DATA TRANSMISSION TO MOVING TRAINS
AND RAILWAY AUTOMATION

BY

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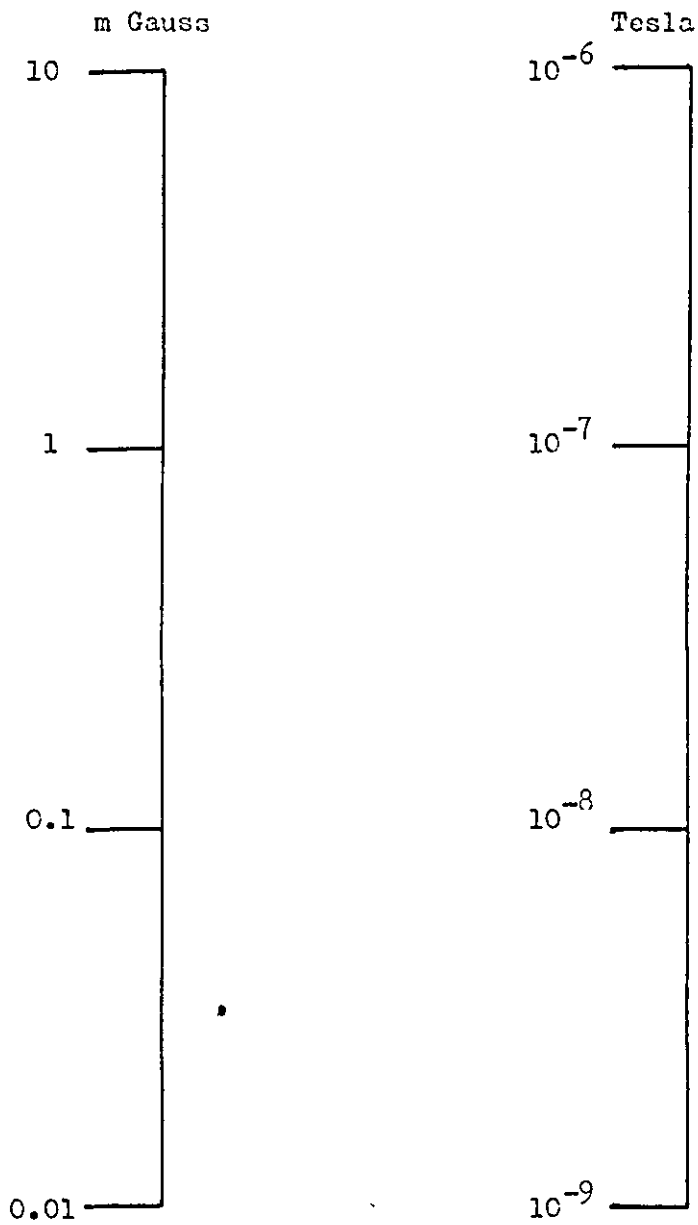
CONTENTS

PART II

NOTES ON THE UNITS OF FLUX DENSITY.

In this thesis the new S.I. unit of flux density has been used - the Tesla. Below is given a comparison between Tesla and Gauss. (1 Wb / m^2 = 1 Tesla).



ACKNOWLEDGEMENTS

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Finally, my thanks are due to Mrs. S. Peach for the typing of the thesis.

SYMBOLS

$\overline{A}_x$ 'X' component of magnetic vector potential.

$\overline{A}_y$ 'Y' component of magnetic vector potential.

$\overline{A}_z$ 'Z' component of magnetic vector potential.

a Half the length of a side of a rectangular coil.

a Radius of a circular coil.

$\hat{a}_x$ Unit vector in the 'X' direction.

$\hat{a}_y$ Unit vector in the 'Y' direction.

$\hat{a}_z$ Unit vector in the 'Z' direction.

$\overline{B}$ Vector of the total flux density.

B Magnitude of the total flux density.

$\overline{B}_x$ 'X' component of flux density.

$\overline{B}_y$ 'Y' component of flux density.

$\overline{B}_z$ 'Z' component of flux density.

B_x Magnitude of 'X' component of flux density.

B_y Magnitude of 'Y' component of flux density.

B_z Magnitude of 'Z' component of flux density.

b Half the width of a rectangular coil.

C_2 Coefficient of z^2 in a binomial expansion (appendix 6).

C_4 Coefficient of z^4 in a binomial expansion (appendix 6).

d Half the spacing between Helmholtz Coils.

d Distance between turns on a multi-turn coil.

e Base of natural logarithms.

e Induced e.m.f.

E Complete elliptic integral of the second kind.

H_z Magnetic field strength in the 'Z' direction.

I_o Peak value of current.

I Instantaneous value of current.

K Complete elliptic integral of the first kind.

k Constant of proportionality.

k Elliptic integral variable.

L Inductance.

N Number of turns of wire on a coil.

R Resistance.

R_x, R_z Ratio of maximum flux density over a coil to the minimum flux density between coils. 'X' and 'Z' components.

R'_x, R'_z Approximate ratio of maximum flux density over a coil to the minimum value between two coils. 'X' and 'Z' components.

R''_x, R''_z Ratio of minimum flux density over a coil to the maximum value of flux density between the coils. 'X' and 'Z' components.

r Radial distance from a point.

S Surface area.

s General length of wire.

v_p Velocity of Propagation.

x,y,z. Rectangular cartesian coordinates.

X_1,Y_1,Z_1. New set of rectangular cartesian coordinates.

Z_{in} Input impedance.

Z_o Height of pick-up above the rail head.

Z_o Characteristic impedance.

α Current Attenuation.

β Phase change coefficient.

μ_o Permeability of free space ($4\pi \times 10^{-7}$ Wb/A-m).

ϕ Cylindrical coordinate parameter.

ρ Cylindrical coordinate parameter.

θ Angle of tilted coil.

ω Angular frequency of alternating field.

λ Wavelength.

SYNOPSIS

In Part I possible methods of improving telegram coil systems for use in a track-to-train communication are examined. These coils are used to convey fixed information, such as the physical limitation of the track on speed, to a moving train. A telegram consists of a number of coils and occurs at various locations along the track. At present only one bit of information is derived per telegram coil and this severely limits the amount of information that can be transmitted, especially in the vicinity of junctions where a lot of information transmission is required. These coils are also restricted to sleeper spacing.

The magnetic fields produced by various sizes and shapes of coils were examined and found to be very similar. A method was developed using field components to double the information capacity of the coils. Rectangular cartesian coordinates are the only coordinates into which the magnetic field can be resolved so that individual field components are capable of being received by a train-borne aerial.

Because of the dynamic range of the system required, the lateral displacement of telegram coils to obtain the extra bit of information and the restrictions on placing them, it was found that only small coils on the rail foot could be used. With the coils in this position they were not restricted to sleeper spacing and were less prone to damage by track maintenance equipment. To increase the information capacity of a telegram still further, coils could be used both sides of the track.

The practical work certainly showed the feasibility of the modified system in a railway environment. It also showed the advantages of feeding half a telegram from each track conductor and combining them in a matching network to minimise reflections on the line.

The section on error rates showed little basic difference between data transmission by telegram coils and various forms of modulation, e.g. PSK, FSK. Before further conclusions can be drawn more detailed knowledge of the noise is required. In the final chapter in this part other possible uses of field components are discussed.

In Part II, Railway Automation is discussed to see what it can offer and how it could be implemented. The various experimental trials taking place at present are also briefly examined.

P A R T I

1. INTRODUCTION

For several years British Rail, together with various railway systems throughout the world, have been considering the possibility of continuous communication with moving trains (see references 1, 2, 3 and 4). This need has arisen through the desire for higher speed working, higher density working and the resulting need for more stringent safety precautions.

The existing signalling system copes well with train speeds up to about 100 m.p.h. (160 km/h) with a possible extension up to 125 m.p.h. (200 km/h) - see reference 5. The main problem with conventional signalling arises when one needs to combine high traffic density and trains of widely differing speeds. Because of braking requirements, signals are spaced to accommodate the long braking distances required by high speed trains (a train travelling at 100 m.p.h. needs 1.27 miles (2.03 km) in which to come to rest). This obviously has an adverse effect on the line capacity at lower speeds and hence the desire to improve the situation. There are two possibilities here, these are :-

a) the provision of an overlay system for high speed working, or

b) the use of moving block working (see ref. 6).

Moving block working, whilst representing the optimum method for any traffic flow, cannot be easily implemented at the present on the railways because of financial, operational and technical difficulties. However, the use of an overlay system is a much more viable proposition and also lends itself to the possibility of conversion to a moving block system at a later stage. The principle of an overlay system is the provision of advance information to the train concerning the conditions of the track ahead (e.g. signals, speed restrictions) and information which can be fed to the train-borne computer to ensure that the train is travelling within the prevailing conditions.

At the moment two possible systems for information transmission are being examined :-

1. the use of high frequency guided electromagnetic waves, and
2. an inductive loop system.

Quite a lot of work has been done on (1) especially in Britain and Japan (see references 7 and 8) and probably offers a better long term solution than (2) due to the increased information capacity available and the possibility of obstacle detection. However, the inductive loop system at present is the more realistic (see references 3 and 4) and is being investigated very thoroughly in Britain and elsewhere.

The information to be transmitted is essentially :-

1. the traffic conditions ahead of the train, and
2. the limitations imposed by the track itself.

In addition it is probably also desirable to have a speech link between the driver and operational staff and vice versa. The transmitted information can also be divided as follows :-

a) fixed information, and

b) variable information

1.1 Description of the Inductive Loop Systems

The inductive loop system consists essentially of two parallel wires running between the rails in the centre of the track and spaced at present one foot (0.305 m) apart. These wires are transposed at 100 metre intervals (see fig. 1) to provide distance markers for the train and to minimise the effects of induced e.m.f's.

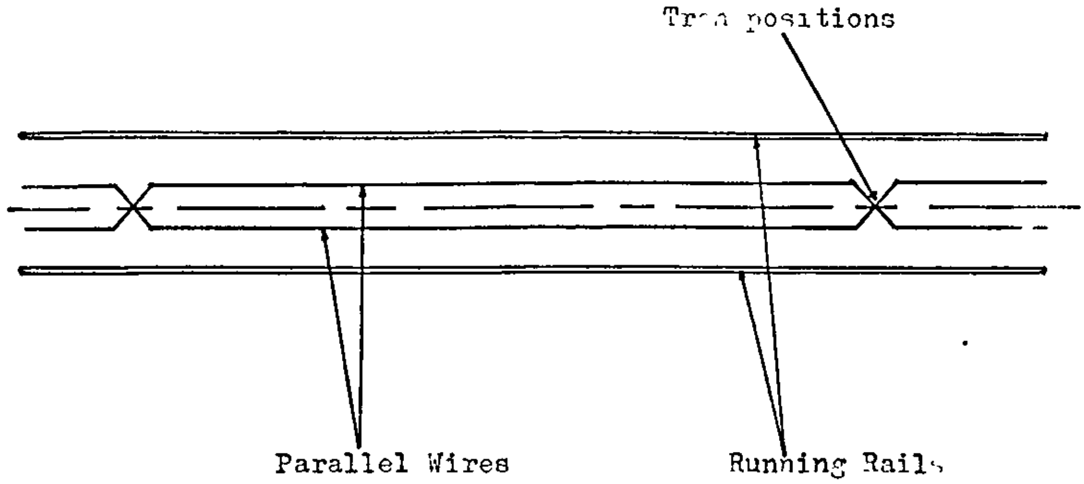


Fig.1. Showing Transpositions.

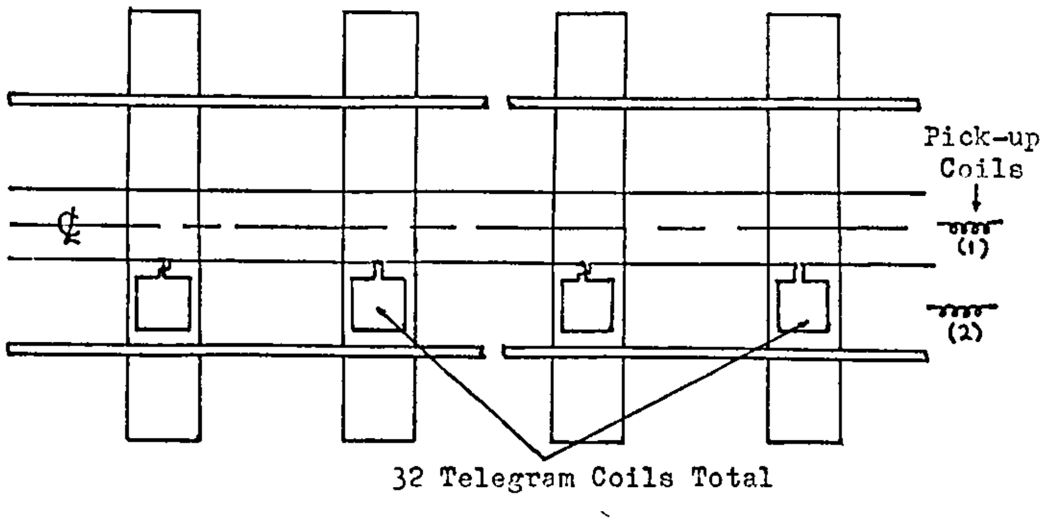


Fig.2. Showing Arrangements for the Telegram Coils.

Information can be fed to the train in two ways :-

1. via a form of modulation, or

2. via telegram coils.

The present trend is to use electronic modulation for the information transmission - both fixed and variable, although this requires more trackside equipment. However, it does provide the possibility of data being re-transmitted. The alternative, (2), provides a cheap and relatively reliable method of transmitting fixed information and is explained below.

The fixed information is transmitted by a "telegram" which consists, at present, of 32 coils connected in series with the track conductors (see fig. 2). The information is extracted from these coils in the following manner. The train has two pick-up coils, (1) over the parallel wires and (2) over the telegram coils. The track conductors are fed with a 29 kHz signal. The two pick-up coils receive the vertical component of the magnetic field from the transmitters on the track and the telegram coils can be wound either clockwise or anti-clockwise (see fig. 2). The phase of the signal received by pick-up coil (2) is compared with that received by (1) and depending on their phase relationship (0° or 180°) either a binary 1 or 0 is transmitted. Thirty two binary bits are at present required in order to :-

1. convey the information, and

2. convey the error detection codes used.

This means that for the telegram system tried (ref. 4), thirty two track coils are needed per telegram - only one bit being derived per telegram coil. These coils also have to be placed one per sleeper so that they do not interfere with tamping

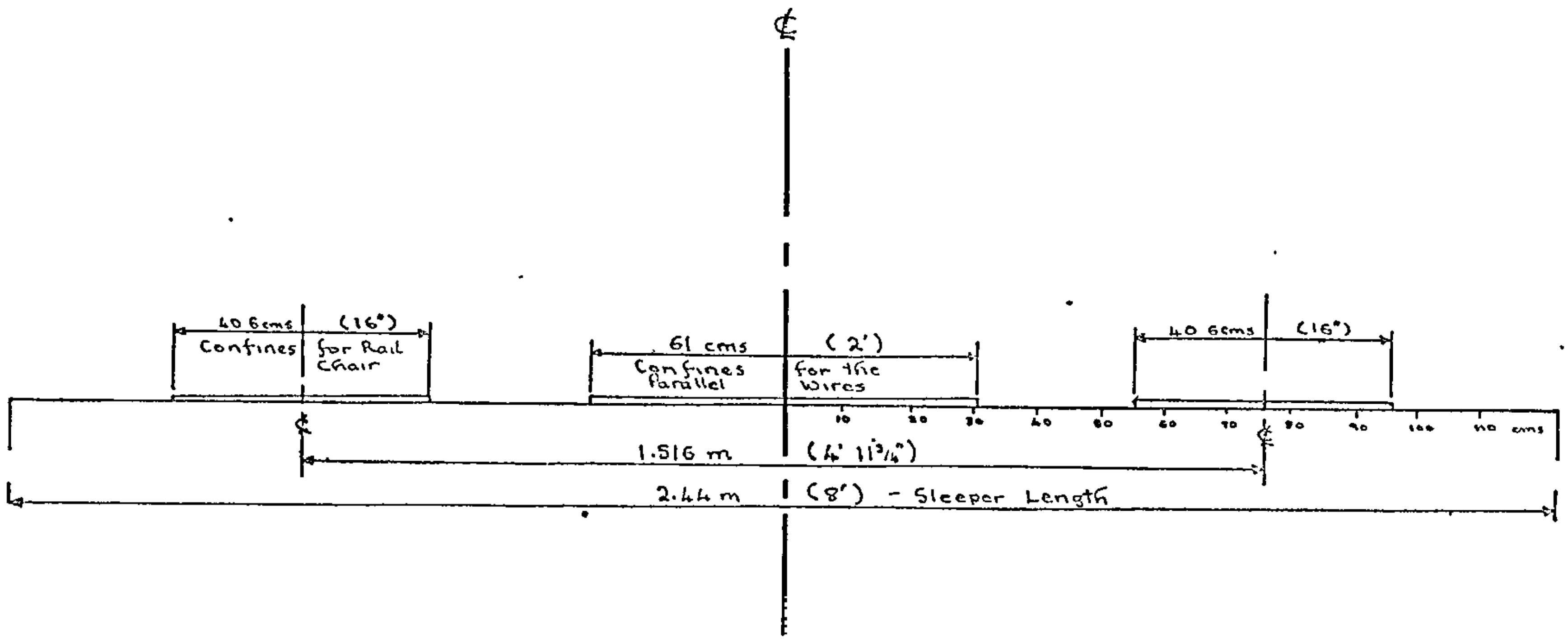


Fig. 3. Allocation of Space on a Sleeper.

operations and other track maintenance. Consequently a telegram occupies thirty two sleepers.

1.2 Restrictions on the Positions of the Parallel Wires and the Telegram Coils.

Unfortunately, severe restrictions are imposed on the placing of the telegram coils and parallel wires. This is due mainly to track maintenance requirements. The parallel wires must therefore be within the central two foot (0.61m) of the track and the telegram coils, as they lie away from the centre of the track, must be placed on a sleeper. The rail chair also takes up a certain area on the sleeper and restricts still further the position of the telegram coils (see fig. 3). In addition, the telegram coil must not overlap the rail chair and for positions between the rails the pick-up coils must be at least 5" (0.127m) above rail head level - i.e. one foot (0.305m) above sleeper level.

1.3 Conclusions

The length of track needed for a telegram severely limits the amount of information that can be conveniently transmitted, especially in the vicinity of points and crossovers. An additional problem in this area is also the need to transmit quite a lot of data just before junctions for the various routes that can be taken. It is these problems which have prompted the following investigations into methods of improving the telegram coil system and to compare its performance against a system using electronic modulation.

As the system uses the magnetic field produced by a current, the initial investigations have been centred around examining the field components produced by various shape coils. Hence, much of the work has involved careful measurements of the fields thus produced and is described in the next few chapters.

2. APPARATUS FOR FIELD STRENGTH MEASUREMENTS.

As the frequency used for evaluating the telegram is so low - 29 kHz - and the dimensions involved are very much less than a wavelength, then all radiation effects can be neglected.

It was first of all decided to look at the magnetic fields from d.c. energised coils using a Hall Effect Gaussmeter. The fields involved were of a very small magnitude and because of extraneous fields it was impossible to take any reliable readings. The Gaussmeter was only capable of working up to about 4 kHz and so readings at the normal working frequency of the telegram coils were not possible. A method of measuring the field was thus required to work at some fixed frequency to eliminate any interference, the obvious choice being 29 kHz.

The method used was to measure the emf induced in a small probe coil, amplify this signal in a tuned amplifier, and to record the output voltage. The emf induced in a small coil, situated in a low frequency field and varying sinusoidally with time, can be shown to be proportional to the flux density (see Appendix I). The complete arrangement for flux density measurements is shown in fig. 4.

2.1 The Probe Coil.

Because the emf induced in an air-cored coil is so small a ferrite-cored probe coil was used as shown in fig. 5. This consisted of a ferrite former wound with 100 turns of 44 swg. copper wire and connected to the amplifier by a coaxial cable.

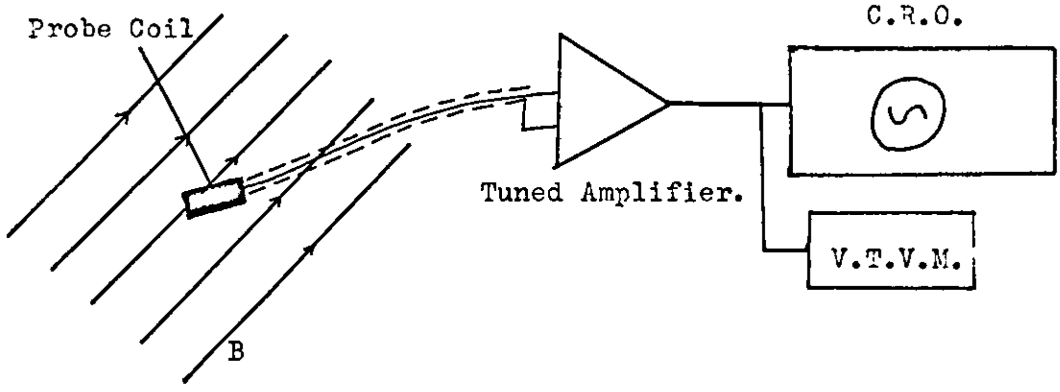


Fig. 4 . General Arrangement for Measuring Flux Density.

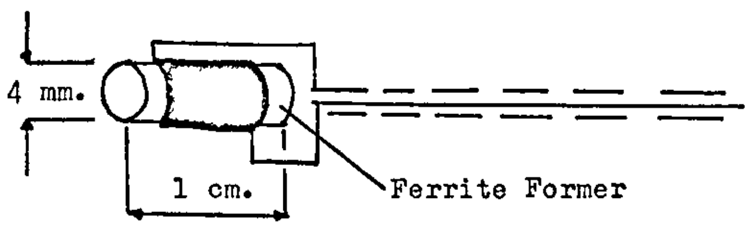


Fig. 5. Enlarged View of Probe Coil.

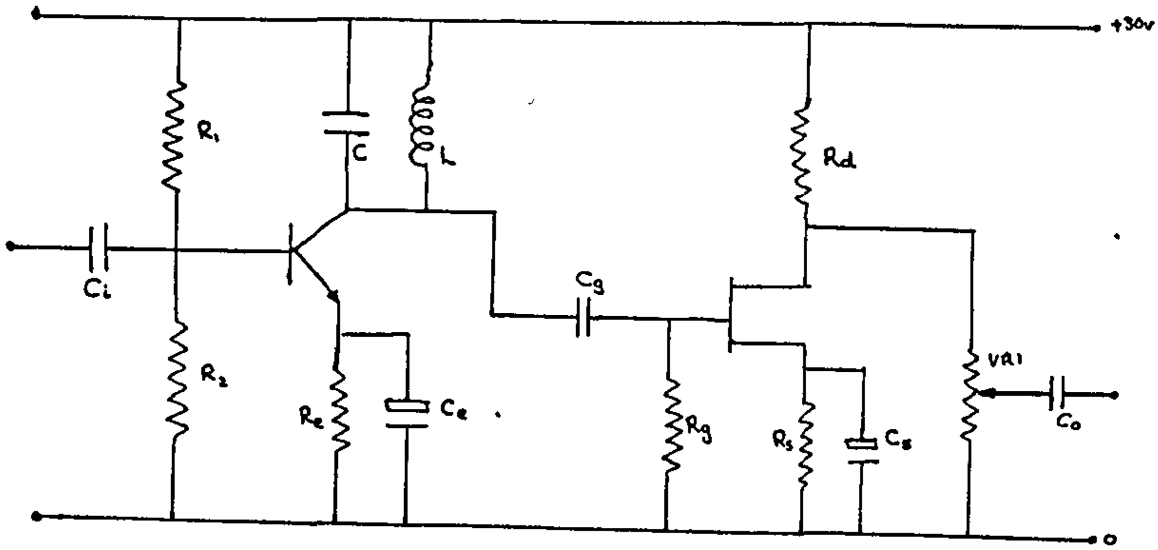


Fig. 6. Narrow Band Tuned Amplifier.

List of Components:-

R1	=	22 kΩ	C_i	=	0.1 μf
R2	=	39 kΩ	C_e	=	5 μf
R_e	=	15 kΩ	C_g	=	0.1 μf
R_g	=	2.2 MΩ	C_s	=	25 μf
R_d	=	5.6 kΩ	C_o	=	0.1 μf
R_s	=	330Ω	C	=	0.084 μf
VR1	=	100 kΩ	L	=	360 μH

2.2 The Narrow Band Tuned Amplifier.

This was a two stage amplifier as shown in fig. 6. The first stage was a common emitter amplifier with a tank circuit as a collector load followed by a field effect transistor in common source connection. The second stage had to have a high input impedance to prevent damping of the tuned circuit. The output was via a potentiometer VR1 so that, if more than one amplifier was used, the gain of each could be made the same and only one calibration curve was required. The amplifier was housed in a steel box to afford some screening from the magnetic fields although this does not give complete shielding. The shielding obtained seemed sufficient.

It is desirable to have a narrow band amplifier in order to cut down any interference which might occur. Figure 7 shows the frequency response of the amplifier, the bandwidth being only 700 Hz and giving a Q of about 41, the centre frequency being 29 kHz.

2.3 Calibration of Amplifier and Probe Coil.

A calibration curve is required before any fields can be measured showing output voltage against flux density perpendicular to the plane of the probe coil. It can be shown (see reference 16) that about the centre of a long solenoid (i.e. length / diameter is greater than say 15) the flux density is virtually constant and has only one direction. This provides an easy method of producing a uniform field for calibrating a small probe coil.

The flux density at the centre of a long solenoid is given by :-

$$B = \frac{\mu_0 N I}{(L^2 + 4R^2)^{1/2}} \quad \text{Tesla} \quad \ldots\ldots\ldots \quad (1)$$

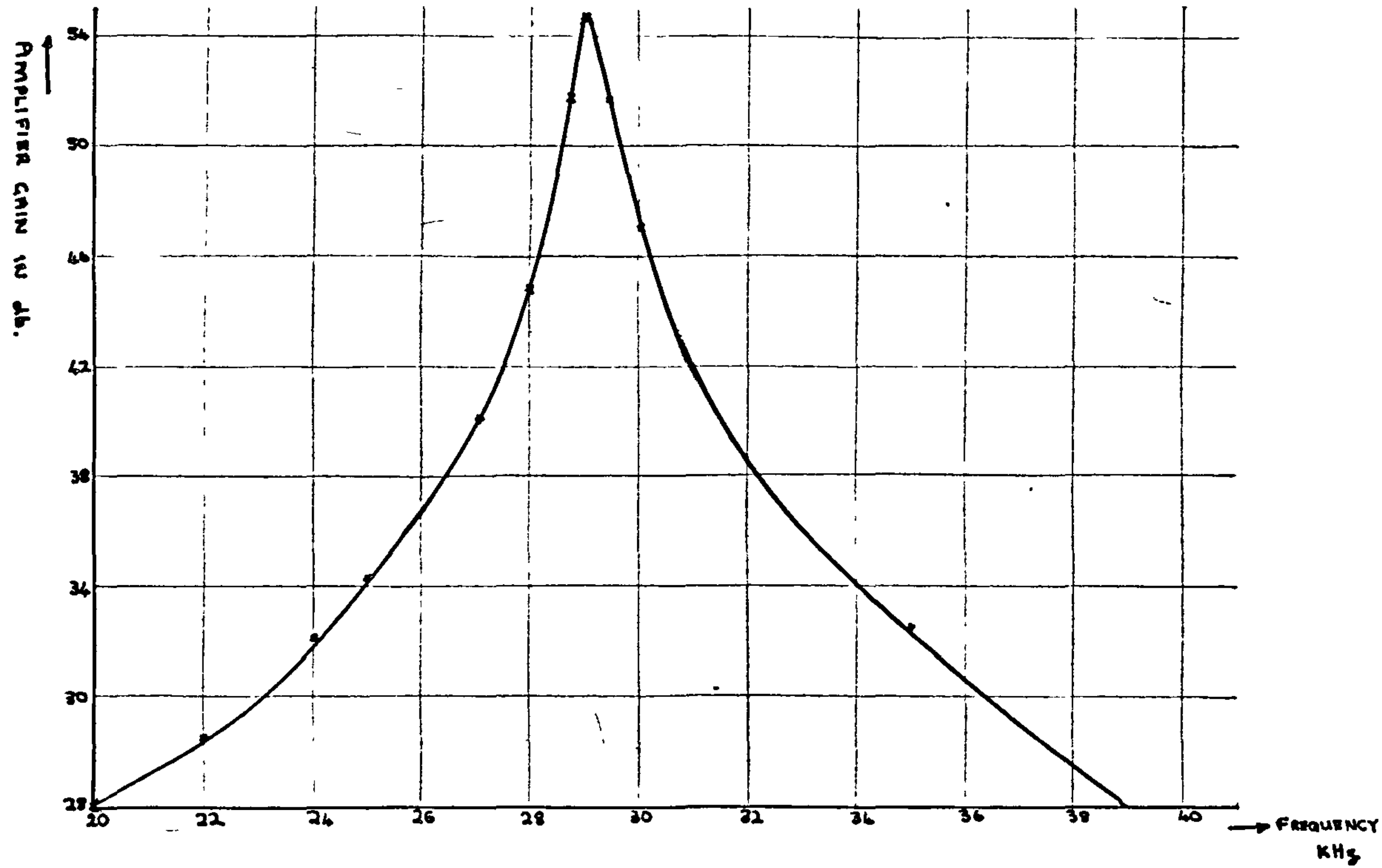


Fig. 7. FREQUENCY RESPONSE OF TUNED AMPLIFIER.

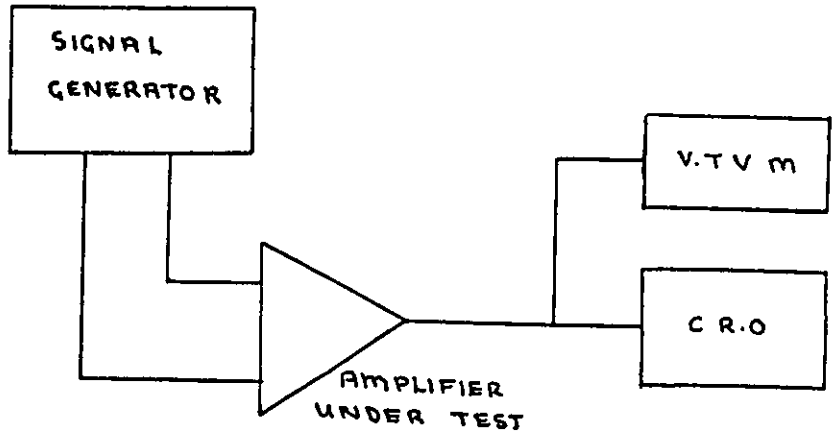


Fig. 8. Determination of Frequency Response of Amplifier.

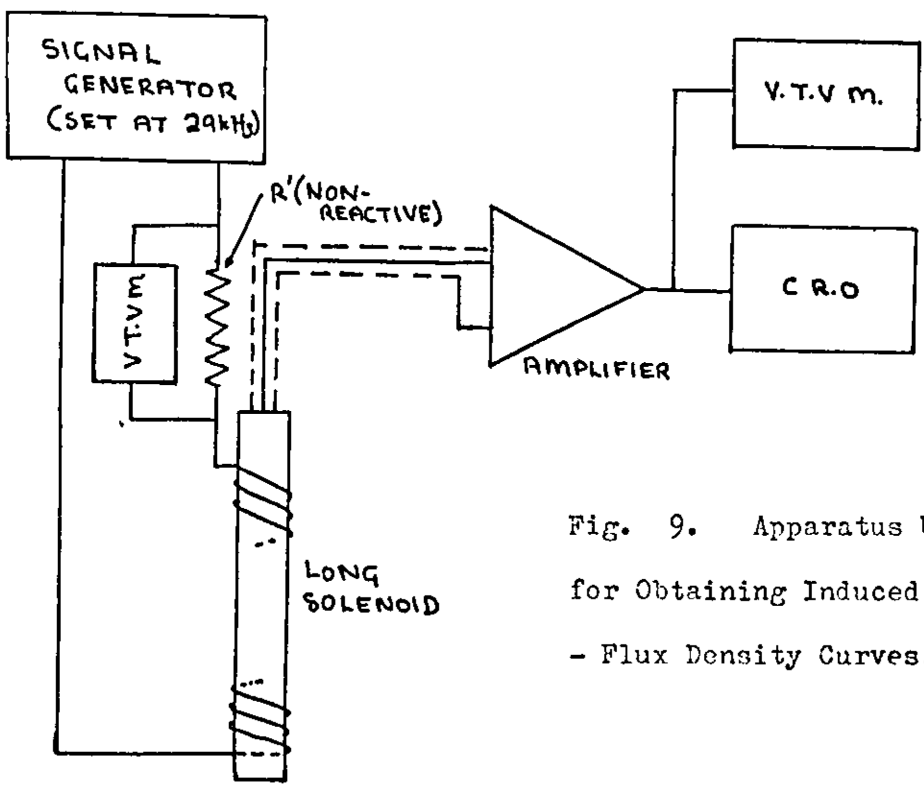


Fig. 9. Apparatus Used for Obtaining Induced Emf - Flux Density Curves.

Where N is the total number of turns on the solenoid,

L is the length of the solenoid, in metres and

R is the radius of the solenoid in metres.

Figure 8 shows the apparatus used for calibrating the amplifier and probe coil.

Now, from figure 9,

$$I = V_R / R'$$

and $\mu_o = 4\pi \times 10^{-7}$ henry's/metre

N = 195 turns

L = 0.10 metres

R = 0.005 metres

R' = 1030 ohms.

Substitution in (I) gives,

$$B = 2.36 \times 10^{-6}\, V_R \text{ Tesla.}$$

The flux density at the centre of the solenoid can thus be calculated for various currents. A plot of output voltage of the amplifier can then be made, for the probe coil in the centre of the solenoid, against flux density produced there. As the output voltage is also displayed on an oscilloscope it is easier to record peak to peak voltages so that the two methods of measuring this voltage can be easily compared. Figures 10 (a), (b) and (c) show the flux density - output voltage characteristics of the measuring apparatus. The calibration of the amplifier was also checked at regular intervals using the above apparatus.

Some trouble was initially encountered from noise introduced by the circuits employed in the stabilised power supply used. The amplifier had a reasonably high gain and the level of some of the output signals was very low; this noise was eliminated by using a decoupling circuit across the power supply of the amplifier.

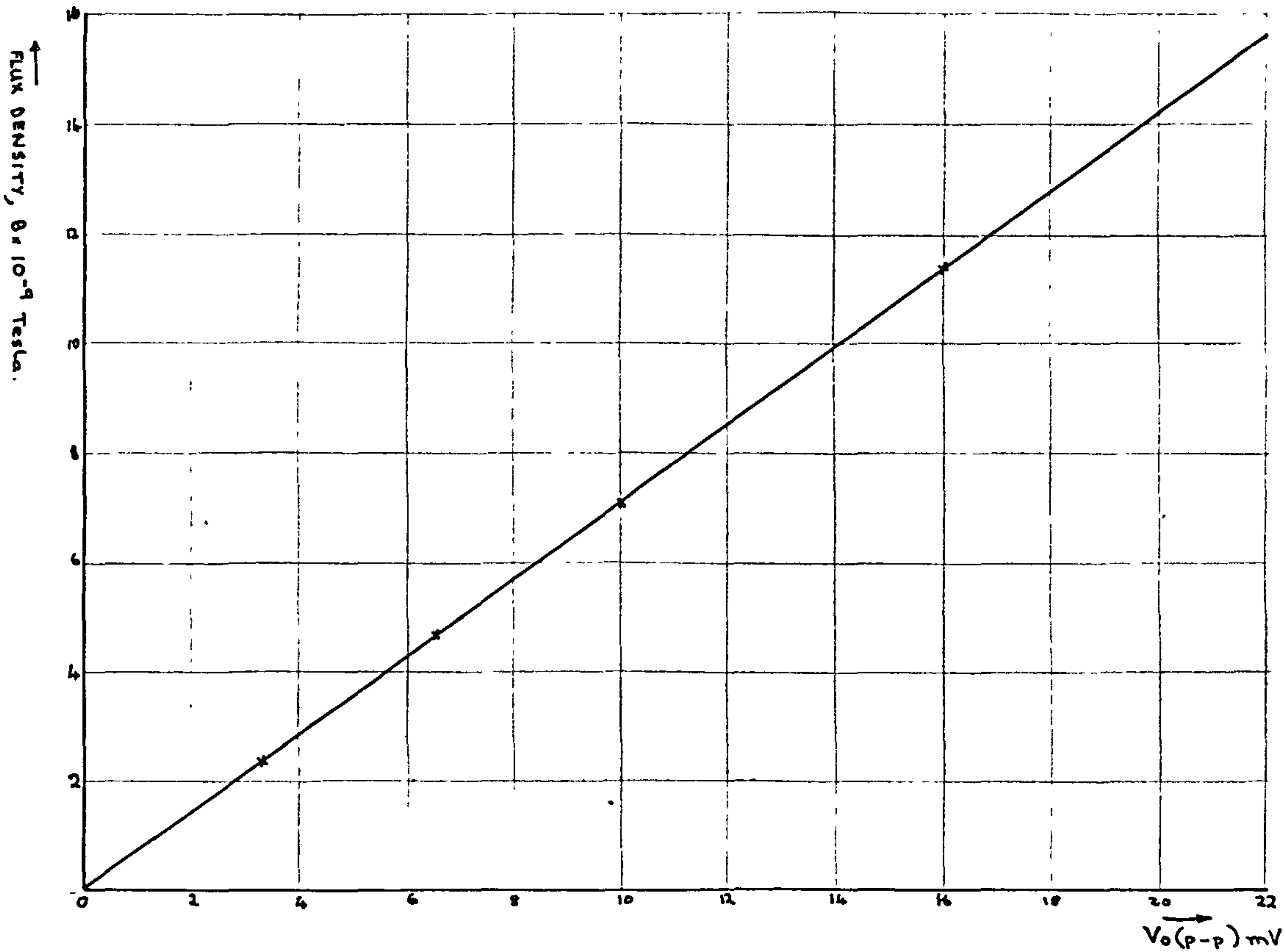


FIG. 10 (a). CALIBRATION CURVE.

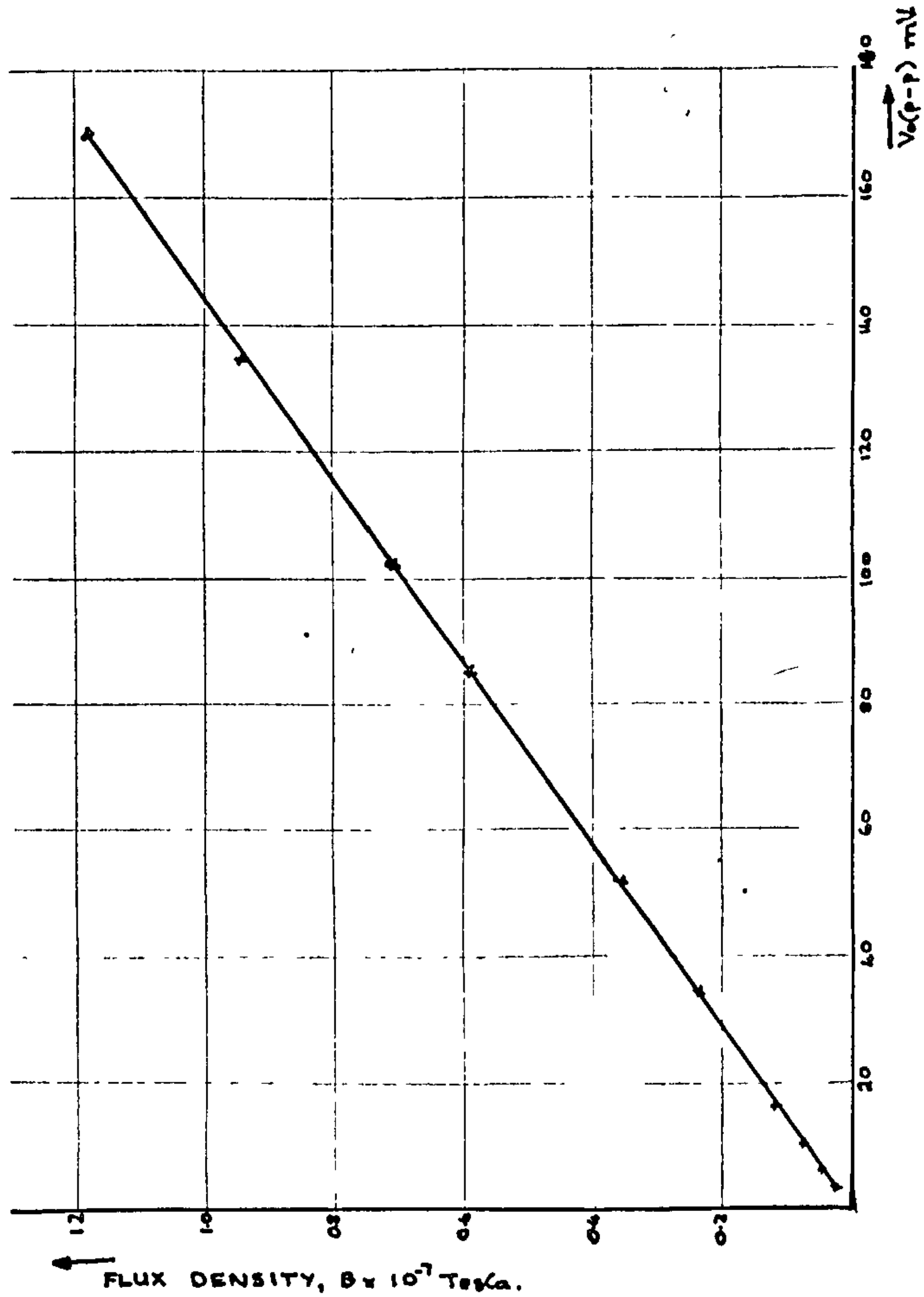


FIG. 10(b). CALIBRATION CURVE.

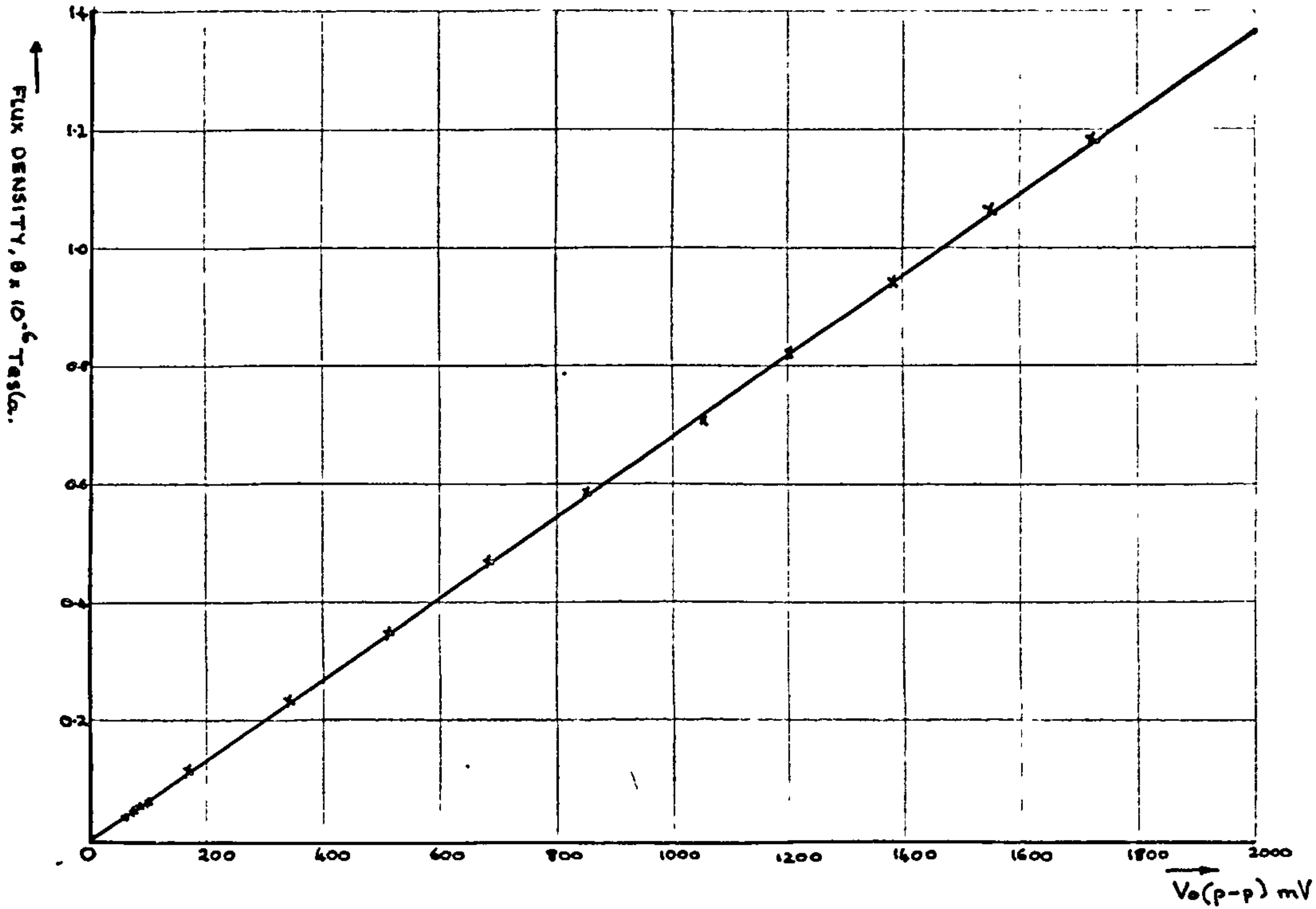


FIG. 10(c). CALIBRATION CURVE.

Fig. 11 . Photograph of the Framework Used.

2.4 Framework.

As it was desired to measure different field components at various positions in space some form of framework was needed so that the probe coil could be moved in three dimensions. The framework had to be made of some non-magnetic material and also had to be rigid. This severely limited the choice of materials and the best one that emerged was 'Tufnol'. The framework dimensions were such that the feet would rest on the sleepers if any tests were required to be done on a railway track and could easily be dismantled if the need arose. Fig. 11 shows a photograph of the framework that was built.

3. ANALYSIS OF THE BRITISH RAIL PROPOSED SYSTEM.

Although British Rail have made some initial measurements on their originally proposed telegram coil system, a full analysis is carried out here. The results of this analysis provide :-

(1) a check on the British Rail readings,

(2) a feel for the problem, and

(3) the magnitudes of the fields involved.

Figure 12 shows a layout of the system and gives the main dimensions.

Figure 13 depicts a telegram coil and shows its construction.

Two signals are picked up from the track :-

(1) over the centre of the parallel wires, and

(2) over the centre line of the coils.

In each case the vertical component (B_z) of the flux density being received. The diagram shows only two coils although thirty-two coils are required to convey all the information. It was found that only the interference from adjacent coils was important and thus two coils were used to evaluate the practical system. Other interference inherent in the system is that between the parallel wires and the coils, the interference of the parallel wire field on the coil field being the most serious.

The calculations of the theoretical values of flux density were done using the magnetic vector potential (see Appendices). The evaluation of the resulting expressions was carried out with the aid of a digital computer (an ICL 1905). Both theoretical and practical results are tabulated here, together with the graphs, to give a comparison between the two sets of data. The curves all show the rms value of the flux density. The value of the coil current I_c(rms) was 100 mA so that the theoretical values had only

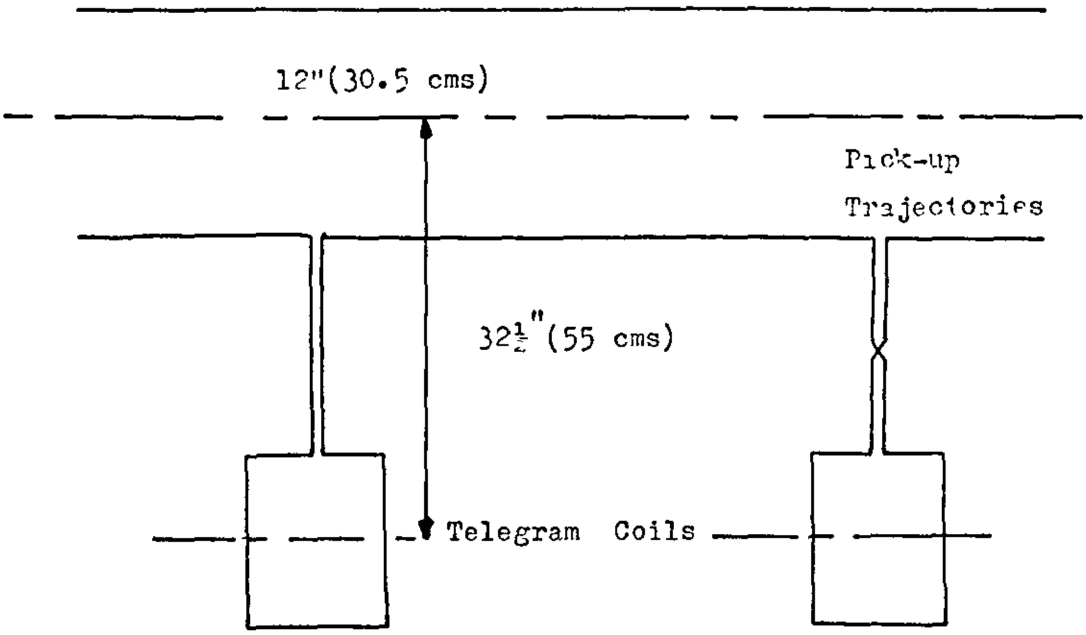


Fig. 12. Main Dimensions of Telegram System.

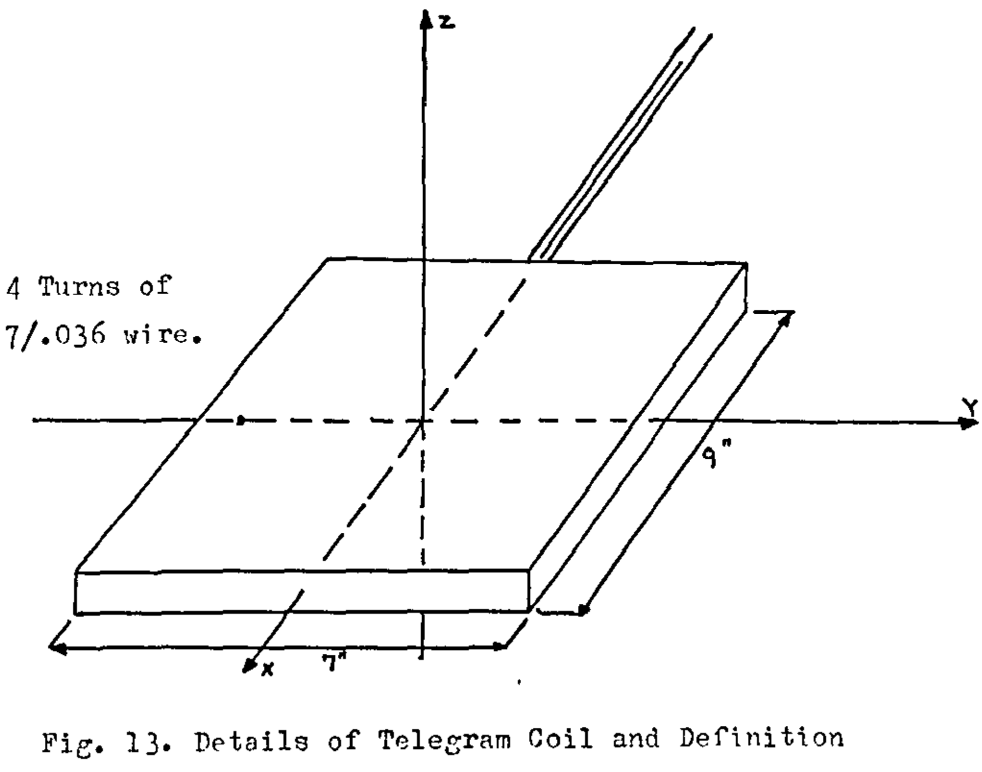


Fig. 13. Details of Telegram Coil and Definition
of Axes Used.

TABLE 1. Theoretical Results for Telegram Coil

$B_z \times 10^{-7}$ I Tesla	Y cms.
-0.164	-80
-0.180	-75
-0.195	-70
-0.207	-65
-0.210	-60
-0.196	-55
-0.151	-50
-0.049	-45
0.152	-40
0.520	-35
1.151	-30
2.164	-25
3.647	-20
5.554	-15
7.585	-10
9.190	-5
9.805	0
9.190	5
7.585	10
5.554	15
3,647	20
2.164	25
1.151	30
0.520	35
0.152	40
-0.049	45
-0.151	50
-0.196	55
-0.210	60
-0.207	65
-0.195	70
-0.180	75
-0.164	80

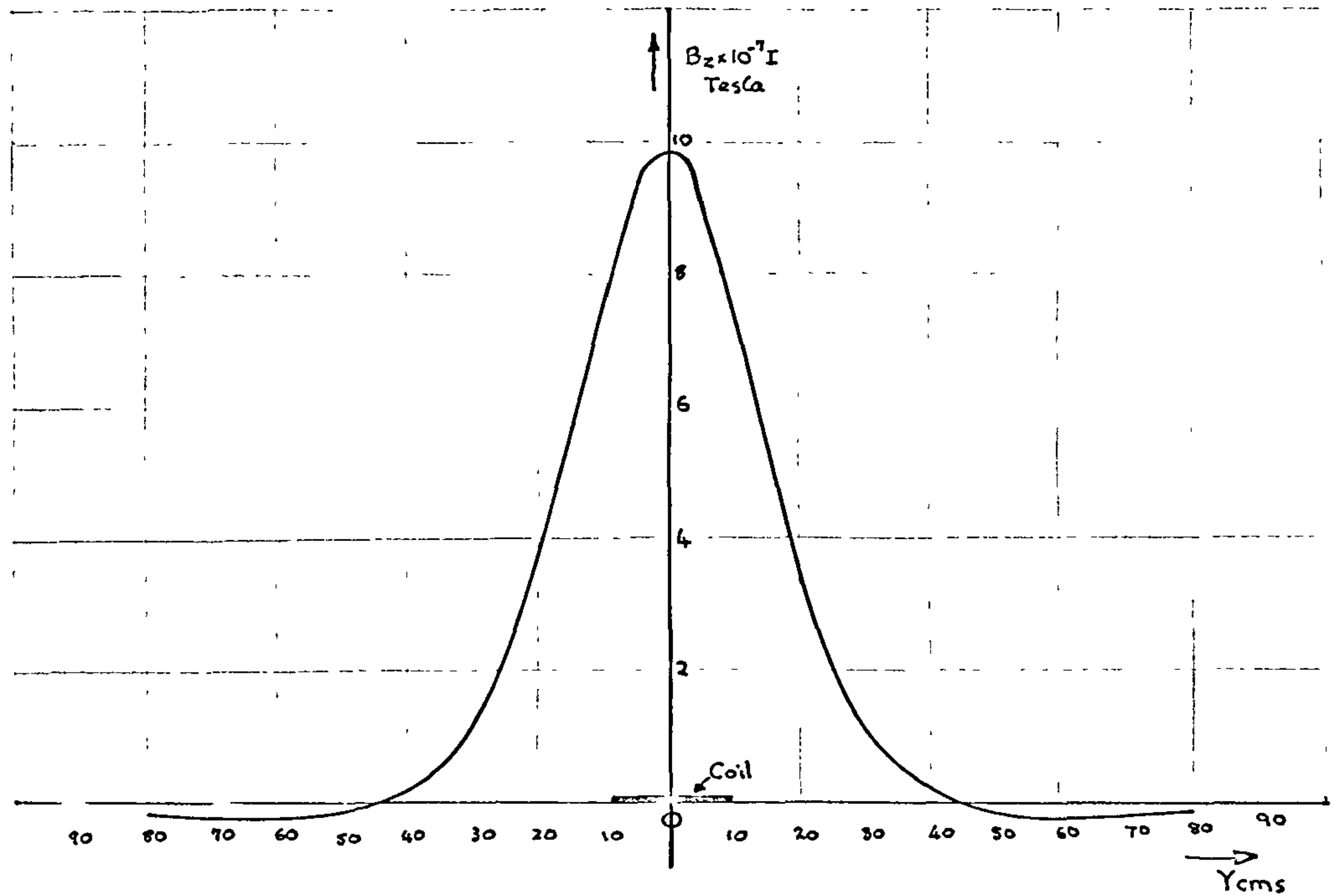


Fig. 14. Theoretical Curve for a 9"x7" Telegram Coil.

TABLE 2. Practical Results for Telegram Coil.

V_o (p-p) mV	$B_z \times 10^{-6}$ Tesla	Y cms.
-2.4	-0.18	-75
-2.5	-0.19	-70
-2.6	-0.2	-65
-2.6	-0.2	-60
-2.5	-0.19	-55
-2.0	-0.15	-50
-0.6	-0.05	-45
2.1	0.16	-40
7.8	0.55	-35
17.4	1.2	-30
32	2.2	-25
55	3.8	-20
82	5.7	-15
112	7.8	-10
134	9.3	-5
142	9.9	0
134	9.3	5
112	7.8	10
82	5.7	15
55	3.8	20
32	2.2	25
17.4	1.2	30
7.8	0.55	35
2.1	0.16	40
-0.6	-0.05	45
-2.0	-0.15	50
-2.5	-0.19	55
-2.6	-0.2	60
-2.6	-0.2	65
-2.5	-0.19	70
-2.4	-0.18	75

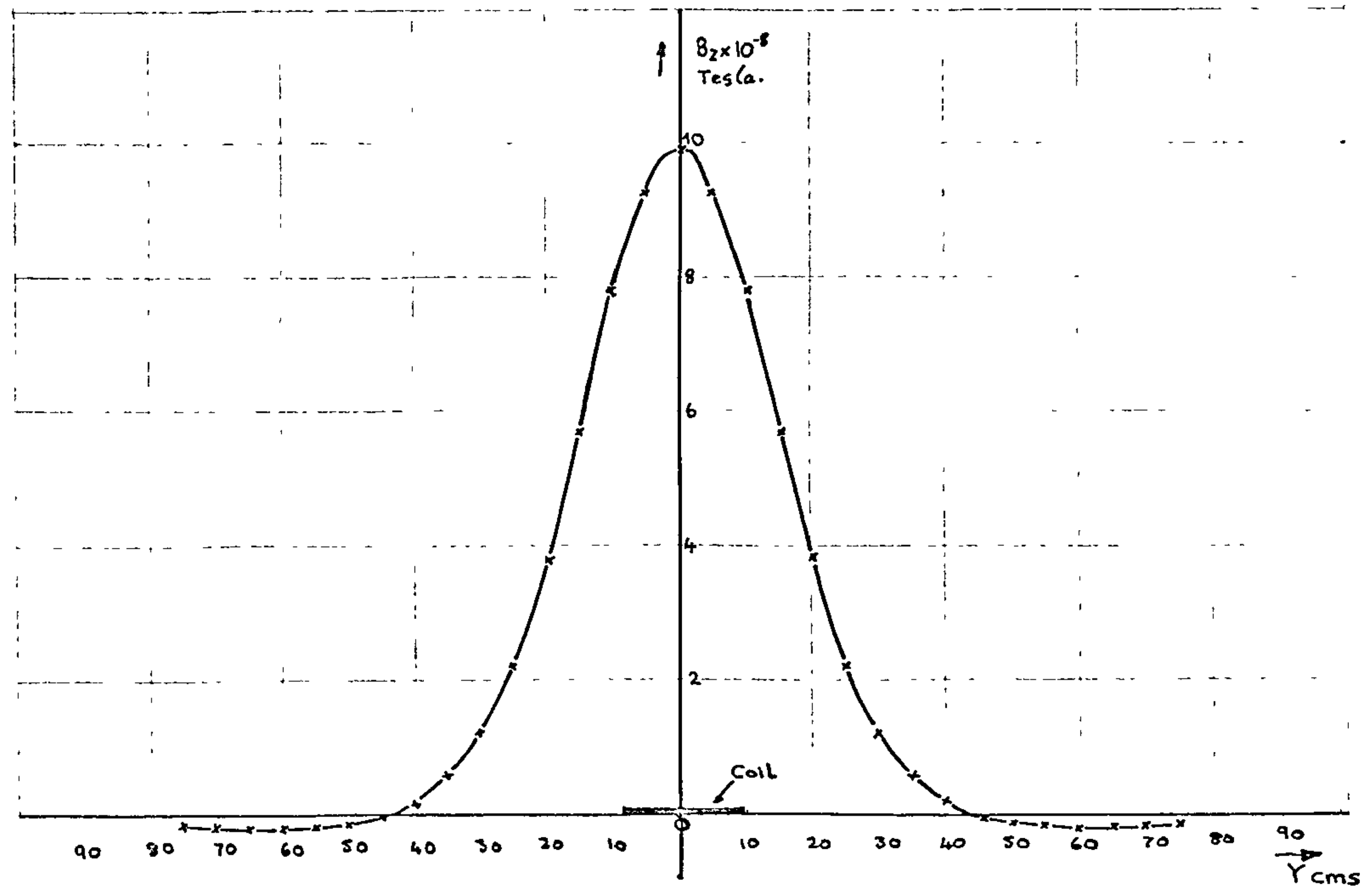


Fig. 15. Practical Curve for a 9"x7" Telegram Coil.

to be divided by 10 to compare them with the practical readings. A change in sign of the flux density on graphs represents a phase change of 180^{o}.

3.1 B_z Field from a Telegram Coil.

Tables 1 and 2, together with figs. 14 and 15, show the theoretical and practical results for the vertical component of magnetic field from a 9" x 7" coil of four turns. The pick-up coil is at a height of 12" (0.305 m) above the coil base and moves along the 'Y' axis, i.e. X = 0. The theoretical and practical values for the fields agree to within 4%, the errors being greatest where the slope of the field is steepest.

3.2 B_z Field from Adjacent Telegram Coils.

Curves (b) on figs. 16 and 17 show the theoretical and practical values of B_z as the coils are traversed in the Y direction for X = 0. From these curves an important ratio emerges - namely the ratio of the maximum value of the field encountered above a coil to the minimum value between the peaks. Let this ratio be denoted by R, and for the different field components be R_x, R_y, and R_z. It is at the minimum value of field where the interference from a neighbouring coil has the greatest effect. An approximate value for R can be obtained from the curve for a single coil. This is the ratio of the maximum field strength to twice the value of the field where the 'trough' would appear - denoted by R'.

For two adjacent coils wound in the same sense and without interference from the parallel wires -

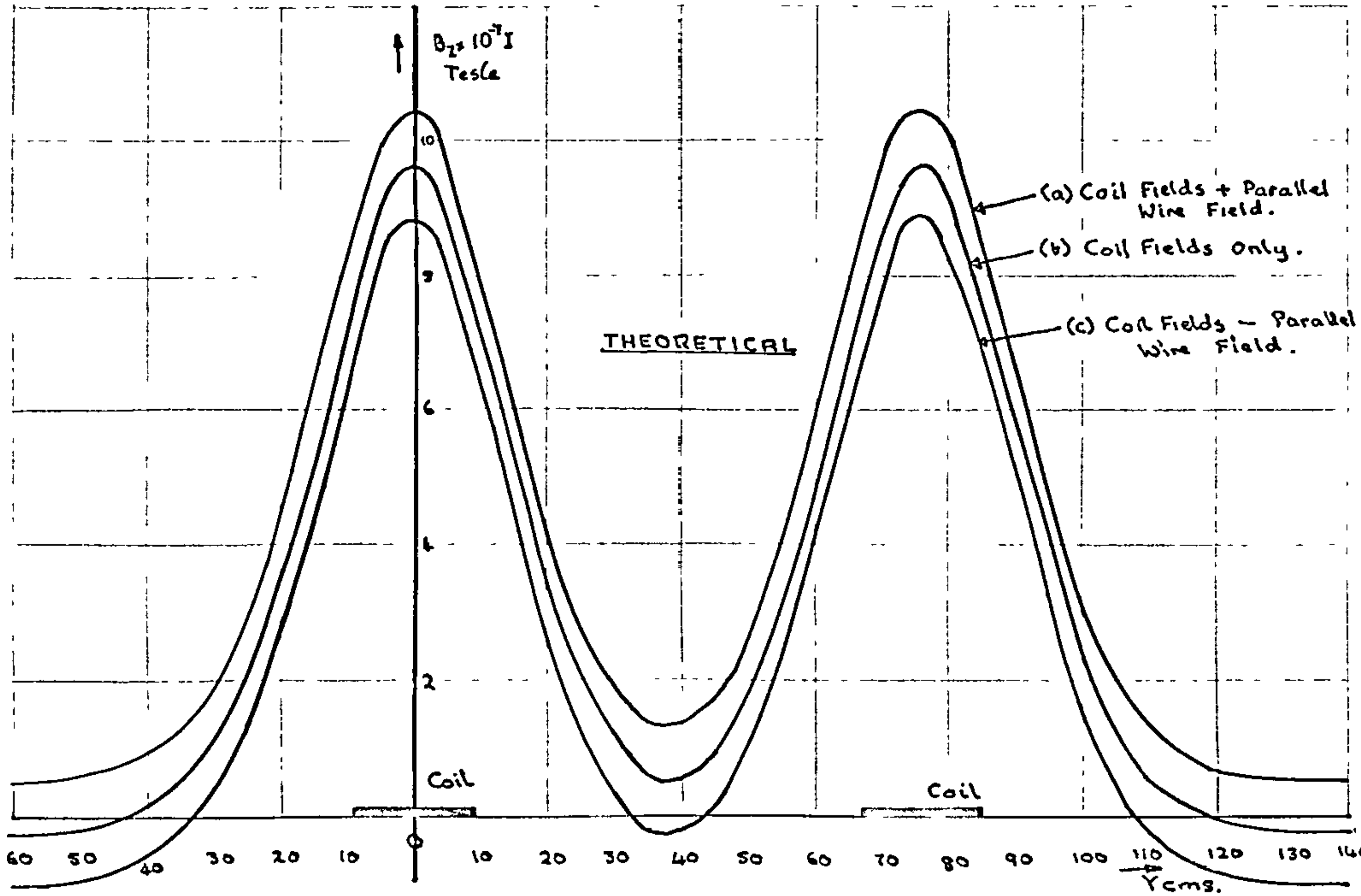


Fig. 16. Effect of Parallel Wire Field on the Field of Two Adjacent Telegram Coils (Wound in the Same Sense).

