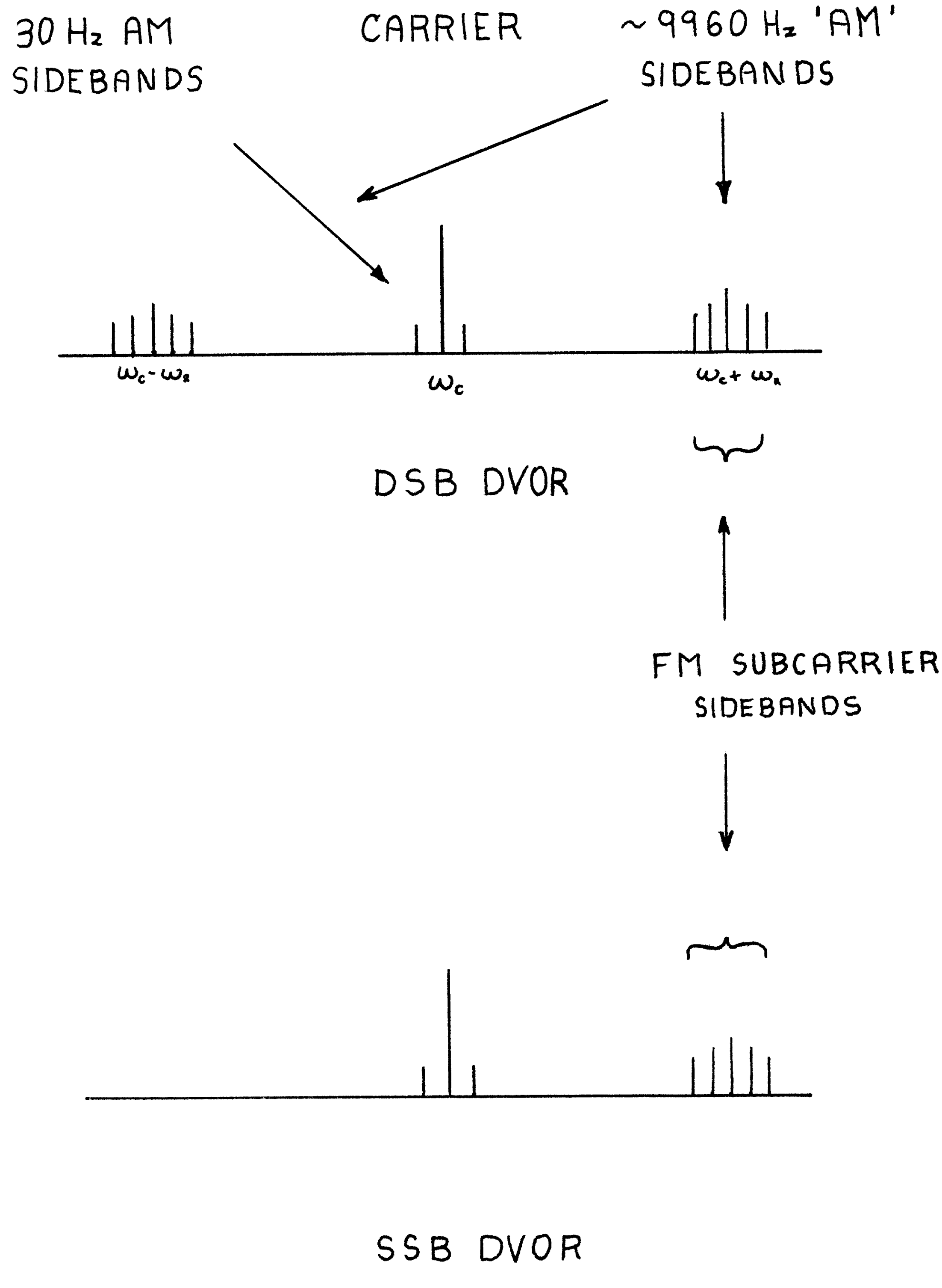
In practice the antenna is electrically rotated by means of careful sequential energising of many antennas (Alford Loops) in a circle, and the frequency it radiates is chosen to be the carrier plus 9960 Hz (see Figs. 1.10 and 1.11). Thus, by appropriate choice of circle dimensions, a 480 Hz deviation is apparent at the receiver, and the varying frequency forms a sideband of the carrier. This may be demodulated by the normal VOR envelope detection, though a Double Sideband version with two "moving" radiators rather than one is sometimes





TYPICAL DVOR ANTENNA ARRANGEMENT

FIGURE 1.10



DOPPLER VOR SPECTRA

FIGURE 1.11

employed to give true "AM" form to the signal. Then, the transmitted signals may be formally written:

$$E_r = \cos \omega_c t \ (1 + m.\cos \omega_s t) \qquad \ldots\ldots \ 1.8$$

for the case of the new reference signal, and:

$$E_v = k. \cos \left[(\omega_c + \omega_r)t + D. \cos (\omega_s t + \emptyset)\right] \qquad \ldots\ldots \ 1.9$$

for the variable signal in the Single Sideband case. It can be shown[9] that the above signals are completely compatible with conventional VOR systems.

The improvement implied by the theory leading to Fig. 1.4 is however not fully realised. The theory used assumes an isotropic scatterer which is not always the case, particularly at a busy airport site. Further investigation shows up other error sources[7] which occur for a Doppler system, but these are not the most significant concerns. The nature of the Doppler system demands a large installation, as depicted in Fig. 1.10. Even for the simpler SSB version, two separate, complete transmitters are required.

Quasi-rotation requires a very complex signal distribution device (goniometer) as well as 50 or so aerials, each carefully fed with the correct phase. Special feeds are often required in an effort to minimise the effects of parasitic currents[4]. In order to maintain omnidirectionality a counterpoise diameter of at least 75 to 150 feet is required. All these factors contribute to an initial cost three times that of a conventional VOR, and up to seven times as much when the exceedingly large establishment costs such as earthmoving and cable-trimming are added. Amalgamated Wireless Australia currently market a DVOR for some $250,000. In addition to this, reliability must also be jeopardised in the complex system, and troubleshooting becomes considerably more difficult. As evidenced by the work being put into alternate approaches[7,10,11,12] there is a strong view that the DVOR is uneconomical, overly complex and probably unnecessary in many cases. It is with these facts in mind that the work in this thesis has been pursued.

2.1 REDUCTION OF SITING ERRORS BY PATTERN CONTROL

The undesirability of signal radiated below the visual horizon has been established in the previous chapter, and the error produced by such a signal described. Evidence of the realisation of this in the form of work produced is not common. Work towards reduction of siting error by control of the elevation pattern at angles close to the horizon has only been published by two sources.

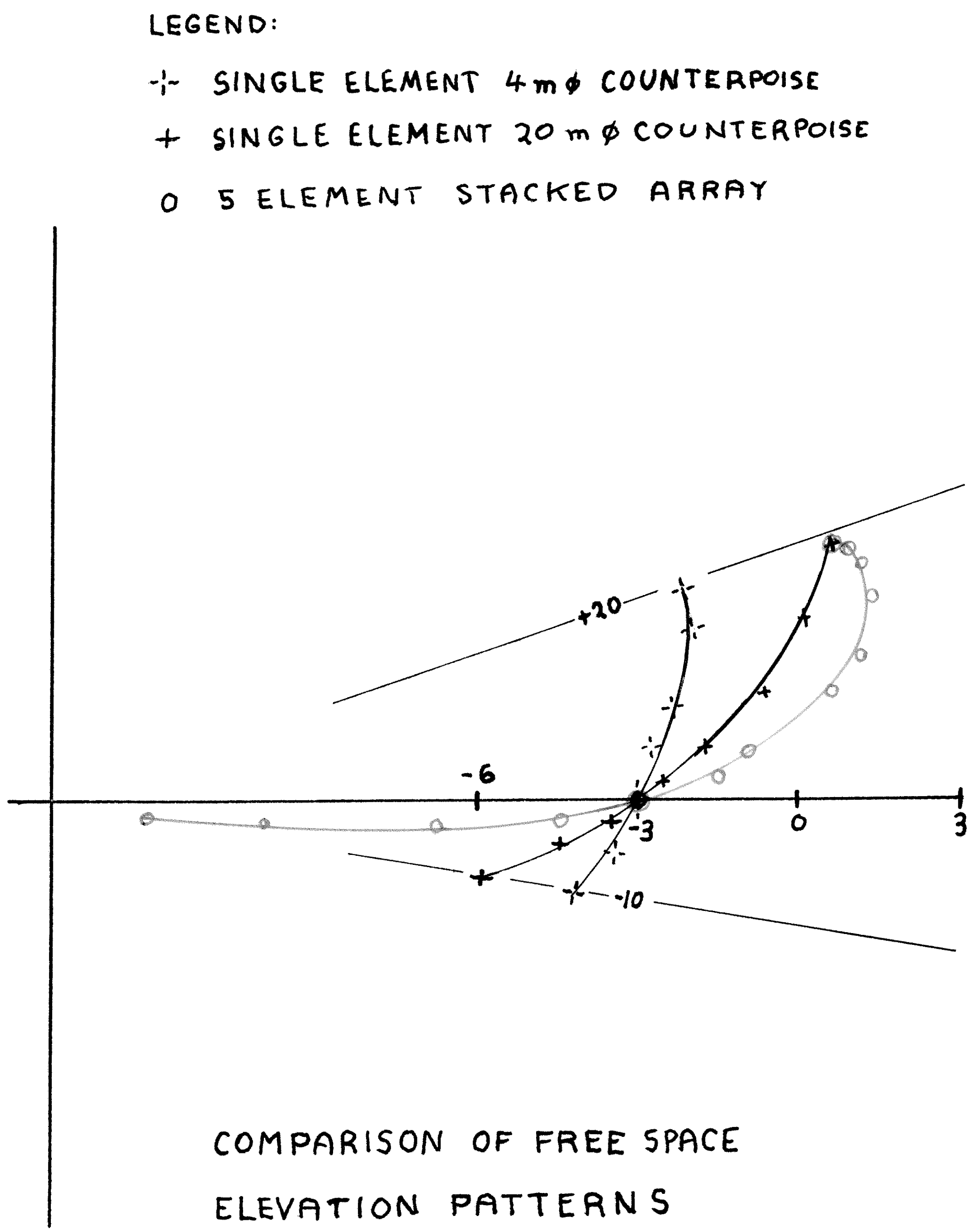
The first to be discussed is the most recent and comes from a private company manufacturing the slot form of antenna in Europe (Ref. 12). The second is the Radiation Laboratory in the department of Electrical Engineering, Michigan University, which is similar to Sydney University's Air Navigation Group in that it is strongly associated with the national Aviation Authority[10,11,11a].

2.2 THOMSON/CSF SPECIAL VOR SYSTEMS

Reference 12 is a report brought out by the technical laboratories of TH/CSF describing improvements achieved in VOR elevation patterns and consequently in scalloping error performance. This is achieved by replacing the single antenna assembly by a group of assemblies forming a circular or linear pattern, or by a vertically stacked array. Early in the discussion on antenna performance an awareness of the consequences of a limited counterpoise size is evident. Several solutions are considered with the stated aim of more closely approaching the field pattern expected with an infinite counterpoise, which as noted in Chapter 1 approximates the ideal. A need to tailor an antenna array for a particular site is recognised, and examples of successful installations are given.

However the merit of this work must be carefully considered. While standard components are employed in the design in order to reduce cost and employ proven technology, no method is given to explain how the number, position or drives of the array elements may be calculated. Many possibilities are left open, with no logic for the selection of any particular one being given to the prospective purchaser. The elements are presumably driven in some fashion as to produce addition or cancellation of some aspect of the field at some specific point, but whether this is in the near or far field is unstated. Also the criticality of these consequent drives is not reported. Some examples of the elevation pattern of proposed arrays are given (See Fig. 2.1) and the improved error performance curves at a site quoted.

Unfortunately these are not supported by any



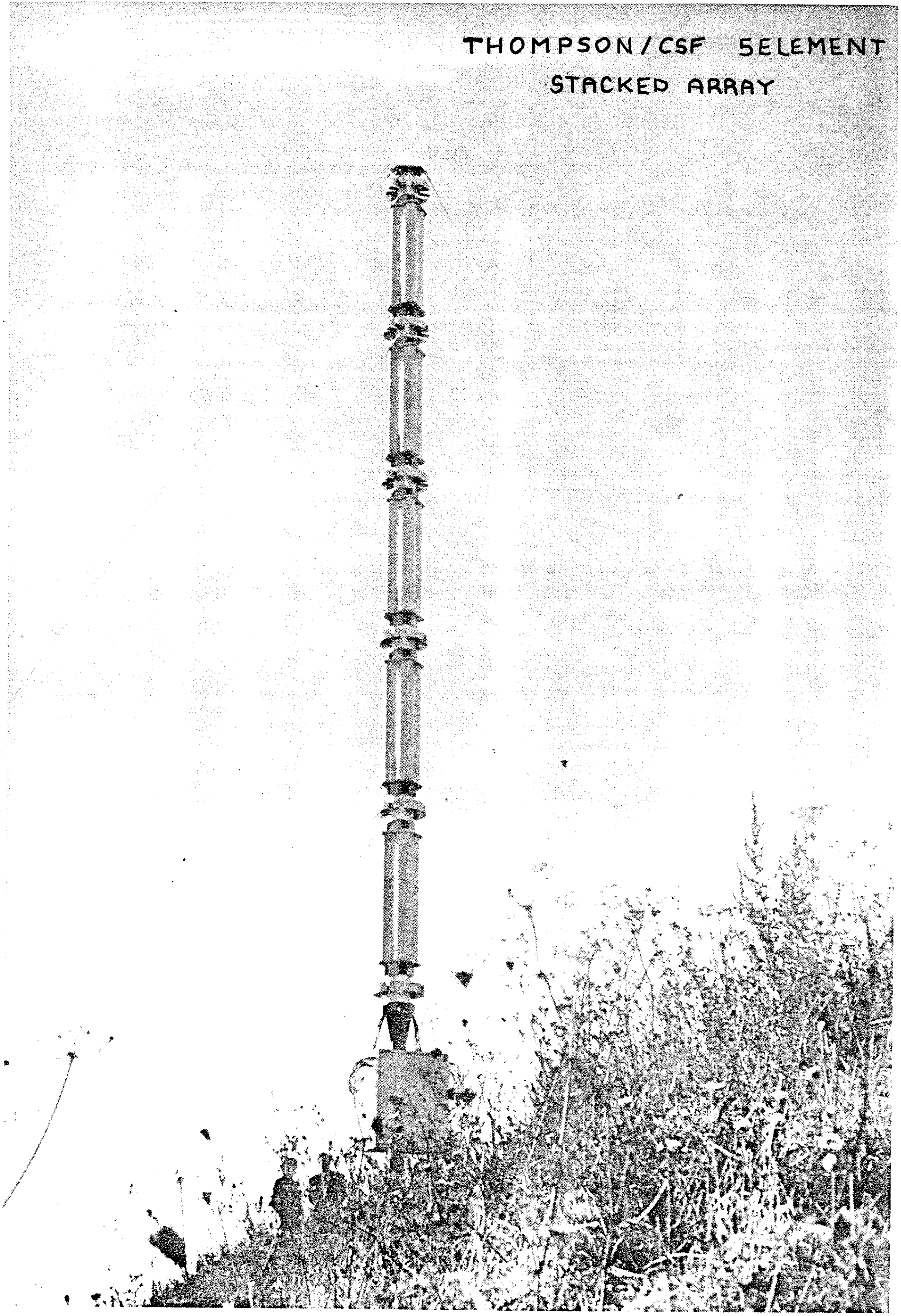
COMPARISON OF FREE SPACE ELEVATION PATTERNS (REFERENCE 12)

FIGURE 2.1

kind of explanatory theory, so reproducibility of results in practice, particularly when the equipment is installed by technicians in countries other than that of the manufacturer, is unguaranteed. Under this condition, and with so little surety, no aviation authority is likely to purchase such a system.

A second suggestion for improvement is to mount the antenna at ground level, situating the electronics some 100 metres away, thus removing the counterpoise whose edges diffract signal below the horizontal. This suggestion has immediate problems. Maintaining the stability of drive phases over such a distance over any consequential period of time would be very difficult, yet again no consideration is given as to how this aspect may be dealt with, or how much the controlled pattern is dependant on the drive phase. As will be seen later, an array of such elements as these can be extremely sensitive to drive phase due to the small interlevel spacing. This suggests that the reliability aspect of this form of installation is questionable. Again, such a system would not be chosen in the face of such an unknown risk, as the cost of frequent realignment of a VOR, especially if sited some distance from an airport, would soon negate any cost-convenience savings from its advantages. As may be seen in photo 2.2 a five-element-high stack is some 12 metres tall (The two figures give some idea of scale). The difficulty in initial erection and adjustment, not to mention durability and robustness, must be adversely affected by the size of the tower-like structure resulting from such a five-element stack.

Overall it may be readily observed that some theoretical development and substantiation of the technique of


THOMPSON/CSF 5ELEMENT
STACKED ARRAY

field control by stacked elements is required before this method could be accepted on a significant scale. Since TH/CSF provide no such basis, and until they do, the concepts embodied in their approach will not come into common practice. This thesis will try to explore some of this area.

2.3 THE WORK OF D.L. SENGUPTA[10,11,11a]

The Michigan University Laboratory, and in particular D.L. Sengupta, has approached the problem of pattern control by introducing parasitic elements above the driven Alford Loops of a simple VOR antenna (Section 1.3). He has developed expressions for the current induced in the parasitic loops and the field that is to be expected from such an arrangement above a specified counterpoise.

Modelling at 1080 MHz he has confirmed that his theoretical prediction of field strength for a given drive/parasitic arrangement is correct within anticipated limits. He has produced dimensions for one and two parasitic elements above the main drive which achieve marked reductions in field at and below zero degrees. With reduction gradients of 7 dB/5 degrees, the approach demonstrates unquestionable potential benefits in comparison to cost.

