The Development of a Hand-held Direction Finder

John Kevin Atkinson

Submitted in partial fulfilment of the requirements for the qualification of Master's Diploma in Technology in the Department of Electronics, Technikon Natal.

Supervisor : Mr S. Shearer M.Sc. (GIT)
Co-supervisor : Dr D.J. Coertze D.Sc. (PUCHE)

Durban
January 1990

ACKNOWLEDGEMENTS

I wish to thank the following people who have contributed towards this dissertation in various ways.

My co-supervisor, Dr. D.J. Coertze, for the many hours of his time he gave up to assist with the methodology of this dissertation, and for the help rendered during the tests conducted in Bloemfontein.

Mr. S. Shearer, my supervisor, for the encouragement and support he offered.

Grinel, Natal, for their financial support and for the freedom to use their equipment as and when I needed to. The staff were most helpful in contributing ideas and giving advice towards the design. Mr. P. Cornelius, Mr. M. Smith and Mr. D. Barnard rendered invaluable assistance in the construction and testing of the units.

Finally, I wish to thank my parents for all the encouragement and support they offered, particularly when the end seemed to be a long way away.

ABSTRACT

This dissertation is primarily concerned with the design, development and performance of a hand-held radio direction finder.

The requirements of the potential end user of the direction finder were used as a guideline in determining the method to be used. The loop and sense antennae system was found to be the most suitable. The frequencies used were the low end of the HF band. At these frequencies the antennae were of the narrow aperture type, and problems, such as the bending of the approaching wavefront around obstacles, had to be investigated. Hills and regions of varying ground conductivity both affect the range and accuracy of the direction finder, and this was investigated during the field tests.
After landing at night paratroopers experience considerable difficulty in regrouping. Night tests were done to establish to what degree the direction finder helped.

The possibility exists that hostile forces may see the light emitting diodes at night. The degree of visibility of red, green and amber light emitting diodes at various distances was established. It was found that the initial choice of red had been the most suitable.

Due to the small capture area of the antennae, as well as the low power being transmitted, the direction finder needed to have a high sensitivity. The unit was required to work at 5 km range, and was found to exceed this figure.

The broadband front stages compound the noise problem, which exists at HF. It was attempted to reduce the noise by a reduction in the bandwidth of the audio stages.

The response of the end user was gauged by means of a questionnaire.

The emphasis was placed on portability, reliability and efficiency in guiding the user to his destination as quickly as possible.

To my parents

CONTENTS

6. GENERAL DISCUSSION

LIST OF FIGURES

LIST OF TABLES

TABLE OF ABBREVIATIONS

A	Amperes
AGC	automatic gain control
AM	amplitude modulation
dB	decibels
DF	direction finder
DZ	drop zone
EMF	electro-motive force
FET	field effect transistor
FM	frequency modulation
HF	high frequency
IC	integrated circuit
JFET	junction field effect transistor
LED	light emitting diode
LOS	line-of-sight
NA	narrow aperture
PDF	personal direction finder
PPM	parts per million
RF	radio frequency

SNR	signal to noise ratio
UHF	ultra high frequency
V	Volts
VCO	voltage controlled oscillator
VHF	very high frequency
WA	wide aperture

CHAPTER 1

THE PROBLEM AND ITS SETTING

1.1 Introduction

Direction finders can be divided into two broad groups, namely narrow aperture (NA) and wide aperture (WA) systems.

A NA system uses antennae which are small in dimension compared to the wavelength at which they operate. A WA system is one in which the antennae in use are an appreciable fraction of the wavelength in use (generally 0.1 Lambda or greater). The direction finder described in this document will be of the NA type.

The art of finding direction by means of a radio system extends back to around the beginning of the 19th century. In 1902 Braun achieved a degree of directional effect with a straight inclined antenna. Three years later Marconi designed an inverted-L transmitting antenna with a similarly designed receiving antenna and patented this system [Keen,1947:6]. Marconi claimed at that time to have achieved very appreciable directional effects. Bellini and Tosi followed in 1907 when they introduced the Bellini-Tosi antenna system [Keen,1947:8; Haigh,1960:15]. This was when the goniometer was apparently first used in radio direction finding systems. This goniometer used two loop antennae at right angles to each other for the purpose of direction finding [Haigh,1960:16]. The earliest goniometers synthesized a rotating loop by electromechanical means. The most recent types have been transistorised. It is also well known that a vertical antenna and a loop antenna can be used together to determine direction. This fact was first demonstrated by Round as early as 1905 [Powell, 1986:293].

From 1920 onwards progress in this field was rapid, owing to the important role it had to play in both of the world wars. In 1935 certain ships in the British navy were required by law to be equipped with direction finders [Cotter,1961:29]. Most of the direction finder (DF) systems described above are physically large and do not lend themselves well to hand-held work.

Infantry still use compasses to orientate themselves and the problems experienced with finding direction at night or in dense vegetation are well known. The need for an alternative method of orientation exists. The advantages of using radio systems similar to those used by ships to enhance direction finding are therefore obvious.

Until the present time, technology has restricted the development of hand-held DF systems, a few of the reasons being :

1. The large size of the components.
2. The large current consumption of the components.
3. The lack of portable, efficient power sources.
4. Insufficiently advanced technology.

With the rapid advance of technology these barriers have fallen away. Portable DF units are used for "fox hunting" and other applications, with design notes for hand-held units included [Anon,1988:ch39]. Welch points out a few of the problems associated with NA systems in trying to achieve a high degree of directional accuracy [Welch,1985:287]. One of these, for example, is the curving of the transmitted wavefront, which gives rise to erroneous readings. This research effort will attempt to solve the problems associated with the design of a hand-held direction finder.

1.2 Statement of the Problem

The purpose of this study is to design a hand-held direction finder capable of operating over a distance of 5 kilometers in terrain encountered during typical military operations in Southern Africa, and to evaluate its performance and reliability under these conditions.

1.3 Statement of the Subproblems

The first subproblem is to identify the elements and techniques needed for formulating the specifications and to design and construct a hand-held personal direction finder (PDF).

The second subproblem is to evaluate the performance and suitability of the direction finder in terms of the specified military requirements.

1.4 Hypotheses

The first hypothesis is that it is possible to identify the elements needed and to design and construct a PDF.

The second hypothesis is that the constructed PDF will meet the requirements specified by the potential user.

1.5 Definitions of Terms

For the purpose of this study frequency ranges are defined as follows :

LF (low frequencies)	= 10 - 1000 kHz
HF (high frequencies)	= 1.6 - 30 MHz
VHF (very high frequencies)	= 30 - 300 MHz
UHF (ultra high frequencies)	= 300 - 3000 MHz

Paratrooper = Troop carried by air, to be dropped by parachute (Chambers 20th Century Dictionary)

1.6 Delimitations

The requirements specified by a potential end user of the PDF were adopted as the delimitations of this study. They were divided into physical and functional specifications.

1.6.1 Physical Specifications

1. The PDF should be small enough to be held comfortably in one hand. It should be able to fit into the breast pocket of a paratrooper's jacket.
2. The shape of the PDF should be one which is practical for a paratrooper to carry. Its mass should not exceed 500 grams.

3. The power source for the PDF must be a cheap, easily obtainable one. For example, a 9 V dry battery.
4. The PDF must distract the user as little as possible, so as to allow him maximum awareness of his surroundings.

1.6.2 Functional Specifications

1. The testing of the PDF will take place over terrain which approximates that typically encountered by army ground forces involved in military engagements in Southern Africa.
2. The transmitter power will be kept to a maximum of 2 watts.
3. It will be possible to operate the PDF while being hand-held.
4. Cost will not be taken into account in the design of the PDF.
5. The average paratrooper should find the PDF simple to operate.
6. The power consumption of the PDF should be such that the user is able to take at least 100 readings of 30 seconds duration and five minutes apart during daylight conditions.
7. The means of indication will be audio or visual, but will not make the user's position known to any person in his immediate proximity. For example, no bright light or loud buzzers.

8. Reliable operation. A 100 % success rate would be ideal up to distances of 5 km over typical landscapes encountered by military forces in Southern Africa. A success rate of 90 % would be acceptable.
9. The PDF should be able to operate satisfactorily with a signal received from a transmitter radiating 2 watts of RF power at a distance of 5 km.
10. Reliable operation should be possible at any time in a 24 hour period.
11. No electronic counter measure (ECM) facilities will be included in the design of the PDF.

1.7 Assumptions

In the course of the tests conducted the following assumptions were made :

1. The five constructed units were assumed to be equal in electrical characteristics. They were of one design and were constructed of low tolerance components.
2. It was assumed that the ground conductivity at Tempe, Bloemfontein (where the tests were completed) was approximately the same as that found in the operational areas of Southern Africa.

1.8 Importance of the Study

Much work has been done on direction finding [Cotter,1961; Gay,1961; Gorst,1973; Hardman,1980; Barton,1983; Bogachev,1986; Karavassilis, Davies & Guy,1986]. Many different methods of direction finding exist [Keen,1947; Cotter,1961; Haigh,1960]. Direction finders have been designed for several different functions. However, most of these functions require a unit which, although perhaps being portable/mobile, is still physically large and is thus not suitable for a hand-held application. Welch (1985:283) describes several DF units for military use which, although are very sophisticated and complex, are not designed for hand-held work. They have been designed to assist in strategic planning in the FEBA (forward edge of the battle area). The primary role of the DF equipment in this application is to monitor selected target transmissions and, by measurement, to establish the target bearing relative to the DF site. Systems which use adaptive null tracking and which are also large are described [Barton,1983:78]. On the other hand, systems which are of a more portable nature, and which are used by radio hams, also exist [Anon,1988:39-1].

The literature does not describe a system suitable for hand-held work by paratroopers in operational situations. There is a lack of DF equipment for military usage which is specifically designed for hand-held applications. The need is real and such a unit would be of value in many military operations. For example, ground forces could make use of such a unit in terrain where vehicles would find it impossible to travel.

The purpose of this investigation is therefore to develop a hand-held direction finder. The emphasis will be placed on portability and reliability under varying conditions of ground conductivity, topography and operating conditions.

CHAPTER 2

REVIEW OF THE RELATED LITERATURE

2.1 Introduction

The successful orientation or even navigation of any unit is dependent upon a number of physical, environmental and technical factors. For example, topography, ground conductivity and type of antenna used will in some way or another affect the accuracy and operating distance of a direction finding instrument. Since environmental factors change continuously and cannot be controlled, the choice of a suitable direction finding system is very critical. A short description of several methods and a discussion on the suitability of each for use in this project are given.

2.2 Amplitude Monopulse Systems

The amplitude monopulse system uses WA antennae and is used at typical radar frequencies (UHF frequency band).

A monopulse receiver is so-named because directional information is collected from a single radar return or emission from the target [Schmidt & Davis,1985:104]. This means that a burst signal is received at the antenna system as opposed to a continuous wave (CW) signal. Two antennas which have a common phase centre are used, thereby ensuring that the signals received are of equal phase (Figure 2.1). The antennas are of a directional nature however, and are offset by a few degrees. The field patterns of the antennae overlap slightly, and the average centre of the two patterns is known as the system boresight. When the target is on the boresight line the amplitude of the signal from each antenna is equal and the difference between the two signals is zero. If the signal arrives on the right side of the boresight axis, the signal received at antenna A is greater than that at antenna B. The difference (A-B) is in phase with the sum (A+B). The system then establishes that the target is to the right of the boresight axis and the actual amplitude difference(A-B) is used to compute how many degrees this difference constitutes. This information is used to calculate the bearing of the target.

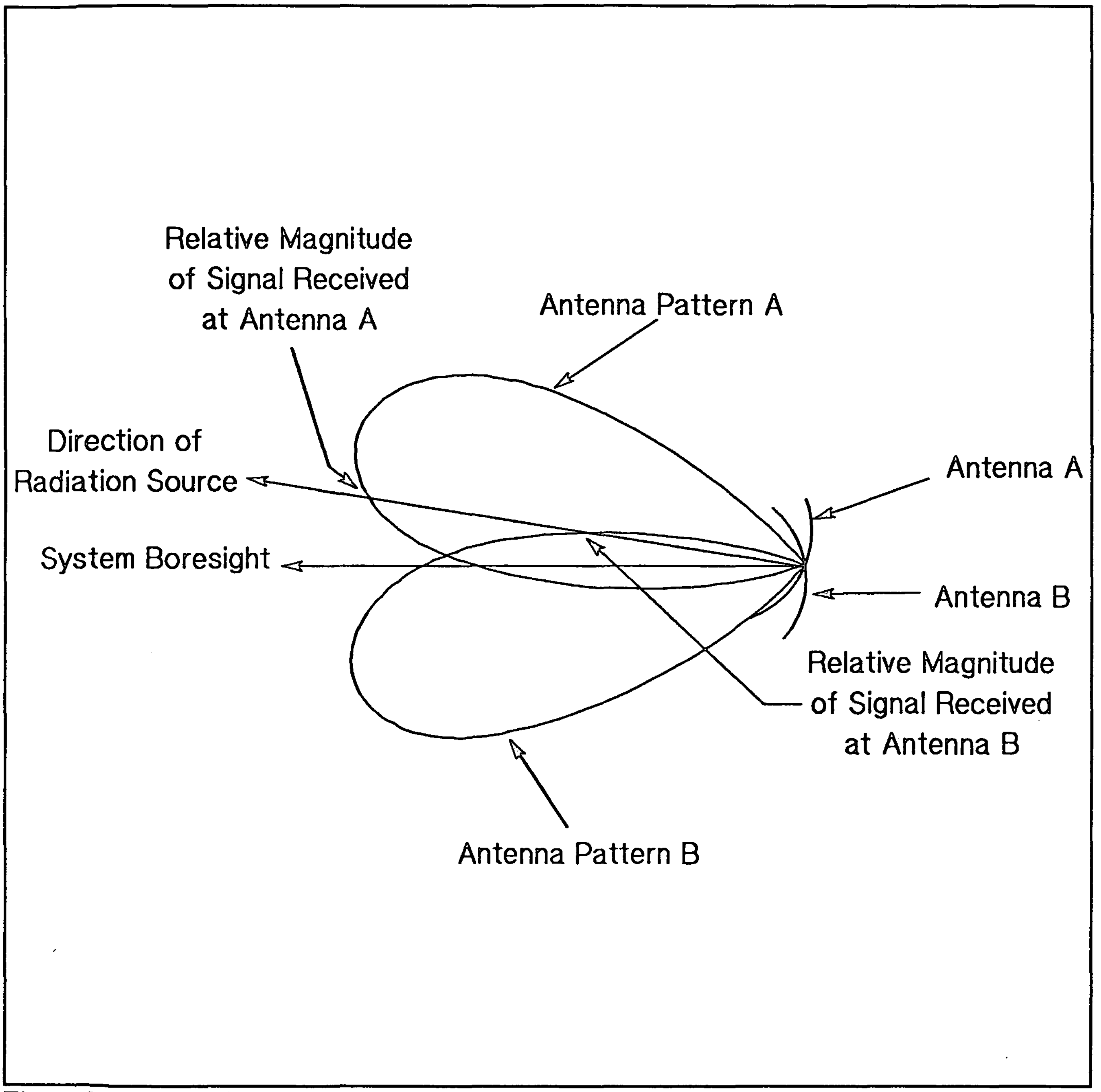


Figure 2.1 Amplitude monopulse system, showing the two antennae used, with their respective polar patterns. The difference in relative magnitude of the signals received by the antennae is used to calculate the direction of the source. (Schmidt & Davis,1985:105)

In older systems the (A-B) signal was used to drive the boresight axis onto the axis of the target signal by repositioning the antenna platform. Directional information could then be ascertained from the position of the platform. Modern systems do not use this method as small, lightweight systems do not employ the luxury of a rotating platform. Furthermore, it is important that accuracy is obtained both on and off the boresight so as to facilitate tracking of multiple targets [Schmidt & Davis,1985:106].

2.3 Phase Monopulse Systems

Phase monopulse systems, like the amplitude monopulse system, employ WA antennae and operate in a similar frequency range.
In the phase system, two antennae are again used, but they are placed apart by a known distance and have the same boresight axis (Figure 2.2). This ensures that the amplitude of the target signal received at each antenna is equal, but the phases differ, as shown in the diagram. Directional information is determined by the phase difference of the two signals [D'Antonio & Gaffney, 1968:728]. The diagram illustrates the wavefront arriving at antenna A before antenna B and this difference in time can be used to determine the offset between the boresight axis and the axis of the arriving wavefront.

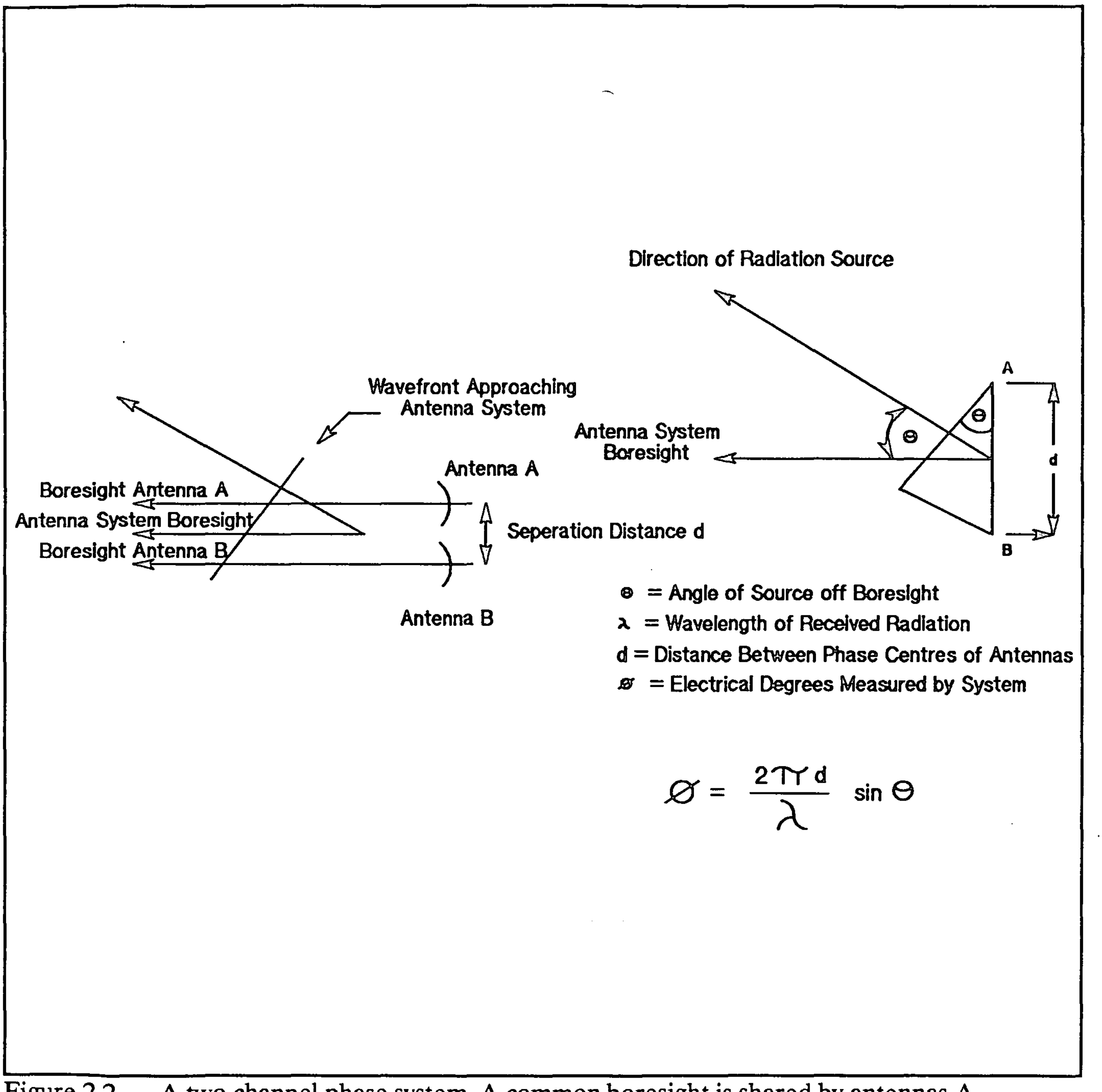


Figure 2.2 A two channel phase system. A common boresight is shared by antennas A and B. A signal arriving from a different direction strikes the antennae at different times. This difference is used to calculate the direction of the signal. (Schmidt & Davis,1985:104)

Both the amplitude and the phase monopulse systems are unsuitable for this project for the following reasons :

1. In order to operate with WA antenna, a frequency of 300 MHz or higher would need to be used to make the antenna as small as possible. This frequency is unsuitable as it is of a line-of-sight (LOS) nature. This means that it will suffer large attenuation if it encounters ground/obstacles in its path, and also will not be able to follow the curvature of the land and so may pass over the head of the person operating the DF [Anon,1988:22-3].
2. Even if the above problems could be overcome, the antenna would still be far too large and cumbersome to be of a hand-held nature. For a system operating at 300 MHz, the antenna would have a diameter of the order of 1 m, and since two antennae are needed, this means that the whole system will not be of a portable nature, especially in dense vegetation.

2.4 Loop and Sense Antenna System

Most DF systems prior to the usage of metric and centimetric waves made use of the loop antenna in one form or another [Haigh,1960:7]. A loop antenna is essentially a large coil, which can be structured with square sides or in a circular shape. A ground wave is usually used with a loop system, as this facilitates the directional characteristics of the loop. A ground wave is an electromagnetic wave which travels along the surface of the ground, with part of the waveform being in the surface of the earth, and part being just above the surface. A ground wave is usually vertically polarised. This is due to the fact that if it were horizontally polarised it would rapidly be attenuated in the surface of the earth. An electromagnetic wave is said to be vertically polarised if the electric field is perpendicular to the surface of the earth.

A vertical loop has the directional characteristics as shown in Figure 2.3. A transmitter sited at T will give rise to a signal proportional to B at the antenna. Two peaks and two nulls exist, the peaks being 180 degrees apart, the same applying to the nulls. A transmitter lying in the plane of the loop will yield a maximum signal from it.

In Figure 2.4 a square loop is considered for simplicity. The horizontal elements do not respond to the vertically polarised approaching wavefront as they are parallel to the plane of the magnetic field. The vertical elements, however, are perpendicular to the magnetic field, and so a voltage is induced into them. This voltage is equal in amplitude in both of the vertical elements but differs in phase due to the fact that the wavefront

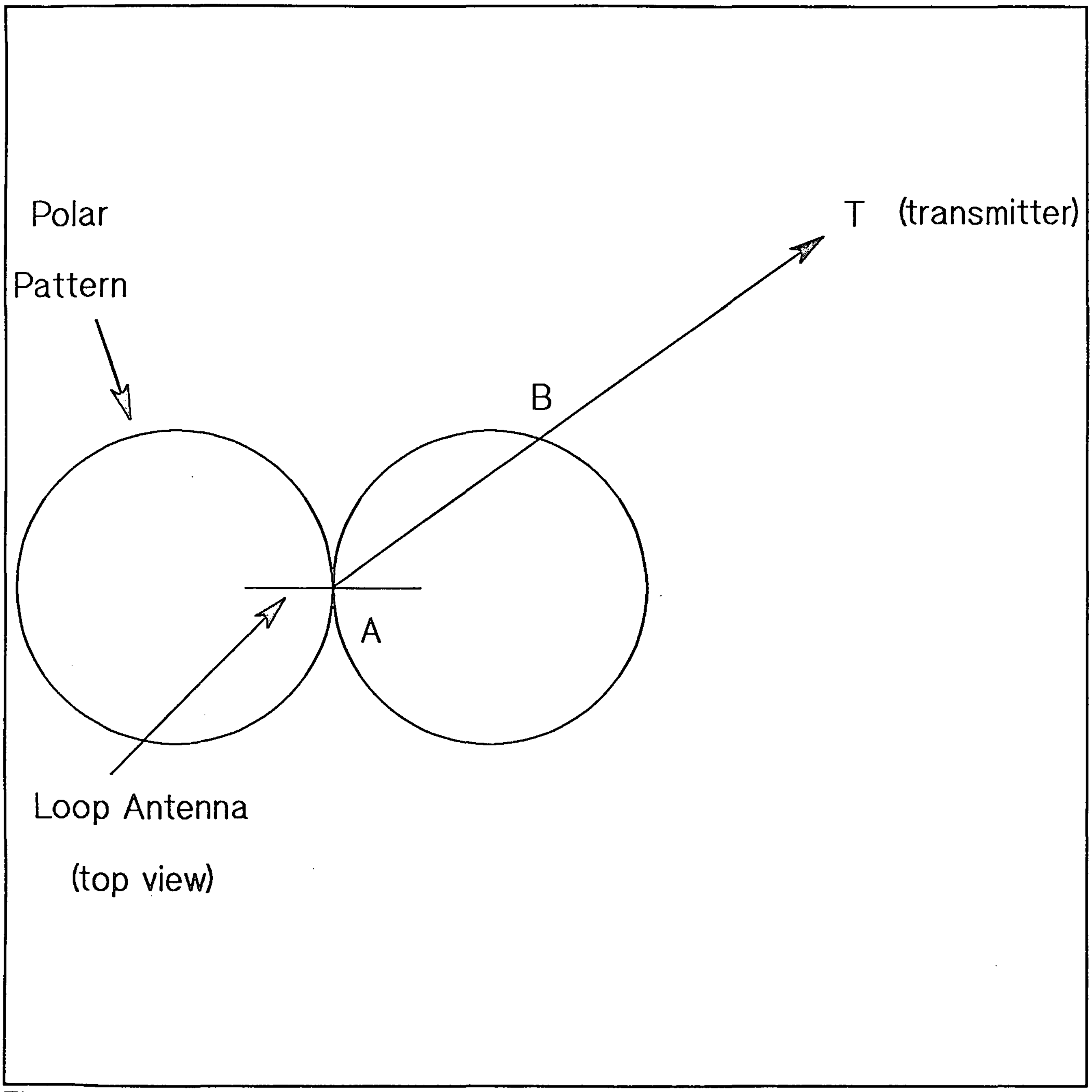


Figure 2.3 Horizontal polar pattern of a loop antenna. The voltage induced into the antenna is proportional to the length of the line A-B.