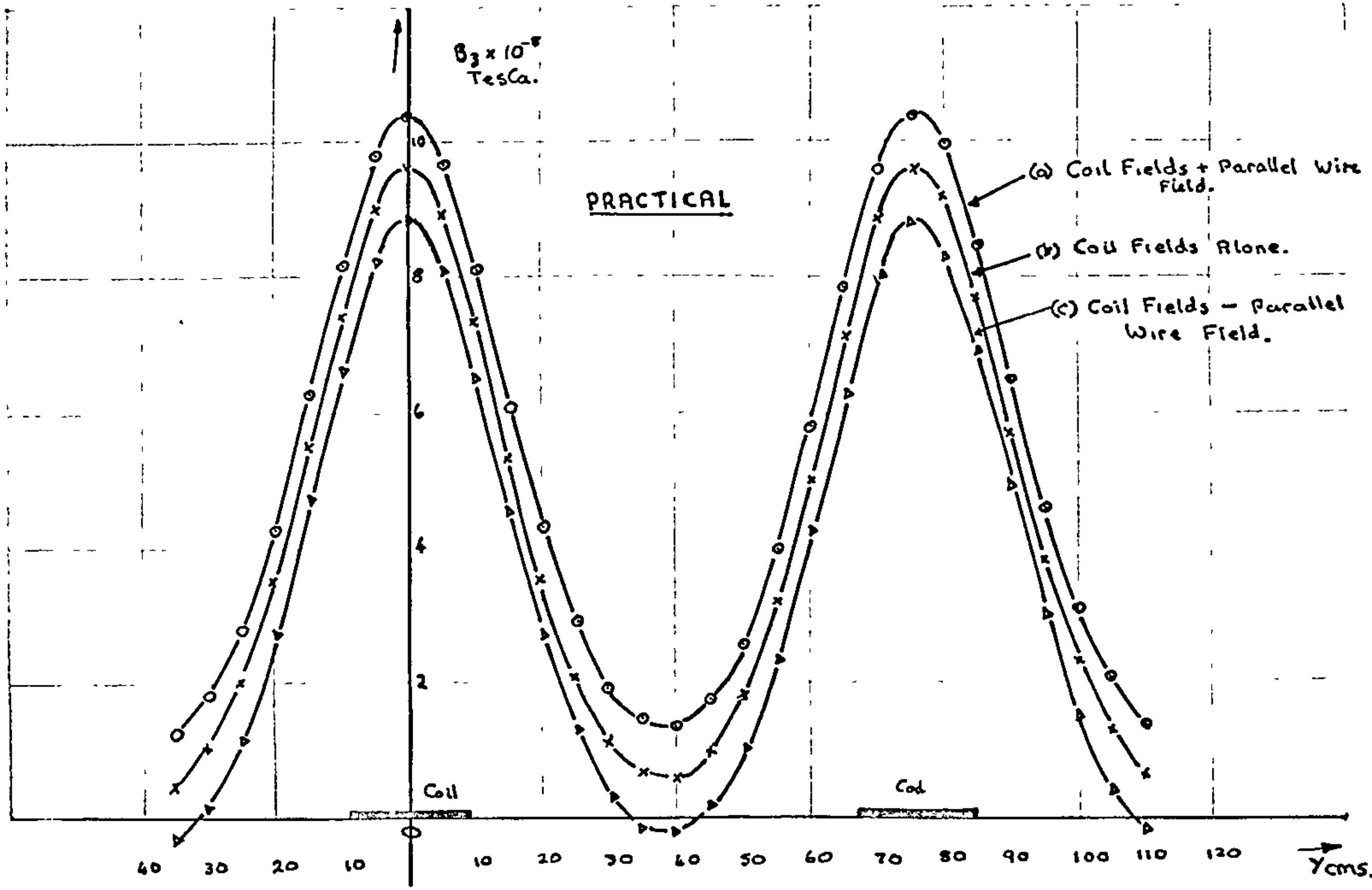


Fig. 17. Effect of Parallel Wire Field on the Field of Two Adjacent Telegram Coils (Wound in the Same Sense).

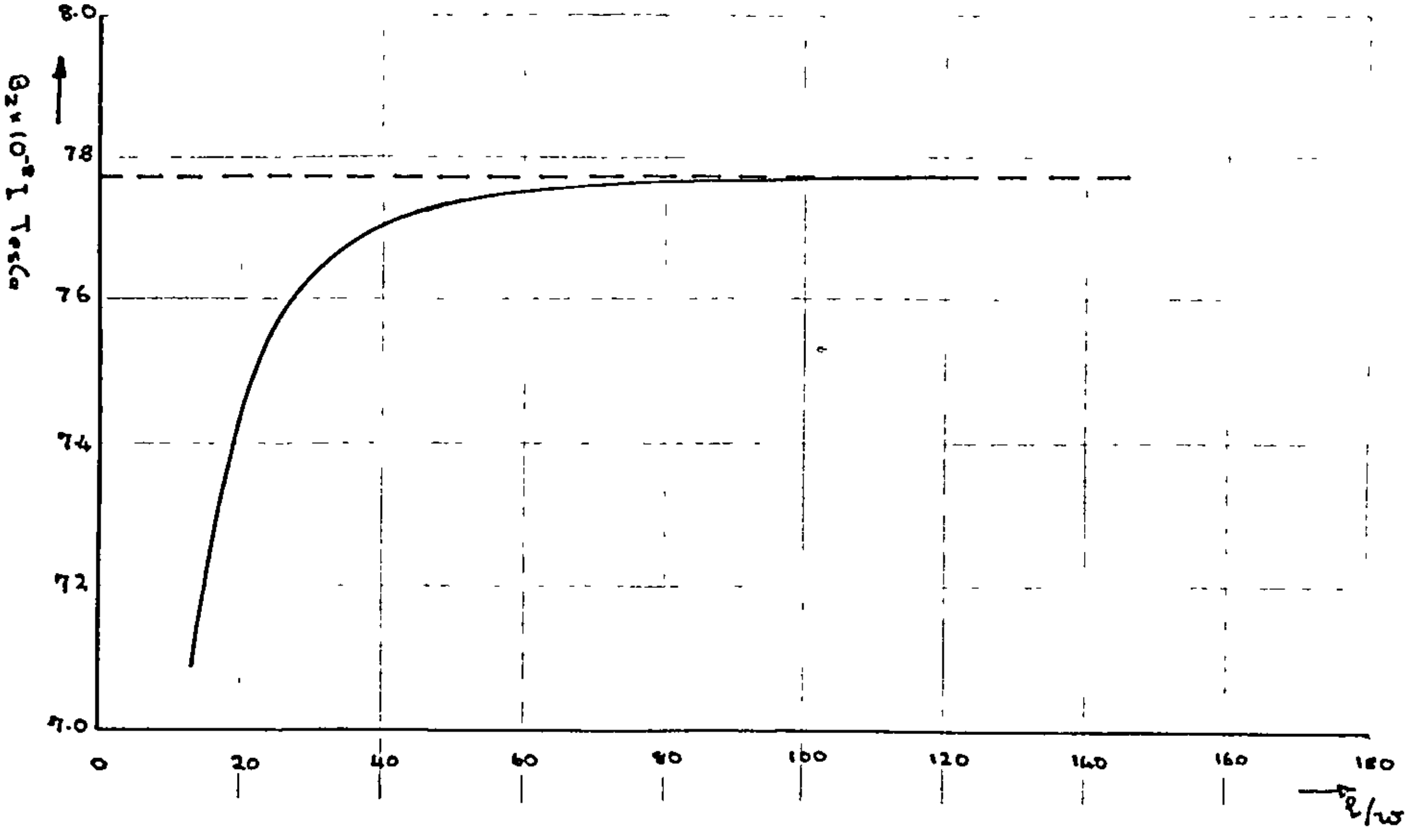


Fig. 18 Variation of Interference of Parallel Wire Field on the Coil Field for Various Length / Width (l/w) Ratios of the Parallel Wires.

$$R_z \text{ (theoretical)} = 17.4$$

$$R_z \text{ (practical)} = 17.5$$

For coils wound in the opposite sense, midway between the coils the flux density is zero and hence the ratio R_z is infinite.

3.3 B_z Field from the Parallel Wires.

Because of space available for practical work a parallel wire system was built 8' (2.44 metres) long and 1' (0.305 metres) wide. Some measurements were carried out on the vertical field component and it was found that the results did not agree with the theoretical values obtained for the wires considered as two long parallel conductors. On considering the wires as an elongated rectangle the theoretical and practical results were in good agreement and hence the end effects of the parallel wires cannot be neglected in a system of these dimensions. A plot of theoretical flux density, occurring where the coils would be, against the length to width ratio of the line is shown in fig. 18. From this curve it would appear that a ratio of about 100:1 must be used before the flux density approaches the value encountered from an infinite line. For this reason no practical results are available and the theoretical values for a long line have been used to give the curves in fig. 16. As all the work is carried out at 29 kHz where the wavelength in air is about 10 km standing waves on the line have been neglected.

3.4 B_z Field from the Combined Parallel Wire and Coil System.

On forming the practical system as shown in fig. 12 it was possible to take practical readings of the fields involved.

interference is produced by the parallel wires on the coil fields and curves (a) and (c) on figs. 16 and 17 show the modifying effect. Because of this interference the values of R_z are affected and become more restrictive. The value of R_z when the coils are wound in the opposite sense, for both additive and subtractive effects of the wires, is still infinite but does not now occur midway between the coils. For the coils wound in the same sense :-

(1) the parallel wire field additive to the coil field

R_z (theoretical) = 8.0

R_z (practical) = 7.7

and (2) the parallel wire field subtractive

R_z (theoretical) = -40

R_z (practical) = -42

- the minus sign denoting a change in phase of one of the fields.

3.5 <u>Discussion.</u>

These values for R_z set a limit for the system and the maximum range over which it will work. For the above system the current attenuation would not have to be greater than 18db (neglecting noise) unless the interference from the parallel wires can be subtracted from the coil field in the receiving apparatus and the range would then be about 17. This problem might also be overcome by using a variable threshold level in the train control equipment. There is also no reason why 7/.036 copper wire should be used.

3.6 Conclusions

Careful attention must be paid to the interfering magnetic field caused by the current in the parallel wires so that reasonable values of R can be achieved. This is so that the dynamic range may be as large as possible and applies to any field component used.

4. EXAMINATION OF FIELD COMPONENTS FROM TELEGRAM COILS.

To obtain more than one bit of binary information per telegram coil, there would seem to be three possible ways of achieving this. These are :-

(1) the use of field components produced by coils lying flat on the sleeper,

(2) the use of field components produced by coils inclined at an angle to the horizontal on the sleeper, and

(3) the use of multi-level fields (i.e. the use of coils with different numbers of turns but using only one field component).

Because of the extra circuitry required in (3) for an analogue to digital converter and the higher error rates involved this method was not considered as a possibility. Investigations were therefore confined to methods (1) and (2).

Using different field components the maximum number of bits of information from a single coil is three, if all the field components are used. For these bits to be independent of one another the coil must have three degrees of freedom. Rectangular cartesian coordinates are used throughout as these represent the only possible field components likely to be picked up by a train-borne aerial.

The coils examined in this chapter are fairly large (smallest dimension $4\frac{1}{2}''$ - 0.057 metre) as the flux density is higher from a larger coil and the inductance of a coil lower for a given field strength (inductance is proportional to the number of turns squared). The use of smaller dimension coils is examined in chapter 5. Rectangular, square and circular coils are all examined here, the relevant theory appearing in the appendix.

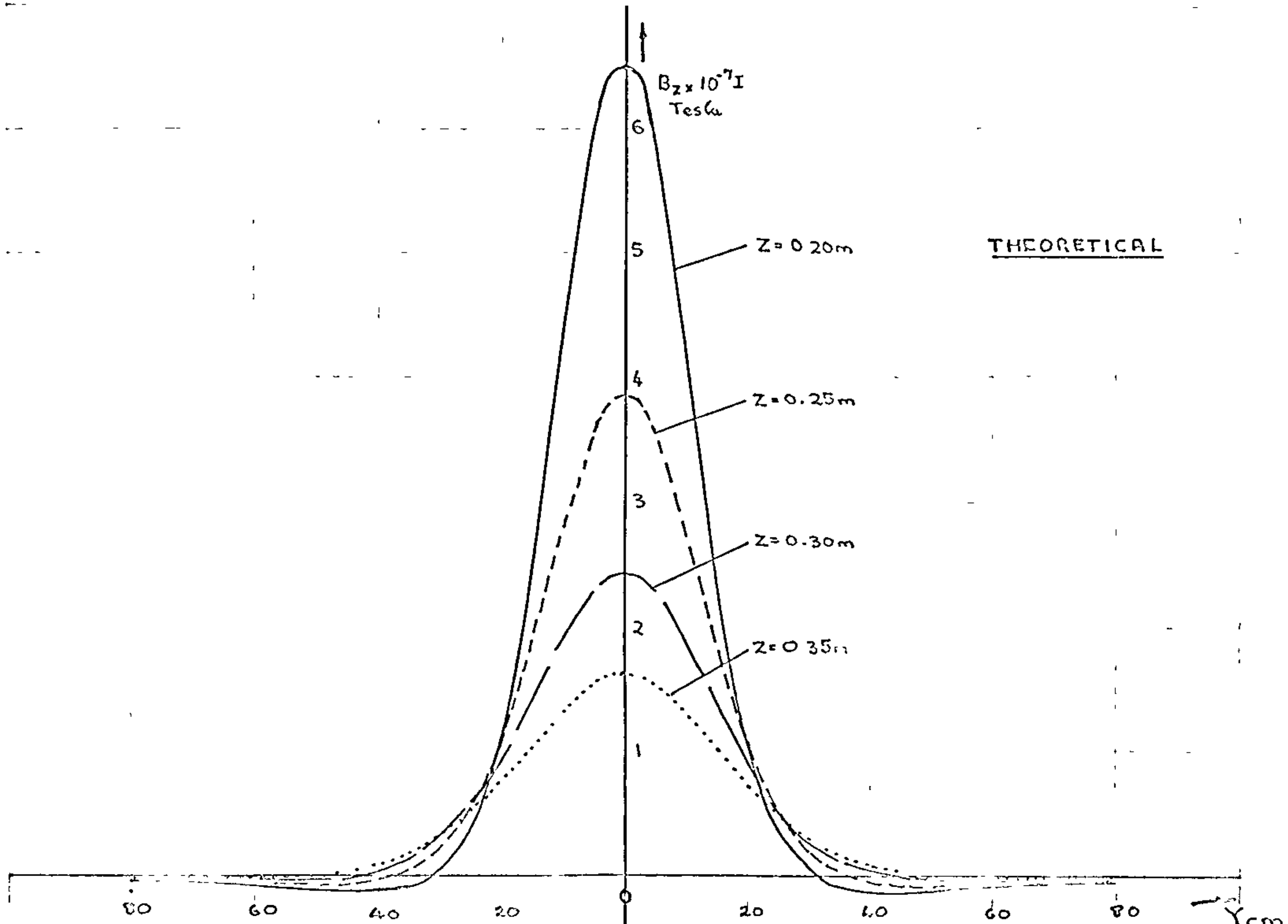


Fig. 19. Variation of Bz with Height above a 9"x 7" Coil (Single Turn).

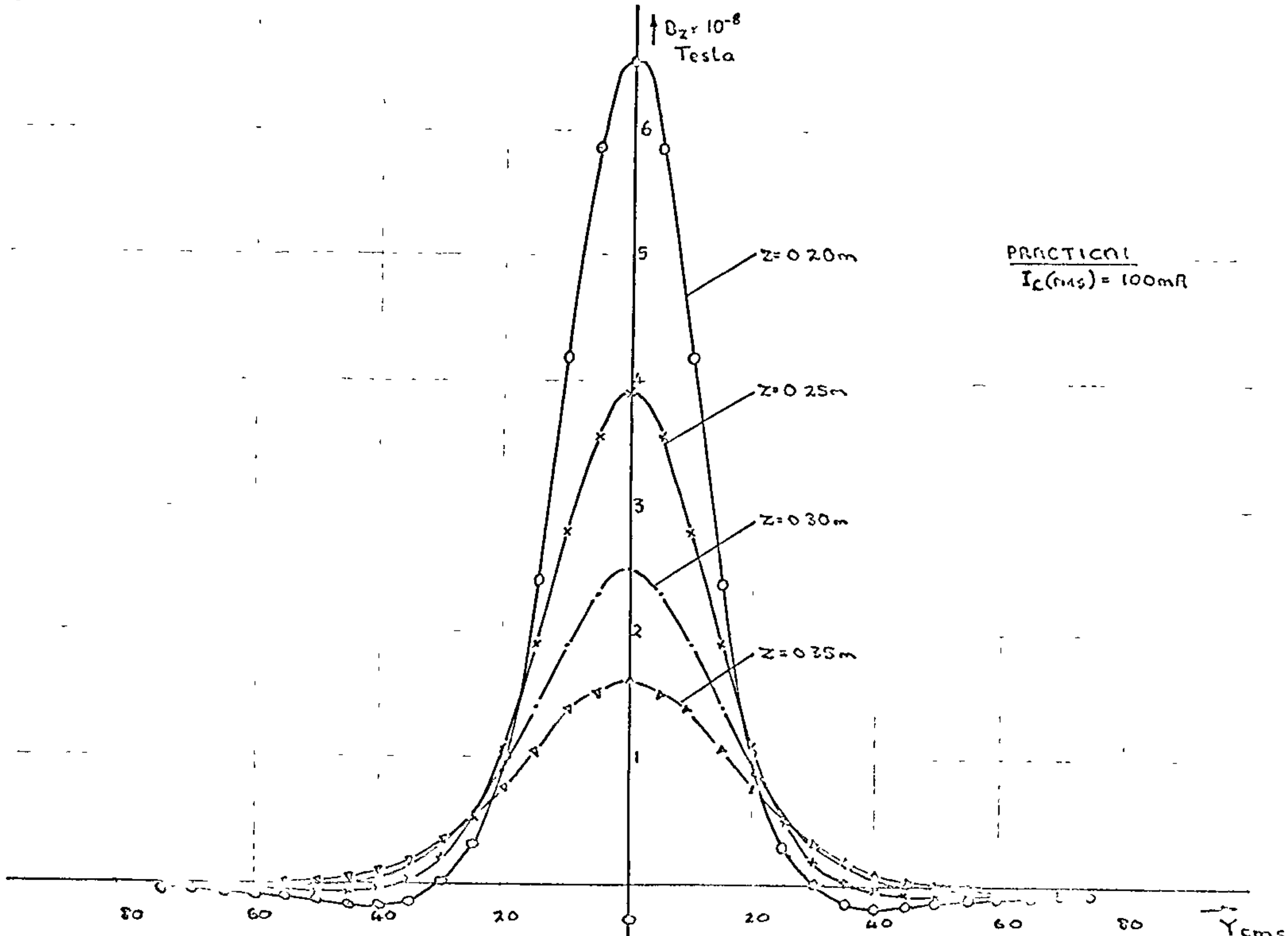


Fig 20. Variation of Bz with Height above a 9"x7" Coil (Single Turn).

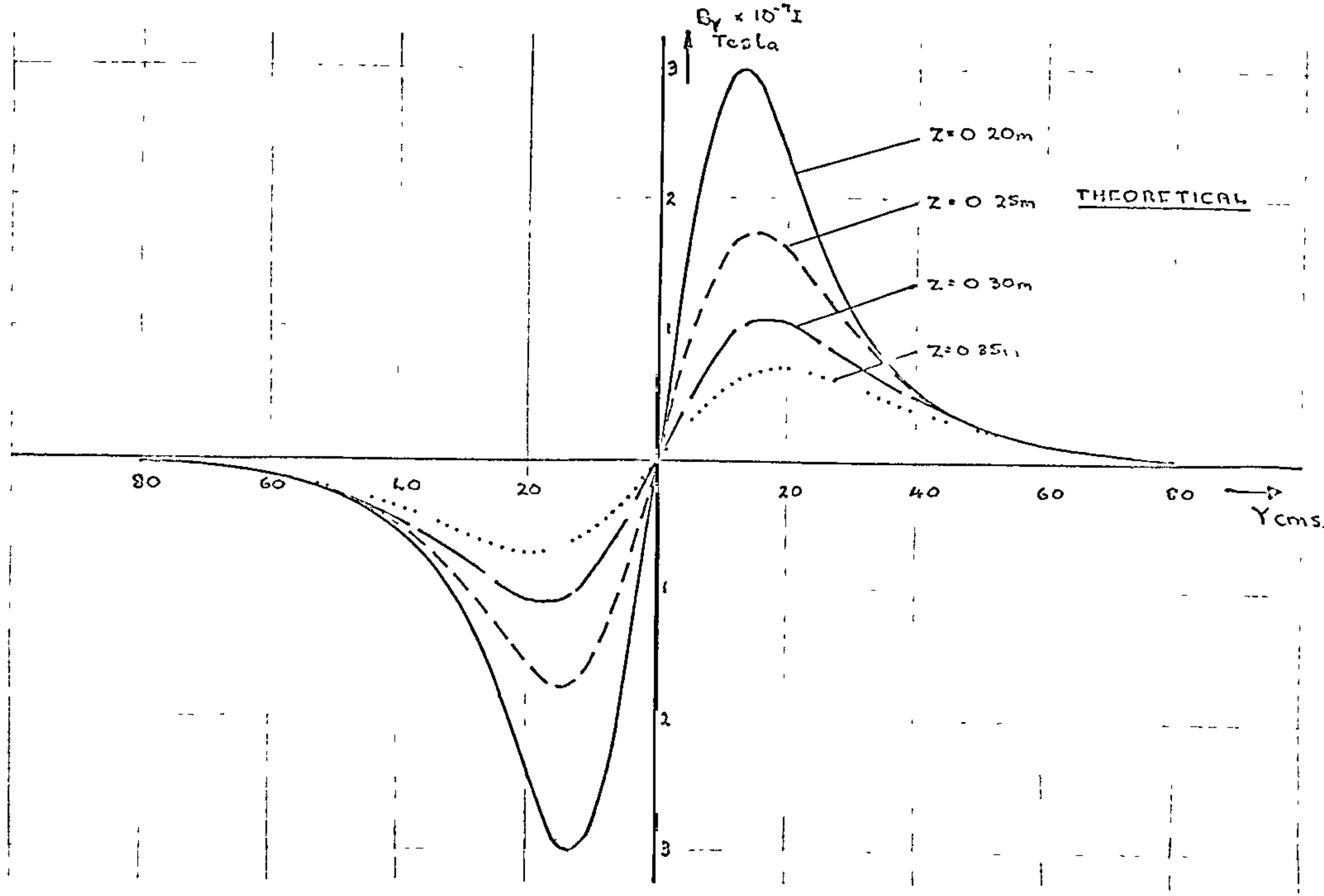


Fig. 21 Variation of By with Height above a 9'x7' Coil (Single Turn).

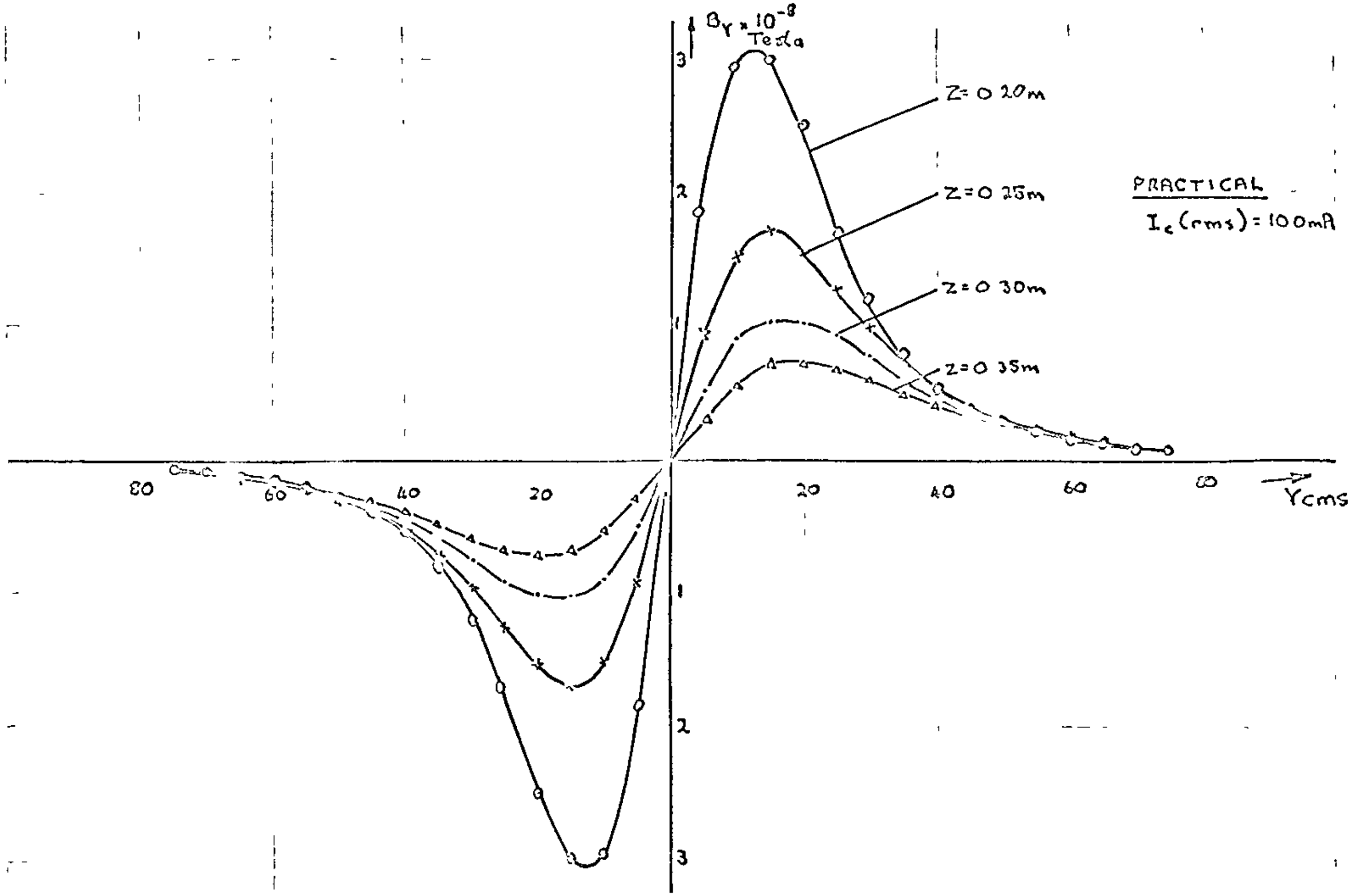


Fig 22. Variation of By with Height above a 9"x7" Coil (Single Turn).

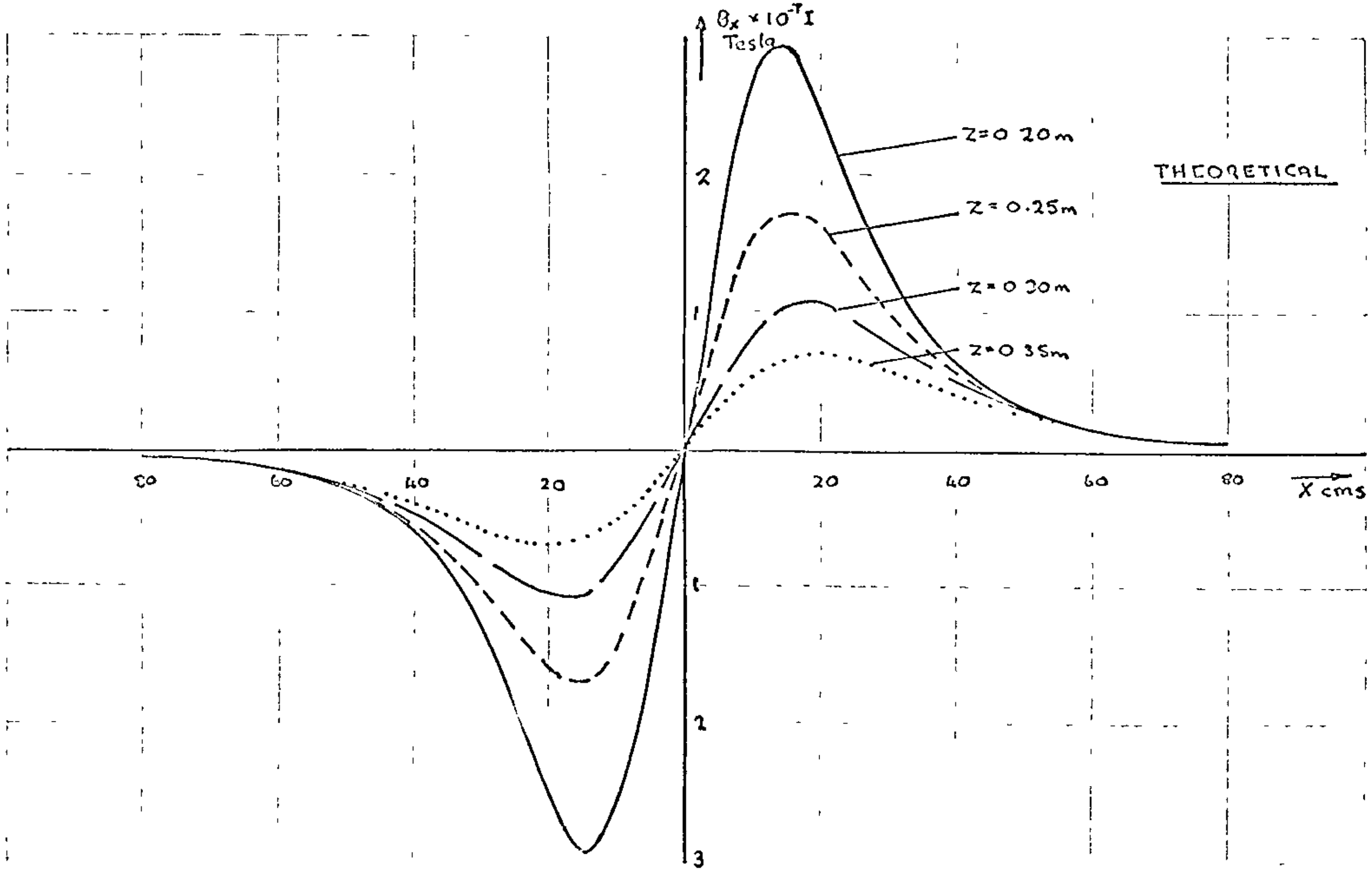


Fig. 23 Variation of Bx with Height above a 9"x7" Coil (Single Turn).

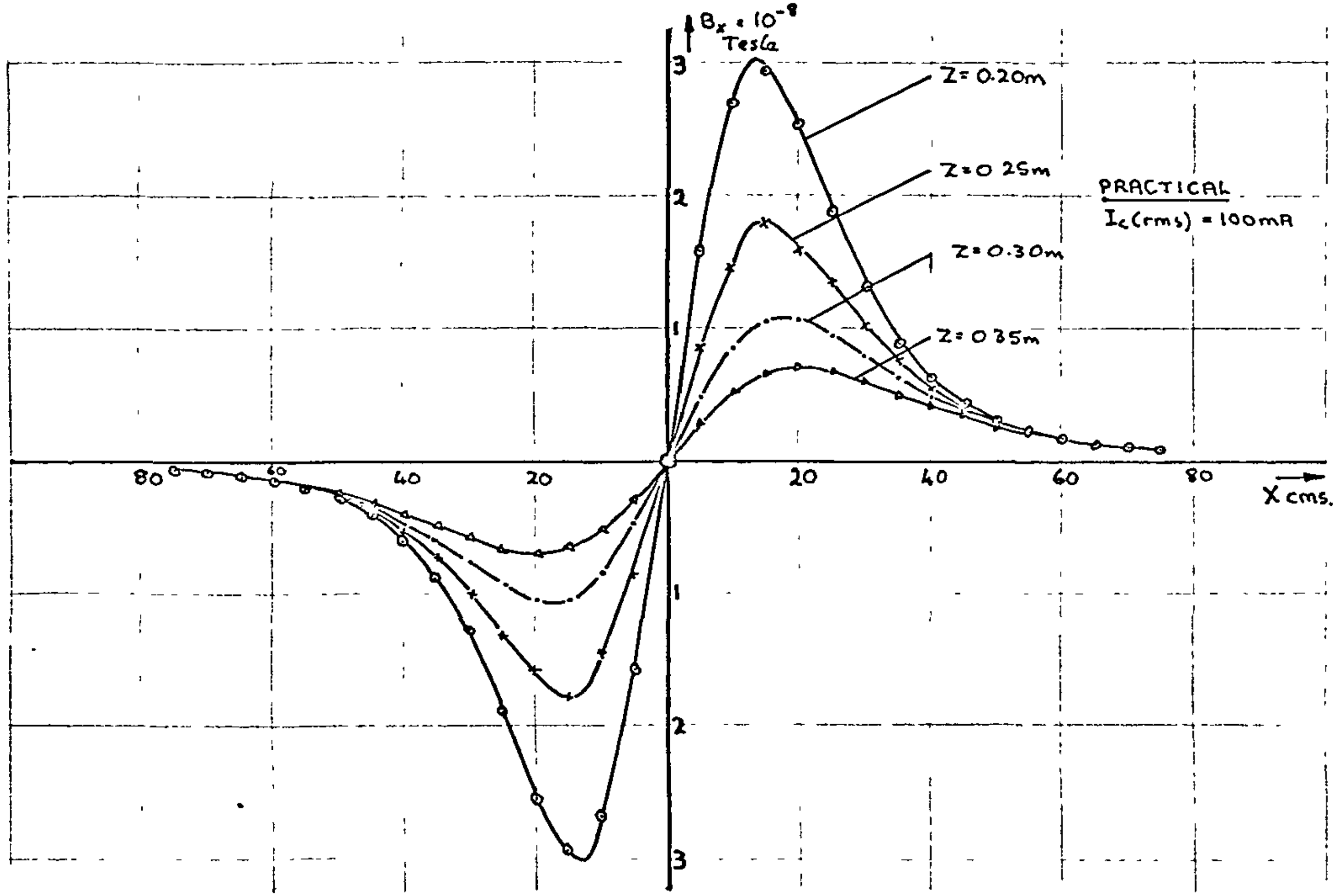


Fig 24. Variation of B_x with Height above a 9"x' (Single Turn).

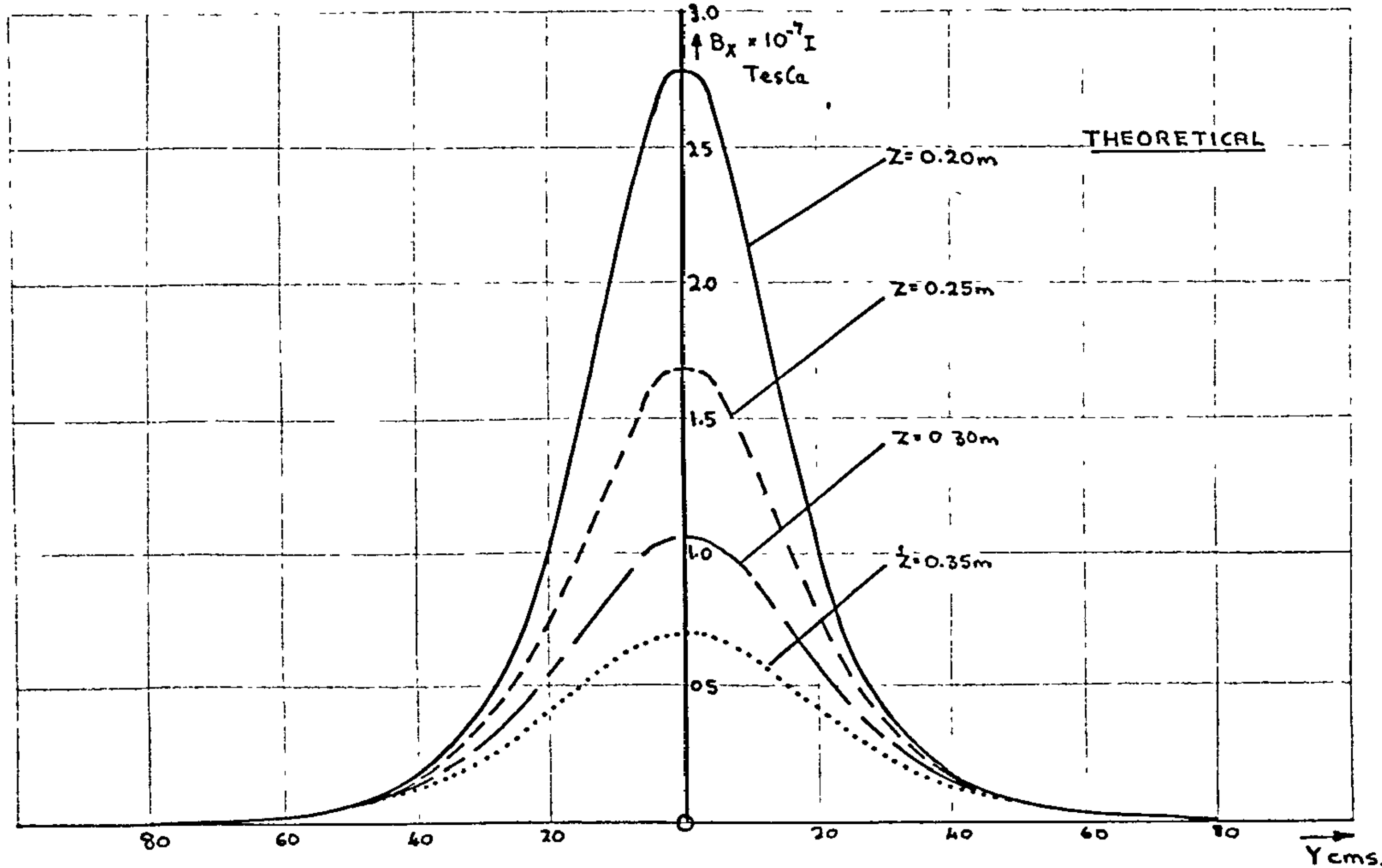


Fig. 25. Variation of B_x with Height above a 9" x 7" Coil (Single Turn).

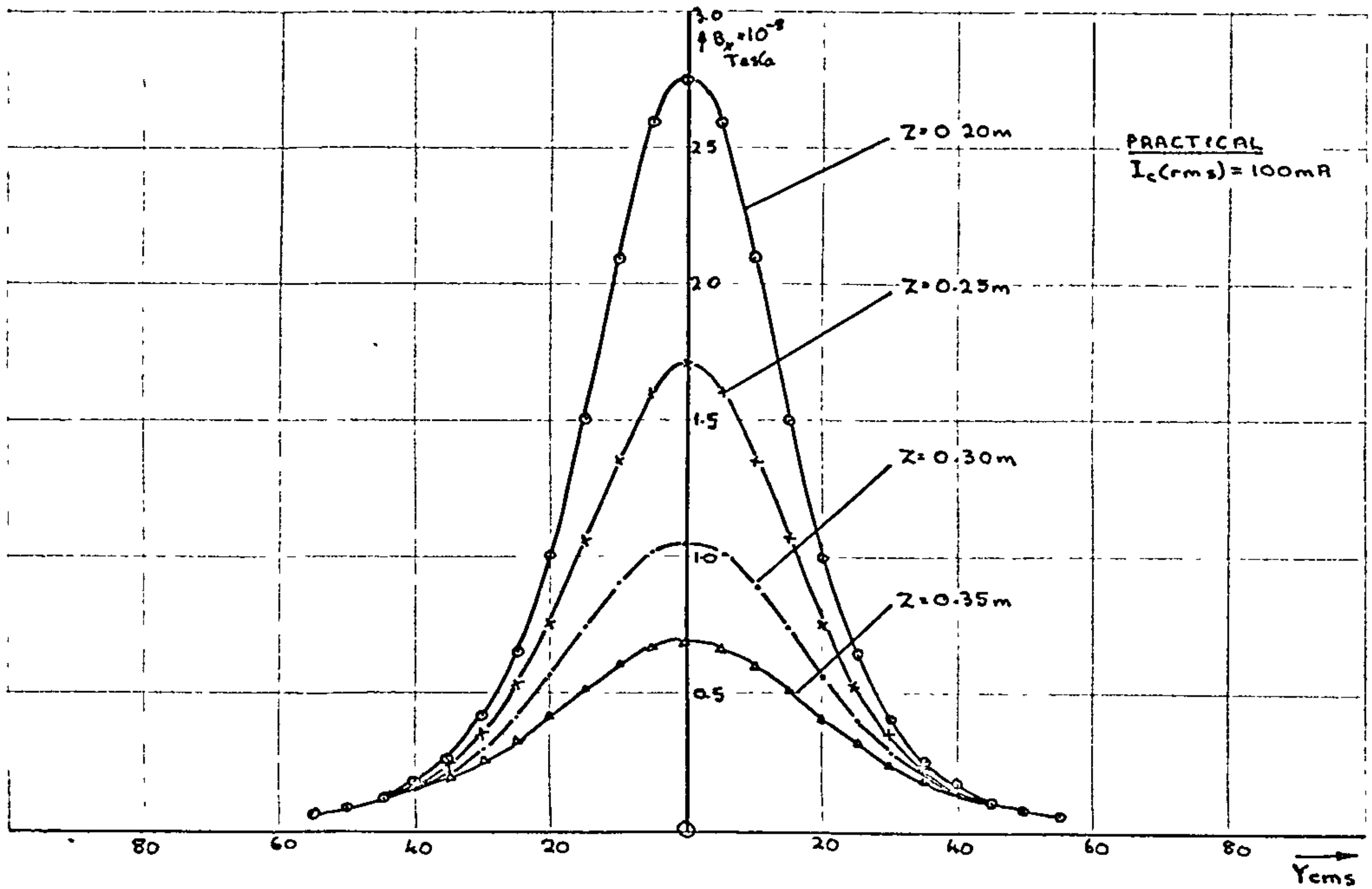


Fig. 26. Variation of Bx with Height above a 9"x7" Coil (Single Turn).

For the first coil examined both theoretical and practical curves are given but for the remainder only the practical curves are shown. Throughout all the investigations theoretical and practical results agreed to within 4%, the greatest error occurring on the steep slopes of the curves and at low flux densities. Because of the restriction on the position of the train pick-up coil the measurements were restricted to heights of 0.20, 0.25, 0.30 and 0.35 metres above the coil. All the coils consisted of only one turn of wire, the rms value of current in the coil in each case was 100 mA.

4.1 Investigation of Field Components from Coils Lying Flat on the Sleeper.

4.1.1 Rectangular, 9" x 7", Coil.

Figures 19 and 20 show the effect of height above the coil on the B_z - Y variations. These are very similar to the plots obtained for the original B.R. four turn, 9" x 7" coil, as should be expected. One interesting fact from these curves is that the curve for Z = 0.25 m. has a zero at about 0.38 m . from the coil centre - half way between adjacent coils - and hence gives a higher value of R_z. The field pattern for the B_z - X variations is very similar to the above. As can be seen from the graphs, by a suitable choice of Z, one phase of the B_z signal can be made predominant and hence it is of use for phase comparison purposes.

The B_y - Y variations with Z are given in figs. 21 and 22. This variation contains equal portions of both phases as the coil is traversed and hence is of no use for phase comparison

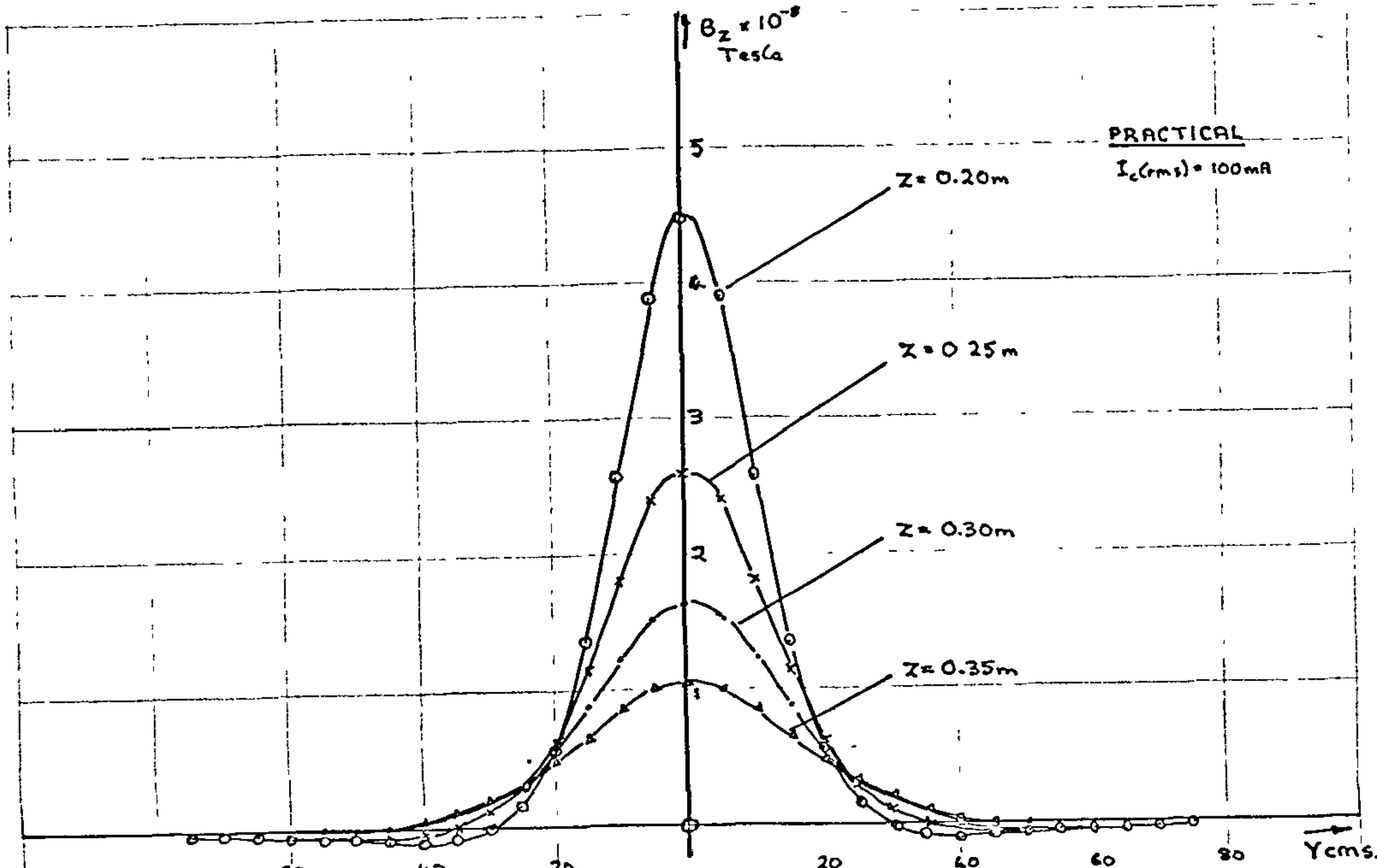


Fig. 27. Variation of B_z with Height above a 9" x 4½" Coil (Single Turn).

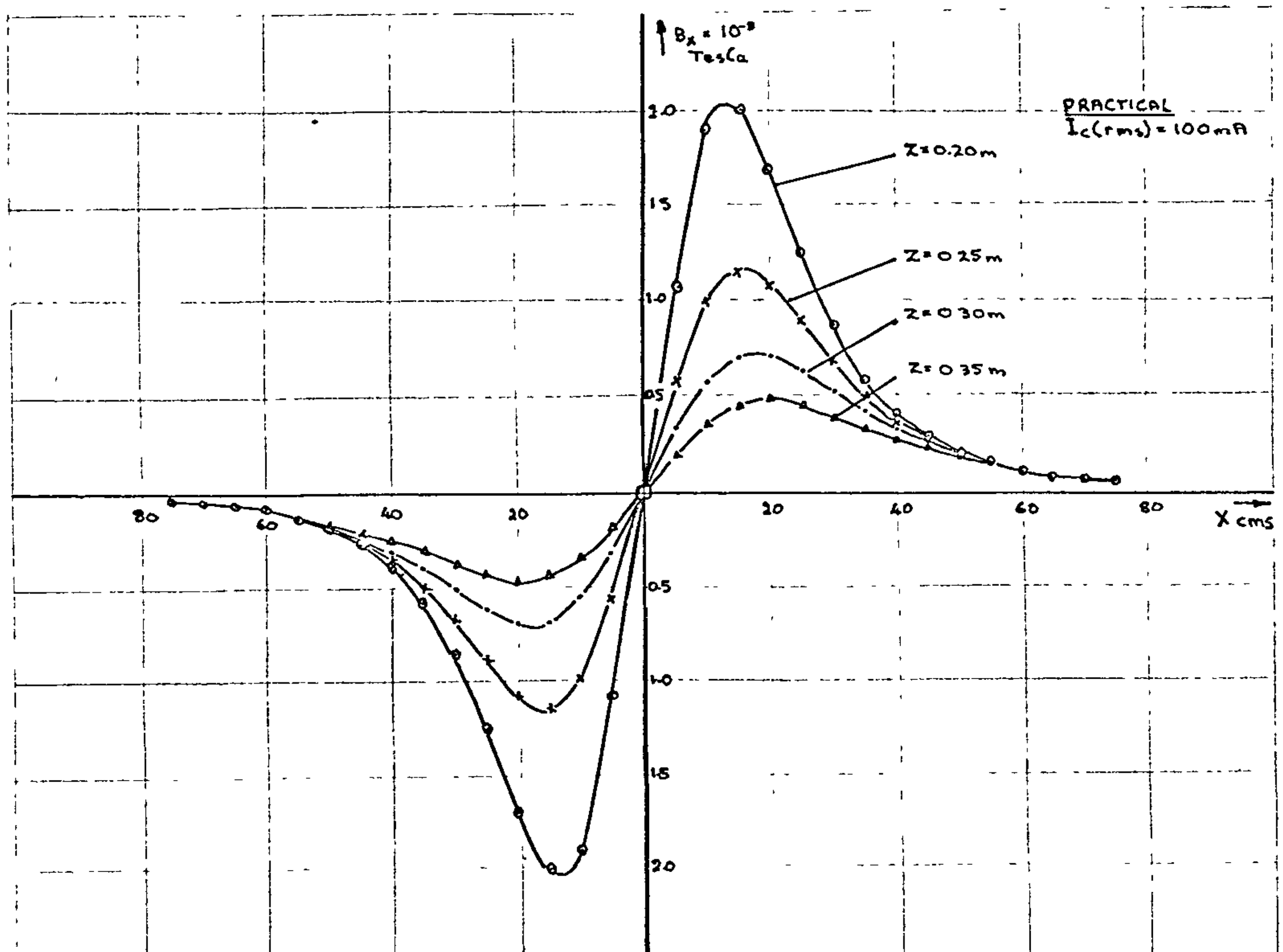


Fig 28. Variation of Bx with Height above a 9" x 4½" Coil (Single Turn).

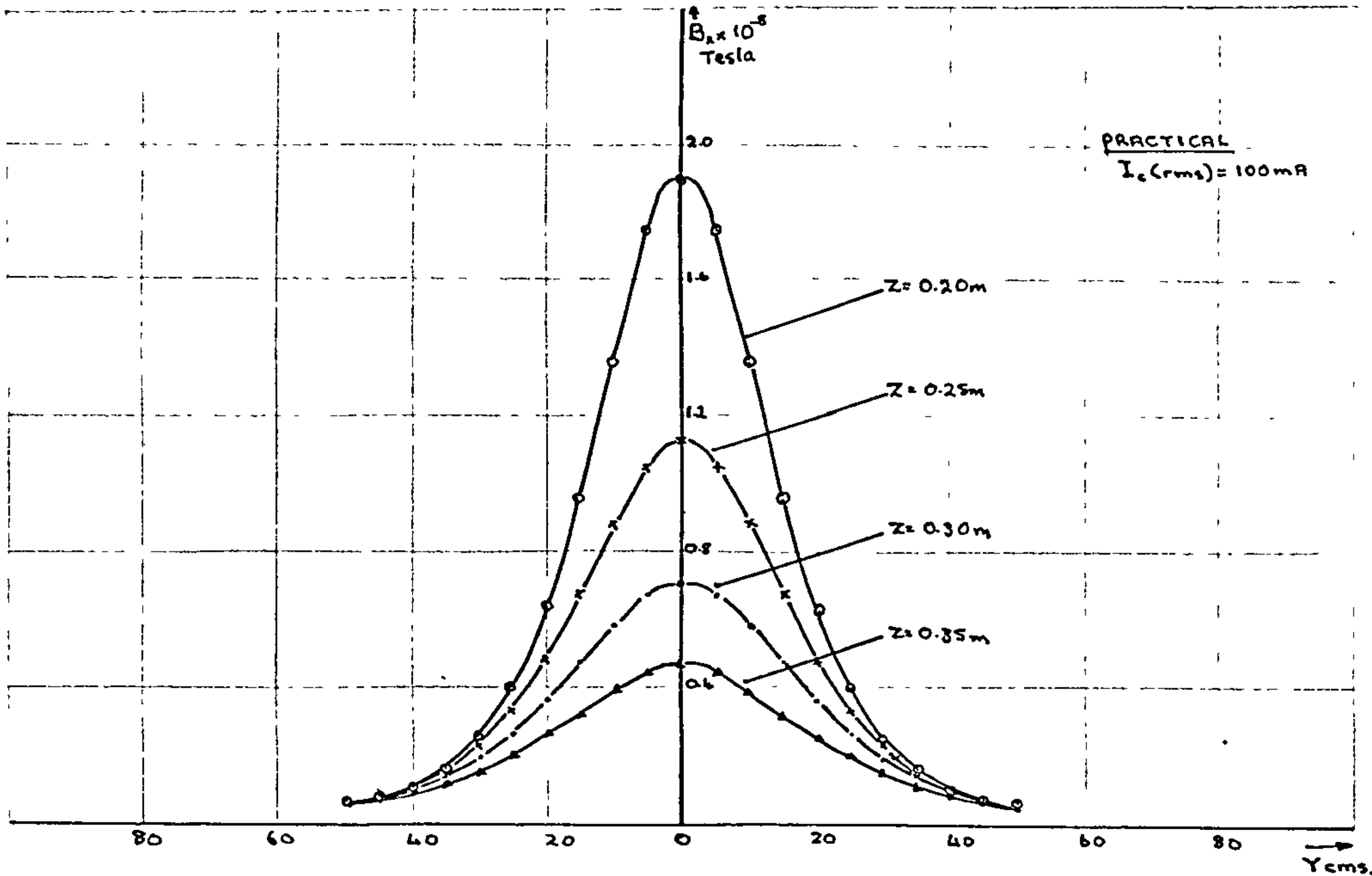


Fig 29. Variation of B_x with Height above a 9" x 4½" Coil (Single Turn).

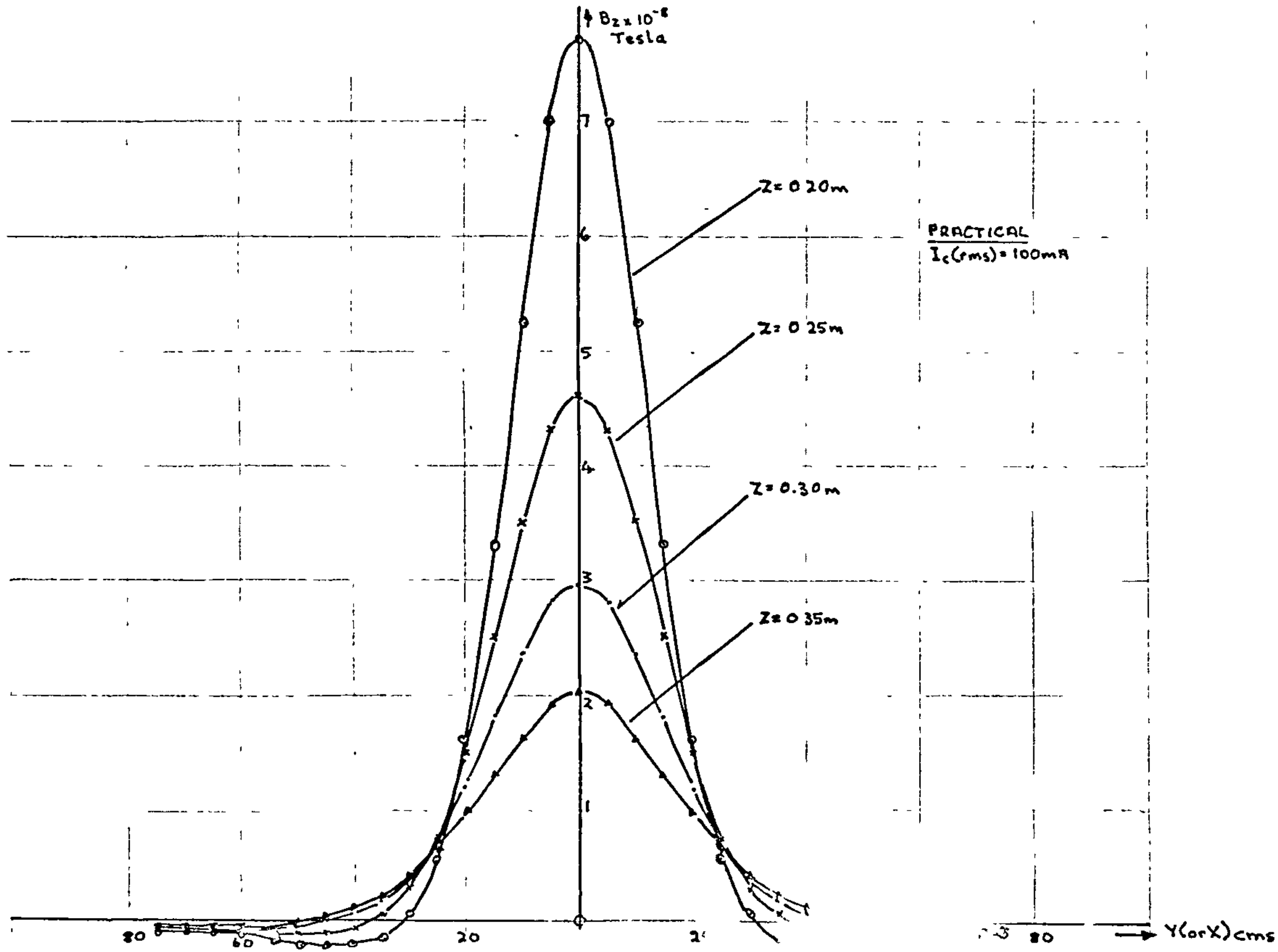


Fig. 30. Variation of B_z with Height above a 9"x9" Coil (Single Turn)

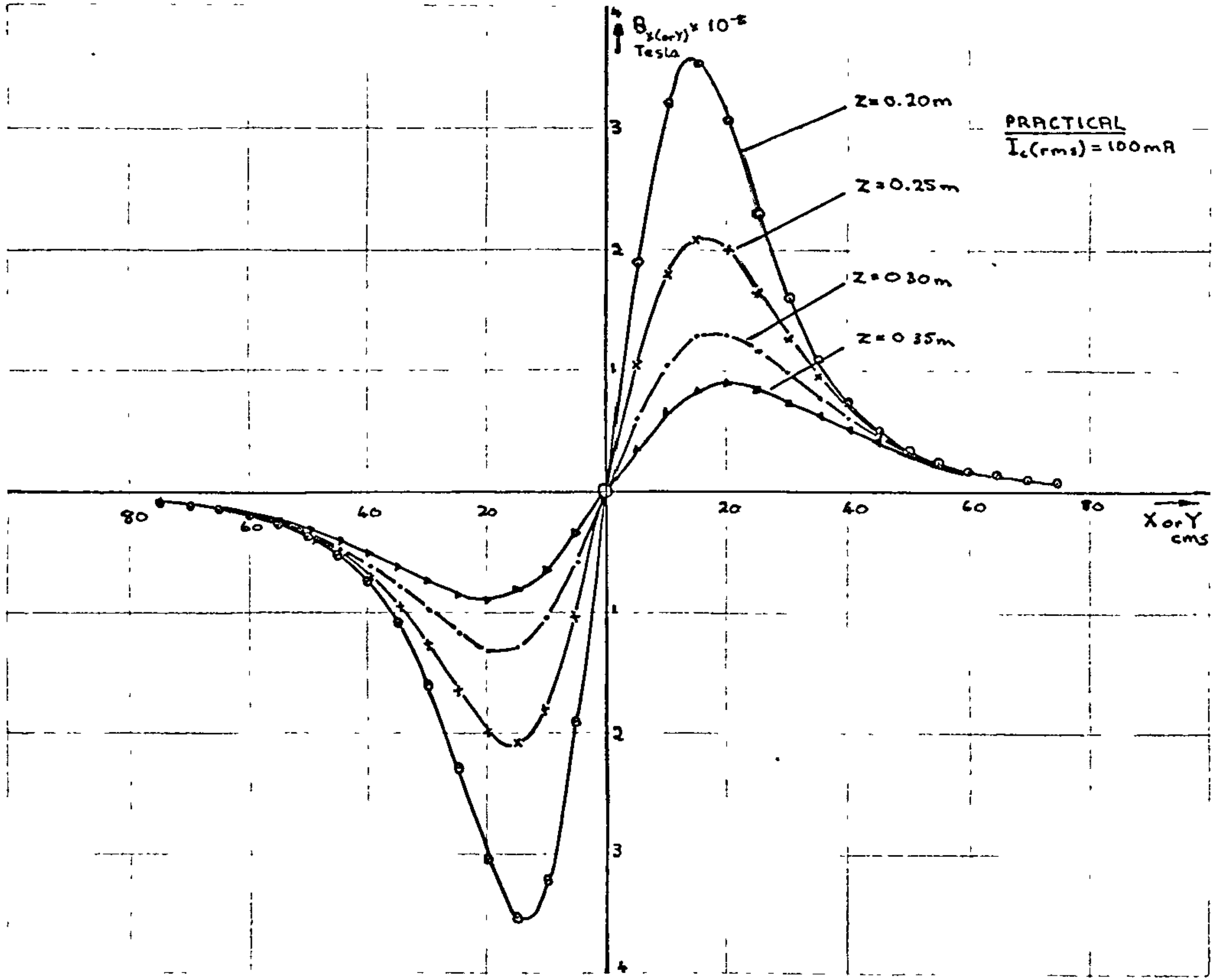


Fig. 31. Variation of B_x (or B_y) with Height above a 9"x9" Coil (Single Turn).

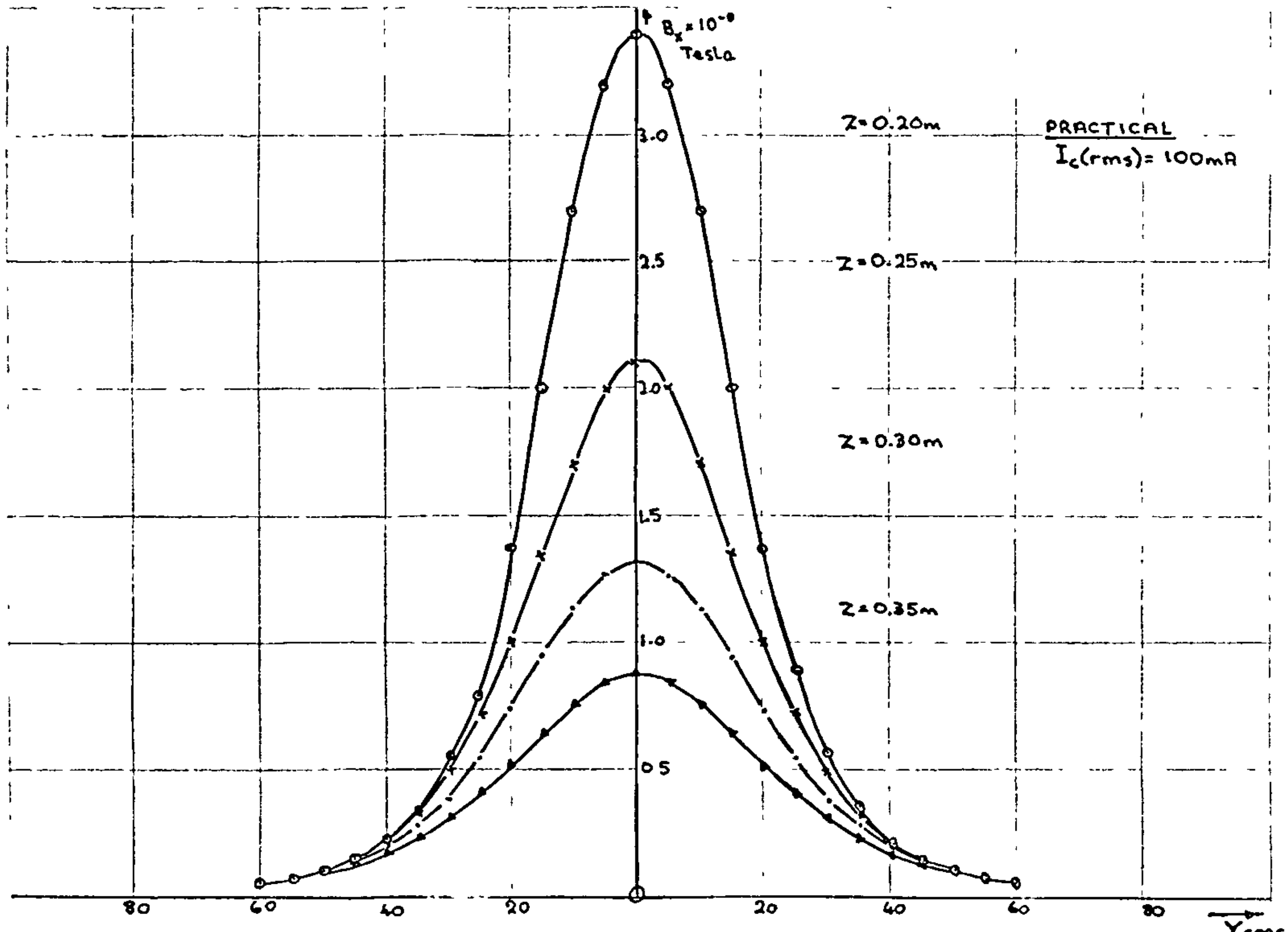


Fig. 32. Variation of B_x with Height above a 9"x9" Coil (Single Turn).

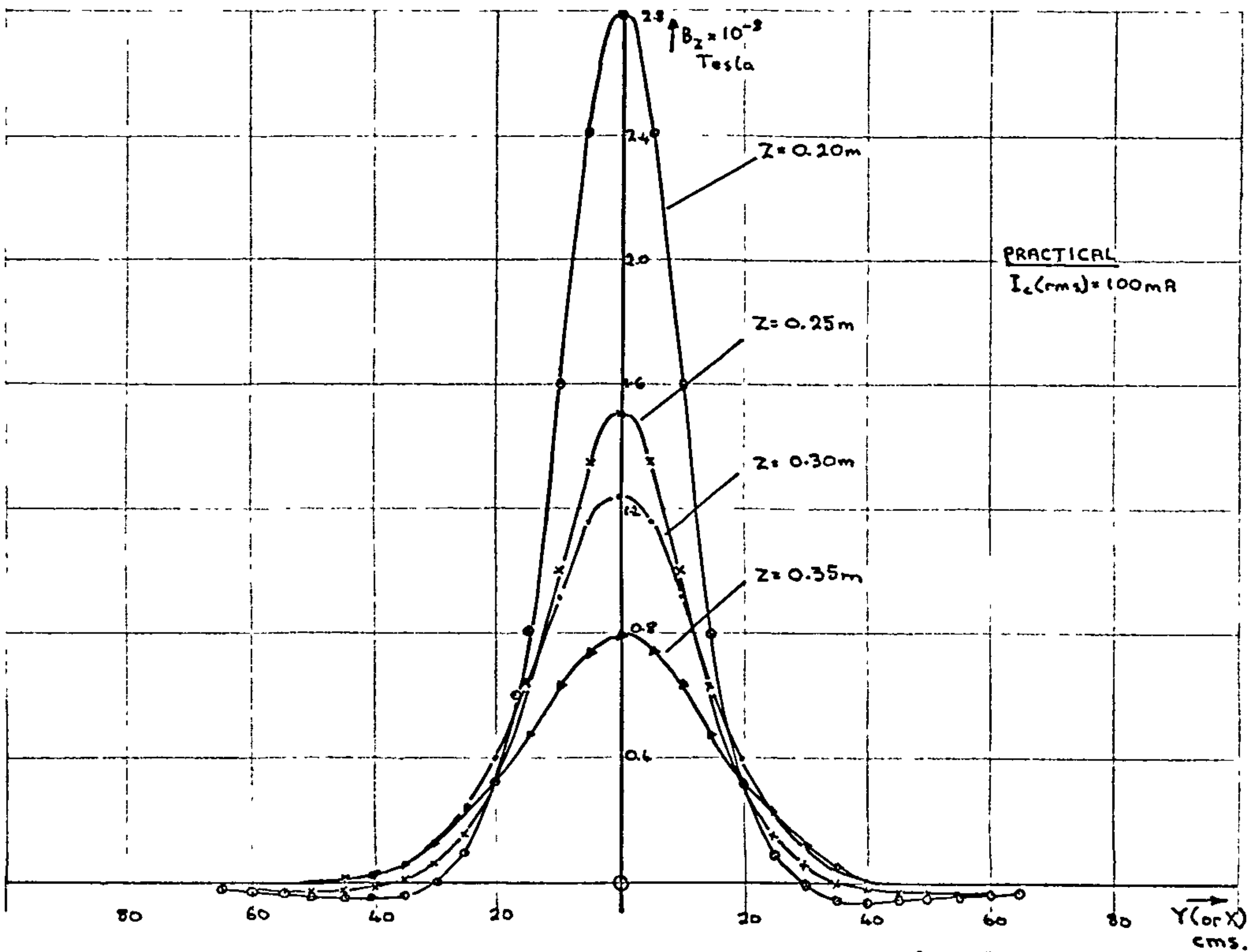


Fig.33 Variation of B_z with Height above a 4½" × 4½" Coil.