Again, however, the proposals must be assessed in the light of their acceptability as a reproducible and reliable way of controlling a VOR radiation pattern. To begin with, the approach relies upon the main drive being of the Alford Loop type. It cannot be applied to the cylinder-slot system, whose superiority over the conventional Alford Loop is fast being shown by its frequent choice for new installations all over the world. Indeed, the parasitic approach would seem to have been designed to be added to existing VOR's of the old type, whose performance was unsatisfactory. With the performance, simplicity and shipping advantages of the single unit cylindrical aerial now well taken for granted, it is unlikely that any authority would prefer the older systems if newer alternatives are available for the better aerials.

Another problem is simply parasite elements. These are supposedly simple things to use as no active feed exists in the normal sense. However, they are 'fed' by their driving elements and this feed has tolerances as does a normal active feed. The parasite current is not easily measured nor is simply varied, and so troubleshooting is difficult. This is aggravated by the fact that the presence of an observer and his equipment will probably disturb the parasitic drive markedly more than an active drive. Furthermore, misplacement can destroy the correct drive and accumulated dirt and corrosion can change the properties of the parasite which depend on such minor considerations[20]. It can also be noted here that a less frequently used advantage of the cylinder-slot aerial is that, in addition to the usual plastic flush-mount seals, it contains heaters to de-ice the unit in extreme weather conditions. Ice that does not cause significant interference in the loop drives could even completely immobilise a parasitic system. These points add up to the conclusion that if one is familiar with Alford Loops and has some practical experience with parasites the system is easy to establish, but if that is not so, there may be considerable difficulty in getting the system operating correctly.

In a publication in 1968[11], measurements of performance in a real-life difficult operational site were promised, as all modelling up to then had been in an indoor range at 1080 MHz. No further reports have appeared. One may infer that it was probably due to a lack of continuing financial support, or because the approach did not merit large-scale implementation.

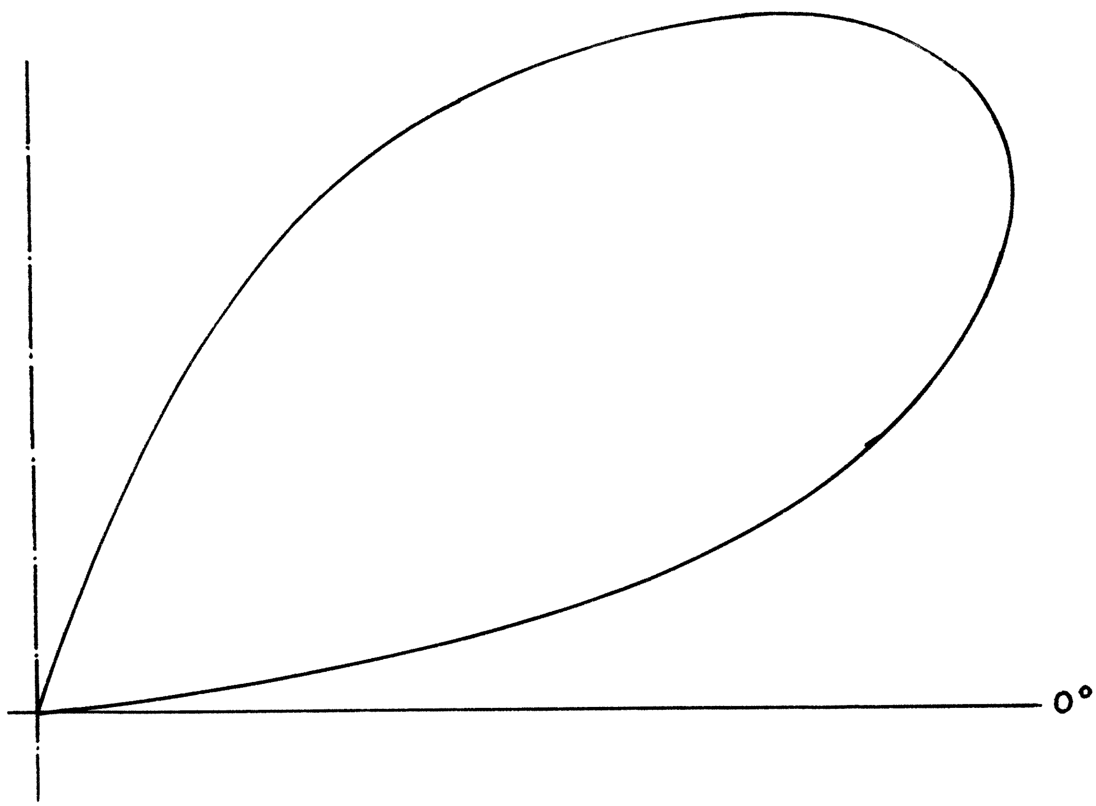
Finally, there is the theoretical observation, or perhaps lack of it. Although excellent results were obtained to match the prediction of radiation pattern, no theory was presented for choosing dimensions of the parasitic, and hence its drive current. The theory seems then to be oriented towards analysis rather than synthesis. It is quite impossible to adapt the theory to a multiple driven element situation except possibly by simulating the parasite with a driven element. This would be difficult indeed as the parasite's dimensions cannot be readily achieved using the Alford current loop synthesis method[15]. It appears then that this approach must be dropped completely if either parasites or Alford loops are rejected, or if an algorithm for choosing the antenna array from pattern considerations is sought.

3.1 THE IMAGE GROUND APPROACH

It is the aim of this thesis to develop and assess a theory which will allow the design of an antenna array which will produce a pattern more closely approaching that of Fig. 3.1, but which requires only a relatively small counterpoise. The ideal VOR pattern has scooping which comes into effect below zero degrees, ensuring that a craft receives bearing information whenever visible. Thus, it is required to arrive at a solution falling short of the infinite ground plane case. It is intended to approach the problem by consideration of the ground currents induced in the image ground. These are responsible for a large proportion of the total radiated field, and it is their perturbation or removal which causes the discrepancy between the ideal and actual patterns.

It is well-known that a radiating element above an infinite groundplane can be replaced by a pair of elements, the real one and its image, for calculation of radiated field (See Fig. 3.2a). The image is negative for the horizontally polarised case. The radiated field at any point is the vector sum of the fields from these two elements. However, the received field may also be considered to be the vector sum of the field from the element and the re-radiated fields from all the incremental currents which are induced in the ground by the original drive (See Fig. 3.2b).

When these radiated fields are integrated over the infinite image ground they will have the same contributed value as the negative image. Consider now the situation where the dimensions of the image ground are limited. The received signal no longer corresponds to an ideal infinite groundplane situation. It is the sum of the field from the



FIELD PATTERN OF SINGLE HORIZONTALLY POLARISED DRIVE ABOVE INFINITE GROUNDPLANE

FIGURE 3.1

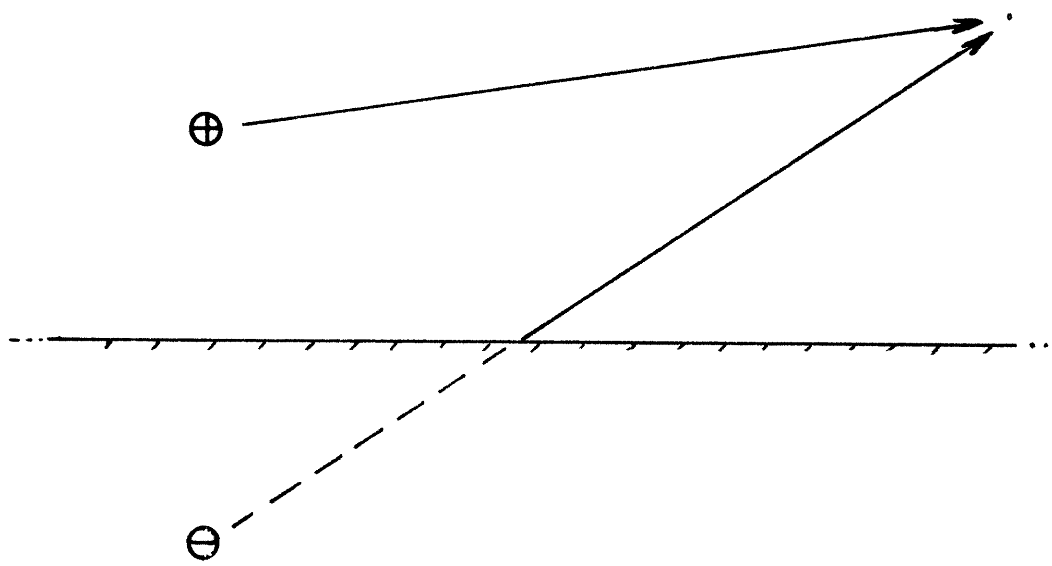


FIGURE 3.2A

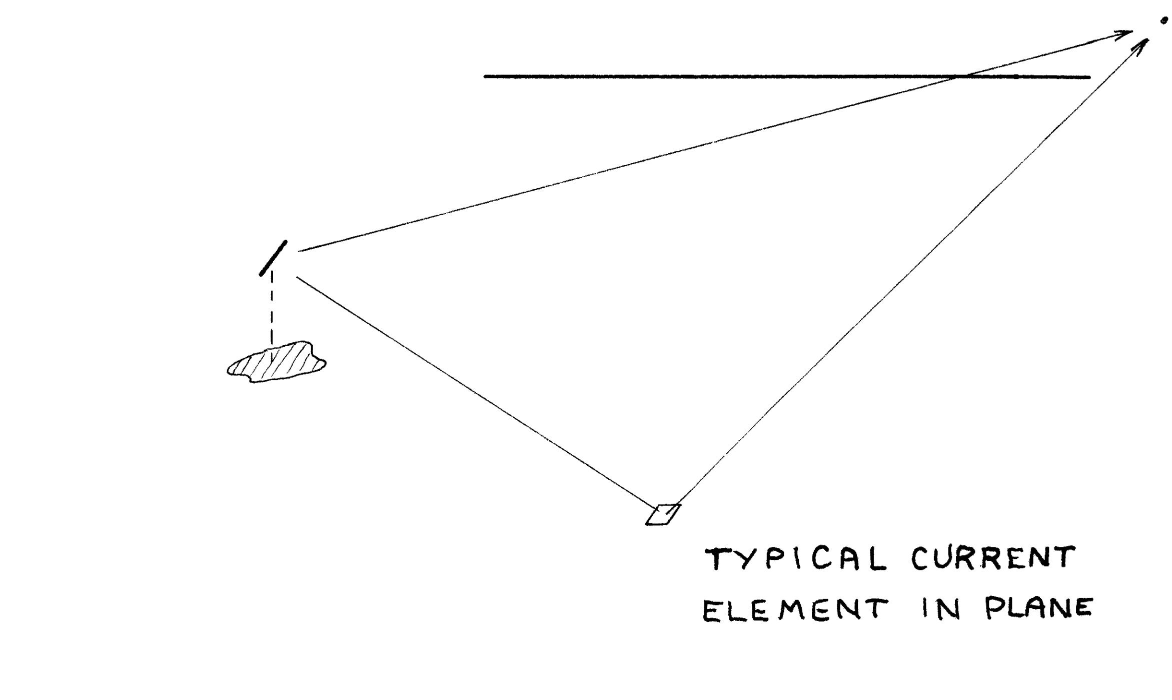


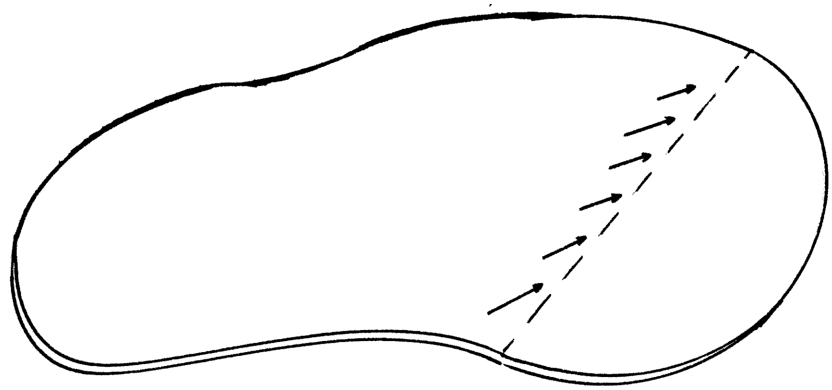
FIGURE 3.2B

original element plus that of the remaining currents in the truncated groundplane.

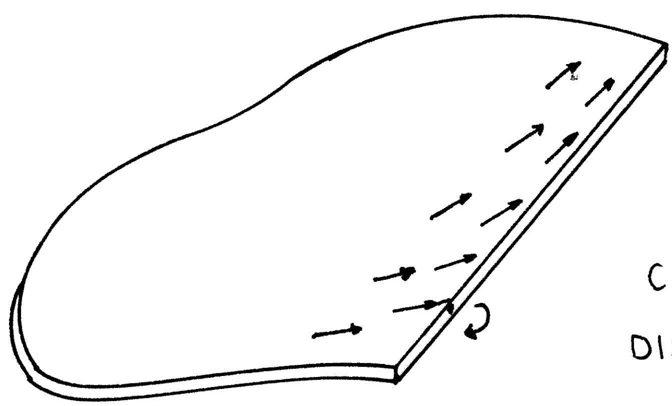
At this point a major assumption is made. The current flows will be, according to basic antenna theory[21], always in the same sense as the drive. Thus in the VOR ground currents will flow in concentric circles, not seeking to cross the circular boundary, if the counterpoise is large with respect to the drive.(In the case of the model to be described they will run parallel to the forward edge). This is a consequence of the equation $J_s = \hat{n} \times H$. While this is known not to be the actual case[22], it is known from the same source that the perturbation is considerably less when the groundplane edge cuts no theoretical current flow lines as is the case here. It is assumed that this perturbation is not so great as to invalidate the approach. The currents which would cross the line of the edge were it not there must, in obeying Maxwell's equations, flow around the edge or disturb the pattern nearby in some fashion as to require no current flow normal to the cut (Fig. 3.3). More will be said about the validity of this assumption when dealing with prediction of a radiated pattern by ground current methods.

Now, this assumption allows the following observation. While the total field for any array above an infinite counterpoise is the sum of the field from the drives and the fields from the remaining currents, it can also be obtained by summing the fields of the elements plus their appropriate images less that due to the now removed ground currents.

This is a critical axiom leading to the method which will be used in order to minimise the distortion of



EXAMPLE OF GROUND CURRENT
BEFORE AND AFTER AN ARBITRARY CUT
IS MADE IN THE CONDUCTING PLANE



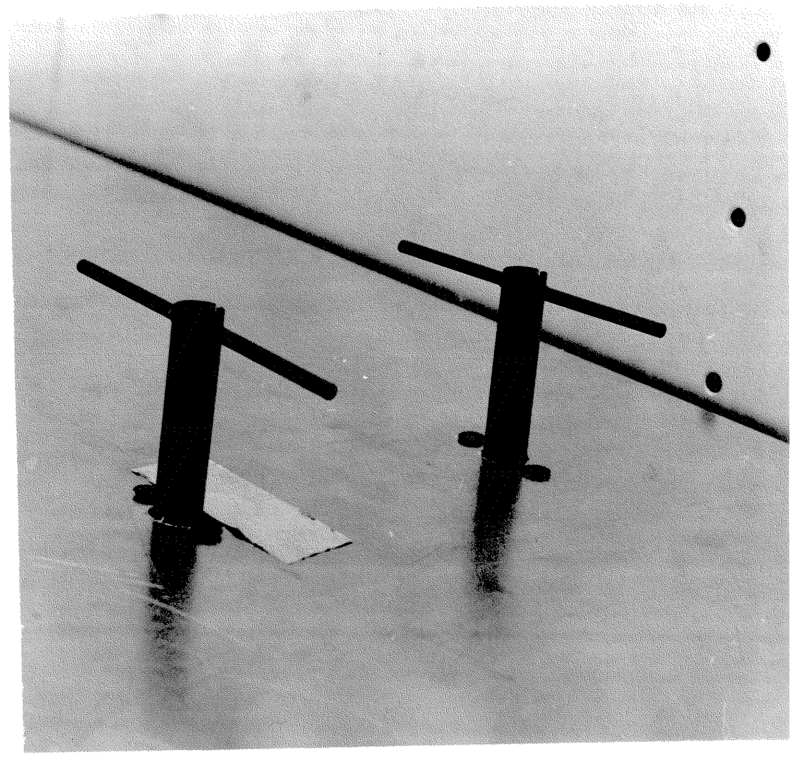
CURRENT IS
DISTURBED OR
FLOWS AROUND EDGE

FIGURE 3.3

the field by the truncation of the image ground.

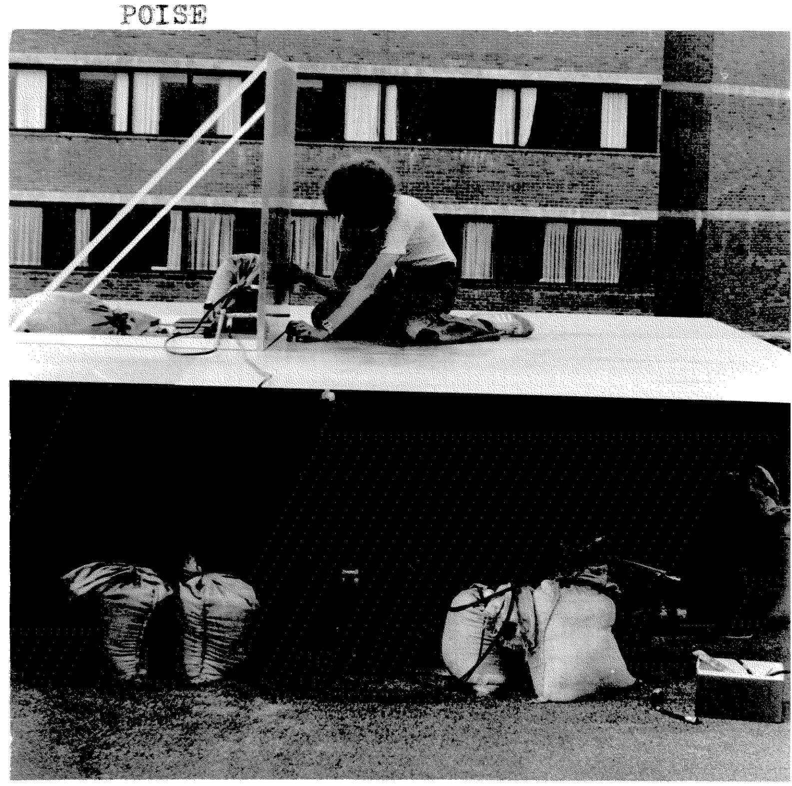
It seems a reasonable first assumption to say that the amount by which the actual field pattern falls short of theoretical is proportional to the amount of ground current contribution missing. It would seem thus to be desirable to devise an aerial system which relies less upon fields reflected (or re-radiated) from the far ground, such that less perturbation occurs upon the removal of this contribution with the implementation of the practical limited size counterpoise. In order to achieve some understanding of how this might be implemented, ground currents induced by an antenna array are considered. This technique has been employed implicitly[22] and explicitly[18] in the Instrument Landing System with success. However, the requirements of an I.L.S. are considerably different to those of a VOR in that approximately 1000 wavelengths of ground are available with the ILS, as compared to about 10 or so with the VOR. Also, a precise field null at a low angle (3 degrees) must be maintained at all costs in the I.L.S., whereas a VOR merely requires no nulls between 0 and +40 degrees.