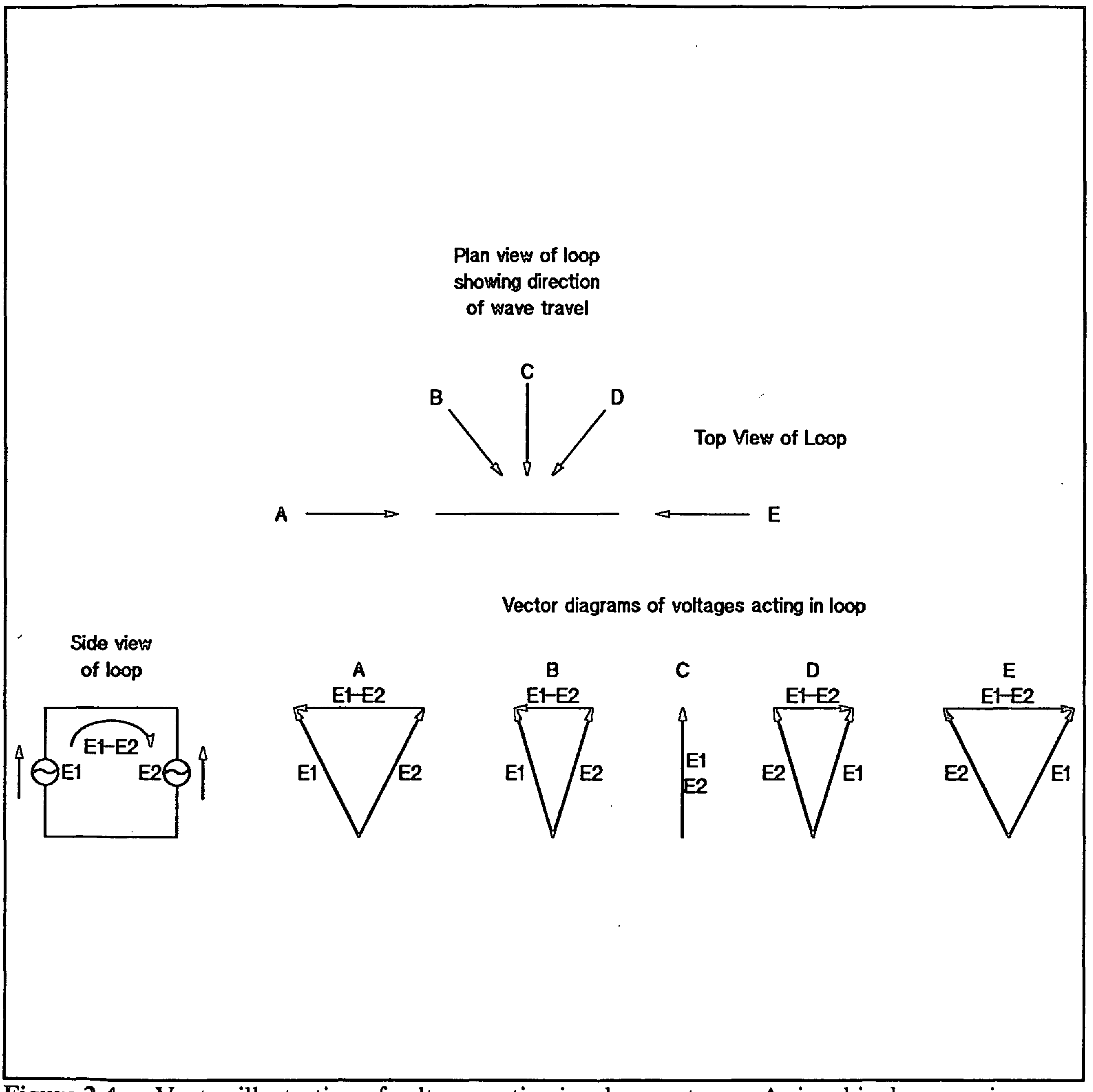


Figure 2.4 Vector illustration of voltages acting in a loop antenna. A signal is shown arriving from different directions (A-E). The resultant loop voltage (E1- E2) is shown for each case. (Terman,1985:589)

passes over the elements at different points in time (Figure 2.4). A loop antenna is also known as a cosine antenna because of its cosine type response (Figure 2.5).
Since the loop has two nulls, an ambiguity of 180 degrees exists as to the direction of the transmitting source. It is necessary to use an additional "sense" antenna to remove one of the nulls and hence the ambiguity of the loop. A vertical antenna has an omni-directional pattern and when the signals from the two antenna are combined the cardioid pattern results (Figure 2.6). The cardioid has only one null and one peak, omitting the ambiguity. The direction of the remote transmitter can now be determined. In Figure 2.6 the polarity of the signal from the loop is shown and it is illustrated how this adds to or subtracts from the output of the vertical antenna.

The loop and sense antenna system has possible application in this project for the following reasons :

1. The antennae used in the system do not have to be WA types and so could be small compared to the wavelength being used. Both the loop and the vertical antenna can thus be physically small antennae, allowing portability of the unit.
2. This system can be used in the lower region of the high frequency (HF) band where a transmitted wavefront follows the profile of the land as it travels away from the transmitter.

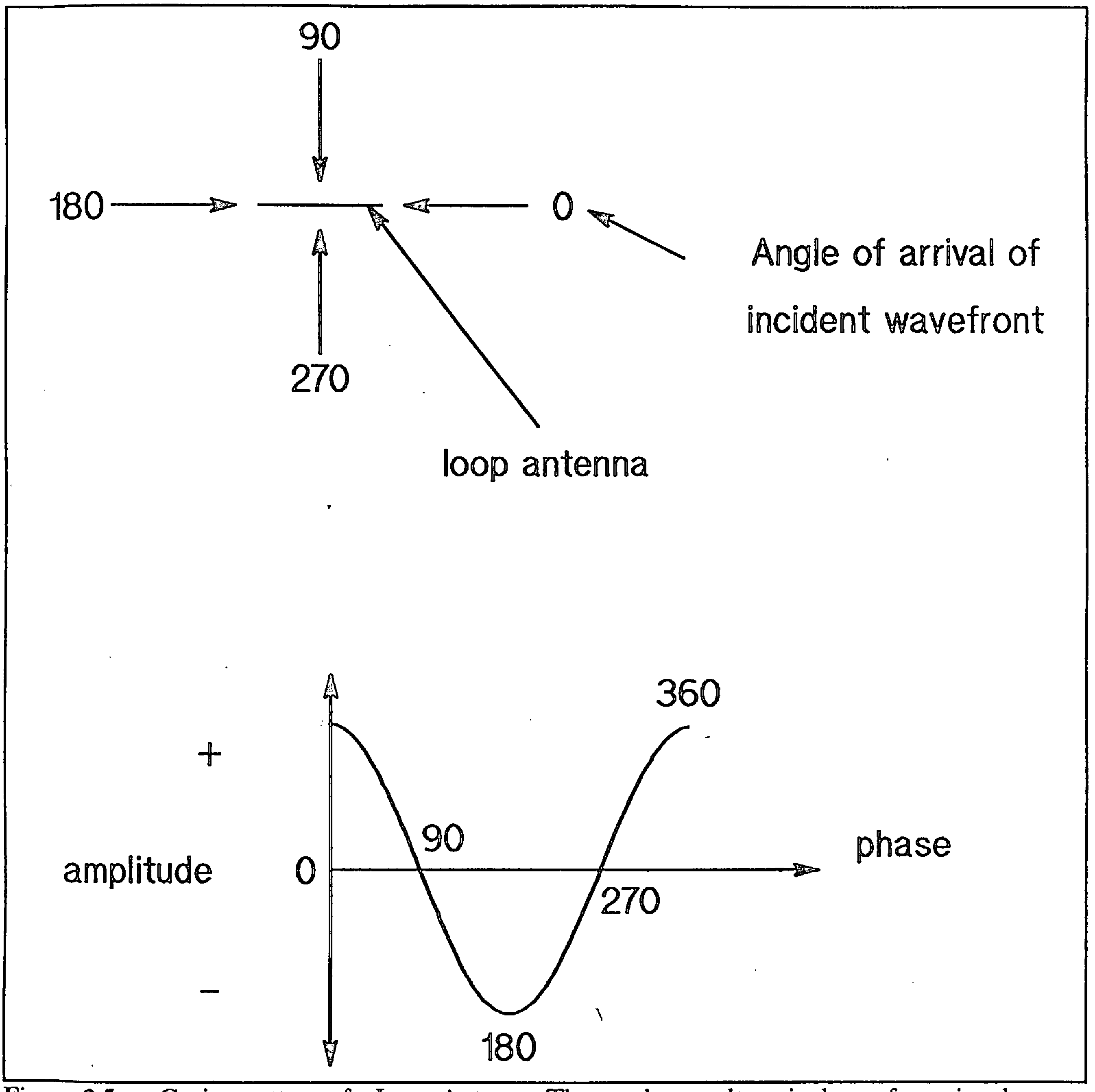


Figure 2.5 Cosine pattern of a Loop Antenna. The resultant voltage is shown for a signal arriving at 0°, 90°, 180° and 270°.

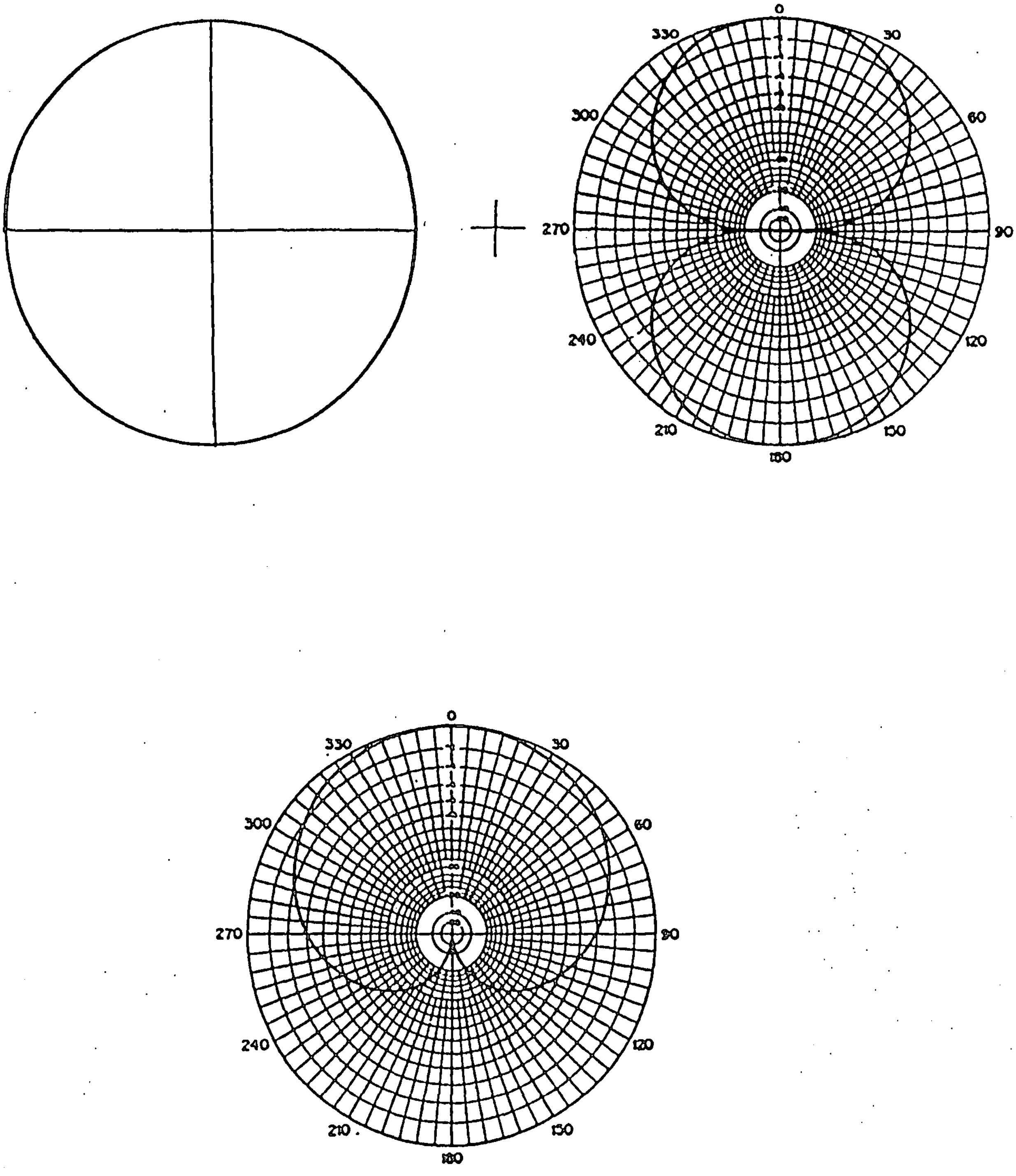


Figure 2.6 The cardioid polar pattern is the result of summing the antenna patterns of the loop and vertical antennae.

2.5 The Doppler Method

The apparent rise in the frequency of a signal being received while the receiving antenna moves toward the transmitter is known as the "Doppler effect". The Doppler effect has been employed for many years [Byatt,1980:49]. In the case of the receiving antenna moving away from the transmitter, the apparent frequency received would be lower than that of the transmitter. This effect has been made use of in direction finders [Appleby & Sager,1984:37]. The principle of the Doppler DF is shown in Figure 2.7. An antenna rotating about a central pivot is shown in (a). This antenna is vertically polarised and is approximately 1/4 Lambda in length. The top view of the antenna is shown in (b). The antenna platform is typically 1 m in diameter. The direction of the incoming signal is indicated. When the antenna is at point A it is moving towards the transmitter at its maximum rate and the received signal frequency will be at a maximum. At B and D the antenna is stationary with respect to the transmitter and the received frequency is the same as the transmitted frequency. At C the antenna is moving away from the transmitter at its maximum rate and so the received frequency is at a minimum. The result of this is that the rotation superimposes a sinusoidal frequency modulation (FM) on the received signal, as illustrated in (c). If the incom-

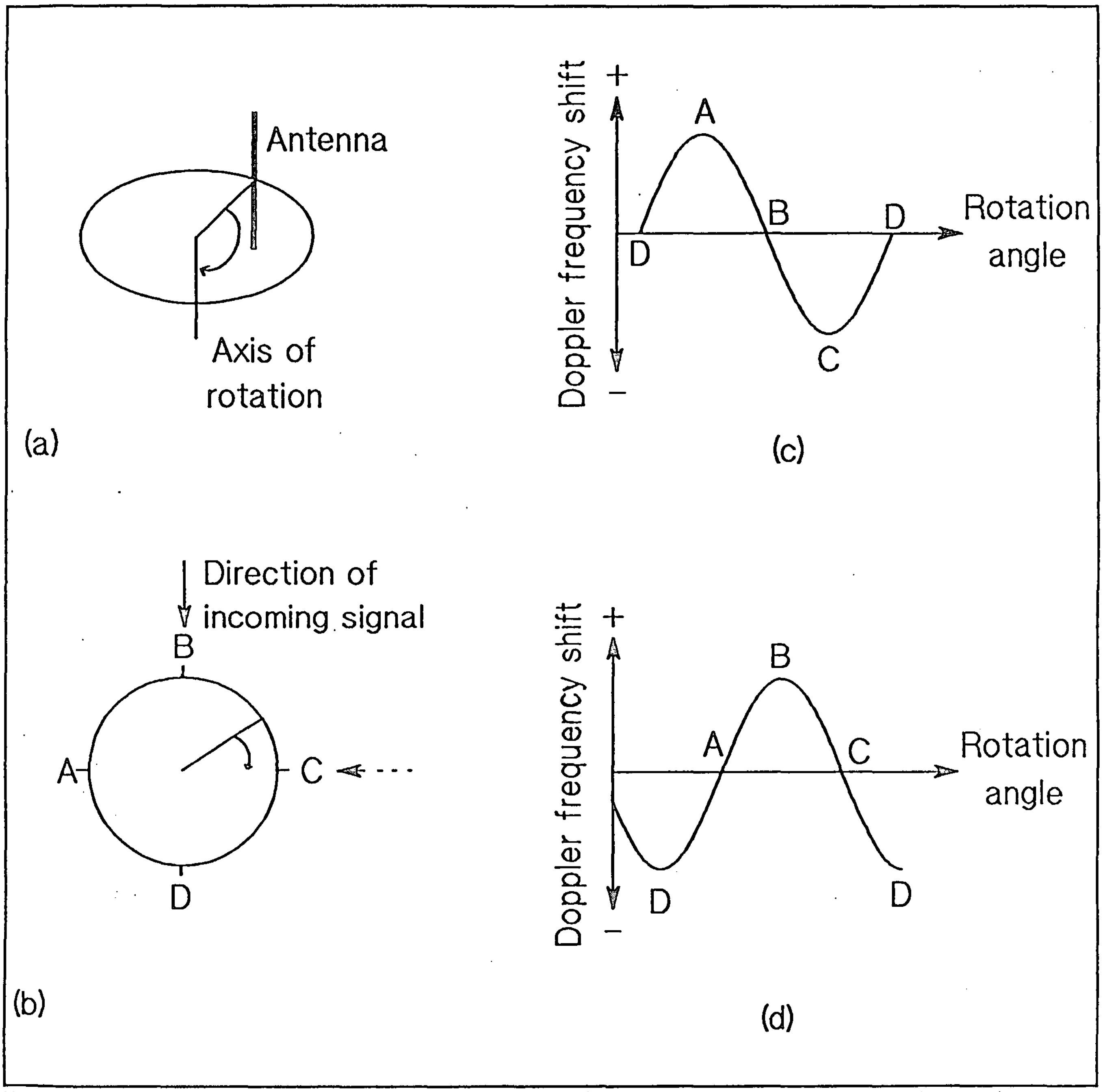


Figure 2.7 Doppler direction finder principle. At (c) the resultant FM is shown for the incoming signal indicated by the solid arrow. At (d) the dotted incoming signal is considered. (Appleby & Sager,1984:37)

ing signal comes from a different direction (dotted arrow), then the phase of the superimposed FM signal will change, as shown in (d).

If the phase of the induced FM is compared with a reference signal derived from the antenna position, the bearing of the transmitter from the receiver can be found. The deviation of the FM generated will be proportional to the carrier frequency, the radius of the circle and the speed of rotation. In practice it is necessary to use several antennae and to switch electronically between them to simulate a high speed of rotation in order to achieve a workable deviation [Appleby & Sager,1984:37].

The doppler method cannot be used in this project for the following reasons :

1. The antennae system is large and unwieldy.
2. The frequency range practical for this system (144 MHz and higher) is of a LOS nature and is hence unsuitable.

2.6 The Goniometer

The first goniometer was invented by Bellini and Tosi in 1907 [Keen,1947:156]. In the same year Alessandro Artom applied for a patent on this system [Meer,1977:102]. The name, goniometer, was derived from the Greek words "gonia" meaning angle and "metron" or meter, meaning a measuring instrument.

The use of the goniometer in the fields of navigation and direction finding has a long tradition. Much literature is available on this topic [Keen,1947:156, Haigh,1960:21, Cotter,1961:42, Hockley,1975:475, Meer,1977:102, Rambaut,1979:130, Powell, 1986:294, Anon,1988:39-4, Grant,1988:220]. The development of the goniometer has undergone several changes as it has evolved through time.

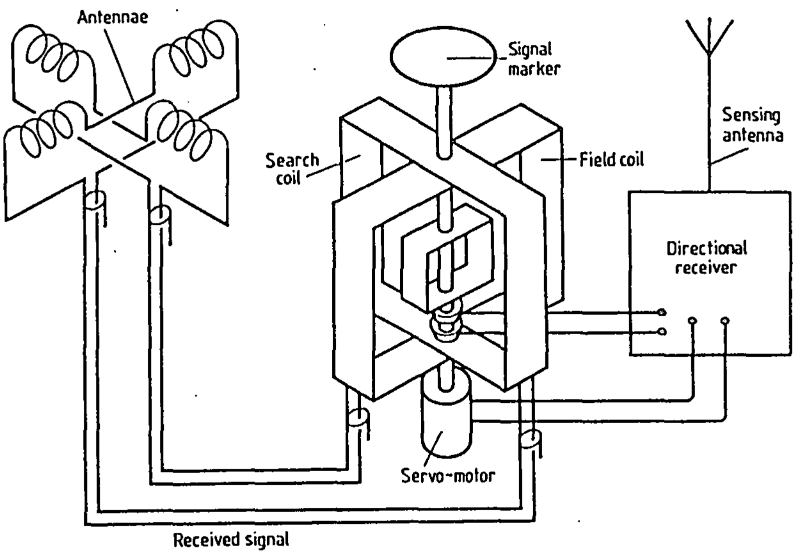


Figure 2.8 The goniometer direction finder. (Grant,1988:220)

The basic goniometer functions as follows. Two loop antennae, situated at right angles to each other, are connected respectively to two small multi-turn coils. These coils are also at right angles to each other (Figure 2.8). A third coil is arranged to rotate in the centre of these two latter coils and is used for the purpose of determining the direction of the arriving wavefront. The arriving wavefront sets up currents in the two loop antennae, which in turn set up magnetic fields in the two smaller coils. These magnetic fields interact and produce a resultant magnetic field. The plane of this field is the same as the plane of the arriving wavefront. A further coil, placed in the centre of the two coils, will produce two peaks and two nulls when rotated 360 degrees. Thus rotating the center coil is effectively the same as rotating a loop antenna. Using a vertical "sense" antenna, the transmitter bearing can now be determined. In the Bellini-Tosi goniometer the center coil is manually rotated until the peak of the cardioid pattern is detected. A pointer on this coil then indicates the transmitter bearing. Artom's goniometer of 1907 had a big impact in the field of direction finders as it was the first type that did not need to have its antennae rotated in order to determine the bearing of a remote signal source.

The term goniometer has since been applied to any type of direction finder which utilizes a device to switch between or rotate the antennae being used. Both inductive and capacitive goniometers have been used for DF purposes [Anon,1988:39-5, Grant,1988:221]. Mechanical rotation means have gradually been replaced by electronic means [Grant,1988:222]. The direction finding goniometer is physically large, owing to the complex coil windings.

The goniometer cannot be used for this project for the following reasons :

1. Due to the fact that the DF must be of a portable nature, the antenna system cannot be large and complex. The antenna types used in goniometer-type DF units do not meet this requirement.
2. The circuitry required to generate the switching and phasing of the antennae is complex and therefore space consuming. It would be very difficult to contain both this circuitry and the balance of the circuitry in a portable, hand-held unit.

2.7 Phased Arrays

Phased arrays have been used in DF work for many years [Hockley,1973:475, Anon,1978:61, Anon,1979:34, Barton,1983:78, Karavassilis & Davies,1985:295, Anon,1988:39-3]. A phased array is basically an antenna array whose elements are spaced apart from each other by a distance corresponding to a desired phase shift. Either one or several of the elements may be active and the others usually behave as reflectors, changing the polar pattern of the array according to their phasing. Phased arrays can be divided into end-fire arrays and broadside arrays. End-fire arrays, depending on the spacing and phasing of the elements, may exhibit a null off one of the two ends of the axis of the elements. A peak may occur at the same time at the opposite end of the axis. An antenna arrangement often used is two elements, fed 90 degrees out of phase, and 1/4 wavelength apart [Anon,1988:39-3]. The cardioid pattern is the result of this configuration. There are other methods of phasing and spacing the antenna elements which are suitable for direction finding. A popular form of end-fire phased array is the Adcock, which was developed by Lt Adcock in the 1914 - 1918 war [Haigh,1960:21]. Two vertical antennae are used, which are coupled together using a screened coaxial lead. The result of this arrangement is that the "night effect" is virtually completely reduced . The "night effect" is the error that results when sky waves strike the horizontal elements of the loop antenna, causing the nulls to become less significant with respect to the peaks. This is also known as the "vertical effect". The Adcock array has the same radiation pattern as the vertical loop. The Adcock system is usually used for fixed station applications.

Broadside arrays are inherently bi-directional. This means that at least two nulls exist in the pattern. This results in ambiguity as to the direction of the transmitter and so these arrays are not often used in DF work.

The Wullenweber antenna is an example of a phased array. This antenna does not fall into either of the two categories mentioned, but may be considered to be a hybrid of the two. The Wullenweber consists of a very large number of antenna elements arranged in a circle. A reflecting screen, also being circular in shape, is placed inside this circle. The elements are connected to a goniometer. The signal received at each element can be delayed by any desired amount. By varying the delay of the individual elements in a calculated manner the radiation pattern of the array can be controlled. The peak can be steered in any direction. This facilitates the ability to determine the bearing of a signal received from any direction without physically moving the antennae at all.

Barton (1983:78) describes a DF unit which treats the received signal as interference and steers a null towards it. He claims that the null, being sharper in depth and narrower than a peak, can possibly be used to determine the bearing of the transmitter more accurately than the peak.
An adaptive circular array for HF direction finding and null steering which is similar to Barton's system is also described by Karavassilis & Davies (1985:295).

Phased arrays cannot be used in this project for the following reasons :

1. In order to use hand-held arrays that consist of elements which are spaced by appreciable fractions of a wavelength (for example 1/4 wavelength) the DF unit would have to operate in the VHF/UHF band. This is not possible as radio signals in this range are of a LOS nature and are thus unsuitable for use. The Adcock array is unsuitable for the same reason.
2. The Wullenweber antenna system has a typical physical diameter of a few hundred meters up to a possible 1.8 kilometers. This is obviously not of a portable nature.

2.8 Choice of a Method

Table 2.1 was constructed subjectively, taking cognisance of the involved factors, such as the background where the PDF was to be constructed, the cost of materials and the time available for construction. No attempt was made to use sophisticated selection techniques (for example the Nominal Group Technique) to assign weights to the various categories.

Table 2.1 The mass, antenna system, performance and complexity of all the systems considered is compared with a view to choosing a method for this design.

METHOD	MASS	ANTENNA SYSTEM	PERFORM-ANCE	COMPLEX-ITY	TOTALS
Amp. monopulse system	3	3	2	3	11
Phase monopulse system	3	3	2	3	11
Loop & sense	7	9	6	7	29
Doppler method	1	1	1	1	4
Goniometer	3	5	6	4	18
Phased arrays	2	1	10	3	16

KEY TO COLUMNS

MASS : This refers to the physical mass that a typical system of this design would be. This is related to the requirement specified, ie the PDF must be of low mass to be hand-held.

Scale : 1...DF system mass far too high

10...DF system mass low

ANTENNA SYST : This refers to the size that the antenna system would be related to that of the specified requirement.

Scale : 1...Antenna system far too large

10...Antenna system small and portable

PERFORMANCE : This refers to the performance of the PDF system compared to that of the specified PDF under the conditions specified.

Scale : 1...Poor performance

10...Excellent performance

COMPLEXITY : This refers to the degree of complexity of the unit related to the level of complexity that an ideal hand-held unit should be. A system which is too complex consumes too much power and space and cannot be hand-held.