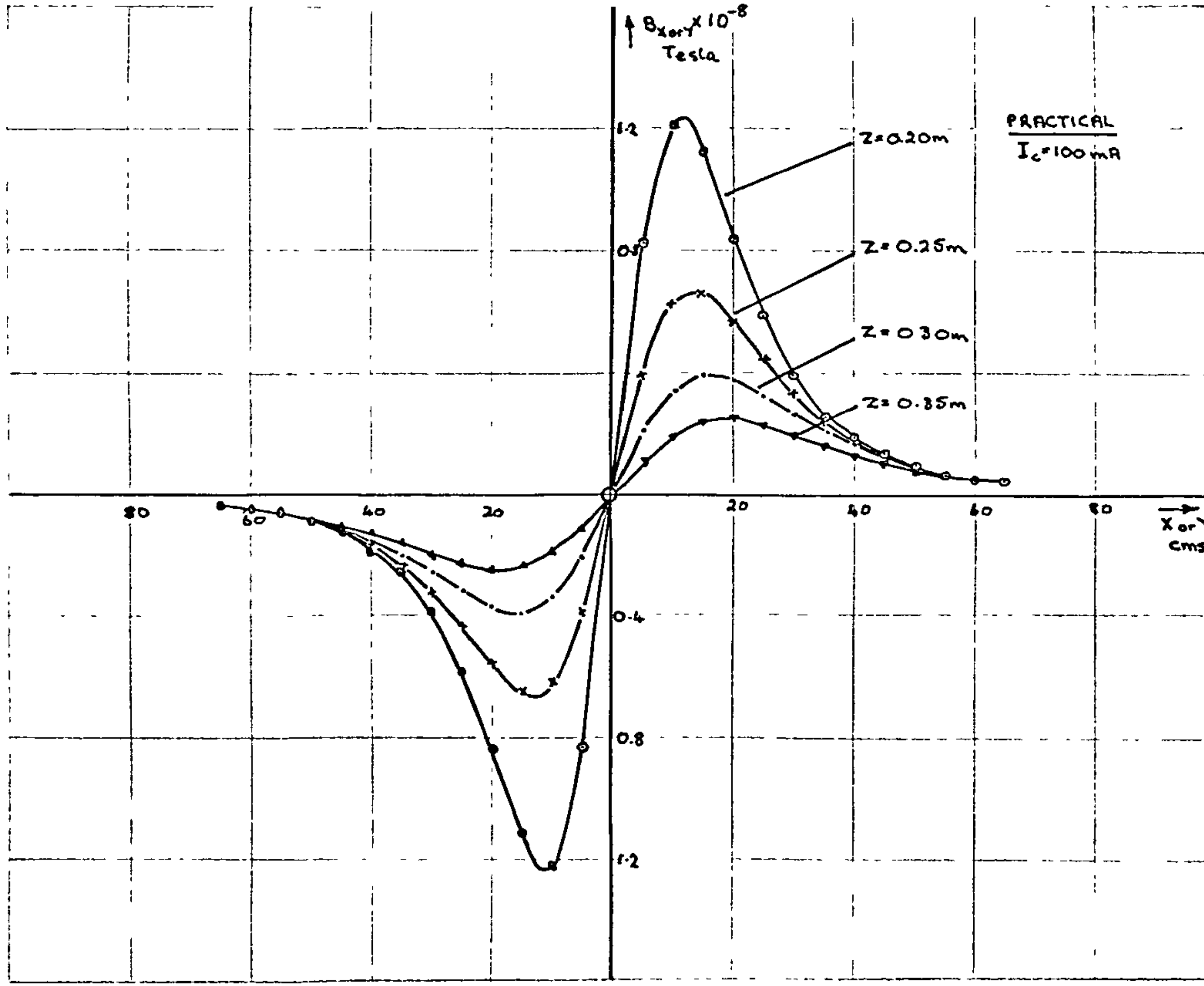


Fig. 34. Variation of B_x (or B_Y) with Height for a 4½" x 4½" Coil (Single Turn).

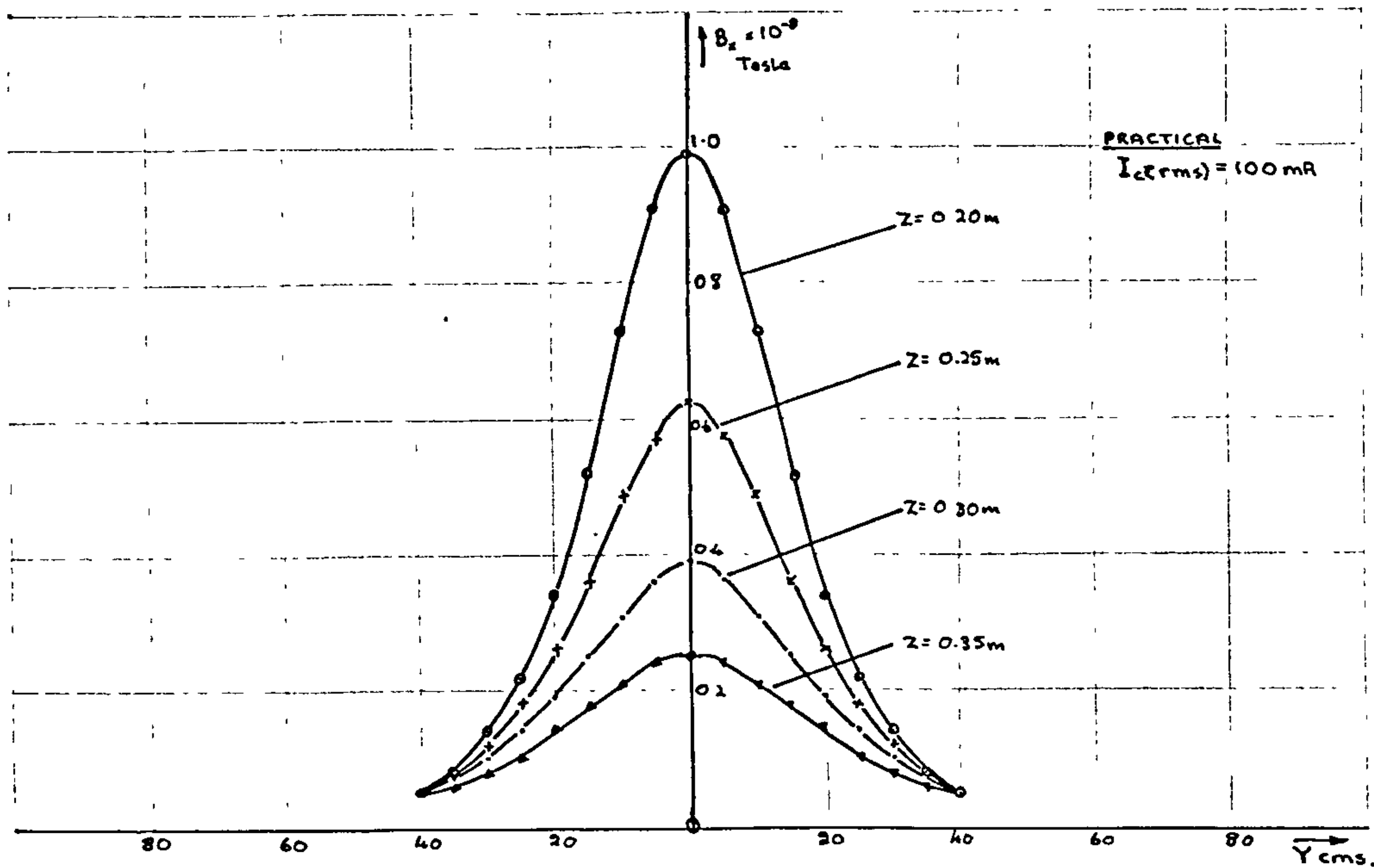


Fig. 35. Variation of B_x with Height above a 4½" × 4½" Coil (Single Turn).

purposes. The B_y - X variations are similar to the B_x - Y variations as given in figs. 25 and 26 and as discussed below.

The B_x - X variations are shown in figs. 23 and 24 and show that, by moving from one side of the coil to the other perpendicular to the direction of motion (i.e. Y), a phase change occurs. Figures 25 and 26 show the B_x - Y variation for positive values of X (for these curves X = 0.175 m.) and, as it is of one phase only, it is of use for phase comparison purposes. The same curves result for the B_x - Y variations for negative X but are of opposite phase.

4.1.2 <u>Rectangular, 9" x 4½", Coil.</u>

The plots of field patterns for this coil (figs. 27, 28 and 29) are similar in shape to those of the 9" x 7" coil. No curves are given for the B_y - Y and B_y - X variations but these are similar to figs. 28 and 29.

4.1.3 <u>Square coils - 9" x 9" and 4½" x 4½".</u>

Again the pattern of the field components are similar to those discussed above. As the coil is symmetrical, the B_z - Y variation is identical with the B_z - X variation as are also B_y - Y with B_x - X and B_y - X with B_x - Y. Because of the larger dimensions of the 9" x 9" coil the flux densities are higher than for the 9" x 7" coil. As with the 9" x 4½" coil, measurements of some values of flux densities were not possible because the measuring equipment was not sensitive enough. However, the measurements could have been done by using a higher value of current and then scaling down.

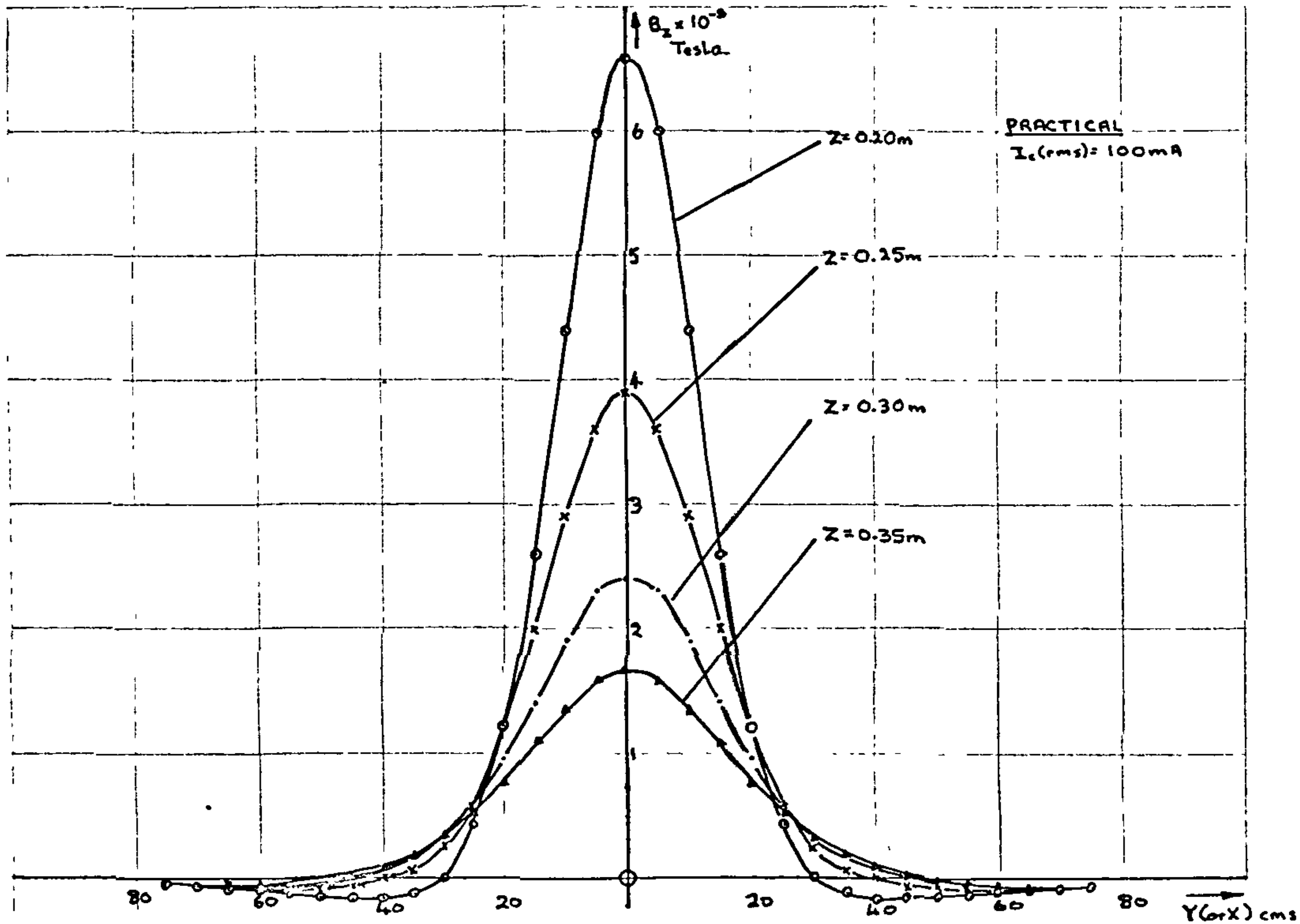


Fig. 36 Variation of B_z with Height above a 9" dia. Coil (Single Turn).

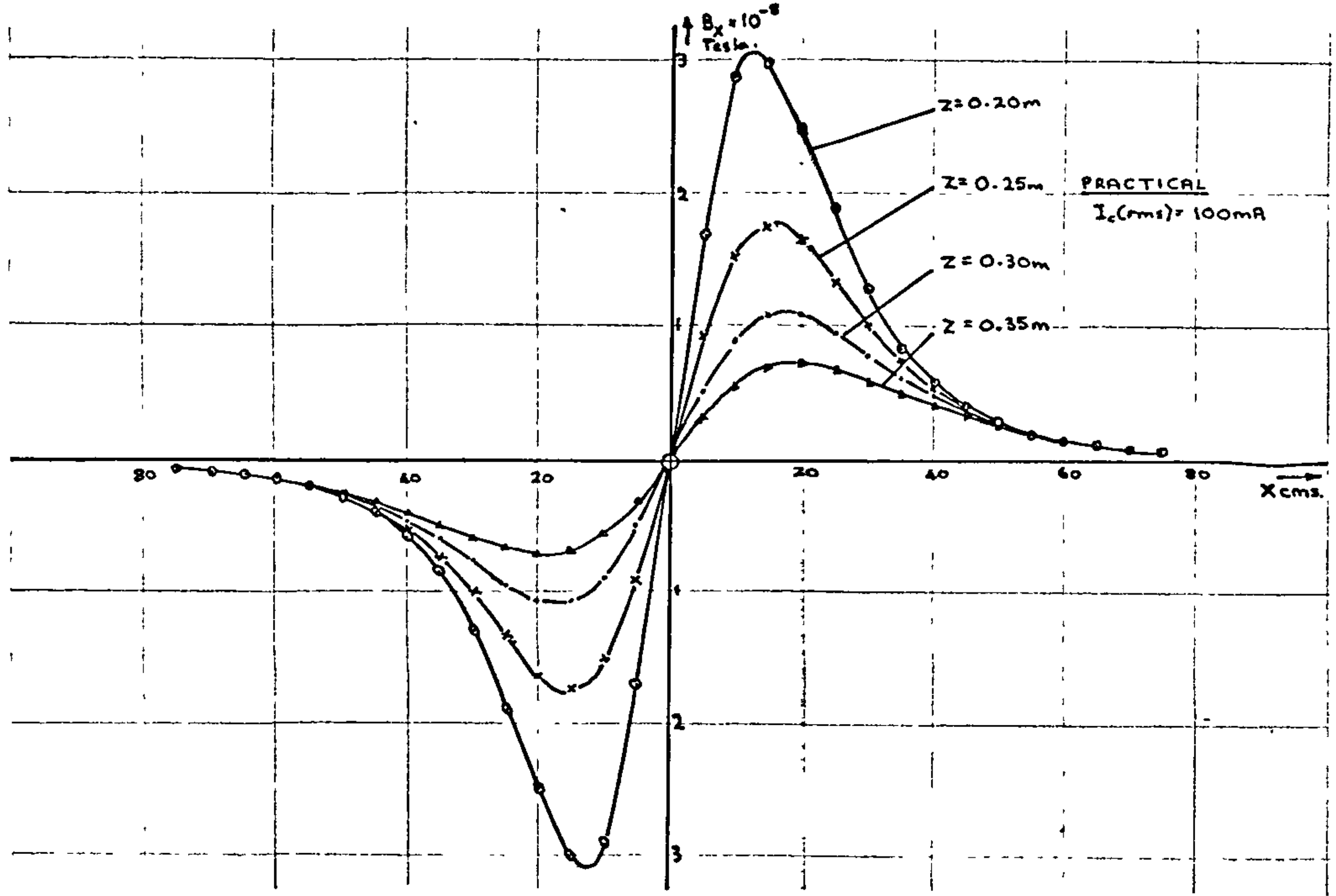


Fig. 37. Variation of B_x with Height above a 9" dia. Coil (Single Turn).

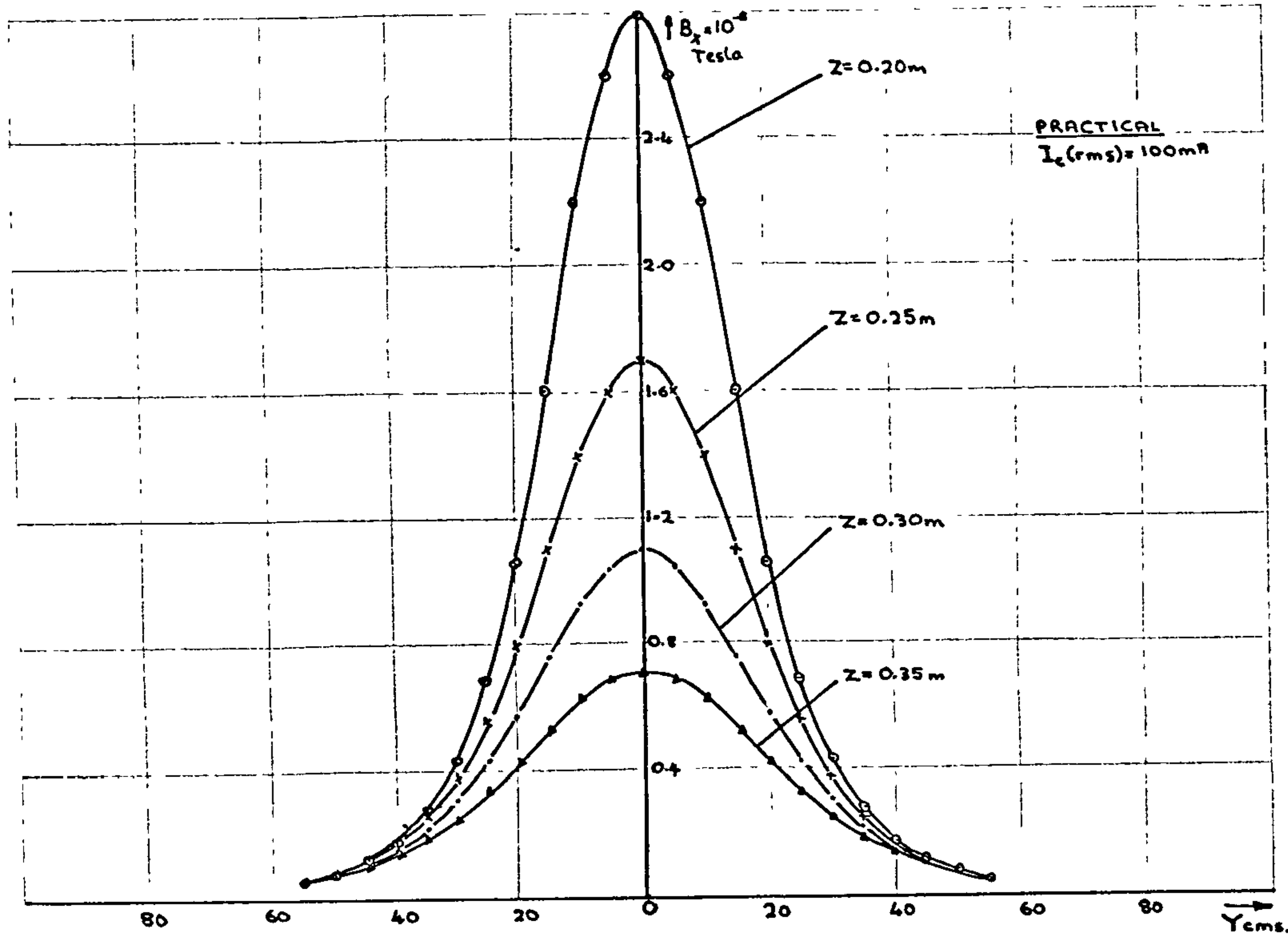


Fig. 38. Variation of Bx with Height above a 9" dia. Coil (Single Turn).

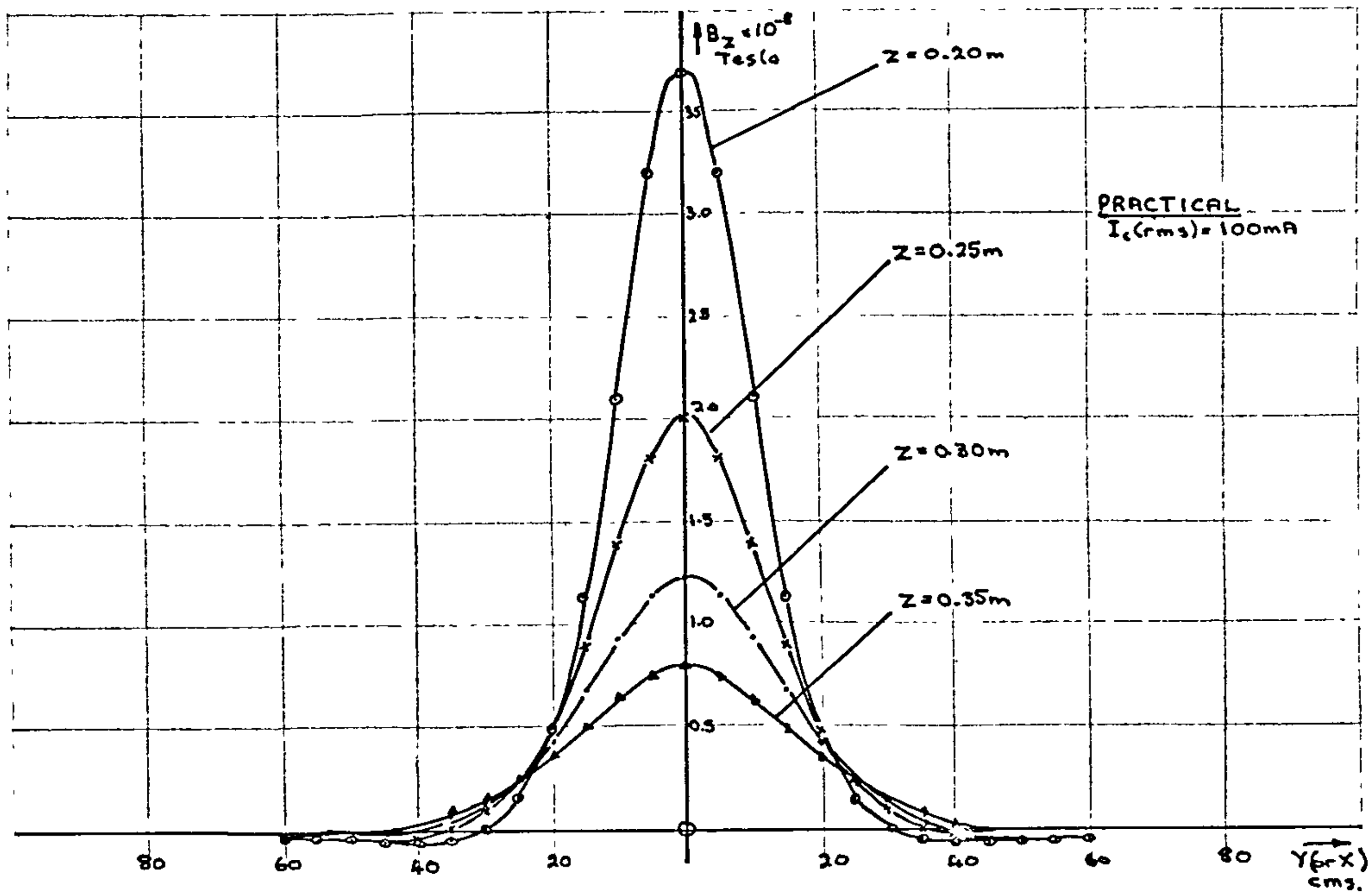


Fig. 39. Variation of B_z with Height above a 6" dia. Coil (Single Turn).

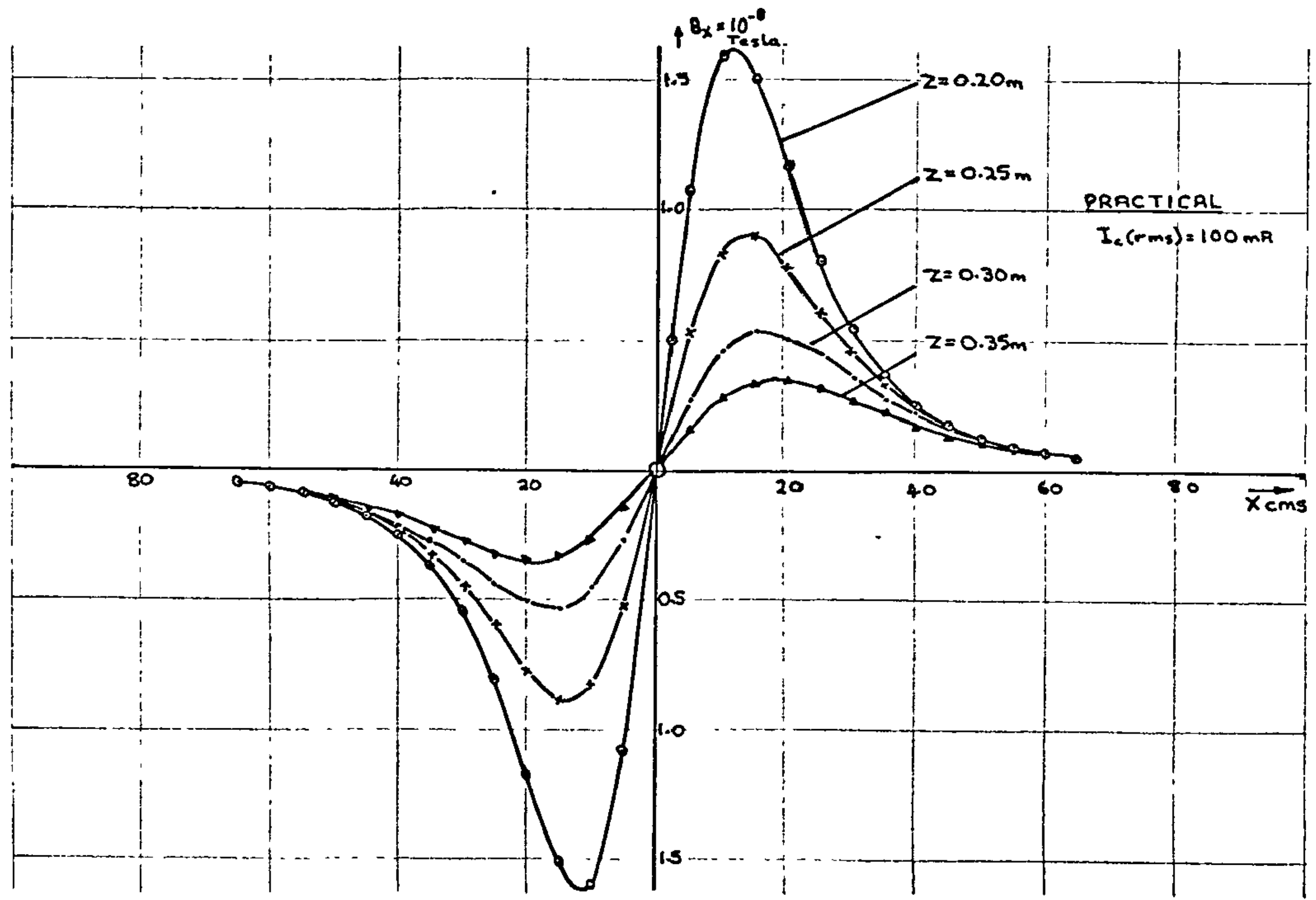


Fig. 40. Variation of B_x with Height above a 6" dia. Coil (Single Turn).

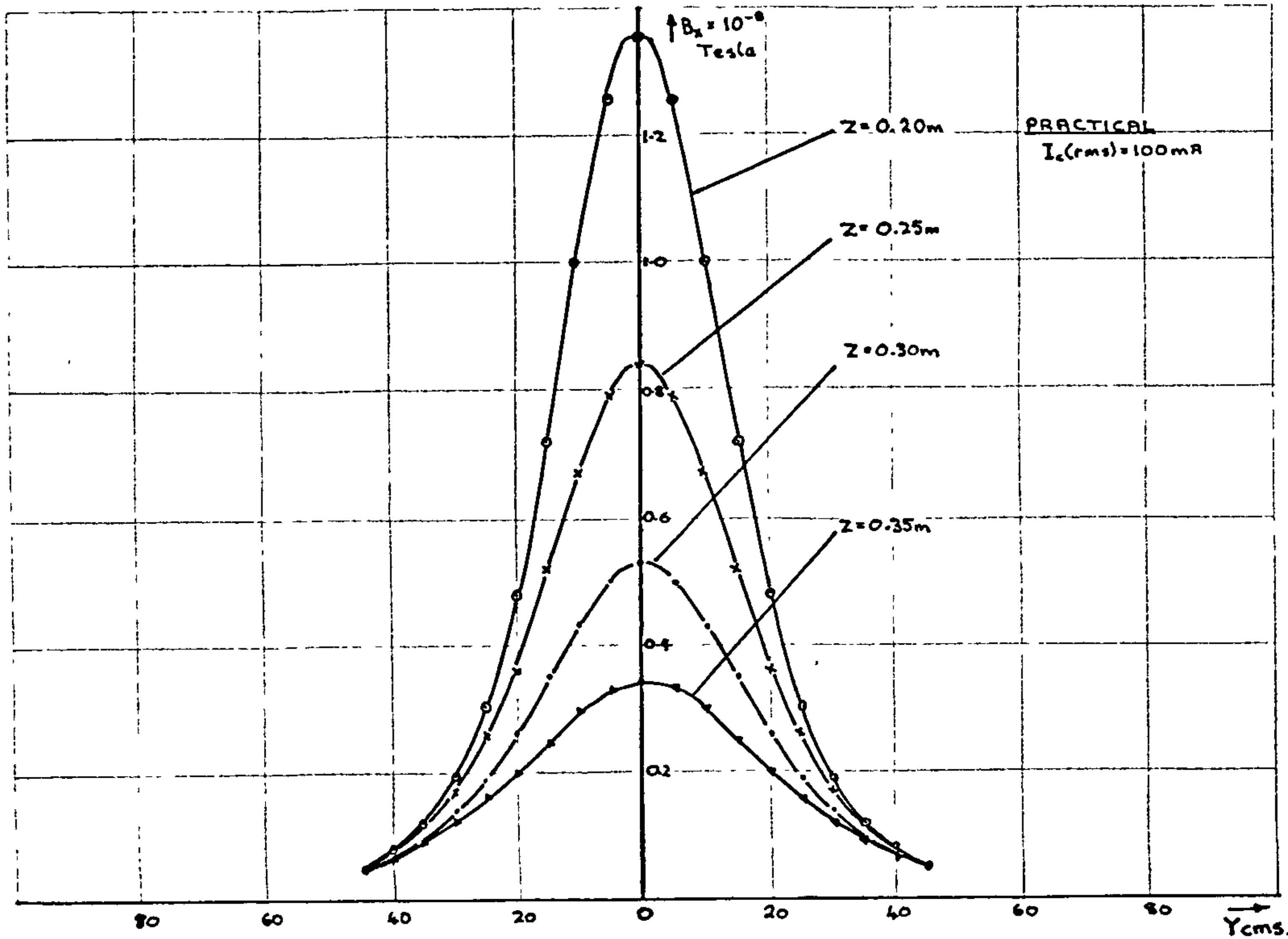


Fig. 41. Variation of B_x with Height above a 6" dia. Coil (Single Turn).

4.1.4 Circular Coils.

Two different diameter coils were examined - 9" diameter and 6" diameter. The field patterns obtained from these are much the same as for the rectangular and square coils. Here again, because of symmetry, the B_z - Y variation is identical with B_z - X, B_y - Y with B_x - X and B_y - X with B_x - Y.

The B_z - Y variation for the 9" diameter coil, fig. 36, also gives an increased value of R_z for Z = 0.25 m. as there is a zero in the field pattern at a position approximately midway between adjacent coils. The flux density at a given height Z above the coil is greater than that from the 9" x 7" coil and the circumference of the circular coil is less than the perimeter of the rectangular coil (28.25" compared with 32") thus representing a saving of over one foot of wire per four turn coil. A circular coil also does not have the disadvantage of sharp corners around which the wire is wound. The 9" diameter coil would therefore seem to be superior to the rectangular 9" x 7" coil, the only disadvantage being a slight decrease in R_z'.

The B_x - X and B_x - Y variations together give field variations suitable for phase comparison purposes as before.

4.2 Investigation of Field Components from Tilted Coils Lying on the Sleeper.

From the previous plots of components of magnetic flux density it can be seen how similar the field patterns are from rectangular and circular coils of varying dimensions. Because of this similarity, only the field patterns from one size and shape of tilted coil were examined - a circular coil of 9"

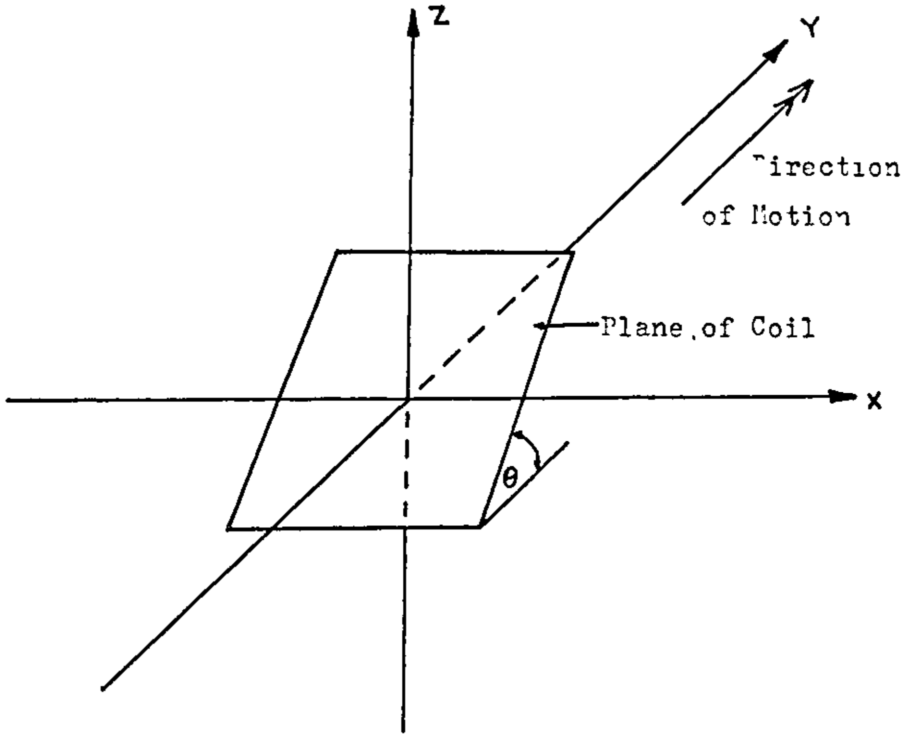


Fig. 42 . One Arrangement for a Tilted Coil.

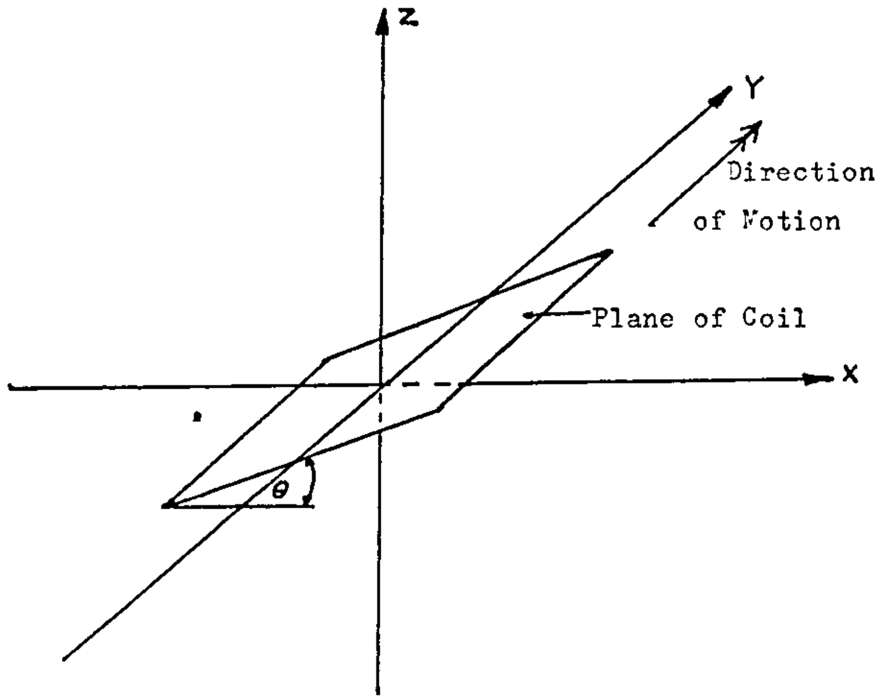


Fig. 43 . Second Arrangement for a Tilted Coil.

diameter (0.228 m) and consisting of a single turn of wire. A maximum angle of tilt of 45° (see figs. 42 and 43) was used. Angles greater than this causing the coil to protrude above rail head level and making it even more susceptible to damage by railway maintenance staff and tamping machines. For angles of tilt between 0° and 45° the field patterns will be intermediate between those shown for flat and tilted coils. The relevant theory is given in appendix 4 and shows how the new field components are a function of the field components from flat coils. The field patterns produced clearly show this property.

Figures 44 to 48 show the field patterns for the coil arrangement depicted in fig. 42. Any other arrangement for the coil tilted at 45° results in curves the same as before but the axes will be interchanged and some phases reversed. As the coil is tilted at 45°, and is 9" (0.228 m) diameter, it will have a height above sleeper level of about 6.35" (0.16 m). Because of clearances involved measurements of height above the centre of the coil were restricted to 0.20 and 0.25 m. or heights above sleeper level of 0.283 and 0.333 m. respectively.

4.2.1 <u>Coil Tilted as shown in Fig. 42</u>.

The B_z - Y variation for the coil is shown in fig. 44, the B_z - X variation is given in fig. 45. Because of the higher percentage of the opposite phase shown in fig. 44 this field component is of no use for phase comparison purposes. The B_y - Y curves are depicted on fig. 46 and again are of no use for phase comparison purposes. The B_x - X curves are symmetrical about the centre line of the coil, fig. 47, and exhibit equal areas of both phases. Fig. 48 shows the B_x - Y variations for X = 0.125 m. and this field component could be of use for phase comparison purposes.

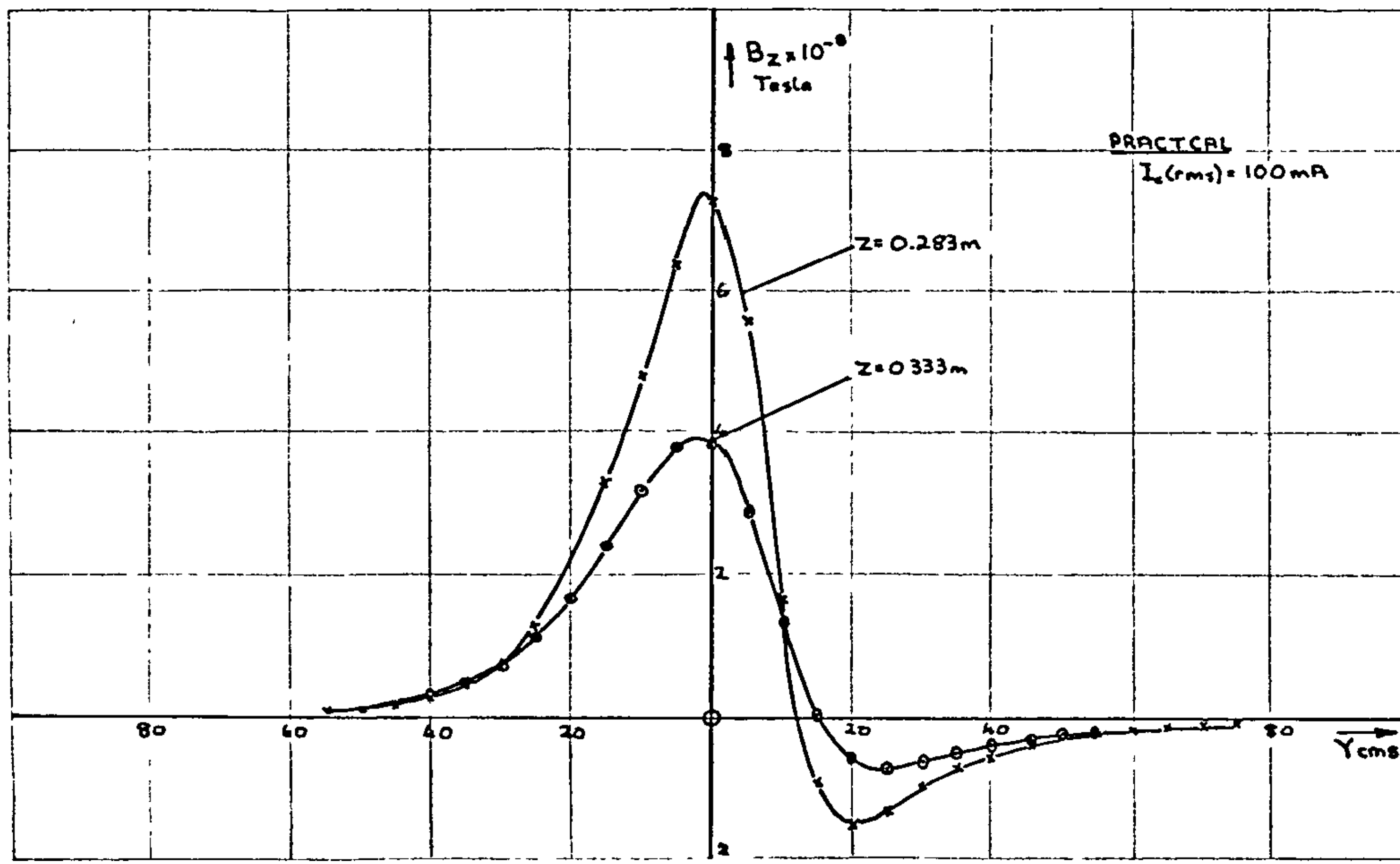


Fig. 44. Variation of B_z with Height above a 9" dia. Coil (Single Turn) Tilted at 45°.

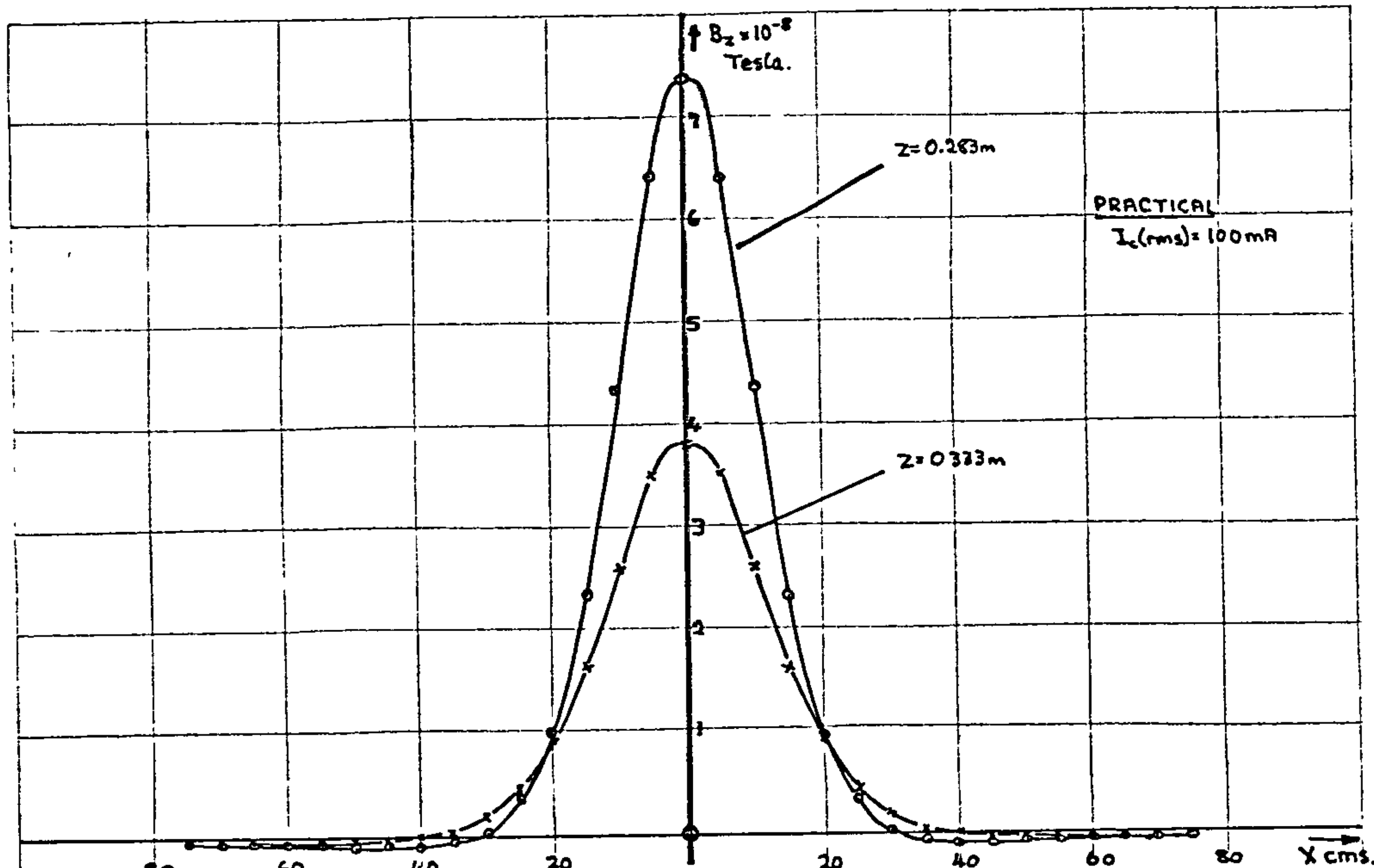


Fig. 45. Variation of Bz with Height above a 9" dia. Coil (Single Turn) Tilted at 45°

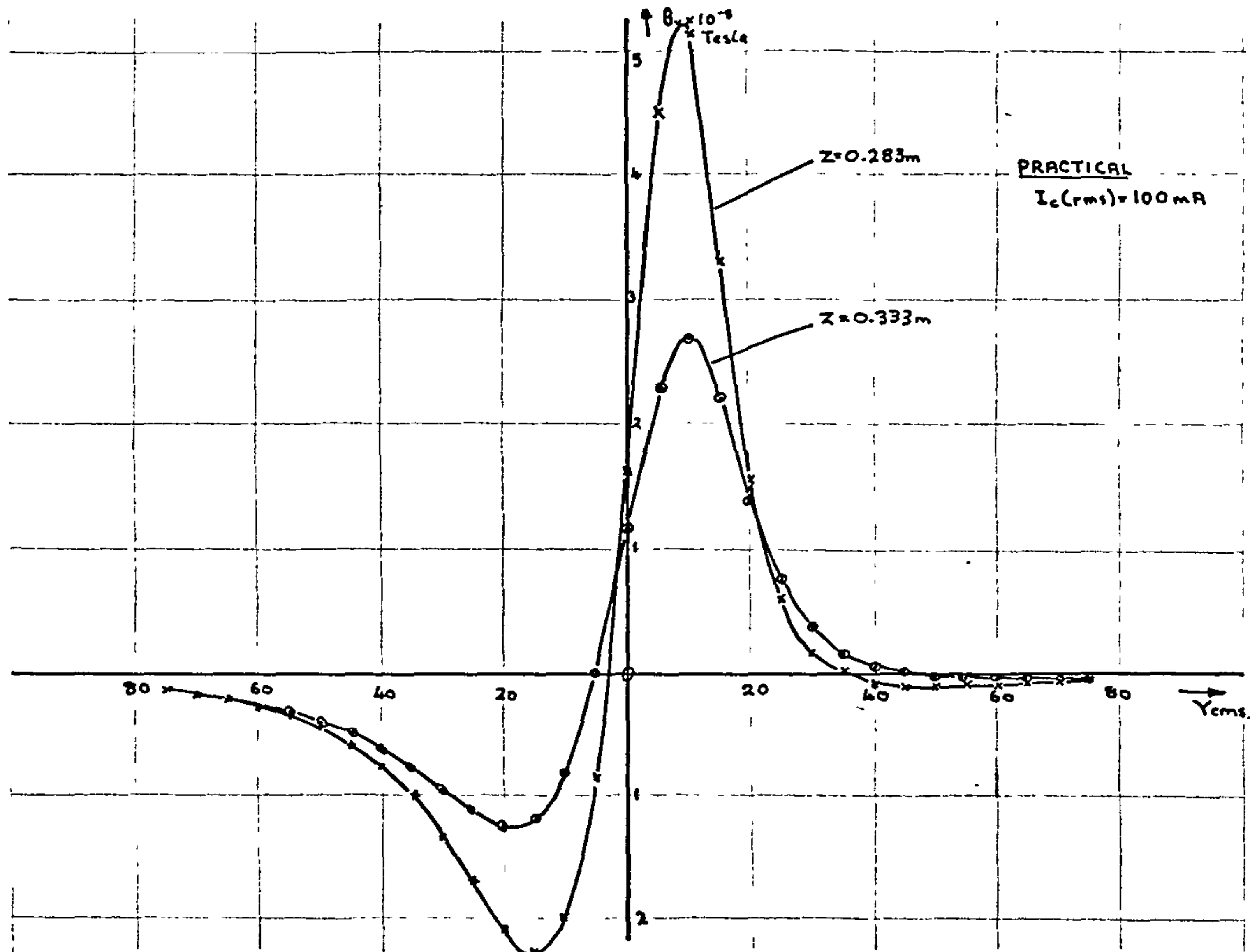


Fig. 46 Variation of B_Y with Height above a 9" dia. Coil (Single Turn) Tilted at 45°.

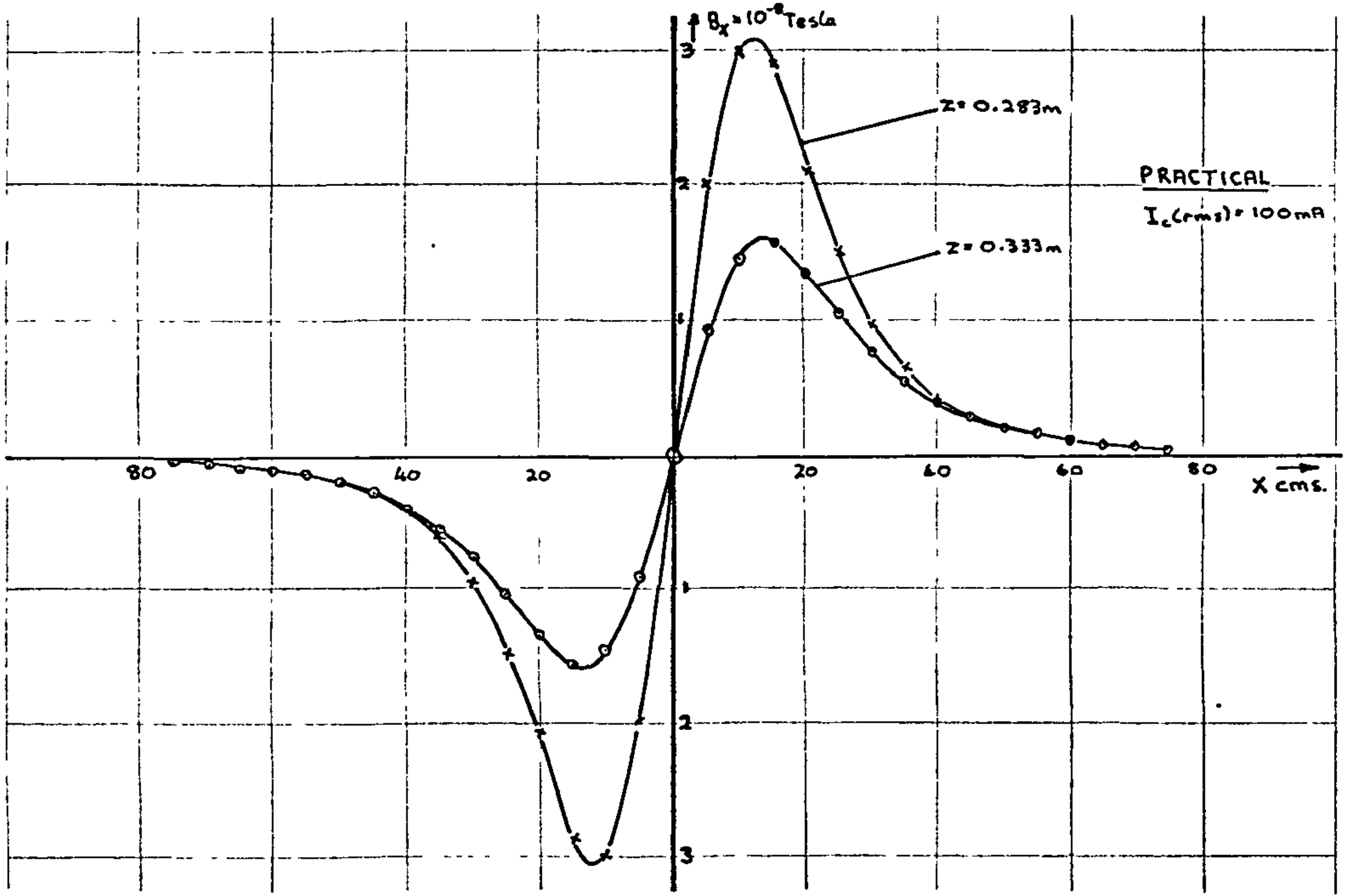


Fig. 47. Variation of B_x with Height above a 9" dia. Coil (Single Turn) Tilted at 45°.

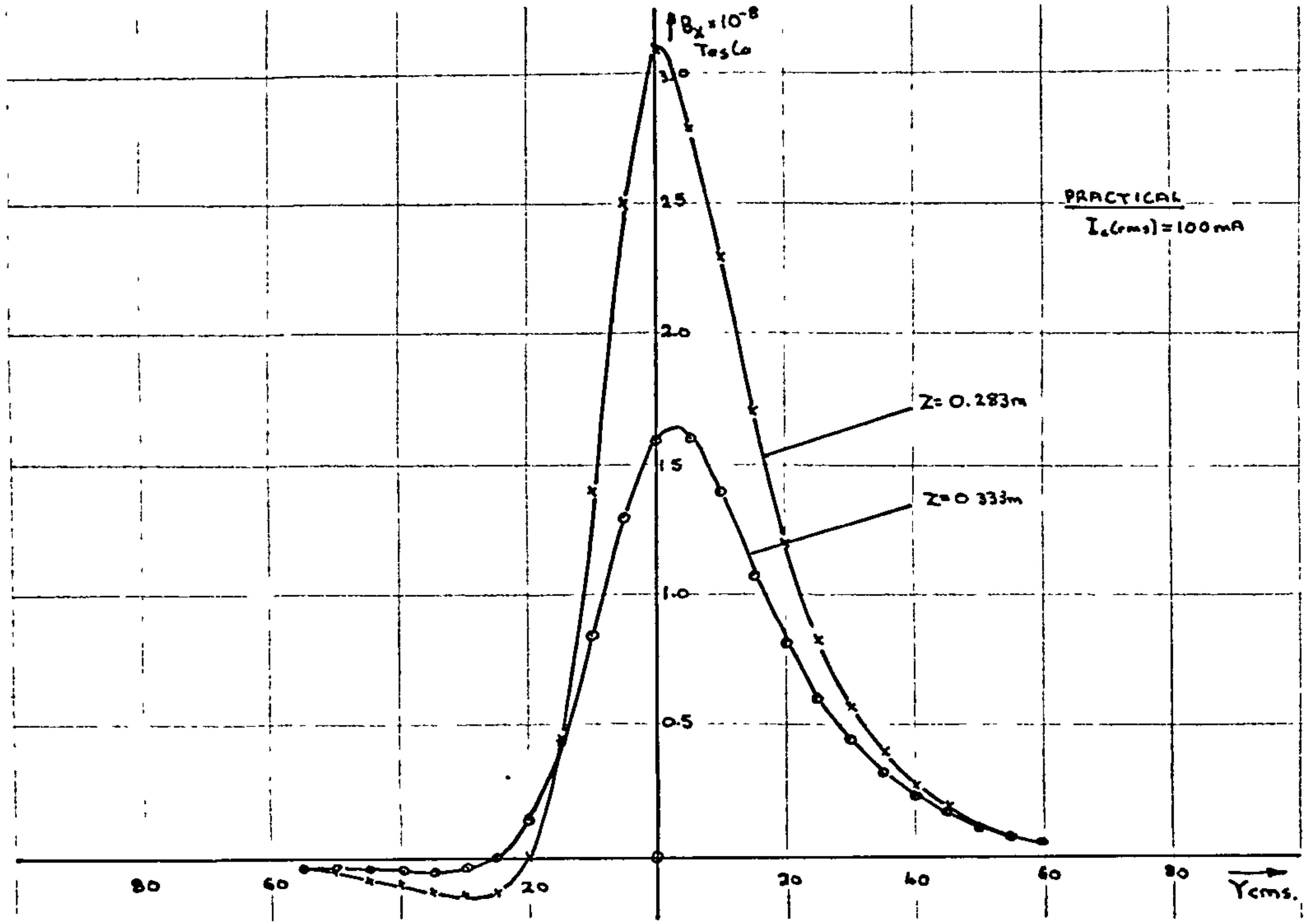


Fig. 48. Variation of B_x with Height above a 9" dia. Coil (Single Turn) Tilted at 45°

Type of Coil	Z metres	R'_z	R'_x
Rectangular Coils	0.20	-19	6.6
9" x 7"	0.25	-76	4.2
(0.228 m x 0.178 m)	0.30	17.8	3.3
	0.35	6.7	2.5
	0.20	-23	7.9
9" x 4½"	0.25	-26	5.6
(0.228 m x 0.114 m)	0.30	16.5	3.2
	0.35	11	2.5
Square Coils	0.20	-21.3	6.8
9" x 9"	0.25	-92	4.2
(0.228 m x 0.228 m)	0.30	14.8	2.9
	0.35	6.7	2.1
	0.20	-25.5	8.2
4½" x 4½"	0.25	-75	5.2
(0.114 m x 0.114 m)	0.30	20.3	3.4
	0.35	13.5	2.4
Circular Coils	0.20	-20.4	6.4
9" diameter	0.25	App. ∞	4.3
(0.228 m dia.)	0.30	16.2	3.3
	0.35	8.3	2.4
	0.20	-26.5	7.6
6" diameter	0.25	-40	4.7
(0.152 m dia.)	0.30	37	3.3
	0.35	12	2.4

Table 3 . Variation of R'_z and R'_x with Different Pick-Up Heights and Various Coil Dimensions.

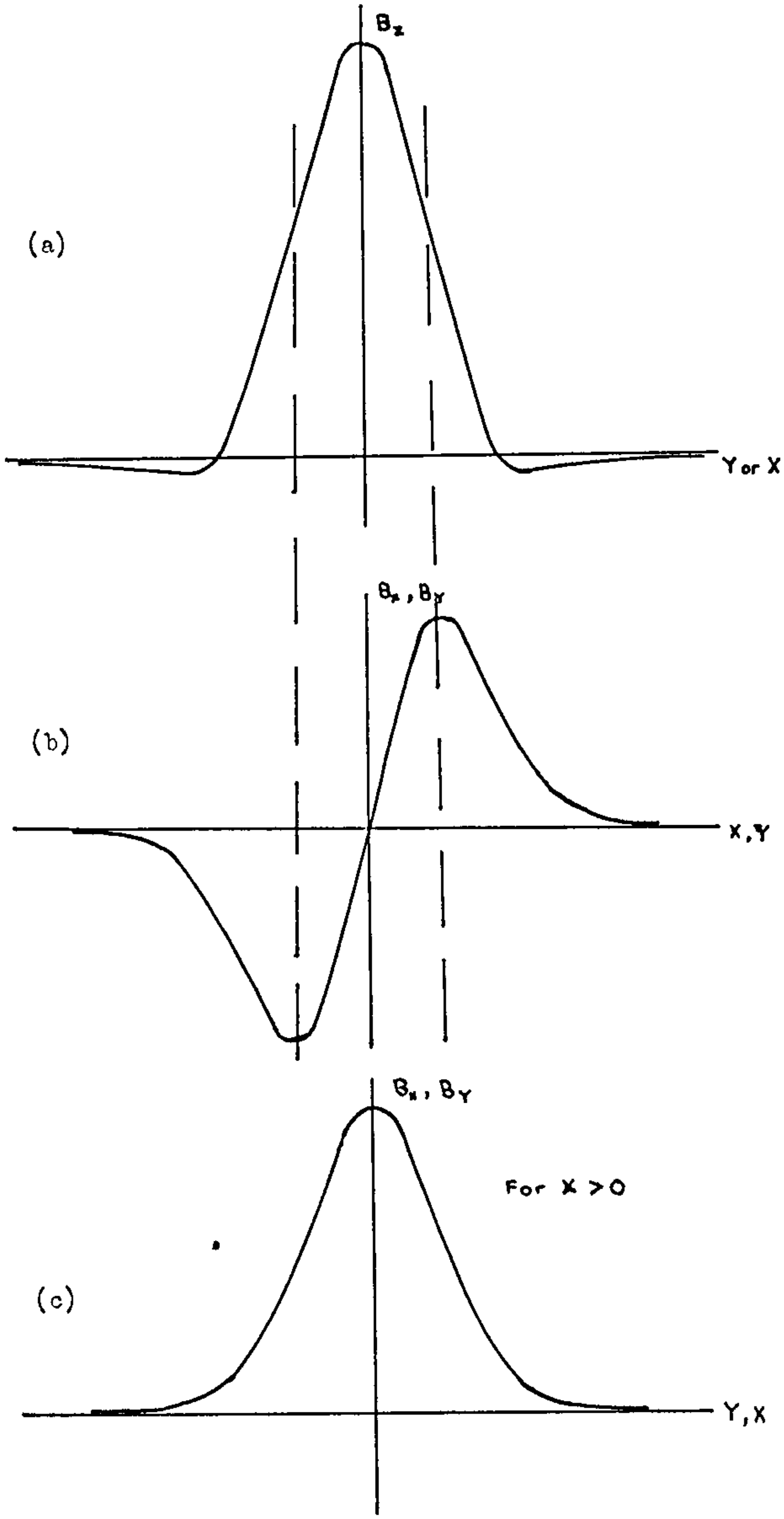


Fig. 49 . Curves Representative of Field Patterns from Coils Lying Flat as Examined.

4.2.2 Coil Tilted as shown in Fig. 43.

Figure 45 now represents the B_z - Y variations and is similar to the B_z - Y curves obtained for a flat coil. These curves could be used for phase comparison purposes. Fig. 47 gives the B_y - Y variations for this arrangement of coil and are of no use for phase comparison. Fig. 46 represents the B_x - X variations (Y = 0).

4.3 A Method for Increasing the Information Capacity of a Telegram Coil.

From the above investigations a possible method emerges of obtaining two bits of binary information from a telegram coil simultaneously. To facilitate the explanation the curves in Fig. 49 have been drawn and are representative of the curves obtained for the coils examined in section 4.1. The following is also applicable to some of the field components obtained from a tilted coil.

Because of the inherent nature of the B_y - Y variations it is of no use for phase comparison purposes. This field component could be of use for error detection on the B_z field component - if B_z changes phase the B_y component reverses its phase sequence. The B_z - Y variation and the variation of B_x - Y with X are suitable for phase comparison purposes and conveying two independent bits of information simultaneously.

The B_z variation with Y or X is similar and is predominantly of one phase, hence conveying only one bit of information. The B_x - X variation reverses phase midway across the coil - fig.49(b) - and results in the B_x - Y variation shown in fig. 49(c) for

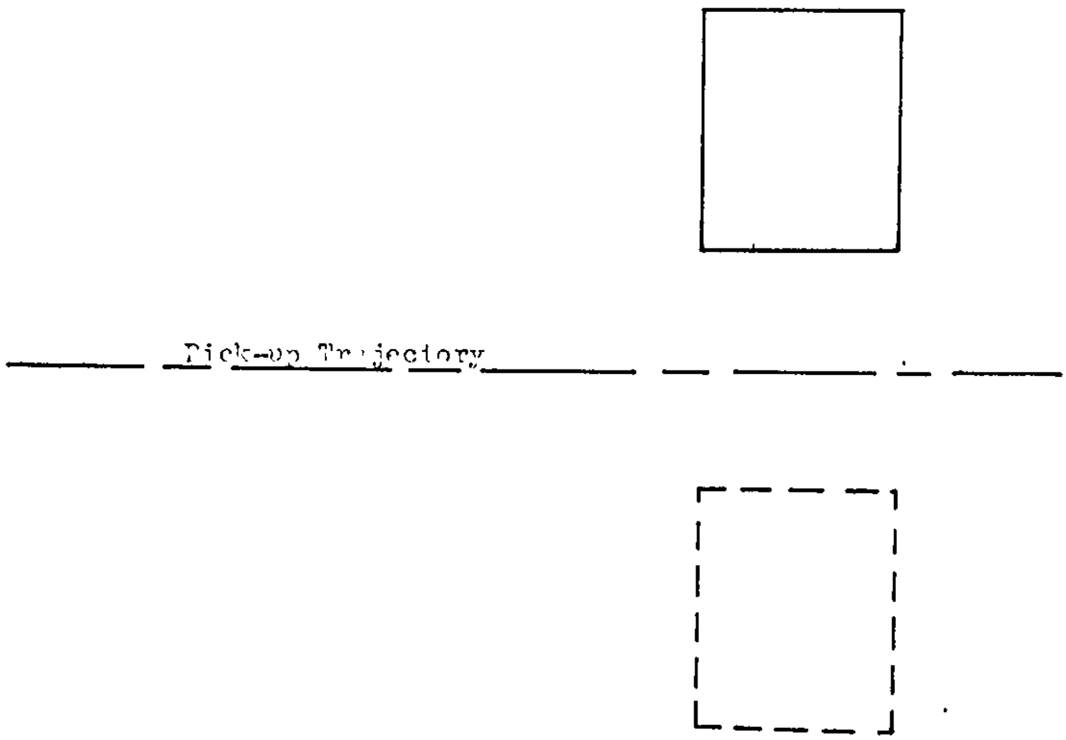


Fig. 50 . Approximate Positions of the Telegram Coil for Receiving Two Independent Bits of Information.