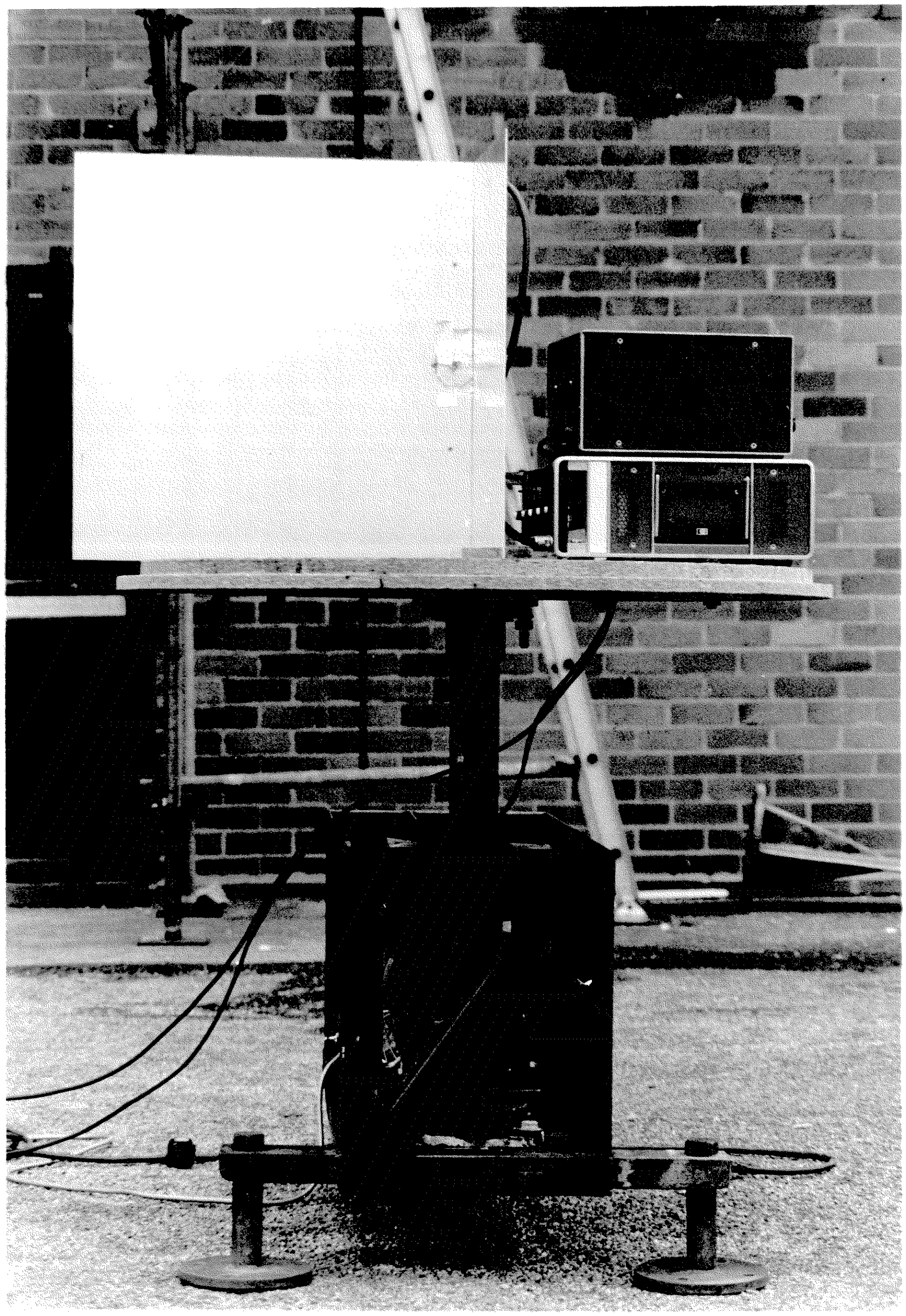
Before continuing it is necessary to introduce a simplification forced upon the author by the brevity of an Honours thesis. This is that the analysis and modelling of a VOR be considered in two dimensions only. This work is exclusively concerned (beyond the understanding of how the VOR works) with the elevation pattern and its effects. This pattern is independant of the azimuth angle considered, and so the analysis is independant of it also. It is shown in Appendix I that about zero degrees elevation, the VOR element radiation pattern is similar to that of a plain horizontally polarised dipole, mounted one quarter wavelength in front of a backing plate of adequate dimensions. This is of course provided that the whole is viewed only at right angles to the line of the dipole (Photo 3.4). This arrangement is experimentally very convenient, as equipment may be placed behind the assembly without interference to the forward pattern (Photo 3.5). The antenna assembly may also be held on its side and rotated in a horizontal plane in order to measure elevation pattern, since there is negligible field radiated along the axis of the drives (Photo 3.6). The work in this thesis is thus conducted assuming a dipole drive situation. Results and conclusions may be directly applied to the actual VOR situations with only minor variations.



3.4 DIPOLES MOUNTED IN FRONT OF BACK PLATE

3.5 EQUIPMENT MAY BE PLACED BEHIND THE BACK PLATE OR BELOW THE COUNTER-POISE





3.6 MODEL 5 GHz AERIAL PLACED SIDEWAYS ON
ROTATOR

3.2 THE SELECTION OF ARRAY PARAMETERS

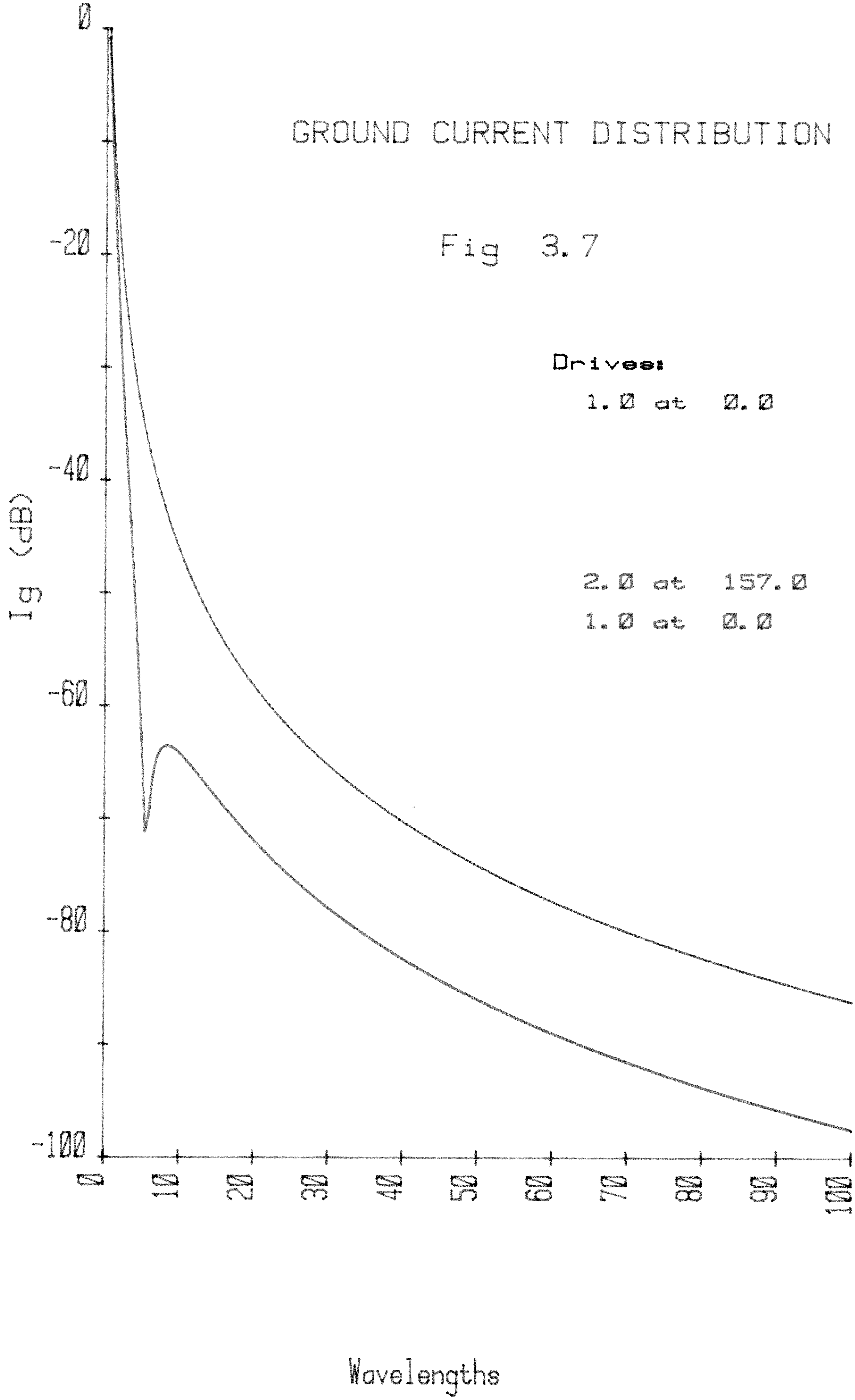
It has been decided to exercise control over the ground currents by means of a vertical array of drives. The array may thus be composed of Alford Loops or the Cylindrical Slot antennas ('T58s'). The spacing and complex drive currents have thus to be selected. In choosing the spacing the aim must be to achieve the minimum size compatible with convenient mounting and required performance. A ground to element spacing of 0.5 wavelengths at midband was chosen in the original C.A.A. specifications. Hence the actual spacing varied with the channel used, since the specification was a constant rather than a function of frequency. A preference arose in practice to use higher frequencies whenever possible so that the spacing was more likely to be 0.47 wavelengths. This value was chosen since it is the smallest spacing which gives a null straight overhead, when above a ground plane. Although the T58 aerial does not require a groundplane at all to deliver a null[13], the sharpness of the null is greatly improved by actually using one, and so the spacing was kept. It is clear that since all elements of an array with this spacing will also cancel with their images, and since the present drive designs can readily be mounted with this spacing it is desirable to retain it. This would also facilitate modification of an existing system to an array system in all cases, as the existing drive corresponds to the lowest element of the array already.

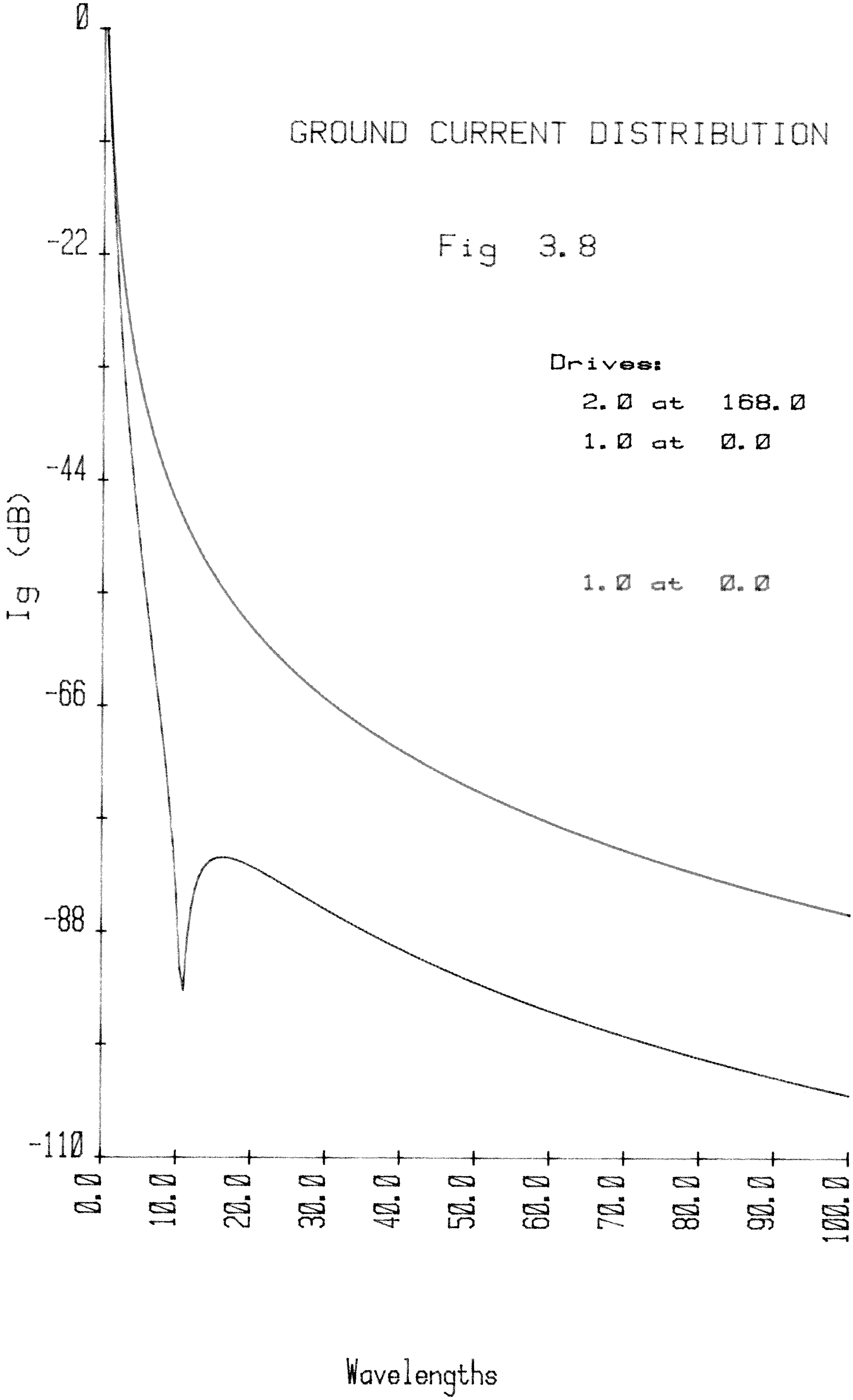
Actual calculations have been carried out at a value of 0.48 wavelengths; however no critical dependence of other parameters upon fractional spacing has been noticed.

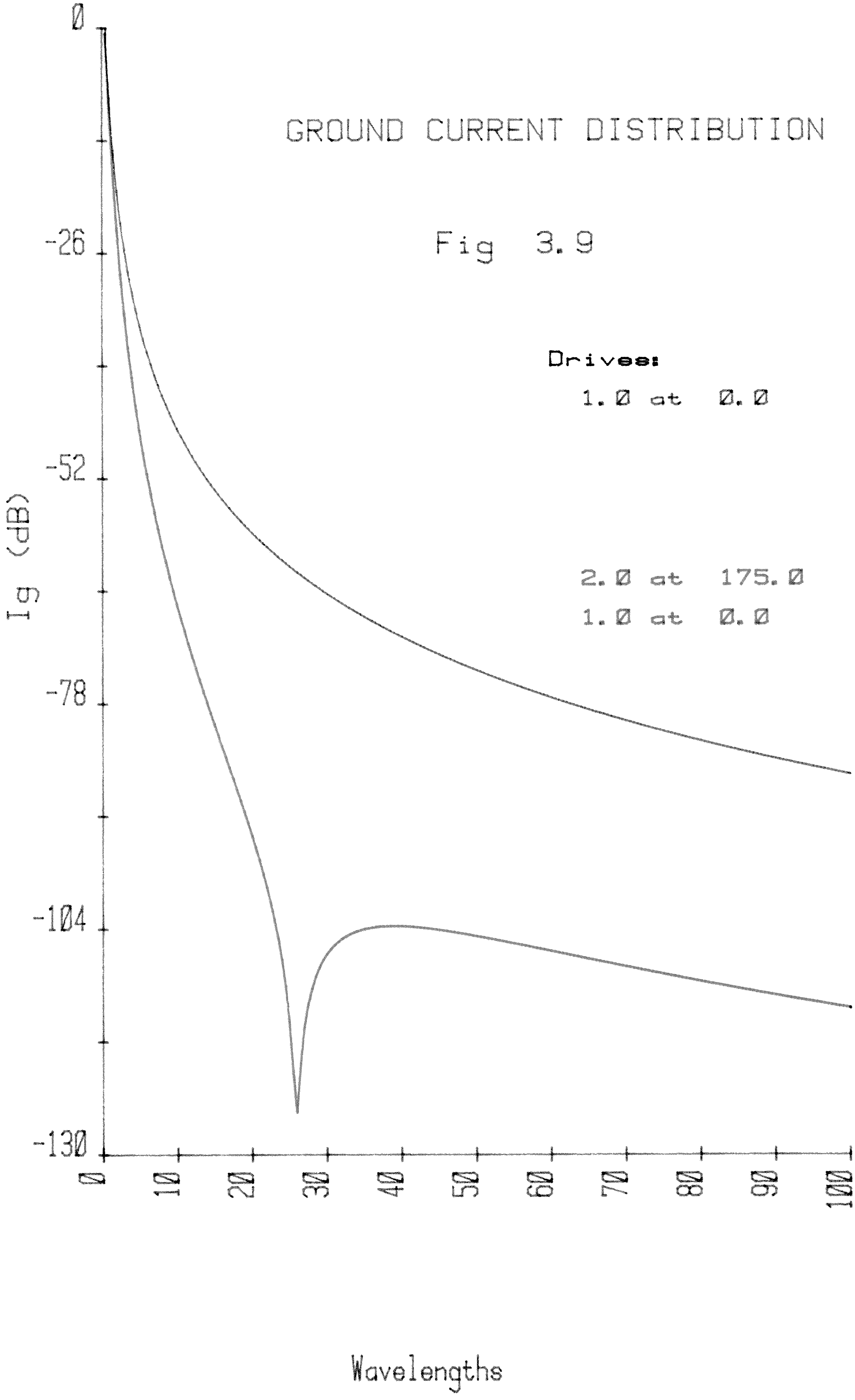
The approach used to select array drives will now be outlined. One cannot solve for the drives of an array producing a field null at infinity for any angle less than zero; however, it is possible to compute drives which will give one or more nulls in the ground current at specified sets of distances from the origin (The origin is taken as the point on the groundplane immediately below the array). The method of computing the n drives required to produce n-1 ground current nulls is given in Appendix II.