Scale : 1...Extremely complex system

10...Moderately complex system

TOTALS : (max possible = 40)

loop & sense	- 29
goniometer	- 18
phased arrays	- 16
amplitude monopulse	- 11
phase monopulse	- 11
Doppler	- 4

The ideal PDF should have a low mass, small portable antenna system, good performance, and be as complex as the space that a hand-held system allows. The loop and sense antenna system is closest to the ideal and was chosen for use in this project.

2.9 Summary

A number of DF techniques were considered in this chapter. In most cases methods were unsuitable due to the characteristics of the antenna system. The chosen method, the loop and sense antenna system, was the only one that satisfied all the requirements.


RAND
TRANSMITTER
LIES IN THE
DIRECTION OF
THE PEAK.
DIRECTION
DISTANCE
4

CHAPTER 3

THE PRINCIPAL, DESIGN AND CONSTRUCTION OF THE DIRECTION FINDER

3.1 Introduction

The loop and sense antenna system was chosen in Chapter 2. In this chapter the choice of operating frequency range is first discussed. The principle of operation of the direction finder is then dealt with. Following this a detailed description of the various stages is given. For many of the stages considered, several solutions are discussed, and the most suitable one is chosen.

3.2 Factors Affecting the Choice of Frequency

One of the most important requirements which the PDF must meet is that of being able to operate satisfactorily over short distances in a variety of terrain types. These types range from, in the extreme cases, flat desert sand to mountainous territory. Topography affects the performance of the PDF and is an important factor to be considered when choosing a suitable frequency for operation. The distance of operation is required to be 5 km. The choice of frequency influences the maximum range of the device. There are different modes of electromagnetic (EM) wave propagation as shown in Figure 3.1. Each of these modes has propagation distance characteristics which must be considered when a choice of operating frequency is made. Once a mode has been chosen it is then possible to choose an operating frequency range for the PDF.

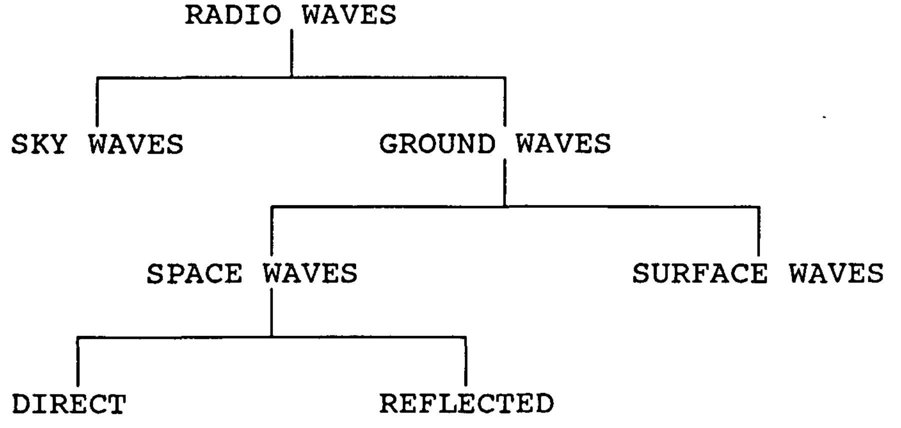


Figure 3.1 General classification of the modes of EM wave propagation.

3.2.1 Sky Waves

In the upper region of the earth's atmosphere there exists a layer known as the ionosphere. The air pressure is very low and free electrons and ions exist for long periods of time before combining to become neutral. A radio wave entering this region is affected in the same way as a wave entering a region of different dielectric constant. Its direction of travel is altered. The sun increases the level of ionization, due to the energy transferred to the layer from the ultraviolet rays. Increased ionisation results in greater refraction of the wavefront on entering the ionosphere.

The ionosphere consists of four layers, each layer being parallel to the surface of the earth and differing in height. Radio waves transmitted into the ionosphere will be refracted by the ionosphere and will return to the earth at some distant point. The frequency used, the angle of elevation, and the time of the day will determine how far away the refracted wave will strike the earth. The longest single hop distance that a sky wave can cover is around 4000 km. The shortest distance that can be covered by sky waves is typically 40 - 70 km [Bodemann,1983:104]. At shorter distances it is highly inadvisable to use sky waves for communication as the absorption and losses involved in the sky wave are excessive.

As stated, the distance of operation of the PDF will be up to a maximum of 5 km, therefore sky waves cannot be used for this application.

3.2.2 Ground Waves

Ground waves fall into two categories, space waves and surface waves (Figure 3.1).

3.2.2.1 Space Waves

Space waves can be either direct or reflected. A space wave is a wave which travels from one point to another, independent of the ionosphere or the earth conductivity. A space wave is usually of a higher frequency than a sky wave, as the atmospheric noise level drops at these frequencies and the antennae become physically smaller and more practical to build. A space wave is usually limited to LOS use, as the frequency is high and thus absorption in path objects encountered is high. The wave may either travel directly from transmitter to receiver (direct), or be reflected off the ground (reflected), or may travel in a combination of direct and reflected modes. Space waves have found use in the UHF band where the transmitted energy can be directed into a pencil beam and can thus travel hundreds or even thousands of kilometers using relatively low transmitter power. Low frequencies cannot be used for space wave propagation as they would need to be mounted extremely high above the earth's surface, so as not to become a surface wave, and would also be large, thus rendering them very difficult to construct.

Due to the possible variation in terrain types that the PDF may be operated over, a LOS path cannot always be guaranteed and so space waves cannot be used in this project.

3.2.2.2 Surface Waves

Surface waves are so-named because they travel along the surface of the earth. In the standard broadcast band the maximum daylight range is about 160 km [Anon,1984:1-3]. The attenuation in the earth's surface is proportional to the frequency in use. Typical surface wave frequencies range from 100 kHz to 4-5 MHz. Surface waves are restricted to vertically polarised waves only as horizontally polarised waves would be rapidly attenuated in the surface of the earth. This makes their use difficult, as large vertical antennae are required as the frequencies are low and thus the wavelength is long. Surface waves are usually used where the distance between the transmitter and receiver is too short to use sky waves, and the frequencies in use are low, thus rendering space wave propagation impossible as well. These waves follow the contour of the ground and so can be used over surfaces which are not flat.

Surface waves satisfy the requirements for the PDF described in this project.

3.2.3 Choice of Propagation Mode

The surface wave has been chosen for the PDF system described in this project for the following reasons :

1. The distance between transmitter and receiver will be a maximum of 5 km and thus sky waves are not suitable.
2. Space waves are also unsuitable because the terrain between the transmitter and receiver could be mountainous and so LOS transmission is impossible.
3. The surface wave does not depend on the ionosphere and so is unaffected by the time of the day or changing solar conditions.
4. The polarisation of the surface wave remains vertical. In the case of a sky wave the returning wave may rotate continually, resulting in an elliptically polarised wave. The space wave at a receiving antenna may have a direct and a reflected component which would interact and change the

resultant phase of the signal. In both of these cases the receiving antenna would have to be more complex than that used in the case of a surface wave.

It is therefore concluded that the surface wave is the most suitable mode of propagation of radio waves for the PDF described in this project. A frequency will be chosen out of the lower portion of the HF spectrum.

3.3 Choice of Operating Frequency

In order to allow the antennae used in the PDF to be as small as possible the frequency range was kept as high as possible. However, a compromise had to be reached as ground absorption losses increase with increased frequency. The following facts were taken into consideration in choosing an operating frequency :

1. The ground absorption is directly proportional to frequency. Thus the lower the frequency the less the absorption.
2. Low frequencies are refracted and reflected less than high frequencies in the surface of the earth. It is desirable to have the signal travel along in a straight path as far as possible to keep the bearing errors to a minimum.

3. If the homing signal does have a sky wave component, then, by keeping the frequency in use as low as possible, the sky wave is returned to earth at a very large distance away from the PDF. This is because the amount of bending an electromagnetic wave undergoes in the ionosphere is inversely proportional to the frequency of the wave. Ideally the transmitter is never more than 5 km away from the PDF receiver. It is important not to have any sky wave component present at the PDF antennae because this leads to bearing errors. Sky waves would induce voltages into the loop sides parallel to the earth's surface which would result in the same conditions that the night effect causes.

The frequency range was chosen as being 3 - 4 MHz.

3.4 Principle of Operation

The loop and sense antenna method has been chosen for the reasons given in Section 2.8.

The vertical loop antenna, as described in Section 2.4, has a horizontal polar pattern as given in Figure 2.3. When the arriving surface wave lies in the plane of the loop, two peaks exist, these being opposite to each other, and lying in the plane of the loop. When the arriving signal is perpendicular to the plane of the loop, two nulls exist, these being opposite to each other, and lying in the plane of the arriving signal [Colligan,1980:227]. These nulls and peaks are illustrated in Figure 2.3. The vector diagram of a loop antenna with signals arriving from several directions is given in Figure 2.4. The loop is considered as being square in shape for the sake of simplicity. No voltages are induced into the sides which are parallel to the ground, as these are never perpendicular to the arriving (vertically polarised) signal. Fleming's right hand rule describes this phenomena [Hughes,1979:50]. The two sides which are perpendicular to the surface of the earth have voltages induced into them. These EMFs oppose each other and differ in phase in accordance with the arriving signal angle relative to the plane of the loop. They are equal in amplitude. At A the arriving field is parallel to the plane of the loop. The field induces a voltage E1 into the first side it passes and a voltage E2 into the opposite side. These voltages give rise to the resultant vector (E1 - E2). In this case the angle between the vectors E1 and E2 is at a maximum and the resultant vector (E1 - E2) is at a maximum. When the wavefront approaches from B the resultant vector lies in the same plane as the resultant vector in A, but differs in amplitude. At C the voltages in the two sides are equal in phase and amplitude and so E1 and E2 cancel each other out. The situation repeats at D and E, except that the phase of the vector (E1 - E2) is 180° shifted from the resultant in A and B.

To summarise, the resultant vector lies in one of two directions only, and varies in amplitude as the angle of arrival of the signal varies.

The vertical loop thus exhibits two nulls and two peaks in its horizontal polar pattern (Figure 2.3). This is not suitable for DF work as a 50 % chance exists of choosing the incorrect peak or null. In order to remove this ambiguity a "sense" antenna is used. The sense antenna is a vertical element placed at the loop centre (Figure 3.2). The voltage (E3) induced into this element is always 90° phase shifted from the vector (E1 - E2). This is because the vector E3 lies midway between E1 and E2, no matter what angle the arriving field approaches from. If this vector is now phase shifted by 90° it will either be in phase with (E1 - E2) or will be 180° out of phase with it. Adding E3 and (E1 - E2) will give rise to a peak in the case of A and a null in the case of E. The result is the cardioid pattern (Figure 2.6). The antenna system as a whole now has only one peak and one null and is suitable for DF work.

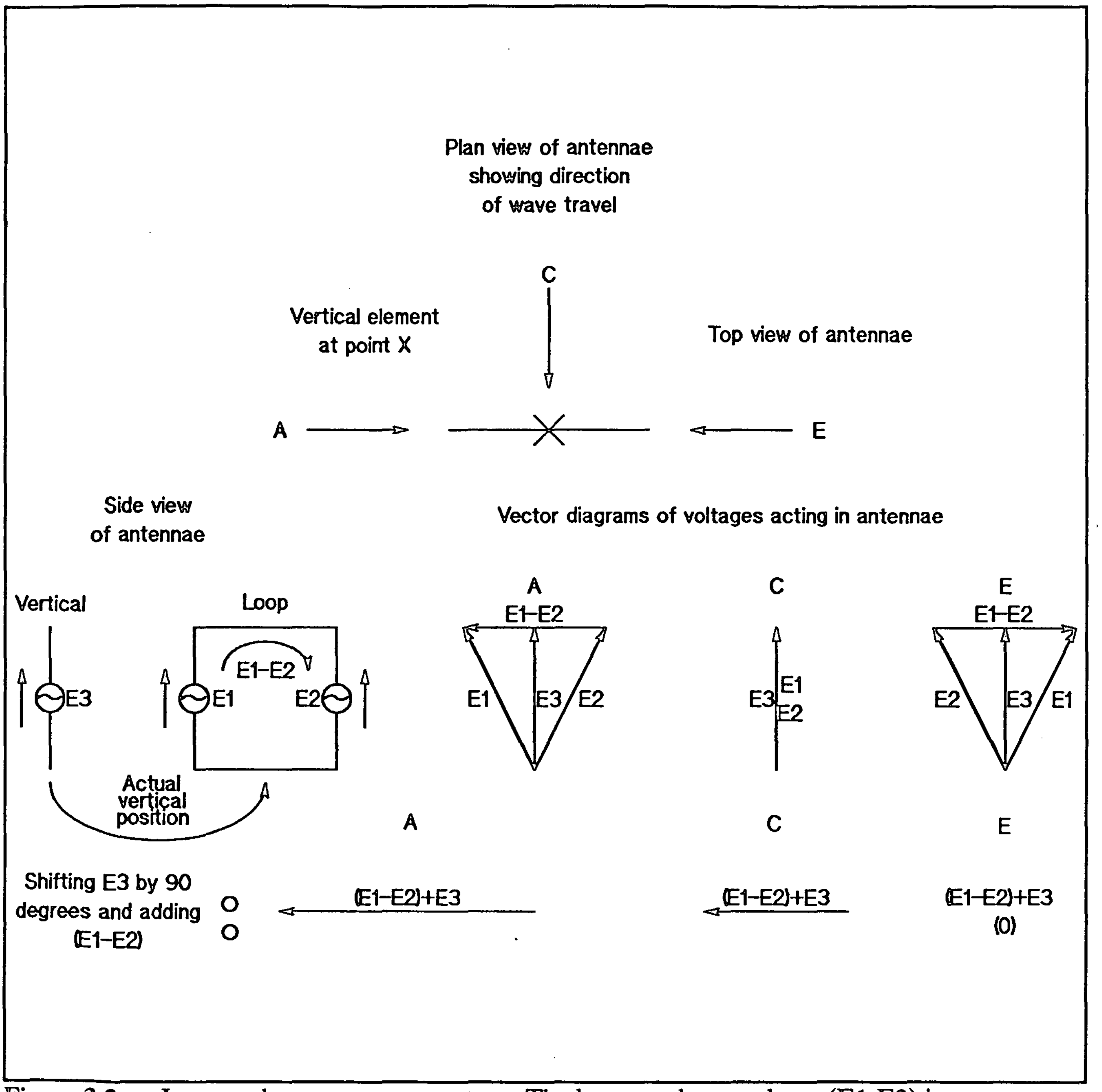


Figure 3.2 Loop and sense antenna system. The loop resultant voltage (E1-E2) is shown for signals arriving at A,C and E. The signal from the vertical antenna (E3) is shifted by 90° and added to (E1-E2) for each case. A peak now exists at A and a null at E. (adapted from Terman,1932:589)

3.5 The Antenna System

Careful attention was paid to the design of the antennae system, as the PDF performance is highly dependent on the design.

3.5.1 The Loop Antenna

The loop antenna was wound on a 80 mm X 10 mm ferrite rod. The rod provides a suitable former and also increases the inductance of the loop. Increased inductance results in a higher induced voltage in the loop, as this voltage is directly proportional to the inductance. By ensuring a relatively high voltage out of the loop, the receiver gain may be lowered and this results in a drop in system noise.

The loop inductance, being a non-perfect component, does have some distributed capacity associated with it. This distributed capacity takes the form of a capacitor in parallel with the inductor (Figure 3.3). This is a resonant circuit and care was taken to ensure that the resonant frequency of the circuit was well out of range of the frequencies being used by the PDF for the following reasons :

1. The impedance of the circuit at frequencies near resonance departs from the impedance which the inductor would have if it were pure (if it had no distributed capacity). In this region it becomes nonlinear as shown by the curving of the impedance close to resonance (Figure 3.3).
2. At frequencies close to resonance large phase shifts occur which affect the operation of the PDF as it relies on constant phase characteristics in the loop antenna.

3. At frequencies higher than resonance the impedance begins to decrease (Figure 3.3), which indicates that the circuit is behaving as a capacitor. The inductance now plays no part in determining the circuit impedance and is thus rendered useless.

The loop winding was distributed evenly over 70 % of the rod for three reasons. Firstly, this facilitates maximum use of the captured magnetic flux in the rod. Secondly, this ensures that the distributed capacity of the winding is kept to a minimum. This is due to the fact that the capacity between adjacent turns is inversely proportional to the distance between them. Thirdly, the inductance is kept to a maximum by ensuring that the loop is as large as possible.

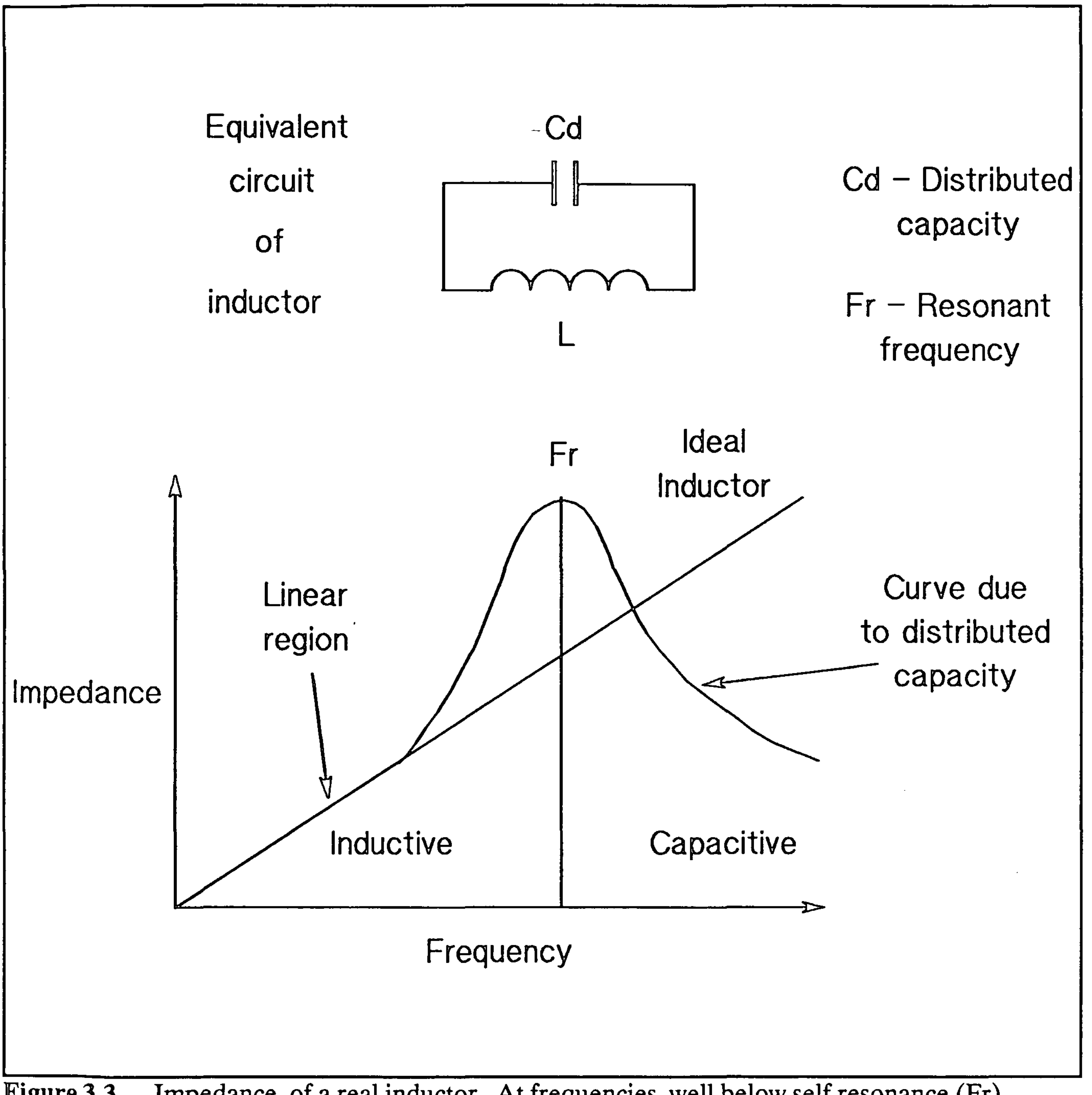


Figure 3.3 Impedance of a real inductor. At frequencies well below self resonance (Fr) the inductance increases linearly with frequency. Above Fr the inductor behaves as a capacitor.

If the loop antenna is not balanced with respect to ground, the effect on the polar pattern is the same as the night effect [Terman,1932:590; Scott,1984:76]. To help prevent this a brass circular shield was placed around the ferrite rod, and the loop output was connected to a balanced load. When the loop is out of balance it begins to behave in two modes of operation. In the first mode it behaves as a true loop. In the second mode it behaves as a vertical nondirectional antenna of small dimensions. The result of these modes is that the nulls lose their depth and the loop approaches the pattern of an omnidirectional antenna. This situation is undesirable as a directional antenna is required for DF work. In placing a shield around the loop, care was taken to avoid closing the loop. This would be the same as having a shorted turn placed on the rod and would short circuit the voltage induced in the loop [Dowding,1976:192].

The ideal loop antenna responds only to the magnetic field and not to the electric field. However, if an imbalance does exist in the loop, it will now become sensitive to the electric field. An electrostatic screen around the loop, besides helping to maintain a balanced antenna, also helps to ensure that only the magnetic portion of the arriving signal is allowed to come into contact with the loop as the electric field is shorted to ground by the shield.

3.5.2 The Vertical Antenna

The design of the sense antenna was less complex than that of the loop antenna. In the description of the principle of operation of the loop and sense antenna method in Section 3.4 it was mentioned that the vertical antenna should, ideally, be situated at the centre of the loop. This is difficult to achieve in practice as the ferrite rod passes through the center of the loop. It would be impractical to drill a hole in the center of the ferrite rod. In the design of the sense antenna the vertical antenna was placed outside the loop, and at the mid-point of the length of the rod because of the following reasons :

1. It is impractical to position the vertical at the loop center.

2. The frequency range used will be 3 - 4 MHz. At 4 MHz the wavelength of the signal received is 3E8/4E6 = 75 m. The diameter of the loop is 10 mm. The vertical is placed at the edge of the loop (5 mm from the center of the loop). This distance is equal to 0.005/75 Lambda at 4 MHz. The error distance is thus 66.67E-6 Lambda. This error is very small and the vertical may thus be considered to be at the center of the loop. At 3 MHz this error will be even smaller as the wavelength is longer.

3.6 Choice of Receiver Type

Up to this stage in the design only the antenna elements have been considered. The signals which the antennae receive are in the order of a few microvolts and thus need to be considerably amplified before they can be used to convey information to the PDF user. Various types of receivers were considered for use in this project. Since the transmitted signal will be in the form of a simple unmodulated carrier it is not required to have a receiver with a wide audio bandwidth or very good distortion characteristics. For this reason an amplitude modulation (AM) receiver type was chosen. A direct conversion receiver type was used for the following reasons :

1. The direct conversion receiver is one of the most simple types of receivers. This allows for a design which would be smaller than other types of DF receivers.

2. Due to the simplicity of the nature of the transmitted signal, it would be impractical to have a complex receiver type.

3. This type of receiver offers adequate noise performance and selectivity for the application.

A block diagram of the direct conversion PDF receiver is shown in Figure 3.4. The gain of each stage at the wanted frequency is indicated. A discussion of the basic operation of each stage follows.

3.7 The Sense Antenna Amplifier

As the PDF is required to be portable the sense antenna has to be physically short. Due to the low frequencies of operation it will also be electrically short. Its length is approximately 30 cm. At the mid-band frequency of 3.5 MHz the wavelength of the signal received is 85.71 m. The electrical length of the vertical antenna is therefore 0.3/85.71 = 0.0035 Lambda. A short vertical antenna has a low radiation resistance and a high capacitive reactance [Anon,1988:2-27]. It is important not to shift the phase of the voltage induced in the sense antenna as the required amount of phase shift is done in the phase shifter. The input impedance of the sense amplifier is thus required to be of a high magnitude, and to be purely resistive. This is achieved by using a field effect transistor (FET). A FET has a high input impedance (typically 10 MΩ) and a low input capacity (typically 2-5 pF). The FET is used in a voltage amplifier configuration having unity gain, thus serving the purpose of being an impedance converter.

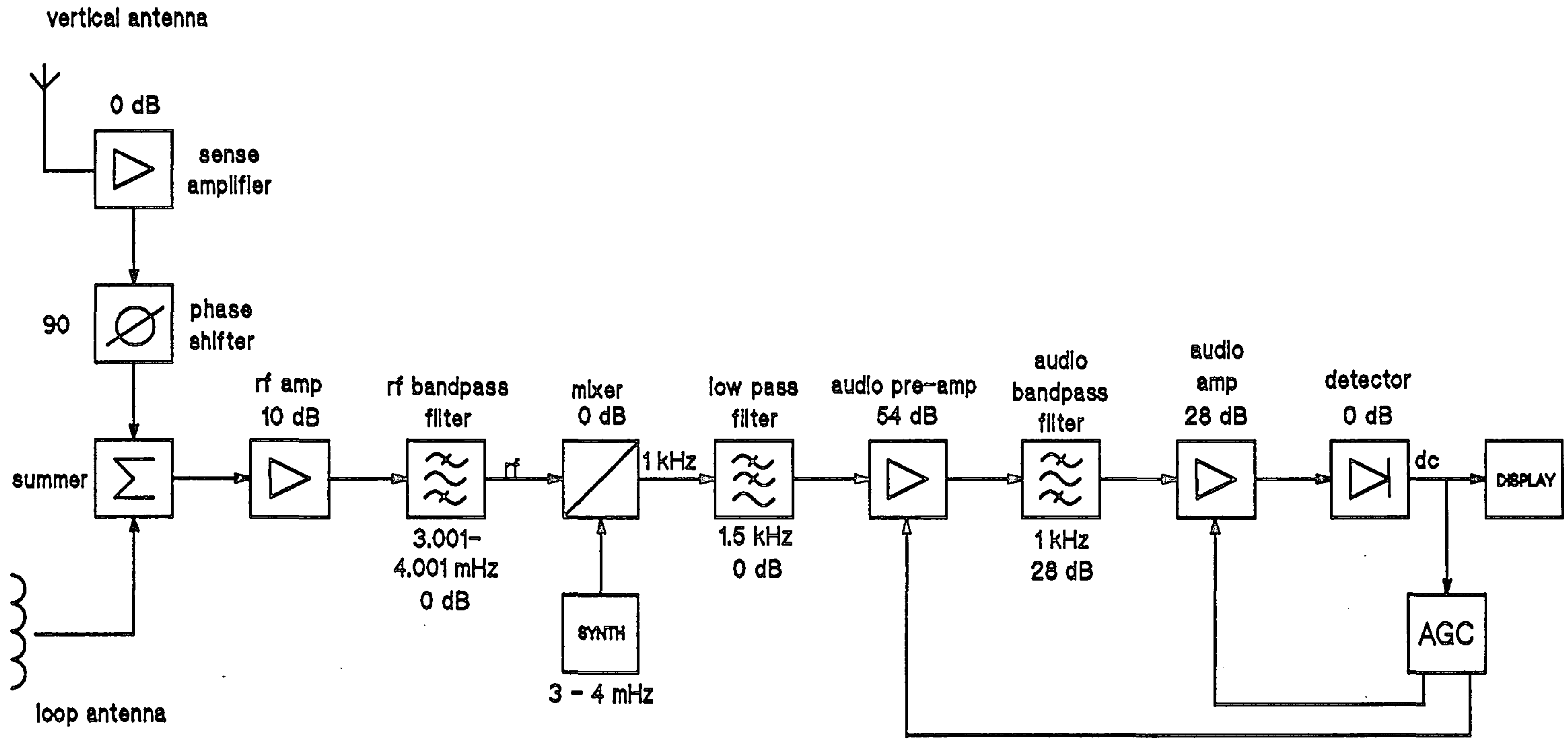


Figure 3.4 Direct conversion DF receiver.