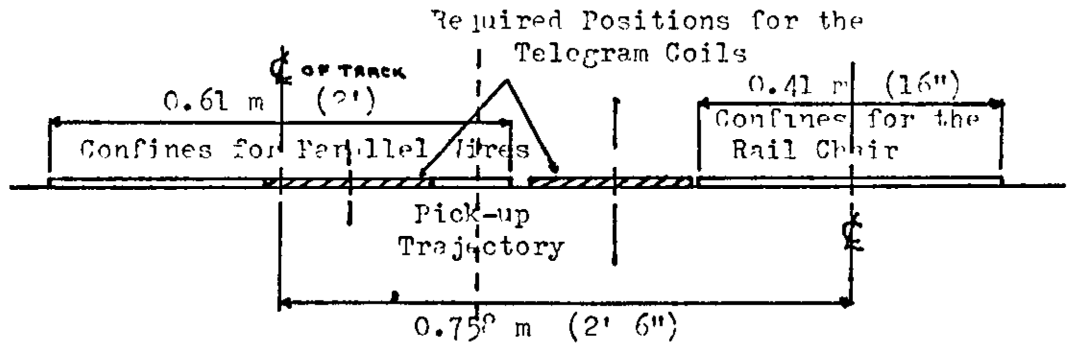


Fig. 51 . Layout of Typical Sleeper showing Required Position for Receiving Two Signals Simultaneously.

positive values of X. For negative values of X the phase is reversed. Hence, depending on which side of the coil is being considered, for one phase of the B_z field, two possibilities exist for the B_x component, thus giving two independent bits of information (see figs. 49(a) and (b)). This same situation arises if the pick-up trajectory remains the same and the coil is moved laterally - see fig. 50. If the coil is now wound in the opposite sense, or turned over, both B_z and B_x are reversed in phase. Some form of truth table is therefore required to determine the bits of information to be picked up - this is discussed in chapter 7. The B_x field is slightly weaker than the B_z field and hence it is desirable to work at or near the maximum of this field. Unfortunately the maximum of this field occurs on the steep sides of the B_z field, any lateral movement will therefore produce a large variation of the induced voltage from B_z and may prove to be a limitation of this system.

There are four other possible restrictions on this system, namely :-

(1) the vertical movement of the train-borne aerial

(2) the lateral displacement of the telegram coil to achieve this system

(3) the values of R_z and R_x, and

(4) the interference of the parallel wires on the coils and vice versa.

Limitation (1) is not considered here for these large coils because the restrictions imposed by (2), (3) and (4) make this version of the system impossible.

4.3.1 Lateral Displacement Required by the Telegram Coils.

From the curves for the B_x - X variations it can be seen that the maxima are closer to the centre of the coil the lower the pick-up height (i.e. Z). A condition imposed by the Railway Authorities is that in the area between the rails the pick-up must be at least one foot (0.30 m.) above sleeper level (see section 1.2) - this then represents the first limitation. The maximum of the B_x field at this height, for the coils examined, lies about 0.175 m. from the centre of the coil - for the system proposed the coils must be symmetrical about the pick-up trajectory and thus requires coil centres to be 0.35 m. apart. This immediately poses problems because there must be at least half a coil width between the coil centre and the edge of the rail chair; this distance is about 0.11 m. The coil will also extend beyond the position of the other coil centre by the same amount, thus requiring some 0.57 m. of space on the sleeper, but there is only 0.55 m. between the track centre and the edge of the rail chair - see fig. 51. Hence, for the parallel wires 0.30 m. apart and offset from the centre of the track, it is physically impossible to insert this arrangement between rails. Smaller coils could be used with increased numbers of turns but for the pick-up at 0.30 m. above sleeper level the inductance of these smaller coils would make the system prohibitive. Another possibility would be the use of narrower parallel wires.

4.3.2 Limitations Imposed by R'_z and R'_x.

As can be seen from table 3, the values of R'_z and R'_x improve with decreasing Z, but the minimum value of Z between the rails is already fixed. The values of R'_z are tolerable at this height but

Type of Coil			L µH	X, ([illegible])
Rectangular	9" x 7"		1.3	0.24
	9" x 4½"		1.1	0.20
Square	9" x 9"		1.4	0.26
	4½" x 4½"		0.95	0.17
Circular	9" dia.		1.2	0.22
	6" dia.		0.95	0.17

Table 4. Inductance and Reactance of Single Turn Coils Used.

those for R'_x would restrict the dynamic range to such an extent as to make the system impracticable.

4.3.3 <u>Interference from the Parallel Wires.</u>

Because of the position of the B_x maxima and the size of the coils, the pick-up trajectory would have to be at about 0.26 m from the centre line of the track, or about 0.40 m. from the centre of the parallel wires if offset. Care would have to be taken with the interference of the parallel wires on the coil field and vice versa. The interference at 0.40 m. from the centre of the parallel wires is greatest on the B_x field component - see figs. 53 and 54. The percentage interference of the parallel wires on the coil fields can be reduced by increasing the number of turns on the coil, but this then increases the interference of the coils on the parallel wire fields - no compromise being possible. British Rail have also mentioned that the parallel wires may well have to run symmetrically about the centre of the track, thus rendering this method not feasible with large telegram coils. By having the parallel wires in the centre of the track, only one pick-up coil is required for them whether the locomotive becomes reversed or not.

If only one field component from the coil was used - B_z - then it might be possible to place the coil centre at the point of zero vertical field from the parallel wires to partially eliminate interference. It would also be possible, for this field component, to feed some of the parallel wire signal to the signal picked up from the telegram coils to cancel the interference. If two signals are picked up simultaneously it is possible also to effect this cancellation with the B_x signal.

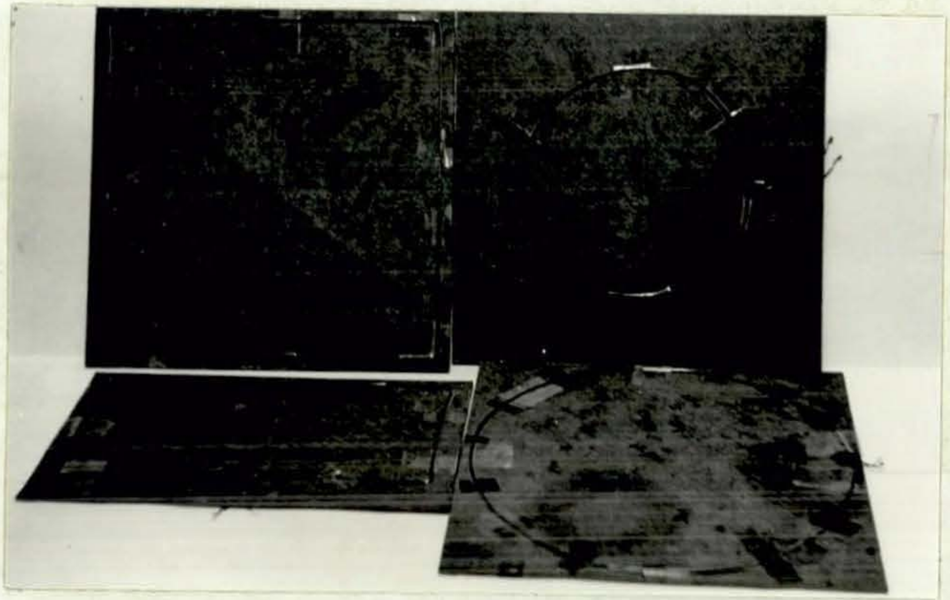


Fig. 52. Photograph of the Large Telegram Coils Used.

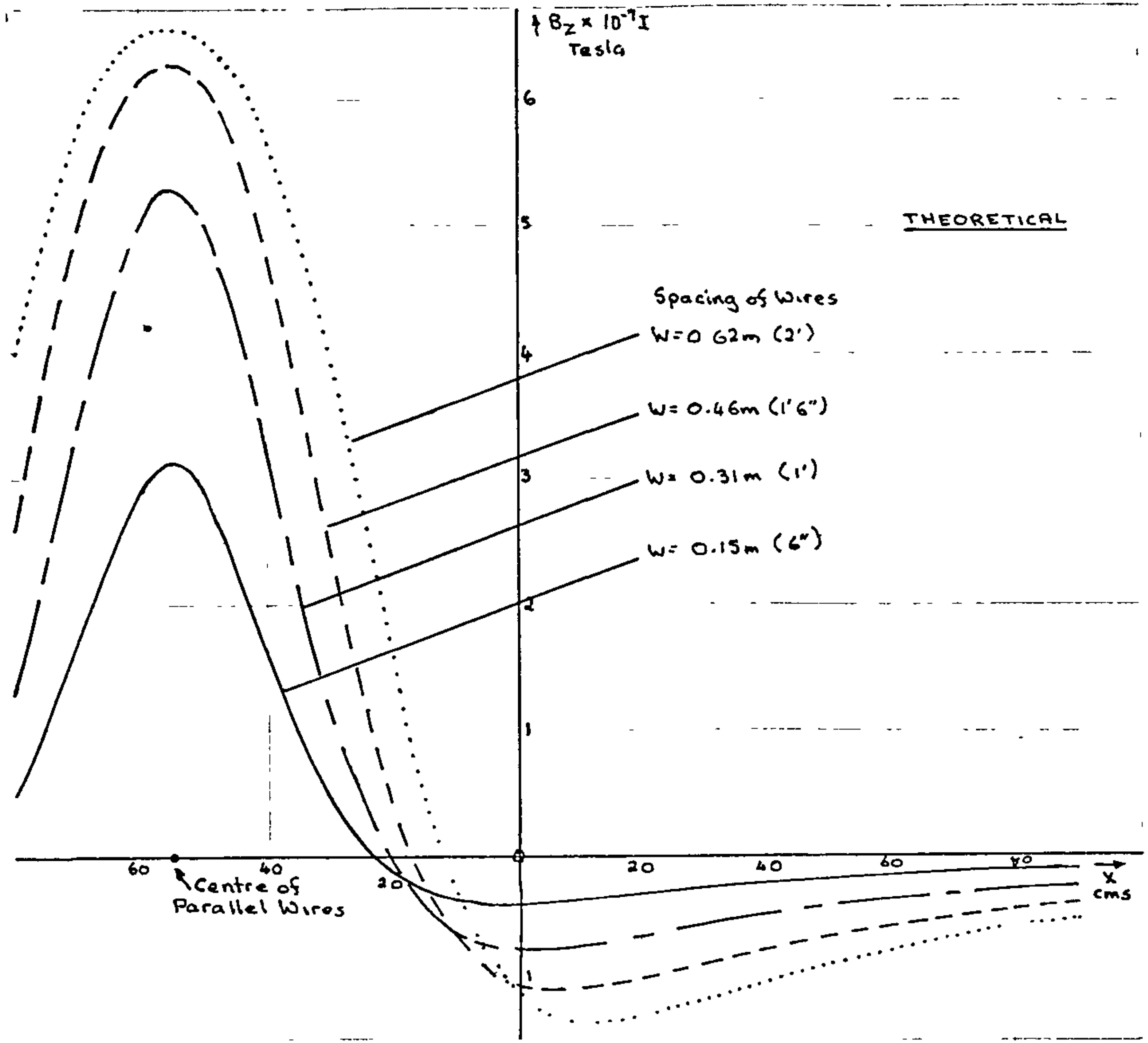


Fig. 53 Variation of B_Z from the Parallel Wires for Different Spacings at a Pick-up Height of 1'. Length of Wires 20m.

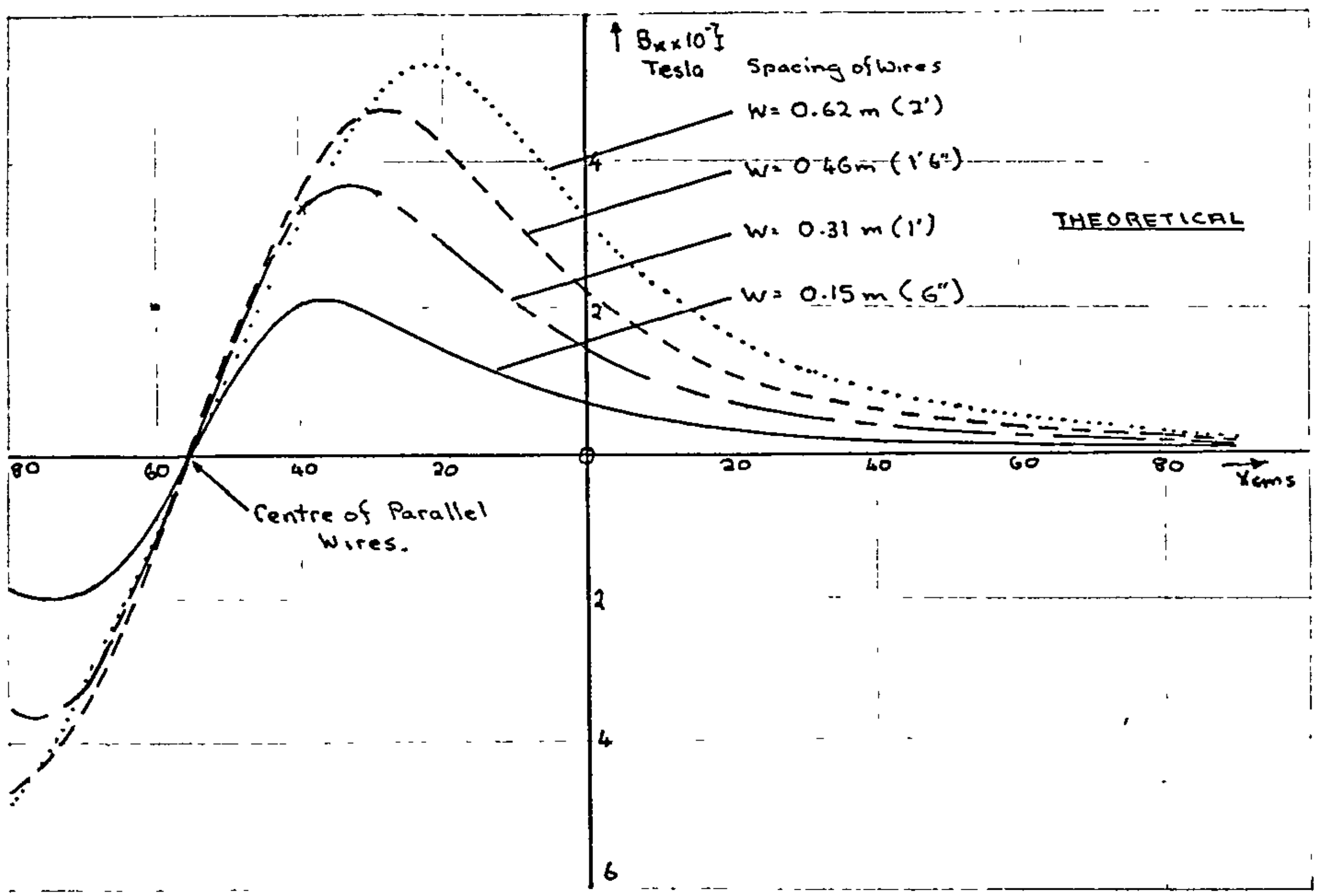


Fig. 54. Variation of B_x from the Parallel Wires for Different Spacings at a Pick-up Height of 1'. Length of Wires 20 m.

4.4 Tilted Coils.

When tilted coils are used only one field component is suitable for phase comparison and hence there is no advantage in using them. Flat coils are also to be preferred.

4.5 Conclusions.

Because of the above limitations on the B_x field for receiving two bits of binary information simultaneously by a moving train from large telegram coils, a practical system is not feasible. The work in this chapter indicates that smaller coils will produce higher values of R_z' and R_x', but will have a higher inductance, and provides the basis for the work in the next chapter. The use of narrower parallel wires would also be advantageous in reducing interference on the coil fields.

5. SMALLER COILS AND THEIR APPLICATION IN A PRACTICAL SYSTEM.

Because of the serious limitations on the system described in the previous chapter and the trend, exhibited in table 3, of R'_z and R'_x increasing with smaller coils and reduced values of pick-up height, a system exploiting these features might be feasible. Unfortunately, to obtain a given flux density with smaller coils, more turns are needed on the coil and hence the inductance of the coil increases. Using the values of flux density in the original B.R. system as a guide, then a flux density of about 10^{-7} Tesla should be produced at the pick-up height used, with a coil current of about 100 mA (rms). The inductance is required to be kept to a minimum as it represents a lump loading of the transmission line feeding it, thus causing reflections which might upset the system. The higher frequencies will be attenuated more and a higher sending end voltage will be required to achieve the same coil current. An additional requirement when using smaller coils, associated with the inductance problem, is the need to use reduced pick-up heights. This requirement would mean that the telegram coils would have to be placed somewhere other than between the rails because of the restrictions imposed there on the pick-up height. There are two possibilities here :-

(1) the coils staggered about the rail foot (figs. 55 and 56) or

(2) the coils both on the outside of the rail (fig. 55).

The use of coils staggered about the rail on the sleeper is not possible because of the area required by the rail chair. Above the rail the pick-up coil could come theoretically down to rail head level but allowance must be made for wheel wear, rail wear

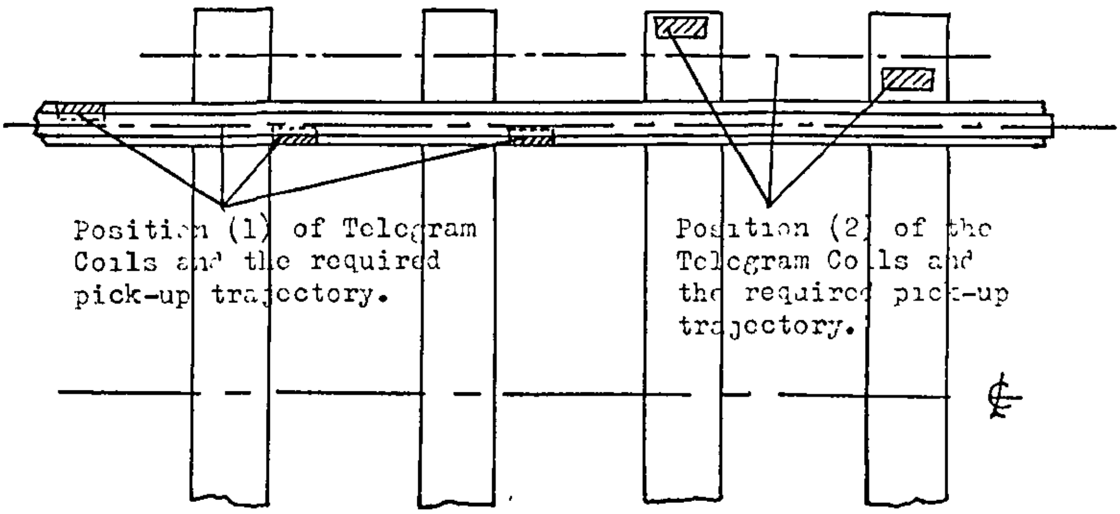


Fig. 55 Possible Positions for the Telegram Coils and the Required Trajectories for the Pick-up Coils.

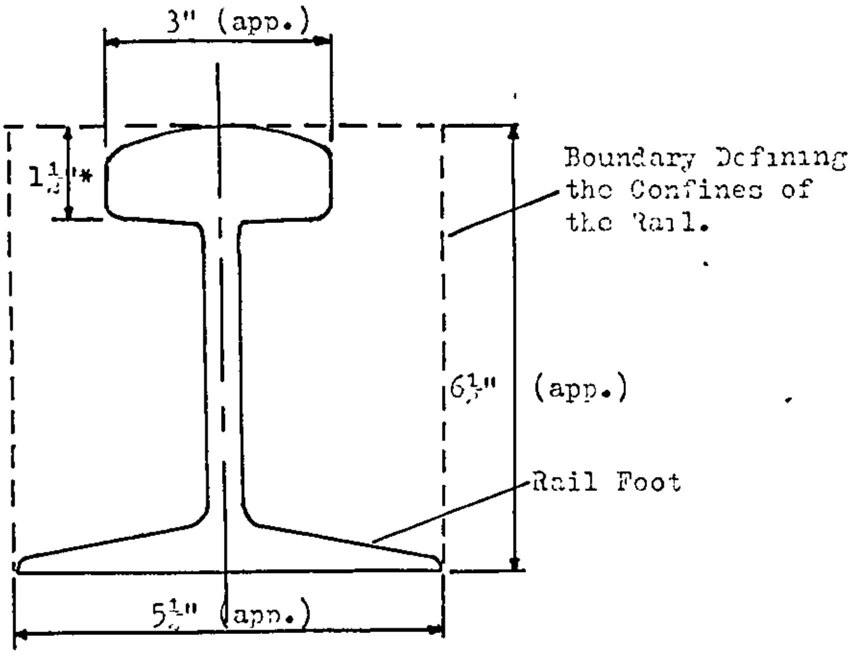


Fig. 56 Approximate Dimensions of Rail.

(* - when new).

and bounce and pitch of the locomotive bogie. To be able to pick up signals from telegram coils situated outside the rails the pick-up coil assembly would have to protrude from the side of the locomotive and in this position would violate the loading gauge. Also, in this position, the use of reduced pick-up heights is prohibited. Because of those restrictions the use of telegram coils in this position is no longer considered. With the coils on the rail foot they must lie wholly within the confines of the rail (see fig. 56) so as not to interfere with tamping operations. The maximum width of the coil (not including encapsulation) is therefore 2" (0.051 m). If the coil is adjacent to a rail fastening (or chair) it might have to be even narrower, but this position is best avoided. Sited thus, the telegram coil does not have to be opposite a sleeper and is far less prone to damage by 'permanent way gangs' or trespassers. Because of wheel and rail wear a minimum distance of the telegram coil below rail head level (when new) must be set. For the work described in this chapter depths of 3" (0.075 m) and $2\frac{1}{2}$" (0.063 m) were used. This is made up from $\frac{1}{2}$" rail wear, $\frac{3}{4}$" tyre wear and about $1\frac{1}{4}$" for the wheel flange, but assuming the flange is turned down as the tyre wears. With the coils in this position, the pick-up coil would have to run symmetrically along the centre line of the rail.

Both circular and rectangular coils were examined remote from the steel rail. The most promising were then examined on the rail foot, the determining factors being :-

(1) the manner in which the steel rail distorts the field of the telegram coil, and

(2) the change in impedance of the coil, if any.

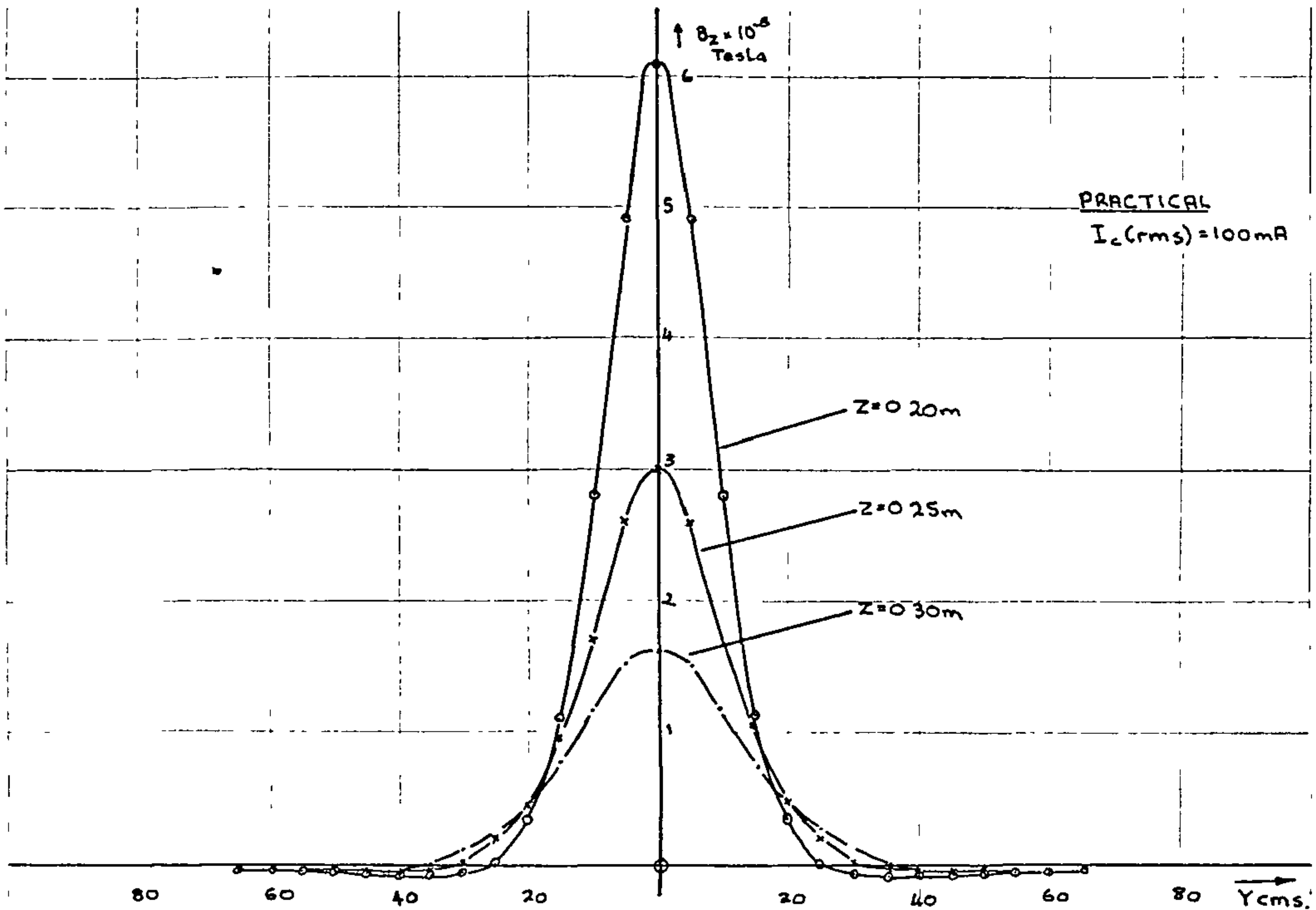


Fig. 57. Variation of B_z with Height above a 1" diameter Bobbin Coil of 34 turns

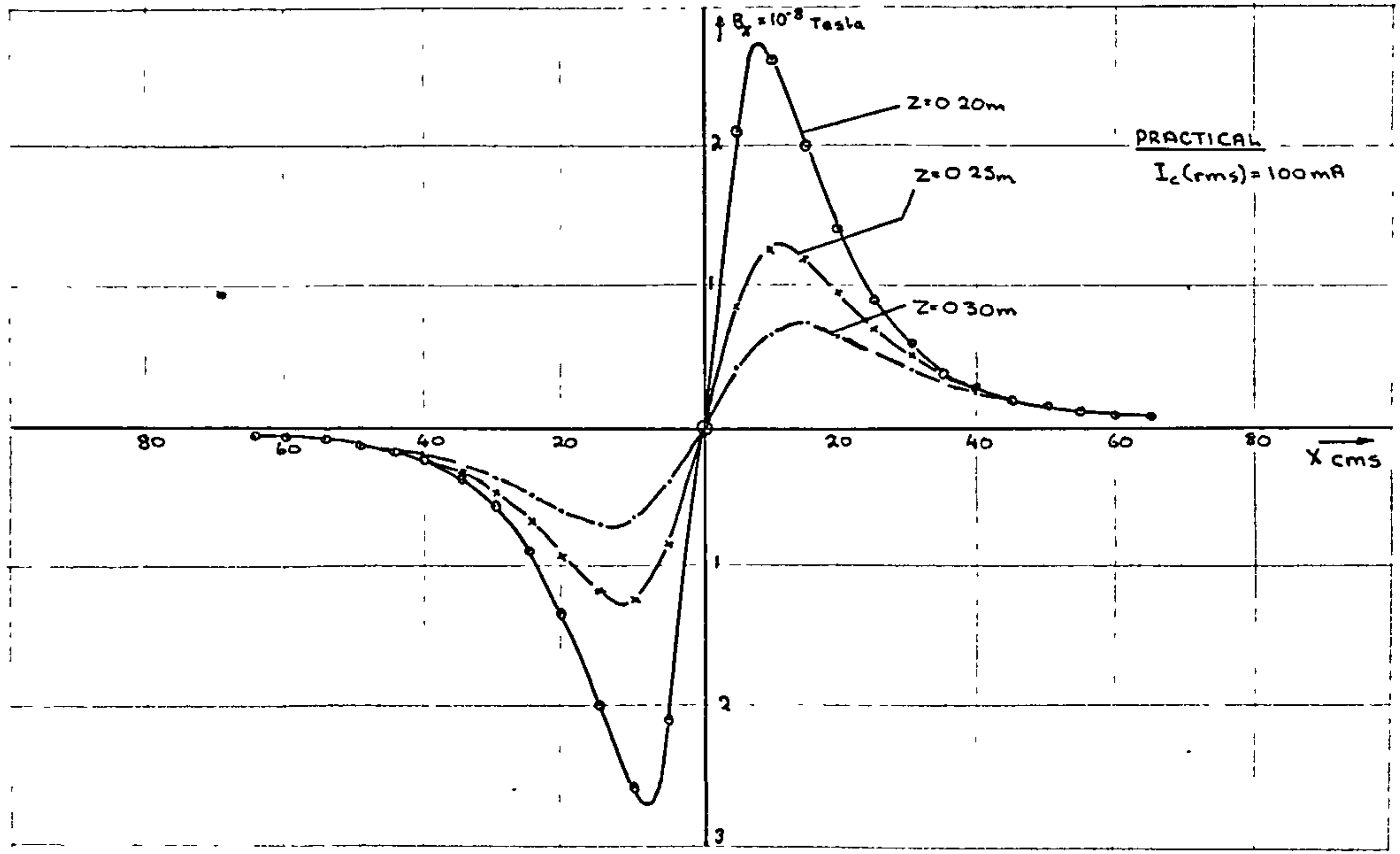


Fig. 58. Variation of B_x (or B_y) with Height above a Bobbin Coil, 1" diameter and 34 turns

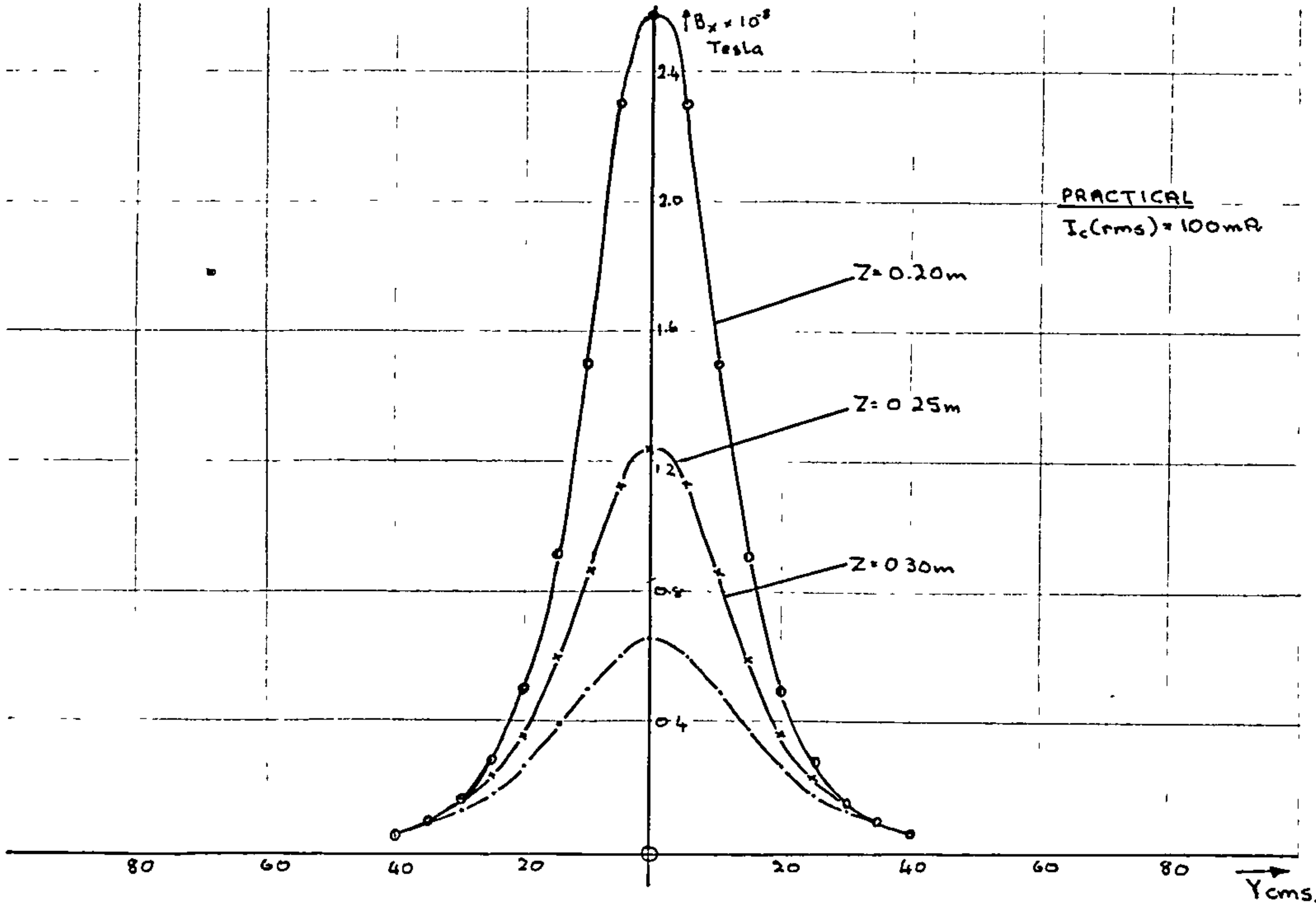


Fig. 59. Variation of Bx with Height above a 1" diameter Bobbin Coil with 34 turns.

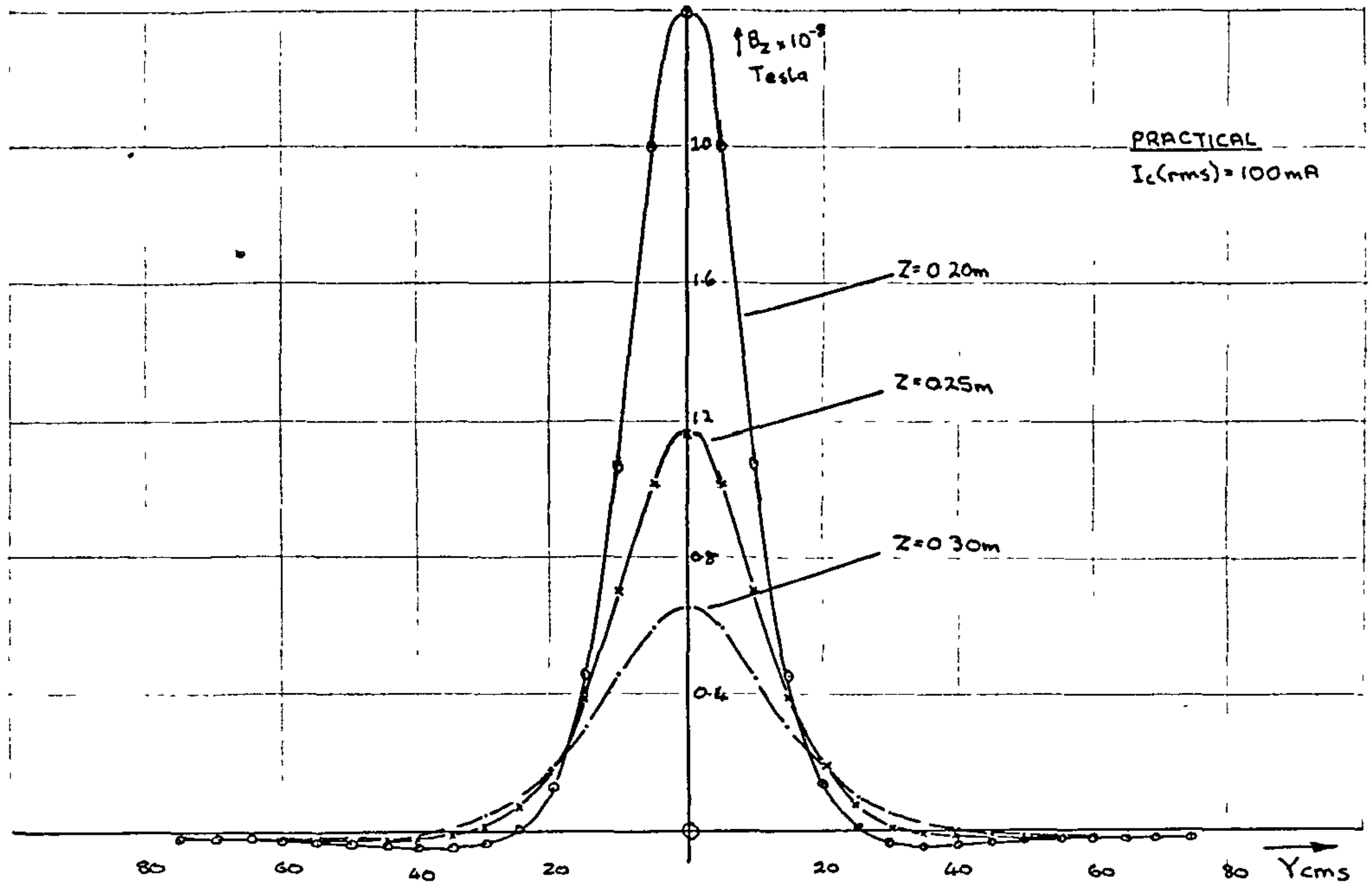


Fig. 60. Variation of B_z with Height above a 2" diameter Bobbin Coil. 34 turns.

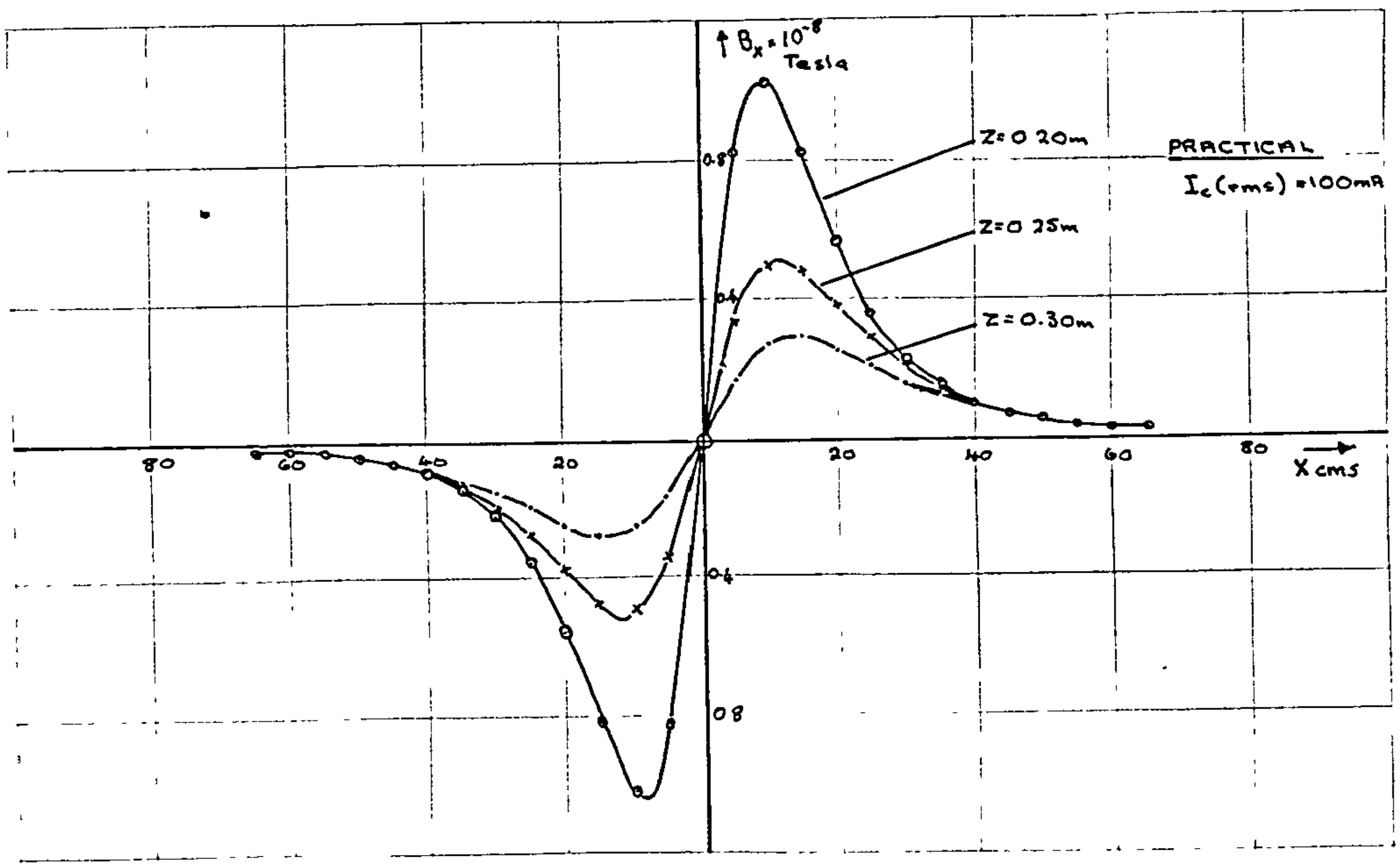


Fig. 61. Variation of B_x (or B_y) with Height above a 2" dia. Bobbin Coil. 34 turns.

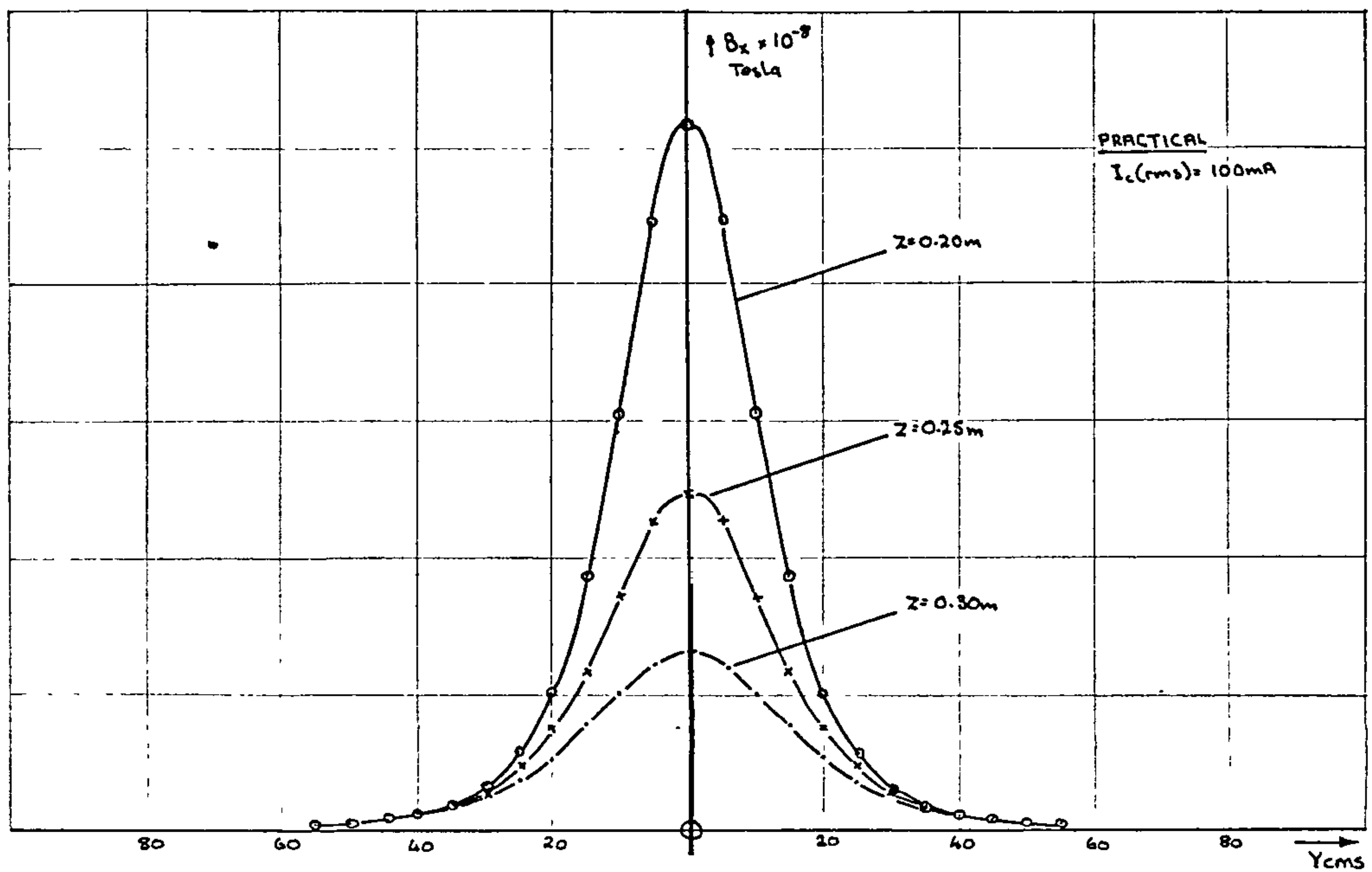


Fig 62 Variation of B_x with Height above a 2" diameter Bobbin Coil. 34 turns.

Both theoretical and practical results are available for the coils remote from the rail but for the coils on the rail foot only practical results are available because of the difficulty in analysing the situation mathematically.

5.1 Circular Bobbin Coils Remote from the Rail.

Two different sizes of coil were examined - 1" (0.025 m) and 2" (0.051 m) diameter. Both coils were wound with the same number of distributed turns (i.e. 34). The method of calculation of the field components is shown in appendix 5. The shapes of the field patterns are very similar to those obtained in the previous chapter and the same method for extracting two bits of information applies. The maximum of the B_x field at a given height has also moved closer to the centre of the coil. The smaller bobbin coil with 34 turns does not produce a high enough flux density to be of use. This value of field could be doubled by using twice the number of turns but the inductance would go up by a factor of four and the reactance at 29 kHz would then be about 10Ω. Sufficient flux density can be obtained from the 2" diameter coil but the reactance of this is again high - 9Ω. It would therefore seem that a somewhat longer coil would afford a better flux density to inductance ratio. Smaller coils do exhibit larger values of R_z' and R_x' (see table 5) and justifies their examination.

5.2 Rectangular Coils Remote from the Rail.

Two different sizes of rectangular coil were examined - 4" x 2" (0.102 m. x 0.051 m.) and 6" x 2" (0.153 m. x 0.051 m.) but with different numbers of turns (12 and 10 respectively).

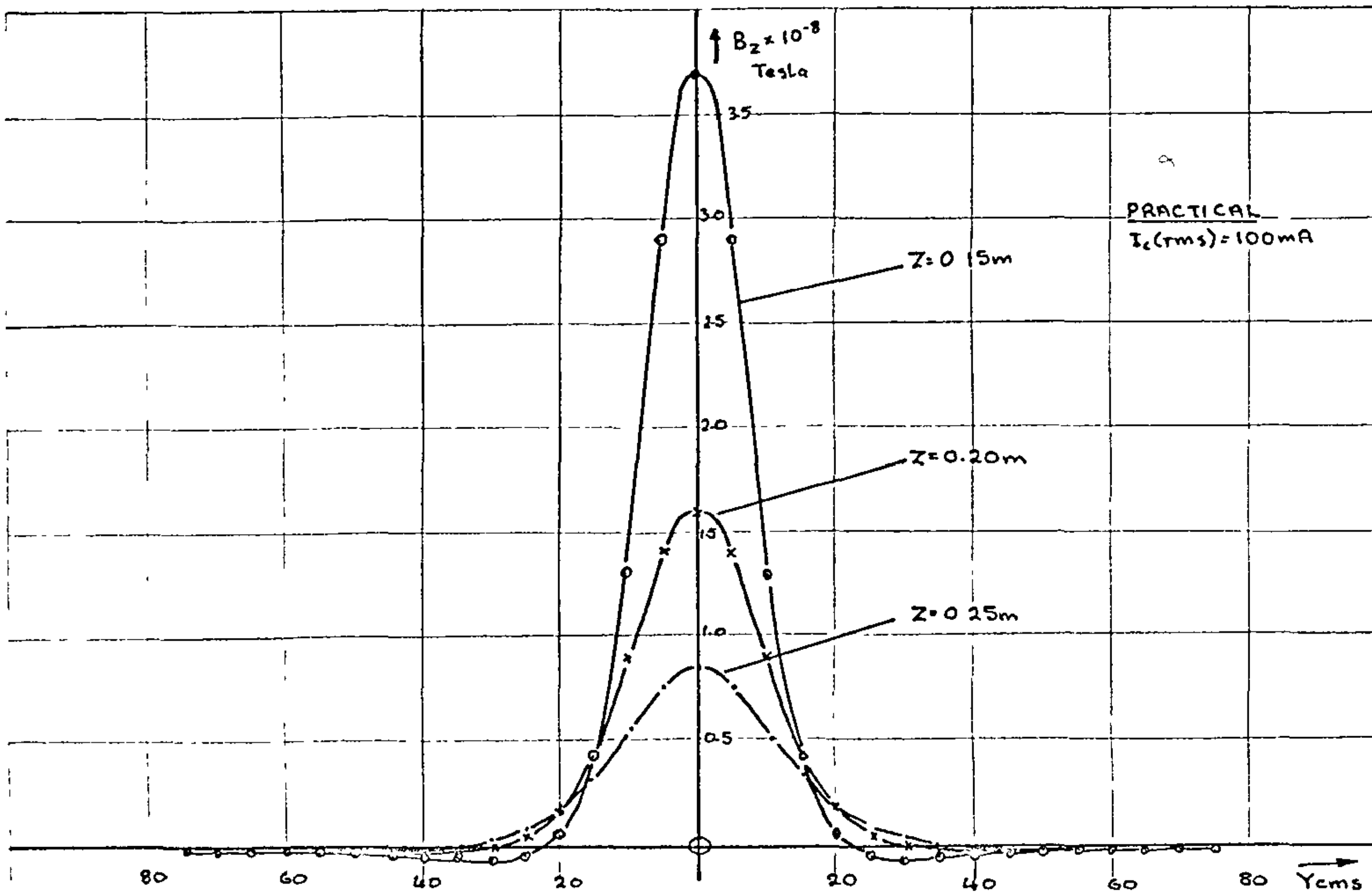


Fig G3 Variation of B_z with Height above a 4" x 2" Rectangular Coil of 12 turns.

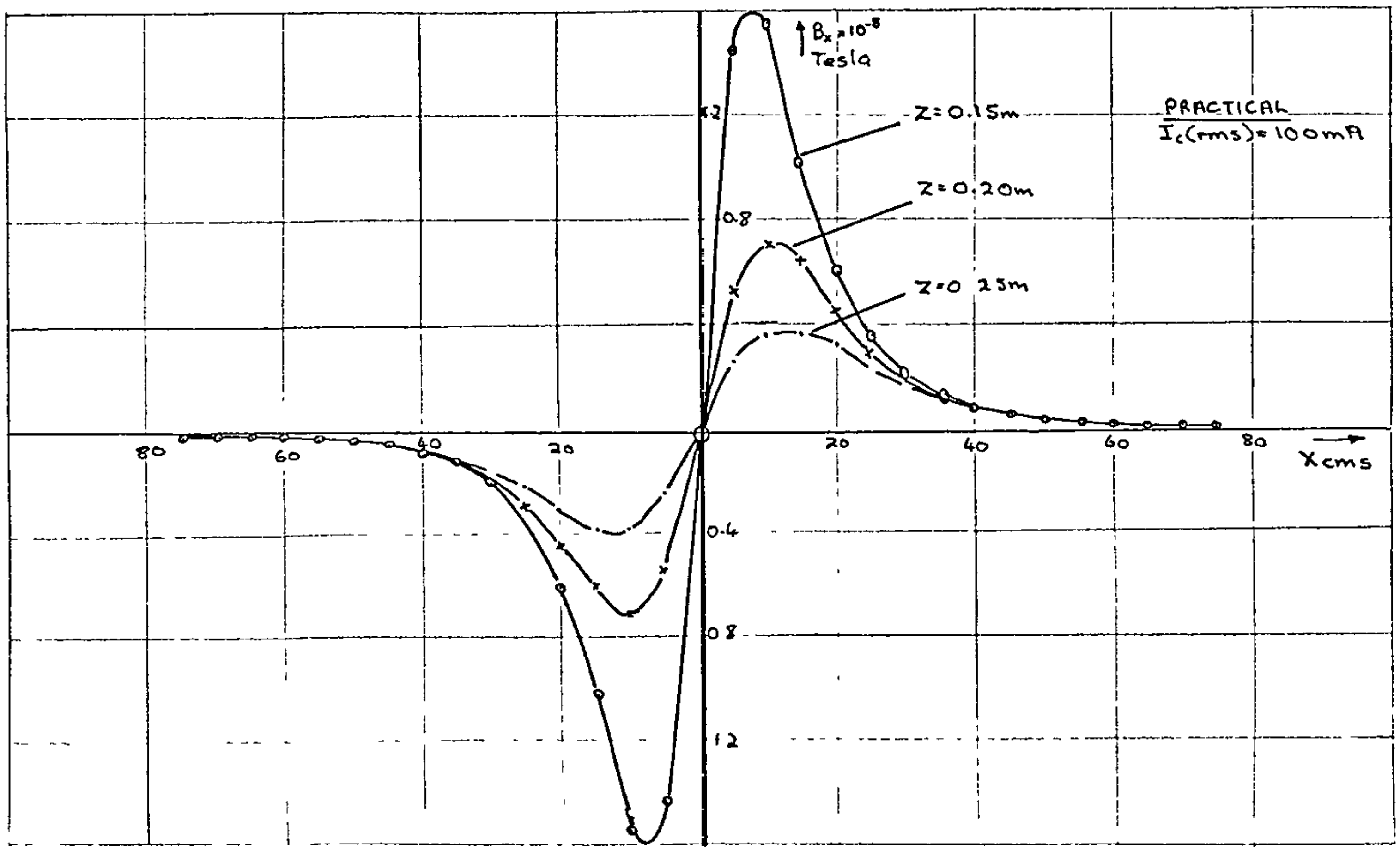


Fig 64 Variation of Bx with Height above a 4"x2" Rectangular Coil of 12 turns

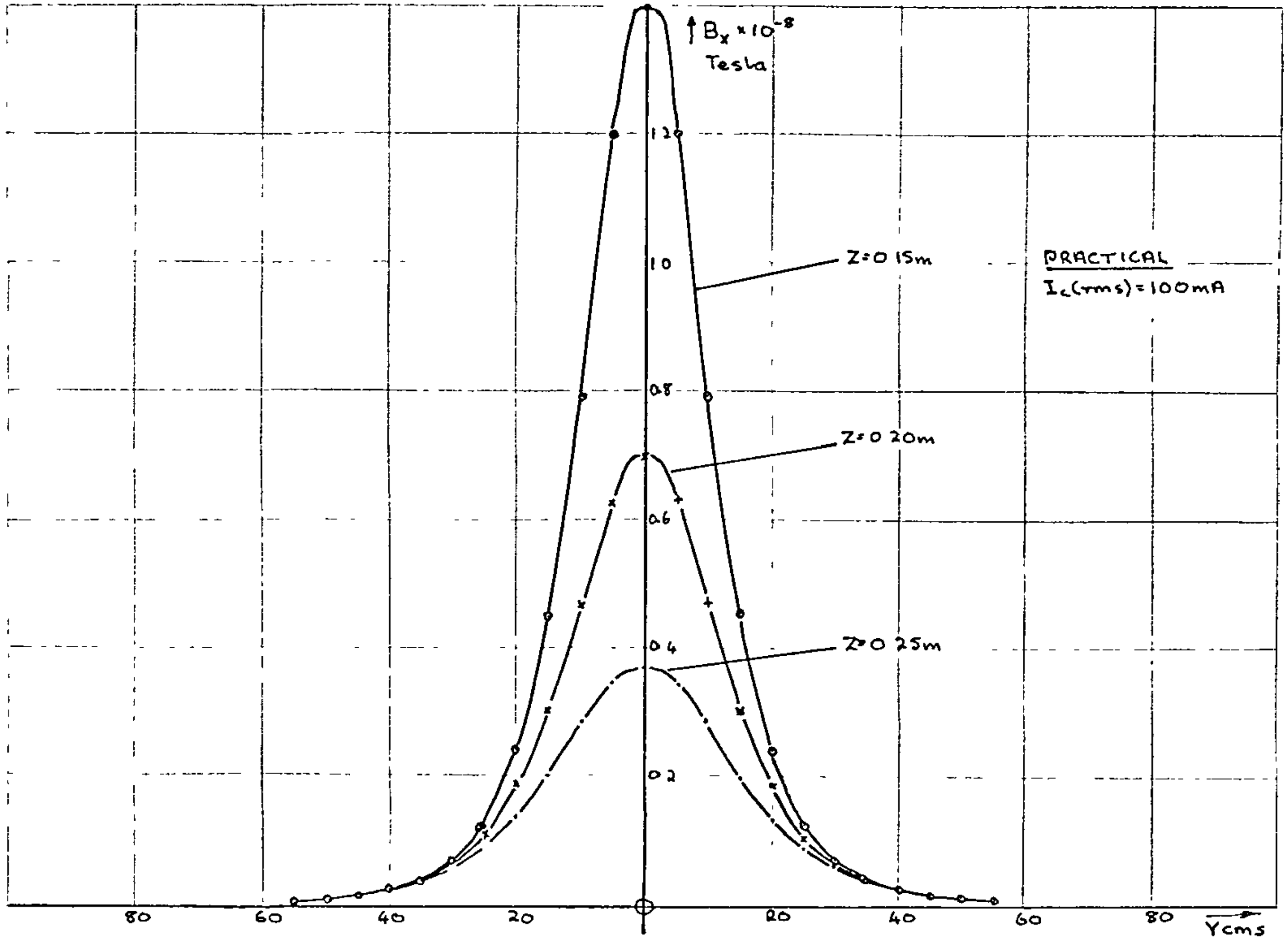


Fig. 65. Variation of B_x with Height above a 4"x2" Rectangular Coil with 12 turns.

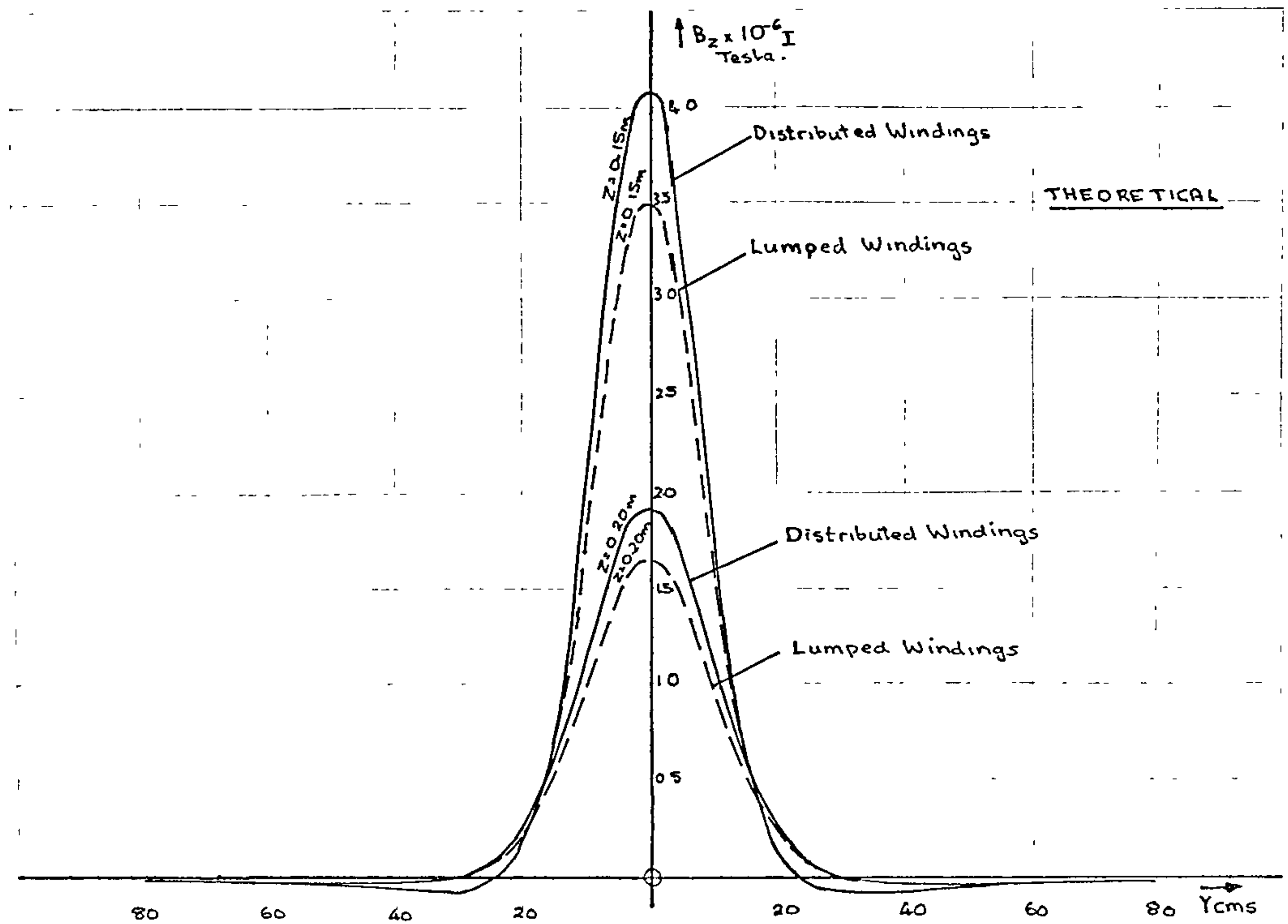


Fig 66 Differences in Bz When Assuming Distributed or Lumped Windings for a 6"x2" Rectangular Coil (10 turns).

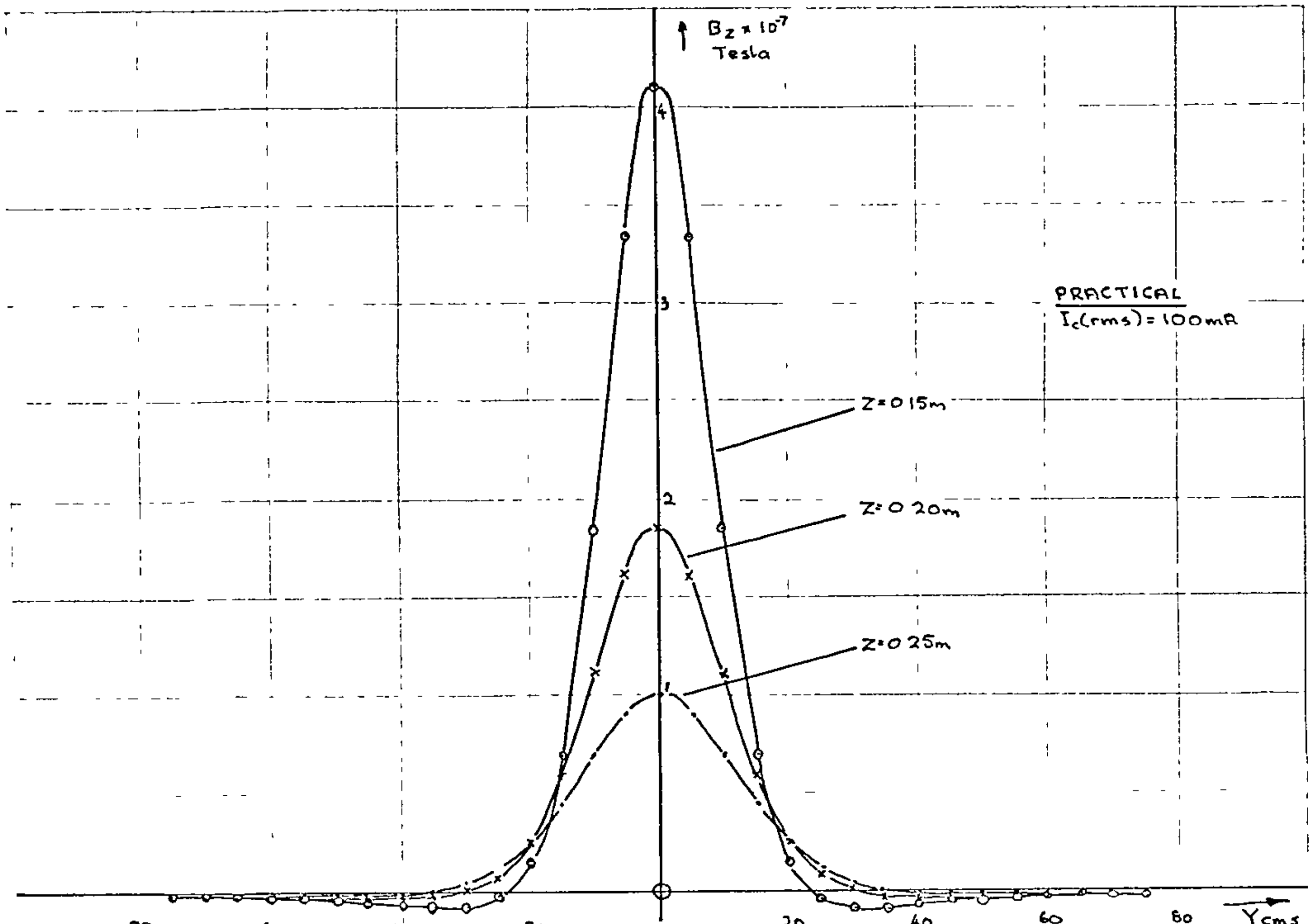


Fig. 67. Variation of B_z with Height above a 6"×2" Rectangular Coil with 12 turns.

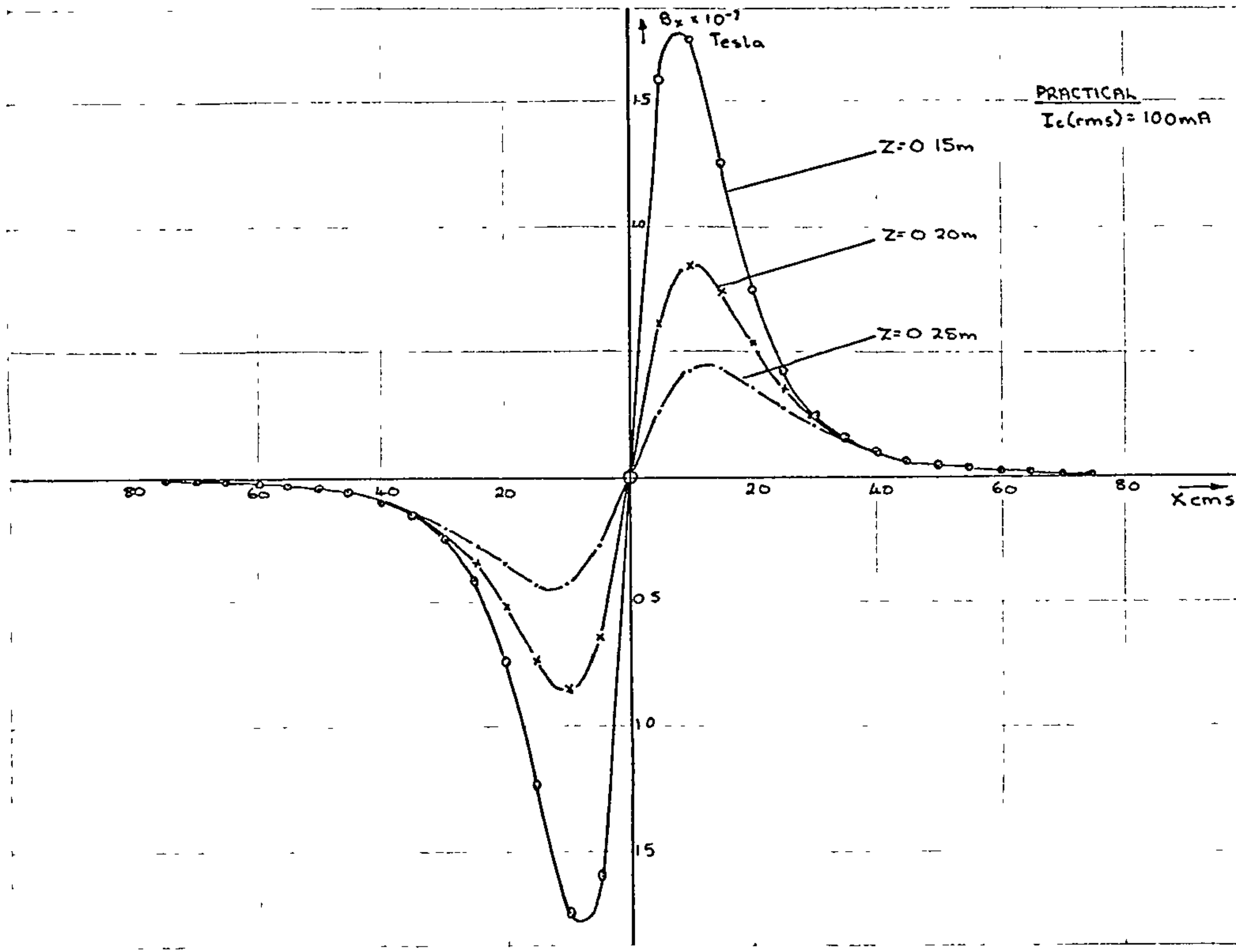


Fig. 68. Variation of B_x with Height above a 6"x2" Rectangular Coil with 10 turns.