Ground current distributions for arrays of 2 elements with nulls placed at 5, 10 and 25 wavelengths are shown in Figs. 3.7 - 3.9 (In these diagrams the current distribution of the ordinary single element drive is given for comparison; magnitudes are normalised for equal field strength at +20 degrees). Several points may be noted immediately:

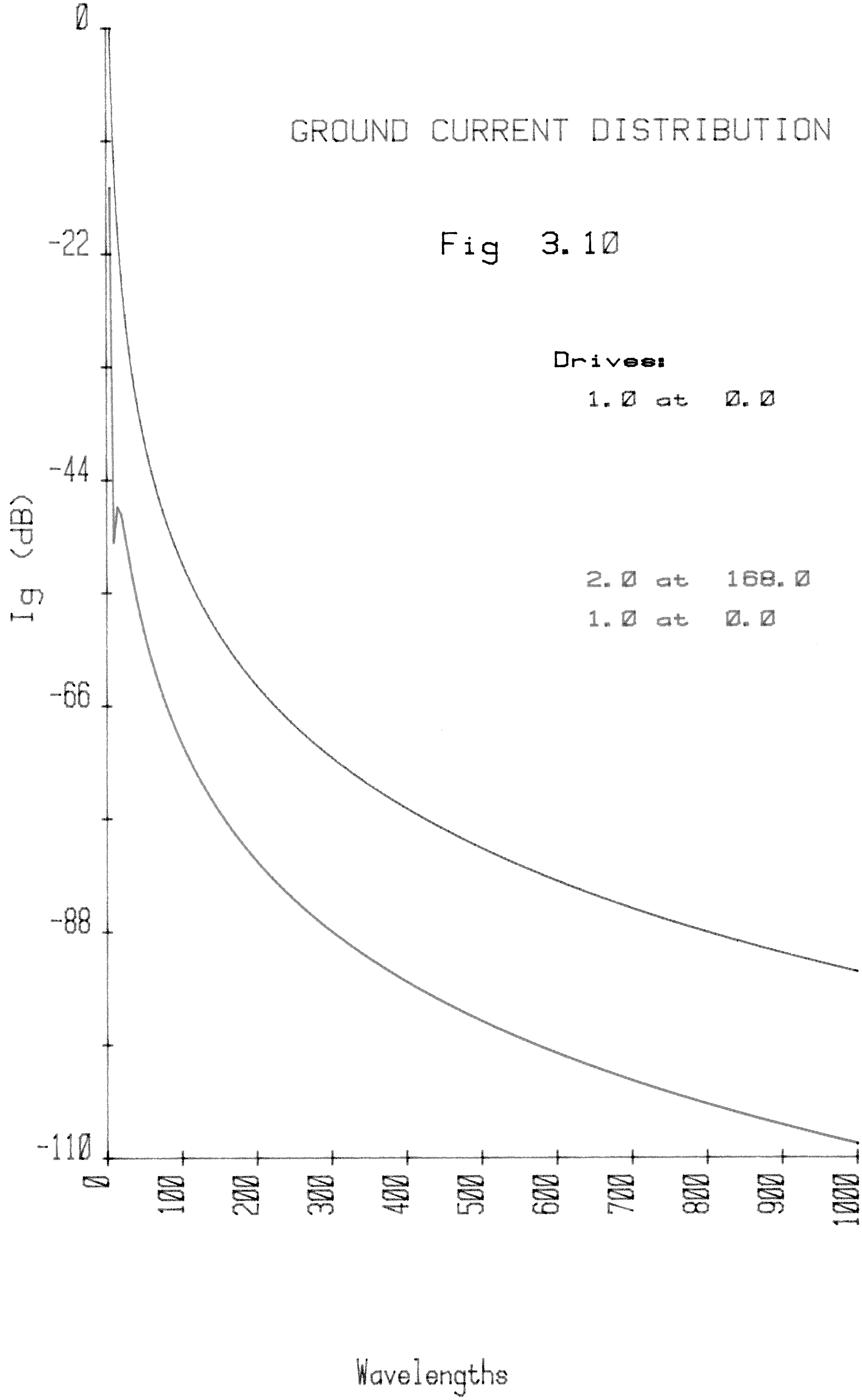
Firstly, the drive phase relationahip between the two driven elements becomes more critical the further out the null position. An error of one or so degrees in relative drive phase is the best one can reasonably expect to achieve without frequent recalibration (at 120 MHz). A dependence upon such attention is unacceptable at a remote site and hence a design which cannot tolerate the anticipated drift is unacceptable also (This feature prevented the wide acceptance of the Redlich I.L.S. array[18]). Any tenable design must therefore, in the two element case, have a null no further than 20-30 wavelengths out, or be able to tolerate considerable drift in its position. No compromise, it turns out, is necessary. The largest practical counterpoise that can be accepted is about twenty wavelengths (50 metres) in diameter, while half this would be much more satisfactory. With these dimensions the null will be either close and its drive not critical or distant and its position not critical.


GROUND CURRENT DISTRIBUTION
Fig 3.7
Drives:
1.0 at 0.0
2.0 at 157.0
1.0 at 0.0
Ig (dB)
0
-20
-40
-60
-80
-100
0
10
20
30
40
50
60
70
80
90
100
Wavelengths


GROUND CURRENT DISTRIBUTION
Fig 3.8
Drives:
2.0 at 168.0
1.0 at 0.0
1.0 at 0.0
Ig (dB)
0
-22
-44
-66
-88
-110
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
Wavelengths



GROUND CURRENT DISTRIBUTION
Fig 3.9
Drives:
1.0 at 0.0
2.0 at 175.0
1.0 at 0.0
0
-26
-52
-78
-104
-130
Ig (dB)
0
10
20
30
40
50
60
70
80
90
100
Wavelengths


GROUND CURRENT DISTRIBUTION
Fig 3.10
Drives:
1.0 at 0.0
2.0 at 168.0
1.0 at 0.0
Ig (dB)
0
-22
-44
-66
-88
-110
0
100
200
300
400
500
600
700
800
900
1000
Wavelengths

Next it is noted that the reduction in induced ground current beyond the null is greater the further out the null is placed. It would seem then that it is desirable, at least from this point of view, to have the null further out, as this should give the greatest improvement in performance. This consideration will be assessed when the evaluation of performance has been discussed.

Three questions must now be answered. Firstly, does the ground current remain lower than in the single drive case at the far distances? Were this not so, the very low angles would show no improvement in ground current in the critical regions corresponding to the first 2 or 3 Fresnel zones. Fortunately the improvement holds to very great distances even for the case of nulls very near the origin. As illustrated in Fig. 3.10 for the case of drives inducing one null at a radius of 10 wavelengths (1N-10 drive)* the current magnitude falls off progressively more rapidly with distance to beyond two nautical miles. This situation is found to be valid for all the drives considered here.

Secondly, do any nulls occur in the region between 0 and +40 degrees from the horizon? The I.C.A.O. recommended specifications for VOR performance demand no nulls in this region as this could, of course, suddenly deprive a craft of signal while it is well in range. It is shown in Appendix III that none of the 'N' type drive combinations can

---

* The particular sets of drives will now be referred to by the format $kN - d_1 - d_2 - \ldots\ldots$

where k = number of nulls
d_i = distance origin to null i

Hence 1N -10 means the two drives giving one null focussed at 10 wavelengths

2N 10 - 20 means 3 drives, 2 nulls, at 10 and 20 wavelengths respectively, etc.

have nulls focussed near infinity except about 0 or 90°.

Finally, what will the optimum position of a null for a groundplane of given radius be? Two possible lines of thought come to mind. It may be better to situate the null near the edge and thus minimise ground current near the potential discontinuity as depicted in Fig. 3.3. Alternately, the currents actually occurring due to the presence of the counterpoise could be maximised in comparison to those deleted. In other words, the ratio of the integral of ground current realised to that of ground current lost (over an infinite plane) could be maximised, i.e.:

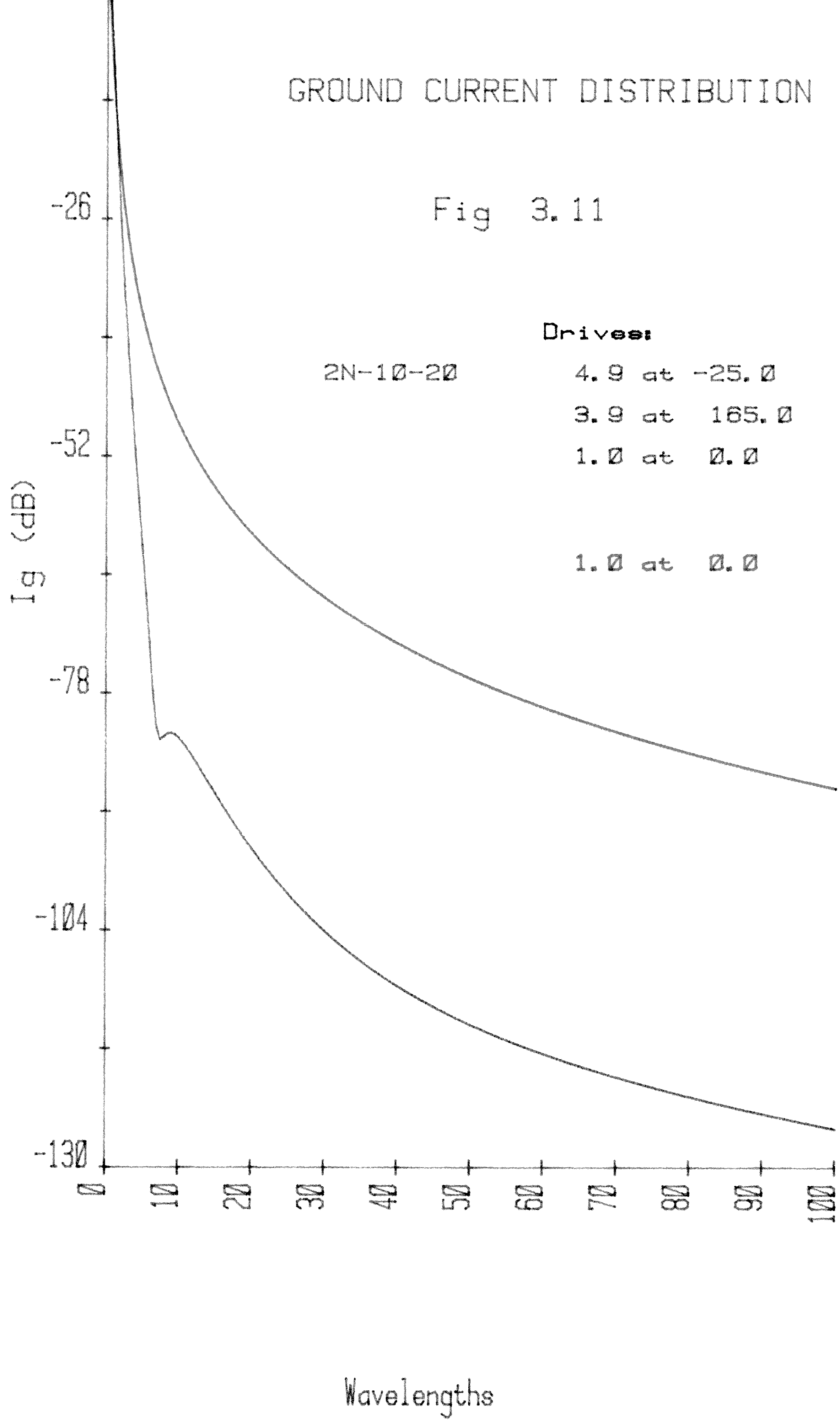
$$\int_0^c I_{ground}\, dx \Big/ \int_c^\infty I_{ground}\, dx$$

where c = counterpoise radius

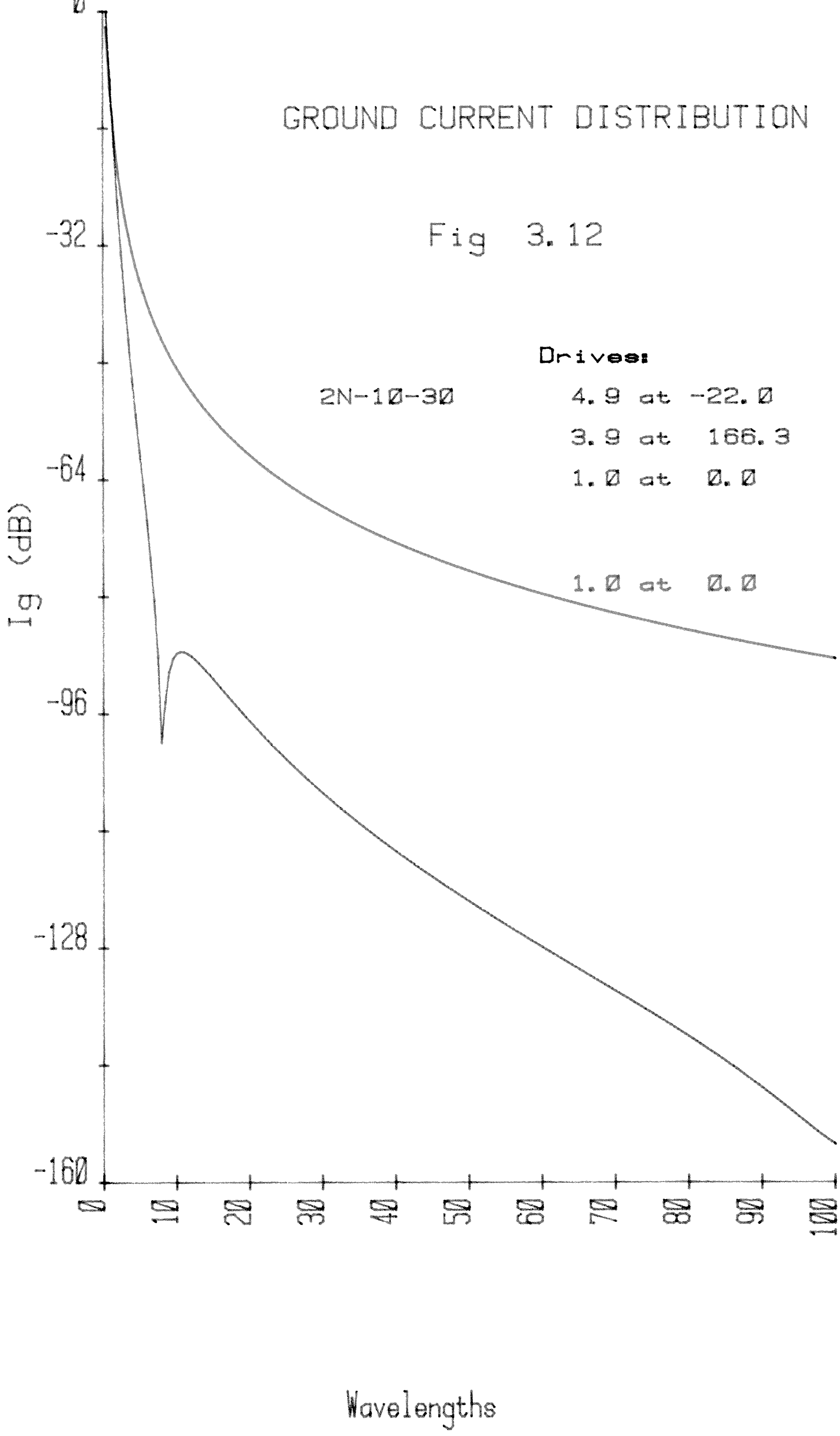
could be maximised as a function of null position for a given c, with null position greater than c.

The exact solution of this is difficult and unnecessary. One may clearly perceive that this will be optimum when the null is somewhere about twice the counterpoise radius from the origin. This question is most easily answered through empirical trials. The question of where the null should be placed will also be dealt with in the next section.