3.8 The Phase Shifter

The signal received by the vertical antenna (Figure 3.4) must be phase shifted by 90° before it can be summed with the signal from the loop. There are various ways of achieving a 90° phase shift. A description of several methods and the suitability of each method follows :

1. A phase shifter can be made using resistors and capacitors as shown in Figure 3.5. The network takes the form of a low pass filter. Figure 3.5 also shows a plot of the phase shift versus frequency of the network. The disadvantages of using this method are, firstly, that the output voltage drops off as the frequency is increased and, secondly, that the phase shift does not remain constant as the frequency changes. The plot shows an error of 5.9° at 3 MHz and 5.1° at 4 MHz. A phase shift of other than 90° would give rise to bearing errors. For these reasons this method is unsuitable for this project.
2. An active phase shift network as illustrated in Figure 3.6 can be designed to yield 90° of phase shift. The advantage of this system over the system described in (1) is that the output voltage remains constant with frequency. The phase shift is, however, still not constant with frequency. In the plot in Figure 3.6 the phase error is 0° at the mid-band

frequency and reaches its maximums at the two extreme frequencies. At 3 MHz the error is 9° and at 4 MHz it is 8°. Although this active phase shifter has better amplitude characteristics than the RC shifter described in (1), it exhibits greater phase errors at the two extreme frequencies. At 3 MHz the percentage error is 9/90 which is 10 % of the total desired phase shift. This method is therefore unsuitable for this project.

3. A third method of introducing the required phase shift is by coupling the signal received from the vertical to that received by the loop by inductive means. This is done by placing a few turns on the rod and coupling the vertical to this winding. The result is two windings on the ferrite rod, the loop winding and the vertical antenna coupling winding. The voltage developed across the vertical winding is in phase with the voltage induced in the vertical. Since the two windings are inductively coupled, the voltage induced into the loop winding by the vertical winding is 90° out of phase with the voltage induced in the vertical antenna. This phase shift will remain 90° across the frequency range used. This is due to the fact that the current in an inductor always lags the voltage across it by 90° [Bell,1978:430]. The magnitude of the voltage induced into the loop winding by

the vertical winding will remain constant with frequency provided that the impedance of the loop is kept suitably higher than that of the vertical antenna winding.

Method (3) was chosen as it provides a constant phase and magnitude response across the frequencies used. It also provides two further advantages over (1) and (2) :

1. It is the most efficient of the three methods in terms of component requirements.
2. Summation of the signals is performed due to the coupling of the respective fluxes of the two signals applied to the windings. This eliminates the need for additional circuitry to perform the summation, so helping to keep the component count, and hence the size, to a minimum.

An illustration of the ferrite rod and its windings is given in Appendix A.

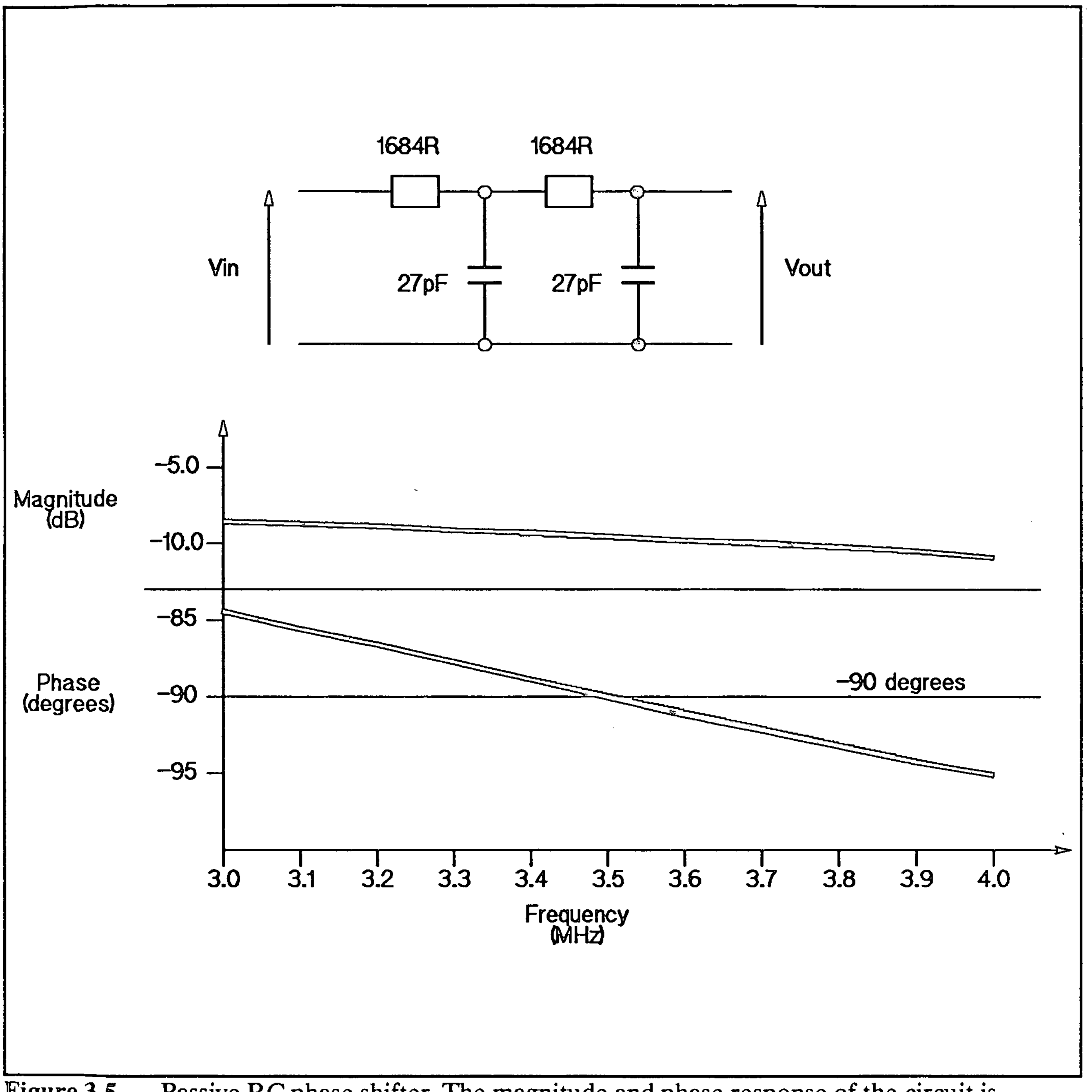


Figure 3.5 Passive RC phase shifter. The magnitude and phase response of the circuit is shown for the frequency range of operation.

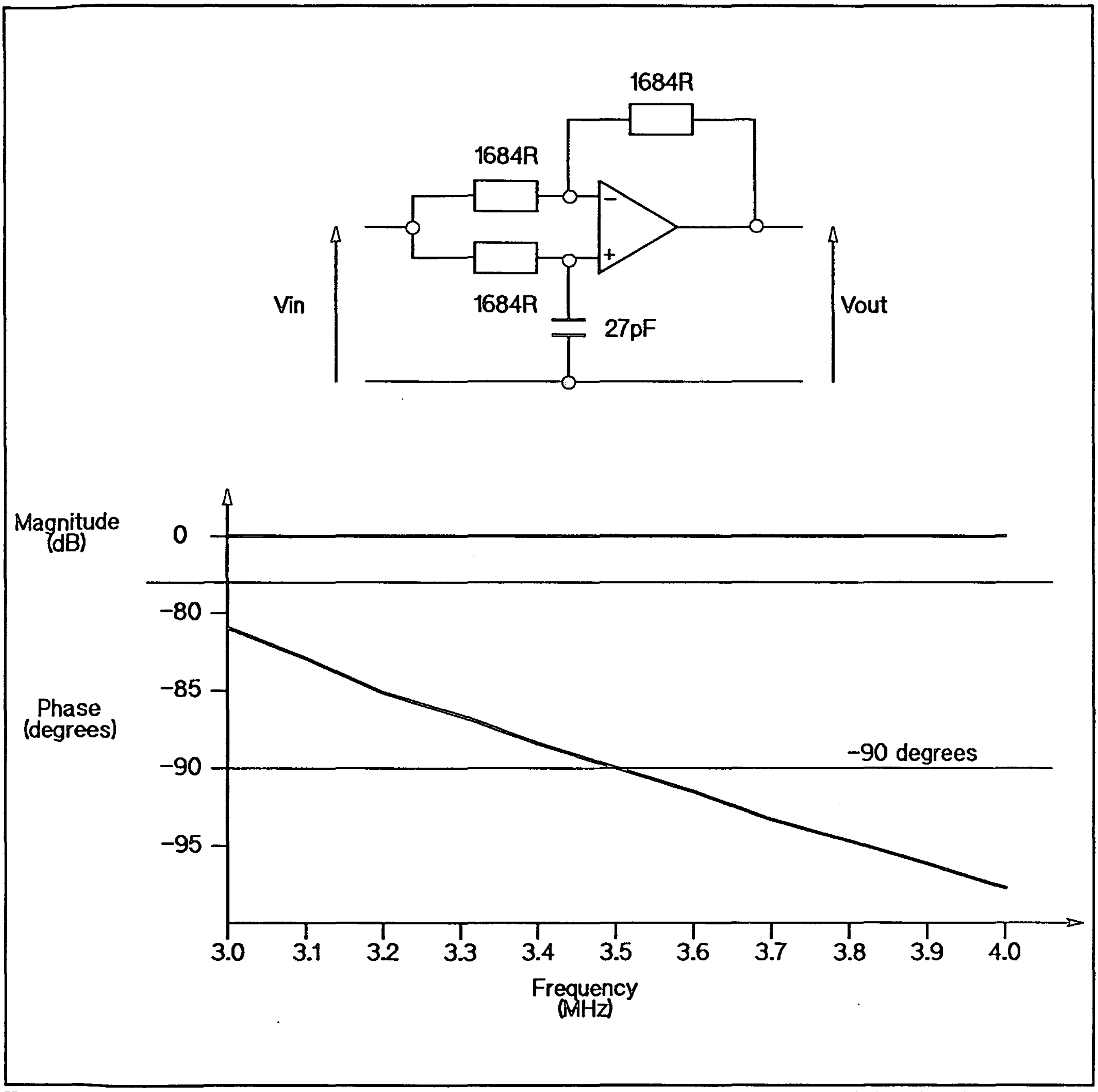


Figure 3.6 Active RC phase shifter. The magnitude and phase response of the circuit is shown for the frequency range of operation.

3.9 The Radio Frequency (RF) Amplifier

The signal in the loop winding is coupled into the RF amplifier (Figure 3.4). This is a broadband voltage amplifier with a gain of 10 dB and provides the following :

1. The function of the RF amplifier is to provide the wanted signal with a suitable amount of amplification, so that it is not masked out by the additional noise that is generated in the mixer. A mixer is required as it is necessary to convert the RF signal to a lower frequency. A disadvantage of using a mixer is that, due to losses incurred in the mixing process, degradation of the noise figure of the receiver results. The noise figure of a network is a measure of how much the signal to noise ratio of the wanted signal is degraded by that network. The mixer is usually situated close to the front end of a receiver as :

   i. it provides a receiver with selectivity. If the mixer is close to the front stages of the receiver, there is less gain in the stages preceding the selective stage, and therefore less chance of a strong unwanted signal blocking the receiver;

ii. this ensures that most of the system gain is at an audio frequency. Frequency conversion is provided by the mixer. In the case of this project the wanted RF signal is mixed down to an audio signal. By placing the mixer close to the front stages it is ensured that there is more amplification at the audio frequency than at the radio frequency. This is desirable as, firstly, amplification at RF is more difficult than at audio frequencies and, secondly, with high RF voltage levels there exists the possibility of RF radiation into other areas of the unit, which could cause problems;

iii. this minimises intermodulation distortion. With less amplification required in the stages before the mixer there will be less of this distortion. Intermodulation distortion produces frequency components at the sum and difference frequencies of the input signals and their harmonics. If one of these products is close in frequency and magnitude to the wanted signal there would be considerable interference and it would be difficult, if not impossible, to operate the PDF. Therefore it is advantageous to minimise the gain which precedes the mixer.

2. The RF amplifier provides impedance matching between the loop winding and the band-pass filter.

3. The RF amplifier is a suitable place to apply a portion of automatic gain control (AGC).It is necessary to apply AGC at various points in the receiver. As the magnitude of the input signal varies it is required to have the overall gain of the receiver vary accordingly so as to maintain a constant level at the output. AGC provides a means of fulfilling this requirement.

3.10 The Band-pass Filter

Unwanted signals which are close in frequency to the wanted signal could cause interference resulting in inaccurate operation of the PDF. The operating frequency range of the PDF is 3 - 4 MHz. Strong transmissions at frequencies which are sub-harmonics of the wanted signal could generate harmonics at the wanted signal frequency. This generation would take place in the active devices which precede the mixer. Active devices yield a nonlinear response which gives rise to harmonics of the signals applied to them. Strong signals at frequencies higher than the operating frequency range of 3 - 4 MHz could also lead to interference problems in the receiver. A band-pass filter (Figure 3.4) has therefore been included in the PDF to filter out these frequencies. Appendix B describes the design of the filter. The characteristic impedance of the filter was kept as low as practically possible so as to ensure that the values of the filter components were realisable.

3.11 The Mixer

A mixer or frequency-converter stage of a receiver is responsible for translating the received signal down to either an audio frequency or an intermediate frequency. In the case of a direct-conversion receiver type the translated signal is at audio frequencies. A superheterodyne type translates the received signal to an intermediate frequency.

For frequency translation to take place, it is required to mix the received signal with some form of an oscillator or carrier signal. Mixing of these signals will only take place if the signals are applied to a nonlinear component or network, such as a diode or transistor. The mathematical treatment of a simple mixer is shown in Appendix C. The output of a mixer usually contains both the sum and difference frequencies and the injection frequencies. Selective circuitry inside the mixer rejects the injection frequencies. In a real mixer this rejection is always finite, and so the injection frequencies do appear at the output, but are of a low magnitude relative to the sum and difference frequencies. As well as the above frequency components appearing at the output, there exist harmonics of the injection frequencies and mixer products of these harmonics. In most mixer applications the unwanted frequency components can be filtered out by using a post-mixer filter.

Mixers are classified in several ways. One of these is to group them according to the type of device they utilise, for example a FET mixer or a bipolar transistor mixer. Mixers are also classified according to their mode of operation, which may be either square-law or switched mode.

A square-law mixer is typified by a mixer which uses a FET. Square-law mixers emphasise the second order curvature of the device transfer function. FETs produce low intermodulation distortion products, but are difficult to use as the I_{dss} and V_p specifications are poorly specified. These parameters may both vary by a factor of 2 in a typical FET. Furthermore, FET mixers suffer from gain compression as a result of excessive drain voltage excursion. This will occur if the drain impedance is made too high.

The bipolar transistor has an exponential large signal characteristic. It also exhibits a very large transconductance when compared with an average FET. It will thus function as a mixer. It is biased into conduction in the normal method, with the signal being injected into the base. The oscillator signal is applied to the emitter. This causes the transconductance to vary. This varying transconductance leads to the mixing action. The transistor is unsuitable as a mixer device when there are large signal levels, as the high order curvature in the device produces considerable distortion.

Switched mode mixers utilise devices which have very high order curvatures in their transfer functions. The devices used in these mixers, which are usually diodes, are not biased in the active region, but are used in a switching mode.

The mixer chosen for this application was of the square-law type. The Plessey SL640C was used. This device has a conversion gain of 0dB as it has an active stage included in it. The signal and oscillator leak to the output is specified as being typically 30 dB below the level of the output signal. The intermodulation products are guaranteed to be lower than 35 dB below the output signal. The device has an input impedance of approximately 500 Ω and an output impedance of around 400 Ω. The noise figure of the mixer is 10 dB.

3.12 The Synthesiser

In order to convert the received signal to an intermediate or audio frequency this signal must be mixed with an oscillator signal. The received RF signal has to be converted down to an audio frequency of 1 kHz (Figure 3.4). The oscillator signal must differ in frequency from the RF signal by 1 kHz. At an RF frequency of 3 MHz the oscillator would be 3.001 MHz. The difference frequency is 1 kHz and the sum frequency is 6.001 MHz.

It was decided to allow the PDF to operate on one of ten frequencies. This was done in order to address the problem of possible interference on the frequency being used. This interference could be in the form of atmospheric noise or a signal from a remote transmitter operating at the same frequency as the PDF. In order to be able to generate any one of these ten frequencies it was necessary to use a frequency synthesiser. The frequency synthesiser generates a highly stable signal as it is controlled by a phase locked loop. The heart of a frequency synthesiser is a voltage controlled oscillator (VCO). The VCO is controlled by a set of dividers, a phase detector, a reference oscillator and a loop filter. A block diagram illustrating the form of the synthesiser used is given in Figure 3.7. The fre-

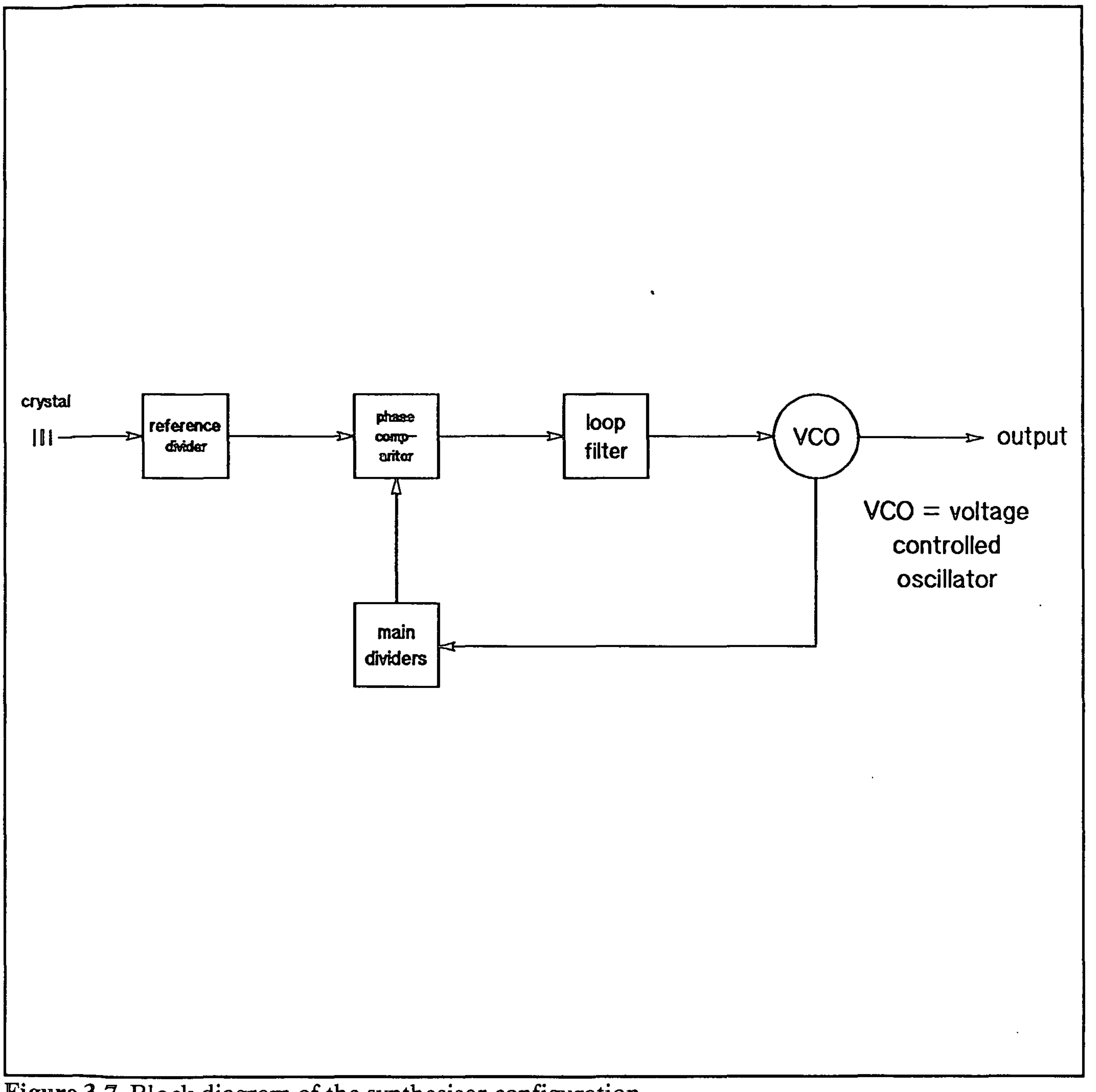


Figure 3.7 Block diagram of the synthesiser configuration.

quency stability of the synthesiser is determined by the reference oscillator. A 6 MHz quartz crystal was used. The temperature stability of this crystal is 10 ppm/°C.

3.13 The Audio Low-pass Filter

The stages discussed up to this point are of a broadband nature. In any receiver it is necessary to include a selective stage at some point. The selectivity of a receiver is the ability to distinguish between the desired signal and signals on closely adjacent frequencies [Orr,1981:10-3]. The selectivity of the receiver used in this project was determined by the mixer and the low-pass filter which followed it.

The output of the mixer contains several frequency components, as mentioned in the description of the mixer. There exist the sum and difference frequencies, the original components and multiples of the original components along with their sum and difference frequencies. The wanted signal is the difference frequency of the original components. The other components are not needed and will merely contribute towards increasing the distortion in the ensuing stages of the receiver. It was decided to use a difference frequency of 1 kHz. This frequency is more easily processed by circuitry than higher frequencies. The closest unwanted component to the wanted frequency is the fourth order product of the original signals. This component would be at 2*3.001 - 2*3.0 MHz. This works out to 2 kHz, which is close in frequency to the wanted component. A low-pass filter with a cutoff frequency of 1.5 kHz was designed and used to filter out the unwanted components. This filter was a 3rd order Butterworth type filter. Figure 3.8 shows the frequency response of the filter.

3.13.1 Filter Design

The Butterworth family of low-pass filters is defined by the attenuation ratio :

$$A = \sqrt{(1+w_r^{2n})} \qquad \text{where } w_r = \frac{w}{w_0} \qquad (1)$$

n = filter order
A = attenuation factor

From this it may be seen that at the frequency where w = 1 the attenuation ratio is $\sqrt{2}$ for all values of n. This corresponds to the cutoff frequency, and yields an insertion loss of 3.01 dB. Element values are calculated from the formula :

$$A_k = 2 \sin \frac{(2k-1)\pi}{2n} \qquad k = 1,2,\ldots,n \qquad (2)$$

where A_k represents the kth reactance in the ladder.

<u>Calculations</u>

Filter order = 3

$f_0 = 1.5$ kHz

desired attenuation at 2 kHz = 8 dB

$Z_o = 350\Omega$ (to match the impedance of the mixer)

$A = \sqrt{(1+w_r^{2n})}$

at 2 kHz : $w_r = \frac{2000}{1500} = 1.333$ rad/sec

$A = \sqrt{(1+1.333^6)}$
$= 2.57$

and attenuation (dB) = 20 log A

= 20 log 2.57

= 8.2 dB

Therefore a third order filter meets the requirement.

applying equation (2) yields :

$C_1 = 303.2$ nF, $L_1 = 74.27$ mH, $C_2 = 303.2$ nF

3.14 The Audio Preamplifier

Up to this stage the input signal has not received a large amount of amplification. It has been increased by 15 dB. Since the antennae being used are of small electrical dimensions, the signals induced into them will typically be in the order of 0.5 μV_{rms}. It was decided to amplify the converted signal to a level of 3 Vp-p (66 % of the supply voltage of 5V). This requires an overall voltage gain of :

$A_v = \frac{1.061}{0.5x10^{-6}}$ where A_v = voltage gain (V_{out}/V_{in})

$= 2.121\times10^{-6}$

Expressed in dB :

$A_V(dB) = 20 \log A_V$

$= 20 \log 2.121\times10^{-6}$

$= 126.5$ dB

Therefore it is still required to amplify the signal by (126.5 - 15) dB = 111.5 dB. All this gain takes place at the audio frequency of 1 kHz. It is spread over several stages so as not to have too much gain in any one stage, which could cause stability problems.

In any receiver it is usually considered good design practice to have most of the gain in the front stages. This is expressed in the following equation :

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_2 G_1} + \ldots + \frac{F_n - 1}{G_n \ldots G_1} \qquad (3)$$

where : F_n = noise figure of the nth stage

G_n = gain of the nth stage

F = system noise

In this expression it is illustrated that the factor G_1 appears in all but the first term on the right hand side. This means that G_1 plays a part in reducing the noise figures of all the stages which follow it. It is thus desirable to have G_1 as large as possible, in order to keep the system noise as low as possible. The first term on the right hand side of the equation has no denonimator, and so this figure should be kept as low as possible. This term is F_1 and corresponds to the noise figure of the first stage.

If the last two conditions are met, then the system noise figure will be as low as possible. In considering the application of these conditions it was remembered that the gain of the stage preceding the mixer has to be only enough to prevent the mixer noise from overriding the signal. Increasing the gain above this point may result in the following problems :

1. The stages prior to the mixer are broadband. If a large amount of gain exists, unwanted signals will be amplified to levels which will cause the mixer to begin to saturate and thus become insensitive to the wanted signal. This is termed "blocking".
2. As the gain of the stages preceding the mixer increases, so the resultant dynamic range of the mixer becomes less, as a smaller signal is required to saturate the mixer. This is an unwanted situation as it is advantageous to have a mixer with a high dynamic range.