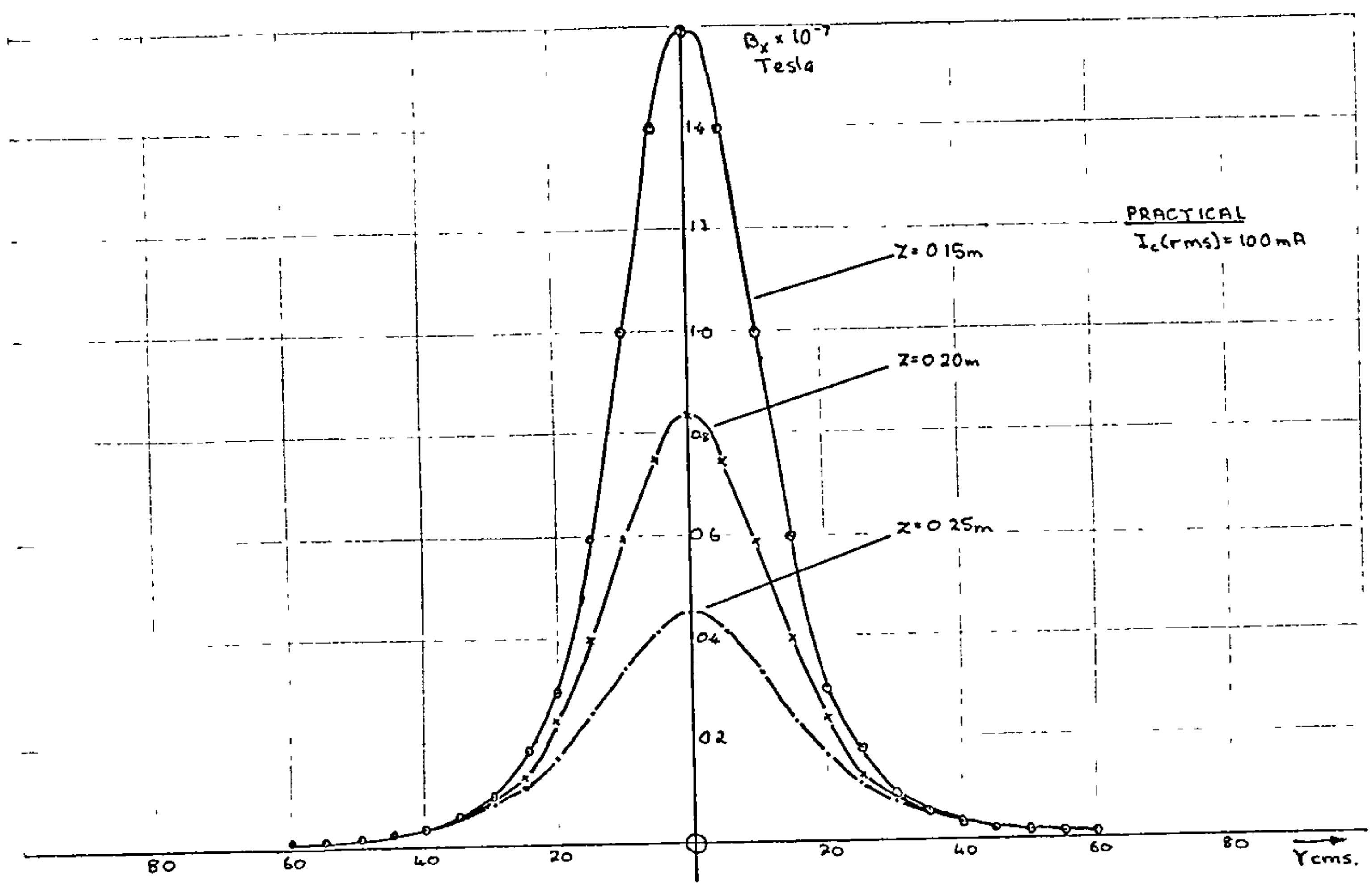


Fig 69 Variation of Bx with Height above a 6" x 2" Rectangular Coil with 10 turns.

Type of Coil	Z metres	R'_z	R'_x
Bobbin Coils	20	-30.5	26
1" dia. 34 turns	25	-30.0	12.4
(0.025 m dia.)	30	-30.0	6.5
2" dia. 34 turns	20	-24	26
(0.051 m dia.)	25	-29	12.3
	30	App. ∞	6.5
Rectangular Coils	15	-27.8	28
4" x 2" 12 turns	20	-24	14
(0.102 m x 0.051 m)	25	-38	7.4
6" x 2" 10 turns	15	-20.5	24
(0.152 m x 0.051 m)	20	-18.5	12.5
	25	-30	6.8

Table 5. Variation of R'_z and R'_x with Z for Small Multi-turn Coils. (These are the worst values for sleeper spacing).

This was to give approximately the same values of flux density at a given height above the coil centre. No curves were obtained for the B_y - Y variations as these are of no use for phase comparison purposes (as explained in the previous chapter). Figures 63 to 69 show the familiar forms of the curves for the various field components. These smaller rectangular coils show improved values of R'_x and R'_z, the values of R'_x being better than those for the bobbin coils. The inductance of these coils is also lower than that of the bobbin coils (see table 6) to obtain a flux density of 10^{-7} Tesla at a given height with a coil current of 100 mA (rms). From the measurements taken, these coils exhibit a larger dynamic range than the original four turn 9" x 7" coils. Figure 66 is included to show the error introduced for these coils when considering them as lumped windings rather than distributed windings. In the analysis here they are taken as distributed windings.

5.3 Rectangular Coils on the Rail Foot.

The above results show that the smaller rectangular coils have a far better performance than the bobbin coils and hence the following investigation as to their suitability for use on the rail foot was carried out.

From the previous work it appears that the B_x field is the most limiting with respect to R'_x and the closer the telegram coil is to the pick-up, the better is this ratio. To obtain the required flux density the pick-up should be reasonably close to the telegram coil and, for the coil remote from the steel rail, this distance is about 0.15 m. Although, as stated previously,

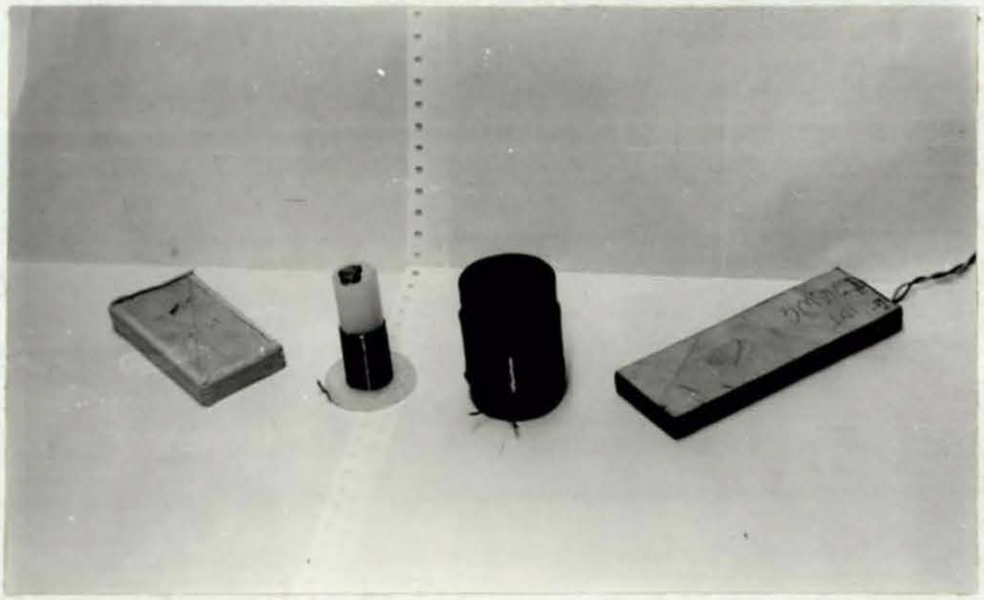


Fig. 70. Photograph of Small Telegram Coils Used.

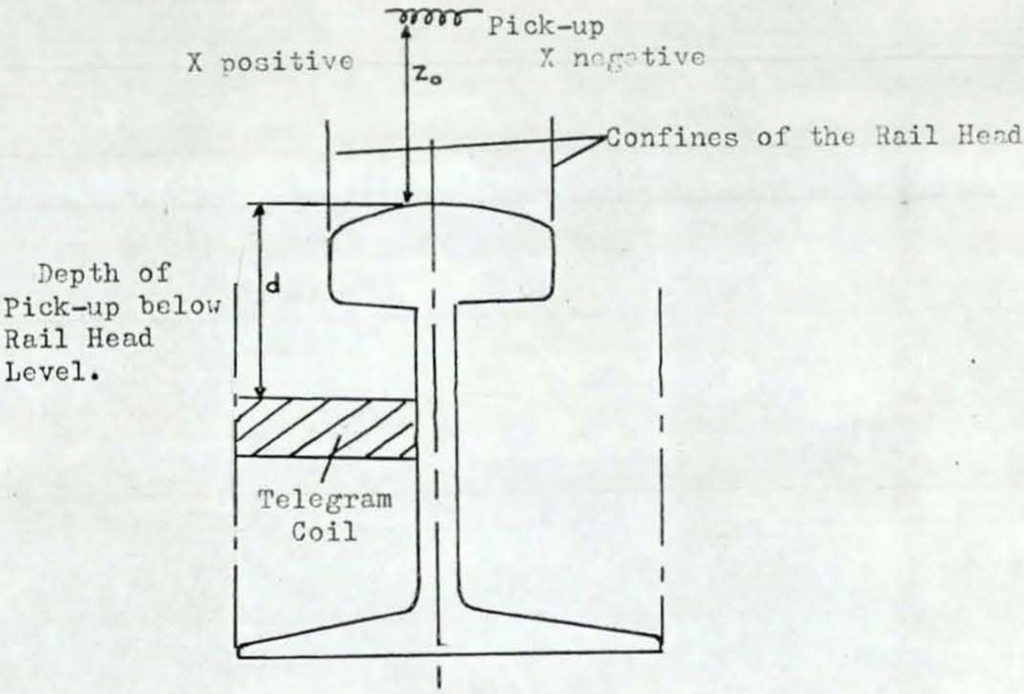
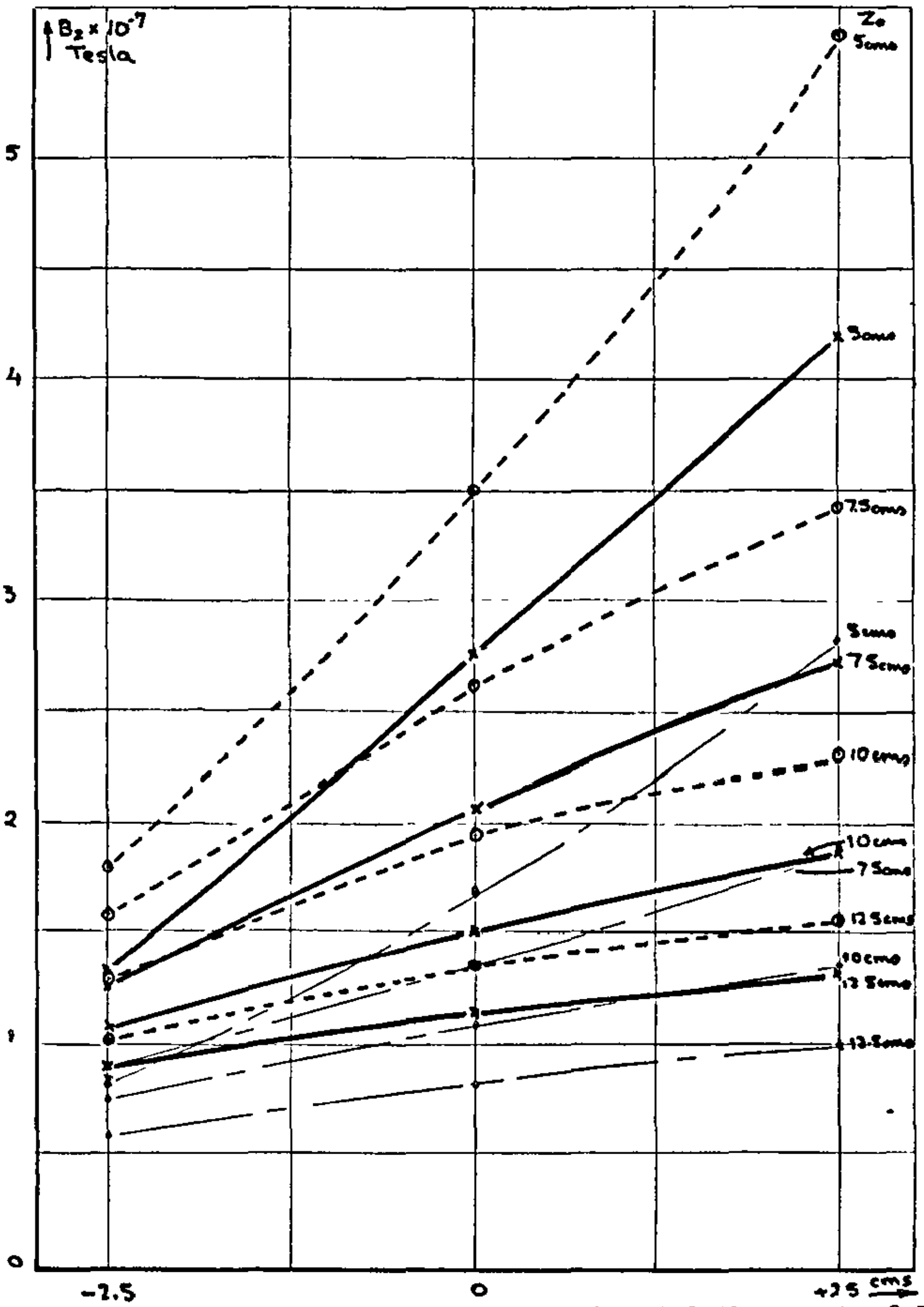


Fig. 71. Definition of Various Measurements Discussed in the Text.



Horizontal Movement of Pick-up Coil about the Centre Line of the Rail.

- - - - Telegram Coil 6.25 cms below rail head level
——— Telegram Coil 7.5 cms below rail head level
— —— Telegram Coil 10 cms below rail head level

Fig. 72 . Practical Curves Showing Variation of Flux Density, B_z, Due to Lateral Movement of the Pick-up Assembly. Telegram Coil 6" x 2" with 10 turns.

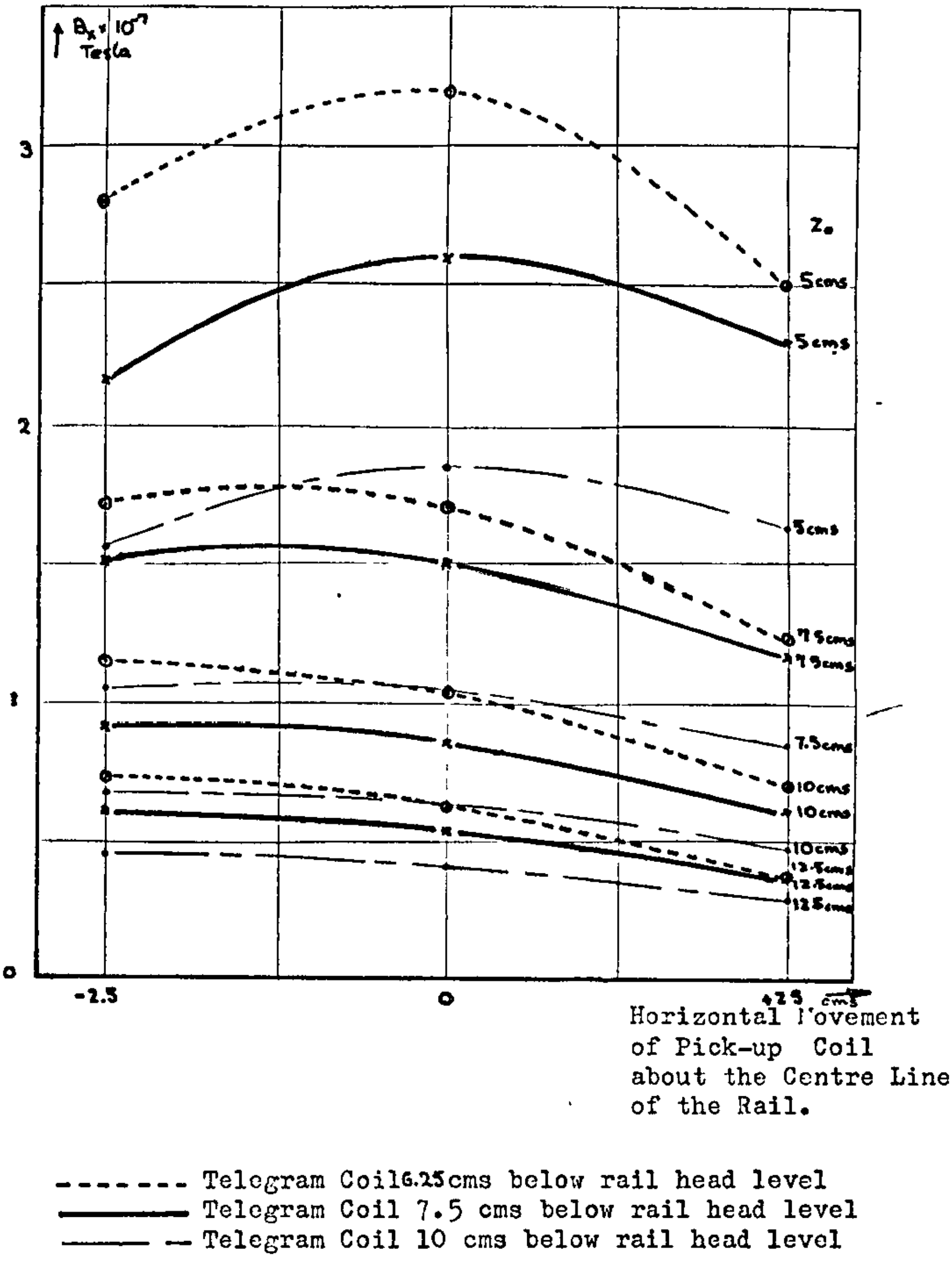
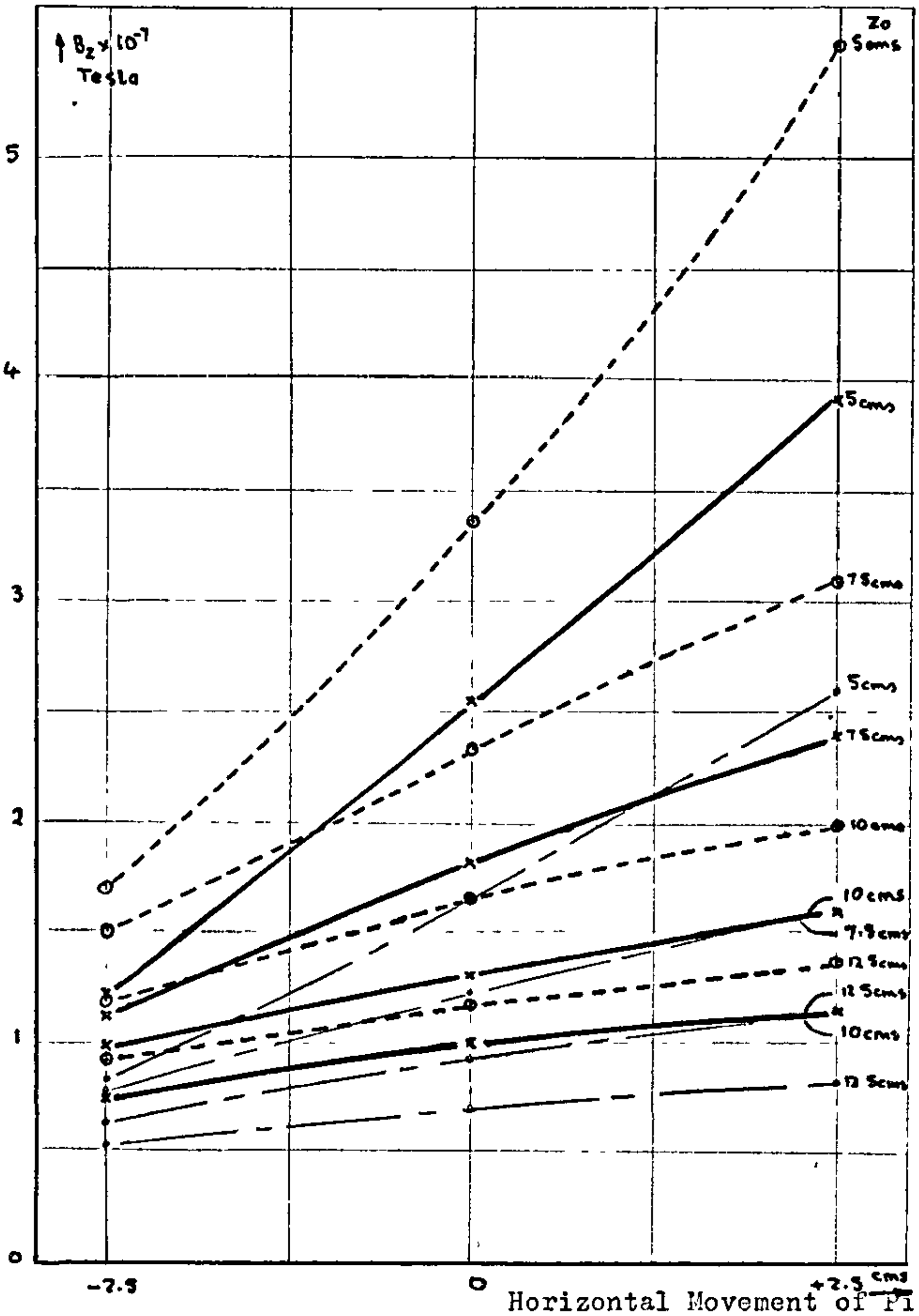


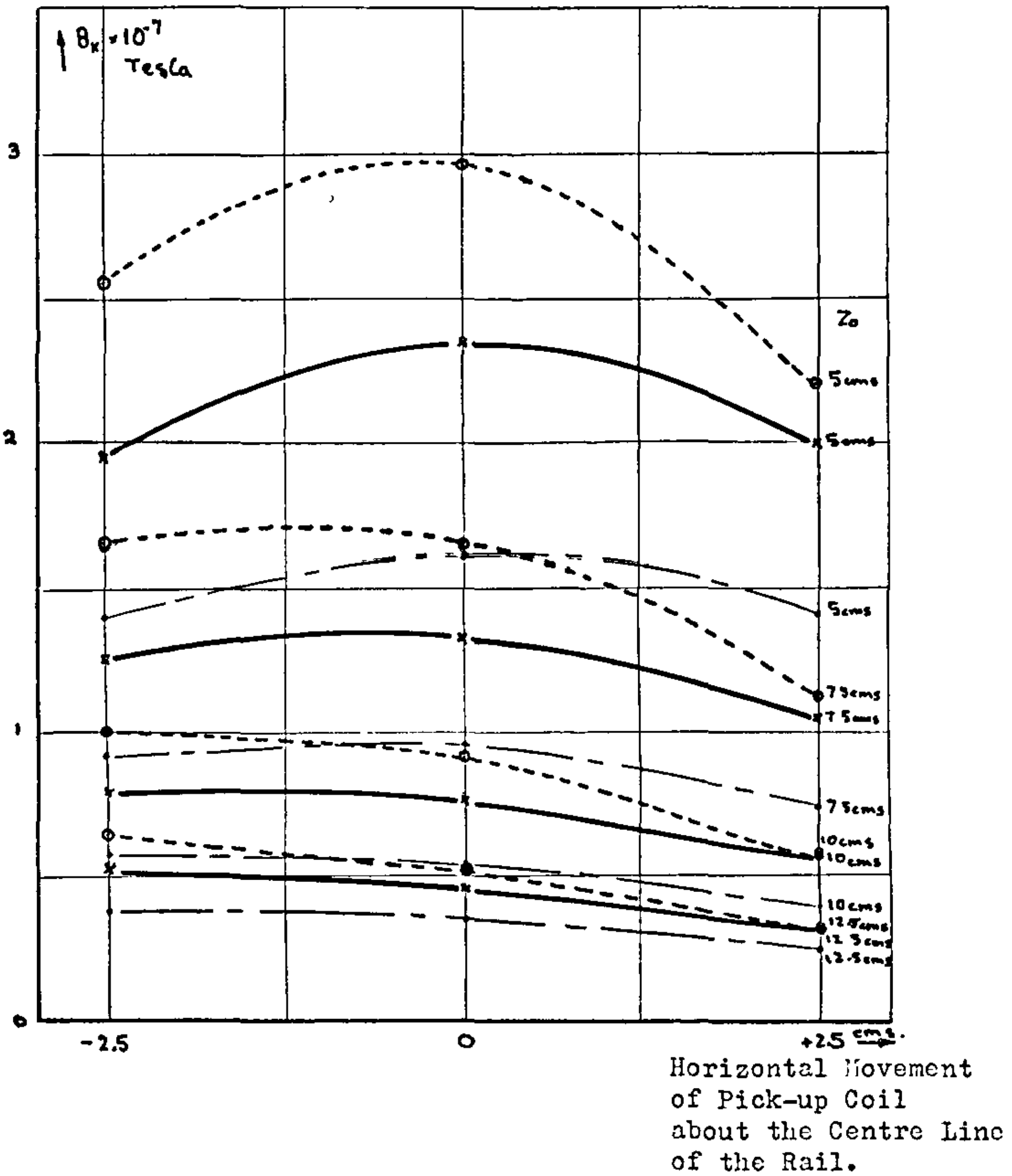
Fig. 73 . Practical Curves Showing Variation of Flux Density, B_x, Due to Lateral Movement of the Pick-up Assembly. Telegram Coil 6" x 2" with 10 turns.



Horizontal Movement of Pick-up Coil about the Centre Line of the Rail.

- - - - Telegram Coil 6.35cms below rail head level
———— Telegram Coil 7.5 cms below rail head level
—— – Telegram Coil 10 cms below rail head level

Fig. 74 . Practical Curves Showing the Variation of Flux Density, B_z, Due to Lateral Movement of the Pick-up Assembly. Telegram Coil 4" x 2" with 12 turns.



------ Telegram Coil 6.25 cms below rail head level

——— Telegram Coil 7.5 cms below rail head level

——— — Telegram Coil 10 cms below rail head level

Fig. 75 . Practical Curves Showing Variation of Flux Density, B_x, Due to Lateral Movement of the Pick-up Assembly. Telegram Coil 4" x 2" with 12 turns.

the pick-up could, theoretically, come down to rail head level some clearance must be allowed for bogie pitching and bouncing and small objects on the track - a minimum clearance of 2" (0.05 m) is therefore suggested by British Rail. For a pick-up height above the rail head of less than 4" (0.01 m) the pick-up assembly would have to be specially engineered so as not to exceed the restrictions imposed by the special guard rails used over viaducts to prevent derailments. The system should also be able to tolerate a lateral movement of approximately $\pm$ 1" ($\pm$ 0.025 m) about the centre line of the rail for the pick-up coils attached to the bogie.

Initial investigations were confined to the determination of what would seem the optimum position of the telegram coil below rail head level and the range of heights for the pick-up coil above rail head to encounter suitable values of flux density. It also helped to show which size of coil was the best choice. The telegram coils were mounted on wooden blocks attached to the rail foot.

5.3.1 Initial Investigations.

Three values of depth of the telegram coil below rail head level were examined - 6.25, 7.5 and 10 cms. A lateral variation of $\pm$ 2.5 cms was assumed about the centre line of the rail and a pick-up height range of 5 cms to 12.5 cms above rail head level (i.e. 2" to 5") was used. Measurements were carried out on both the B_z and B_x fields for both coils and the results can be seen in figs. 72 to 75. From these graphs, to obtain a reasonable flux density over a given pick-up height range, (i.e. about 10^{-7} Tesla), the telegram coil should be between 6.25 and

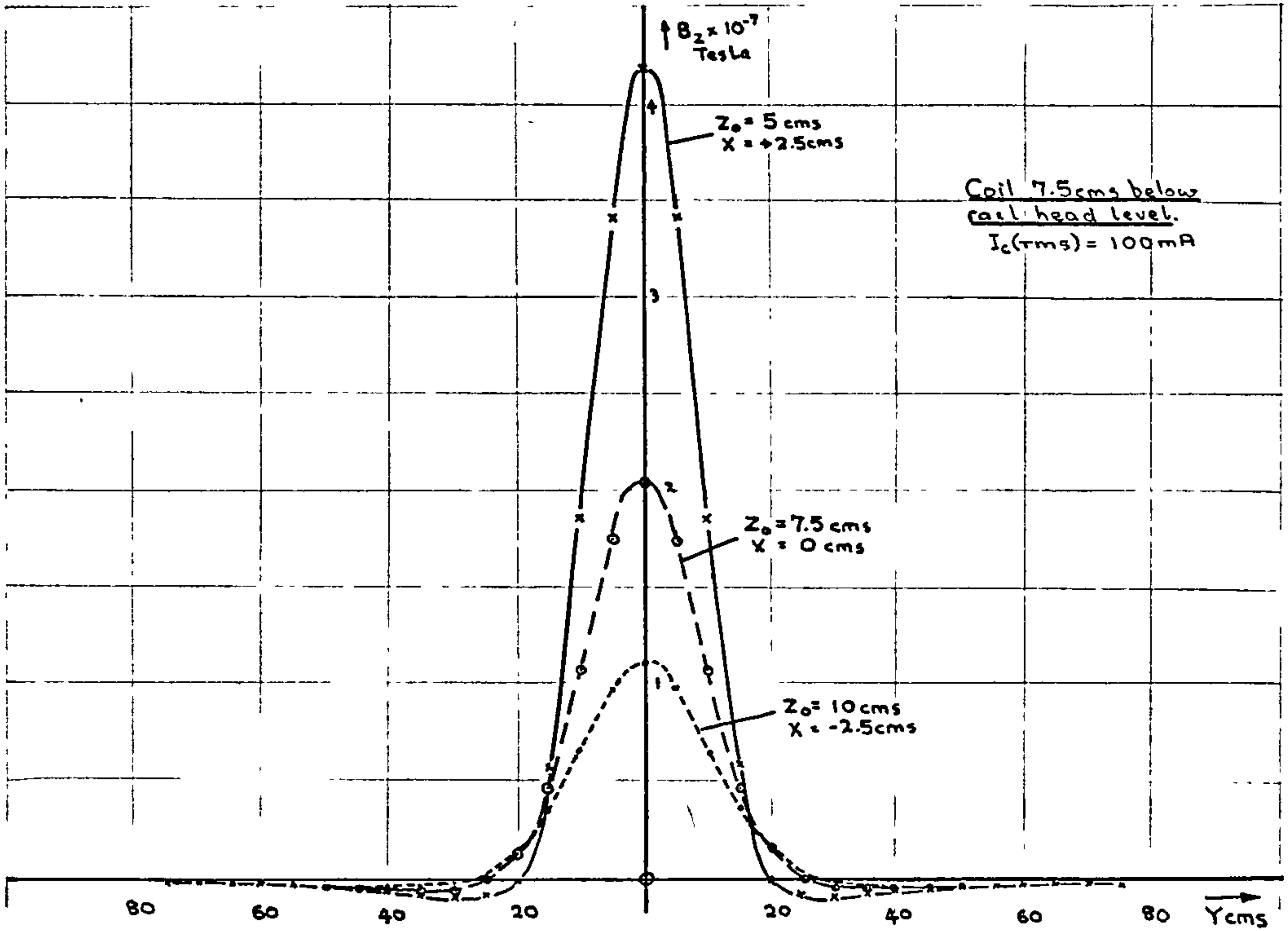


Fig. 76(a). Curves Showing Extreme Variations of B_z-Y and an Intermediate Position of the Pick-up Assembly Coil 6"x2", 10 turns.

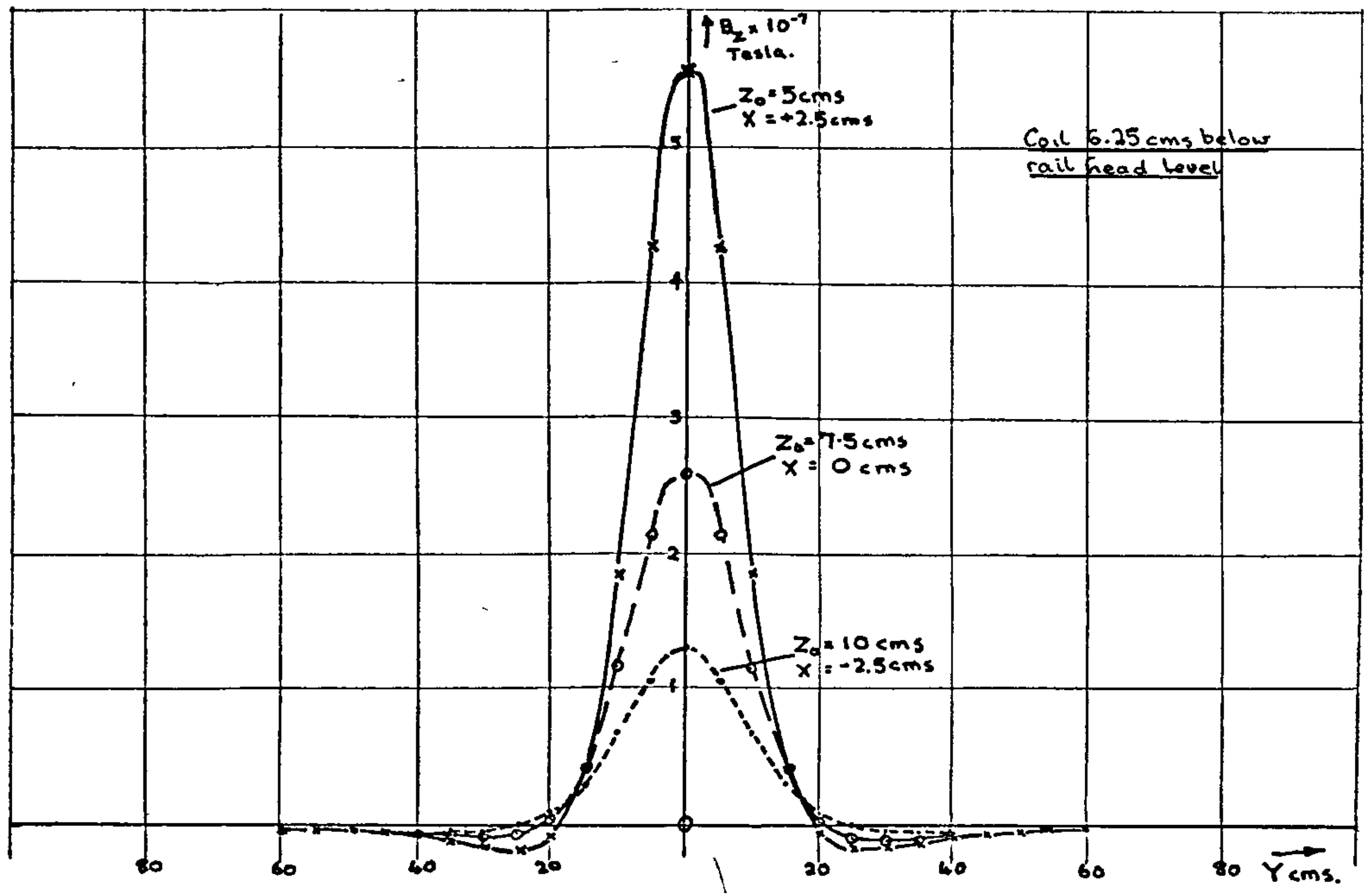


Fig. 76(b). Curves Showing Extreme Variations of Bz-Y and an Intermediate Position of the Pick-Up Assembly. Coil is 6" x 2" with 10 turns. Coil Current 100 mA.

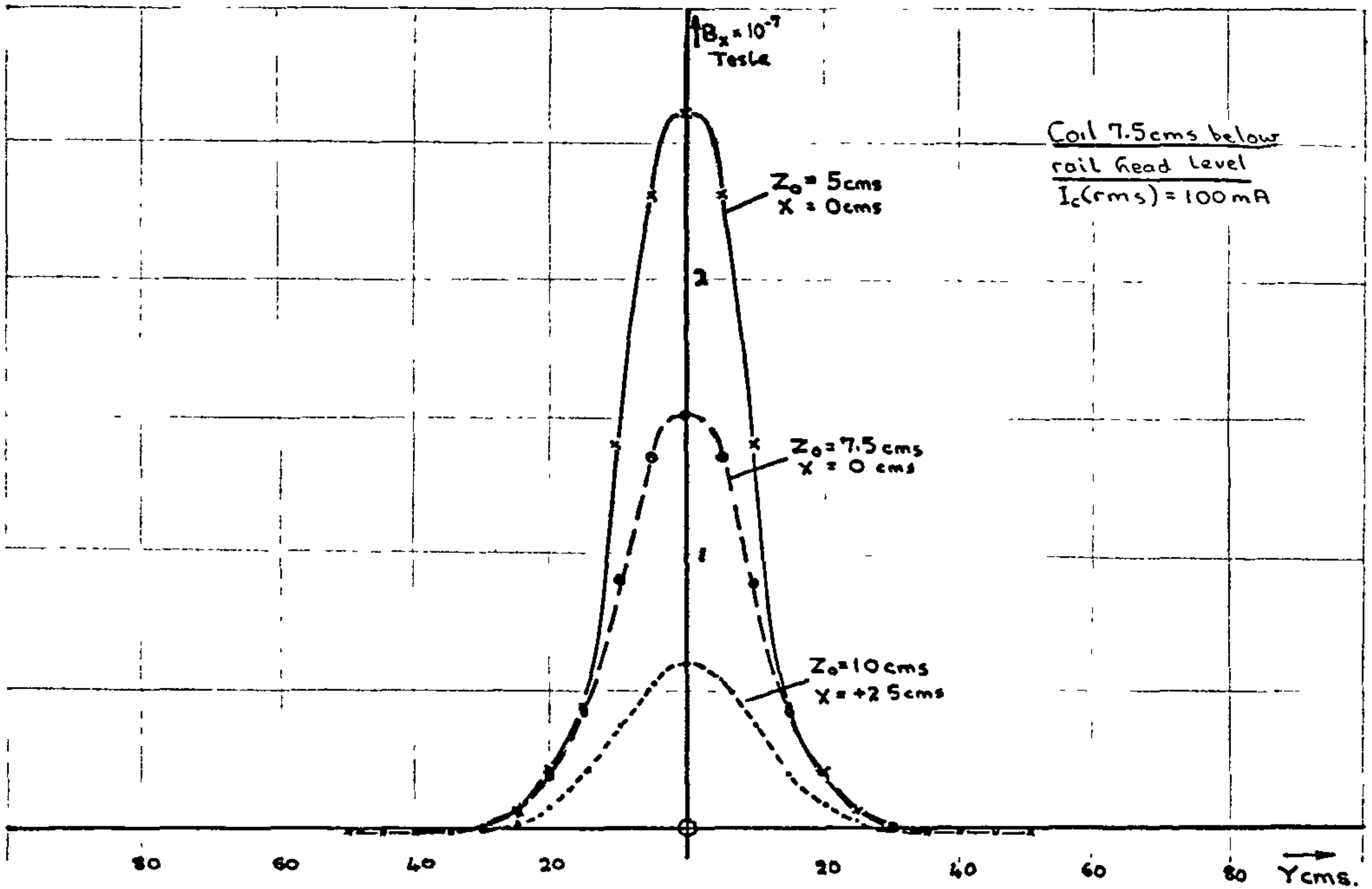


Fig. 77(a). Curves Showing Extreme Variations of B_x-Y and an Intermediate Position of the Pick-up Assembly. Coil 6" x 2", 10 turns

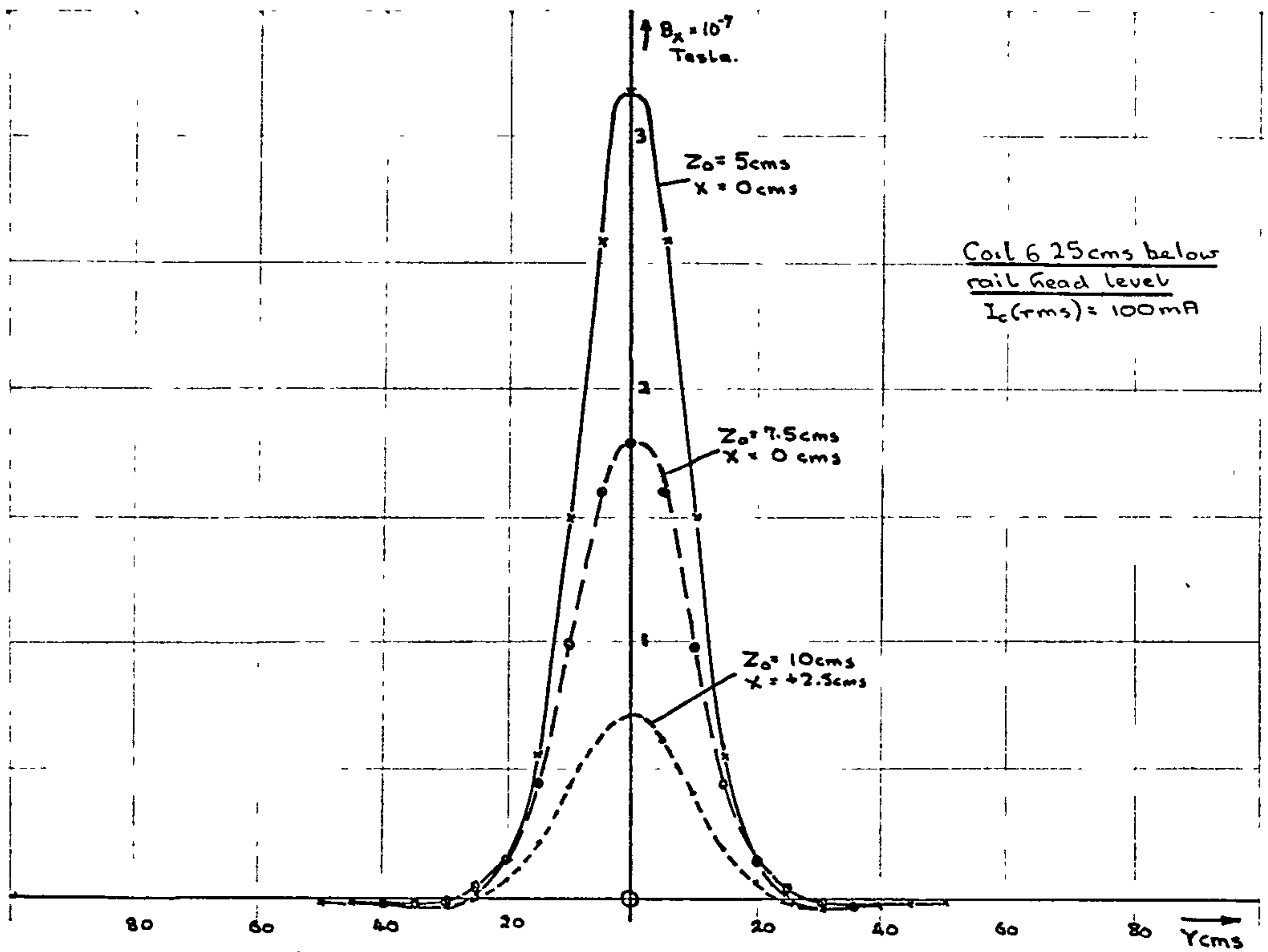


Fig. 77 (b). Curves Showing Extreme Variations of B_x-Y and an Intermediate Position of the Pick-up Assembly. Coil 6"x 2", 10 turns.

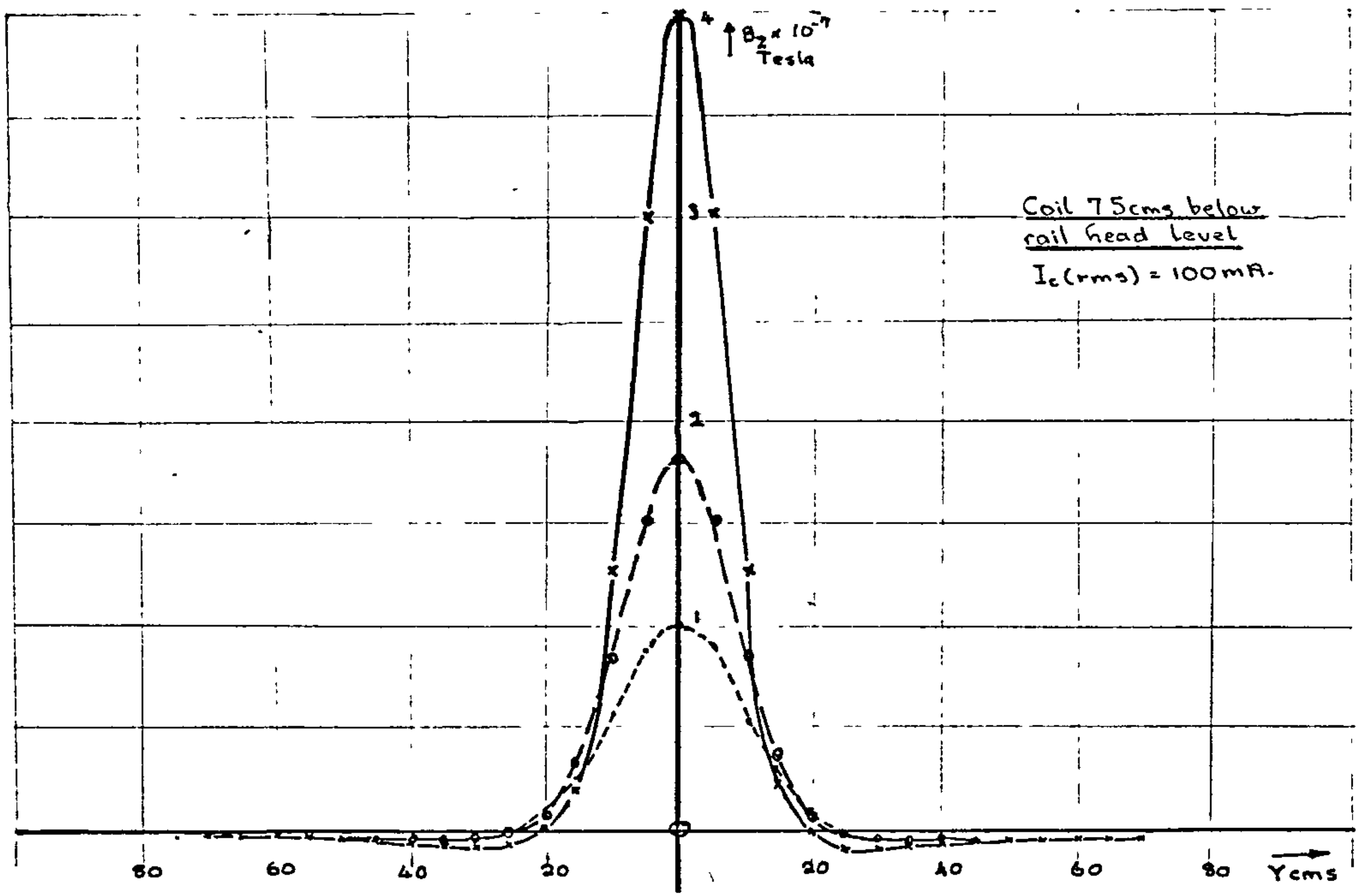


Fig 78 (a). Curves Showing Extreme Variations of B_z-Y and an Intermediate of the Pick-up Assembly. Coil 4"x2", 12 turns.

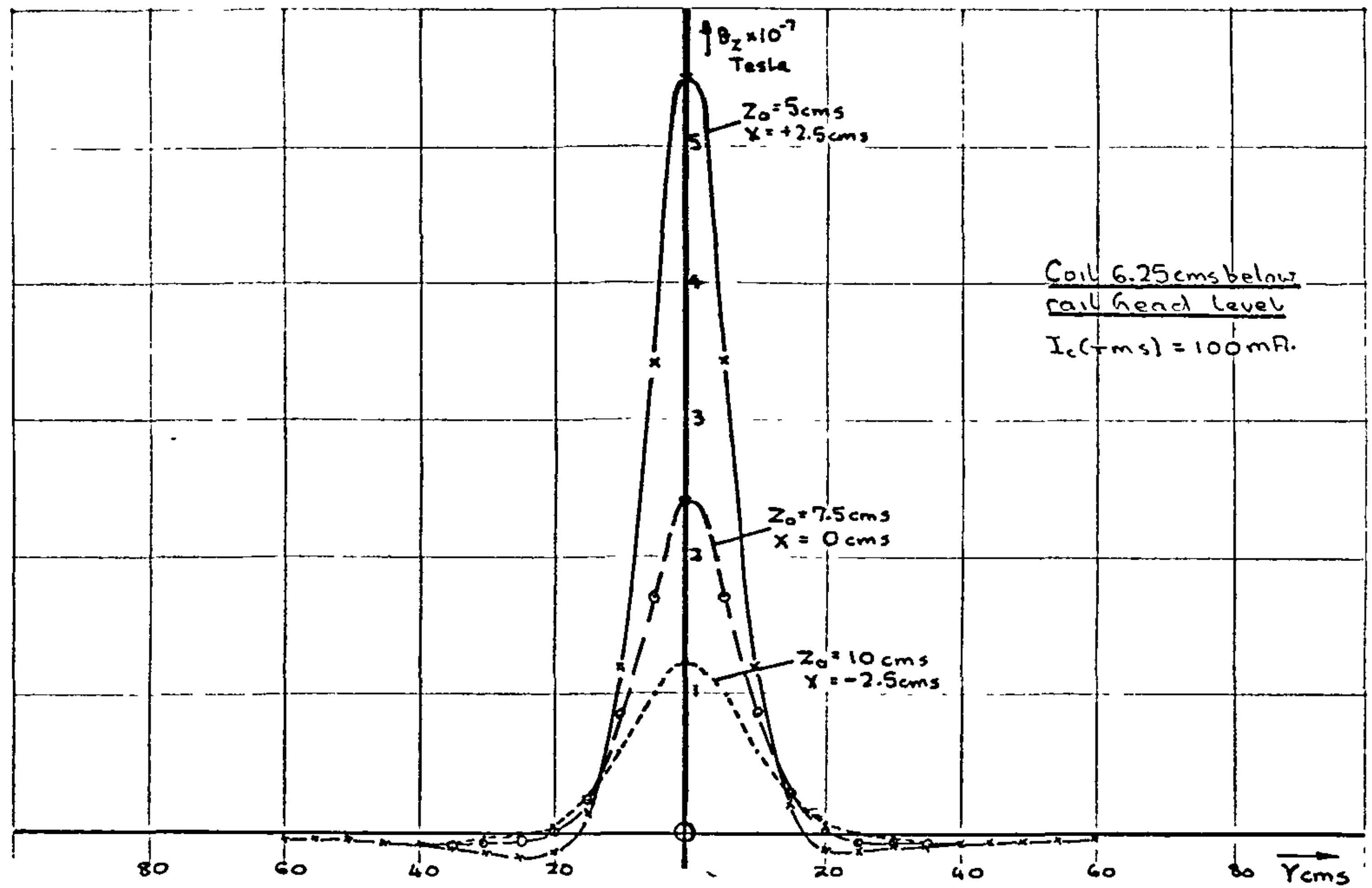


Fig. 78 (b). Curves Showing Extreme Variations of B_z-Y and an Intermediate Position for the Pick-up Assembly. Coil 4"x2", 12 turns.

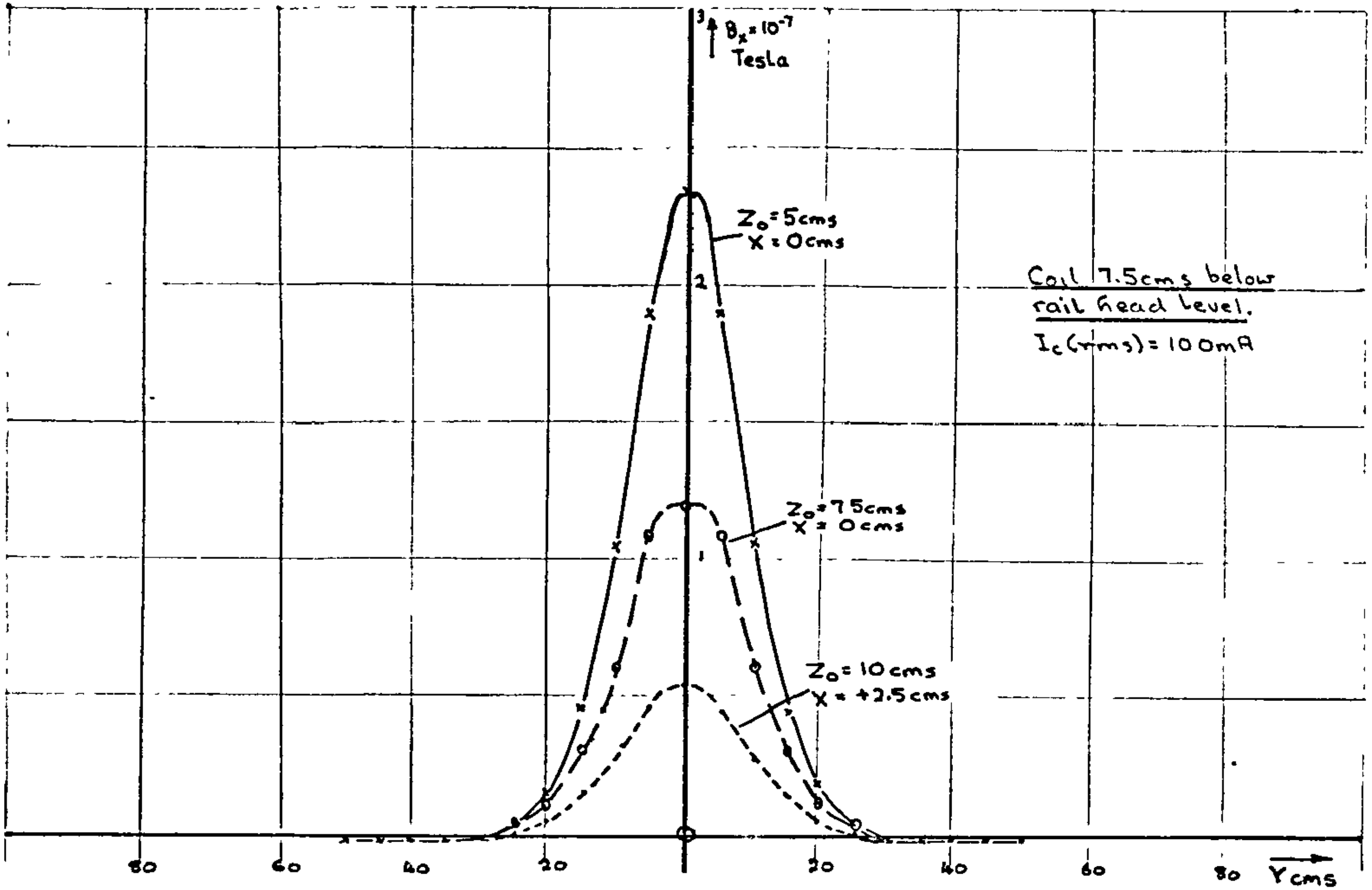


Fig. 79 (a). Curves Showing Extreme Variations of B_x-Y and an Intermediate Position of the Pick-up Assembly. Coil 4"x 2", 12 turns.

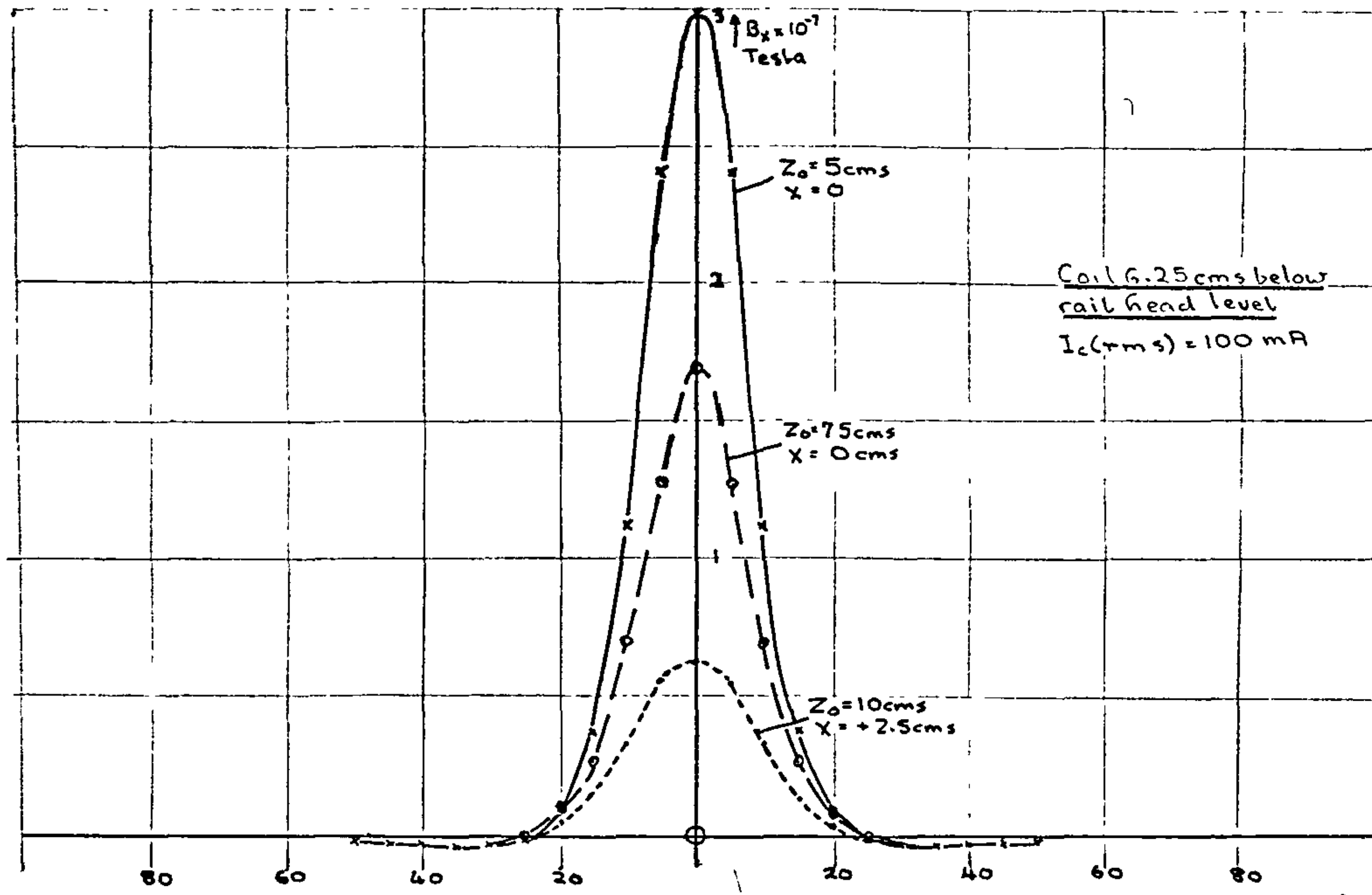


Fig. 79(b). Curves Showing Extreme Variations of B_x-Y and an Intermediate Position for the Pick-up Assembly. Coil 4"x2", 12turns.

Type of Coil	Size	R Ω	L μH	X_L (@29kHz) Ω
Bobbin Coil	1" dia.	0.076	15	2.7
	2" dia.	0.155	50	9.1
Rectangular	4" x 2"	0.256	25.1	4.6
Coils	6" x 2"	-	27.5	5
Rectangular Coils (with	4" x 2"	-	27.5	5
connecting leads)	6" x 2"	0.375	30	5.5
* on the rail foot	6" x 2"	0.375	29	5.3

Table 6. Inductance, Resistance and Reactance of Small Circular and Rectangular Coils Remote from the Rail.

Type of Coil	Size	Depth below rail head level - dcm.	R''_z	R''_x
Rectangular	6" x 2"	7.5	-7.4	-23
		6.25	-7.4	-11.5
"	4" x 2"	7.5	-8.7	-25
		6.25	-7.8	-10

Table 7. Variation of R''_z and R''_x for the Telegram Coils on the Rail Foot with Depth of Tele gram Coil Below Rail Head Level.

7.5 cms below rail head level (for both coils) but the 6" x 2" coil giving the higher values of flux density. The magnitude of B_x would also appear to be a limiting factor. The best range of pick-up height would appear to be between 5 and 10 cms above the rail head (Z_o) providing the fall off in B_x at Z_o = 10 cms can be tolerated (fig. 73).

5.3.2 Variation of R'_z, R'_x with Lateral Displacement X and Z_o.

An examination of the B_z - Y and B_x - Y variations for both coils was carried out and the results are shown in figs. 76 to 79, (a) and (b), for the telegram coil 6.25 and 7.5 cms below rail head level. Readings were obtained for the extreme variations of the B_x and B_z fields and an intermediate position of the pick-up assembly - Z_o = 7.5 cms and X = 0 cms. The original definition of R'_z and R'_x is now meaningless, the important ratio being that of the minimum value of field encountered at Y = 0 to twice the maximum value of flux density encountered midway between adjacent coils wound in the same sense - denoted by R" and the appropriate subscript. Table 7 shows values of R" for the spacing of the coils 0.76 m (i.e. one sleeper spacing apart). This table gives the worst possible values of R", excluding interference from the parallel wires and neglecting noise. The values of R''_z are much smaller than those hoped for, but the values of R''_x are encouraging. It would therefore seem that, as the pick-up height cannot be varied much, the telegram coils must be spaced differently or some compensation may be obtainable by suitable arrangement of the pick-up assembly, or both. On increasing the spacing of the telegram coils to 1 metre the values obtained in Table 8 result.

Type of Coil	Size	d cms	R''_z	R''_x
Rectangular	6" x 2"	7.5	-14.5	-28.6
		6.25	-14.4	-21.2
	4" x 2"	7.5	-14.2	-23.8
		6.25	-15.9	-17.3

Table 8. Values of R''_z and R''_x for a Coil Spacing of 1 metre.

These values for R''_z and R''_x look far more promising and would seem to represent a practical system. One interesting fact, with the steel rail present, is the reversal, away from the coil, of phase of the B_x field component; this is due presumably to the distortion of the field by the steel rail.

5.4 Coil Impedance on the Rail Foot.

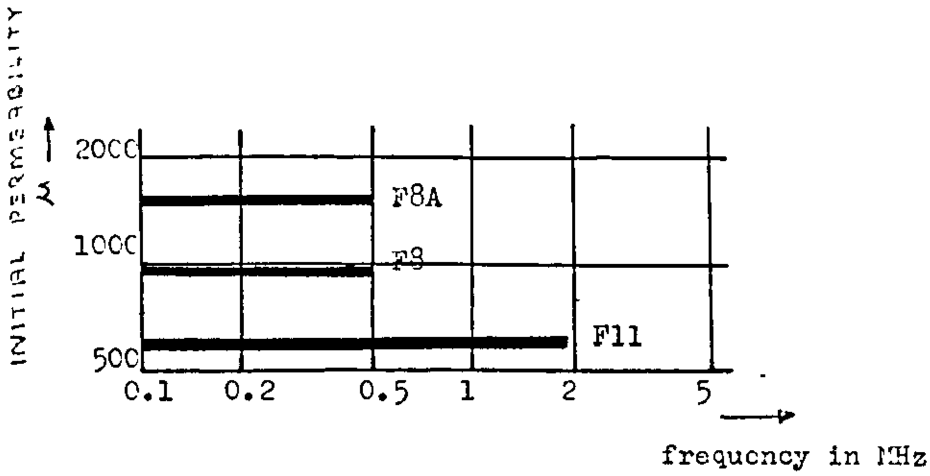
Placing the coil on the rail foot, together with its connecting wire, a small decrease in the reactance of the coil is observed - see table 6 for the actual values. Although it is only a small percentage change, for sixteen coils it represents a change of about 3 ohms. total. This decrease is due to the distortion of the flux passing through the coil by the presence of the steel rail.

5.5 Conclusions.

The reception of two bits of information simultaneously is certainly feasible but the vertical and horizontal movement of the pick-up assembly may prove to be a limiting factor. By using the coils on the rail foot, due to distortion of the steel rail, a slight increase in flux density is obtained. The use of the telegram coils 6.25 cms. below rail head level also gives higher values of flux density.

6. THE TRAIN PICK-UP COILS.

The signals transmitted from the track coils must be received by the train and hence some form of train-borne aerial is needed. The magnetic fields used are weak (less than 10^{-6} Tesla) and the use of high permeability material for the aerial is therefore desirable. The introduction of a magnetic material in the pick-up coil makes it possible to concentrate through the coil the magnetic flux from a larger area, thus reducing the size of the loop needed and producing a higher induced emf; the obvious choice for the magnetic material in this case is a ferrite rod. The increase in flux linkages which result, when a ferrite rod is used, is a strong function of the geometry of the core (see reference 9), cylinders with a relatively large length to diameter ratio yielding a larger increase in the flux passing through the receiving coil. By increasing the flux passing through the coil, a higher induced emf is produced and hence an effective amplification is obtained. The ratio of the emf induced with the rod present to that without the rod is referred to as the effective permeability - μ_{eff}. This is not the same as the initial permeability of the material (see reference 10). The parameter $\mu_{eff.}$ varies almost parabolically over the length of the rod, being a maximum at the centre, for the rod in a uniform field. Hence, there is an optimum position for the coil on the rod (see reference 11). The maximum value for the flux density to keep the ferrite on the linear portion of its B - H curve is about 0.15 Tesla and, for the flux densities used in this communication system, there is no likelihood of saturation occurring.



Optimum Frequency Range of Ferrites Used

Ferrite Grade		F8A	F8	F11
Initial Permeability		1500	1000	600
B(sat) Gauss		3000	3500	3500
Wavebands		LONG	LONG	LONG AND MEDIUM

Fig. 80 . Specifications of Ferrite Rods Used.

(From Manufacturer's Data - Neosids Ltd.)

In the original British Rail system a single vertical rod was used above the coils. This was a rod 3.2" long by 9/16" diameter (eg FX 1183) wound with 108 turns nearer the 'receiving' end of 28 swg enamelled copper wire. It had an inductance of 600 μH.

As specific field components are to be received, the pick-up system is required to be directional. Tests were carried out with various grades of rod with different length to diameter ratios in a uniform field to see if the 'reception' pattern of the aerial could easily be made directional. An examination of a rod in a non-uniform field was also carried out. Finally an investigation was made into the use of two perpendicular rods for receiving two field components simultaneously.

6.1 Examination of Ferrite Rods in a Uniform Field.

Various grades of ferrite rod were used and fig. 80 gives an indication of their properties. The types of rod supplied were :-

1/4" diameter	F8	
3/8" diameter	F8A	Straight Rods
1/2" diameter	F8	
10 mm diameter	F11	Fluted

Two types of coil were used on the rods :-

(1) a single layer 100 turn coil, and

(2) a single layer coil - 50 turns per layer.

To obtain a uniform field a Helmholtz Coil arrangement was used. This consists of two coils of equal diameter separated by a distance equal to the radius of the coils. The field in the centre is found to be uniform and of one direction (see Appendix 6 for the relevant theory). Figure 81 shows a photograph of the Helmholtz Coils and the turntable used for rotating the pick-up coils. The coils were 30" (0.76 m) diameter, the turntable $11\frac{1}{2}$" (0.28 m) and calibrated every 10° (see fig. 82). A computer program was run to evaluate the field between the Helmholtz Coils and showed that within an area of approximately 0.10 m. radius from the centre of them a variation of flux density of less than 1% occurred and, for all practical purposes, this field can be assumed uniform. From Appendix 6 the flux density at the centre of the Helmholtz Coil arrangement is given by :-

$$B_z = \frac{4\mu_o d^2 I}{\sqrt{(5d^2)^3}} \text{ Tesla}$$

where

μ_o = $4\pi \times 10^{-7}$ Wb/A-m

d = radius of the coils = 0.191 m.