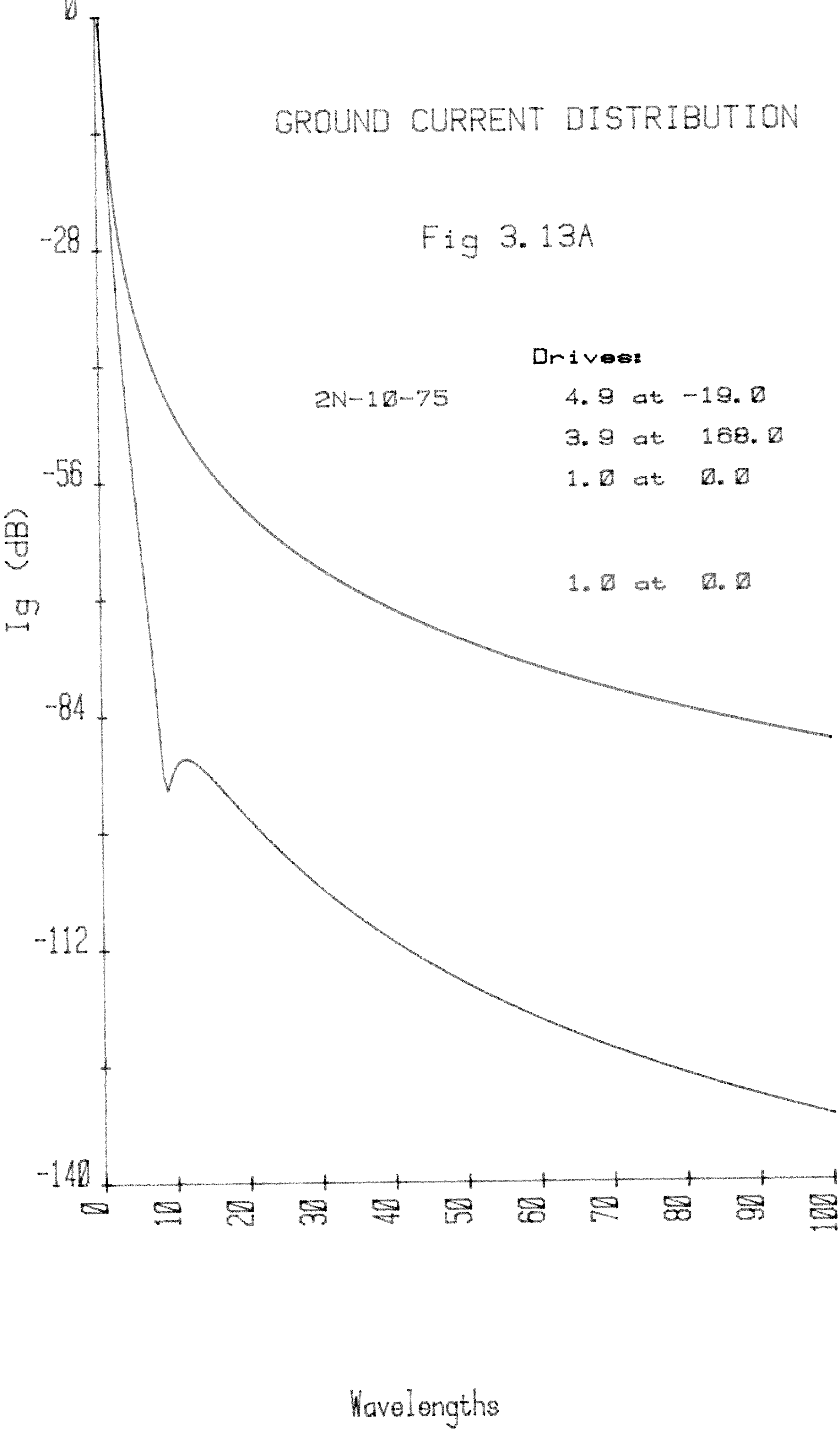
The null positioning decision becomes slightly more complex when 3 drives, giving the 2 nulls, are considered. Figures 3.11, 3.12 and 3.13a give the resulting current distribution for 2N 10 - 20, 2N 10 - 30 and 2N 10 - 75 drives respectively. The first observation is that the outer null is not sharp. This is a product of the extremely critical nature of the drives. They are easily defocussed by small phase errors. The disappearance of a deep null point at the position of the second theoretical zero in Figs. 3.11 to 3.13 is a result of

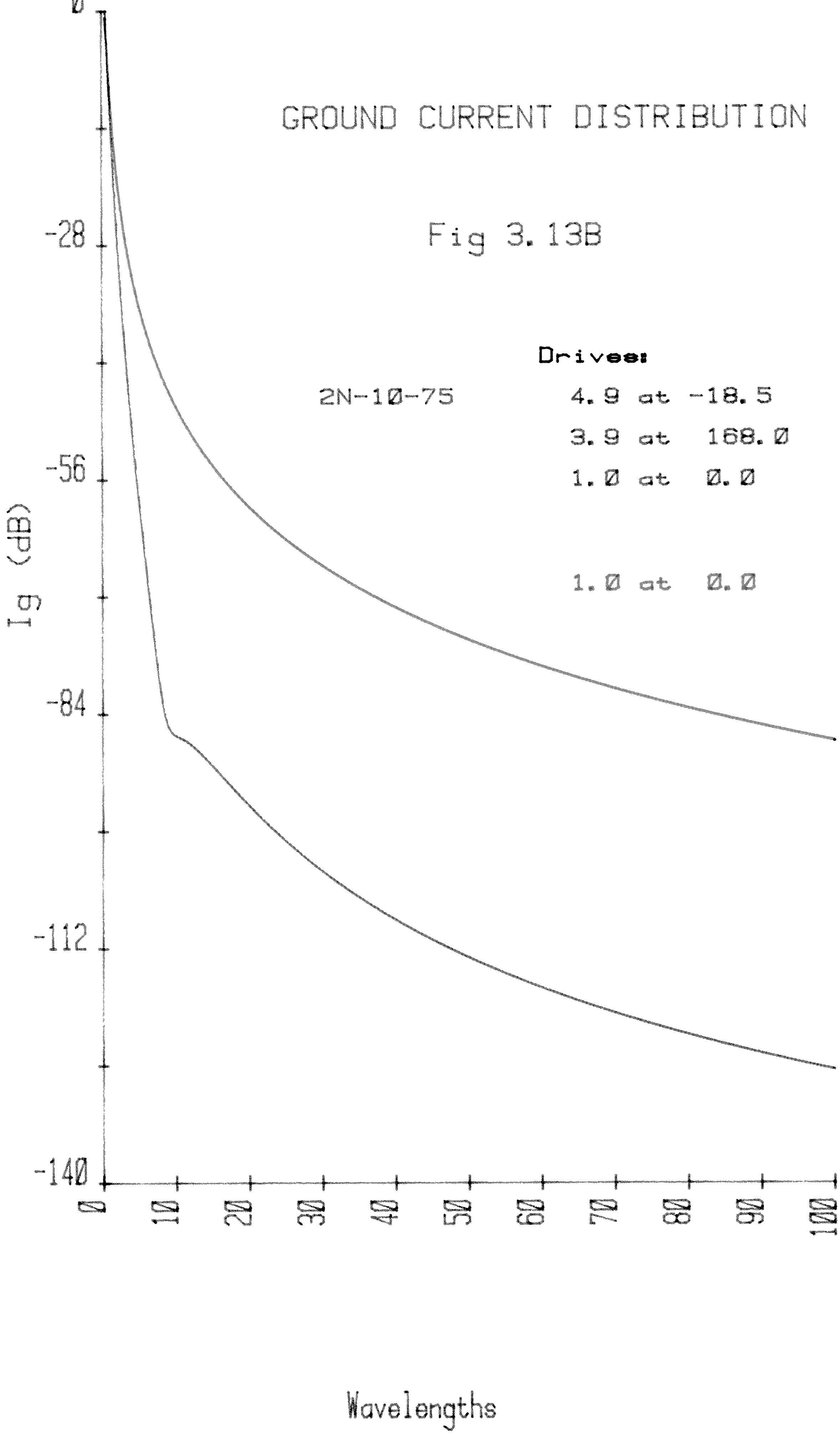


GROUND CURRENT DISTRIBUTION
Fig 3.11
Drives:
2N-10-20
4.9 at -25.0
3.9 at 165.0
1.0 at 0.0
1.0 at 0.0
Ig (dB)
-26
-52
-78
-104
-130
0
10
20
30
40
50
60
70
80
90
100
Wavelengths

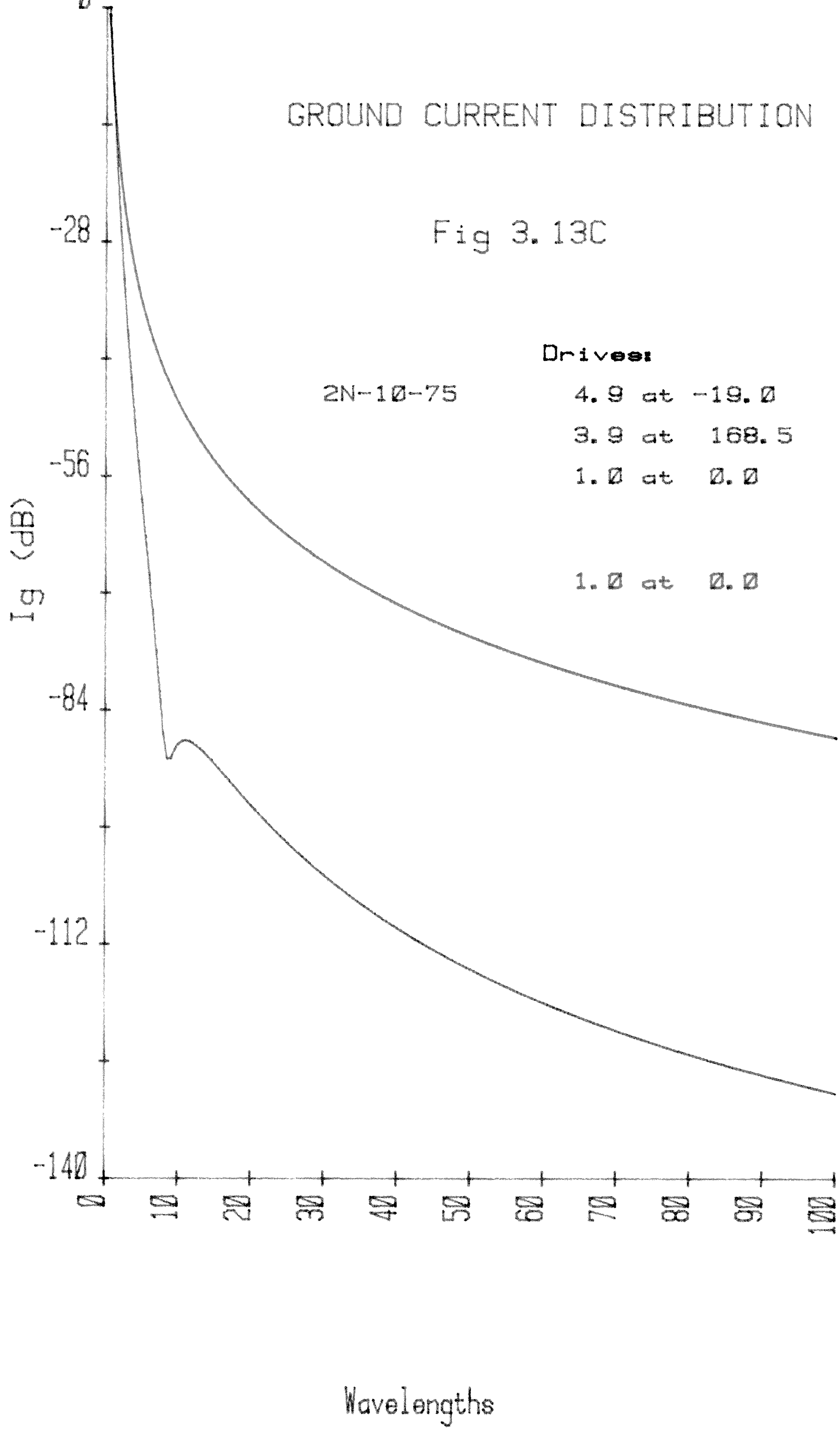


GROUND CURRENT DISTRIBUTION
Fig 3.12
Drives:
2N-10-30
4.9 at -22.0
3.9 at 166.3
1.0 at 0.0
1.0 at 0.0
Ig (dB)
0
-32
-64
-96
-128
-160
0
10
20
30
40
50
60
70
80
90
100
Wavelengths


GROUND CURRENT DISTRIBUTION
Fig 3.13A
Drives:
2N-10-75
4.9 at -19.0
3.9 at 168.0
1.0 at 0.0
1.0 at 0.0
Ig (dB)
0
-28
-56
-84
-112
-140
0
10
20
30
40
50
60
70
80
90
100
Wavelengths



GROUND CURRENT DISTRIBUTION
Fig 3.13B
Drives:
2N-1Ø-75
4.9 at -18.5
3.9 at 168.Ø
1.Ø at Ø.Ø
1.Ø at Ø.Ø
Ig (dB)
Ø
-28
-56
-84
-112
-14Ø
Ø
1Ø
2Ø
3Ø
4Ø
5Ø
6Ø
7Ø
8Ø
9Ø
1ØØ
Wavelengths


GROUND CURRENT DISTRIBUTION
Fig 3.13C
Drives:
2N-10-75
4.9 at -19.0
3.9 at 168.5
1.0 at 0.0
1.0 at 0.0
Ig (dB)
-28
-56
-84
-112
-140
0
10
20
30
40
50
60
70
80
90
100
Wavelengths

the phase drives being rounded to the nearest half degree or so. Figs. 3.13 a, b and c give some idea of the change which may be expected for small drifts in drive phase. However, while the drift may markedly vary the curve shape, the effect is not lost. In all cases the current at one hundred wavelengths is 30 dB down instead of 10 to 20 for the single null case. It would seem therefore that the second null position is not critical to the reduction of ground current at greater distances. A one degree phase drift could be tolerated if this proves to be the case.

Also, comparison of Figs. 3.8 and 3.12 suggests that the presence of a second null does not perceptibly affect the current distribution before the position of the first null; it merely improves the situation beyond. One can now infer that the introduction of a second null will not seriously demand a shift of the first, but will, if one is willing to tolerate three driven elements with critical phasing allow further improvement still over the 2 drive case (even before considering the performance achievement).

It is encouraging to recall that Thomson/CSF proposed a 5 element array. The critical nature of even 3 elements leads one to wonder if 5 might not demand so precise a set of drive phases as to require special feed gear. It is possible that the additional elements are used to desensitise the array to drift, but to the best of the author's knowledge, no work at all to this effect is available in the literature.

3.3 THE EVALUATION OF ARRAYS

It is necessary in order to evaluate the usefullness of the 'N' type arrays, firstly to develop and clarify the desirable features of a radiation pattern for a VOR. Secondly, it is desirable to develop and verify a method for predicting the field pattern from the array and counterpoise dimensions. These topics, as well as a discussion of the experimental setup and its limitations are covered in this section.

As noted in Chapter I the ideal VOR elevation pattern maintains adequate signal strength down to the horizon, where it falls to zero, preventing signal radiation towards potential error-causing reflectors. This is, of course, unrealisable in practice, expecially as the horizon is not at the same level for all azimuth angles. In that case, variation of cutoff angle with azimuth angle would be necessary. In practice a finite cutoff slope at 0° is the best that can be achieved, and a design aim must accept this compromise. Also in order not to require specific setting up it will need to have an elevation pattern independant of azimuth angle.

Consider now what is the critical region in the elevation pattern. If a VOR was 250 metres from even a ten storey building or 30 metre tower, this object would subtend an angle of less than 5 degrees above the horizon. A mountain of some 3000 feet only 10 kilometres away also subtends a similar angle. Thus +5 degrees or so is the upper limit of the critical region. If we allow consideration to +10 degrees the critical region is comfortably included. Similarly for angles of declination, considering down to -10 degrees will comfortably include the region where obstructing reflectors might lie. Provided signal strength continues to fall at larger angles of declination, no consideration of field gradient will be required.

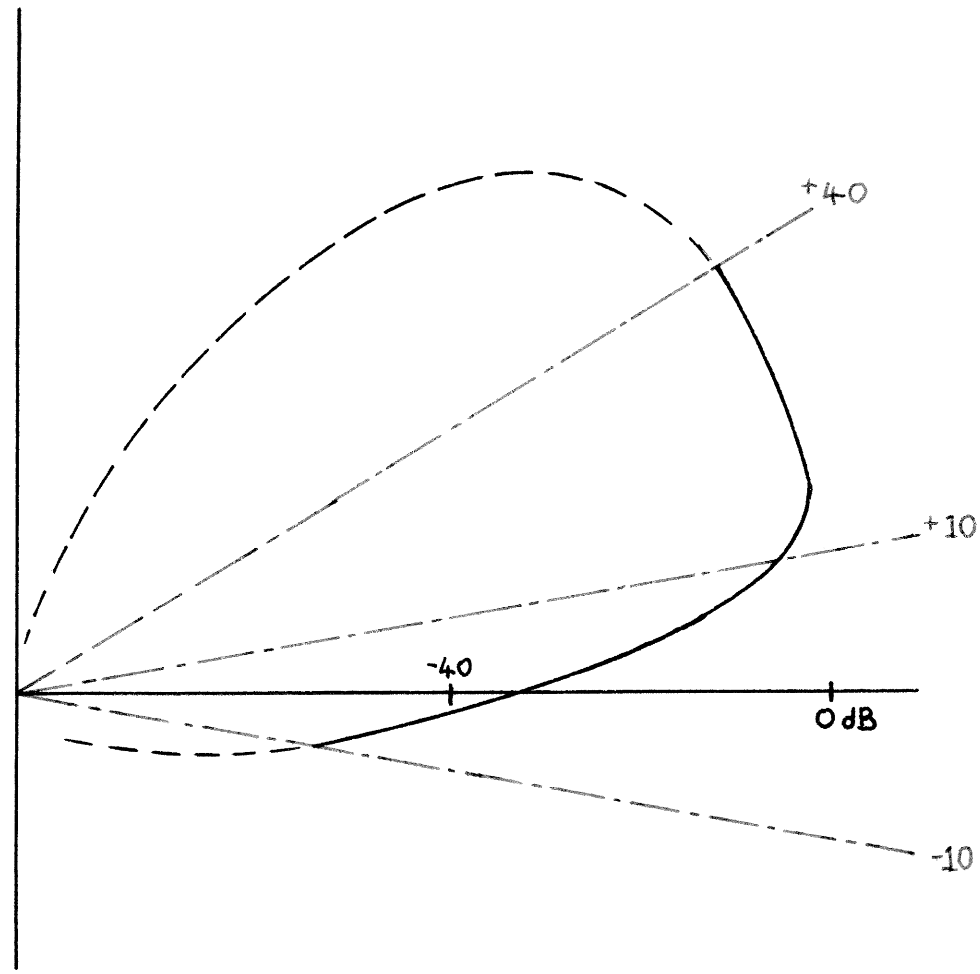
Having established the critical region, the desirable pattern shape within these bounds will be discussed. It should be noted that since it is sought to reduce bearing error by altering elevation pattern to illuminate the reflector less intensely, it is necessary for it to subtend a different angle of elevation from that of the receiver. This is usually the case, as an aircraft will, in the worst case, be on the horizon while a reflector will most likely be below it. This is especially so when the VOR is located on the highest ground, which is most often the situation. On the assumption that the receiver and reflector do subtend different angles, it is clearly desirable to have the largest possible drop in signal strength between them, which implies the maximum slope.