3. The selectivity of the receiver is proportional to the amount of gain which follows the mixer. Therefore an increase in the gain of the stage preceding the mixer reduces the selectivity of the receiver.

For the above reasons the audio preamplifier is considered to be the first stage in equation (3). It was decided to give this stage a gain of 60 dB (Figure 3.4). The Plessey SL561C ultra-low noise preamplifier chip was used. This device has an equivalent input noise voltage of 0.8 $nV/\sqrt{Hz}$. The bandwidth of the device was set to 1 kHz. This results in an equivalent noise voltage of 25.3 nV. The theoretical noise figure of this stage is calculated below :

Assuming the signal to noise ratio (SNR) of the input signal to be approximately 10dB :

$$E_s(in) = 0.5*10^{+6} * \text{antilog}\left[\frac{15}{20}\right] \ \mu V$$

$$= 2.81 \ \mu V$$

$$E_n(in) = 2.81 * 0.3163$$

$$= 0.888 \ \mu V$$

and $E_n(added) = 25.3$ nV

where $E_s(in)$ = input rms signal voltage

and $E_n(in)$ = input rms noise voltage

thus total input noise = $E_n(T)$ = 888 nV + 25.3 nV

= 913.3 nV

gain of amp. = 60 dB (1000*)

So : $E_s(OUT) = 1000 * 2.81\ \mu V$

$= 2.81\ mV$

$E_n(OUT) = 1000 * 913.3\ nV$

$= 913.3\ \mu V$

$$\text{Output SNR} = \frac{2.81}{0.9133} = 3.077$$

$$\text{noise figure} = 10 \log \left[\frac{3.077}{3.162}\right]$$

$$= 0.118\ dB$$

3.15 The Audio Band-pass Filter

The output signal of the audio preamplifier is passed into the audio band-pass filter (Figure 3.4). This filter performs two main functions :

1. It keeps the system noise as low as possible by limiting the bandwidth of the audio signal. The thermal noise power available from a resistor is defined by the formula :

$$P_n = KTB \qquad (4)$$

where P_n is the available noise power in watts

K is Boltzmann's constant, $1.38*10^{-23}$ W/K

T is the temperature in ° Kelvin

It is illustrated in (4) that the noise power is independent of the value of the resistor. It is directly dependent on the temperature and bandwidth of the stage. Hence, if the bandwidth of the signal is halved, the available thermal noise power from the stage in question is reduced by 3 dB. The signal from the audio amplifier has a bandwidth of 1 kHz. The band-pass filter has a center frequency of 1 kHz and a bandwidth of 80 Hz. The available noise power is reduced as follows :

$$\text{reduction} = 10 \log \frac{1000}{80}$$
$$= 10.97 \text{ dB}$$

2. The selectivity of the receiver is improved by the band-pass filter. The mixer output contains the sum and difference components of the signals applied to it. The sum component is filtered out by the low pass filter which follows the mixer. The difference component, if below 1.5 kHz, will pass through the audio preamplifier. If this signal is not at 1 kHz then it is an undesired signal, and must be filtered out, or else it will interfere with the wanted signal. The bandpass filter performs this function.

An active fourth order filter was used. The filter was given a gain of 26 dB at the centre frequency.

3.16 The Audio Amplifier

The audio amplifier amplifies the signal by the amount of gain required to make up the overall receiver gain (Figure 3.4). This works out to be 126.5 - (15+60+26) = 25.5 dB. This is a broadband amplifier which uses an operational amplifier. The output impedance of this stage must be low enough to be able to supply the detector with the current it requires. The output voltage of this amplifier is 1.057 V_{rms} (2.978 V_{p-p}). As most of the receiver gain takes place in the stages prior to this stage, the noise figure of this stage plays a small part in determining the overall receiver noise figure. The following calculation illustrates this fact :

Let the noise figure of the audio amplifier be 10 dB.

Hence the amplifier contribution to the system noise figure is :

$$F = \frac{F_a - 1}{G * G_a} = \frac{10 - 1}{1.1*10^6*18.84} = 434.3 * 10^{-9}$$

where : F_a is the noise factor of the audio amplifier

G is the gain in the stages preceding the amplifier

G_a is the gain of the audio amplifier

F is the system noise factor

in dB : $NF = 10 \log F = 10 \log 434.3 * 10^{-9} = -63.6$ dB

3.17 The Detector

Since the signal being processed is a sine wave of frequency 1 kHz with no modulation, this stage, strictly speaking, is not a detector. Its function is to detect the amplitude of the signal only. The amplitude of the signal at this point is related to the cardioid pattern. Instead of rectifying the signal, and then working with half the peak to peak voltage, the detector uses a diode pump circuit to shift the centre point of the waveform so that the whole cycle of the signal is above ground. The signal is then used to charge a capacitor which stores the peak voltages. The capacitor is suitably loaded so that it will discharge fast enough if there is a drop in the signal received. The detector has no active devices in it and has a small loss due to the voltage drop across the diode. At the desired output level of 2.978 Vp-p this loss is :

V_d = 0.2 V (hot carrier diode) where V_d = diode voltage drop

$V_{in} = 2.978$ V

$V_{out} = 2.978-0.2 = 2.778$ V

$$\text{loss} = 20 \log \frac{2.978}{2.778} = 0.603 \text{ dB}$$

3.18 The Display

The display provides a means of indicating the amplitude of the output signal to the user. It is possible to achieve this end by using either an audible or a visual indicator. The visual method was chosen for the following reasons :

1. An audible signal may not be effective in a noisy environment.
2. The user may not want to use a unit which emits sounds and may give his position away to hostile forces.
3. The eye can detect smaller changes in a signal than the ear can.

It was decided to use 10 light emitting diodes (LEDs). The display circuit was designed to allow the LEDs to light linearly in relation to the voltage out of the detector. At 0 V no LEDs light and at 3 V all the LEDs light. Successive LEDs will light for every 300 mV of voltage increase. An automatic dimming facility was included to dim the LEDs as the ambient light dropped, and vice versa. This facility will help to minimize the current drain on the battery and will make the PDF less visible at night. The LM3914 integrated circuit was used, which has the necessary comparators built into the chip, and so helps to save space on the printed circuit board. The LEDs chosen were of a high intensity, high efficiency type so as to keep the current consumption of the display stage as low as possible.

3.19 The Automatic Gain Control

AGC provides the receiver with a means of coping with input signals of varying strengths. The user may be as far as 5 km away, or as near as 100 m from the transmitter. The corresponding change in signal strengths received at the antenna is approximated below :

$$P_r = \frac{P_t}{4 \cdot \pi \cdot d^2} \, W$$

where P_t is the transmitted power in watts and P_r is the power intensity at the receiving antenna in watts.

expressed in dB :

$$P_r = 10 \log P_t - 10 \log \frac{1}{4 \cdot \pi \cdot d^2} \text{ dB}$$

Assuming the transmitted power is 2 watts :

then $P_t = 10 \log \frac{2}{10^{-6}} = 63$ dBμW

At a receiving distance of 100 m :

$P_r = 63 - 10 \log 4 \cdot \pi \cdot 100^2 = 12.01$ dB

At a receiving distance of 5 km :

$P_r = 63 - 10 \log 4 \cdot \pi \cdot 5000^2 = -21.9$ dB

Thus the change in level received (P_C) is :

P_C = 12.01 - (-21.9)

= 33.91 dB

The above calculation ignores the effect of ground losses and antenna inefficiencies, which could make P_C even higher. If the gain of the receiver is not reduced as the strength of the input signal is increased, excessive distortion results in many of the stages, and the unit becomes impossible to use. It was decided to give the AGC a control range of 100 dB. The AGC circuit samples the output voltage of the detector and adjusts the gain of several of the stages so that this voltage is kept to a desired level. The attack time of the AGC has to be short so that the receiver gain can be decreased quickly when a strong signal is received. The decay time of the AGC has to be long so that when the user points the unit in the direction of one of the nulls the gain of the unit does not increase quickly and so mask out the null which the user should be seeing. The level of the AGC is set according to the strength of the peak signal received.

3.20 Summary

1. The different modes of propagation were discussed. The surface wave mode was chosen.
2. An operating frequency range of 3 - 4 MHz was chosen.
3. The principle of operation of the loop and sense antenna system was discussed.
4. The antenna system was described, with design details included.
5. A direct conversion receiver type was selected as it was the most suitable for the application.
6. A detailed description of the design of the various stages in the PDF was presented.

CHAPTER 4

THE MEASUREMENT OF THE DATA

4.1 Introduction

Once the design of the PDF was completed the unit was constructed. It was then necessary to perform tests on the unit to determine whether it fulfilled the requirements specified. This was necessary in order to solve subproblem two. It would have been convenient to have had many PDF units to aid with the measurements, but only five were constructed due to the time and cost factor. This chapter discusses the methods used to evaluate the PDF in terms of the specifications described in Section 1.6. The validity of each method is discussed.

4.2 The Second Subproblem

The second subproblem is to evaluate the performance and suitability of the PDF in terms of the specified military requirements.

4.3 The Overall Requirements

In Section 1.6 the delimitations of this study were stated. For the sake of convenience the physical and functional specifications (requirements which the PDF should meet) are stated again in this chapter. The overall requirements are the sum of the physical and functional requirements.

4.3.1 The Physical Requirements

The average paratrooper, on completing a parachute drop, has the burden of carrying all that he requires during the operation. This places heavy physical demands on him and so the PDF must inconvenience him as little as possible. It should be such that :

1. The PDF should be small enough to be held comfortably in one hand. It should be able to fit into the breast pocket of a paratroopers jacket.

2. The shape of the PDF should be practical for a paratrooper to carry. Its mass should not exceed 500 grams.
3. The power source for the PDF must be a cheap, easily obtainable one, for example a 9 V dry battery.
4. The unit should distract the user as little as possible, so as to allow him to have maximum awareness of his surroundings.

4.3.2 The Functional Requirements

The paratrooper may have to operate the PDF in operational conditions and therefore the functional performance of the instrument should be such that :

1. The average paratrooper should find the PDF simple to operate.
2. The power consumption of the PDF should be such that the user is able to take at least 100 readings, each of 30 seconds duration, and five minutes apart during daylight conditions.
3. The means of indication can be by audio or visual means, but must not make the users position known to any person close by. (for example, no bright light or loud buzzers)

4. Reliable operation. A 100 % success rate would be ideal up to distances of 5 km over typical landscapes encountered by military forces in Southern Africa. However, a success rate of 90 % would be acceptable.
5. The PDF should be able to operate satisfactorily with a signal received from a transmitter radiating 2 watts of RF power at a distance of 5 km.
6. Reliable operation should be possible at any time in a 24 hour period.

4.4 The Constructed Units

As mentioned in the introduction to this chapter, five PDF units were constructed. These units were assumed to be identical in performance. This was due to the fact that they were of one design and were constructed using the same methods and components. The tolerance of the components was kept as low as possible in order to keep the electrical characteristics of the units the same.

4.5 The Measurement of the Data

In order to obtain the data required to solve subproblem 2 it was necessary to perform several tests on the PDF. Due to the differences in the requirements of the PDF the tests demanded varying conditions. Of the following tests described, tests 1 to 3 were performed in a laboratory, whilst tests 4,5,6 and 7 were completed at 1 Parabat Battalion, Tempe, Bloemfontein, OFS.

The data was categorised in the same way that the requirements were, namely physical and functional. Some of the tests done yielded data in both groups whilst others were category specific. In the following sections the method of measurement of each requirement is discussed. Where necessary the validity of the measurement is pointed out.

The measurements were carried out in two stages, firstly those which could be done in a laboratory, and then those which had to be carried out in the field. A questionnaire was completed by the paratroopers after they had used the PDF units in order to ascertain their responses.

4.5.1 Laboratory Tests

In the laboratory the following measurements were taken :

Test 1. The mass of the PDF, including the battery, was measured. It was expressed in grams.

Test 2. The type and size of battery required by the PDF was noted.

Test 3. The current consumption of the PDF was measured. This was done as follows :

1. The battery used was a Duracell PP9. A fresh battery was used.
2. The unit was set to channel 6 (3.500 MHz). A sinusoidal signal of 1 μV EMF at 3.501 MHZ was injected into the vertical antenna terminal.
3. A digital multimeter (Fluke 75) was connected across the battery terminals so as to monitor the battery voltage.
4. A bright light was placed above the PDF in order to simulate daylight conditions. This would ensure that the LED brightness regulator kept the LEDs at maximum brightness and hence worst case current consumption.
5. The unit was switched on. The battery voltage was noted every 10 minutes over a period of 3 hours.
6. The battery voltage was plotted against time.

4.5.2 Field Tests

Once the laboratory tests were completed the balance of the measurements was completed in the field. Since the objective was to determine the response of several paratroopers towards the PDF a group of 30 paratroopers from Tempe assisted with the tests. The paratroopers were all required to have completed basic parabat training and to be at the same level in their current training. They were all healthy and fit and were classified G1K1. Permission was granted to utilise the paratroopers for 24 hours. This would enable tests to be done both at day and at night. The discipline and co-ordination of the paratroopers was controlled by a senior officer.

Before the testing with the paratroopers could commence preliminary preparations were done. The first day was used in preparation for the tests. On the second day these were carried out.

4.5.3 Preparation of the Test Area

The available test areas were the Vaalbank 2926AA area and the De Brug 2926AB area. The De Brug area was chosen for the following reasons :

1. This area had bushes and vegetation, which allowed the concealment of the transmitter.
2. A greater variety of terrain types was found here than in the Vaalbank area. (more hills, valleys, vegetation)
3. The Tempe base was closer to the De Brug area, which would reduce the travelling time each day.

Figure 4.1 shows the 2926AA De Brug area used. The scale of the map is 1:50 000 (2 cm = 1 km). The area was prepared as follows :

1. A suitable position was found for the transmitter.
2. Five outer points, ranging from 1.1 to 3.9 km were identified. These points were suitably selected so as to ensure that no visual contact would take place as the paratroopers moved from them towards the transmitter. Markers were put at these points and accurate compass bearings were taken from each point to the transmitter point, using a standard military prismatic compass (the six points are indicated on Figure 4.1).
3. The test area was comprised of mainly relatively flat terrain, with a few hills and slight valleys. Parts of the area were under dense bush whilst other parts were open grasslands. The contours of the area can be seen on Figure 4.1. The contour lines are in 20 m intervals.

Figure 4.1 Map of the day field test area (overleaf).

Map : 2926AA Bloemfontein

Scale : 1:50 000

North : indicated by arrow

Black lines indicate direct routes between the outer 5 positions and the transmitter.

Dotted red lines indicate approximate routes followed by the paratroopers in group 6.

Tx indicates the transmitter position.

Tx2 indicates the position of the second transmitter used for group 6.

Distances from transmitter to outer points :

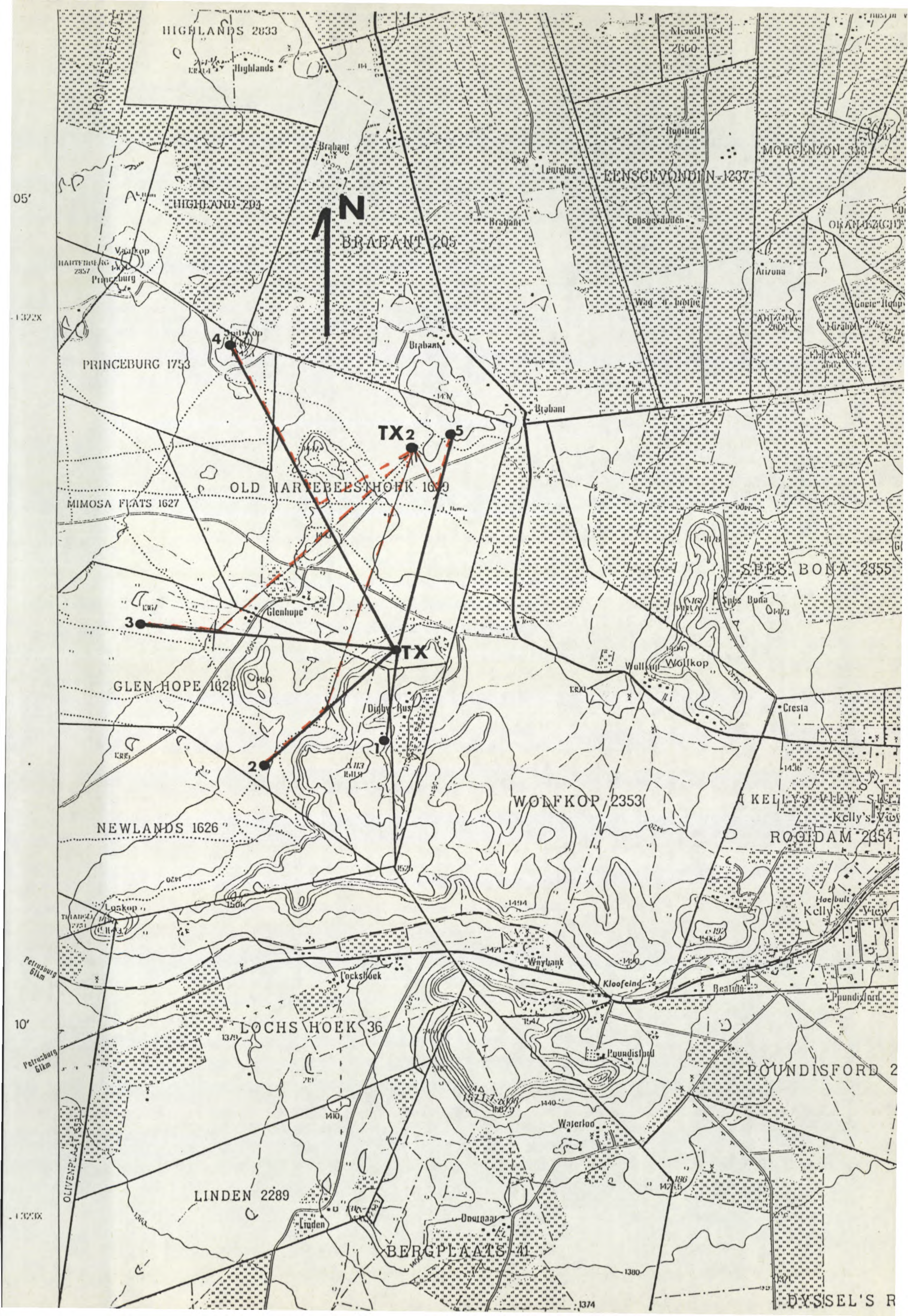
1 - 1.1 km

2 - 2.0 km

3 - 2.75 km

4 - 3.9 km

5 - 2.6 km



HIGHLANDS 2833
Highlands
Brabant
BRABANT 205
HIGHLAND 204
N
Princeburg
PRINCEBURG 1753
MORGENZON
Arizona
TX2
TX
1
2
3
4
5
OLD HARTEBEESTHOEK
MIMOSA FLATS 1627
Glenhope
GLEN HOPE 1628
Digby
NEWLANDS 1626
WOLFKOP 2353
Wolfkop
Spes Bona
SPES BONA 2355
Cresta
Kelly's View
ROOIDAM 2354
Hoebult
Loskop
Waybank
Kloofeind
Lockshoek
LOCHS HOEK 36
Poundisford
POUNDISFORD
Waterloo
LINDEN 2289
Linden
Doornaar
BERGPLAATS 41
DYSSEL'S R
05'
10'
Petrusburg 6km

4.5.4 Orientation Tests

The paratroopers helping with the PDF testing were due to complete a night parachute drop during the course of the tests, which presented the opportunity to do night testing under parachute-drop conditions. The orientation tests are therefore divided into day tests and night tests.

4.5.4.1 Day Orientation Tests

Objective

The objective of this test was to establish the effectivety of the PDF with regard to the daylight regrouping of paratroopers scattered over a wide area.

Requirements

1. Thirty paratroopers who had received parabat training and possessed compass reading skills.
2. Equipment as follows :
   - 5 PDF units
   - 2 transmitters
   - 2 A53 VHF radios
   - 5 compasses

- The De Brug area map
- Bearing cards and pencils
- Binoculars

Precautions / Controls

In order to ensure the validity of the results the following controls were introduced :

1. A random selection of paratroopers had been taken for the tests.
2. The paratroopers were all on the same parabat course and had completed 8 out of 12 months of their training. All of them were classified G1K1 and were physically fit. Compass reading skills had been developed in the course of their training.
3. The gathering point where the paratroopers waited was suitably hidden from the six selected points.
4. The same PDF unit was used from each marker to eliminate unnecessary variables.
5. The paratroopers were blindfolded before being driven to the markers in order to ensure that they lost their bearings along the route.

6. Each time a paratrooper was dropped off at a marker the time was sent by radio to the transmitter operator as a control to allow him to check the information on the bearing cards.
7. Only magnetic bearings were used in order to eliminate possible magnetic declination calculation errors.
8. The transmitter was suitably concealed so as to prevent the paratroopers from seeing it until they were approximately 50 m away.
9. On reaching the transmitter, the paratroopers were prevented from rejoining the waiting paratroopers and possibly revealing the direction of the transmitter.

Execution

On the morning of the tests a group of 30 parabat paratroopers were driven out to the gathering point. They were unaware of the existence of the six points. The paratroopers were clothed in browns and carried skeleton webbing and rifles. The average age was 19 years. The directional tests were carried out as follows :

1. A brief explanation of the PDF, outlining the operating procedures, was rendered and a demonstration followed.
2. The assistant was then taken to the transmitter point.
3. The first five paratroopers to use the PDF were then given compasses, bearing cards and pencils. They were blindfolded.

4. One at a time, they were dropped off at the markers.

5. On removing the blindfold they were instructed to :

   i. Take an initial bearing on the transmitter using the PDF and compass and to write both this and the time on the bearing card.

   ii. They were then to use the PDF to locate the transmitter.

   iii. At five minute intervals they were to take a bearing using the PDF and compass and to note both the bearing and the time.

   iv. On reaching the transmitter they were to note the time.

6. A questionnaire was then completed, under the supervision of the assistant.

7. The assistant was notified each time a paratrooper was dropped off at a marker.

8. Once all five paratroopers had reached the transmitter the compasses and PDF units were retrieved from them and the next cycle started.

9. Steps 4 to 8 were then repeated.

10. The above procedure was followed until all thirty paratroopers had operated the PDF.

4.5.4.2 Night Orientation Tests

Objectives

The objective of the night tests was to establish the effectiveness of the PDF in the regrouping of paratroopers after a night parachute drop.

Requirements

- Five paratroopers having had previous exposure to the PDF.
- 5 PDF units.
- 1 transmitter.
- Night training exercise.

Precautions / Controls

In order to obtain valid results the following controls were introduced :

1. It was certain that the paratroopers using the PDF had no idea where the transmitter was going to be placed as it was taken out to the drop zone by vehicle, whilst the paratroopers were transported there by a C130 troop carrier aeroplane.
2. The test took place under the cover of a cloudy, moonless night.
3. The path that the paratroopers would follow to reach the transmitter would be different to that followed by the rest of the paratroopers.
4. The paratroopers using the PDF units were evenly distributed in the drop order. This means that, on reaching the ground, they would be evenly distributed across the drop zone.

Execution

A C130 dropped 64 paratroopers over the Vaalbank area (indicated in Figure 4.2) in two loads of 32 each. This was to be the second night jump that the paratroopers had done. The drop was done on a cloudy, moonless night from a height of 1000 feet. A static line was used to release the parachutes. The drop zone was indicated to the pilot by means of a system of lights on the ground. This is shown in Figure 4.2. The impact point (the point where the first paratrooper released should land) is also indicated. Five of the first load of 32 paratroopers were equipped with PDF units. A transmitter had been placed adjacent to the drop zone, and would be switched on once the paratroopers landed. They had been instructed prior to take-off that on landing they were, after they had rolled up their parachutes, to use the PDF to locate the transmitter. They were to ignore the rest of the paratroopers, who would be regrouping by other means. The others would be regrouping in secions first, and then moving down, as a group, to the impact point. The transmitter was placed at a point about 500 m from the closest paratrooper and 2 km from the furthest. The approximate positions that the paratroopers landed in as well as the routes they followed are indicated in Figure 4.2.

Figure 4.2 Map of the night field test area (overleaf).

Maps : 2926AB Maselspoort, 2826CD Glen

Scale : 1:50 000

North : indicated by arrow

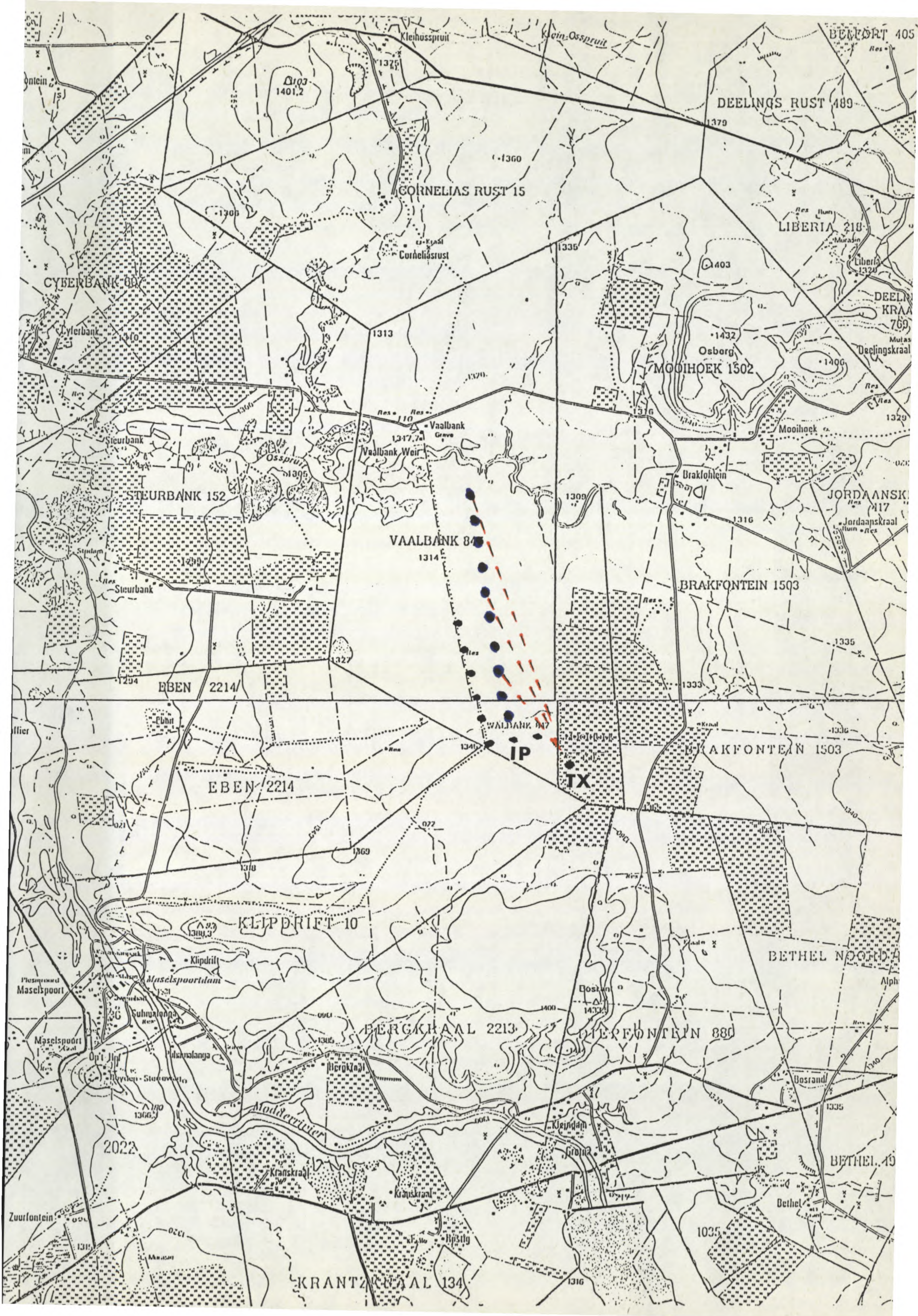
Black markers indicate drop zone lights.