I = coil current in amperes.

From the above equation any desired value of B_z can be obtained.

Various ferrite rods were used with the two types of coil and figs. 83 to 87 are representative of their 'reception' patterns. These curves show the normalised induced signal with angle of rotation of rod to the magnetic field. The normalised signal is the ratio of the induced signal at some angle θ (see fig. 82) to the maximum induced signal. A plot for an air-cored coil is also shown.

Fig. 81 . Photograph of Helmholtz Coils.

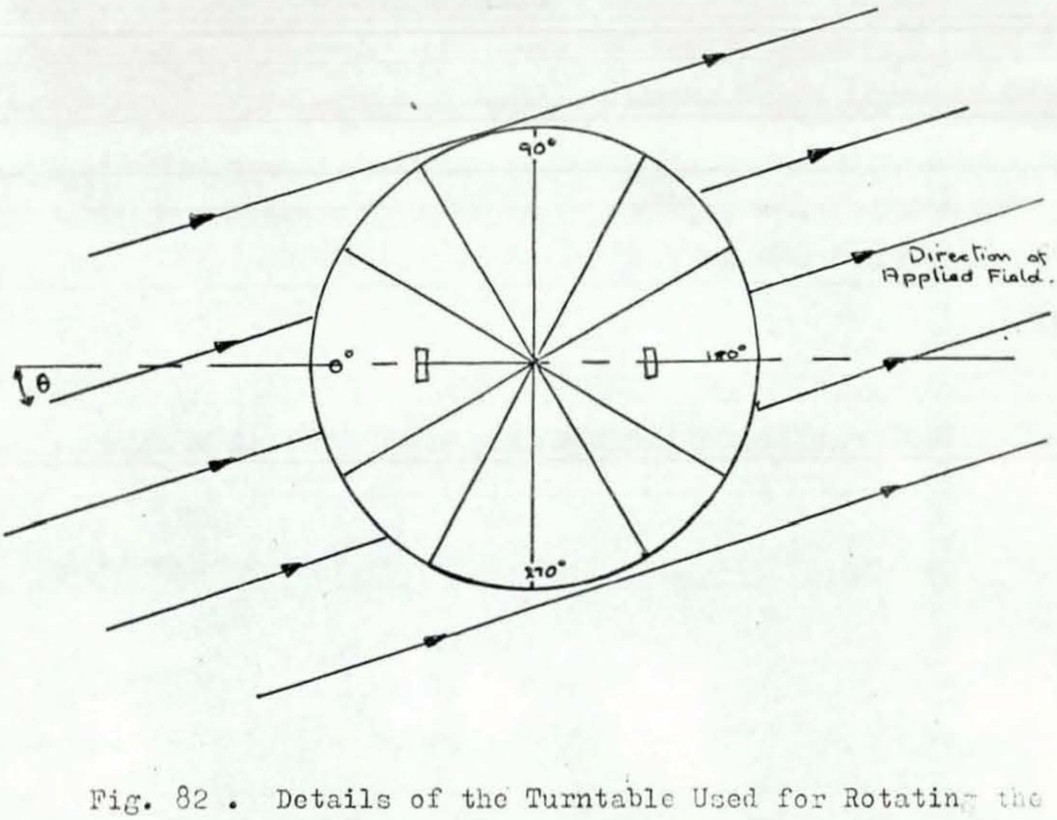


Fig. 82 . Details of the Turntable Used for Rotating the Pick-up Coils .

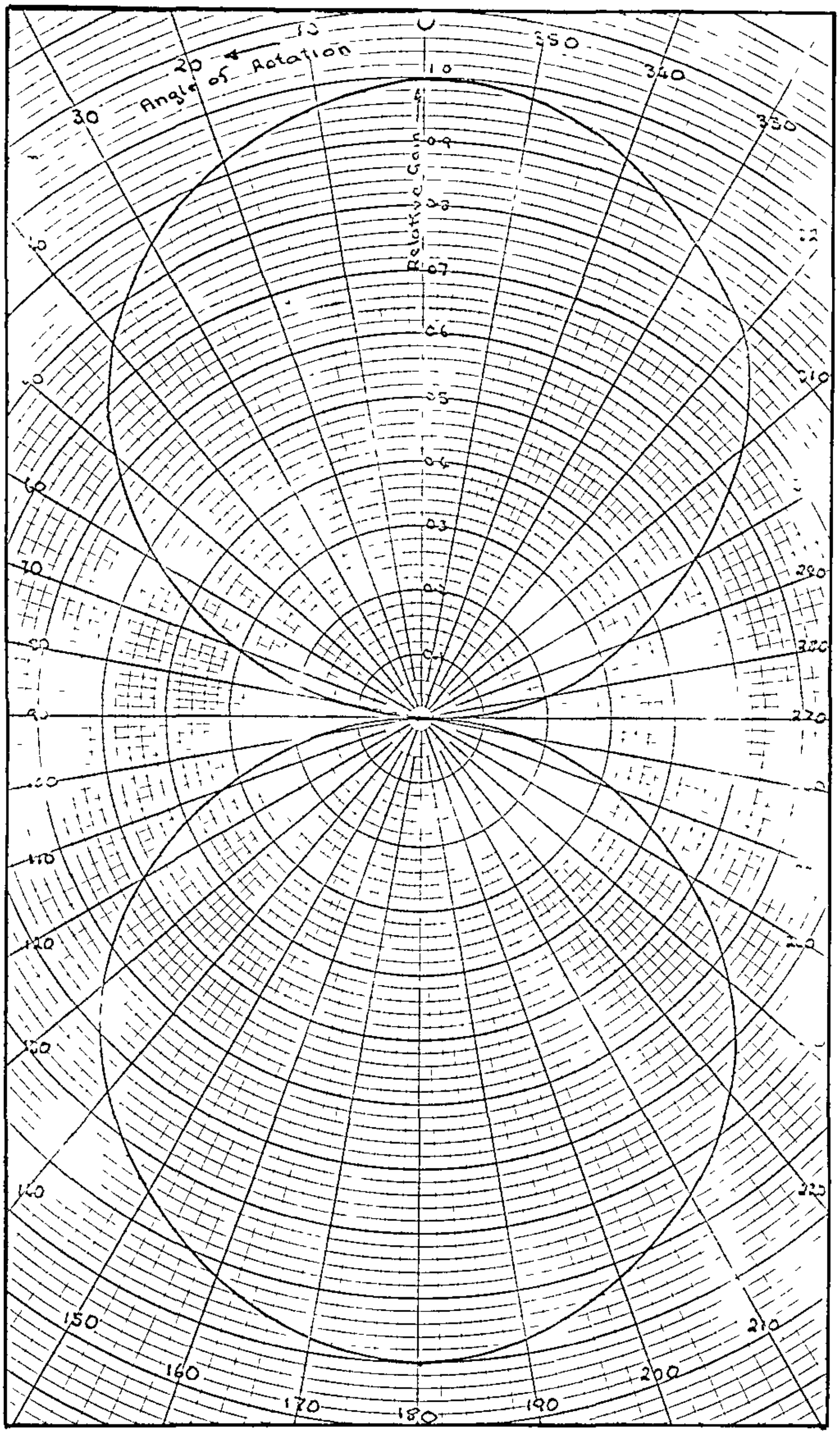


Fig. 33 . Reception Pattern of an Air-cored Coil of 100 turns

and length to diameter Ratio of 5.3 .

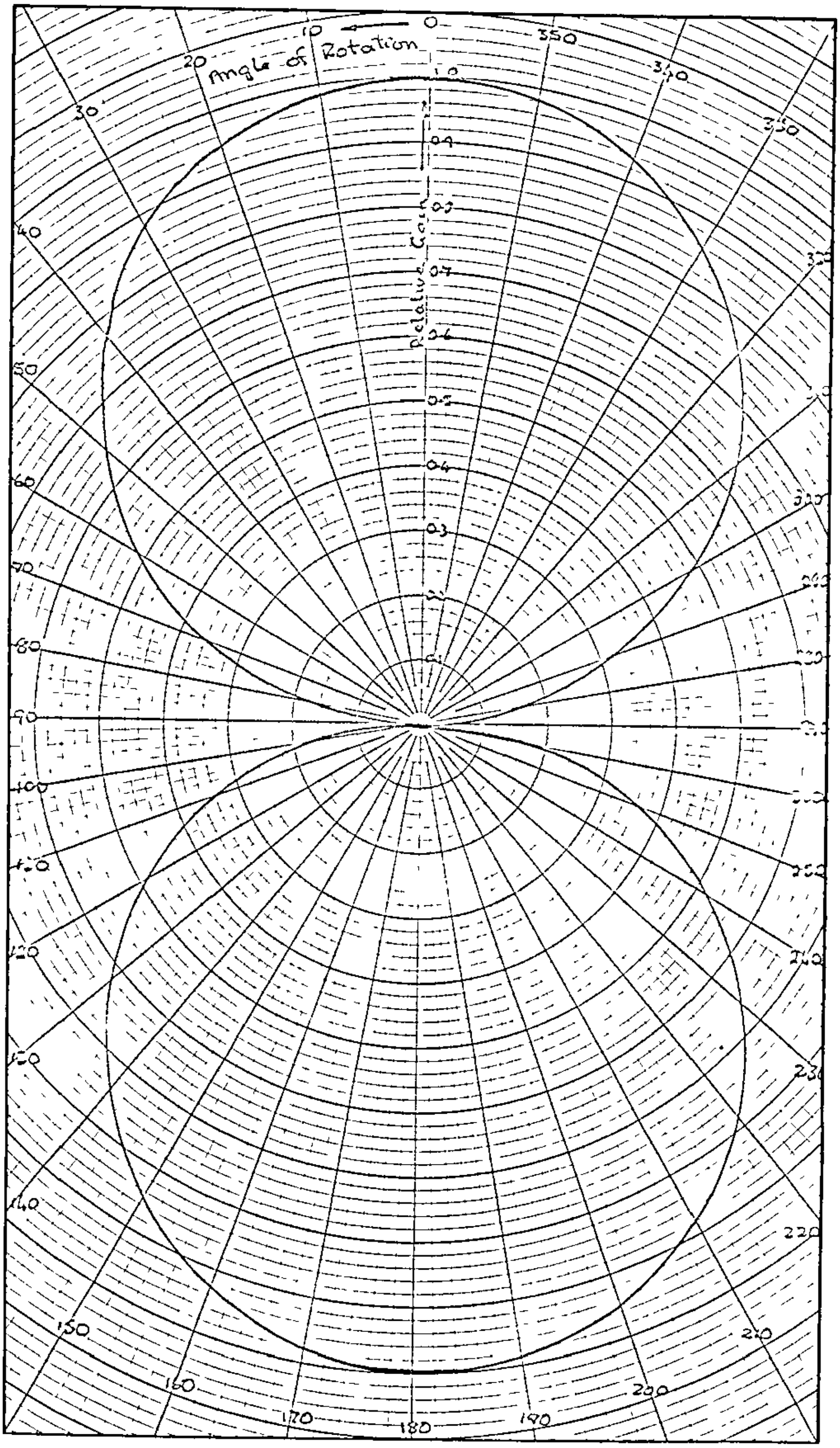


Fig. 34 . Reception Pattern of a Ferrite Cored Pick-up Coil; Type F3, ½" dia. x 4½" with a Single Layer Coil Placed Symmetrically about the Axial Centre of the Rod.

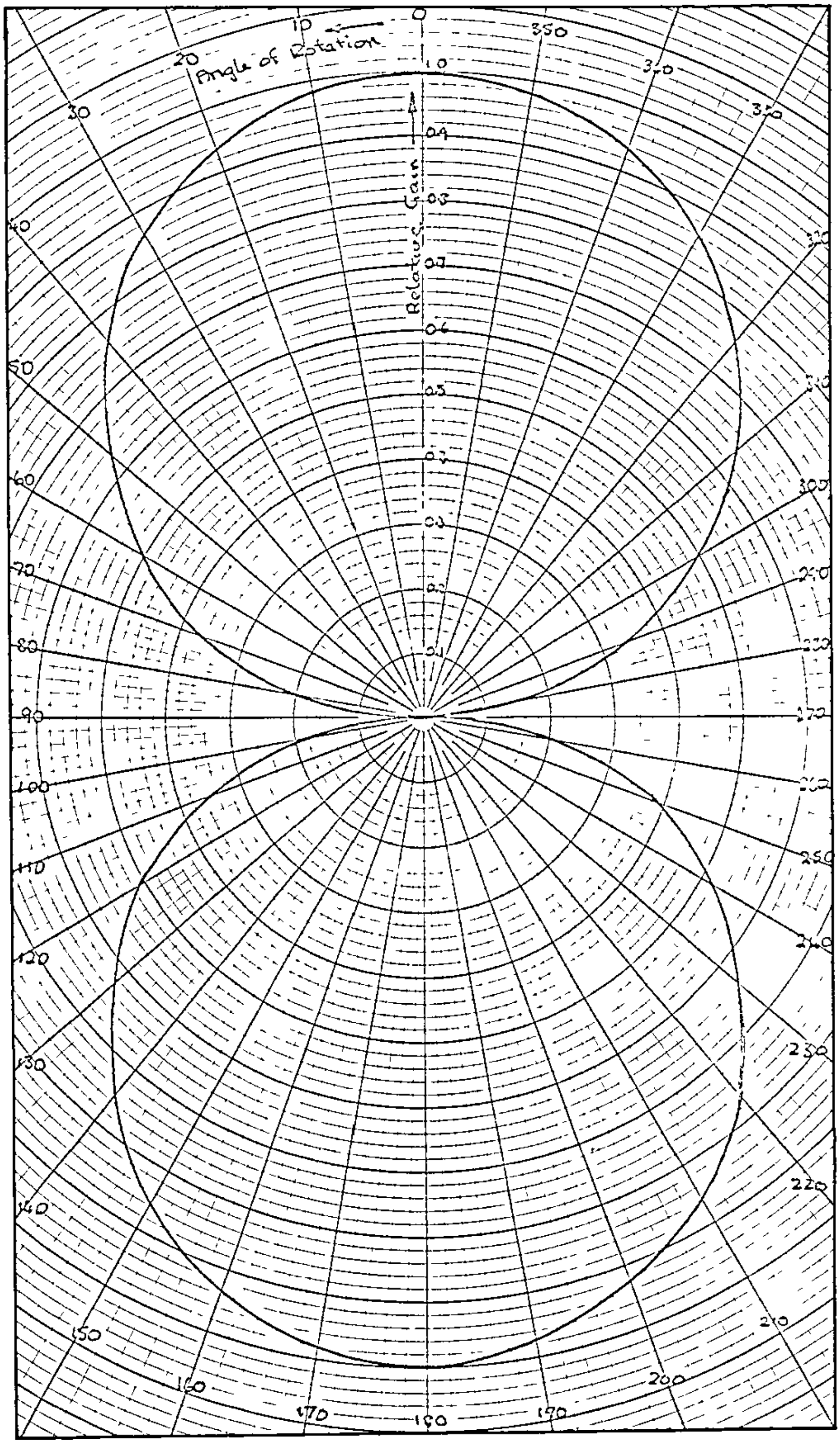


Fig. 55 . Reception Pattern of a Ferrite Cored Pick-up Coil: type F 11 - fluted - 10 mm dia. x 200 mm with a Single Layer Coil placed at One End of the Rod.

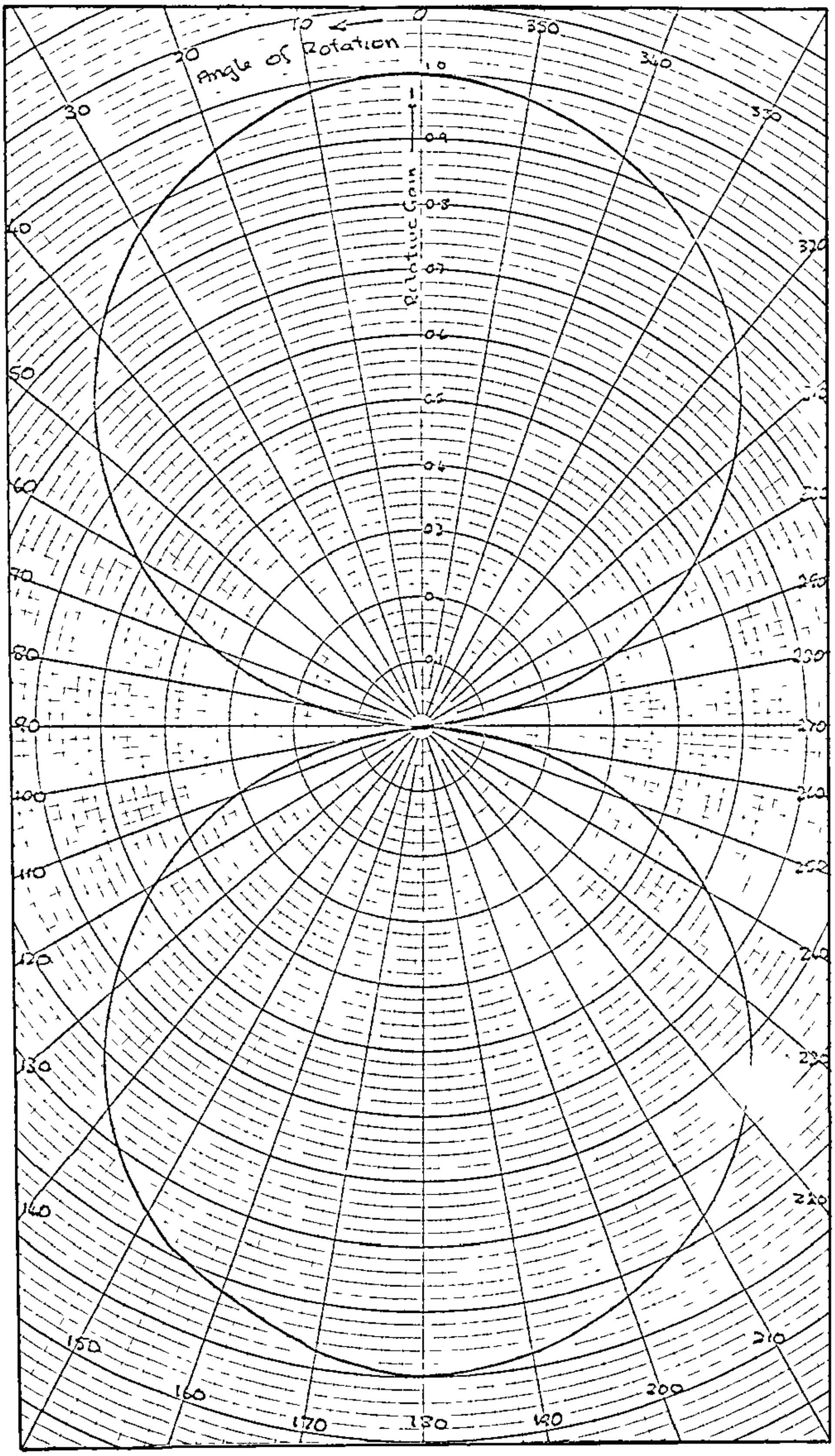


Fig. [illegible]6. Reception Pattern of a Ferrite Cored Pick-up Coil; type F[illegible]A, [illegible]" dia. x [illegible]" with a Double Layer Coil Placed Symmetrically about the Axial Centre of the Rod.

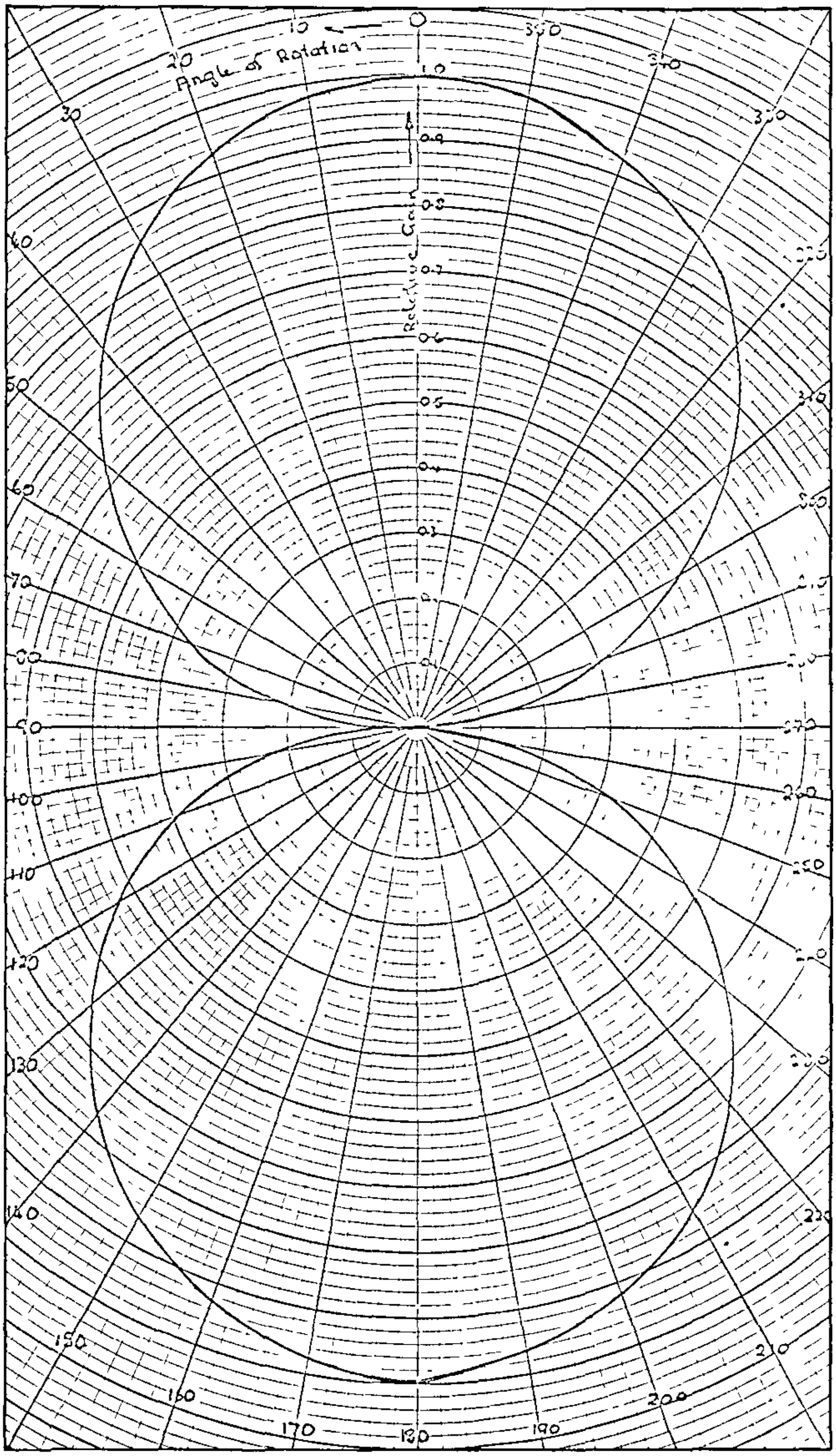


Fig. 37 . Reception Pattern of a Ferrite Cored Pick-up Coil; type F8, $\frac{1}{4}$" dia. x 6" with a Single Layer Coil Placed Symmetrically about the Axial Centre of the Rod.

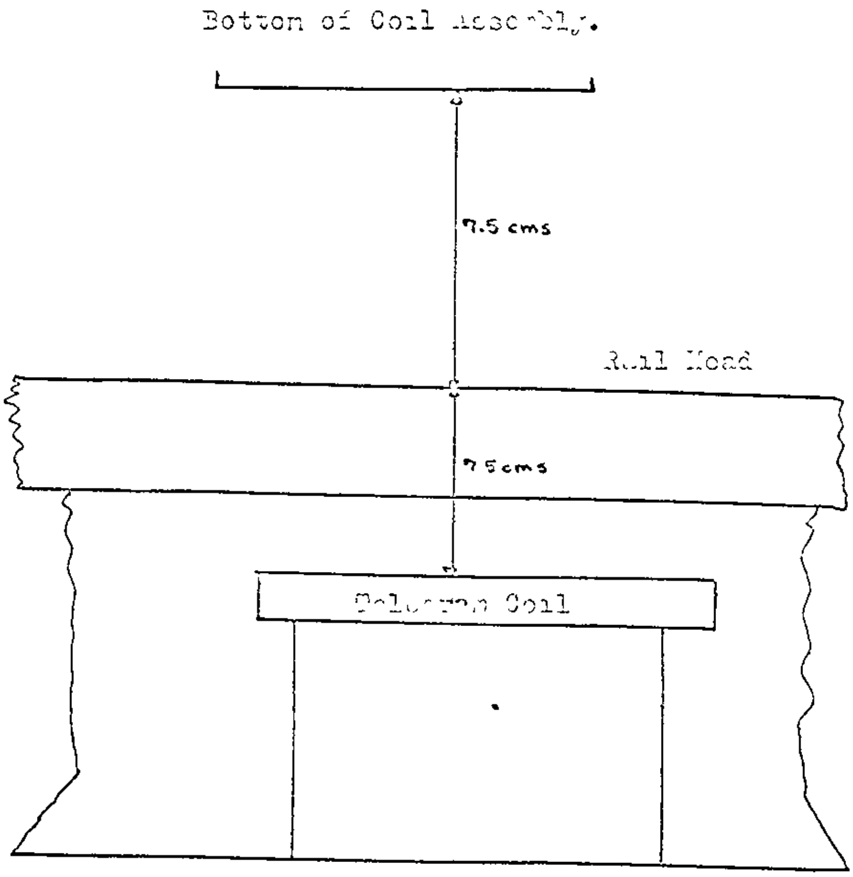


Fig. 88 . General Relation of Pick-up Coil Assembly to the Telegram Coil for Measurements in this Chapter.

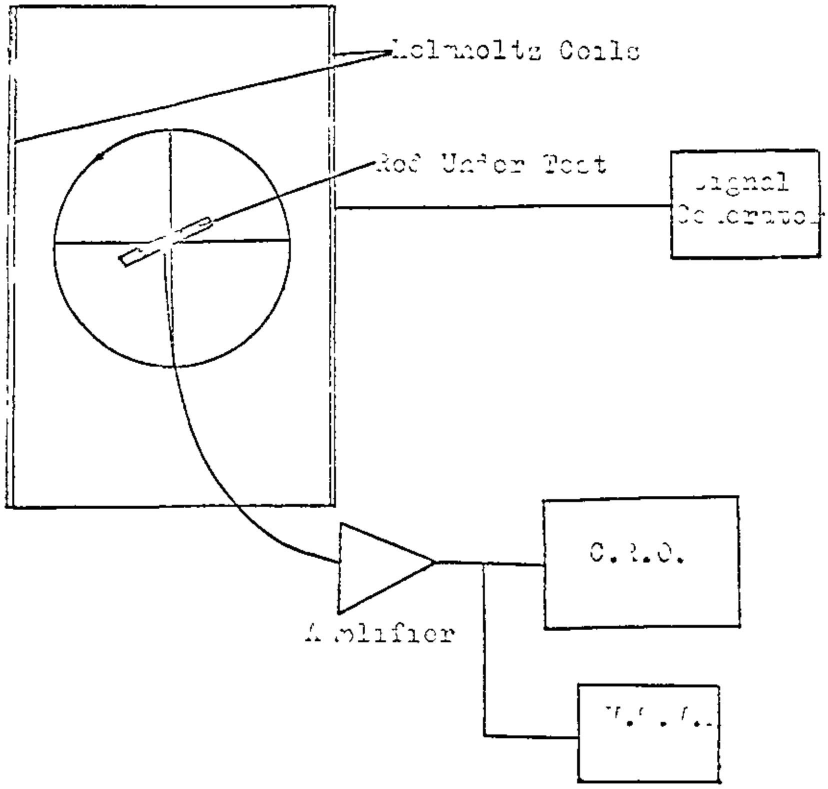


Fig. 89 . Method of Determining the Reception Patterns of the Pick-up Coils.

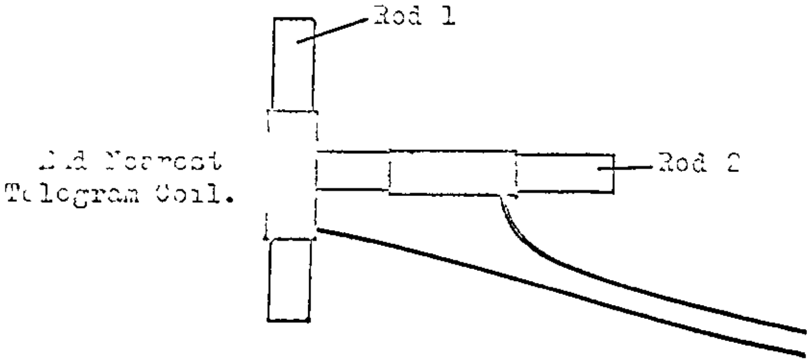
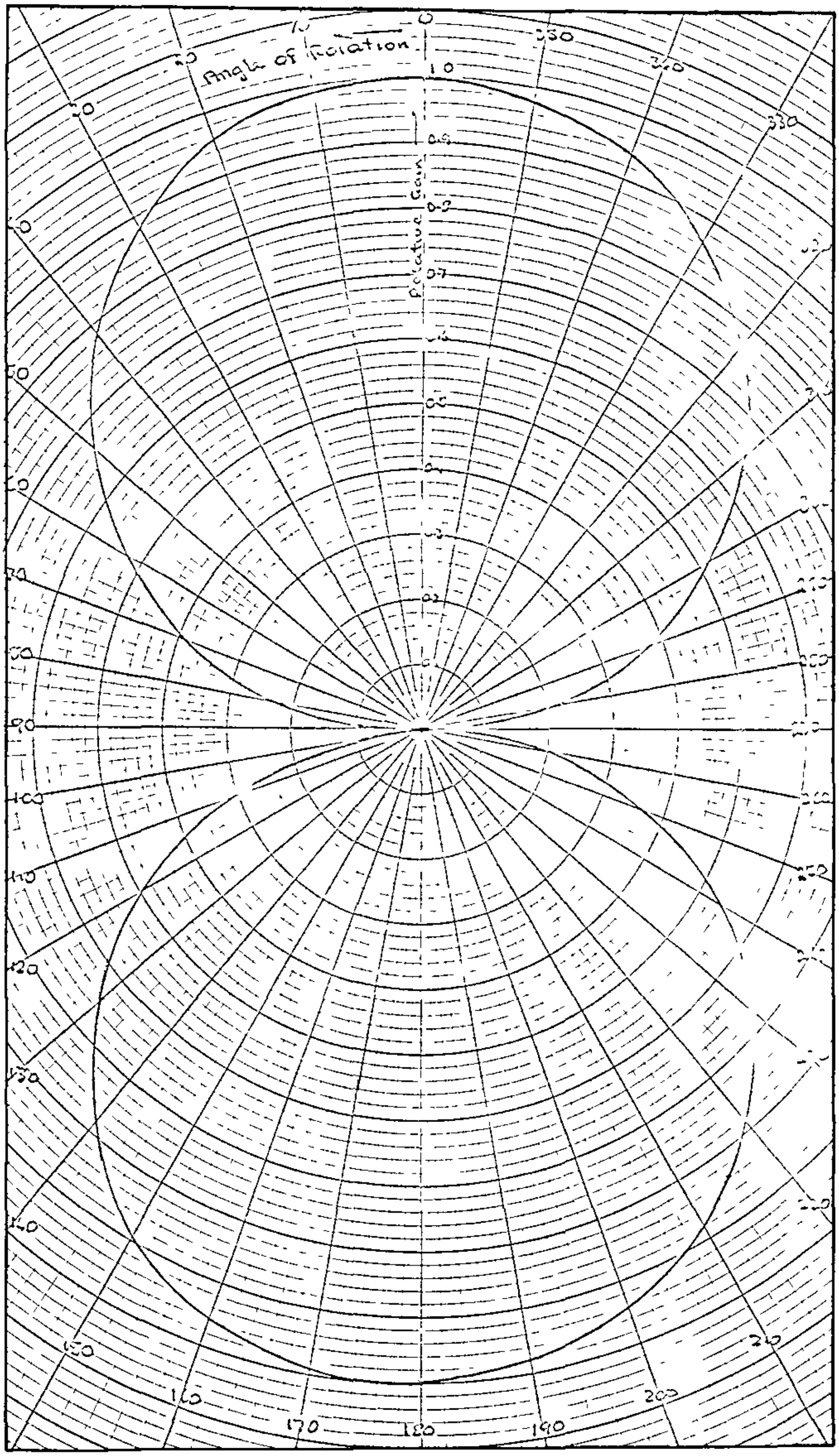


Fig.90 . Arrangement A of the Rods for Receiving Two Bits of Information.

The 'reception' pattern of the rods and the coil have a figure of eight pattern - i.e. the induced signal is proportional to Cos θ. The pattern does not seem to vary with the length/diameter ratio of the rod, the type of coil used or the position of the coil on the rod. The maximum induced emf in the coil was observed to be when the coil was symmetrically placed about the centre of the rod. The method of measurement is depicted in fig. 89. A frequency of 29 kHz was used throughout the tests.

To obtain two bits of information simultaneously from a telegram coil, a ferrite rod aerial is required for each field component and the pick-up coils must run symmetrically about the centre line of the rail - this is because the coils are staggered about this line. As the B_x field is the weakest, the pick-up coil for this component should be closest to the telegram coil and hence an arrangement for the aerial as shown in figs. 90 and 93 is required.

A test was carried out in the Helmholtz Coils to find the mutual interaction effects between two rods placed perpendicularly as in fig. 90. Figures 91 and 92 show the results and the patterns are still of the familiar figure of eight shape. From the practical readings taken there was only a small change between the values of the induced emfs in the rods by themselves and the emfs induced in the rods when in an inverted 'T' configuration. From the measurements recorded the $\frac{3}{8}$" rod (F8A) seemed to have a higher value of μ_{eff}. than the other grades of rod, but otherwise it had no outstanding advantages.



... 1 . Reception Pattern of Rod 1 for Arrangement A.
(N.B. This Pattern is Rotated through 90°)

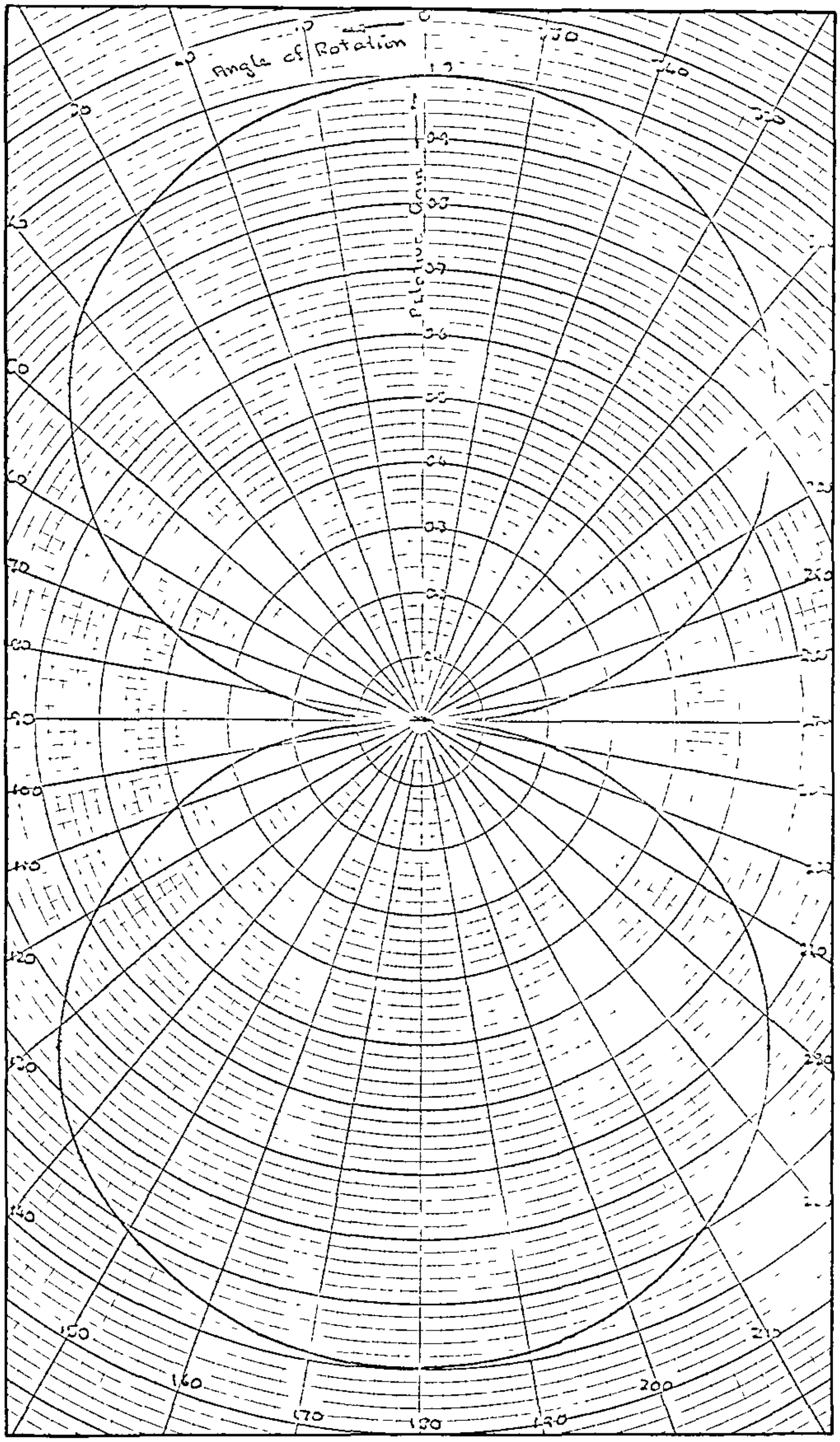


Fig. 92. Reception Pattern of Rod 2 for Arrangement A.

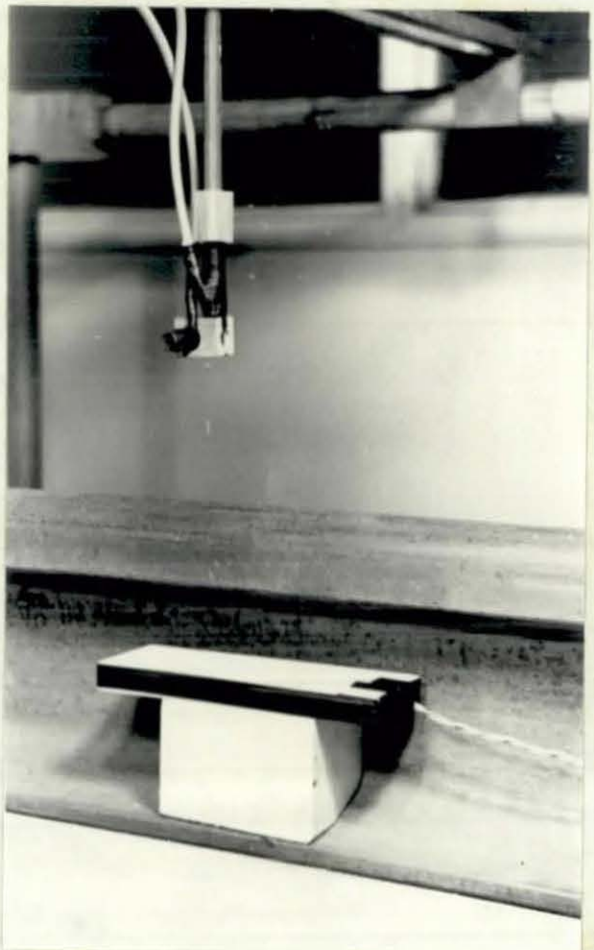


Fig. 93 . Photograph of the Pick-up Coil Assembly (Arrangement B)

and Position of the Telegram Coil on the Rail Foot.

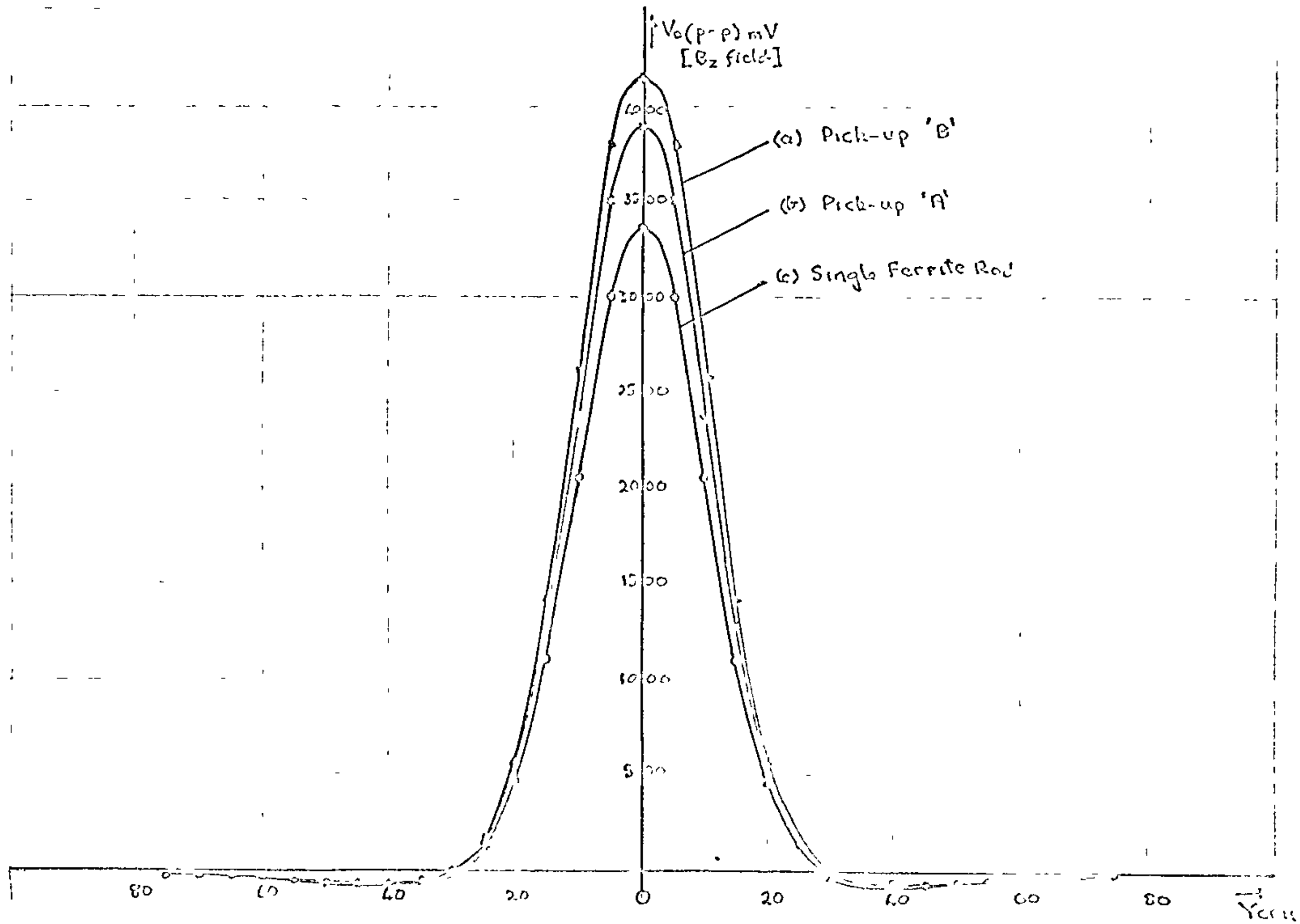


Fig 94. Effects of Rods in a Inverted 'T' Configuration
[Z field]

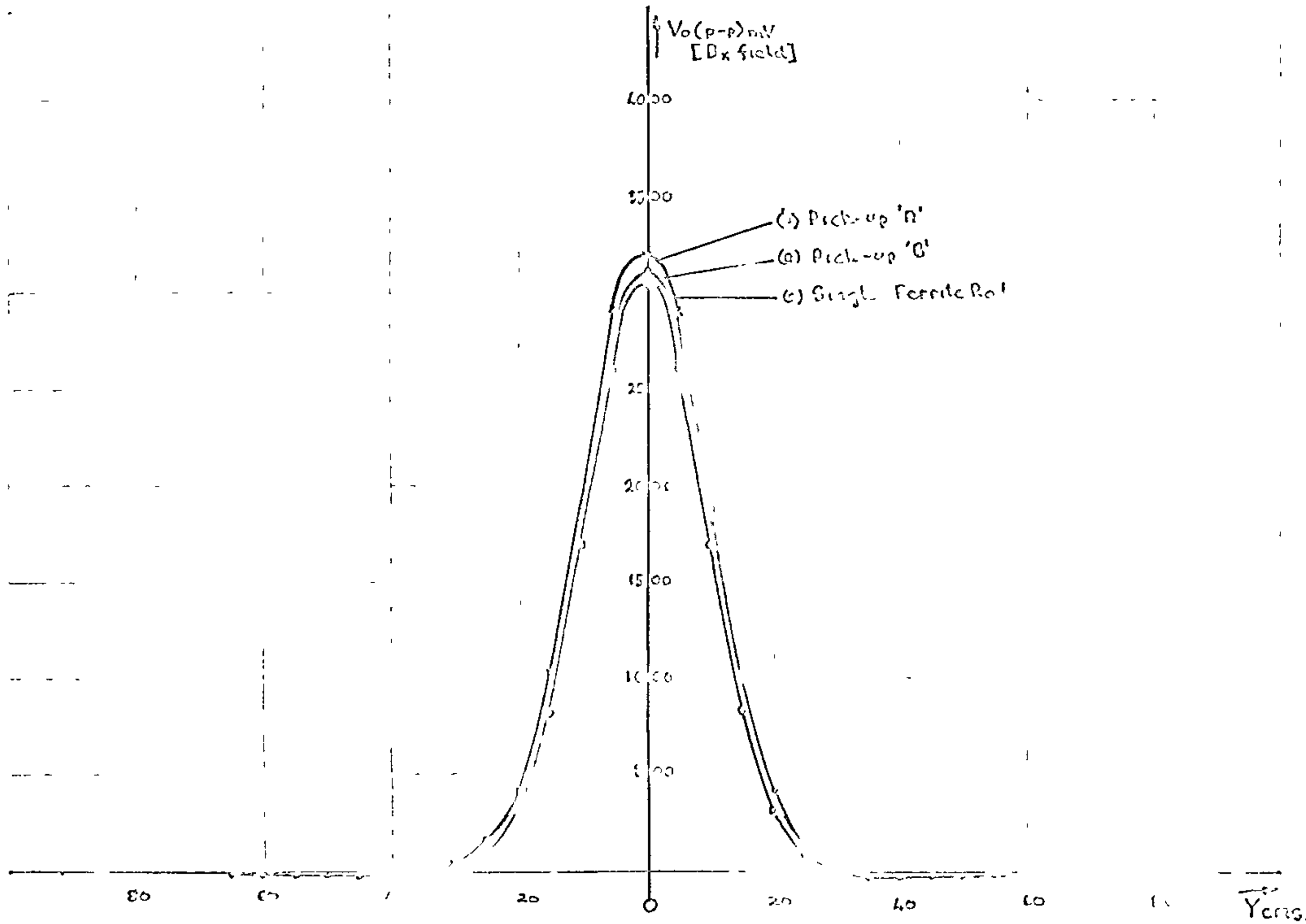


Fig. 46. [illegible] of Rods in an Inverted 'T' Configuration. [X Field].

6.2 Tests in a Non-Uniform Field.

An examination of a single rod in the non-uniform field of a 6" x 2" rectangular coil on the rail foot yielded the curves shown in figs. 94 and 95. It was found that there was a position of the coil on the rod which produced a maximum induced emf - this was towards the end nearest to the telegram coil. This is because μ_{eff} of the rod varies almost parabolically in a uniform field but when placed in a non-uniform field, such that the flux density at one end of the rod is greater than at the other end, the position of the maximum effective permeability will shift towards the stronger field.

The effect of having two pick-up coils placed close together (as in figs. 90 and 93) was also examined. Two rods of F8A material ($\frac{3}{8}$" dia. x 2$\frac{1}{4}$") were each wound with 100 turns of 28 swg enamelled copper wire. The induced emf in each coil was passed to a tuned amplifier, the output of which was fed to a valve voltmeter. Figures 94 and 95 also show the proximity effects of the ferrite rods, the B_x field being affected the least. No tests were carried out here on the reception patterns of the rods in a non-uniform field as the fields from the telegram coils were not uni-directional and hence the reception pattern does not have much meaning.

6.3 Conclusions.

From the investigations carried out in this chapter it can be seen that the reception patterns of rods in an inverted 'T' configuration are not significantly different to those from single rods. It would appear, also, that it is not easy to alter the reception patterns of ferrite rods. The induced emf from coils in an inverted 'T' configuration near the maximum field from a telegram coil is increased and hence provides slightly higher values of R'_z and R'_x.

7. A MODEL OF THE SYSTEM AND DISCUSSION

To provide a practical demonstration of the proposed system a third scale model was built. This consisted of a section of scale track, ten feet long, and a small truck. The telegram coil and parallel wire dimensions were scaled down (see appendix 7) as also were the pick-up coils. Figure 96 shows a general view of the system, whilst the following photograph shows details of the telegram and pick-up coils used.

The electronic apparatus on the train was required to do two things :-

(1) effect a phase comparison of the received signals and give a visual indication of the bits of information being picked up simultaneously, and

(2) store the received message and also give a visual readout of the store.

7.1 The Receiving Amplifiers and Phase Comparison.

Figure 98 shows a block diagram of the system to fulfil requirement (1). The signal from the parallel wires and the two signals from the telegram coils were first of all amplified in a tuned stage - f_o = 29 kHz. The signals were then amplified again so that the amplifiers were overdriven, thus producing an approximate square wave. A threshold device was also required to determine whether a telegram coil was being traversed - this was achieved by rectifying the received signal and applying the resulting d.c. level to a Schmitt trigger circuit. The threshold level of this circuit was determined by the potentiometer connected to the base of T6 (see fig. 99).

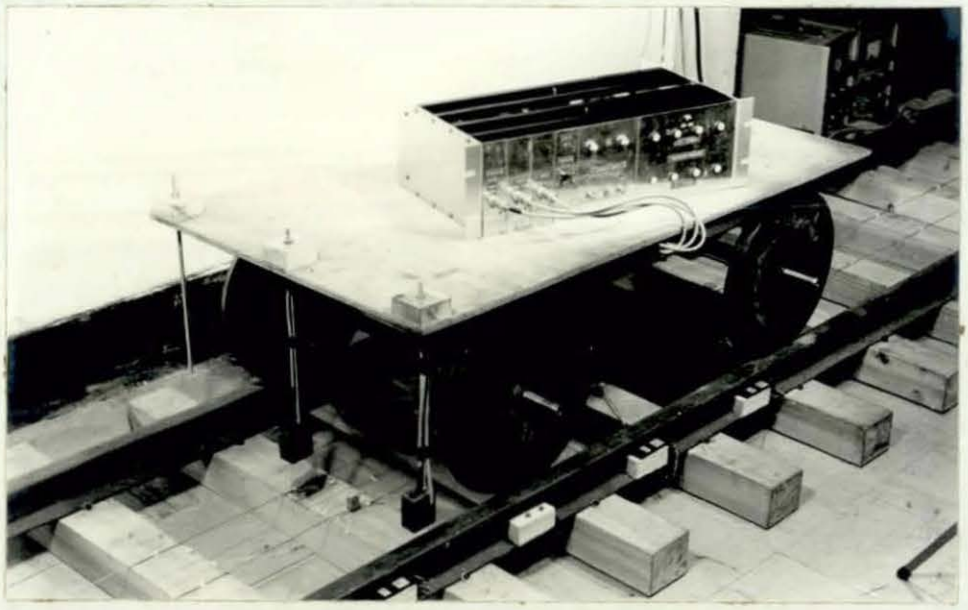


Fig. 96. Photograph Showing the General Layout of the Model.

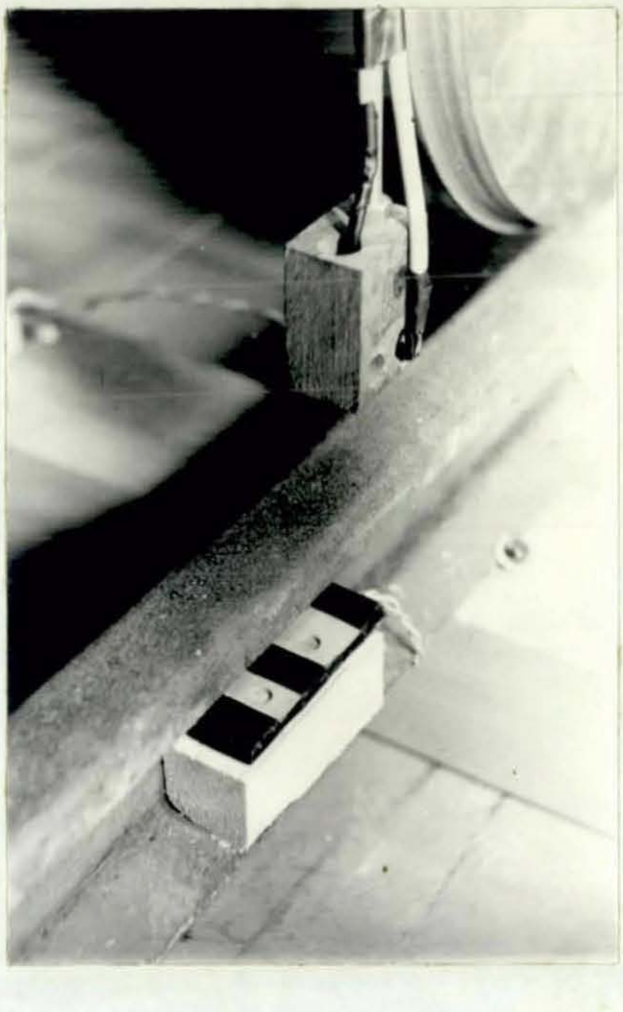
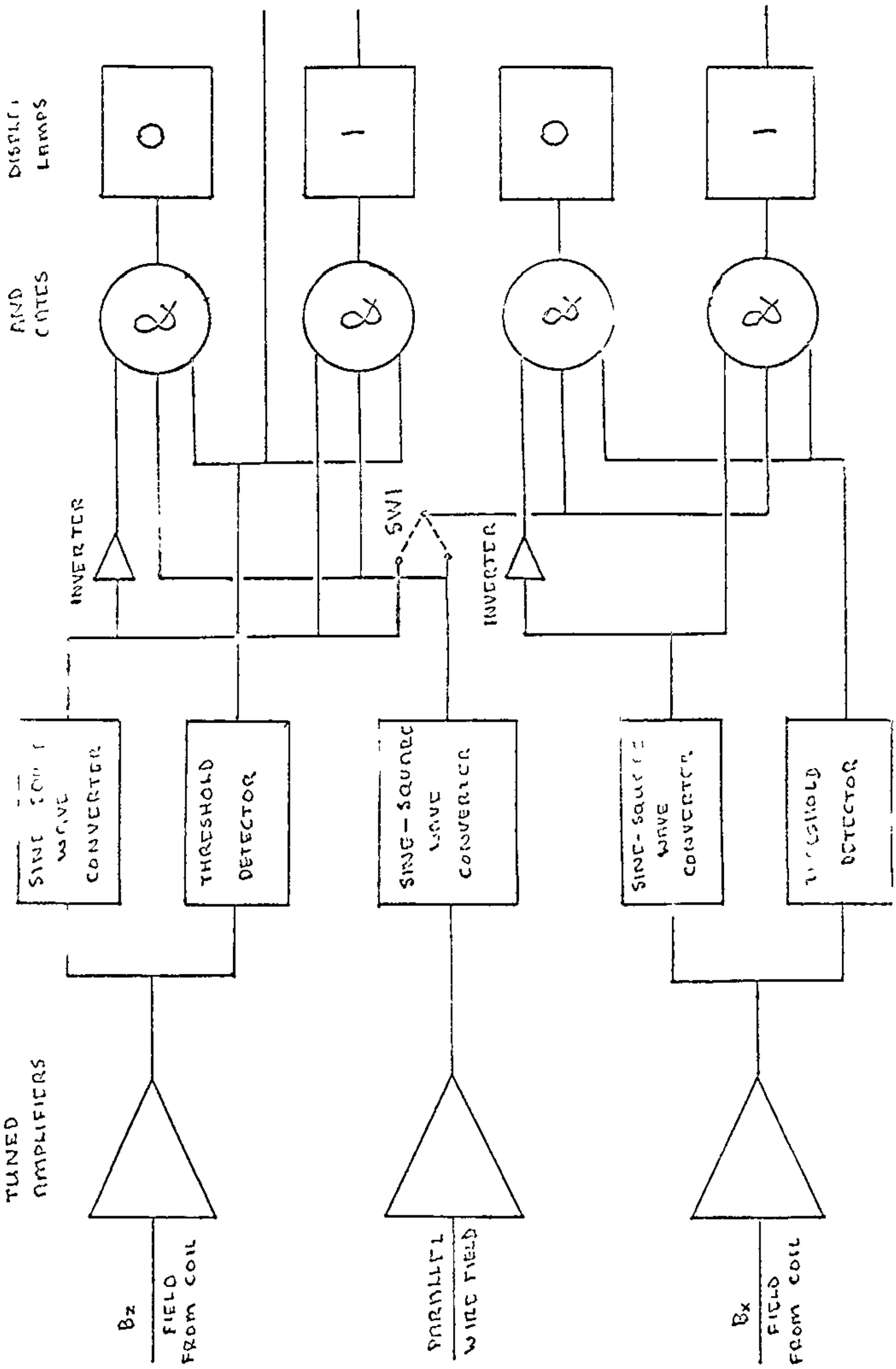


Fig. 97. Photograph of the Scaled Down Telegram and Pick-up Coils.



[illegible]. 6[illegible]. Block Diagram of the Train [illegible] and the

Display Unit for Each Bit of Info[illegible]

[illegible]

The signal from the telegram coil, the signal from the parallel wires and the output of the threshold circuit were fed to AND gates as shown in fig. 98. (The AND gates were made up from inverters and NOR gates). If all three signals were present, and the telegram coil signal was in phase with the parallel wire field, then the gate would have operated and a '1' would have been shown on the display panel, the inverted signal to the other gate making it inoperative. If the signals were out of phase then the AND gate with the inverted signal would have operated and a '0' would have resulted. To simplify the logic for laying the coils the B_x signal could be compared with the B_z signal and hence a switch, SW1, was included to show this principle (for a more detailed discussion see section 7.4 in this chapter). Some trouble was encountered with the mark to space ratio of the supposed square waves and the AND gates. The potentiometer in the emitter circuit of T3 was included to change its operating point and to give some control over this ratio and hence minimise the spikes appearing at the output of the inoperative AND gate.

7.2 The Telegram Message Store and its Visual Display.

For the second requirement of the receiving equipment some form of store was required into which the received information could be fed. Two stores were required - one for the B_z signal and the other for the B_x signal. The obvious choice for these stores was shift registers. To be able to feed the information into shift register three signals were required :-

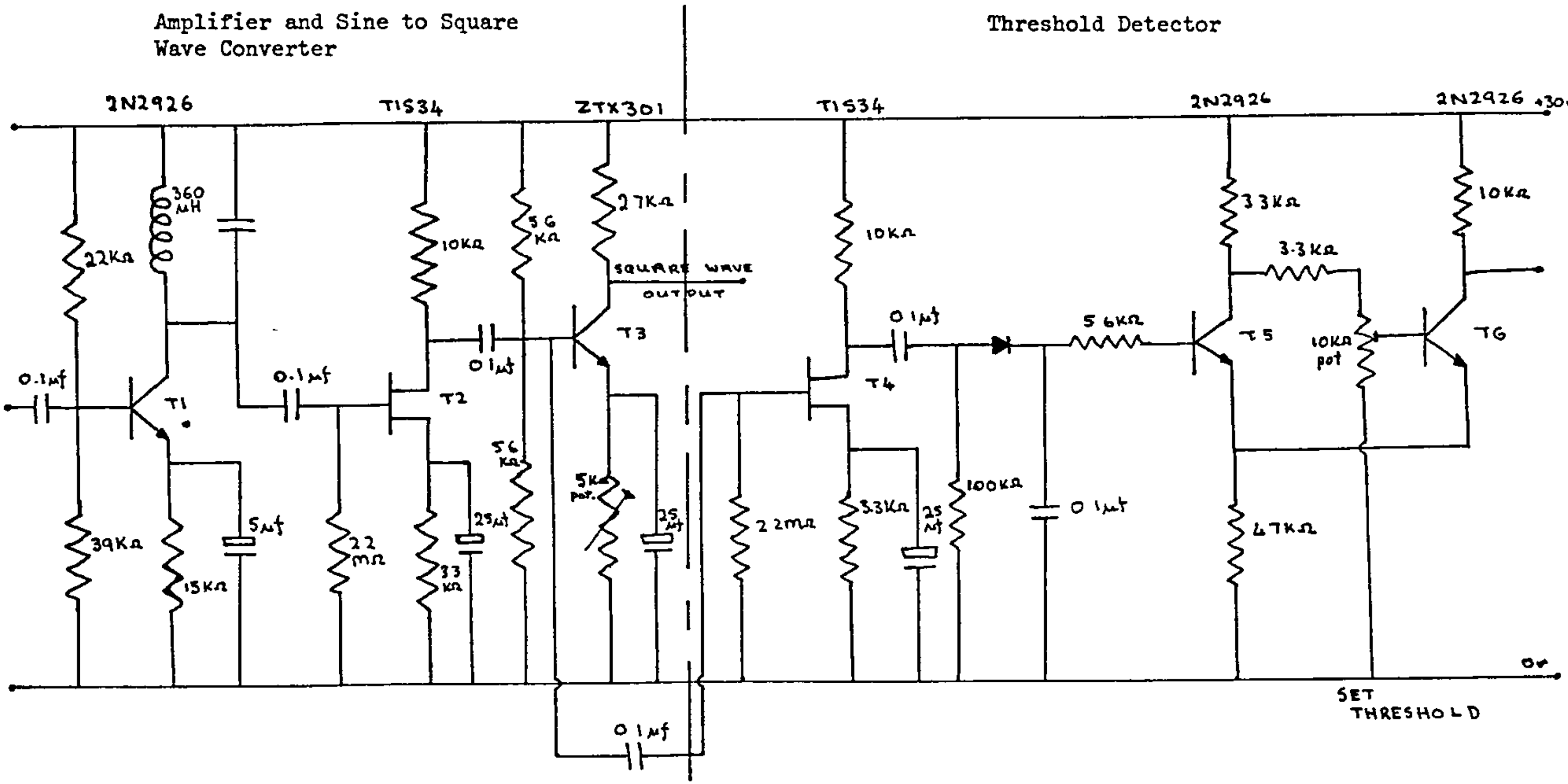


Fig. 99. Circuit Diagram of Train Receiver Unit, showing Sine-Square Wave Converter and Threshold Detector.

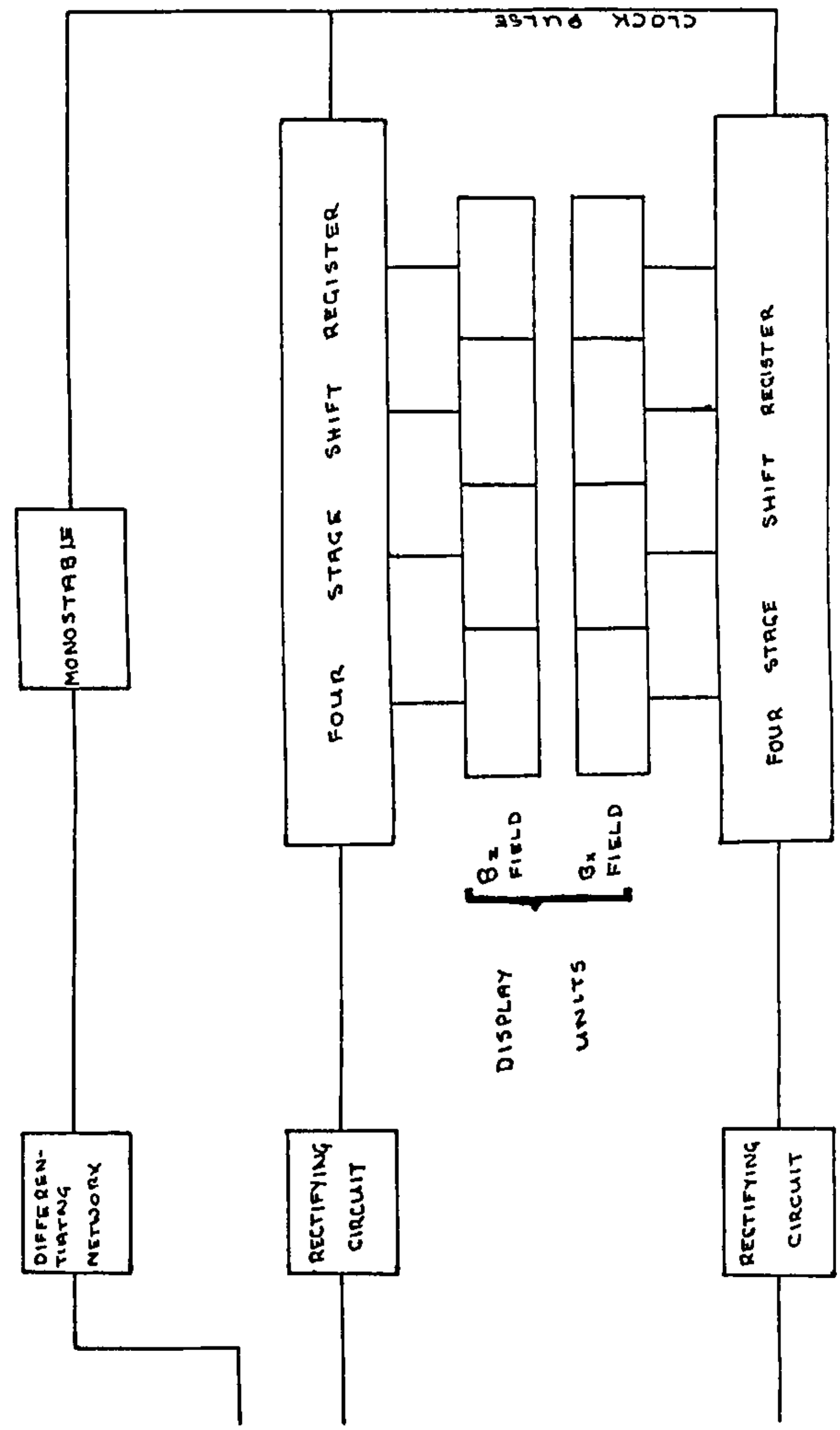


Fig. 10C Block Diagram of a System for Storing the Received Information and also Giving a Visual Readout.

(1) a two level signal representing B_z

(2) a two level signal representing B_x, and

(3) a clock pulse to cause the above information to be read into the store.

The first two signals were obtained by rectifying the input signal to a lamp driver of the instantaneous display. For the model a lamp driver for a '1' was used but one for a '0' would have sufficed - the logic being reversed. This d.c. level was sampled by the clock pulse and at the same time fed into the store. The clock pulse appeared a short time after the lamp drivers had operated so that the capacitors in the rectifying circuits had time to charge up. The clock pulse was obtained by differentiating the output of the Schmitt trigger, using an invertor to buffer it and to clip the negative going pulse of this signal. The resulting inverted signal was fed to a monostable in order to produce the delayed clock pulse. Figure 100 shows a block diagram of this system. The outputs of the shift registers were taken via buffers to lamp drivers to give a visual indication of the message stores. For this display a lighted lamp indicates a '1' and a '0' is shown by an extinguished lamp.

7.3 Reduction of Telegram Coil Length

From the investigations described in this thesis, it would appear that only two independent bits of information can be derived from one telegram coil in this type of inductive loop system. However, it is possible to reduce the length of the telegram further, but still needing the same number of coils.