However, the signal must not fall below a receivable limit until say-2 or so degrees is reached. Since the peak signal is limited by practical transmitter size and cost, the slope may not be too steep. A steep slope is not required, of course, above the critical region, so it is desirable that the falloff occur between +10 and -10 degrees. A level of not less than -40 dB with respect to peak should be maintained above -2 degrees in order that the 100 watts or so available from the standard equipment should remain adequate.

Figure 3.14 illustrates these points by showing what is regarded as an ideally realisable elevation pattern. A slope of about 3.2 dB/degree would seem to be the best which can be achieved, allowing -40 dB at -2 degrees. Less signal than this is undesirable since it would risk depriving an aircraft of signal at low angles. As the peak is broad this allows about 30 - 35 dB less signal at 0°. The following figures may then be used to evaluate how ideal a pattern is: up to 4 dB/degree the greater the slope the better; a signal below peak at 0 degrees is tolerable; the slope should be a maximum at least between +5 and -5 degrees. These are only guiding figures of course, but do give an idea of the desirable performance and acceptable bounds. The region between 0 and -4 degrees is the most critical and it is here that slope will be evaluated when considering array performance.

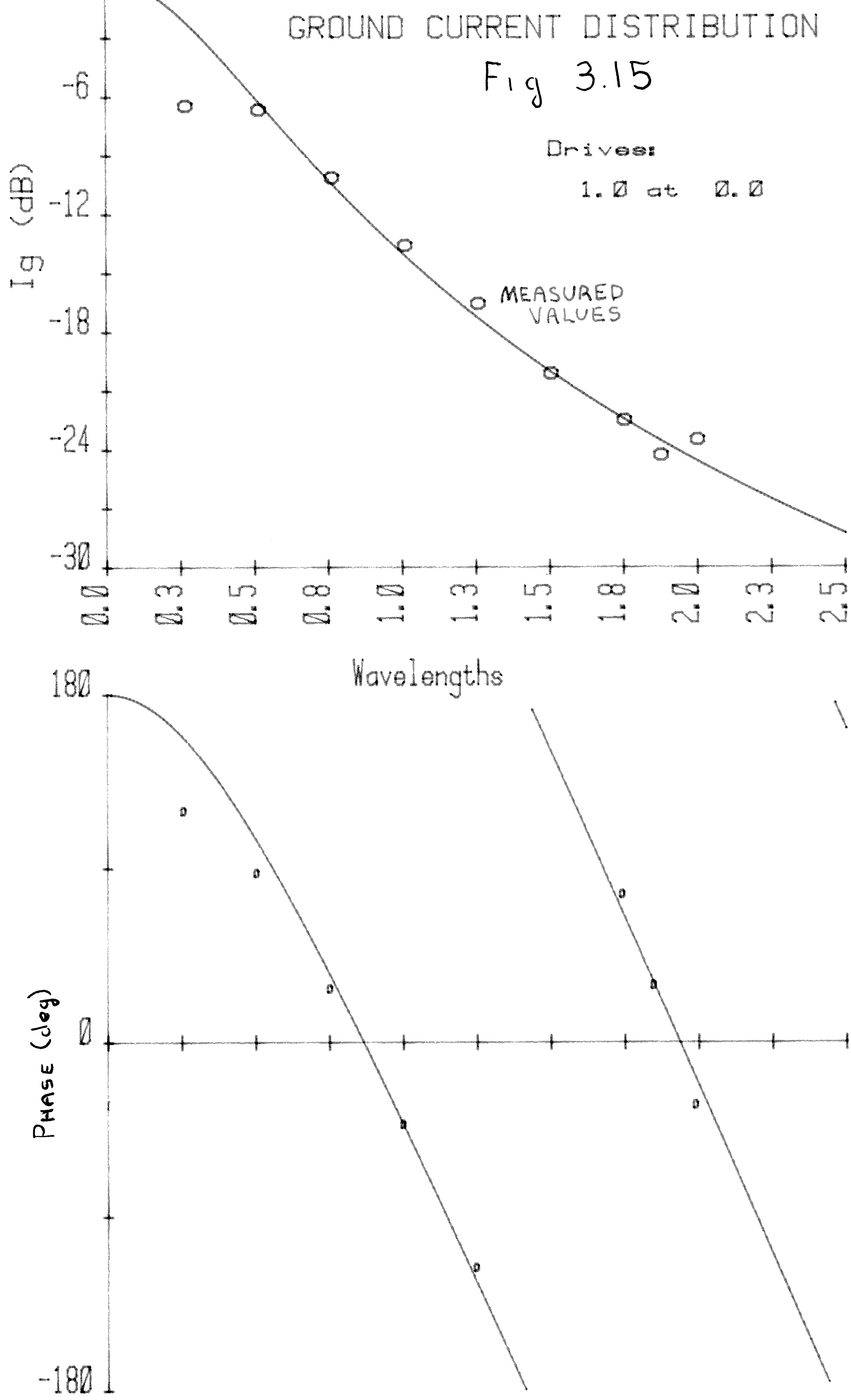
Two methods of tackling the problem of computing actual array performance above a counterpoise of specified dimension are available. The first involves computation of ground current re-radiation from aerial theory. The second employs a ray optics approach to calculate edge diffraction effects. Both of these have been investigated and both have been found to be unsatisfactory. A discussion of these investigations follows, with comments on their failings and how these might be dealt with in the future.

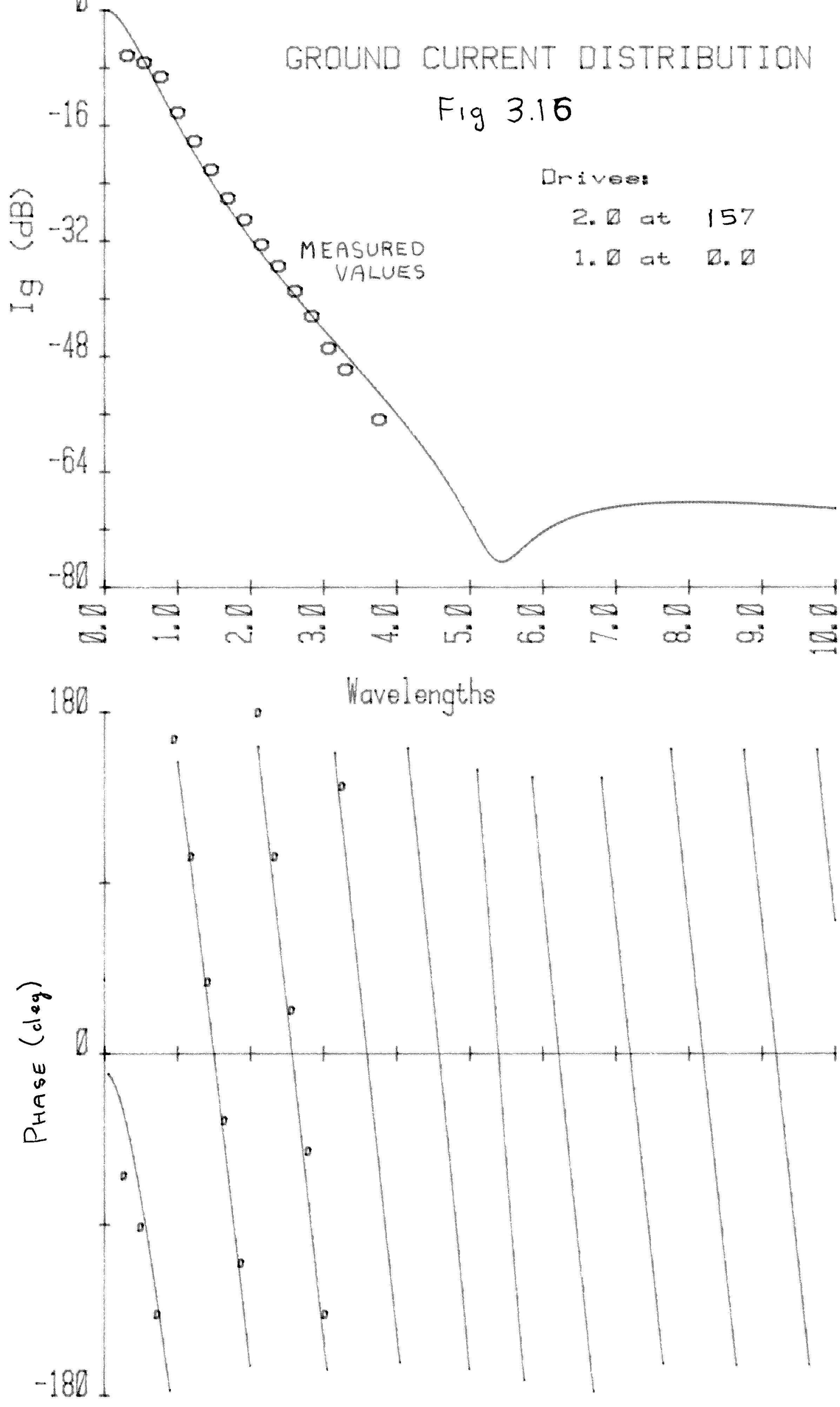
It has been suggested[24] and verified for the I.L.S. situation[18] that the radiated field of an array above a limited groundplane can be calculated by numerically summing the fields radiated by the drives and all the incremental ground currents induced by them. This method has the advantage that it is physically close to what is actually happening, and so allows the significance of different contributing areas to be assessed if so desired. Furthermore it has been shown to work for (small) negative angles as well. It assumes by the use of fundamental antenna theory that the ground currents are actually those predicted in the infinite ground plane case, despite any truncation edges. This can be thought of as equivalent to taking a vector integral under the current lines



IDEAL REALISEABLE VOR
ELEVATION PATTERN

FIGURE 3.14


GROUND CURRENT DISTRIBUTION
Fig 3.15
Drives:
1.Ø at Ø.Ø
Ig (dB)
-6
-12
-18
-24
-3Ø
MEASURED VALUES
Ø.Ø
Ø.3
Ø.5
Ø.8
1.Ø
1.3
1.5
1.8
2.Ø
2.3
2.5
Wavelengths
18Ø
Ø
-18Ø
Phase (deg)


GROUND CURRENT DISTRIBUTION
Fig 3.16
Drives:
2.Ø at 157
1.Ø at Ø.Ø
MEASURED VALUES
Ig (dB)
Ø
-16
-32
-48
-64
-8Ø
Ø.Ø
1.Ø
2.Ø
3.Ø
4.Ø
5.Ø
6.Ø
7.Ø
8.Ø
9.Ø
1Ø.Ø
Wavelengths
Phase (deg)
18Ø
Ø
-18Ø

of Figures 3.8 - 3.13, though of course the integral is taken over X and Y dimensions.

The current in a small element of ground is calculated assuming the element to be part of an infinite plane. As pointed out earlier this is known to be inaccurate in close proximity to an edge of the conductor. At first it was believed that the perturbation would not result in significant discrepancy between practical and theoretical cases, as in the I.L.S. situation. The measured ground current for a 2-wavelength counterpoise, shown in Fig. 3.15, is substantially in agreement with infinite groundplane theory. The smooth departure from theory just below the drives is due to failure of the approximations of Appendix I. Small perturbations are visible near 2.0 wavelengths. It seems reasonable to suppose that so small a departure would not destroy the basic assumption. The perturbation is even less pronounced when a null is placed in the ground at the edge (Fig. 3.16).

However, the program devised fails to deliver reasonable results. The principle of stationary phase indicates that when performing an integration of the type involved here the main contribution will be due to the central peak and the areas at the two limits of integration (the edges of the conducting plane). The perturbation in the current very close to the edge (less than $\frac{1}{4}$ wavelength) of this conducting plane is so violent that the ideal model is hopelessly inadequate, even when a current null is placed at the edge.

Attempts to measure the actual currents and to substitute these into the program also failed. This is substantially due to the rapidity with which they vary and the relatively narrow zone where perturbation occurs. Various artificial adjustments to current were tried in an attempt to obtain results approaching the actual case. This also did not work. The program repeatedly predicts a field pattern which is very close to the theoretical infinite ground case, or produces absurd results related to the precise complex value of the current calculated directly on the edge.

This method fails because Maxwell's Equations do not permit the ideal infinite groundplane currents to continue as such near an edge. With hindsight a new approach can be suggested. It seems feasible, though difficult, to solve for the actual currents by means of Successive Over-Relaxation (SOR) if the difficulty of bounding the infinite solution can be overcome. By consideration of skin-effects it might be possible to produce a two-dimensional model which wraps around the edge of the plane and is something similar to the exploded view of the solid depicted in Fig. 3.3. This is, of course, a difficult approach as the boundary conditions are extremely difficult to satisfy. Alternately, a simple two-dimensional model might be found adequate. This approach has not been undertaken here because of the sheer immensity of the problem in comparison to the time available, and so the ground current approach is now abandoned.

An analysis based on ray optics assumptions has been employed with apparent success by D.L. Sengupta[10]. He develops very complex and, unfortunately, very abstract equations to predict the performance of a driven element above a finite groundplane. Figure 3.17 gives a comparison between the predictions obtained by diffraction theory and the author's measured results. Agreement is good, as may be seen. Based on the same method a program for computation of the field produced by an array of elements was developed. This approach also failed to