IP indicates the impact point as well as the regrouping point of the paratroopers not using the PDF.

Blue dots indicate approximate positions where paratroopers landed.

Red lines indicate approximate routes followed by paratroopers using the PDF units.

Tx indicates the transmitter position.



BELFORT 405
Kleinosspruit
Klein-Osspruit
DEELINGS RUST 489
CORNELIAS RUST 15
Cornelliasrust
LIBERIA 218
Liberia
CYBERBANK 607
Cyferbank
MOOIHOEK 1502
Osborg
Deelingskraal
Mooihoek
Vaalbank
Vaalbank Weir
Steurbank
Osspruit
STEURBANK 152
Brakfontein
JORDAANSKRAAL 417
Jordaanskraal
VAALBANK 847
Steurbank
BRAKFONTEIN 1503
EBEN 2214
VAALBANK 847
IP
TX
BRAKFONTEIN 1503
EBEN 2214
KLIPDRIFT 10
Klipdrift
Maselspoortdam
Maselspoort
BETHEL NOORD
Boskuil
BERGKRAAL 2213
DIEPFONTEIN 880
Maselspoort
Bergkraal
Bosrandt
Modderrivier
Kleindam
2022
Kranskraal
BETHEL
Bethel
Zuurfontein
1035
KRANTZKRAAL 134

4.5.5 Range Tests

Objective

The purpose of the range test was to determine the maximum range that the PDF was capable of giving readable bearings at.

Requirements

- 1 transmitter
- 1 PDF unit
- A straight road, as flat as possible, and long enough to cope with the maximum range capabilities of the PDF.

Execution

The maximum range capability of the PDF was measured along a straight stretch of road, which was found on the N1 north of Bloemfontein. The transmitter was placed at a suitable point and the PDF was moved along the road in 1 km increments until the reading on the LEDs reached the point where the direction of the transmitter was only just discernable. At the maximum distance covered there was no LOS link between the transmitter and the PDF as gentle hills and valleys separated them.

4.5.6 Colour Tests

Objective

The objective of the colour tests was to determine which colour of red, green or amber was the least detectable by the naked eye at night, for the purpose of selecting a suitable colour for use in the PDF.

Requirements

- A dark night.
- Three PDF units, having different colour LEDs.

Precautions / Controls

The LEDs were connected so as to all be permanently on when the unit was activated. They were all set to be of the same illumination. The test was done on a cloudy, moonless night.

Execution

1. The assistant stood at a distance of 25 m from the PDF.

2. The unit with the red LEDs was switched on and held waist high, parallel to the ground and pointing towards the assistant. He was asked to confirm whether he could see the LEDs at all and, if so, what the colour of the LEDs were.
3. The above step was repeated using the units with the green and amber LEDs.
4. The unit with the red LEDs was then switched on and held at face height with the LEDs pointing towards the assistant. He was again asked to confirm whether he could see the LEDs at all and, if so, what the colour of the LEDs were.
5. The above step was repeated using the units with the green and amber LEDs.
6. Steps 2 to 5 were then repeated at distances of 50, 75, 100, 125, 150, 175, 200, 225 and 250 meters.

CHAPTER 5

DIRECTION FINDER TEST RESULTS

5.1 Overview

In Chapter 4 the test procedures were discussed. This chapter is concerned with the reporting of the results that were generated from the tests. The initial and final bearing accuracies taken whilst attempting to locate the transmit / regroup point are the most important of all the readings taken by the paratroopers. These accuracies are presented and analysed. The limitations and problems of the practical field work are pointed out. The results are presented and briefly discussed.

5.2 Laboratory Tests

5.2.1 Tests 1 & 2 : Mass and Power Source Required by the PDF

Due to the fact that the PDF will probably be used by paratroops, who carry heavy loads in combat conditions, it is important that the unit be as light as possible. It is also imperative that the power source for the unit should be cheap and easily available. Tests 1 and 2 addressed these criteria. The results of these tests are presented in Table 5.1 and show that both of the requirements were met.

Table 5.1 The mass and power source requirements of the PDF. The mass was measured with the battery installed. The power source was the most efficient battery in the category which would fit in the unit.

Test 1 : Mass of DF		Test 2 : Power Source	
desired	actual	desired	actual
500 grams	367 grams	small, cheap, light	Duracell PM3 9 V

5.2.2 Test 2 : Current Consumption

The current consumption of the PDF was measured following the method outlined in Section 4.5.1. A Duracell 6LR61 battery was used. The battery voltage is plotted against time (Figure 5.1).

The voltage regulator used in the design requires a head voltage of 2 V. Its output voltage is 5 V and so, for reliable operation, the battery voltage must be 7 V or higher. The PDF performance becomes unpredictable below a supply voltage of 7 V. The cut-off point is defined as 7.2 V and is indicated (Figure 5.1). This corresponds to 110 minutes of continuous operation. Under conditions of normal usage the unit would be operated every 10 minutes or so for a duration of about two minutes. This would enable the battery to last longer. At least 55 readings of 2 minutes each would be possible. If a reading was taken every 10 minutes then the battery would last for at least 550 minutes (just over 9 hours). Even if the regrouping took two hours (a long time by existing standards), the unit would still only be drawing on around 20 % of the life of the battery.

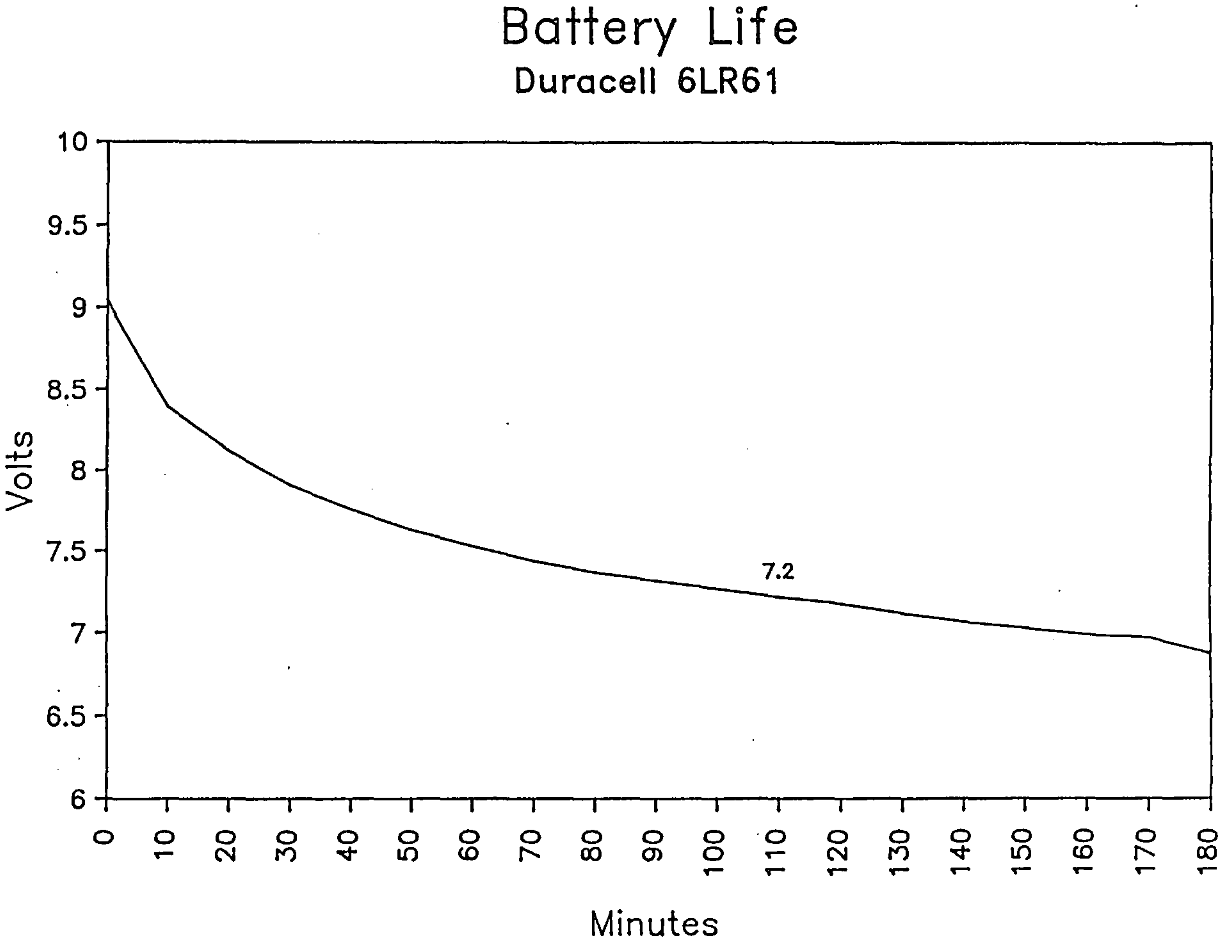


Figure 5.1 The PDF current consumption.

5.3 Orientation Tests

On the first day of the day tests, 10 paratroopers were used to locate the transmitter. The remainder of the daylight tests were completed the following day. During the first test on the second day a technical problem (intermittent dry joint) occurred with unit 1, so only four PDF units were used for the last three groups of paratroopers. The symptom of the fault was that the unit behaved as though the vertical antenna was not connected. The unit exhibited a "figure of eight" loop polar pattern. This gave the user two peak and two null indications, thereby throwing him into a state of confusion as to the direction of the transmitter.

Two critical factors influence the successful location of the regroup point, namely the initial and final bearing accuracies.

5.3.1 Initial Bearing Accuracies

The first priority of the paratroop, on reaching the ground after a drop, is to locate his regrouping point as soon as possible. In combat situations speed is essential in order to keep the element of surprise. The initial bearing the user takes on the transmitter is therefore of paramount importance for two reasons :

1. If the initial bearing differed substantially from the actual bearing of the transmitter the paratrooper would start out in the wrong direction and would, therefore, be adding on extra distance (and time) for himself to cover right from the start of his traverse towards the regrouping point.

2. If the paratrooper was at the extreme range of the PDF, where the received signal was very weak, and he headed off in the opposite direction to the regrouping point, he would soon be out of the range of the PDF. At this point the PDF would be of no help to him in determining the direction of the regrouping point. He would be in a potentially very dangerous situation and would thus have compromised both his own safety and the safety of his companions waiting for him.

The initial bearing accuracies, as recorded by the paratroopers, are shown in Table 5.2. (overleaf)

Table 5.2 A comparison of the initial bearings taken by the paratroopers. The comparison is made between the readings for each terrain position separately. The initial errors are indicated. All figures are expressed in degrees.

Position 1

Troop no.	Reading	Actual	Error	
1	23.62	20.47	3.15	
2	invalid readings taken*			
3	11.25	20.47	9.22	
AVERAGE ERROR				6.19

Position 2

Troop no.	Reading	Actual	Error	
1	57.94	75.37	17.44	
2	67.50	75.37	7.87	
3	75.37	75.37	0	
4	73.12	75.37	2.25	
5	65.81	75.37	9.56	
6	56.25	75.37	19.12	
AVERAGE ERROR				9.37

Table 5.2 (cont)

Position 3

Troop no.	Reading	Actual	Error
1	129.37	120.37	9
2	123.75	120.37	3.37
3	124.87	120.37	4.5
4	104.62	120.37	15.75
5	123.75	120.37	3.37
6	123.75	120.37	3.37

AVERAGE ERROR 6.56

Position 4

Troop no.	Reading	Actual	Error
1	180	168.75	11.25
2	184.5	168.75	15.75
3	168.75	168.75	0
4	196.87	168.75	28.12
5	180	168.75	11.25
6	180	168.75	11.25

AVERAGE ERROR 12.94

Position 5

Troop no.	Reading	Actual	Error
1	235.68	219.37	16.31
2	225	219.37	5.62
3	invalid	readings	taken*
4	219.37	219.37	0
5	225	219.37	5.63
6	185.62	219.37	33.75

AVERAGE ERROR 12.26

OVERALL AVERAGE ERROR 9.46

* Invalid readings were recorded.

In order to express the degree of accuracy of the initial bearings the difference between the measured and actual bearings was calculated. The overall average of the errors was 9.46°. It is significant to note that in spite of very brief training in the use of the PDF, and no briefing at all as to the direction of the transmitter, the average initial error was less than 10°.

Table 5.2 illustrates that the initial readings taken from position 3 were the lowest. There could be several reasons for this. One reason could be that the terrain between position 3 and the transmitter could have been more suitable for accurate measurements than that between the transmitter and the other positions. Under ideal conditions, it would have been beneficial to take more readings from each position. This would have served to give a more accurate indication of the effect of the terrain on the initial readings taken.

5.3.2 Final Bearing Accuracies

One of the greatest difficulties the paratroops are faced with when executing an operation at night in hostile conditions is regrouping after a parachute drop. The present practice is to use "Lumi-Stiks" (a luminescent tube) to reveal the regroup point. The use of any form of lights could reveal their position to hostile forces. It is hoped that in this situation the PDF could help to overcome these difficulties. However, under very dark conditions and/or dense bush, the regroup point may be missed by the paratroop. It is therefore important that the PDF be capable of giving accurate readings at short distances from the transmitter, given the time available for taking a bearing.

Table 5.3 A comparison of the final bearings taken by each paratrooper. The comparison is made between readings for each terrain position separately. The errors are indicated. All figures are expressed in degrees.

Position 1

Troop no.	Reading	Actual	Error
1	9	7.2	1.8
2	invalid readings taken*		
3	11.25	11.97	0.72
AVERAGE ERROR			1.26

Position 2

Troop no.	Reading	Actual	Error
1	230.62	147.13	83.5
2	70.31	126.63	56.32
3	353.25	22.72	29.47
4	73.12	99.46	26.33
5	speed**		
6	292.5	110.06	177.56
AVERAGE ERROR			74.64

Table 5.3 (cont)

Position 3

Troop no.	Reading	Actual	Error
1	123.75	202.36	78.61
2	112.50	166.90	54.4
3	83.25	58.12	25.13
4	135	185.22	50.22
5	speed**		
6	337.5	290.88	46.42

AVERAGE ERROR 50.96

Position 4

Troop no.	Reading	Actual	Error
1	101.25	142.5	41.25
2	184.5	96.54	87.95
3	109.69	223.57	113.89
4	146.81	129.88	16.93
5	speed**		
6	337.5	290.88	46.42

AVERAGE ERROR 61.29

Position 5

Troop no.	Reading	Actual	Error
1	211.5	187.81	23.69
2	241.87	202.82	39.06
3	invalid readings taken*		
4	258.75	218.25	40.5
5	speed**		
6	337.50	419.83	82.33

AVERAGE ERROR 46.4

OVERALL AVERAGE ERROR 46.91

* Invalid readings were recorded

** This paratrooper took part in a speed test in which the final bearings were not recorded

The final bearings shown above are not as accurate as the initial bearings. If the paratroopers had followed these bearings they would have passed by the transmitter and would then either have approached it from another side or strayed away from it. However, the test area allowed visible contact between the paratrooper and the transmitter once about 50 m separated them, which assisted the paratroopers once they were within this radius.

The final bearing errors in reality are not as high as indicated in Table 5.3. for the following reason :

The initial errors are easily calculated as the bearing from each position to the transmitter had been measured prior to the tests. However, the measurement error made during the last reading taken by each paratrooper is not simple to calculate. In most cases, as the paratrooper moves away from the start position and towards the transmitter, he follows a line other than the shortest route between the two points. The length of this route is unpredictable. If the speed of the paratrooper was known the distance traversed could be calculated. However, the speed is not known but is approximated as follows. From the map in Figure 4.1 the LOS distance can be read off. The travelling times are recorded by the paratroopers. This enables the calculation of the theoretical speed of the paratrooper had he travelled the shortest distance possible. This speed is therefore an estimation. In reality the speed would have been lower. This deviation gives rise to errors in the calculation of the actual bearing of the transmitter from each measurement point. The errors are cumulative, and thus at the last bearing taken, the actual bearing could deviate from the calculated bearing by an appreciable measure. The errors are also proportional to the degree of deviation between the route followed and the actual route. The latter two points possibly explain why the errors made from position 1 (the shortest distance) are the lowest.

A further factor which could have contributed to the high final bearing errors was the short training given to the paratroopers. The PDF units become more difficult to use as they get closer to the transmitter due to :

1. The attack time of the AGC becomes fairly long. If the paratrooper attempts to establish a bearing before the AGC has stabilised, the reading could be erroneous as the peak indication will be very wide.
2. The peak reading is wider at short distances than at greater distances from the transmitter. In bisecting a large angle there is a chance of making a larger error than for a small angle.

5.3.3 Group Errors

A breakdown of the initial bearing errors made by the paratroopers as a group is shown in Table 5.4.

Table 5.4 The initial bearing accuracies of the whole group. The accuracy range is shown together with the percentage of the paratroopers whose initial bearings fell into that category.

0° - 2°	11.5%
2° - 4°	19.2%
4° - 6°	11.5%
6° - 10°	15.4%
10° - 15°	11.5%
15° - 20°	19.2%
above 20°	11.5%

From these figures it can be seen that 57.6 % of the initial bearings taken had an error of less than 10° and 30.7 % were between 10° and 20°. This totals to 88.3 % of the initial bearings being below 20°. More than 10 % of the paratroopers had initial accuracies of less than 2°. In no instances did any paratrooper start walking in the opposite direction to the transmitter.

5.3.4 Speed Tests

The fifth group to use the direction finders completed a "speed" test. They took only one initial bearing, noted it, and then headed for the transmitter as quickly as they could. They used the PDF as they deemed necessary. Table 5.5 (overleaf) illustrates the times taken for the paratroopers to travel to the transmitter from the various start points. A comparison is made between the times of group five and the average of the other groups.

Table 5.5 Bearing and time measurements. The start and end times of all the paratroopers are displayed. The travelling times are indicated. Group five's times are compared with the average of the other groups.

Group	Position no. »	1	2	3	4	5
1	start time	11:29	10:28	10:37	10:52	11:10
	end time	12:08	11:21	11:38	12:04	12:06
	total	0:29	0:53	1:01	1:12	0:56
2	start time	13:50	13:04	13:12	13:24	13:35
	end time	14:24	13:49	14:24	14:49	14:28
	total	0:34	0:45	1:24	1:25	0:53
3	start time	09:22	08:34	08:40	08:55	09:07
	end time	10:42	09:32	09:43	10:09	09:52
	total	1:20*	0:58	1:03	1:14	0:47
4	start time		10:57	11:00	11:17	11:25
	end time		11:50	12:18	12:35	12:18
	total		0:43	1:18	1:18	0:53
5	**start time**		**13:16**	**13:18**	**13:30**	**13:40**
	end time		**13:43**	**14:01**	**14:20**	**14:43**
	total		**0:27**	**0:43**	**0:50**	**1:03******

Average times of groups 1 to 4 :

	1	2	3	4	5
Position no. »	1	2	3	4	5
Average time »	0:31	0:50	1:11	1:17	0:52
Group 5 times »		0:27	0:43	0:50	1:03

* This PDF began to malfunction.
** This paratrooper misread the PDF and so travelled a distance than required.

Table 5.5 illustrates that the times established by group 5 are shorter than the other groups. Unfortunately the results from the paratrooper leaving from position 5 could not be used due to the fact that he misread the PDF and so covered a far larger distance than required. The other results, however, indicate that the paratroopers doing the speed test travelled at almost twice the speed than the others. This test suggests that it is possible to regroup paratroopers at distances of up to 3.9 km within approximately 50 minutes. It must, however, be pointed out that the paratroopers were not carrying full battle kit and thus these times would become slightly longer under combat conditions.

5.3.5 The Re-location of Grouping Point Test

Owing to the fact that the paratroopers using PDF units to locate a regroup point do not have to depend on any other form of navigation, it should be possible to change the regroup point whilst the paratrooper is in motion. It would then be possible to draw the paratrooper to any desired position. The object of this test was to demonstrate this facility.

Whilst the sixth group were travelling towards the first regroup point, the transmitter at this point was switched off and a second one was switched on at a different regroup point location. All four paratroopers responded by changing course and heading towards the second regroup point. Their change in direction is indicated by the dotted lines in Figure 4.1 as well as by the recorded bearings.

The results of this test indicate that it is possible to move the regroup point whilst the paratrooper is in motion. The PDF can therefore be used to "steer" the paratroopers to any desired location. This test also serves to validate the recorded bearings of the other orientation tests as it shows that the paratroopers were in fact responding to each reading they took as opposed to just walking in the direction of the original bearing.

5.3.6 Night Tests

The assistance rendered by the PDF for regrouping at night is probably the most important application. Under cover of a dark cloudy night the paratrooper will have no view of his surroundings or orientation. It is in this situation that he relies solely on the PDF in order to find the regroup point.

As described in the previous chapter, five of the 64 paratroopers that were dropped at night used PDF units to assist in regrouping. These five had used the units during the day tests and so were familiar with the operation of the units.

The arrival times of the first three paratroopers to locate the transmitter after the drop are recorded in Table 5.6. The unit used by the fourth paratrooper initially gave correct readings but, after some distance had been traversed, began to malfunction. He was about 20 m from the transmitter at this time and, because it was evident that he was having difficulty with the unit, was called over. This PDF unit was the same one that had given trouble during the course of the orientation tests.

The paratrooper using the fifth PDF unit managed to get within about 120 m of the transmitter. At this point he took another bearing and misread the PDF. Whilst heading in the wrong direction he was stopped by the drop zone officer who was concerned that he may get lost. He was sent to a nearby road and told to wait to be picked up at the end of the exercise. The unit was checked later and was found to be functioning correctly.

The paratroopers regrouping by conventional means took over an hour. Their regroup point was in the centre of the drop zone. They used lumi-stiks to assist them to regroup. The maximum distance covered by any of these paratroopers would have been around 750 m in comparison with that covered by the paratroopers using the PDF units being about 2 km.

These results suggest that the paratroopers can be drawn away from the drop zone and regrouped in a shorter time than that obtained by conventional means. It must be emphasised that the paratroopers using the direction finders had, on landing on the ground at night, no indication of the direction of the regroup point. They relied solely on the direction finders for their orientation and had to walk in a direction contrary to that followed by the paratroopers not equipped with direction finders. In spite of these difficulties they located the regroup point before the other paratroopers found theirs and also covered more distance in less time.

Table 5.6 The drop and arrival times of the paratroopers partaking in the night test.

Drop time : 19H15
Arrival times of troops at transmitter :

1st troop : 19H40 (time taken : 25 mins)
2nd troop : 19:45 (time taken : 30 mins)
3rd troop : 19:55 (time taken : 40 mins)

5.4 Range Tests

The possibility exists that the paratroop, on landing in a hostile area, may have drifted several kilometers from the regroup point during his descent. The topography may also force him to move in the opposite direction to the regroup point until the obstacle met is overcome. In this situation it is important that the PDF be sensitive enough to operate satisfactorily over long distances. The range required for normal operation by the paratroops has been specified as being 5 km. The operating range is directly proportional to the sensitivity of the PDF.

Table 5.7 PDF range test results. The tests were done on a straight stretch of the N1 north of Bloemfontein.

distance(km)	reading*	null LEDs on**	range LEDs on***
1	9 - 10	0	4
2	9 - 10	0	3
3	9 - 10	0	3
4	9 - 10	0	3
5	8 - 10	0	2
6	8 - 10	0	2
7	8 - 9	0	1
8	8 - 9	0	1
9	5 - 7	0	0
10	5 - 6	0	0
11	3 - 4	0	0
12	2 - 3	0	0
13	2 - 3	0	0

* All 10 of these LEDs light up when the PDF is pointing towards the transmitter.

** There is a null opposite to the peak. When pointing the PDF towards the null all the LEDs should extinguish.

*** These LEDs indicate **relative** distance to the transmitter. As the PDF gets closer to the transmitter more of these LEDs will light.

Note : The direction indicators on the PDF are ten LEDs which all light up when pointing the unit towards the transmitter. As the range increases, less of these LEDs will light up, as shown in Table 5.7.

The results of the range tests are displayed in Table 5.7. From this table it may be seen that the PDF unit could be used over relatively flat terrain to distances of 10 km, provided the user was reasonably familiar with the unit. This corresponds to an area coverage around the transmitter of 314 square kilometers (πr^2 where r = 10 000 m). This distance is far in excess of the maximum distance that the paratroops could have drifted from the drop zone (average 1.8 km - maximum 3 km). This test was done over dry sandy ground having poor ground conductivity. Over areas of higher annual rainfall this range may increase slightly. However, it is also true that the range may decrease over more mountainous terrain. It is doubtful that the reduction in range would be as much as 3:1, in which case the unit would still perform satisfactorily over 3 km range.

5.5 Colour Tests

When using the PDF in a combat situation the possibility exists that hostile forces could detect the user. Under dark conditions the light from the LEDs may be seen. It is thus important that the colour of the LEDs used be the least visible of those available to the naked eye. A comparison of the visibility of red, green and amber LEDs is given in Table 5.8.

Table 5.8 Colour test results. The test was done on a dark, moonless night on a straight dust road at various distances.