As the coils are to be staggered about the rail foot, there would seem to be no reason why four signals should not be picked up simultaneously by having a coil on the foot of each rail. The locomotive or train must have pick-ups each side for the telegram coils in case it gets turned round, therefore why not use both of them all the time? It would probably be necessary to connect a switch to the train controller so that the pick-up connections can be reversed if the locomotive becomes reversed but this would seem to represent no serious problem. The electronics in the receiver unit would have to be slightly more complex as four, instead of two, signals would be received in parallel and may then have to be converted to a serial output for the train-borne computer. If sleeper spacing is used (0.76 m) for this system, then the telegram length will have been reduced by a quarter, but for one metre spacing it will have been reduced by a third - both spacings giving good reductions in the physical length of the telegram. For this system it might be more convenient for several coils to be connected to a single common connection to the parallel wires. In any case a system run from both sides of the parallel wires helps to keep the line electrically balanced. This would ease the problems of feeding the line.

7.4 Logic for the Telegram Coils

When picking up two bits of information from a telegram coil, and assuming that the 'Z' signal is always compared with the parallel wires, two ways of evaluating the 'X' signal exist. These are :-

(1) comparing the 'X' signal with the parallel wire signal, or

(2) comparing the 'X' signal with the 'Z' signal.

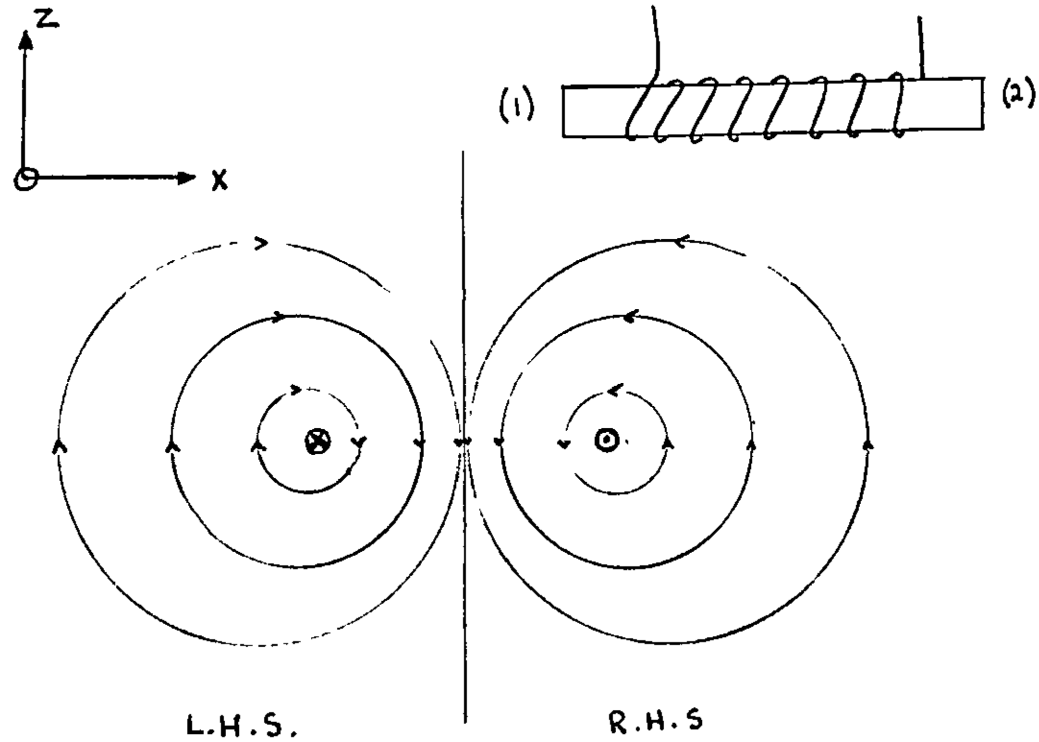


Fig. 101. Lines of Flux Through the Centre of a Coil and the Direction of the Induced Emf.

Z	X	
	L.H.S.	R.H.S.
A	A	B
B	B	A

Fig. 102. Truth Table for Both Signals Compared With the Parallel Wires.

Assuming the coils to be always wound and connected to the amplifiers in the same manner, the following discussion holds. If not, some signals will be reversed by 180° and the following is invalid. Consider the flux lines around the coil as shown in fig. 101 at a given instant in time. If the pick-up is kept as shown and moved from the right hand side of the coil to the left hand side a phase change will occur in the induced emf. Assume also that end (2) of the rod is always nearest to the track for picking up the B_z field. Let A represent a signal in phase with its reference and let B be out of phase with the reference signal. If both the 'X' and 'Z' signals are compared with the parallel wires then the truth table in figure 108 holds. If, on the other hand, 'Z' is compared with the parallel wires and 'X' is compared with 'Z' the truth table in fig. 103 holds. From fig. 102 it can be seen that on turning the telegram coil over, for both signals compared with the parallel wires, not only does B_z change phase but B_x also changes. This would therefore require some skill when laying the coils in order to get the logic correct. If B_z is compared with the parallel wires and B_x then compared with the B_z field, the in-phase or out-of-phase signal from B_x is always on the same side of the coil whether B_z is reversed or not (see the truth table in fig. 103). This second method of determining the logic would therefore seem to be easier for both a designer and the person laying the coils.

7.5 Interference from the Parallel Wires

Throughout the work in chapter 5 no quantitative results have been given for the interference of the parallel wires on

Z	X	
	L.H.S.	R.H.S.
A	A	B
B	A	B

Fig. 103. Truth Table for the 'Z' Signal Compared with the Parallel Wires and the 'X' Signal Compared with the 'Z' Signal.

the coil fields. This is because there is the possibility of the parallel wires being placed closer together to keep encapsulation costs down, the final separation distance not having been decided yet. With decreasing separation of the parallel wires, the interference from them will decrease (see figs. 53 and 54). There is also another possible method of decreasing the interference from the parallel wires. This is by subtracting or adding a given portion of the parallel wire signal, of the correct phase, to the telegram coil signals. This will ideally give complete cancellation of the interference at only one position of the pick-up assembly, except for cases of field distortion due to metal such as cross over rails and A.W.S. magnets, but will give partial cancellation at other positions of the pick-up assembly (due to vertical and horizontal movement of the train). This cancellation should be nearly complete because of the small changes in field strength from the parallel wires with distance at this position. For the B_z field of the telegram coil a fraction of the signal over the centre line of the parallel wires must be added to it - due to a change in the phase of the parallel wire field where the telegram coil occurs. For the B_x field a different fraction of the signal picked up over the centre line of the parallel wires must be subtracted from it.

7.6 Vertical and Horizontal Movements of the Pick-Up Assembly

One disadvantage of this system is the large variations of induced signal in the pick-ups due to horizontal and vertical movements of the train. It would appear, from measurements taken in Chapter 5, that a horizontal movement of $\pm$ 1" ($\pm$ 0.025 m) and a vertical movement of $\pm$ 1" ($\pm$ 0.025 m) can be tolerated with a

6" x 2" coil on the rail foot and preferably $2\frac{1}{2}$" (0.0625 m) below rail head level. The B_x field is the most limiting component - see fig. 73. At the extreme position of the pick-up assembly, values of flux density of less than 10^{-7} Tesla occur adjacent to the centre of the telogram coil (at Z_o = 10 cms and X = +2.5 cms). The values of B_z are all greater than 10^{-7} Tesla for the pick-up assembly movements considered. It would also appear from chapter 5 that it is advantageous to increase the coil spacing to one metre to give higher values of R_z'' and R_x'' and hence produce a larger dynamic range of the system.

The 29 kHz signal picked up is also modulated by various frequencies, the phase comparison being effected over the frequency range 29 kHz $\pm$ 3.3 kHz. The modulations represent the aspects of the signals ahead of the train. Fortunately, the carrier is frequency modulated so that the excursions of the pick-up assembly due to train movement, which represents an amplitude modulation of the received signal, should in no way interfere with the phase comparison. The large variations can also be clipped to give an approximately constant amplitude output when over a telegram coil.

7.7 Fixing of the Pick-Up Assembly

With the telogram coils on the rail foot the pick-up assembly requires to be mounted on the train so that it is normally about 3" (0.075 m) above the rail head. The obvious place for this would seem to be the wheel guard in front of the leading wheel of the train which comes down to within about two inches of the rail head. However, from figures quoted by British Rail, it might appear that the movement expected here is too great for this system - mainly because of the Southern Region Electro-Diesels. On the other hand it may be possible to place the telegrams where these large excursions of the pick-up assembly are unlikely to occur. Alternatively, it may be necessary to have a bracket specially fabricated so that the pick-up assembly can be fixed adjacent to the bogie pivot. At this position no bogie pitching or twisting should occur, thus reducing the movement of the coils. Another possibility for fixing is a bracket attached to the axleboxes - this would give even less movement than the previous suggestion.

7.8 Future Work

The work still to be carried out can only really be done by a practical evaluation of the system. This should involve testing the complete system in a railway environment and will require the building of suitable receivers as well as laying the telegram coils. The problem of connecting the telegram coils into the line should also be thoroughly examined.

7.9 Conclusions

The investigations in this thesis definitely show that it is possible to obtain two independent bits of information simultaneously from a telegram coil and hence improve the system. There are, however, certain restrictions to overcome but there would seem no very serious problems here. Work still needs to be done on various aspects of the system before a full analysis is complete and this is described in the following chapters.

8. INTRODUCTION TO PRACTICAL WORK

The practical work was divided into two main sections, those were :-

1) the construction and initial testing of equipment required
2) testing of the complete system on a moving vehicle.

The electronic equipment consisted of receivers, decoding logic and a parallel-serial converter. Because of time available no attempt was made to make the electronics 'fail-safe'. The inputs to the receivers were from ferrite rod aerials which, because of their fragile nature, were encapsulated. Telegram coils also had to be made but these were very simple in construction. The final testing was made on a motorised vehicle (Wickham Trolley - see Fig. 104) on the test-track at Derby Friargate.

On the tests for the complete system all constraints suggested by the British Rail Research Department were adhered to (see page 8 and below). The telegram coils used were 6" x 2" (0.15m x 0.051m), with ten turns of wire, situated 3" (0.075m) below rail head (new rail) giving about 1.3/16" (0.032m) clearance between the bottom of the rail head and the coil. The range of line currents used was from 100 mA to 300 mA (rms) - this being typical of current variation in the open wire track conductors due to change of line attenuation with weather (see reference 12).

Another problem that had to be considered was the matching of the telegram coils into the transmission line in order to provide minimum attenuation and reflections (mainly

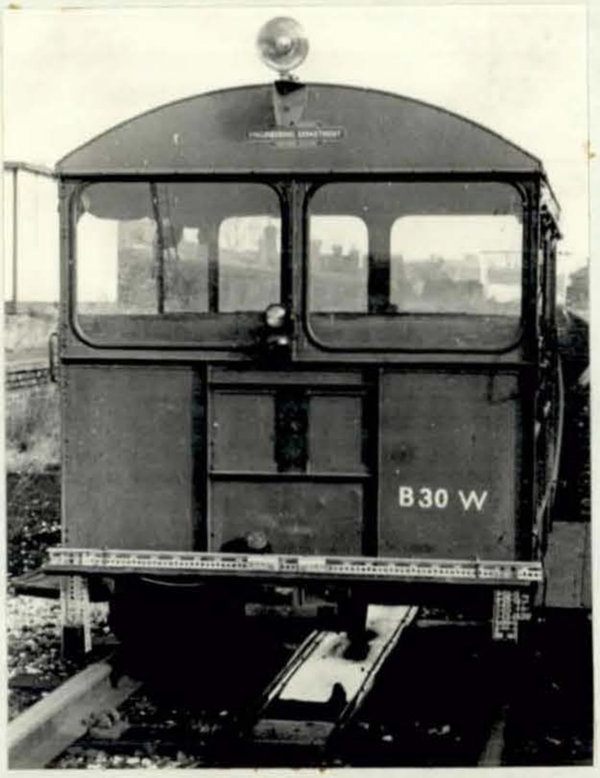


Fig. 104. The Wickham Trolley.

at the higher frequencies on the shorter sections or for all frequencies on the longer ones). The conductors used were twelve inches apart although reduction of spacing is under consideration as is also the type of track conductor (see page 63 for actual details of track conductor system used).

8.1 Clearance Restrictions Imposed by the Railway Loading Gauge.

These further restrictions are concerned with clearances due to guard rails (especially over viaducts) about the rail head. This obviously influences the size and type of encapsulation for the pick-up coils. Figure 105 gives details of the clearances that exist. This means for a ferrite rod $2\frac{1}{2}$" (0.0635m) long, plus $\frac{1}{2}$" (0.0127m) for encapsulation, symmetrical about the centre line, clearance each way is approximately $2\frac{1}{2}$" (0.0635m). With the rod 2" (0.051m) long, and $\frac{1}{2}$" (0.0127m) for encapsulation, clearance each way is reduced to about $2\frac{3}{4}$" (0.07m). The pick-up coil and assembly should also be able to stand up to the following conditions on the bogie.

8.2 Bogie Movements

The following sets of figures were arrived at after a discussion with rolling stock development. They can be split into two sections, as follows :-

Vertical Movement :-

The movement here is due to bounce and pitch of a locomotive bogie superimposed on wheel wear.

Bounce	$\pm\frac{1}{2}$" ($\pm$0.0127m)	
Pitch	$\pm\frac{1}{2}$" ($\pm$0.0127m)	at bogie ends
Wheel wear	- 3/16"(-0.0048m)	

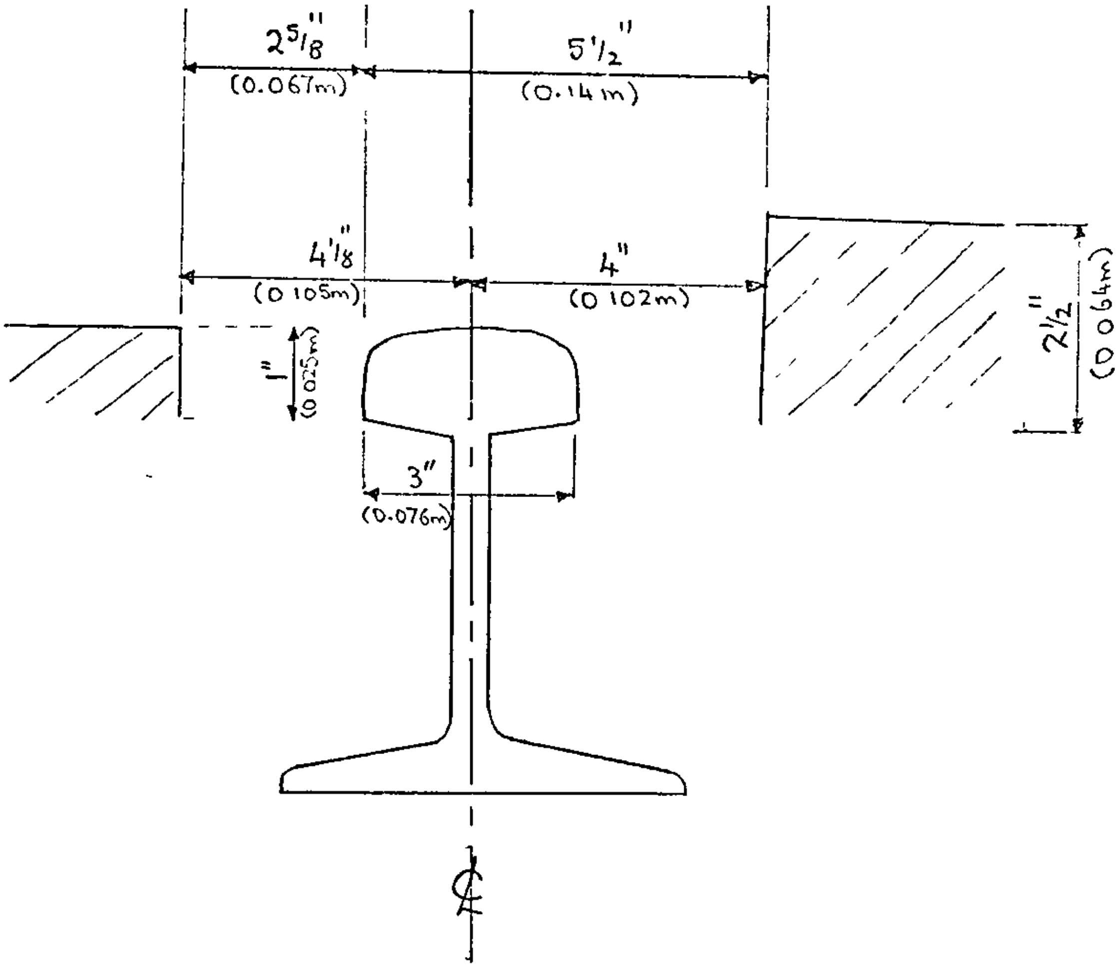


Fig. 105. Clearances about Rail Head.

(The shading represents forbidden areas).

Hence the ± 1" (±0.0254m) dynamic bogie movement at bogie ends will give an overall movement of + 1" (+0.0254m), -1.3/16" (-0.032m), (+ upwards,- downwards). Adjacent to the bogie pivot the vertical movement will have reduced to about +½" (+0.0127m), -11/16" (-0.0179m), (i.e. no pitching component). Moving to the axle boxes the movement is again reduced but only by about ± 1/10" (±0.0025m).

Horizontal Movement :-

As no gauge widening now occurs on main lines the horizontal movement is restricted to bogie twisting and voids and lies between ± ¾" (±0.0.19m) to ± 1" (±0.0254m) at bogie ends. Adjacent to bogie pivots or at axleboxes this will be about ±¾" (±0.019m). The encapsulation must stand up to these movements and accelerations which could reach as high as 9g.

8.3 Rail Wear

This only affects the limits of the vertical movement. The total amount rails on main lines are allowed to wear is ⅜" (0.0095m). As this movement is downwards it brings the pick-up coils closer to the telegram coil, hence flux densities are increased. All designs should therefore be done on the flux densities encountered on extreme excursions of the pick-up coils.

9. EXPERIMENTAL EQUIPMENT BUILT

Three basic pieces of equipment had to be constructed for the practical system. These were :-

1) the receivers and decoding logic.

2) the pick-up coils, and

3) the telegram coils.

The signal frequency used to feed the track conductors was the same as for the original B.R. telegram coil system, i.e. 29 kHz. There is, however, no reason why the system should be confined to this frequency.

9.1 The Electronic Equipment

This equipment was built, wherever possible, using integrated circuits (both linear and digital) but was not designed to be 'fail-safe'. The decoding circuitry did however have various checks to prevent unwanted signals getting through and generating wrong bits of information. All voltage rails required were generated from thd $\pm$ 12v supply - although this minimises on power supplies required, noise appearing on one rail will appear on the others. Indication lamps were fitted at various points so that a visual inspection of operation could be accomplished. Hysteresis was employed on all comparators to try and counteract the large flux density variations due to the pick-up movement. Diagrams of all circuits used are included in Appendices A-E.

9.1.1 Amplifier, Filter and Squaring Circuits (All Channels)

The circuit diagram is given in Appendix B. The input from the pick-up coil was fed into a reasonably low impedance, about 47 ohms. This is because a voltage virtually independent of frequency is required (the voltage induced in the pick-up coil is directly proportional to frequency) - see Appendix 8 for analysis. At about 29 kHz, there is still a small change with frequency and a small phase shift can be obtained by varying the shunt input resistor. This method was used to give the PW (Parallel Wire) Channel a slight phase lead to prevent any leading edge overlap problems in the phase detectors, especially due to the telegram coil matching network as described in section 10.2. The signal then goes via the set gain control to the first stage amplifier. A large feedback stabilising capacitor was also used to help make the output voltage of the first stage not frequency dependent. Figure 106 gives the output voltage-frequency plot for a constant line current.

The signal was then fed to two active filters, with staggered tuning, forming a bandpass filter, the characteristic of which is given in fig. 107 for a constant input voltage. The bandwidth is $\pm$ 4 kHz, with a centre frequency of 29 kHz. Compensation of the required phase is applied to the non-inverting input of the third stage (telegram coil channels only) to partly cancel the effect of the residual field from the parallel wires at the position of the telegram coils. This cancellation is not complete due to the slight phase changes in each receiver with respect to the parallel wires and the movement of the pick-up coil. The output of this stage is then fed to :-

1) a peak detecting circuit, and
2) an operational amplifier in open loop configuration, acting as a sine to square-wave converter.

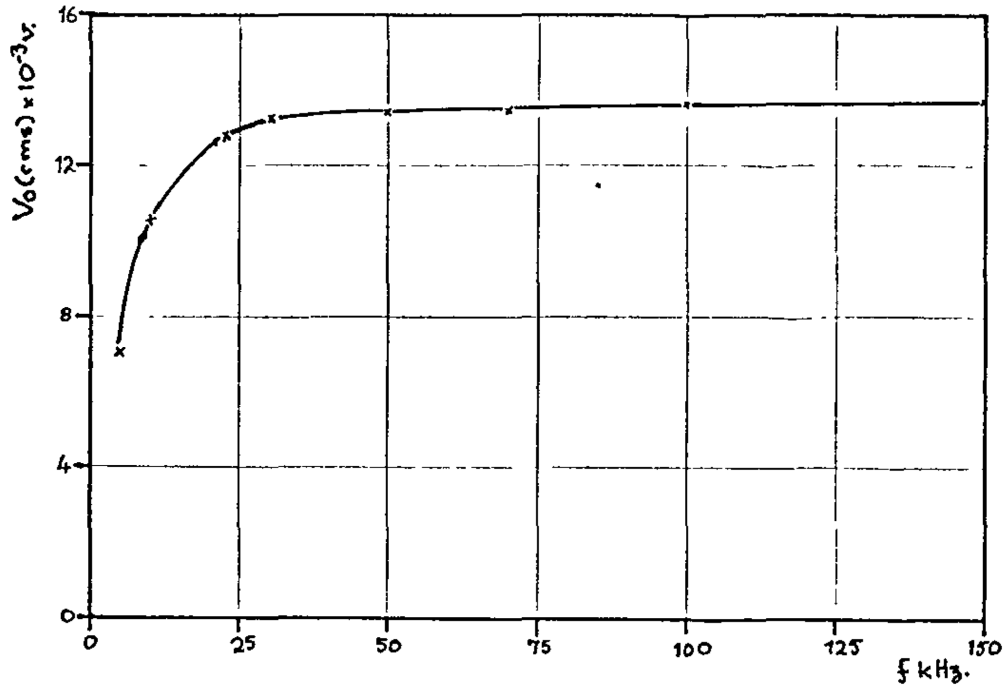


Fig. 106. Preamplifier Characteristic.

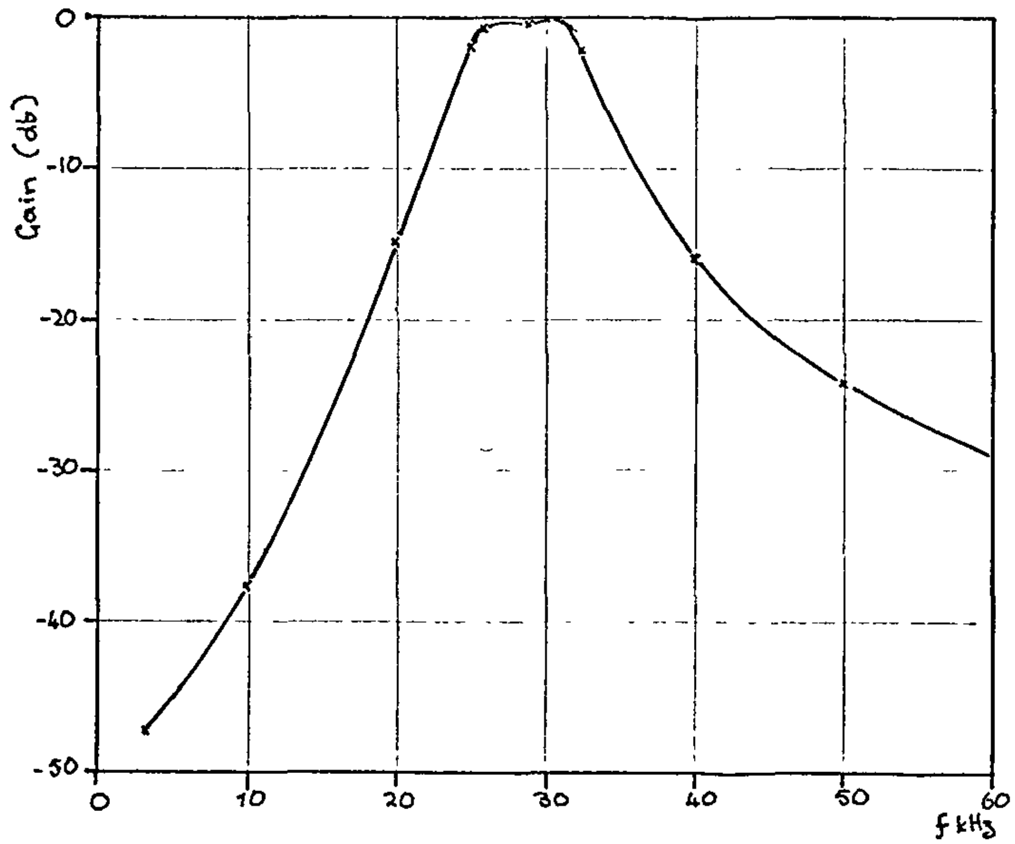


Fig. 107. Filter Characteristic.

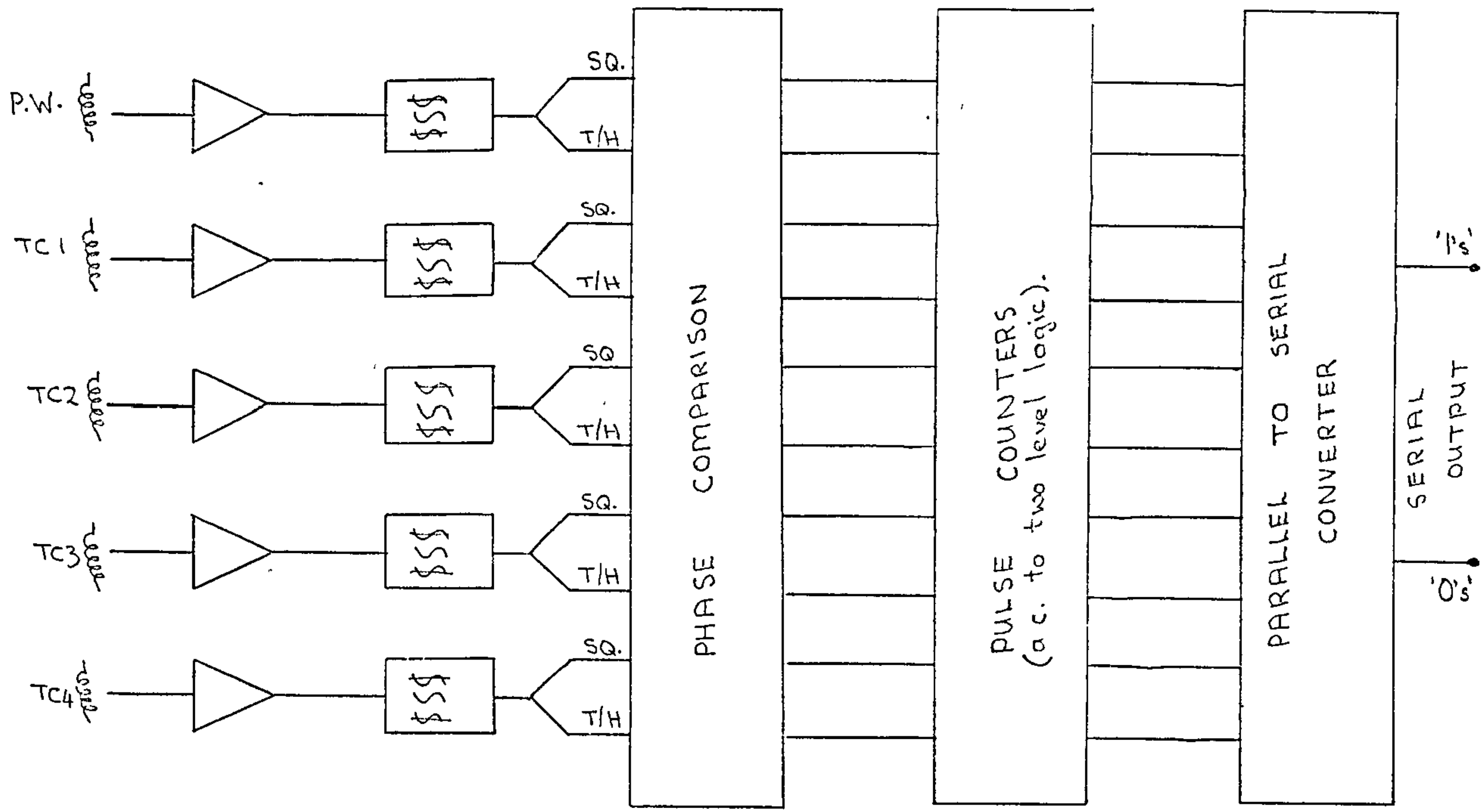


Fig. 108. Diagrammatic Layout of Receiver

The output of the squaring circuit is fed to the decoding circuits and the monostable.

9.1.2 Peak Detection and Decoding Circuit (PW Channel)

The circuit diagram for this is in Appendix C.

The sinewave output from the third stage is fed to a voltage doubler and then peak detected, the time constant of the following RC network (0.27 mS) being sufficient to allow high speed running over the telegram coils. At high coil currents it must be able to discharge rapidly between reception of bits and at low currents to charge rapidly enough to allow reception of information when the flux density from the telegram coil is only above threshold for a very small distance. The peak detected signal is then fed to the non-inverting input of a voltage comparator, the reference signal being applied to the inverting input. Care must be taken in this configuration so that the feedback does not cause the comparator to 'lock-on'. The generated square wave is then gated with the comparator output to produce the two reference signals A and $\overline{A}$ and the lamp driver input which gives a visual indication as to whether the reference signal is present. Compensation is provided for the telegram coil channels (TCI, 2, 3 and 4) as already explained.

9.1.3 Peak Detection and Lamp Drivers (Telegram Coil Channels)

The input circuitry for this is the same as above but the inputs to the threshold comparator are reversed (see Appendix D). This configuration does not provide the condition where it can 'lock-on'. The lamp indication shows the state of the threshold device, an inverted threshold signal also being obtained from this part of the circuit where required.

9.1.4 Decoding Logic

The function of the decoding logic is twofold:-

1) to effect a phase comparison of reference and telegram coil channels, and
2) to provide a serial output from the parallel input.

The circuit diagram is given in Appendix E.

The monostables used at the output from TC1, 2, 3 and 4 are to provide a standard length pulse (approx. 12 μS), the period of which is about one-third that of the lowest frequency reference signal. This eliminates any overlap on the trailing edges of the two square waves being compared due to phase discrepancies between channels and the phase differences due to the telegram coil matching capacitors (see section 10.2). Phase comparison is effected by gating the relevant reference signal with a monostable output and the associated threshold level in a NOR gate, the resulting output being predicted by De Morgan's Theorem ($\overline{A + B} = \overline{A}.\overline{B}$). The output is a train of 12 μS pulses at the line current frequency denoting either '1's' or '0's' (see fig. 109 for a typical set of waveforms). The pulse train lasts for as long as the telegram channel threshold is 'tripped'. This pulse train is applied to a pulse counting circuit which will not trip the following Schmitt Trigger until about 10 pulses have been received. This provides an a-c to two level logic converter. The Schmitt trigger, which has hysteresis, controls a lamp driver, giving a visual indication of the received signal and also the sampling gates. The reference signals for TC2 and TC4 can be compared with

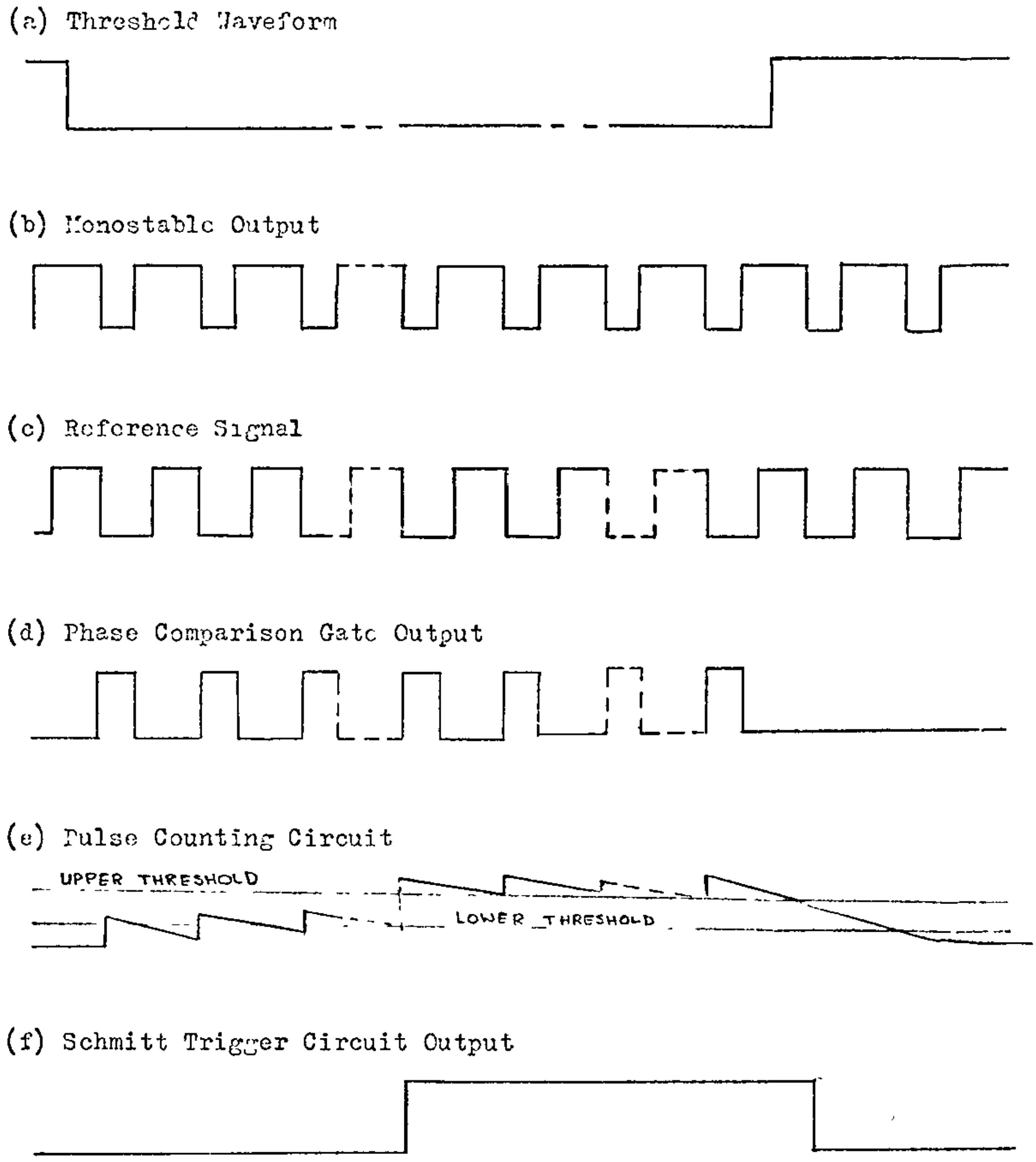


Fig. 109. Decoding Logic Waveforms.

either the parallel wire signal or TC1 and TC3 respectively (see pages 45 and 46), the SN7400 and SW1 providing the necessary reference signals and switching accordingly.

When all telegram channels required (i.e. TC1 and TC2 or TC1, 2, 3 and 4) are present an initiate sampling pulse is applied, via SW2, to the sampling pulse generator. This consists of five 'D-type' Bistables, four of which use the parallel wire reference signal A as the clock pulse. On receiving an initiate sampling pulse a '1' is fed to the output of the first flip-flop, Qo. This is then propagated through the other flip-flops by the clock pulse A. The output of the second flip-flop $\overline{Q1}$ is fed back to the first flip-flop. When $\overline{Q1}$ goes low it resets Qo to zero and the outputs from the flip-flops are as shown in fig. 110. The first flip-flop also synchronises the initiate sampling pulse with the clock-pulse. The sequential outputs Q1 - Q4 are gated with the clock pulse and the Schmitt Trigger outputs such that the sampling pulses are equivalent to those shown in the last four waveforms on figure 110. The '1' outputs are then fed to a NAND gate and the '0' outputs to another, thus giving separate outputs for '1's' and '0's'. No initiate sampling pulse will occur until all the inputs in use are present, and the reference signal A is used as the clock pulse so that no information can be 'clocked' out if it fails. The resulting output was compatible with a telegram address register or a train-borne computer.

9.2 The Pick-Up Coils

Because of the fragile nature of ferrite rods it was decided to encapsulate them. The ferrite rods were mounted in

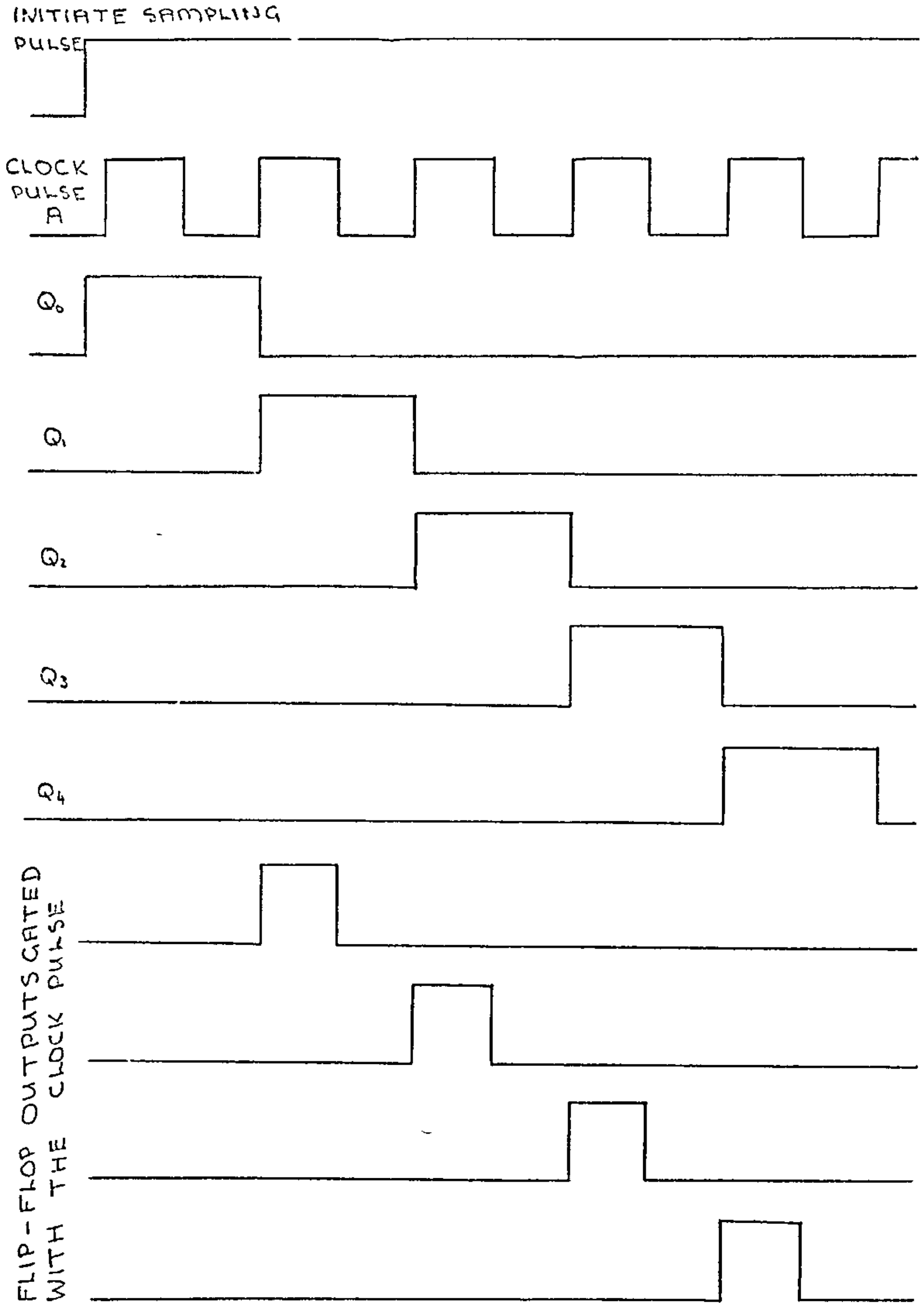


Fig. 110. Production of Sampling Pulses.

a free-standing assembly which made the unit self-supporting and meant that no jig (apart from the mould) was required for the encapsulation process. Two methods of fixing were required to keep the assembly fixed rigidly on to the train, as well as for safety and reliability reasons. After consulation with the B.R. Plastics Development Department it was decided to test two types of material for encapsulation, these were :-

1) a hard type of epoxy resin.

2) a more flexible type of epoxy resin.

Each encapsulation was tested on a vibration machine (see fig. III) at frequencies between 10 and 20 Hz. It was not possible to use lower frequencies due to the limitations of the vibrating machine. The coils were subjected to accelerations up to 9g. The tests for each type of encapsulation consisted of vibrating them in S.H.M. for half an hour at values of acceleration from 1g to 9g in steps of 1g, the values of 'g' being that experienced by the assembly as it reversed direction (i.e. maximum values). An acceleration of 9g is likely to be the maximum experienced on a bogie. A more prolonged test was also made at 4g for three hours. The inductance of the ferrite rods was measured before and after the tests, a visual examination also being undertaken at these times. The inductance in all cases was virtually unaltered, the variation being attributed to the measuring instrument, and the rods were assumed to be undamaged. The encapsulation in both cases showed no visible signs of damage. Appendix A shows the dimensions of the complete pick-up assemblies.

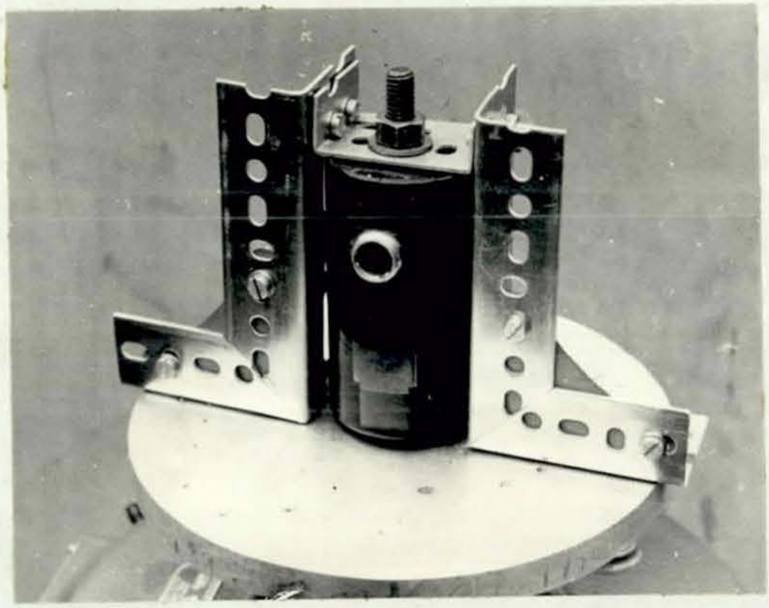


Fig. 111. Detail of the Test Jig for the Pick Up Coils.

Fig. 112. Photograph of Telegram Coil and Fixing.

From the above tests no firm conculsions could be drawn as to which encapsulation is the better. It is felt that more exhaustive and prolonged testing may well bring out fatigue problems and show which is the better encapsulation. However, it was decided to use the more flexible encapsulation for the ensuing tests as it was less likely to damage by being hit with ballast etc.

9.3 The Telegram Coils

These coils were wound on wooden formers so that with the wire on them, they measured 6" x 2" (0.152m x 0.051m). They were closely wound with ten turns of stranded wire (see fig. 112), the connecting leads being coded so that direction of winding could be quickly ascertained. The windings were covered with a thin layer of "Araldite" and, after drying, the whole assembly dipped in paint to provide some protection against the weather. The mounting blocks were also made of wood, painted and fixed to the rail by "Araldite" and a metal bracket (see also fig. 112). For fixing the mounting blocks to the rail, it had to be cleaned and for this two methods were tried:-

1) cleaning the rust and dirt off by a mechanical method (e.g. rubbing down or sanding) and
2) by chemical cleaning; this consisted of using hydrochloric acid, sulphuric acid, phosphoric acid and then passivating the surface with methylated spirits.

The first method gave the best results, the second method being rather messy and employing concentrated acids. It is felt, however, that a fixing method not requiring cleaning the rail and an adhesive would be better. This could probably take the form of a spring clip holding the blocks and passing under the rail. The encapsulation of the pick-up coils would seem to present no problems except that the outgoing leads must be identified - it might even be possible to make the coil without the wooden former. One side of the telegram coils should also be coded in some way to help lay the correct telegram message. The main physical problem with the telegram coils was, and still is, their connection into the track conductors.

10 TELEGRAM COILS AND LINE MEASUREMENTS

The work described in this chapter is concerned with the method of connecting the telegram coils into the track conductors and the resulting problems.

10.1 Line Requirements

When connecting telegram coils into the track conductors, it is desirable to :-

(a) match them into the line to provide minimum reflections

(b) introduce as little extra attenuation into the line as possible, and

(c) provide a reasonably simple connection into the line to facilitate changes.

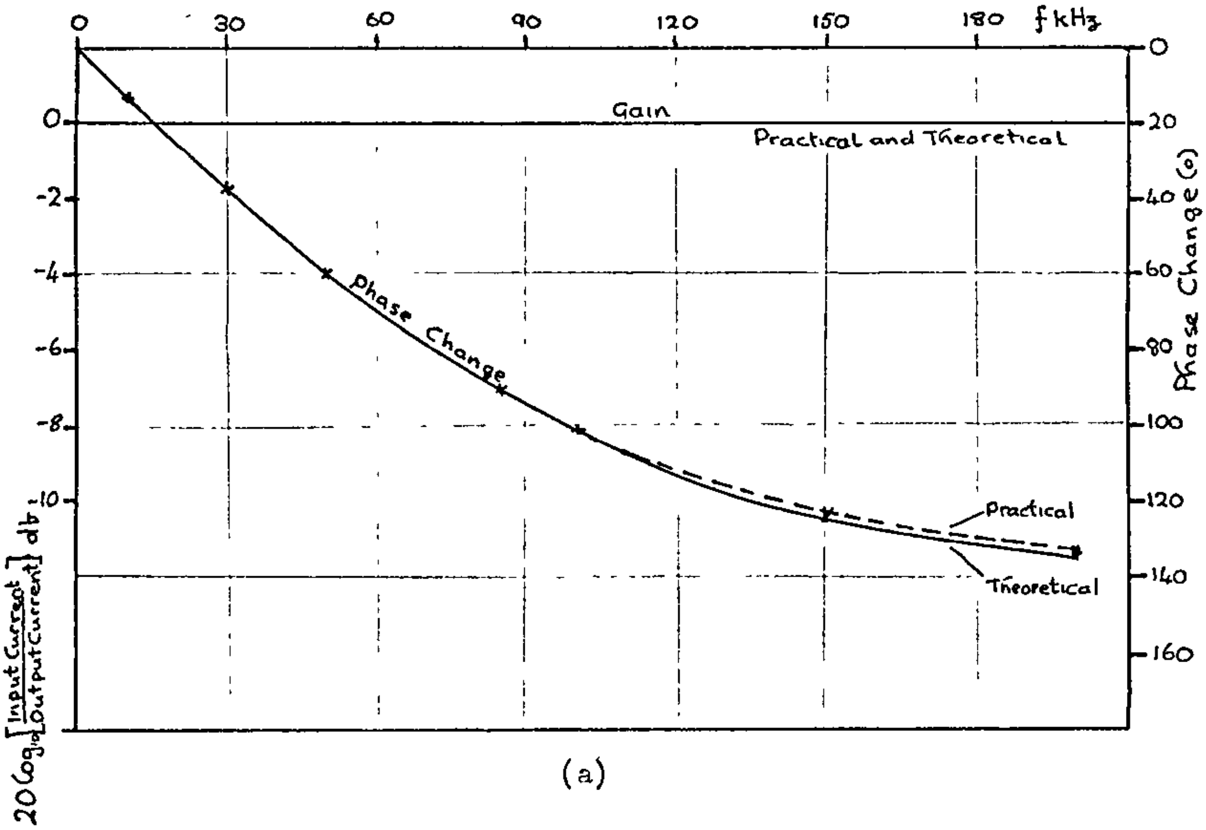
The telegram used in the tests had five coils each side of the track, although a normal telegram at present would have eight either side (i.e. 32 bits total). If only one side is used in practice, there would be 16 coils on one side but, to keep the transmission line balanced, it might be advisable to feed half from each conductor. Any matching network developed then would be useful in both cases.

10.2 Matching Networks

As the matching network was required to be symmetrical so that it could be fitted anywhere on the line, yet keep the line balanced and be as simple as possible, there was only one network possible. This was a lattice network (see fig.115 the input impedance of which is given by :-

$$Z_{in} = \sqrt{\frac{L}{C}}$$

Figure 113(a) shows the practical and theoretical curves of insertion loss (the ratio of output to input current) and phase change with frequency for a lattice network. Whilst the circuit has ideally no loss there is a gradual phase change which would probably appear as noise on f.m. carriers when traversing a telegram. The other equally important variation is the coil current to input (or output) current with frequency and the associated phase shifts. This is shown in figure 113(b). The most important frequency range is that about 29 kHz when the telegram is decoded by a phase comparison method. Using 8 coils each side of the track, the loss is about 0.5db, which is not significant. The coil current then either lags the input current or leads the output current, hence there being a difference between laying the coils forwards or backwards from their connection point to the track conductors (i.e. towards or away from the feed end). This means that the pulse counting circuit must accept a minimum pulse width of about 12µS - 20% (i.e. 9.6µS) assuming telegram coils could be laid in both directions. If they are restricted to being fed backwards towards the generator then the monostable takes care of all the phase shift problems. By reducing the number of telegram coils the value of the capacitor in the network is decreased as is also the phase shift. This suggests the possibility of splitting the telegram into (say) two sections - but whilst reducing the phase shift between lines and coil currents for each section, the overall phase change is increased. This method unfortunately increases the complexity of matching and connecting the coils into the line.

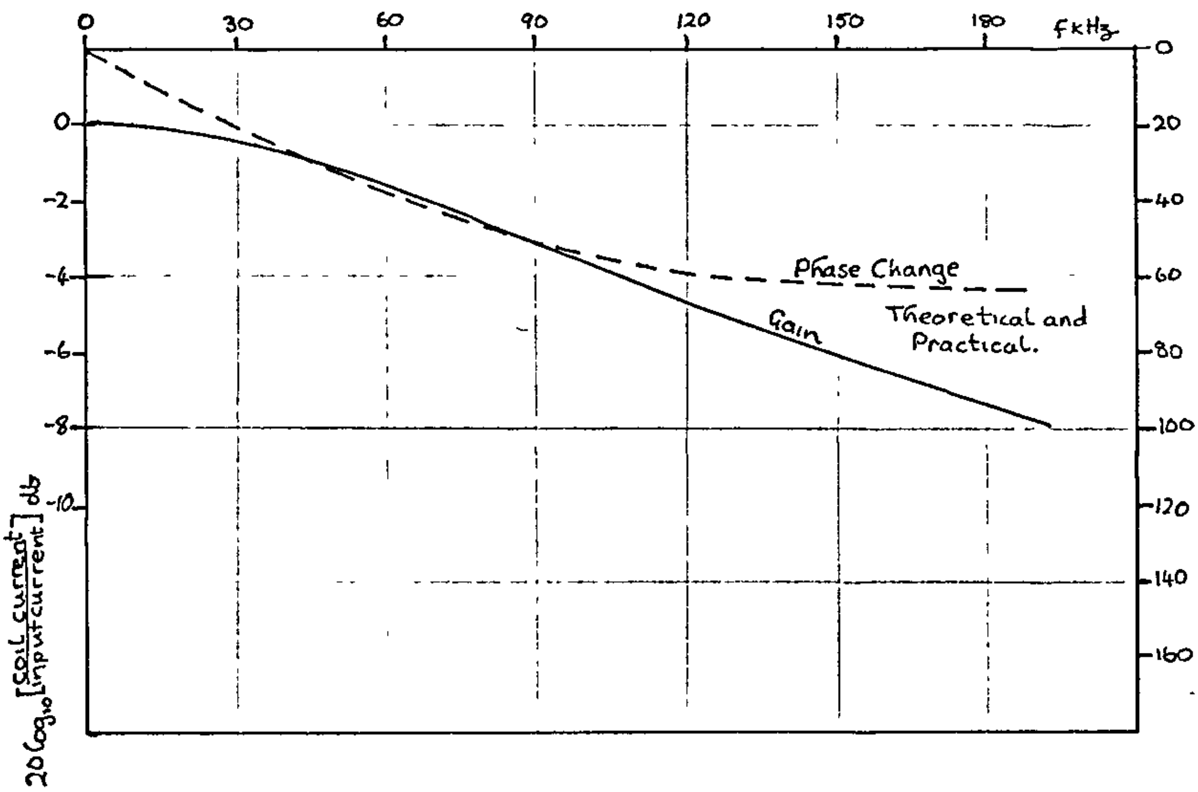


(a)

Fig. 113. Coil and Line Current Variations for a

Lattice Network.

(b)



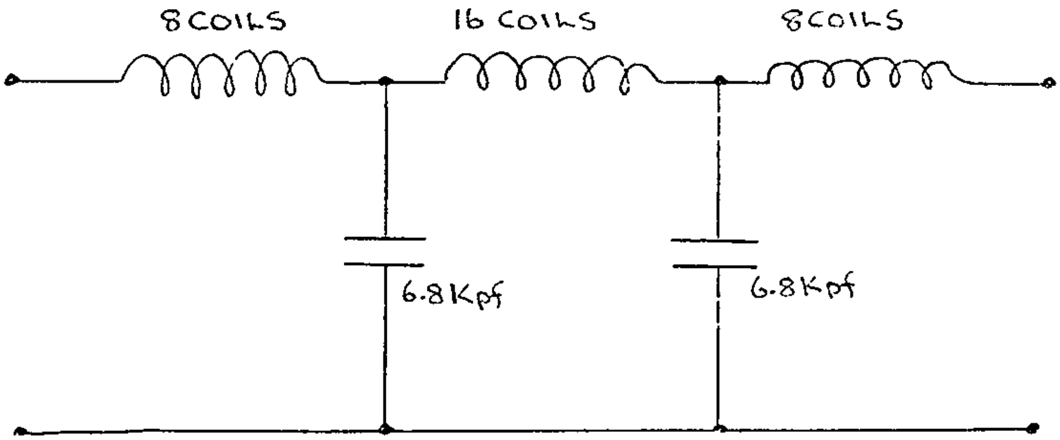


Fig. 114. One Proposed B.R. Arrangement for
Telegram Coil Matching.
(1 coil = 10 μH)

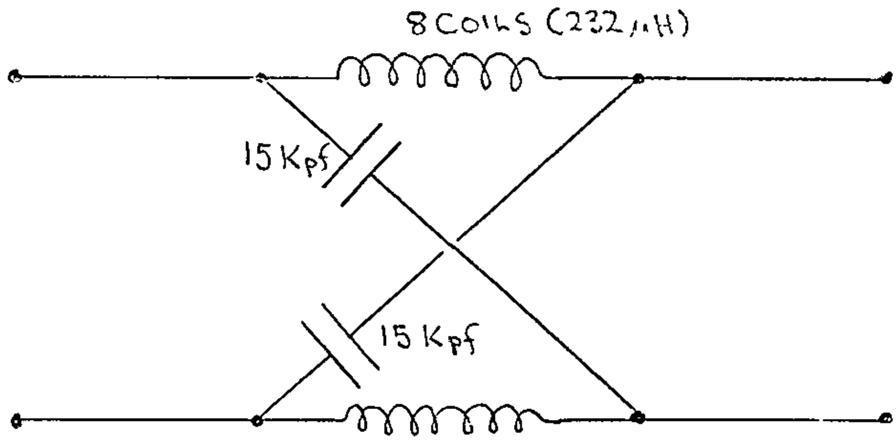


Fig. 115. Simulation Network for Loughborough
Telegram Coils showing Lattice
Network for Matching.
(1 coil = 29 μH)

The practical measurements of phase shift and insertion loss were made with a telegram simulation network, (see fig. 115, where L is half the total inductance of the telegrams). Any differences in results are probably due to the finite resistance of the coil windings. Not very different results are to be expected from actual telegram coils in situ. With the network used it is not really practical to use frequencies much higher than those used now because of the decrease of coil current with frequency and the associated phase shift.

10.3 Line Measurements

Having decided on the form of matching network to be used, various measurements were made of input impedance and its phase angle with frequency for various line and telegram configurations. The configurations used were :-

1) The track conductors only
2) B.R. telegram coils in situ
3) B.R. telegram coils and their matching network in situ
4) Loughborough telegram coils in situ, and
5) Loughborough telegram coils and the lattice matching network in situ.

The track conductors used were the experimental screened line. This consists of two screened cables with the screening cut circumferentially at regular intervals connected together as shown in fig. 116. By doing this, the losses between the two cables are fixed. This produces a track conductor system that has excellent low attenuation properties and constant input impedance over the desired frequency band

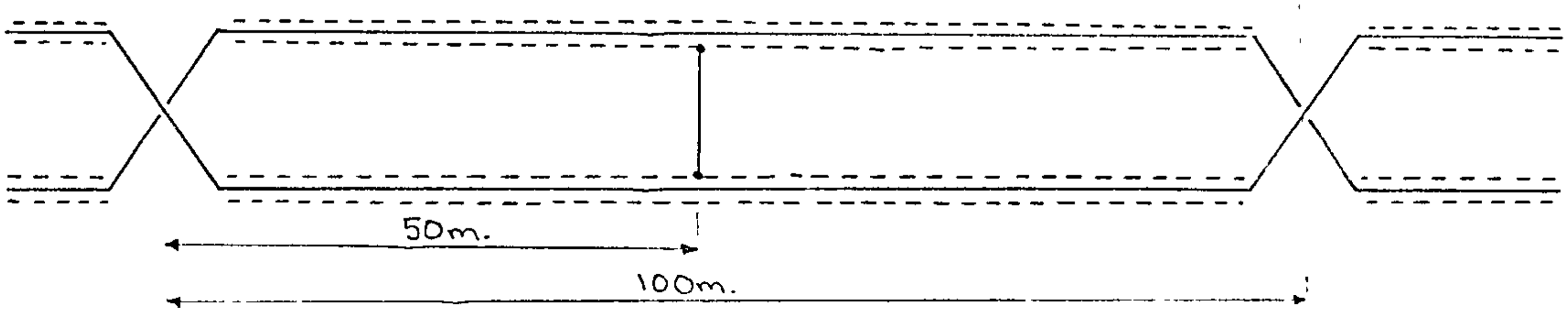


Fig. 116(a). LINE ARRANGEMENT ON 1 KM LOOP.

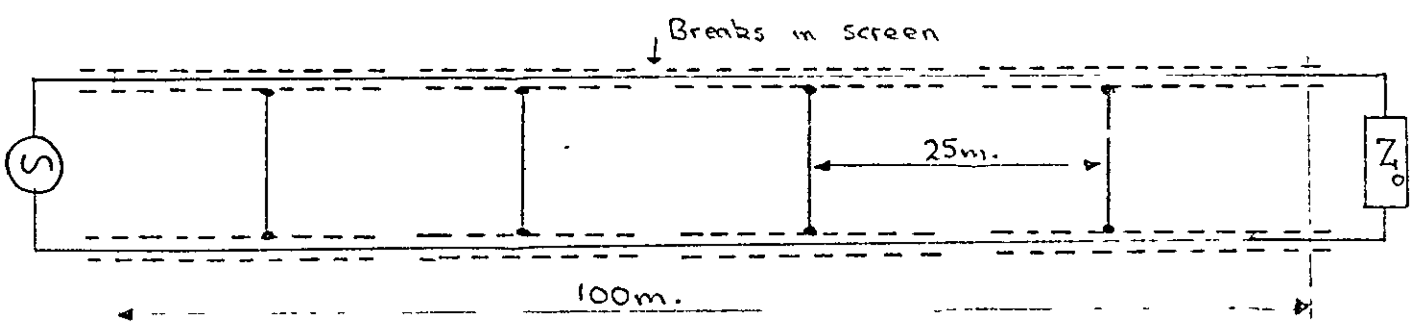


Fig. 116(b). SCREENING FOR 100m EXPERIMENTAL SECTION

(20 kHz - 150 kHz) regardless of the weather conditions. The constant input impedance makes it much easier to match telegram coils into the line as well as reducing reflections on the line and easing the line feed requirements. For a more detailed description of the screened line see reference 12.

Two configurations of this cable were used :-

(a) 1 km length with screens shorted at 50m intervals

(b) 100 m length with screens shorted at short intervals.

See figure 116 for details. With configuration (a) situations 1, 2 and 3 were used and also the Loughborough telegram coil simulation network. With (b) conditions 1, 4 and 5 were used. It was only possible to do this combination of tests because the 1 km test section into which the B.R. coils could be switched was required for other purposes and in any case did not include any flat bottom rails. This left only a 100m section of screened line which was used for this project, and other purposes, and for which there were no B.R. telegram coils already laid. The measurements given are for dry conditions, although measurements were also taken under wet conditions. Readings under both conditions were very similar thus showing the excellent properties of the screened track conductors. Two types of impedance meter were used for the measurements, one going up to about 100 kHz only, the other up to about 500 kHz. The first one was available for the longest time and hence the most readings but all measurements above 100 kHz must be used with some caution. The second instrument only became available in time for work on the 100m loop and hence its use there.

Figure 117 shows the variation of input impedance and phase angle for the track conductors alone (the 1 km loop) and for the B.R. telegram coils with and without matching capacitors (the track conductors were terminated with a 130 ohm resistor). Whilst the input impedance for the telegram coils alone varies wildly with frequency, when used with compensation capacitors, as shown in Figure 117, the variation is much less, it starting to fall off quickly above 100 kHz - probably due to the range of the impedance meter. The use of compensation capacitors certainly stabilises the input impedance and phase angle and show nearly matched conditions. Figure 118 shows the input impedance and phase angle variation with frequency for the line and Loughborough telegram coil simulation network, with and without capacitors for matching purposes. Again the telegram coils alone give large variations with frequency of both input impedance and phase angle. With the matching capacitor included (see figure 118) the variation is much less, a value of C = 0.015 μf probably giving much better results. Again the large decrease in impedance is observed above 100 kHz.

Figure 119 shows the variation of input impedance and phase angle with frequency for Loughborough telegram coils, with and without compensation, against the input impedance of the 100 m loop. Again the capacitors bring the line much closer to match conditions. No fall-off is observed above 100 kHz in this set of measurements - probably due to the fact that the impedance meter with the larger bandwidth was used.

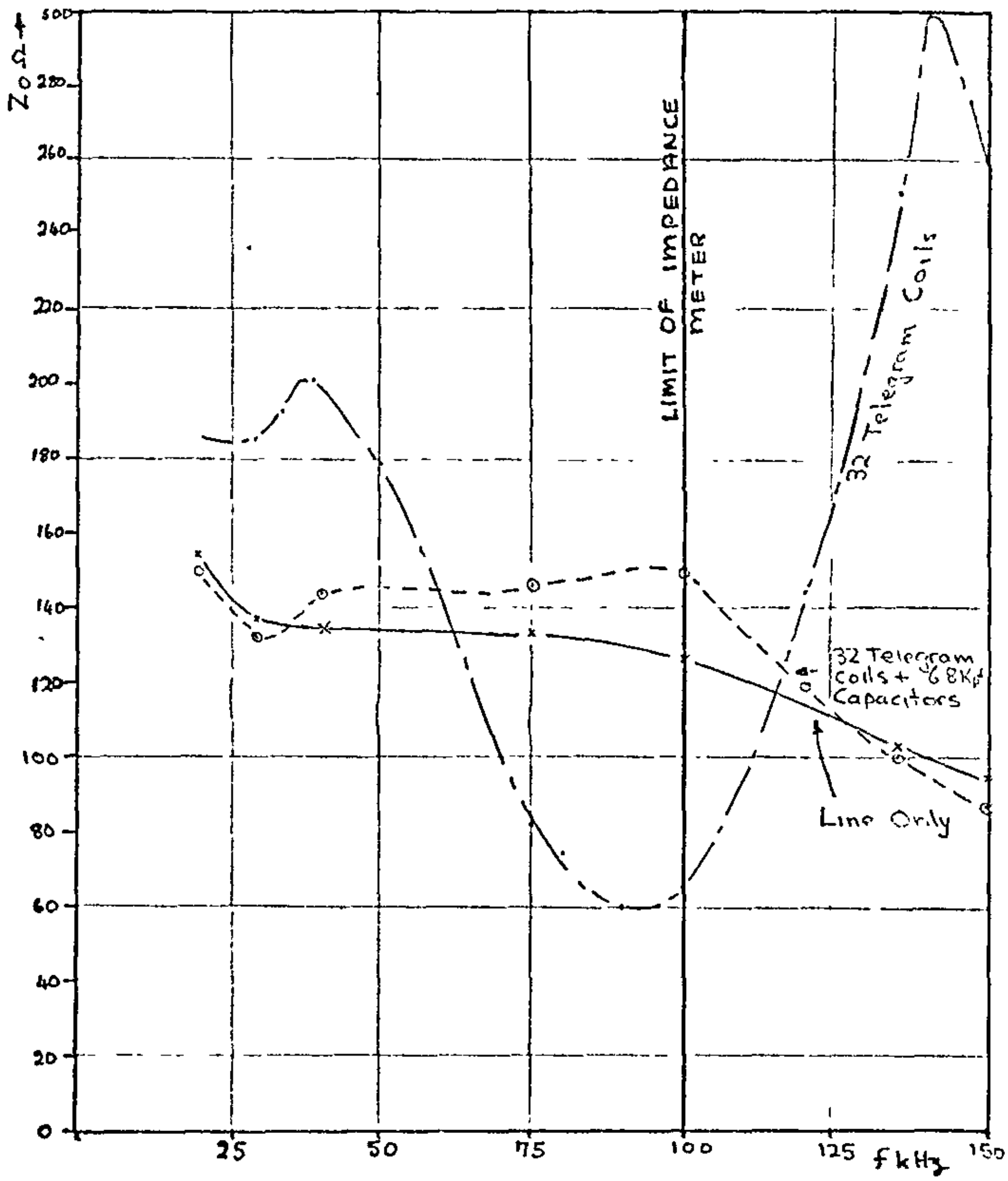
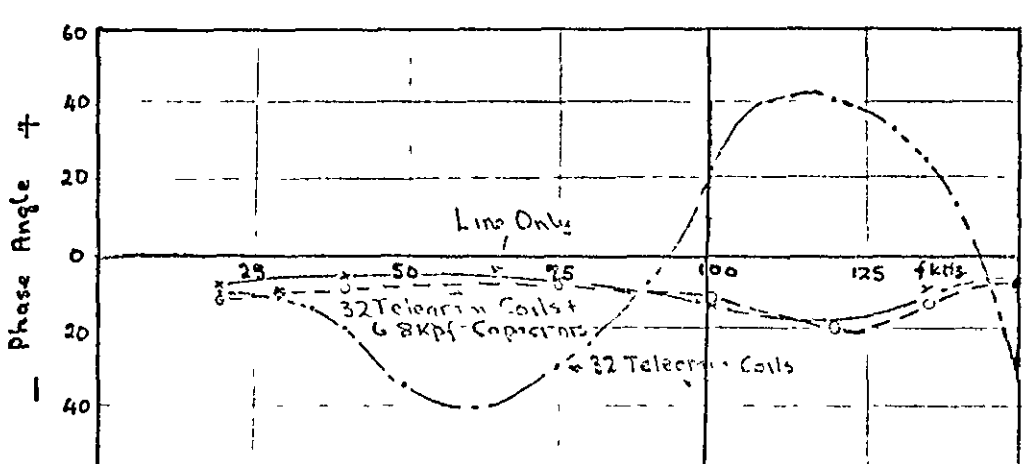


Fig. 117. Line Input Impedance - Frequency Variations.