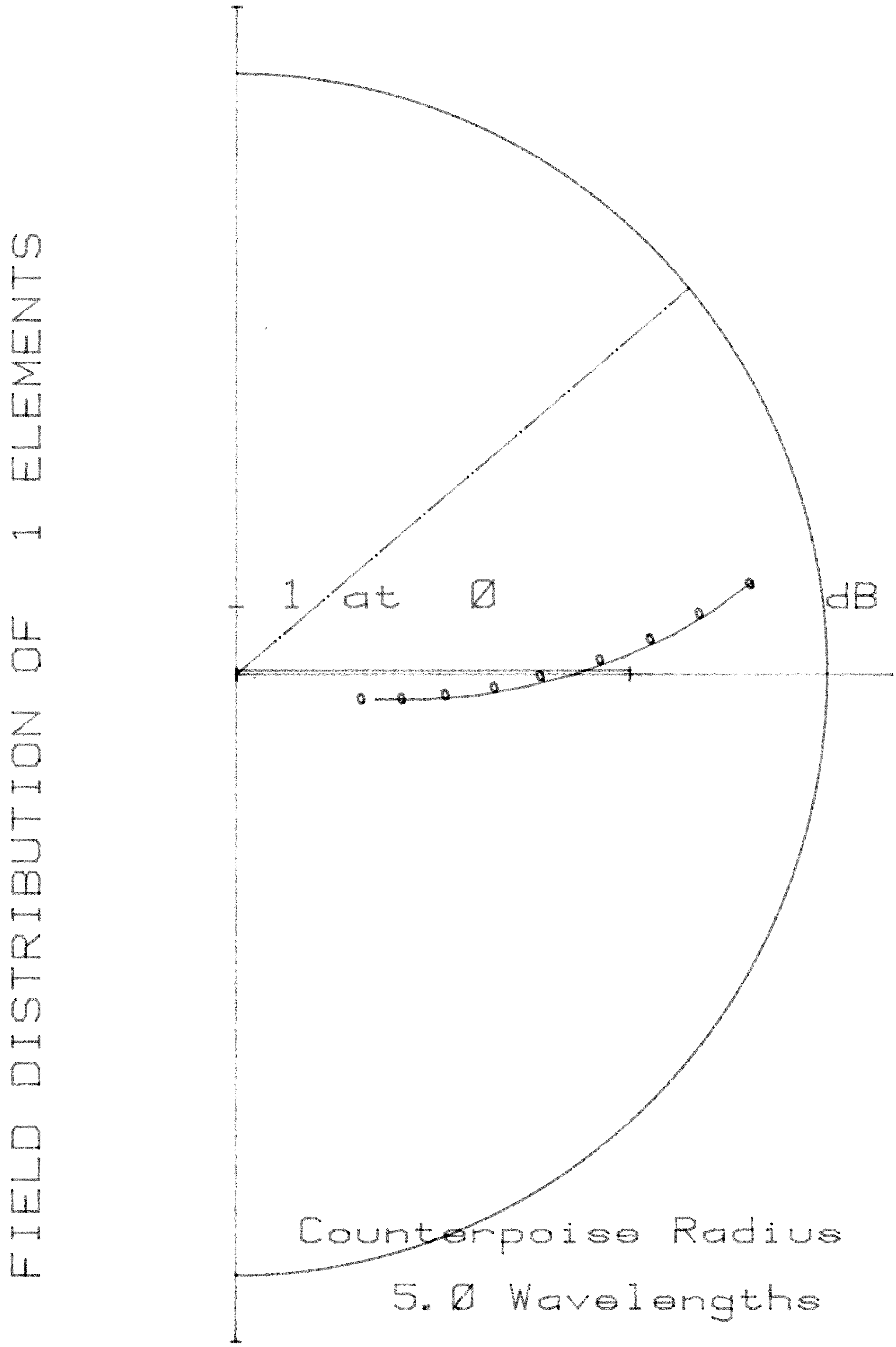

FIELD DISTRIBUTION OF 1 ELEMENTS
1 at Ø
dB
Counterpoise Radius
5.Ø Wavelengths

FIGURE 3.17

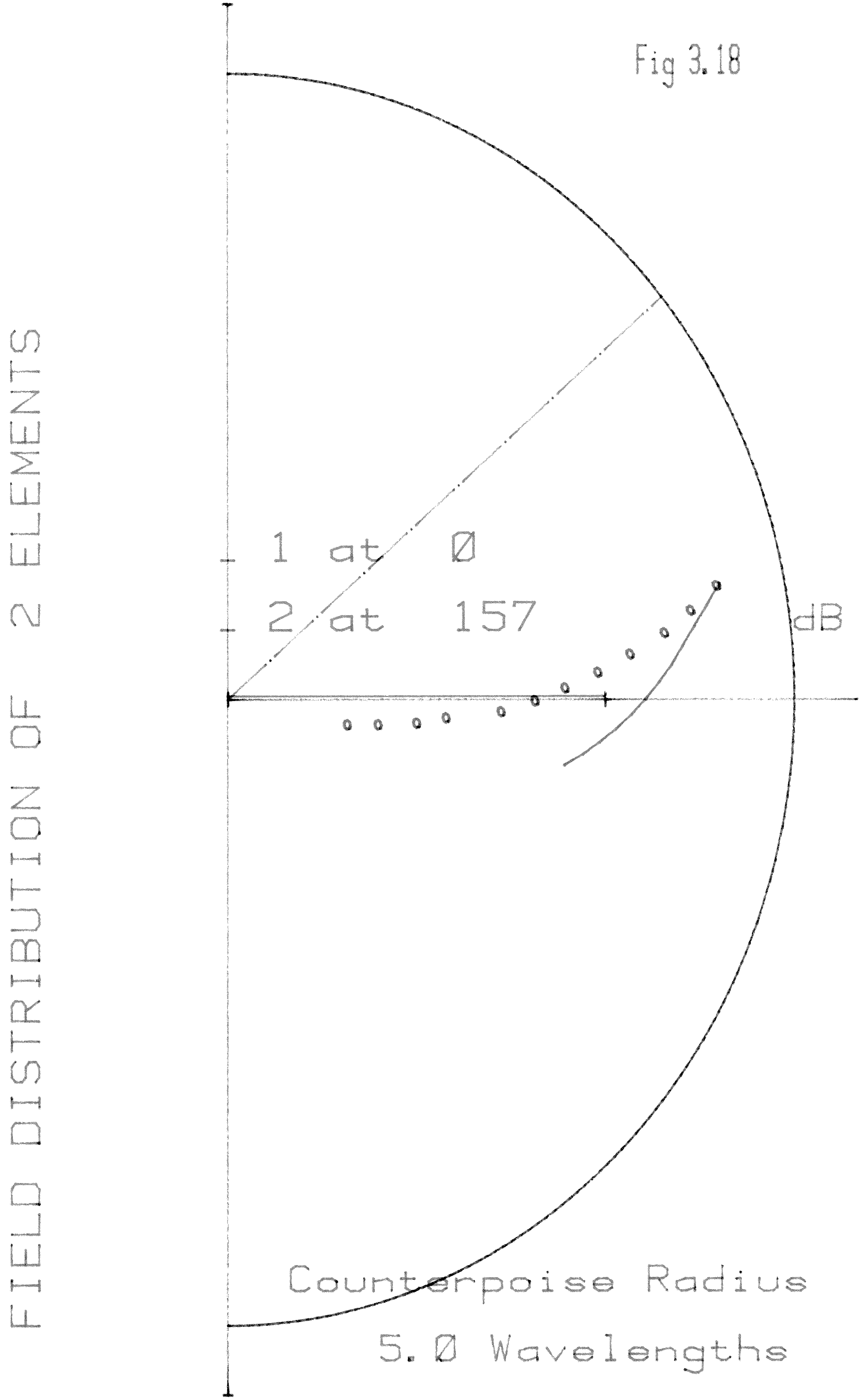
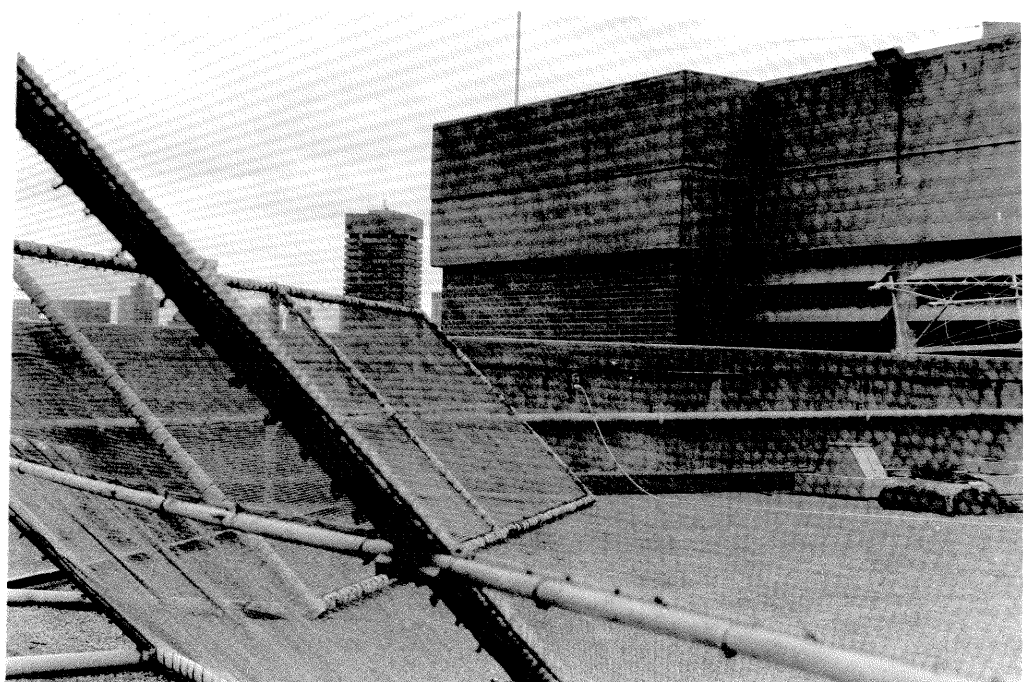

FIELD DISTRIBUTION OF 2 ELEMENTS
1 at Ø
2 at 157
dB
Counterpoise Radius
5.Ø Wavelengths

Fig 3.18

produce agreement with measured results (Fig. 3.18 shows the theoretically predicted and the measured results for the 1N-5 drive above a 5 wavelength counterpoise). Although it is difficult to break the diffraction approach into its contributing parts it appears that the edge-diffraction part does not accurately predict the phase of the resulting field. When this part has a significant contribution the fields cannot be superimposed as vector addition involves the phase of the signal. When only one drive is considered the phase is discarded. Sengupta assumes that, because his practice confirms theory, the ray optics assumptions are sound. This is suspect, as there are no other obvious places to seek a subtle deviation in phase. The ray optics approach must for the purposes of this work now also be abandoned. It is possible that some small correction term could be introduced to restore phase validity but the magnitude of the task of locating the source of the error is such as to rule this out in this work.

With no sound theory being available a great deal of emphasis must be placed on measured results, and so the arrangement which was employed and its limitations are carefully reviewed. In order to measure <u>far</u> field radiation pattern a separation of 100 wavelengths between transmitter and receiver is required. This consideration as well as the need to be able to place the model sideways on the available rotator to measure field pattern in the "vertical" plane (Photo 3.6) demand modelling to be done above 4 GHz. Equipment was avilable at 5.18 GHz and sothis frequency was chosen. While physically convenient, working with a wavelength of 58 mm produces a number of difficulties. Since the amplitudes and phases of drives are critical, the feed circuit must be carefully set up. Dirty

3.19 VIEWS OF THE TRANSMITTING TOWER AND REFLECTING SCREENS USED FOR ELEVATION PATTERN MEASUREMENTS



connections can easily cause fluctuations of more than 1 degree. Cable flexing also introduces excessive phase shift. Attenuation in various parts of the feed must be determined with an accurate Network Analyser as no vector voltmetering equipment can be used at this frequency. Precision attenuators must be used and they must be placed at several positions in between potential bad matches to remove dangerous reflections. A Time Domain Reflectometer is used to check the feeds for bad connections and to initially estimate line length. When readings are taken the calibration should be checked before and after the measurement to eliminate drift errors.

The range itself presents severe problems. Only when both transmitter and receiver are placed on 30 foot towers can the interference from reflectors be reduced to an acceptable level. In addition a directional horn receiving antenna must be used as well as screens to reflect ground path rays up into space (Photo 3.19). Even with these measures a maximum dynamic range of 25 dB was achieved. Results were found to be repeatable from one day to the next; however, the setting up procedure including all the careful calibration required to achieve this situation took some days to develop. Rain and winds of more than 5 knots prevent repeatable experimental measurements. Consequently only a limited number of runs with known accuracy were possible, and these with only 2 drives.

One final comment on the experimental method must be made before proceeding to the analysis and discussion of results. The model antenna is known to have an elevation pattern similar to that of a VOR element, but the ground current disturbance is not known to be similar. In the 2D model the crucial forward edge runs parallel to the theoretical current lines but the theoretical current at the edge is not constant in magnitude. In the case of the circular VOR counterpoise with omnidirectional antenna, the current is not perfectly parallel to the edge since the drive has finite width, but it is constant in magnitude. Any approach which derives some effect from adjustment of the edge current may thus produce slightly different results in the model to those which would be obtained with a VOR. While no method of assessing the discrepancy is available it is believed that it will be small especially in the case of the T58 aerial since its width is small with respect to the size of the counterpoise.

4.1 THE SIGNIFICANCE OF GROUND CURRENT DISTURBANCE AND THE PERFORMANCE OF THE NEW ARRAYS

A number of elevation pattern measurements were made using the 5.18 GHz model previously described. Key results are summarised in Table 4.1. The asterisked points are readings which require special consideration. These neatly highlight the limitations of the model used. These readings are less certain owing to particular drawbacks of the modelling frequency. They occur in two groups: (a) In dealing with a null precisely on the ground plane edge at 2 or 10 wavelengths distance; (b) Locating a null at 20 wavelengths. Three practical experimental limitations account for the uncertainty of these readings. The first is simply that at 5 GHz using a variably frequency source it is extremely difficult to guarantee drive phase to the same precision as is obtainable when using a crystal-locked source operating below 120 MHz. The resolution of the apparatus did not permit a null to be located with any certainty at 20 wavelengths or further. For this reason the null could not be guaranteed to be exactly on the edge in the 10 wavelengths case. The results quoted for this case could be repeatedly obtained, though superior results were seen on occassion. These cannot be claimed correct, though from other trends it seems likely that they represent the true case.

The second limitation is the dimension of the current probe. The probe represents a significant fraction of a wavelength and causes some field disturbance. Therefore locating the null at exactly 2.0 wavelengths is difficult. The table quotes the range of values obtained. It is very likely, from theoretical and experimental considerations that the value of 0.9 represents the null-on-edge situation, but again this

LEGEND

AT Ø deg.
dB down AT Ø deg.

GROUNDPLANE RADIUS (c)	TYPE OF ARRAY: SINGLE ELEMENT	NULL AT C	NULL AT 2C
10λ	0.85	>0.9 *	0.95
	16	19 *	*
5λ	0.66	1.1	0.80
	14	24	27
2λ	0.35	0.6 - 0.9 *	0.63
	10	16	16

* SEE TEXT

TABLE 4.1

cannot be absolutely guaranteed.

The third limitation is one external to the range. A number of readings, in particular those over a 5 wavelength groundplane were taken on a Sunday, during a strike which had immobilised Mascot Airport long range radar. The reduced interference on these occassions allowed some 5 dB further dynamic range, which proved to be significant, as values approaching 30 dB dynamic range were readily obtained.

The limitations discussed have prevented quantitative conclusions from being reached, but result trends are unquestionably discernible. The success of the Image Ground approach is indicated by the improvement obtained in all cases. The significant effect of the ground current perturbation near counterpoise edges upon field pattern, when the counterpoise is only a few wavelengths long, is also indicated. These will now be discussed, and the anticipated performance improvement of a VOR using a new array calculated.

Placing a null beyond the edge of the counterpoise can be seen to give almost a factor of 2 improvement over a 2-wavelength groundplane. The improvement is not so great with large counterpoises. However, reduction of disturbed edge current can be seen to give much more significant improvement. Also the degree of improvement increases with decrease in groundplane dimension,although the larger groundplane gives the best final result. It should be recalled here that the drive phases to produce one null are less critical the closer the null. It may be concluded now that it will be better practice to introduce a second antenna than to extend the counterpoise, should the improvement afforded by this be adequate. Since a 15 wavelength (80m diameter) counterpoise gives only -19 dB with 1 dB/ degree at 0 degrees it is seen that a pair of elements above, say,

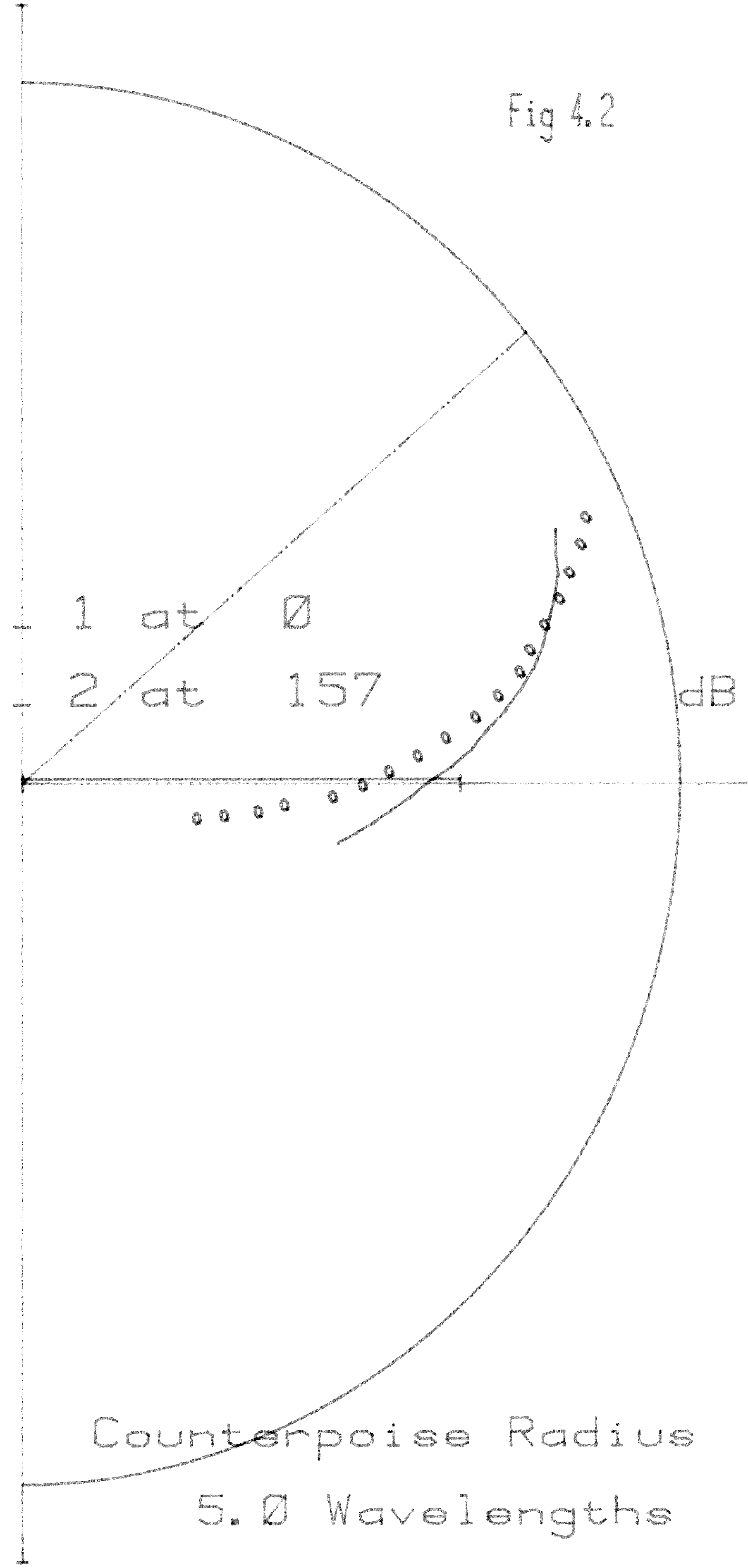
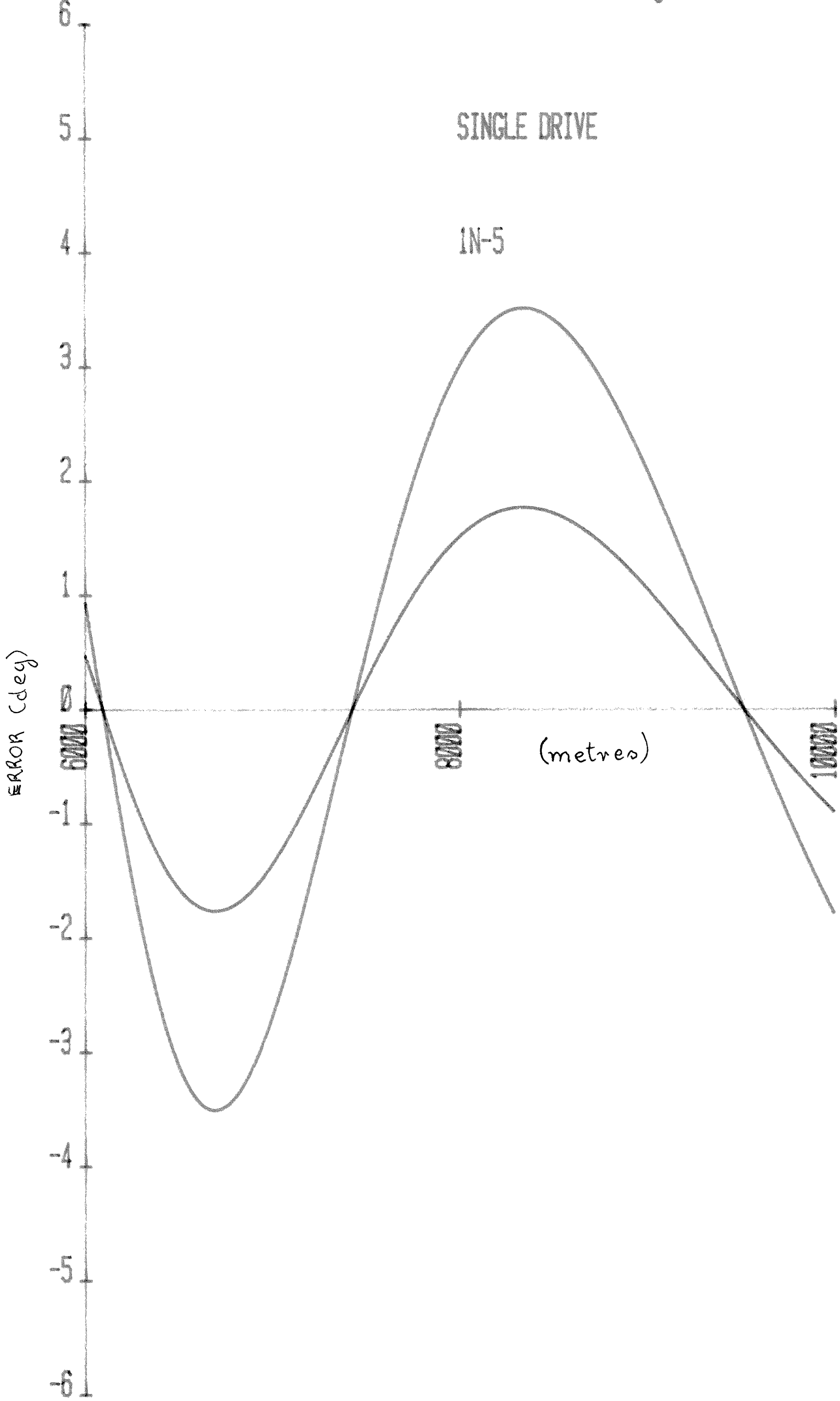


Fig 4.2

FIELD DISTRIBUTION OF 2 ELEMENTS

SIMULATED RUN IN SCALLOPING ERROR Fig 4.3



an existing counterpoise of 3 wavelengths (17m diameter) will give better performance in less than 1/20th the area of ground. At an airport where land may be at a premium due to the inevitable expansion of facilities this advantage cannot be overlooked. Figure 4.2 shows the pattern obtained with a 1N-5 drive over a 5 wavelength counterpoise in comparison to the single drive case. A computer simulation of the anticipated course error reduction in a typical situation is given in Fig. 4.3.