Position 1 : The PDF unit was held horizontally, at waist height, and pointing towards the observer.

Position 2 : The PDF unit was held vertically at face height with the LEDs pointing directly towards the observer.

(Table 5.8 overleaf)

Distance	colour	position 1 visible	position 1 colour	position 2 visible	position 2 colour
25M	red	no	-	yes	red
	green	no	-	yes	green
	amber	no	-	yes	amber
50M	red	no	-	yes	red
	green	no	-	yes	green
	amber	no	-	yes	amber
75M	red	no	-	yes	red
	green	no	-	yes	green
	amber	no	-	yes	amber
100M	red	no	-	yes	red
	green	no	-	yes	green
	amber	no	-	yes	amber
125M	red	no	-	yes	? red
	green	no	-	yes	green
	amber	no	-	yes	amber
150M	red	no	-	yes	? red
	green	no	-	yes	green
	amber	no	-	yes	amber
175M	red	no	-	no	-
	green	no	-	yes	? green
	amber	no	-	yes	? amber
200M	red	no	-	no	-
	green	no	-	yes	unsure
	amber	no	-	yes	unsure
225M	red	no	-	no	-
	green	no	-	yes	unsure
	amber	no	-	yes	unsure
250M	red	no	-	no	-
	green	no	-	yes	unsure
	amber	no	-	no	-

From Table 5.8 it is evident that none of the colours were visible to the naked eye when the PDF unit was held in position 1. This can be attributed to two factors :

1. The LEDs used were of a very high intensity type. High intensity LEDs usually have a very small beamwidth angle so as to concentrate all the light energy in one direction. This serves to reduce the visibility of the LED from any other direction. The observer was viewing the LEDs from almost 90° to their direction of maximum emission.
2. The PDF box was designed with the LEDs recessed below the lid, which would make them invisible when viewed from the side of the box.

The red LED is the most suitable for the application as it becomes undetectable sooner than the other colours as the range increases. At 175 m the red LED was undetectable, whilst both the green and the amber LEDs were still visible.

It must be remembered that the colour tests were done with only the naked eye. In the case where advanced infrared or passive night vision equipment was used the results might differ.

5.6 The Response of the Paratroopers

In Section 1.6 the physical and functional requirements which the PDF should meet are mentioned. The tests described up to this point addressed the requirements which involved the performance parameters of the PDF units themselves. In order to address the requirements which involved the response of the paratroopers it was necessary to have them complete a questionnaire after they had used the PDF. The questionnaire was of the form shown in Appendix E.

The completed questionnaires indicated the response of the paratroopers towards the size, portability, mass, ease of use, visibility of the LEDs, preferred colours, number of hands used and awareness levels. All of the paratroopers completing the questionnaire had used the units during the day. The responses are shown in Figures 5.2 through 5.8.

From the graphs it may be seen that 52 % of the paratroopers felt that the unit was too large with respect to handling. However, in the case of size with respect to portability, the majority (56 %) indicated that the unit was the right size. The majority of the paratroopers felt that the units were the right weight.

All of the paratroopers found the unit easy to operate. It is significant that no paratrooper had difficulty in operating the units in spite of the brief training they received.

The degree of visibility of the LEDs is indicated in Figure 5.5. Figure 5.6 indicates the colors preferred by the paratroopers.

The number of hands used each time a bearing was taken is indicated in Figure 5.7. This is important because, if the unit could only be used with two hands it would mean that the paratrooper would not have his rifle in his hand, thus being unable to use it at short notice if required. The majority of the paratroopers used one hand to operate the PDF.

In most cases the paratrooper will land in a hostile environment. Whilst proceeding towards the transmitter, he will need to be highly aware of his surroundings, in order to be able to react quickly should a threat to his well-being arise. It follows that the PDF should be as simple to operate as possible in order to allow the paratrooper's attention to remain on his surroundings. Figure 5.8 indicates the level of awareness of the paratroopers whilst using the PDF. The graph suggests that 80% of the paratroopers felt they were aware, to some degree, of their surroundings.

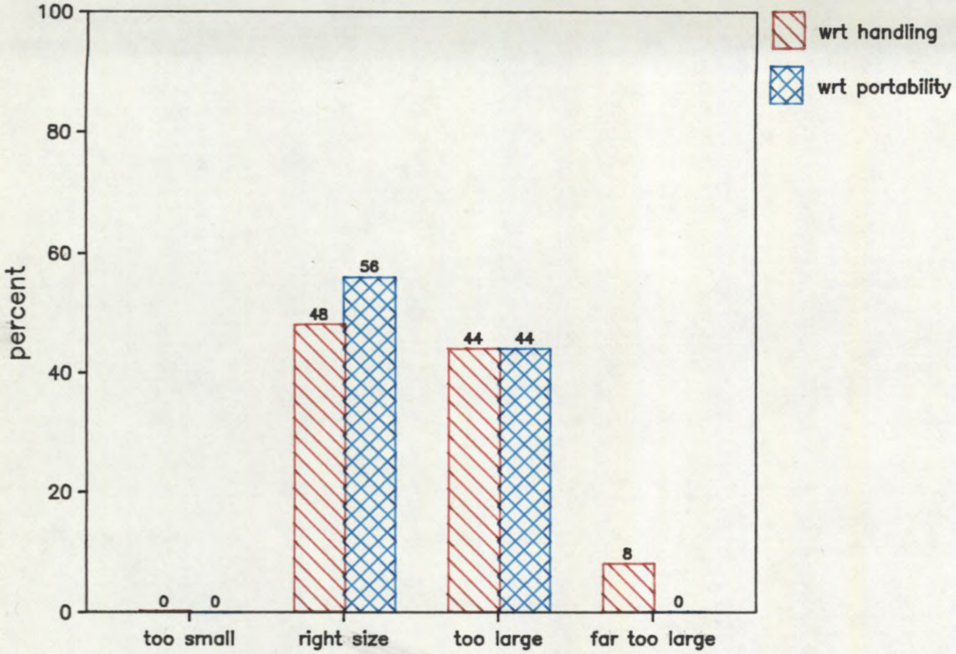


Figure 5.2 Size of the PDF.

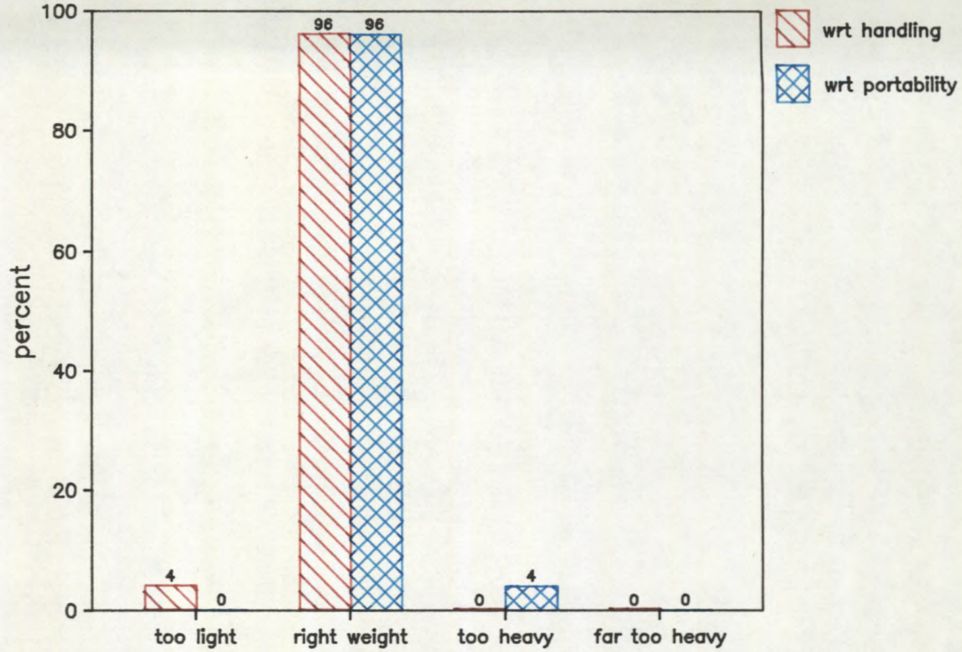


Figure 5.3 Weight of the PDF.

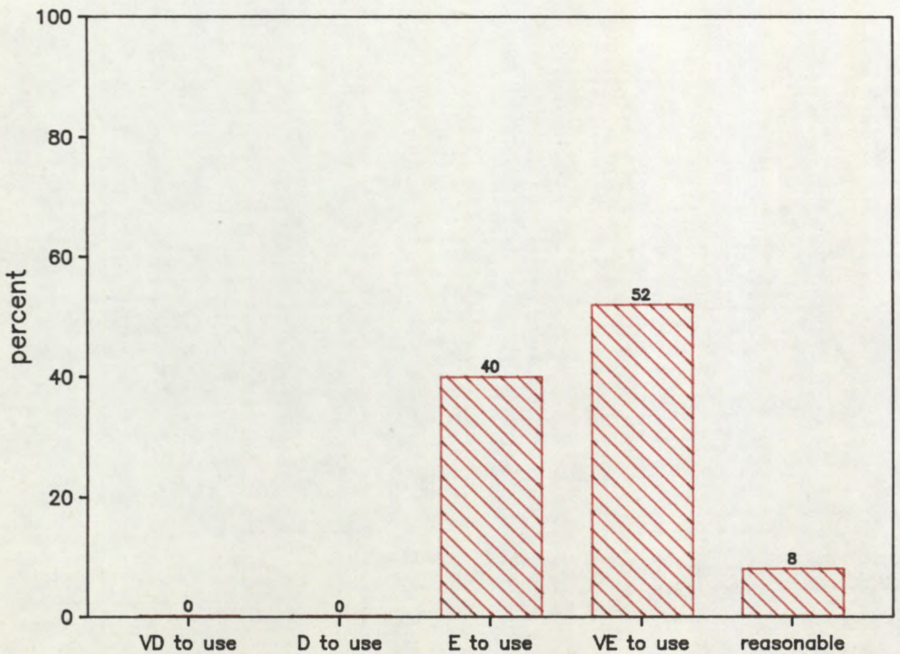


Figure 5.4 Ease of operation.

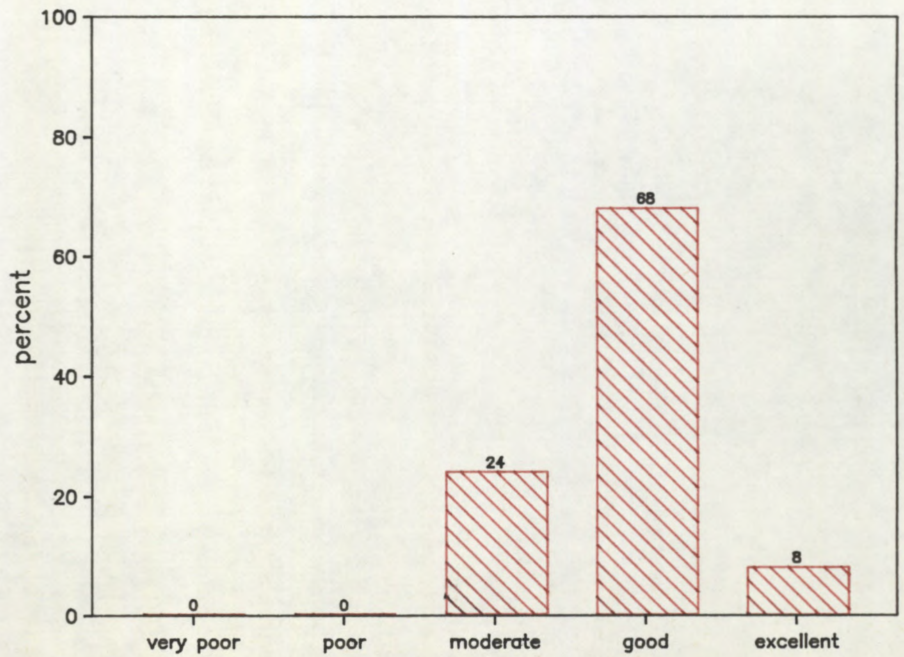


Figure 5.5 Visibility rating.

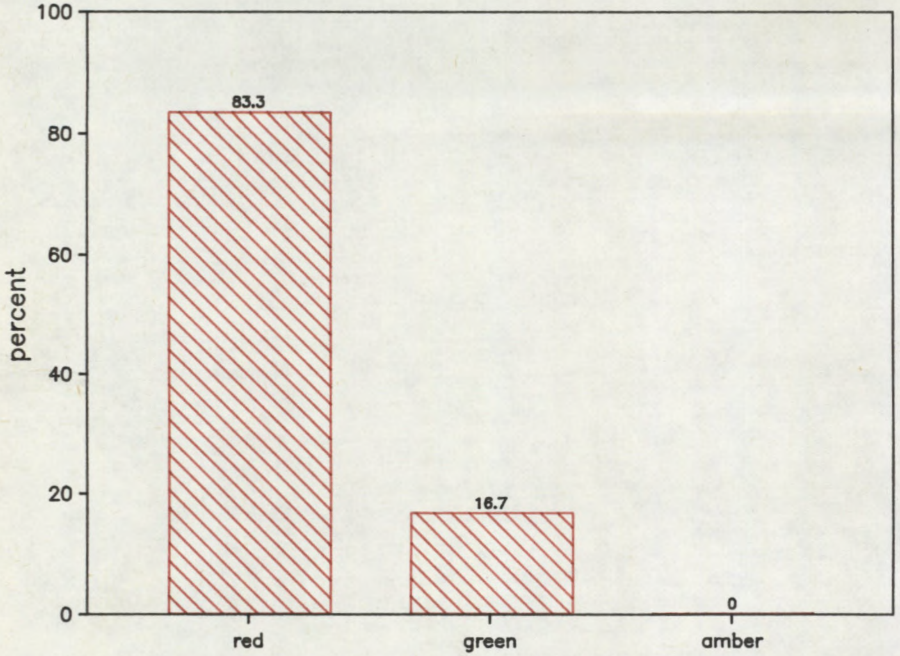


Figure 5.6 Preferred LED colours.

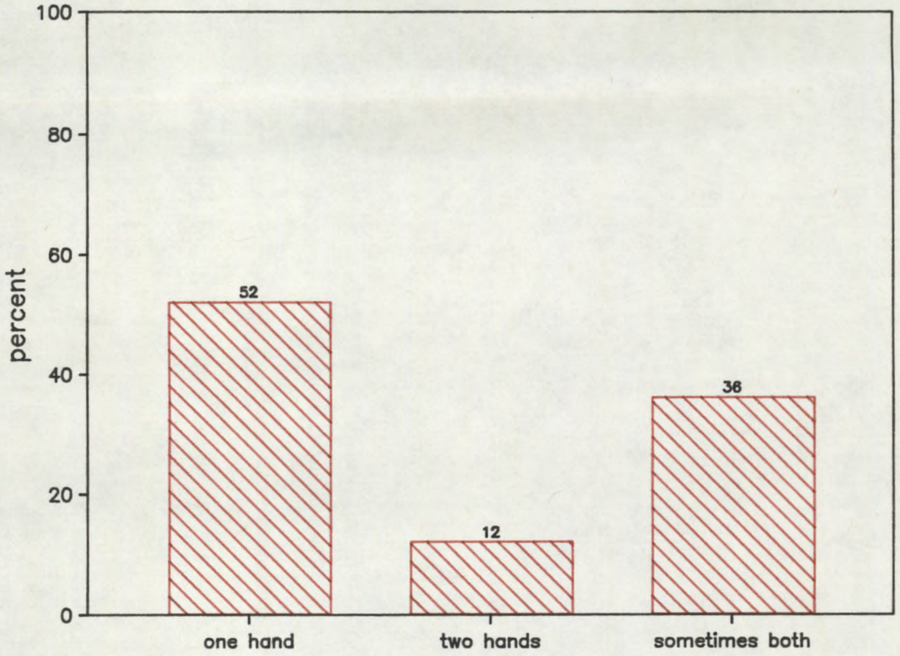


Figure 5.7 Hands used to operate the PDF.

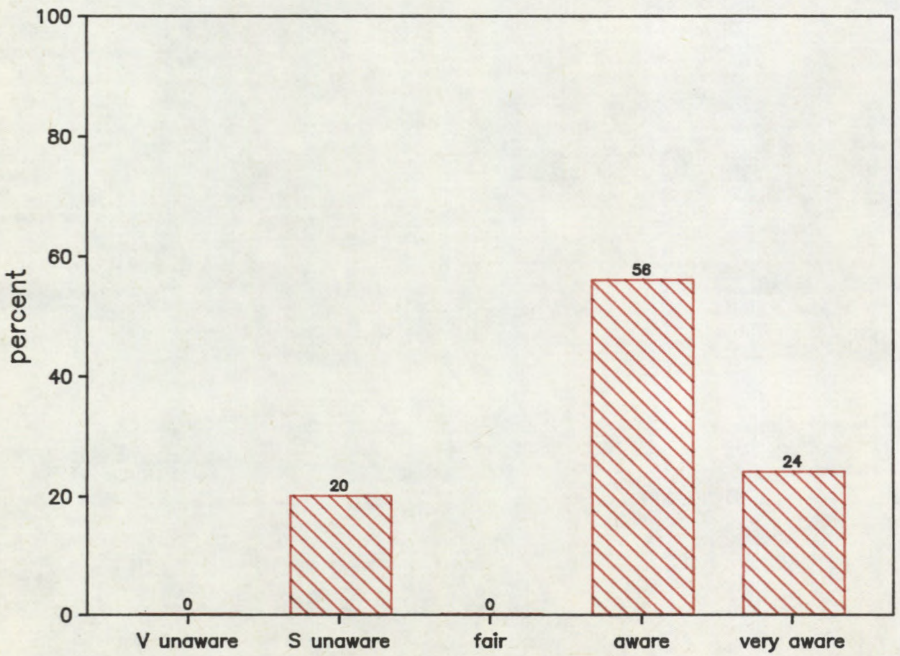


Figure 5.8 Awareness levels.

5.7 Summary

1. The mass, power source and current consumption requirements were met.
2. Twenty seven paratroopers utilised the PDF. All of them arrived at the transmitter, in spite of very brief training and an absence of initial orientation.
3. The average initial bearing error was 9.46°.
4. The average final bearing error was 46.91°.
5. The speed test results indicated that it was possible to regroup paratroopers from distances up to 3.9 km in approximately 50 minutes.
6. It was demonstrated that the re-directing of paratroopers whilst they were in motion was possible by relocating the regroup point.
7. The night test results suggest that regrouping at night is enhanced using the PDF, with the regroup times becoming shorter as well.
8. Range tests indicate that an area coverage of approximately 314 km^2 by the PDF is feasible over relatively flat terrain.
9. The colour tests suggested that red LEDs were the most suitable for use in the PDF.

10. The paratroopers responded favourably towards the questions posed in the questionnaire. These were related to size, portability, mass, ease of use, visibility of the LEDs, preferred colours, number of hands used and awareness levels.

CHAPTER 6

GENERAL DISCUSSION

6.1 Introduction

In Chapter 5 the results of the direction finder tests were reported. No detailed discussion of the results or limitations of the tests was given. These are given in this chapter.

6.2 Technical Design of the Direction Finder

The designed receiver was of the direct conversion type. The reasons for this choice are given in Chapter 3. One of the factors which contributed the most towards this choice was the requirement that the direction finder should be as small as possible. The direct conversion receiver is one of the simplest and smallest of receiver topologies. Superior performance may have

been possible with a more complex receiver. However, it was found during the tests conducted that the chosen receiver type met all the specified performance requirements.
The ferrite rod used was of the shortest possible length. The length is inversely proportional to the directivity of the antenna and thus a compromise between performance and size had to be reached. The vertical whip antenna was also kept as short as possible.
As only a carrier was to be received, it was possible to reduce the bandwidth of the receiver to 100 Hz. This results in increased receiver selectivity as well as reduced noise bandwidth.
LEDs were used as a means of conveying directional and range information. A change of one LED lighting/extinguishing corresponds to a change of 0.9 dB in the received signal.

It was found that the technical design of the PDF had been adequate as the test results were favourable.

6.3 Related Literature

The direction finder described in this document was of the narrow aperture type as described in section 1.1.
There is much literature to be found on wide aperture direction finders [Bullock, Oeh & Sparagna,1971:188, Hockley,1973:476, Anon,1978:61, Barton,1983:78, Welch,1985:283, Schmidt &

Davis,1985:103]. Most of the WA direction finders operate at VHF or UHF where the construction of portable antenna systems is possible due to the short wavelength being used. As discussed in Chapter 3 the direction finder described in this document was chosen to operate in the lower HF band. It is unfeasible to construct WA portable antennas for the HF band. A NA antenna system was therefore designed for use in this direction finder.

Although the literature describes WA systems extensively, there is a distinct lack of literature related to NA direction finder systems. Hawker (1989:531) points out that since the "ABC" trial few papers have been launched into the public domain. Where there is a lack of literature on NA systems, there is an even greater lack of literature pertaining specifically to hand-held direction finder systems for use by paratroopers. This is evidenced by the fact that the potential end user of the PDF could not find information on any similar product in the military forces of other countries. There also exists an air of secrecy amongst companies engaged in military electronic design, in order to prevent their competitors from "stealing" ideas, and also in the interests of general military security.

6.4 Assumptions

The five PDF units used were assumed to be identical (Section 1.7). The antenna sections were the most important and their performances were compared to ensure that no differences existed. There may have been slight differences in the overall sensitivities of the PDF units (Figure 6.1), but the AGC in each unit adjusted the gain to ensure that the display response was uniform. At the extreme operating range of the PDF, where the AGC is not operating, these differences will be apparent. It must be pointed out that this difference will affect only the maximum distance of operation of the PDF and not the directional characteristics.

In any surface wave situation, ground conductivity is an important parameter as it influences transmission range. The ground conductivity at Tempe was assumed to be similar to that found in the operational areas of Southern Africa. This was a safe assumption to make because, even if the ground conductivity was vastly different in some areas, only the operating range of the PDF would be affected. The directional characteristics would be unaltered.

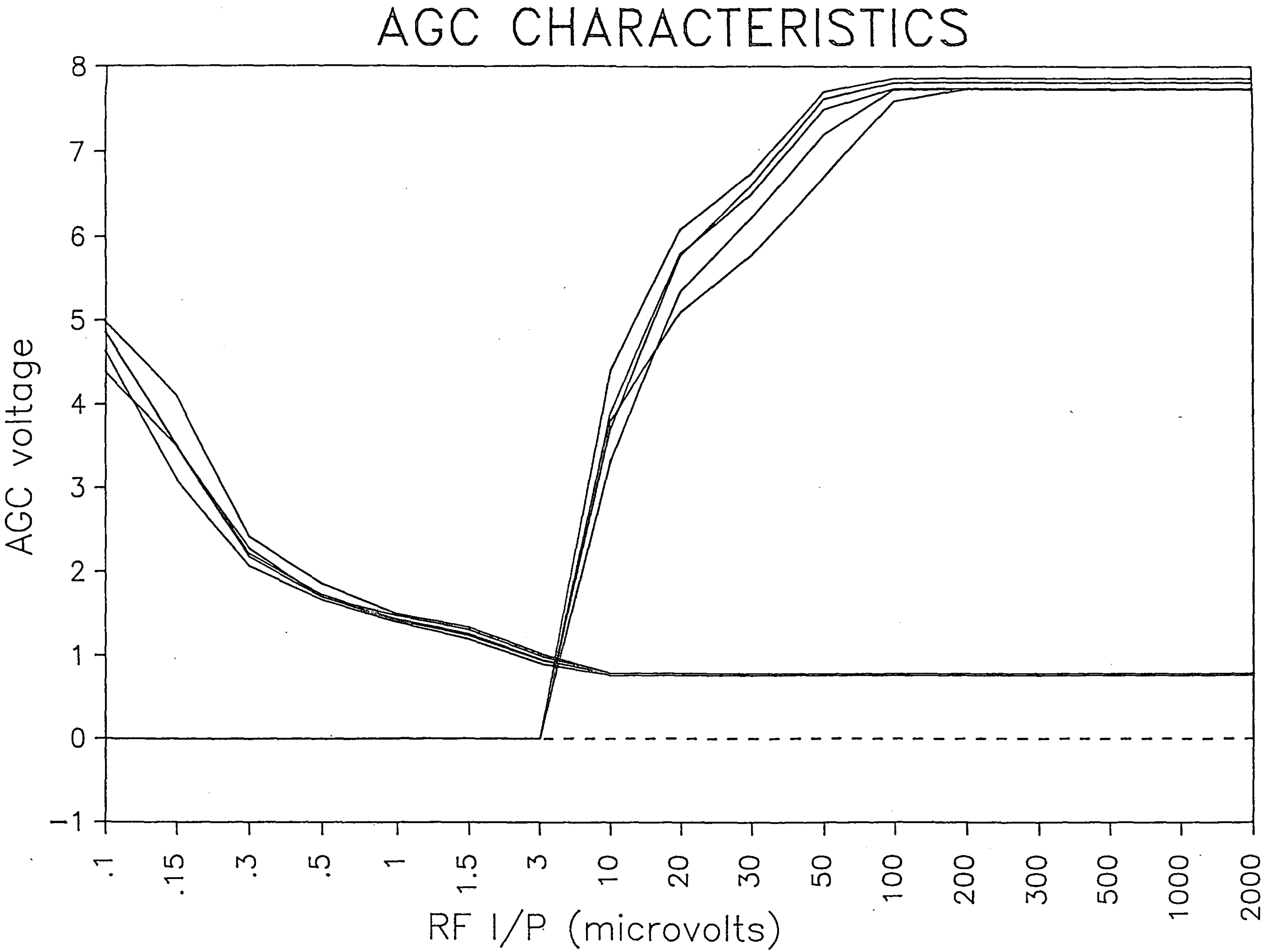


Figure 6.1 The AGC response of the five constructed units.

6.5 The Author's Bias

It was attempted, as far as possible, to eliminate any bias from affecting the tests and/or the results. However, the data was probably contaminated by some form of bias. Leedy (1985:163) points out that the researcher cannot avoid all bias from affecting his data.

The following sections describe how it was attempted to avoid bias in each section.

1. The Specifications which the PDF should Meet.

The PDF was required to comply with certain specifications. It would have been easy to identify easily obtainable specifications (for example, using a high power transmitter, reducing the range of the PDF, increasing the size of the PDF), hence biasing the project, and making the goals easier to attain. However, the specifications were from a potential end user of the PDF and so the effect of bias was reduced in that context.