As can be seen, the error has been brought to an acceptable level. It may further be noted that the null position can readily be changed by realigning the feed so that should a null used with an existing counterpoise be found to be inadequate, it is a simple next step to extend the counterpoise.

4.2 CONCLUSION

This thesis has studied the design and performance of VOR arrays operating over severely limited counterpoises. Also the problems of predicting the performance of such an array have been discussed. Two methods of theoretical calculation of radiation pattern have been investigated. While both of these were unsuccessful, the work is useful in the negative sense that such approaches have been shown to be unreliable in the case of the dimensions with which this situation is concerned. Moreover, the need for the investigation by another method, such as relaxation, has been highlighted.

A theory based on consideration of ground currents has been used to select the drives of an array in order to achieve, by induced current nulls, superior performance in the presence of limited groundplane. With the experimental facilities available important observations have been made regarding the significance of the current discontinuities at the edge of a counterpoise.

However, before any of the results obtained here can confidently be applied to the VOR, further investigation is required. As outlined in the appropriate section, modelling must be undertaken at a lower and moremanageable frequency, especially for 3-drive situations, and hence on a larger scale. It should finally be confirmed with actual omnidirectional loops. It is highly desirable that a computer programme be developed which allows the accurate analysis of array performance.

I hope that this thesis will provide a sound basis for guiding further work towards the understanding and use of the Image Ground Approach for improving VOR performance, and arrays above limited counterpoises in general.

APPENDICES.

APPENDIX I

It is required to show that the field radiated by a VOR antenna element can be approximated by a half-wave dipole positioned one-quarter wavelength in front of a backing plate as shown in Fig. A1.

The field from a half wavelength resonant dipole is given in the far field by[21]:

$$E_\theta = j\,\frac{60\,I}{r}\,e^{-jkr}\,\frac{\cos(\pi/2.\cos\theta)}{\sin\theta} \qquad \ldots\ldots\ A.1$$

where r = distance to the receiving point

$k = 2\pi\,/$ wavelength

I = complex drive current

θ = angle between the observer and the plane perpendicular to and bisecting the dipole

and $e^{-j\omega t}$ time dependance is assumed

All consideration is in the plane perpendicular to the dipole and bisecting it, so A.1 reduces to:

$$E = j\,\frac{60\,I}{r}\,e^{-jkr}$$

Now, the field due to the drive in Fig. A.1 may be computed by replacing the backplate with the negative image, provided it is adequately large (Fig. A2). For the situation where ϕ is small, the Fresnel zones will be small and this will readily be practically realisable.

Then, the complete field may be written:

$$E_T = E_1 + E_2 \doteqdot j\,\frac{60\,I}{R}\,(e^{-jkr_1} - e^{-jkr_2}) \qquad \ldots\ldots\ A.3$$

Now, if the receiving point P is distant from the drives,

$$r_1 = R - \frac{\lambda}{4}\cos\phi \qquad \ldots\ldots\ A.4$$

$$r_2 = R + \frac{\lambda}{4}\cos\phi \qquad \ldots\ldots\ A.5$$

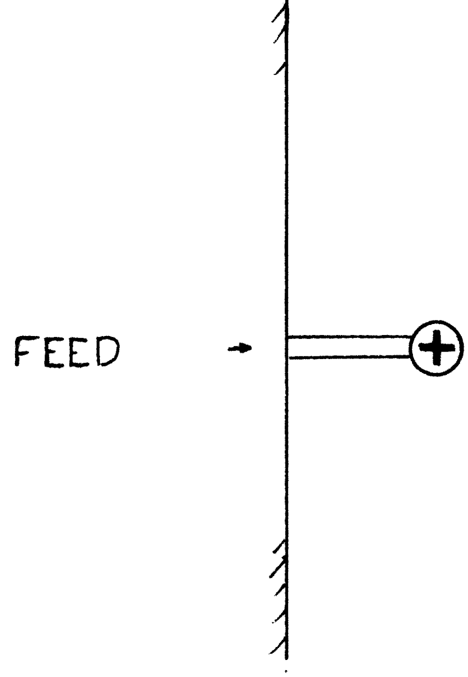


FIGURE A.1

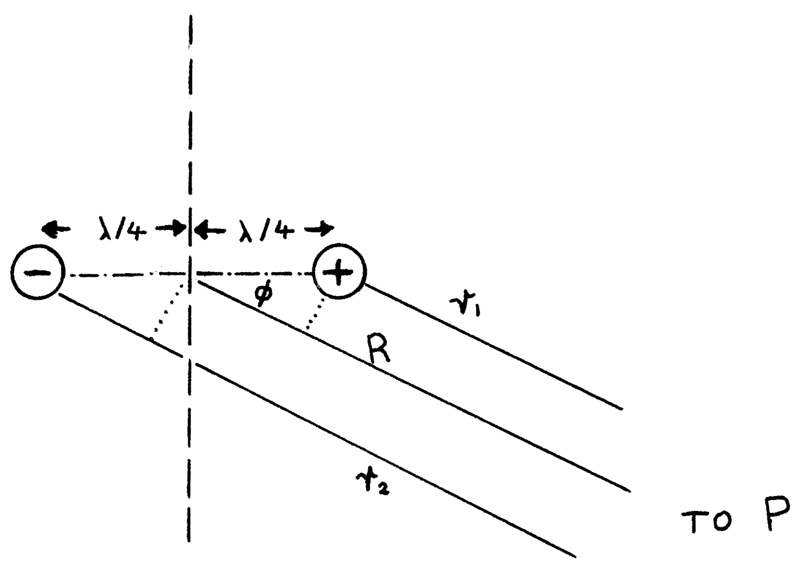


FIGURE A.2

Using A.4 and A.5 in A.3, discarding the constant multiplying terms and constant phase shift terms, it may be found that:

$$E_T \propto e^{+j\frac{\pi}{2}\cos\phi} - e^{-j\frac{\pi}{2}\cos\phi}$$
$$= 2i \sin\frac{\pi}{2}\cos\phi$$

which shows that the drive has a ϕ directional component of

$$\text{Sin}\,\frac{\pi}{2}\cos\phi \qquad \ldots\ldots \text{A.6}$$

which has the same dependance as a cylindrical antenna element and very similar response to an Alford loop antenna for small ϕ [13,15].

APPENDIX II

It is required to compute the set of n complex drives required to produce n-1 nulls in ground current at distances D_1 to D_{n-1} from the centre of the counterpoise (The point below the array).

Now $\qquad J_s \propto n \times H_T \qquad$ (Fig. A.3)

where $\qquad H_T$ = tangential H field

J_s = induced current

Computing H_T and summing over all elements of the array[17,18],

$$J_s \propto \sum_{m=1}^{n} (I_m . h_m \,/\, R_m^2)\; e^{-jkR_m}$$

where $\qquad R_m = (D_m^2 + h_m^2)^{\frac{1}{2}}$

$k = 2\pi$ / wavelength

h_m = height of m^{TH} element

I_m = complex drive current of m^{TH} element

For n-1 nulls in J_s it is then required to solve the n-1 linear equations:

$$0 = \sum_{m=1}^{n} I_m \left\{ h_m . e^{j(-2\pi \sqrt{(D_z^2 + h_m^2)})} / (D_z^2 + h_m^2) \right\}$$

with z running from 1 to n-1.

These may be solved 'uniquely' by giving I_n the real value unity, which has been done here.

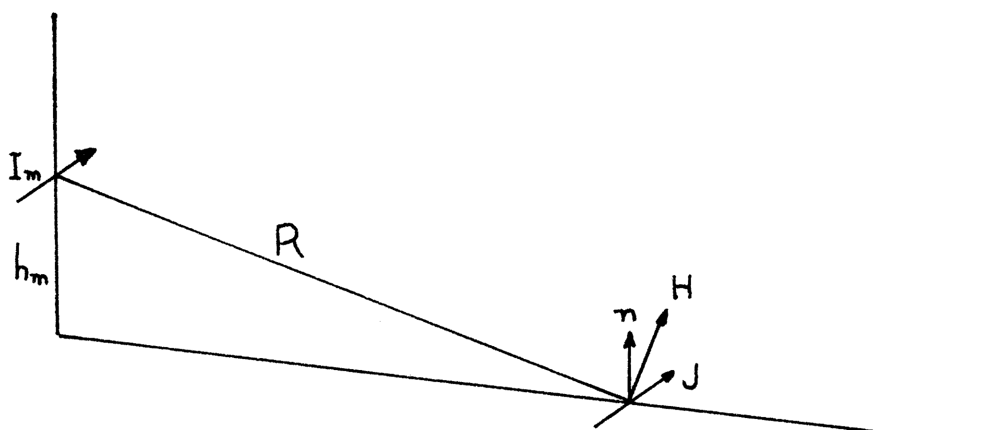


FIGURE A.3

APPENDIX III

This section will show that no array of the N type discussed in the main text will produce unexpected nulls in the region 0 to +40 degrees. This is proved by considering the Circle Diagram Approach. This method of analysis provides clear insight into the performance of an array and so the discussion is somewhat longer than is required to merely prove the above. Note that it is in fact faster to verify numerically that 'N' arrays have no unexpected nulls at infinity than it is to prove this analytically.

Schelkunoff has shown that a colinear, equally spaced array has a simple polynomial whose zeroes describe its far field pattern. As shown in Fig. A.4 a vertical array of drives above an infinite groundplane can be written as a Schelkunoff array by taking the images as elements of the array and putting the drive of the centre element equal to zero. It has also been shown[18] that for this case the far field has an angular variation

$$F(Z) = \sum_{n=1}^{N} A_n \left(Z^n - Z^{-n}\right) \qquad \ldots\ldots \text{ A3.1}$$

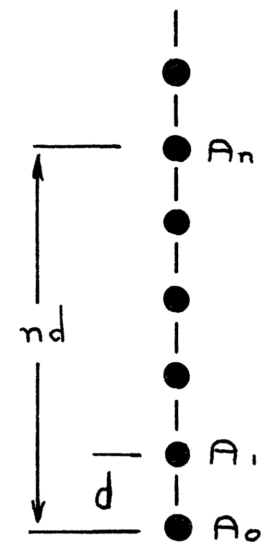
where
- N = number of active real elements
- A_n = Complex drive of nth element
- $Z = e^{jkd.\sin\theta}$
- $k = 2\pi/\lambda$
- d = interelement spacing
- θ = angle from horizon

This polynomial has 2N zeroes and can be written as the product of N factors:

$$F(Z) = \left(Z - Z^{-1}\right) \prod_{n=2}^{N} \left(Z + P_n + Z^{-1}\right) \qquad \ldots\ldots\ldots \text{ A3.2}$$

where $$P_n = -\left(Z_n + 1/Z_n\right) \qquad \ldots\ldots\ldots \text{ A3.3}$$

There are always 2 zeroes, at ± 1.



FORM OF SCHELKUNOFF ARRAY

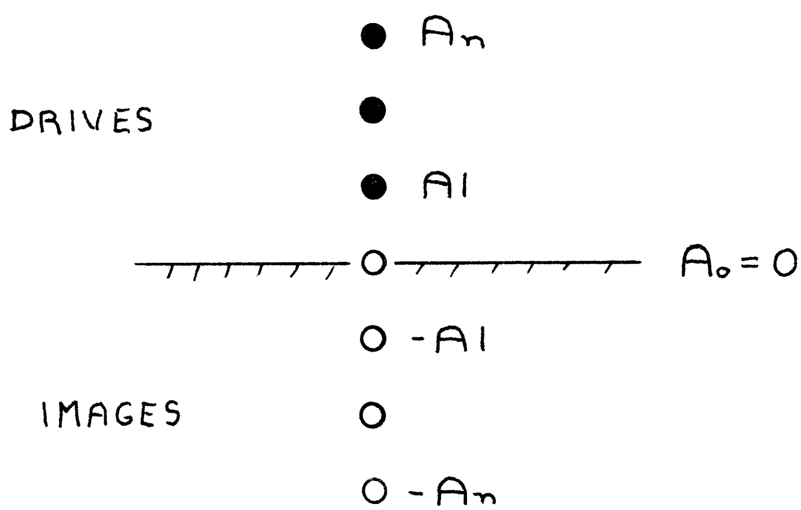


IMAGE ARRAY IN SCHELKUNOFF FORM

FIGURE A.4

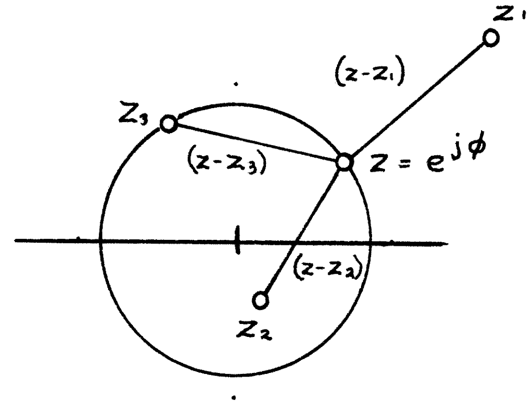
The other zeros can be seen to occur in reciprocal pairs. The total radiated field intensity will be proportional to the product of all the distances between these zeroes and the point $Z(\theta)$:

$$F(Z) = \prod_{n=1}^{N} (Z - Z_n) \qquad \ldots\ldots \text{A3.4}$$

This is graphically represented in Fig. A.5. $Z(\theta)$ varies about the unit circle.

A field null at infinity obviously occurs when the point $Z(\theta)$ coincides with a zero of $F(Z)$. In the case of the 'N' arrays $d = 0.5$ and so the zeroes at ± 1 correspond to the (theoretical) field nulls at $\theta = 0$ and 90 degrees. (Remember that the angle that a zero on the unit circle makes with the zero degree point does not correspond exactly to the angle from the real array but is related by $\phi = kd. \sin\theta$). The Circle Diagram representation of the single element case is given in Fig. A.6.

It is now shown that if the additional drives are focussed in the near field they correspond to the addition of zeroes which lie off the unit circle. In Reference 18 it is shown that a zero point can lie on the unit circle, and hence represent a null at infinity; this requires that the drives producing the null are real. All solutions for 'N' array drives are complex; and it can be shown, though it is not considered worthwhile to reproduce the development here, that all solutions for two drives give complex currents whose phases differ by an angle that lies between 0 and 180 degrees. The phase difference tends to these limits as the null position tends to 0 or infinity respectively. The three drive situation has not been analysed theoretically as again all drives considered are clearly complex.



$$F(z) = \prod_{n=1}^{N} (z - z_n)$$

FIGURE A.5

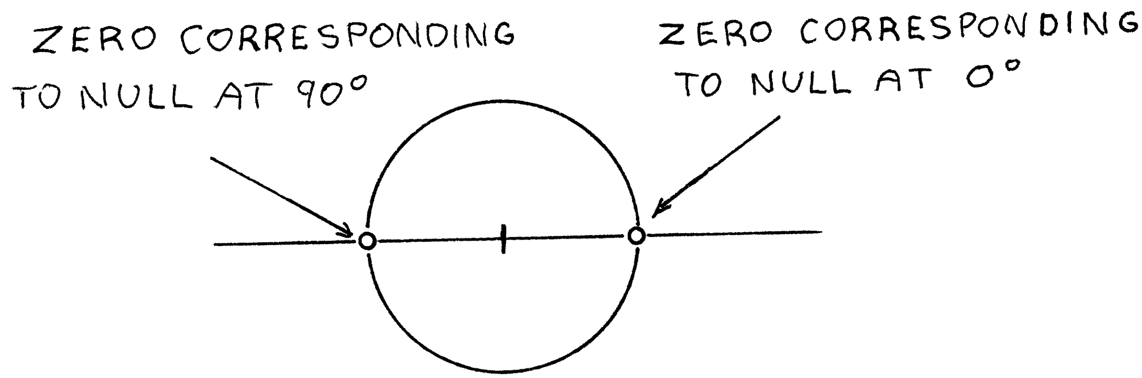


FIGURE A.6

Hence, all 'N' drives have only two zeroes on the unit circle, and only the two field pattern nulls at 0 and 90°.

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