2. The Choice of a DF Technique.

In choosing a method of direction finding a number of options were considered. The advantages and disadvantages of each method were summed up and were used to aid the selection process (Table 2.1). The most suitable method was chosen, based upon the totals obtained after summing up the characteristics of each DF method. The end choice was therefore the result of a careful selection process which took only the characteristics of the DF method into account.

3. The Selection of the Test Personnel.

In the selection of the personnel required to help conduct the PDF tests, it would have been convenient to choose thirty highly trained technicians. These people would have had a good grasp of the equipment and the tests would probably have yielded better results. However, paratroopers were selected for the following reasons :

i. The paratrooper was the potential end user of the PDF and so his feedback was important.

ii. A comparison between regrouping by conventional methods and by using the PDF could only be done if the personnel were familiar with the conventional methods, as these paratroopers were.

Thirty paratroopers from 1 Parabat Battalion assisted in the execution of the PDF tests. As mentioned in Section 4.5.2 they all had the same military background and experience. The selection of these paratroopers had been done by an independent person. It cannot, however, be guaranteed that the selection was entirely random. The selector was in a position of leadership in the Battalion and may have chosen paratroopers he considered to be of a high standard in the unit in order to convey the impression of an excellent unit. Therefore, although no control existed over the selection of the test personnel, it was assumed that they were randomly chosen. The paratroopers were found to be co-operative and enthusiastic.

4. The PDF Tests.

In all the tests which included the paratroopers they were required to use the PDF to locate a distant transmitter. If they had been accompanied by the author or assistant, they would have been conscious of the company and may also have established the direction of the transmitter by gauging the reaction of the author / assistant on taking a bearing. For these reasons the paratroopers were dropped off in the bush and were left entirely on their own. They had no idea as to the direction or range of the transmitter. Their only hope of locating the transmitter was by the correct use of the PDF. Each bearing taken was recorded on a card. The cards were numerically processed to see how efficiently each paratrooper located the transmitter. The information on the cards was therefore a direct indication of the degree of ease with which the paratrooper located the transmitter.

6.6 Results

The tests were divided into laboratory tests and field tests. The field tests were comprised of the orientation tests, range tests and the colour tests.

6.6.1 Laboratory Tests

A description of the laboratory tests is given in Section 4.5.1. The mass of the PDF was measured as being 367 grams. The maximum allowed mass was 500 grams. Therefore the actual mass was 73 % of the maximum mass, or a mass saving of 27 % was achieved. By comparison, a tin of condensed milk has a mass of 397 grams and a small tin of corn 420 grams. The PDF is about a third of the mass of a full army water bottle.

The battery used was a Duracell PM3. This battery measures 46 * 25 * 16 mm. This is the smallest battery which has the required voltage and charge suitable for powering the PDF.

The current consumption of the PDF is discussed in section 5.2. It was concluded that 55 readings of 2 minutes duration were possible before the battery voltage became too low for reliable operation. It must be pointed out that the current consumption test was done with an uninterrupted load and, if the battery were allowed recovery time between readings (as is the case in practice), its life would be extended by some 20 - 30 %.

To summarise the laboratory tests, it was established that the PDF is truly portable and makes efficient use of a small power source for extended periods of time.

6.6.2 Orientation Tests

The orientation tests (Section 5.3) were done over two days, with 10 paratroopers on the first day and 17 on the second. It was intended to use 30 paratroopers, but one of the PDF units malfunctioned, so only 27 were used. The precautions and controls are discussed in section 4.5.4.1. It was felt that these controls were adequate and therefore that useful results would be obtained from these tests.

In Section 5.3.1 the initial bearing errors are presented and discussed. These errors were calculated with the confidence that they were correct as both the start and the transmitter points were known and thus the bearing between the two was easily measured. The overall average of the initial bearing errors was 9.46°. With increased training this figure could be reduced.

The final bearing errors are discussed in Section 5.3.2. The average of these errors is 46.91°. As explained in the section, these errors are not as accurate as the initial bearing errors. The limitations of the AGC are pointed out. White (1982:43) mentions a further factor which could have contributed towards the high final bearing errors. At close distances to the transmitter the electromagnetic field is very strong and radiates not only into the PDF antennae, but also into the circuitry. This causes the PDF to be less directional, resulting in difficulty in taking accurate bearings. Plummer (1984:34) suggests that placing an electromagnetic screen around the circuitry is a possible solution to this problem.

6.6.3 The Re-location of Grouping Point Test

The re-location of grouping point test was used to determine whether paratroopers could be guided whilst on the move by a moving transmitter and is described in Section 5.3.5. As mentioned, when the transmitter was moved, the four paratroopers responded by changing direction and heading towards the second transmitter. As well as serving to validate the measurements taken by the paratroopers this test illustrates a few alternative applications of the PDF :

1. In a combat situation, the regroup point could be moved whilst the paratroopers were heading towards it with a view to "guiding" them around a hostile or unsuitable area.

2. A transmitter could be placed in an enemy vehicle, facilitating the ability to follow that vehicle easily.

6.6.4 Range Tests

The importance of range with DF was underscored in Section 5.4. As can be seen from Table 5.7 the PDF yielded useful readings at distances up to 13 km from the transmitter. This test was done with the transmitter radiating 2 W of RF energy. If the transmitted power was increased by a factor of ten then the range would be increased by the square root of this factor, or approximately three times. The PDF would then have a range of almost 40 km.

The maximum range will vary with regions of different ground conductivity, as well as with the contours of the region. It is felt that, in the light of the distance covered, a range of 5 km would be achieved over any terrain in Southern Africa, using 2 W of transmitted power.

6.6.5 Colour Tests

The constructed PDF units were fitted with red LEDs. However, green and amber LEDs were also available. It was desirable to choose a colour which was clearly visible in bright daylight, but visible only at short distances at night, in order to minimise the chance of being detected whilst using the PDF at night. The colour tests were conducted in order to ascertain which colour of red, green or amber was the most visible at night to the naked eye (Section 5.5). The results indicated that red was the least visible. The green LEDs were the most visible. These results agree with Hutson's comment (1971:11) that the eye is not uniformly sensitive over the visible spectrum. Figure 6.2 illustrates the approximate relative sensitivity of the average human eye to different wavelengths. As indicated the maximum sensitivity region shifts down in wavelength at night. This corresponds to a shift away from the red region and towards the violet region (thus making red less visible at night). During the day the maximum sensitivity region moves towards the red end of

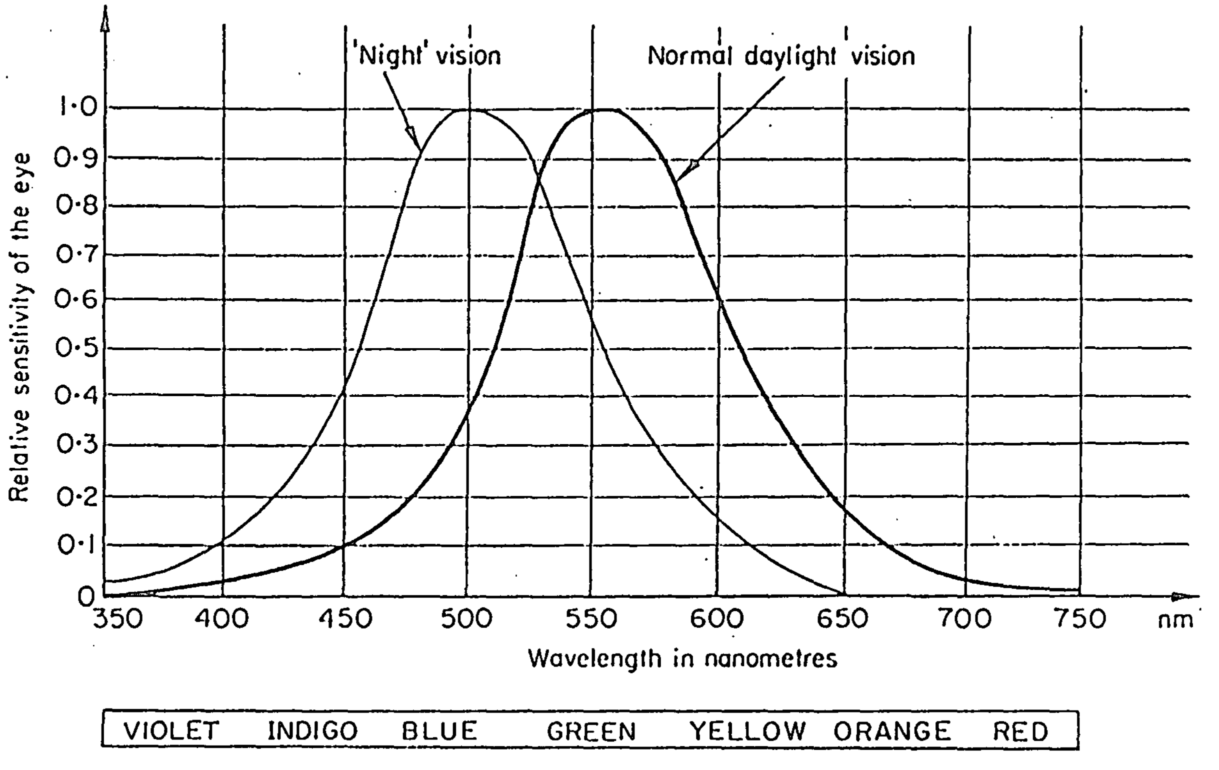


Figure 6.2 Approximate relative sensitivity of the average human eye to different wavelengths. (Hutson,1971:12)

the spectrum. This is to the advantage of the PDF user as, with the brightness and reflections of daylight, the more sensitive his eye is to the LEDs the better.
It was thus concluded that the initial choice of red LEDs was the most suitable.

6.7 Statistics

No statistical techniques were used to process the data in this study as the results yielded were not suitable for statistical analysis.

6.8 Direction Finder Applications

It has been demonstrated that the PDF has possible application in the paratrooper environment. There are other military and non-military areas where the PDF could be applied, such as :

1. In dense vegetation or at night air cargo dropped by parachute could be difficult to locate by ground personnel. If a transmitter was fixed to the cargo it could be quickly located.

2. Retreat / rendezvous points could be marcated by transmitters and found using PDF units.

3. Pathfinders could sneak up to an enemy installation and place a transmitter there. This would enable a destruction force to land and quickly locate and destroy the installation.

4. If more than one transmitter was transmitting at one time, on different channels, and the positions of the transmitters were known, then the position of the PDF user could be found by using triangulation techniques. A third transmitter could be used for more accurate position fixing.

5. Scientists working in arctic conditions often have to work in heavy blizzards. Hardman (1980:312) comments on the difficulties in erecting and maintaining DF antennae at Sanae, Antarctica. In these conditions the possibility exists that the scientist may not be able to locate his base on returning. The PDF could give them a reliable indication as to the direction of their base.

6.9 Suggestions for Future Work

1. The direction finder unit described in this document responds to the peak of the cardioid pattern. It is well known that the null is sharper than the peak [Dowding,1976:193]. The reasons for the usage of the peak as opposed to the null are given in Chapter 4, where the design of the unit is outlined. It would be beneficial if more investigation into the possible use of the null were to be done, as more accurate results may be possible. In a tactical situation it is desirable to take as accurate an initial bearing as possible in order to minimise the distance covered when regrouping.

2. It has been speculated that an audio indication as to the direction of the transmitter would distract the user less than the LEDs. An audio indicator may also be less detectable. On the other hand, an audio indicator may prevent the user from hearing hostile forces close to him. Further research work in this area may prove invaluable in optimising the direction finder means of display.

3. As far as the paratroopers are concerned, the smaller and lighter the unit the better. No single size or mass is correct. The circuitry of the PDF could be hybridised onto

thick film substrates. This would greatly reduce both the size and mass, but has the disadvantage of being an expensive process, which requires sophisticated production line equipment.

4. The attack time of the AGC could be decreased. As the PDF user approaches the transmitter, the attack time of the AGC becomes longer. This has the disadvantage of forcing the user to spend more time taking a bearing, thus increasing exposure to possible hostile forces.

5. There are no ECM facilities built into the PDF. This was listed as one of the de-limitations in section 1.6. The danger does exist that, if hostile forces know where the drop area is and also what frequency the PDF is operating on, they could transmit a decoy carrier to lead the unsuspecting paratroopers into an ambush. If two signals were received by the PDF on the same channel, the user would experience difficulty in determining direction. It is possible to include a code in the transmitted signal, which the receiver would wait for before displaying directional information. This would increase the cost and probably also the size of the PDF. Unless a sophisticated code recognition

system was implemented, hostile forces could detect the transmitted code and replicate it, thereby making the code redundant.

REFERENCE LIST

Anon
New transmitter locator system operational.
Electronic Warfare / Defense Electronics.
vol. 10, no. 8, August, 1978.

Anon
Digital bearing discriminator details divulged.
Defense Electronics.
vol. 11, no. 8, August, 1979.

Anon
The ARRL antenna handbook.
The American Radio Relay League.
14th ed., 1984.

Anon
The ARRL Handbook
The American Radio Relay League.
1988.

Appleby, M.A. & Sager, J.
The Datong direction finding system.
Radio Communication.
vol. 60, no. 1, January, 1984.

Barratt, J.
Automated direction finder.
Wireless World.
vol. 88, no. 1552, January, 1982.

Barton, P.
Direction finding using an adaptive null tracker.
I.E.E.E. proceedings
vol. 130, parts F&H, no. 1, February, 1983.

Bell, D.A.
Fundamentals of electric circuits.
Reston Publishing Company, Inc., 1978.

Bodemann, G.
HF direction finding for short distances.
Communications International.
vol. 10, no. 9, September, 1983.

Bogachev, A.S.
An integrated radio direction finder with electronic radiation pattern-stabilization.
Telecommunication and Radio Engineering.
vol. 39, no. 6, February, 1986.

Bullock, L.G., Oeh, G.R. & Sparagna, J.J.
An analysis of wideband microwave monopulse direction finding techniques.
I.E.E.E. Transactions on Aerospace and Electronic Systems.
vol. aes-7, no. 1, January, 1971.

Byatt, D.W.G.
Radio navigation and radar.
Wireless World.
vol. 86, no. 1529, January, 1980.

Colligan, F.S.
Field intensity measurements in the nulls of a directional antenna pattern.
I.E.E.E. Transactions on Broadcasting.
vol. BC-26, no. 2, June, 1980.

Cotter, C.H.
The Principle and Practice of Radio Direction Finding.
Sir Isaac Pitman and Sons Ltd.
1961.

D'Antonio, R.A. & Gaffney, J.E.
Pseudo noise interferometer
I.E.E.E. Transactions on Aerospace and Electronic Systems.
vol. aes-4, no.5, September, 1968.

Dowding, P.
A 1.8 MHz direction finding receiver.
Radio Communication.
vol. 52, no. 3, March, 1976.

Gay, L.S.
The design and application of a low frequency direction finder.
M. Sc. Thesis.
University of Natal, Durban, 1961.

Gorst, C.W.
New mixer designs boost D/F performance.
Microwaves (USA).
vol. 12, no. 10, October, 1973.

Grant, G.M.R.
The goniometer in electronic air navigation.
Electronics and Wireless World.
vol. 94, no. 1625, March, 1988.

Haigh, J.H.
Radiolocation Techniques.
Her Majestys Stationery Office.
vol. 7, 1960.

Hardman, G.E.
VLF Direction finding at Sanae, Antarctica.
M. Sc. Thesis.
University of Natal, Durban, 1980.

Hawker, P.
RF Commentary : Direction finding update.
Electronics & Wireless World.
vol. 95, no. 1639, May, 1989.

Hockley, J.
A goniometer for use with high frequency circularly disposed aerial arrays.
Radio and Electronic Engineering.
vol. 43, no. 8, August, 1973.

Hughes, E.
Electrical technology.
Longman Group Ltd.
5th ed., 2nd impression, 1979.

Hutson, G.H.
Colour television theory.
McGraw-Hill Book Company (UK) Limited.
1971.

Karavassilis, N. & Davies, D.E.N.
An adaptive circular array for HF direction finding.
4th Int. Conf. on Antennas and Prop.
proceedings no. 248, 1985.

Karavassilis, N., Davies, D.E.N. & Guy, C.G.
Experimental HF circular array with direction finding and null steering capabilities.
I.E.E.E. proceedings.
vol. 133, no. 2, April, 1986.

Keen, R.
Wireless Direction Finding.
Iliffe and Sons Ltd.
4th ed., 1947.

Leedy, P.D.
Practical research planning and design.
Macmillan Publishing Company.
3rd ed., 1985.

Meer, S.A.
A digital goniometer for VOR.
Navigation.
vol. 24, no. 2, summer, 1977.

Orr, W.I.
Radio handbook.
Howard W. Sams and Co., Inc.
22nd ed., 1981.

Plummer, C.
Top-Band direction finder.
Practical Wireless.
vol. 60, no. 4, March, 1984.

Powell, C.
Radio Navigation in the 1920s.
J.I.E.R.E.
vol. 56, no. 8/9, 1986.

Rambaut, M.A.
Marine direction finder.
Electronic Communications.
Vol. 54, no. 2, 1979.

Schmidt, E. & Davis, C.
New directions for the army's DF receivers.
Defense Electronics, USA.
vol. 17, no. 10, October, 1985.

Scott, L.J.
Lightning strike location systems.
Int. Conf. on lightning and power systems, I.E.E.
publ. no. 236, 5-7 June, 1984.

Terman, F.E.
Radio engineering.
McGraw-Hill Book Company, Inc.
1st ed., 6th impression, 1932.

Welch, K.A.
Vampire - a proven capability in tactical direction finding.
I.E.E.E. proc.
vol. 132, no. 4, July, 1985.

APPENDIX A

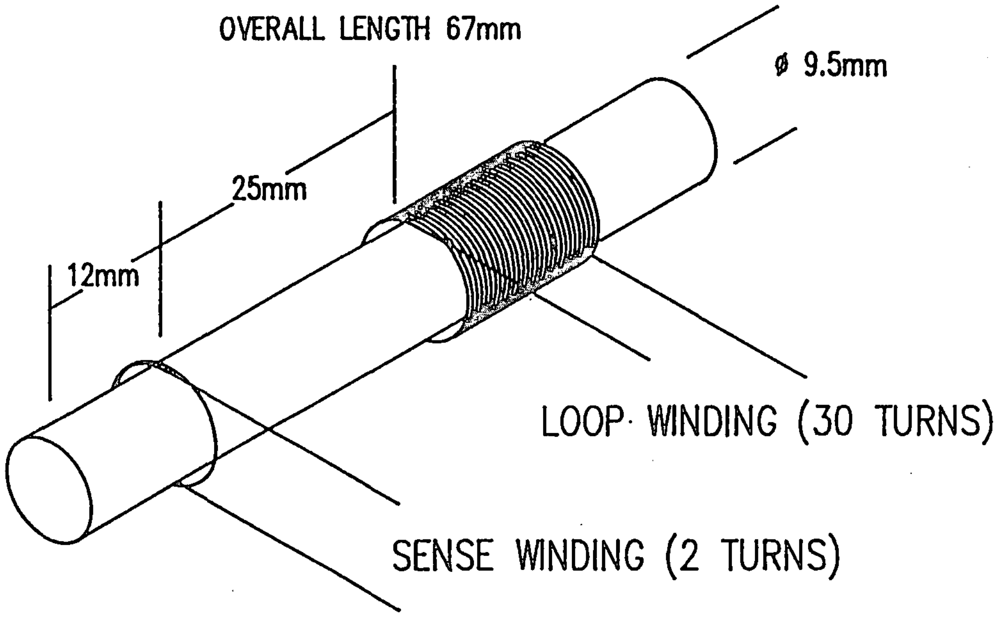


ILLUSTRATION OF THE LOOP ANTENNA

APPENDIX B

Design of the RF Band-pass Filter

The Chebychev filter was chosen above the elliptic or Butterworth filters as, for the same order filter, it yields the sharpest cut-off slopes of the three. It has the disadvantage of having higher pass-band ripple than the other two, but this is not an important consideration in this application.

<u>Filter requirements</u>

center frequency (f_o)	:	3.5 MHz
3 dB bandwidth (bw)	:	1.4 MHz
filter order	:	4
pass-band ripple	:	0.5 dB
characteristic impedance (Z_o)	:	50Ω

In designing the band-pass filter, the low-pass prototype was first designed and then the band-pass element values were derived from this.

$$d = \frac{A}{8.68589} \quad \text{where } A = \text{pass-band ripple in dB} \qquad \text{C-1}$$

$$d = \frac{0.5}{8.68589} = 0.0575646$$

$$B = \frac{1}{2n} \ln \left[\frac{e^{d} + 1}{e_{d} - 1} \right] \qquad \text{C-2}$$

$$B = \frac{1}{2*4} \ln \left[\frac{e^{0.0575646} + 1}{e_{0.0575646} - 1} \right] = 0.4435338 \qquad \text{C-3}$$

$$N = 0.5 * (e^{B} - e^{-B}) = 0.5 * (e^{0.4435338} - e^{-0.4435338}) \qquad \text{C-4}$$

$N = 0.4582197$

$$a_k = \sin \left[\frac{(2k - 1)}{2n} \right] \quad \text{for } k = 1,2,3,\ldots.,n \qquad \text{C-5}$$

$$b_k = N^2 + \sin^2 \left[\frac{k\pi}{n} \right] \quad \text{for } k = 1,2,3,\ldots.,n \qquad \text{C-6}$$

The g_k values are calculated using these parameters

$$g_1 = \frac{2a_1}{N} \qquad \text{C-7}$$

using C-5 : $a_1 = 0.382683$

thus $g_1 = \dfrac{2*0.382683}{0.4582197} = 1.670306$

$$g_k = \frac{4a_{k-1}a_k}{b_{k-1}g_{k-1}} \qquad \text{C-8}$$

using C-8 to calculate $g_2 - g_4$:

$g_2 = 1.1926 \quad g_3 = 2.3661 \quad g_4 = 0.8419$

Since these figures are normalised to 1 ohm and 1 rad/sec it is necessary to scale them to the parameters being used.

for the inductances :

$$L_k = \frac{g_k Z_o}{w_c} \quad \text{where } w_c = \text{the cut-off frequency in rad/sec} \qquad \text{C-9}$$

$$C_k = \frac{g_k}{Z_o w_c} \qquad \text{C-10}$$

which yields :

$L_1 = 67.789\ \mu H \qquad L_2 = 47.854\ \mu H$

$C_1 = 379.77\ pF \qquad C_2 = 537.97\ pF$

To convert the low-pass filter to a band-pass filter the individual components are resonated at the center frequency with inductors or capacitors as required.

using $F_o = 3.5$ MHz and

$$L/C = \frac{1}{4\pi^2 F_o^2 L} \qquad \text{C-11}$$

yields :

$L_3 = 5.4448\ \mu H \qquad L_4 = 3.843\ \mu H$

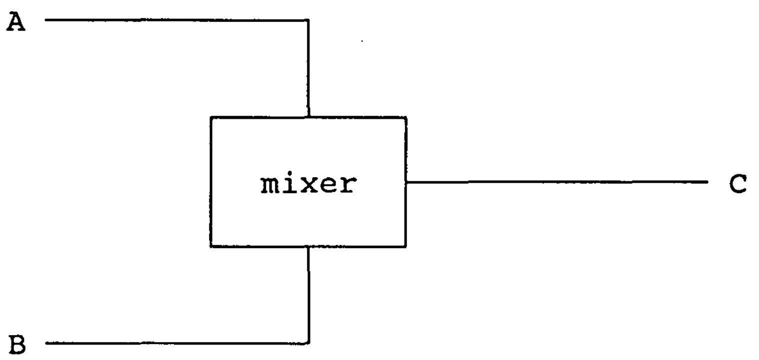
$C_3 = 30.503\ pF \qquad C_4 = 43.21\ pF$

The closest E12 series values were chosen for the calculated values.

APPENDIX C

Mathematical treatment of a simple mixer

Considering the following diagram :



let

$$A = E_1 \cos w_1 t$$

and

$$B = E_2 \cos w_2 t$$

C is the mixer output and is the arithmetical product of A and B.

$$C = A * B$$

$$= E_1 \cos w_1 t * E_2 \cos w_2 t$$

$$= E_1 E_2 [\cos w_1 t * \cos w_2 t]$$

This can be written in the form

$$2[\cos A * \cos B] = \cos(A + B) + \cos(A - B)$$

thus

$$C = \frac{E_1 E_2}{2} \left[\cos(w_1 t + w_2 t) + \cos(w_1 t - w_2 t) \right]$$

$$C = \frac{E_1 E_2}{2} \left[\cos(w_1 + w_2)t + \cos(w_1 - w_2)t \right]$$

The above two components are at the sum and difference frequency respectively. In a real mixer there will also be small components at the original frequencies and at the harmonics of the originaland mixed components. In this application the difference frequency will be used and the sum filtered out.

APPENDIX D

DIRECTION FINDER QUESTIONNAIRE

Surname .... First names ....

Age .... Home Language ....

Height .... Weight ....

Highest Qualification ....

Place a cross in the applicable box.

1(a) How would you rate the size of the direction finder with respect to handling?

☐ too small ☐ the right size

☐ too large ☐ far too large

1(b) How would you rate the size of the direction finder with respect to portability?

☐ too small ☐ the right size

☐ too large ☐ far too large

2(a) How would you rate the weight of the direction finder with respect to handling?

☐ too light ☐ the right weight

☐ too heavy ☐ far too heavy

2(b) How would you rate the weight of the direction finder with respect to portability?

- [ ] too light
- [ ] the right weight
- [ ] too heavy
- [ ] far too heavy

3. Indicate your opinion as to the ease of operation of the direction finder.

- [ ] very difficult to use
- [ ] difficult to use
- [ ] easy to use
- [ ] very easy to use
- [ ] reasonable

4. When did you use the direction finder?

- [ ] during the day
- [ ] during the night

5. How would you rate the visibility of the LED's?

- [ ] very poor
- [ ] poor
- [ ] excellent
- [ ] moderate
- [ ] good

6. What color LED's do you feel are the most suitable for this application?

- [ ] red
- [ ] green
- [ ] amber

7. Could you use only one hand or did you have to use two hands each time you operated the direction finder?

☐ one hand ☐ two hands ☐ sometimes both

8. How would you rate your level of awareness of your surroundings whilst you were taking a reading on the direction finder?

☐ very unaware ☐ slightly unaware

☐ aware ☐ very aware

☐ fair

How did you hold your rifle whilst you were taking a bearing with the direction finder?

....

....

....

....

If this instrument is going to be standard military equipment how/where would you prefer to carry it?

....

....

....

....

....

If you have any suggestions or criticisms please state them below. Remember that this questionaire will be treated confidentially.

....

....

....

....

....

....

....

....

Thank you for your co-operation.