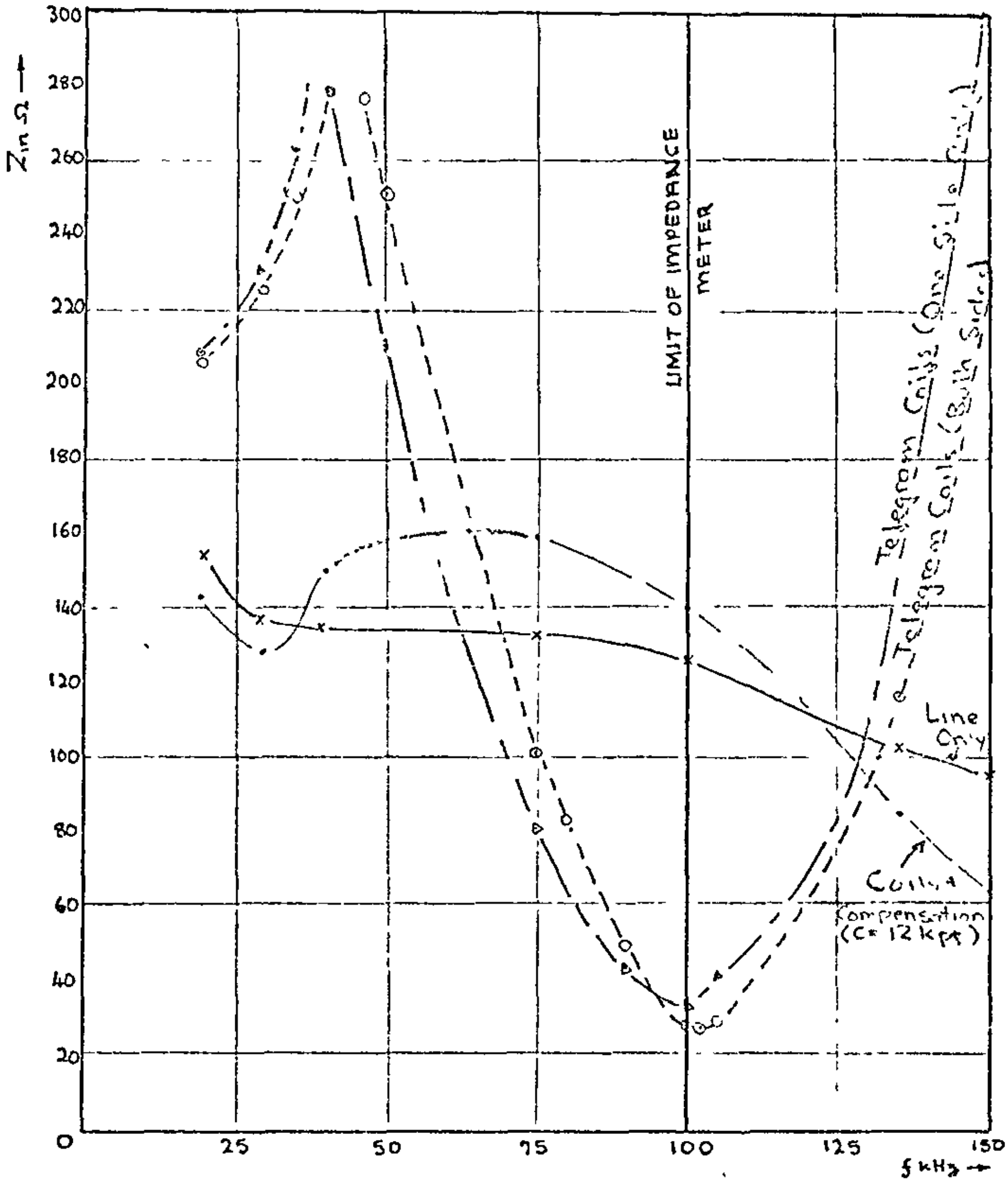
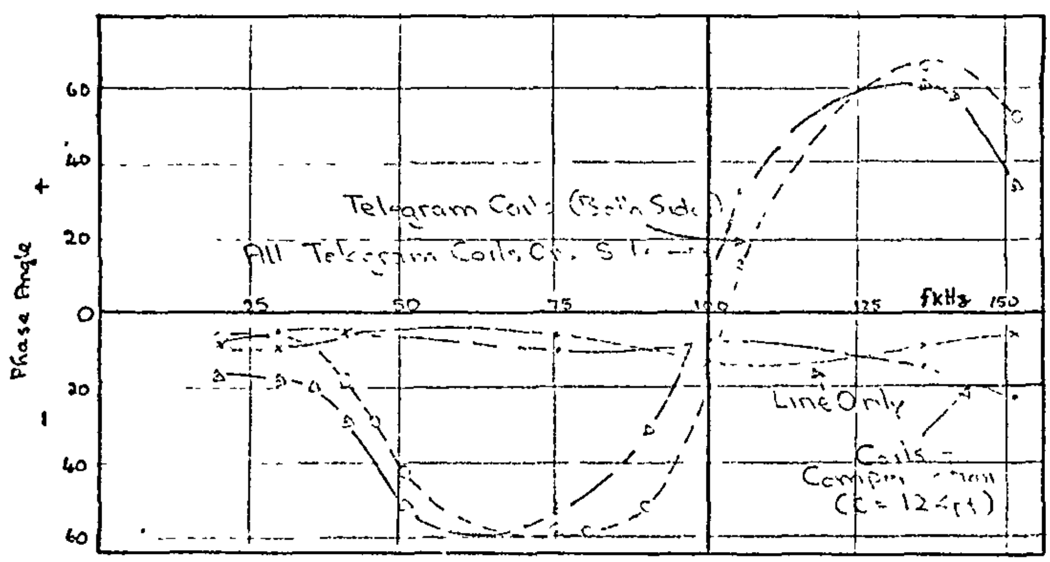


Fig. 118. Line Input Impedance and Phase Angle Variation with Frequency (1 km. loop).



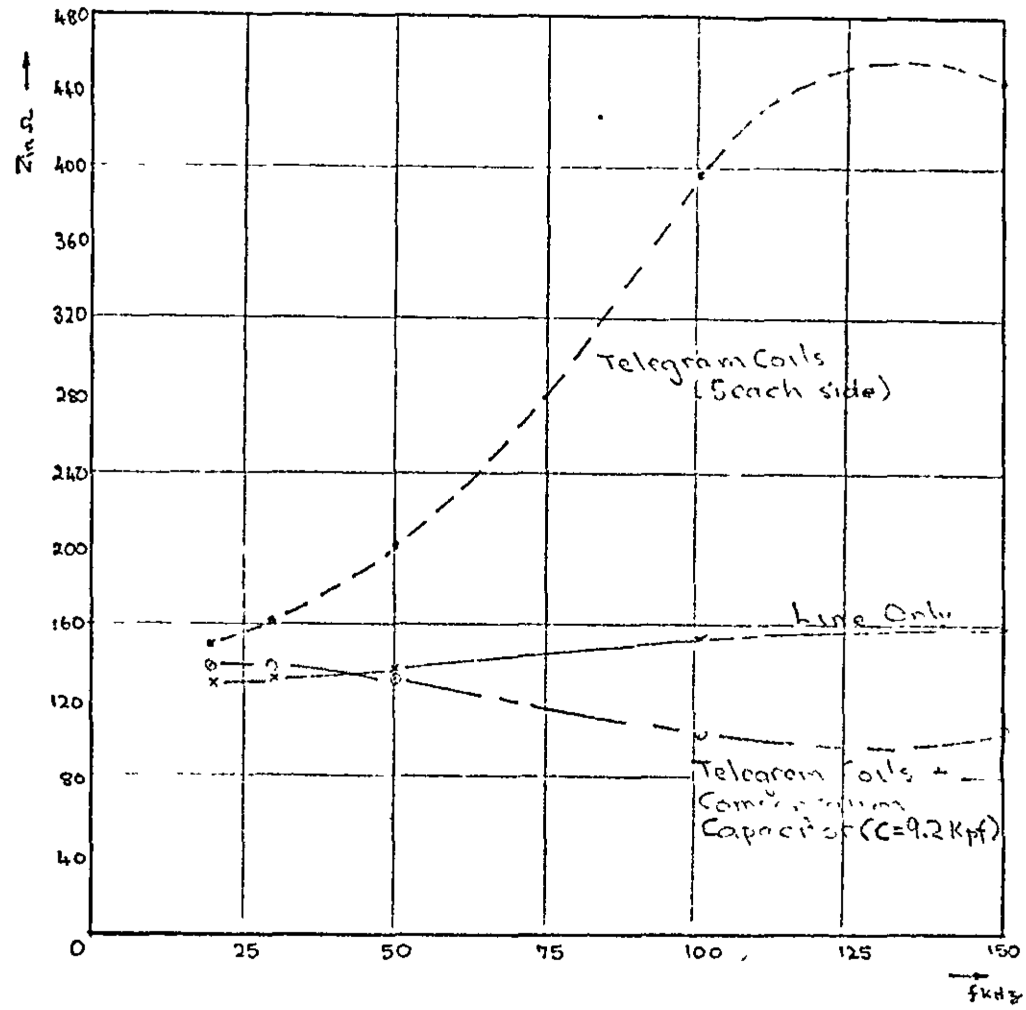
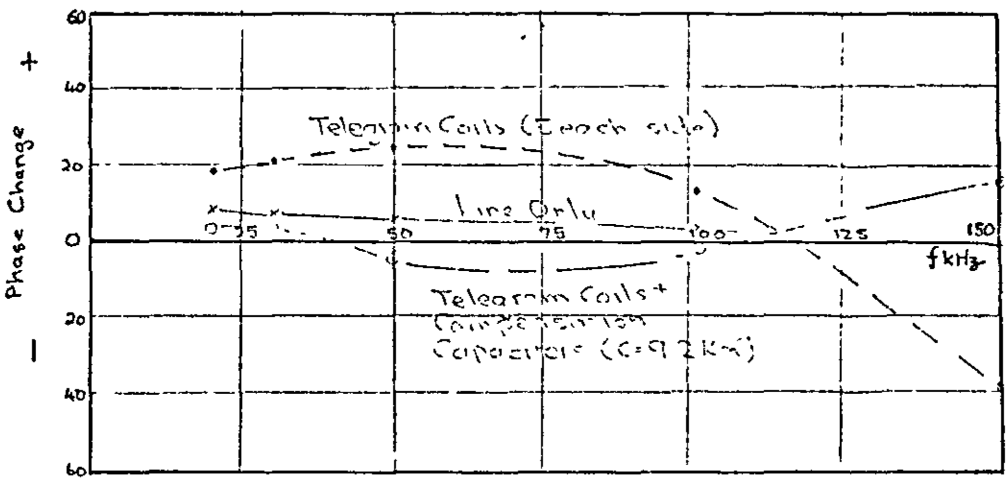


Fig. 119. Line Input Impedance and Phase Angle

Variation with Frequency (100m. loop).



These results certainly show the advantage of matching the telegram coils into the track conductors. This not only helps in feeding the line but also the minimisation of standing waves which could upset the system at higher frequencies on long sections of line. The extra cost of putting in the capacitors on the other hand must be weighed against the advantages obtained.

10.4 Connection of the Telegram Coils Into the Line

The connection of the telegram coil into the line was made via two metal junction boxes. The switching gave facilities for :-

(a) line only

(b) telegram coils only, and

(c) telegram coils plus matching network

In practice only the matching network will be connected across the line, the telegram coils being connected straight to the transmission line. The connection of telegram coils, network and line being either crimped or soldered together, or both, and then covered by some suitable material. The matching capacitors would probably be encapsulated in a resin block and mounted underneath the track conductor encapsulation. Care must be taken when laying the telegram coils and connecting them in to get the phase relationship correct. Feeding all the telegram coils from one connection per side of the track conductors makes it easier to connect different matching networks than if each coil was connected directly to the parallel wires.

10.5 Line Attenuation due to Telegram Coils

Two measurements were made here - both in wet weather - which should represent worst possible conditions. The measurements were :-

(a) received signal over 100m track conductor loop energised at 29 kHz, and

(b) current attenuation in the range 10 kHz to 200 kHz measured as the ratio of input current to output current.

10.5.1 Received Signal Variation at 29 kHz

The object of this exercise was to determine the insertion loss, if any, of the telegram coils as laid on the test section (i.e. 10 coils only) at the frequency that they are evaluated. For this test the r.m.s. output of the P.W. Channel was monitored as the 100m track loop was traversed (136 sleepers). The output voltage was monitored for the following conditions (see Figure 120) :-

(1) line only

(2) line and coils only, and

(3) line, coils and matching network

The input voltage to the line was left unaltered throughout the tests and hence a variation of line current was to be expected due to the change of input impedance of the line. This can be confirmed from figure 119 (Z_I - f curve) and hence the variation in received voltage. The irregularities at the end of the line are due to line end effects - a decrease in output voltage at the feed end probably being due to the metal junction boxes used there.

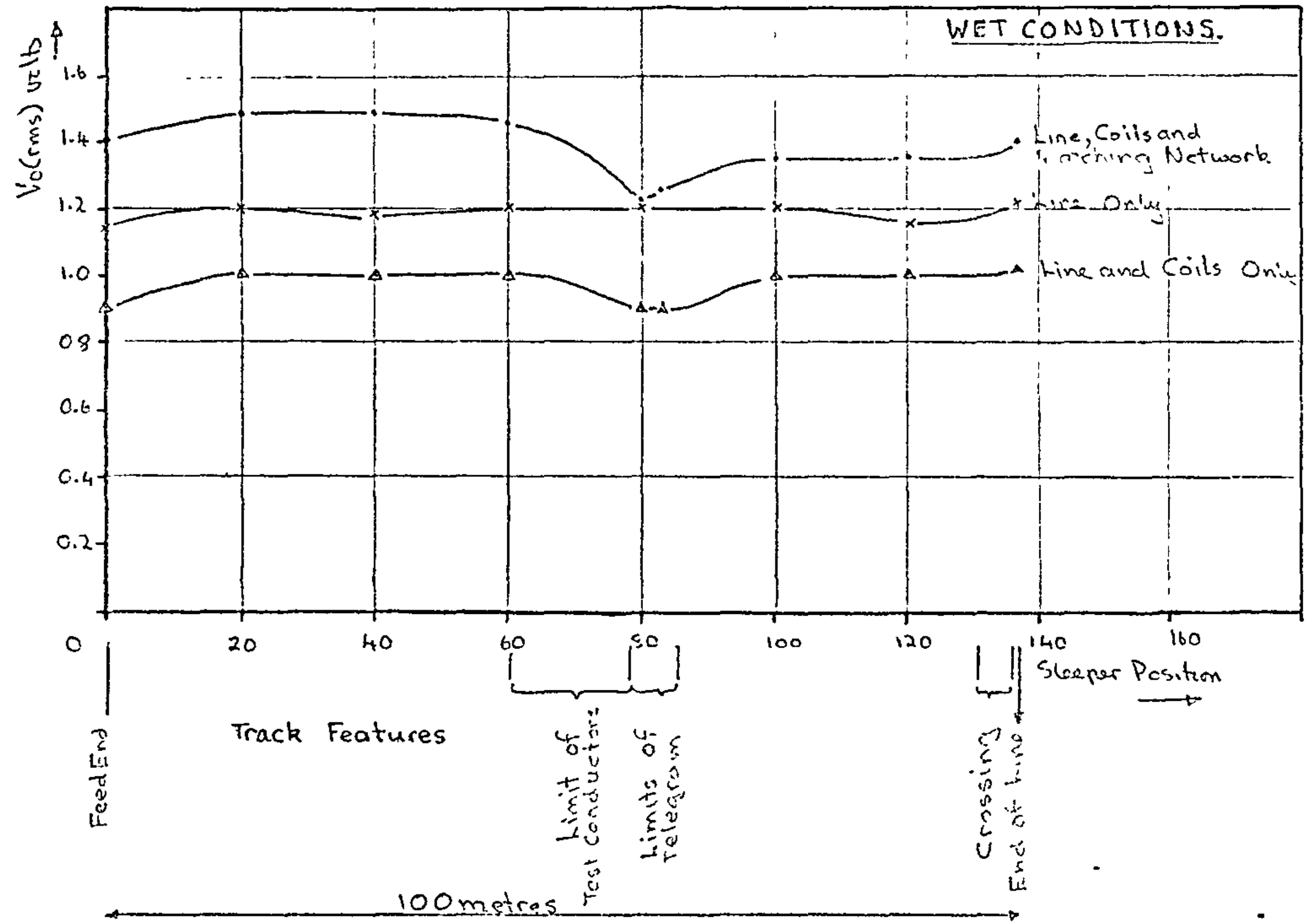


Fig. 120. Received Signal Variation over the 100 metre Loop.

As expected, there is little variation in received signal over the 100m section for the line only condition. For the coils and line only there is some variation in received signal strength adjacent to the telegram coils, this can be attributed to :-

1) the interference fields from the telegram coils, and

2) to a lesser extent the metal junction boxes connecting the telegram coils to the line.

There might also be a slight effect from some other track conductors (not energised), immediately before the telegram, which are used for another purpose. For the line, coils and matching network condition there is certainly a marked difference between the average signal before and after the telegram coils. The difference between these levels is about -0.75db (0.92) and is probably due to the resistance of the telegram coil windings in conjunction with the matching network. Again, there is a dip (about 1.6 db) adjacent to the telegram coils and is due to (1) above. This dip is probably not constant over the telegram but varies according to the phase of the interfering fields. However, the readings taken from the trolley probably represent the average condition. Some variation in received signal strength must also be expected due to trolley movements and variations in track conductor positioning.

10.5.2 Line Current Attenuation

From these measurements the insertion loss of the telegram and input impedance of the line can be determined for frequencies 10 kHz - 200 kHz. The measuring configuation is shown in Figure 121. The conditions used were as those in 10.5.1. The input impedance was taken as :-

$$Z_{in} = V_2 / I_1 \quad \Omega \qquad - \quad (1)$$

and the current attenuation as

$$\alpha = -20 \log_{10} (I_1 / I_3) \text{ db} \qquad - \quad (2)$$

This last definition has significance under matched conditions but not under mismatch. Taking the ratios of powers also does not have much significance under mismatch but, as the magnetic field is proportional to current, the ratio as defined in (2) is used.

The impedance - frequency curves (figure 122) certainly show the advantage of matching the coils into the track conductors. For the line only, the input impedance is constant at about 130 ohms whilst for the matching network case it is about 140 ohms. The condition for line and coils only shows violent fluctuations with frequency and shows resonance effects at about 112 kHz and just over 200 kHz. These would seem to suggest resonances caused by mismatch at a quarter wavelength and half wavelength conditions. Assuming the inductance of the telegram coils is distributed over the 100m then $v_p/c \doteq 0.14$ and the 100m line is about $\lambda/4$ at 112 kHz and $\lambda/2$ at just over 200 kHz. The characteristic impedance of the line for these parameters ($Z_o = \sqrt{L/C}$) is 194 ohms - compared to 130 ohms without the coils. The terminating resistance is 127 ohms so that a large mismatch is prevalent. On the 100m loop this condition could probably be remedied by using the correct

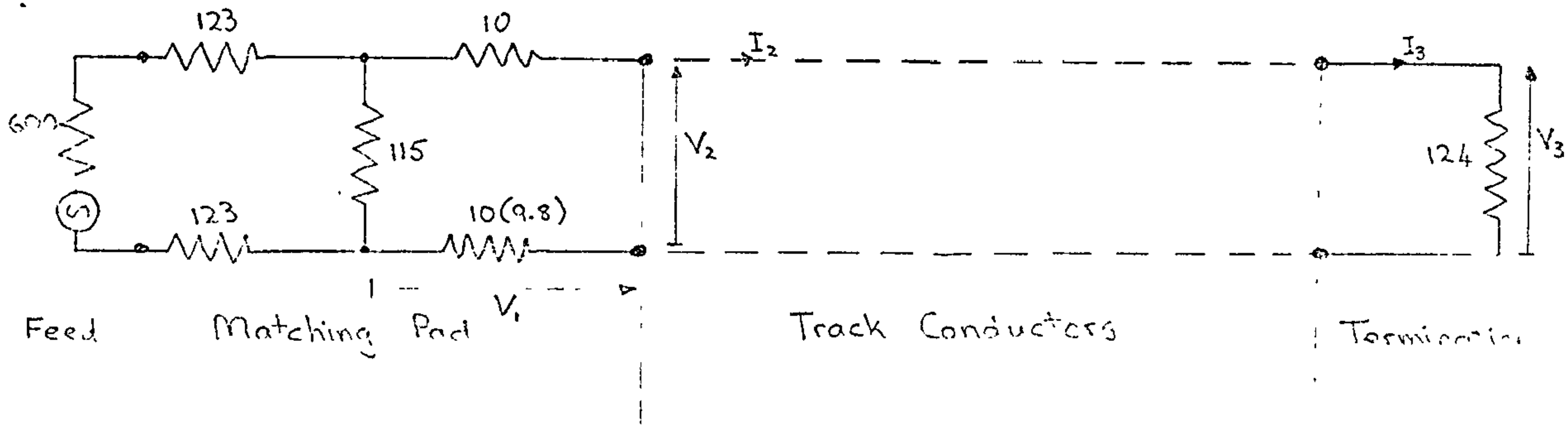


Fig. 121. SET-UP FOR LINE ATTENUATION MEASUREMENTS.

N.B. Resistor values are nominal (values in brackets are measured values).

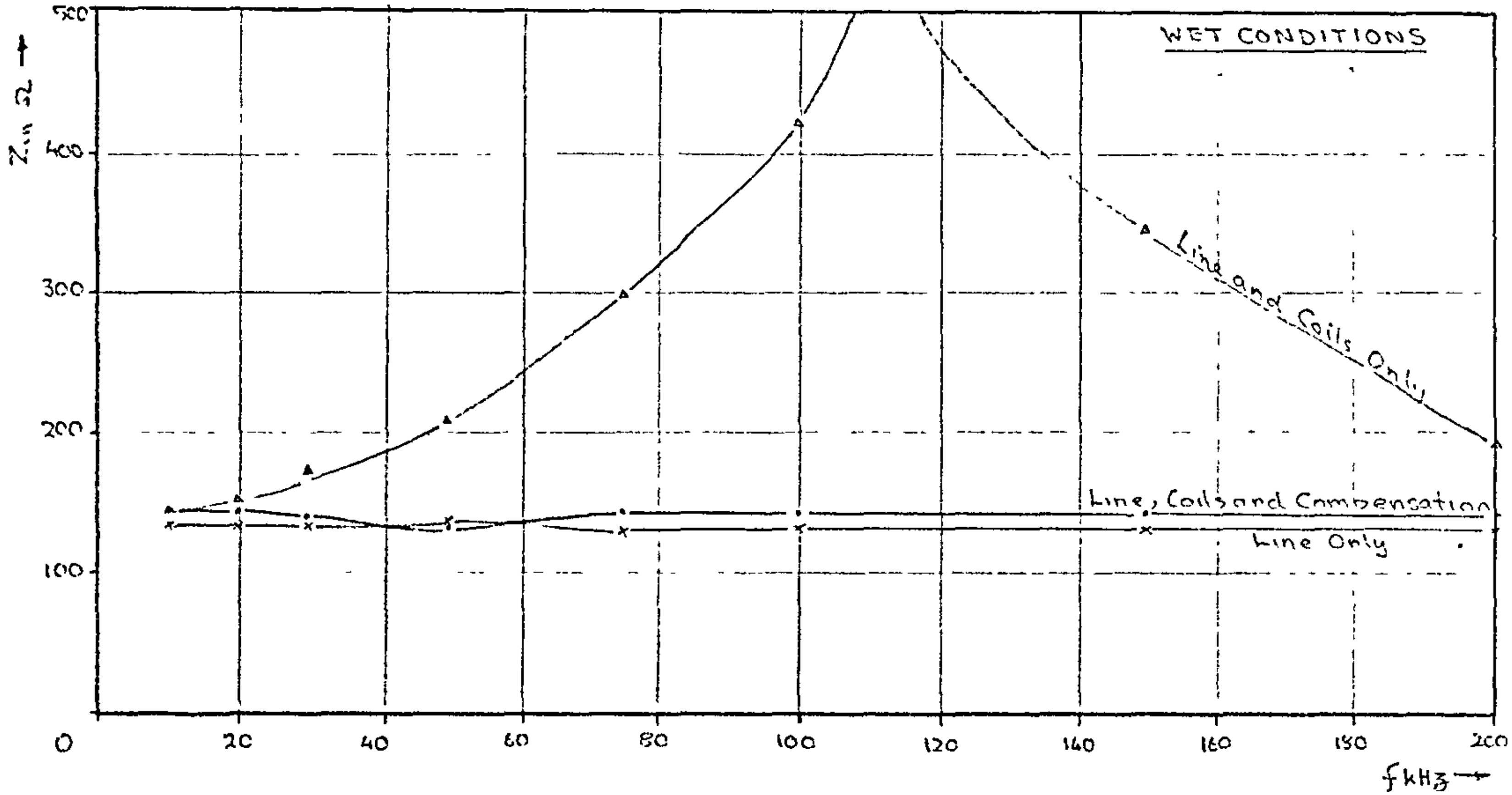


Fig.122. INPUT IMPEDANCE - FREQUENCY CURVE, 100 METRE LOOP.

terminating resistance but for a longer line it is probably best to match the coils into the line. It should also be remembered that only 10 coils are being used, not 16 as in a full system so that the resonanceswill occur at lower frequencies without matching and the calculated characteristic impedance would be higher.

The current - attenuation curves in figure 123 certainly show the effects of resonance and the existence of a standing wave for the condition of line and coils only. Above about 50 kHz for the line only and line, coils and matching network it is not possible to distinguish between the insertion losses for the telegram (assuming line attenuation is negligible for this length of line at this frequency). The variation in attenuation at about 30 kHz is probably due to coil resistance not being negligible to the reactance of the coil. The worst value of attenuation is about -0.26db (0.965) from these measurements (c.f. -0.75db (0.92) in section 10.5.1). The difference between these readings is about 4.3% and is within the experimental error to be expected - mainly due to the method used in 10.5.1. The second set of results is probably the better and, for a 16 coil telegram, would increase the insertion loss to just below -0.5 db. The resonances, without the matching network, with the increased number of telegram coils would be decreased in frequency, the characteristic impedance of the line increasing as would the mismatch.

The impedance - frequency curves obtained in section 10.5.2 for line only and line, coils and matching network are much more constant than those shown in Fig. 119 and are

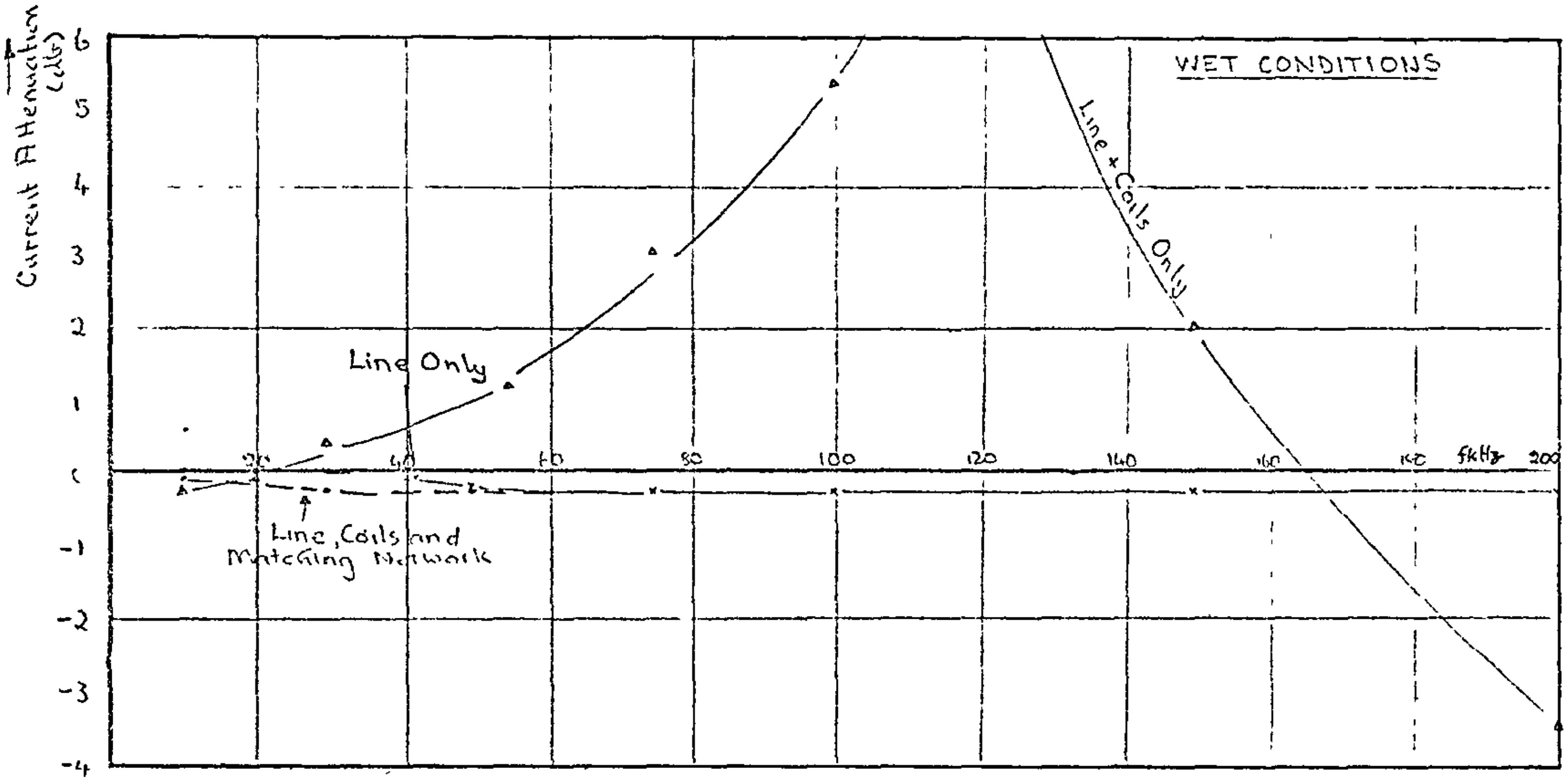


Fig.123. LINE CURRENT ATTENUATION-FREQUENCY CURVE, 100 METRE LOOP.

probably more reliable. The above resonances will also affect the transmission from train to track at 135 kHz.

10.6 Conclusions

By matching the telegram coils into the line their effect is certainly minimised. However, as their inductance decreases the velocity of propagation on the line, so is the wavelength of signals on the line reduced. This means that mismatch problems could become more noticeable. This is certainly a disadvantage of telegram coils, especially if the screened conductors are not used.

11. A WORKING SYSTEM

Having carried out some initial testing of the receivers in the laboratory, the equipment was moved out to the test track and mounted on the trolley shown in fig. 104. Due to the mobility required the mains supply on the trolley was derived from an inverter fed from two 12v batteries. The amount of mains powered equipment used was therefore severely restricted, the maximum output of the inverter being 100w (maximum required by receivers, and lamp displays was nearly 60w). Fig. 124 shows a photograph of the Rx and telegram address register in situ.

11.1 Pick-Up Coils

These were mounted as shown in fig. 125 and the following photograph gives a close-up of fixing details. The bottom of the telegram pick-up coils was about 3" (0.075m) above railhead. The same type of pick-up was used for the parallel wire signal but this was 12" (0.305m) above the track conductors and only the vertical pick-up rod was used. It was thought that the cross-fixing bolt on the telegram pick-ups might have a drastic effect on the field distribution due to its forming a 'shorted-turn' with the framework. However this was found not to be the case, although it did decrease the induced emf in the horizontal pick up coil by 2-3%.

11.2 Telegram Coils

The method of fixing is described in section 9.3 (page 59). They were mounted 3" (0.075m) below rail head, when new, and there was about $1\frac{3}{8}$" (0.035m) between the top of the coil and the bottom of the rail head. The actual telegram

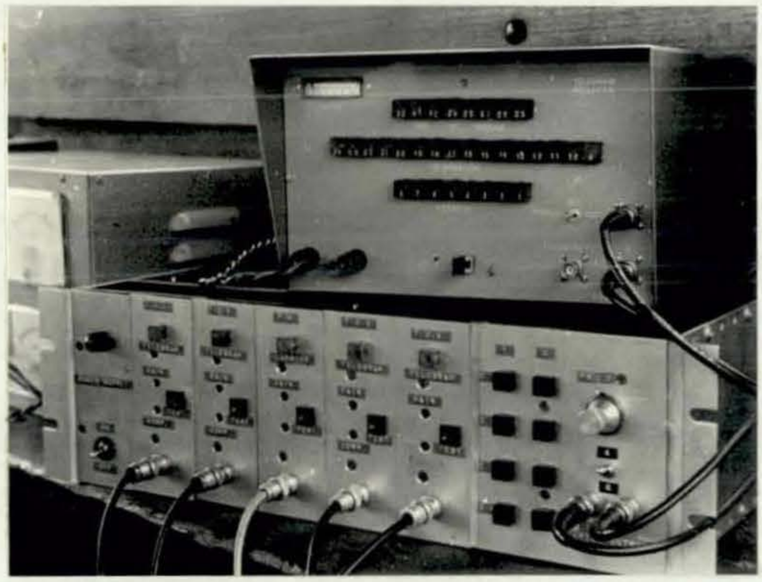


Fig. 124. Receiver and Telegram Address

Register.

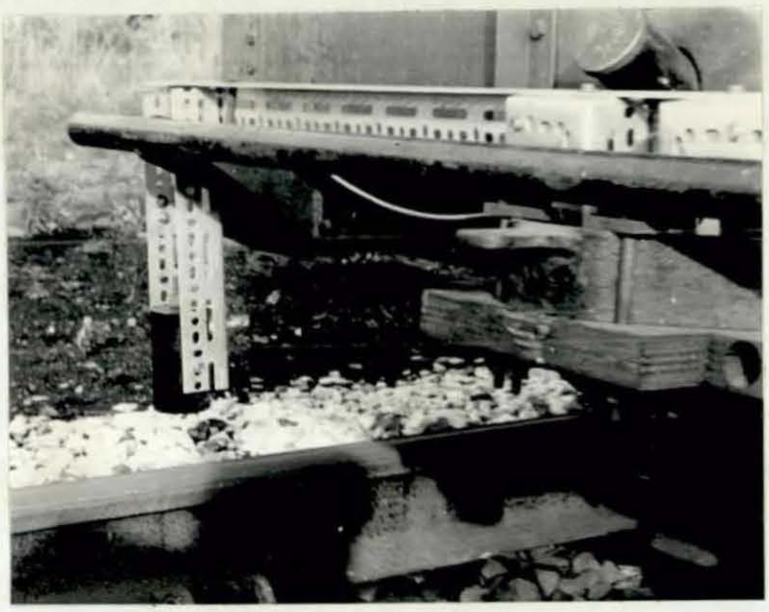


Fig. 125. Pick-up Coils in Situ.

laid contains only 10 coils (5 each side) instead of 16, with spacings of 0.76 metres (sleeper spacing) and one metre - see photograph. The larger spacing was to examine the increase of dynamic range R", afforded by this spacing. The actual 'message' laid down in the telegram had no significant meaning but each possibility for laying the coil appeared at least once. The telegram was fed 'forward' (i.e. away from the feed end) from the junction with the parallel wires - the worst possible case due to phase shift between the main current and the coil current (see section 10.2, p 61). Figure 127 shows a photograph of half the telegram coils in situ, switching giving the following conditions :-

1) line only
2) line and coils only, and
3) line, coils and matching network

The channels received are defined as (see fig. 128) :-

Side nearest platform:-

TC1 - vertical signal

TC2 - horizontal signal.

For the rail away from the platform:-

TC3 - vertical signal

TC4 - horizontal signal

Figure 129 shows the information available from the telegram coils as laid using the two different methods for evaluating TC2 and TC4.

11.3 The Reception of Telegrams

The initial testing was restricted to channels PW (Parallel Wire), TC1 and TC2 but subsequent work was done

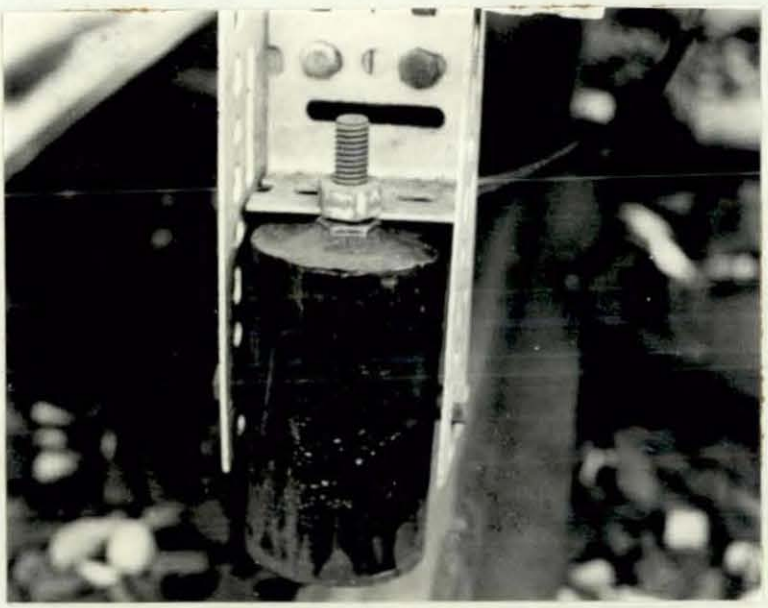


Fig. 126. Fixing of the Pick-up Coil.

Fig. 127. One Side of the Telegram (Channels TC3 and TC4).

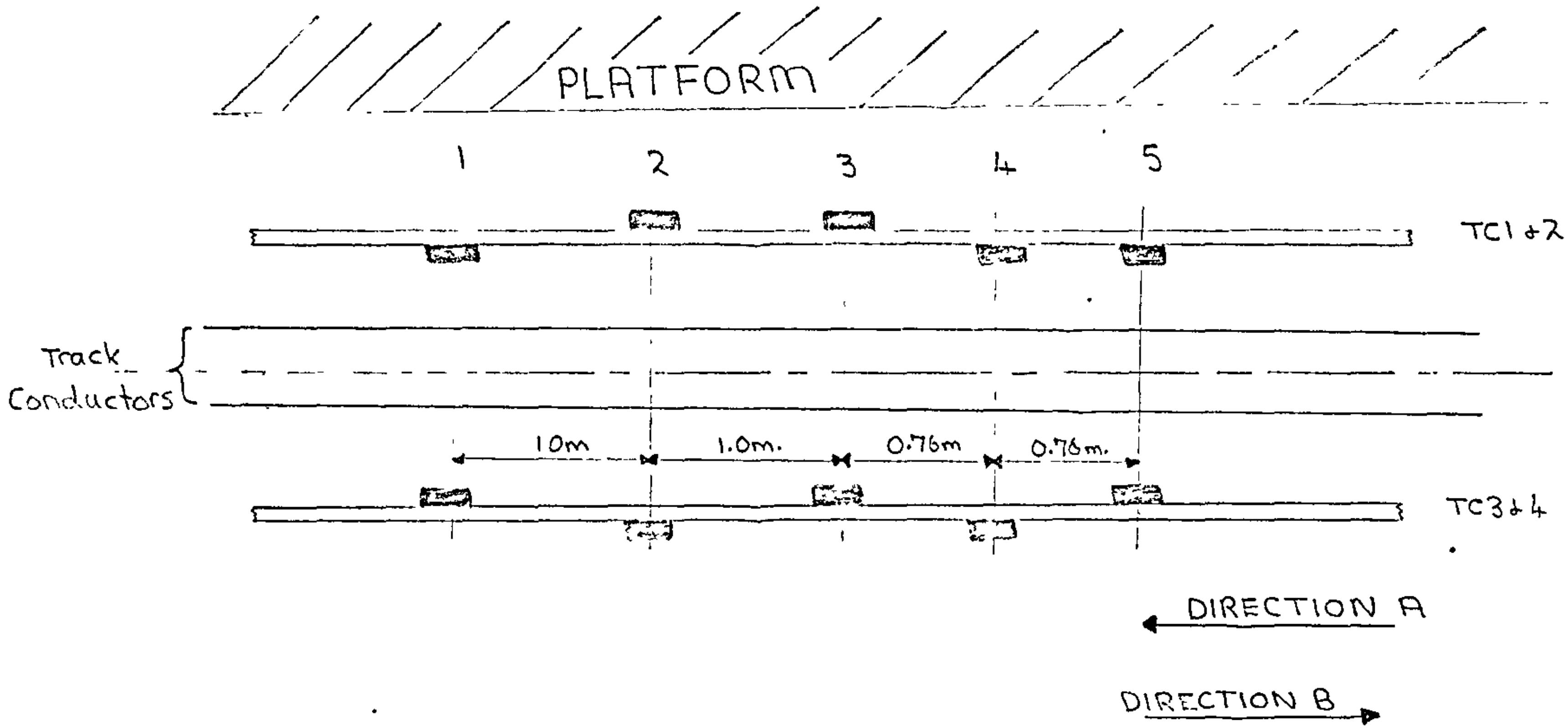


Fig. 128. POSITIONING OF TELEGRAM.

with all telegram coils channels. The receiver seemed to function well with minor modifications, over the range of speeds the trolley was capable. Taking the minimum value of flux density BR use in their system - 6×10^{-8} Tesla - as a guide to the minimum permissible, then, for bogie movements of $\pm$ 1" ($\pm$0.0254m) horizontally and vertically, the minimum line (and coil) current permissible with the modified system is 100 mA. The receiver was certainly capable of working over a line current range of 100-300 mA. The hysteresis employed on the envelope detector seemed sufficient for all but the very slowest speed in coping with the large variations of flux density encountered when on the point of triggering. Trouble occurred sometimes at very slow speeds, due to horizontal and vertical movement of the pick-up and any amplitude modulation of the 29 kHz carrier due to noise and beating effects with other safety carriers in the vicinity.

If the telegrams are fed backwards from their feed point and a matching network is used, then the PW channel will lead TC1 and TC2 and for comparison of both with the parallel wire signal all is well. If, however, TC2 is compared with TC1 some trouble may be encountered with the phase shifts. When the telegrams are fed forward from their junction point with a matching network then the PW signal lags TC1 and TC2 and trouble was encountered with phase shifts. This does show a shortcoming of the receiver built. These same problems were encountered when channels TC3 and TC4 were connected up. Because of these phase shifts, inherent or otherwise, complete cancellation of the 'residual' received on channels TC1-4 cannot be fully effected and so slight degradation of R" results.

Figures 130 and 131 show some of the combinations of telegrams capable of being received. With channels TC1, 2, 3 and 4 being used twenty independent binary bits of information can be received, and for channels TC1 and TC2 only half that number.

From the photographs it can be seen that the received messages shown tally with those predicted in fig. 129. Also, from the photographs, it can be seen that the message running forward over a telegram is not the reverse of the message received when running in the opposite direction. This is because the sampling in the Parallel-Serial converter always starts at channel TC1 and goes in numerical order - this is shown below for two channels only. If the received messages are:-

TC1	A C E G I
TC2	B D F H J

in direction A, the combined output is :-

A B C D E F G H I J

When running in the reverse direction, these combined to give :-

I J G H E F C D A B

- not the reverse of the message for direction A.

11.4 Practical Determination of R''

These measurements were made by recording the output voltage from each channel when the pick-up coils on the trolley were over telegram coils and when they were mid-way between. These recordings were made with :-

1. No compensation for the residual, and
2. Compensation for the residual

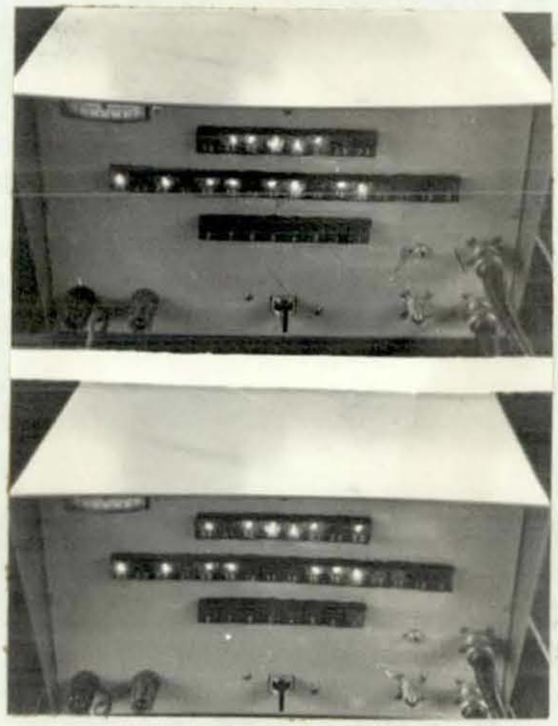
COIL POSITION \ CHANNEL	TC1	TC2	TC3	TC4
5	1	1	1	0
4	0	0	1	1
3	0	1	0	1
2	1	0	1	1
1	1	1	0	1

(a) All Signals Compared with the Parallel Wire Signal.

COIL POSITION \ CHANNEL	TC1	TC2	TC3	TC4
5	1	1	1	0
4	0	1	1	1
3	0	0	0	0
2	1	0	1	1
1	1	1	0	0

(b) TC1 and TC3 Compared with the P.W Signal and TC2 with TC1, TC4 with TC3.

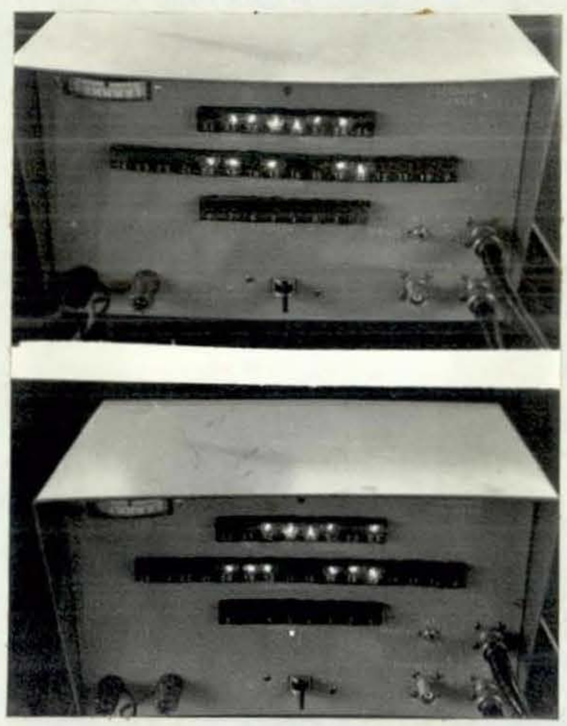
Fig. 129. Possible Telegrams Written.



(a) Direction B

Fig. 130. Received Messages. All Channels Compared with the PW Signal.

(b) Direction A



(a) Direction B

Fig. 131. Received Messages. TC1 and TC3 compared with PW and TC2 and TC4 compared with TC1 and TC3 respectively.

(b) Direction A

Four readings were made at relevant positions - with the trolley wheel flanges hard up against the rail and two intermediate positions, - this gave a total lateral movement of about $\pm \frac{3}{4}$" (0.019m). The worst possible case for the maximum interference between two coils and the effect of the parallel wires is different for the two sides of the track. For TC1 and TC2 this is Z = 1, X = 0, for TC3 and 4 this is Z = 1, X = 1· this can be determined from the field distribution pattern around the telegram coils and the parallel wires. Because of the slight variation in setting the gain of the amplifiers a minimum value of R" was determined for each channel and the worst values recorded in tables 9 and 10. R" (for a fixed threshold) was defined as:-

$$R'' = \frac{\text{Worst value of } V_o \text{ over a telegram coil (1's or 0's)}}{\text{Maximum value between two coils in the worst possible configuration}}$$

It is hoped that this definition will take into account any misplacement in laying the telegram coils and subtractive interference from the parallel wires. This definition should represent the worst possible condition ever to be encountered. The values in brackets are predicted values from results taken at Loughborough University for a movement, horizontally and vertically, of $\pm$ 1" ($\pm$0.0254m).

Out on the track and with the trolley exact measurements are difficult to make but the results in tables 9 and 10 are as expected. As the nominal movement of the trolley is about $\pm \frac{3}{4}$" ($\pm$0.019m) the values of R" are slightly larger than the values in brackets. The advantages of compensation are shown

	Without Compensation	With Compensation
R''_z	-11.5 (-5.5)	-12.5 (-7.4)
R''_x	-9.5 (-7.2)	-10.4 (-23)

Table 9. Worst Values of R" (0.76m spacing).

	Without Compensation	With Compensation
R''_z	-13.0 (-7.3)	-14.4 (-14.5)
R''_x	-9.8 (-7.5)	-10.9 (-[illegible])

Table 10. Worst Values of R"(1.0m spacing).

but not very clearly because of the problem of phase shifts between filters. For a larger lateral and vertical movement the values of R''_Z are expected to be most affected due to the larger variation in field strengths encountered. However, it would seem that the values in brackets are representative of the $\pm$ 1" ($\pm$0.0254m) variation. The values of R''_X for both spacings and compensation seem to show the most discrepancy - this could be due to experimental error due to the small value readings or due to longitudinal currents in the rail causing an interfering field. The values measured on the track do tally with those predicted by measurements taken previously in this thesis.

The dynamic range of the system, assuming balanced line currents, is determined by the minimum value of R" encountered (i.e. the minimum value of flux density over a telegram coil at the 'cold' end of the track conductors must be greater than the maximum flux density between two telegram coils at the feed end of the line for a fixed threshold). Using the predicted values of R" for the two spacings, then for sleeper spacing (0.76m), the range is 5:1 (14.0 db) and for one metre spacing is 7:1 (16.9 db) - leaving a margin for error and with no compensation for the parallel wire residual.

11.5 Induced Rail Currents

Because of the possibility of currents being induced in the rails from the track conductor system, it was decided to try to measure them as the fields thus produced will interfere with the magnetic fields from such systems,

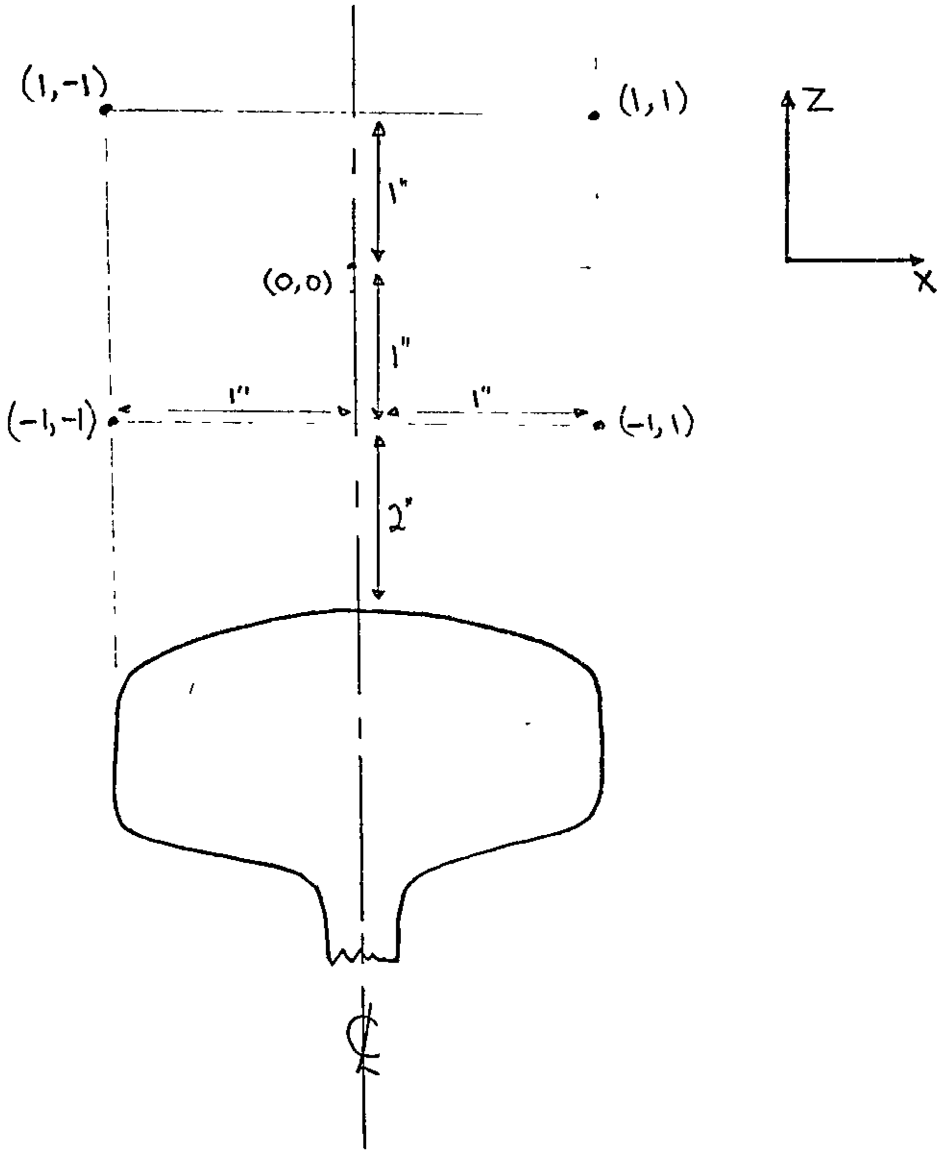


Fig. 132. Coordinates used for Measurements about Railhead.

especially if using telegram coils placed on the rail foot. Ideally the nett mmf in the rails should equal zero but due to rail discontinuities, the wires being offset from the centre of the track and any other irregularities, it is probable that a rail current will flow. If there is no train on a particular section of track then the connection between rails is made up from capacitance to earth and ballast conductance. When a train enters a section then the axles and wheels effectively short the two rails together causing an increase in rail current (a typical change from 2mA to 10mA was recorded - 5:1). The rail current was measured by removing a fishplate, shorting the rails with a 10 ohm resistor, and measuring the resulting voltage drop across it. Rail currents of up to 18 mA have been noted with the train on the section.

This rail current could be of prime importance if the interfering field it produces is comparable with the minimum values of field encountered between telegram coils. As the rail currents are longitudinal then the lines of force will be parallel to the rail head but perpendicular to the direction of motion and the horizontal field, B_x, will be most affected. Measurements were made to determine the values of flux density encountered by using a standard pick-up coil, the output of which had previously been recorded in a known flux density and was therefore calibrated. Figure 132 shows the limits of movement and the co-ordinates used. The following graphs (fig. 133 and 134) show recorded flux densities about the rail head. It can be seen that the maximum induced rail current is much less than that which can cause the receivers

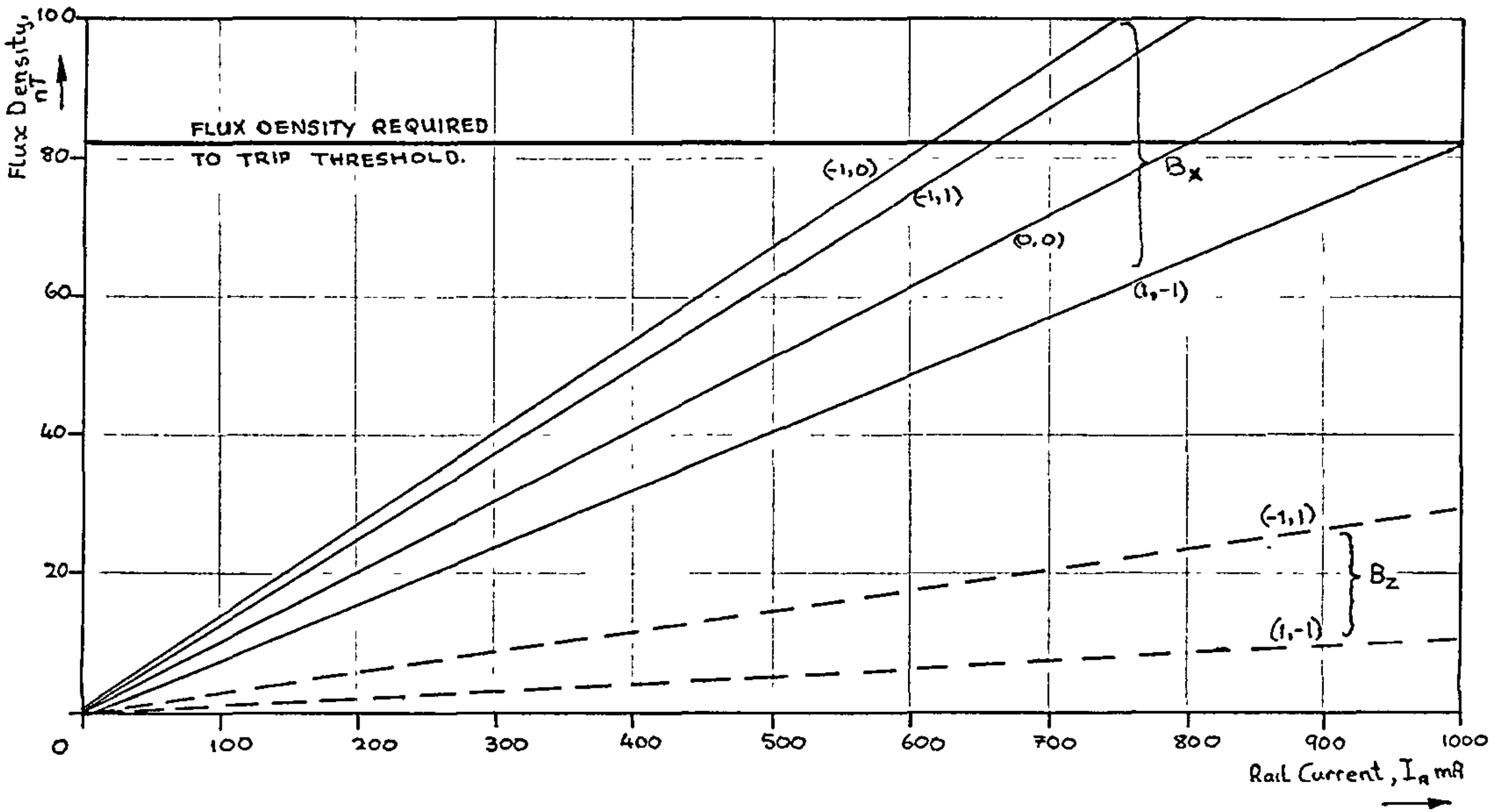


Fig. 133. FLUX DENSITY - RAIL CURRENT GRAPH FOR VARIOUS PICK-UP COIL POSITIONS (HIGH VALUES OF CURRENT)

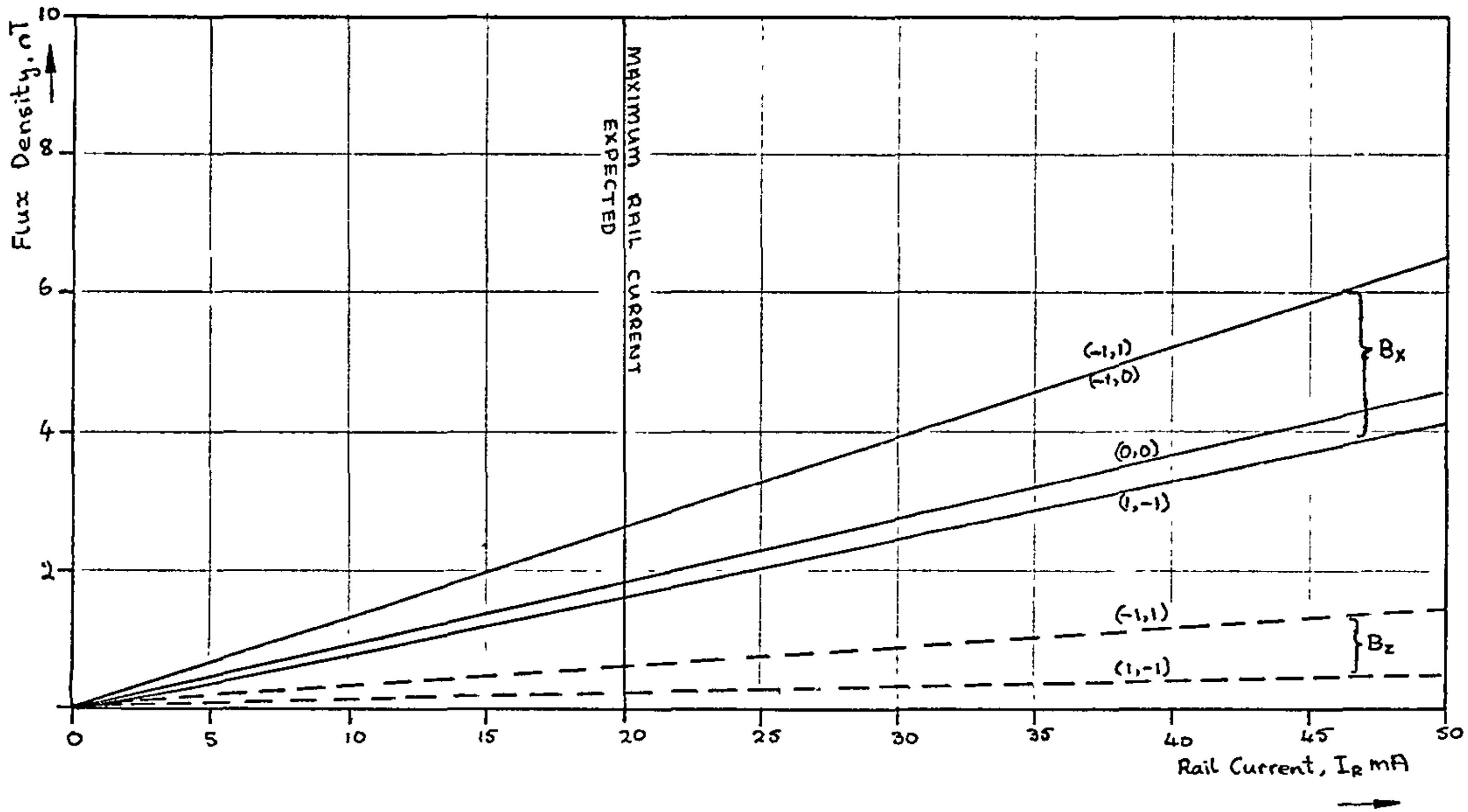


Fig. 134. FLUX DENSITY-RAIL CURRENT GRAPH FOR VARIOUS PICK-UP COIL POSITIONS (LOW VALUES OF CURRENT)

to 'trip', the B_x field being most affected as predicted. Whilst the maximum rail current expected here causes no significant degradation of the dynamic range of the system, if the rail current becomes greater, which could happen if there is much interference from adjacent tracks, it could be seriously affected.

12. COMPARISON OF ERROR RATES FOR DATA TRANSMISSION USING TELEGRAM COILS OR DIFFERENT FORMS OF MODULATION

To complete the analysis of the system described in the previous chapters an attempt has been made here to examine the effects of noise and to compare the theoretical probability of error rates for information transmission using telegram coils with that obtainable using alternative forms of data transmission such as direct electronic modulation of the carrier. The analysis has been based on assuming the noise to be white and Gaussian, although in reality the noise received along a railway track tends to be impulse and burst noise and which is generated mainly by the electric traction equipment of the locomotive. The magnitude of the noise varies greatly according to the type of locomotive used (e.g. electric, diesel-electric or diesel) and the position of the traction current supply, when used - viz. third rail, overhead or even battery driven. The nature of the current supply, i.e. direct or alternating current, also determines the amplitude and frequency spectrum of the noise. Some interference measurements have been done by British Rail (see refs. 15 and 16). The condition of the train or locomotive as regards whether it is accelerating, braking or coasting has a marked effect on the noise produced as does the ride of the current collector - see ref. 15. Measurements have also been done in Germany on the noise produced along a railway line. Buckel (ref. 13) has written a paper on the general production and effects of noise on a main line railway (which also contains an extensive bibliography) whilst Form (ref. 14) has made measurements on a third rail system (the Hamburg Underground) for noise induced into a pick-up coil similar to that for automatic train control purposes. The results have been similar to those obtained in this country and show that it is preferable to use the upper end of the band 20 kHz - 200 kHz for data transmission. However a compromise has to be made here due to the increasing attenuation of the track conductors with frequency. The above references have been able to give practical results for the rate at which noise bursts exceed given levels but no work has been done on the error rates likely for actual data transmission.

The noise received comes basically from two sources - it will appear either as an induced current or it will be space-borne i.e. not emanating from the parallel wires but directly from its physical source. It is assumed that receiver noise is much less than the received noise and is therefore neglected. Whilst for the various forms of electronic modulation one can consider the received noise as one entity, in the case of telegram coils this is not so. Because of the nature of the system the line current flows in the track conductors and the coils and so for all channels concerned the line noise is always fully correlated between them. For space-borne noise there may be varying degrees of correlation between the noise on the channels, this is explained later in section 12.5 and in the appendix.

Various assumptions have been made in the analysis in deriving the expressions and these are given in the appendices or as the chapter proceeds, where necessary. The results can only hope to give bounds to the error rates involved due to the lack of knowledge about the noise sources. To obtain results various values have been given to the parameters involved and a physical explanation given to the various conditions where possible. It is hoped that the results obtained will give some idea of the order of magnitude of the error rates to be expected but should certainly provide some comparison between the various transmission systems examined. The signal to noise ratios have been limited to a maximum of 20 db. This is because of difficulties with calculations with the computer. Using DOUBLE PRECISION on the computer, calculations can be made to about 20 significant figures but with the expressions obtained here it has been necessary to subtract very small numbers from unity and hence results less than 10^{-20} are very unreliable.

Two error rates have been calculated :-

1. the probability that a digit received will be in error, and
2. the probability that a telegram will be received but will be false (i.e. for the message received the error detection digits are incapable of detecting an error) - see appendix II.

In all the work in this chapter it is assumed that a Hamming Code of distance 4 is used as at present and that a telegram comprises 32 bits in total.

12.1 Permissible Forms of Modulation

The forms of modulation that can be used are restricted due to the nature of the communication system. Because of train movement any form of amplitude modulation is forbidden as the train movement will generate unwanted modulation frequencies which could upset any data transmission. The line attenuation and its variance with weather prohibits the use of modulation that requires any form of discrimination between different signal levels (other than no signal and a signal present). This basically leaves three forms of modulation :- frequency shift keying (FSK), phase shift keying (PSK) and on-off keying (OOK). The various possible forms of these are :-

1. Phase Shift Keying
   a) Phase/Coherent PSK
   b) Phase/Coherent DPSK (Differential PSK)
2. Frequency Shift Keying
   a) Coherent FSK
   b) Non-coherent FSK
3. On-Off Keying
   a) Coherent Detection
   b) Envelope Detection

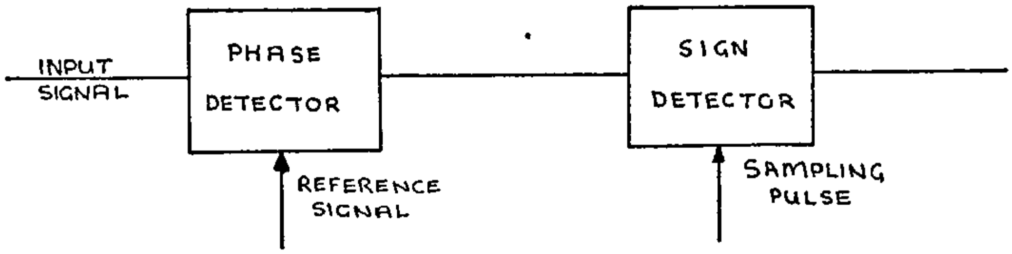
The use of on-off keying is not further considered because of the much poorer error rates (see ref. 18). All these systems are well described in References 18 and 19 although block diagrams of receivers are given in this chapter. In the following analysis it is assumed that a synchronising signal is available on the train for sampling purposes and that the sampling occurs at such a time that intersymbol interference is avoided. The form of the input signal to the receiver is given in Appendix 9. Cases are considered for the noise on the reference channel correlated with that on the signal being received and that between two different channels and being correlated

12.2 Phase Shift Keying

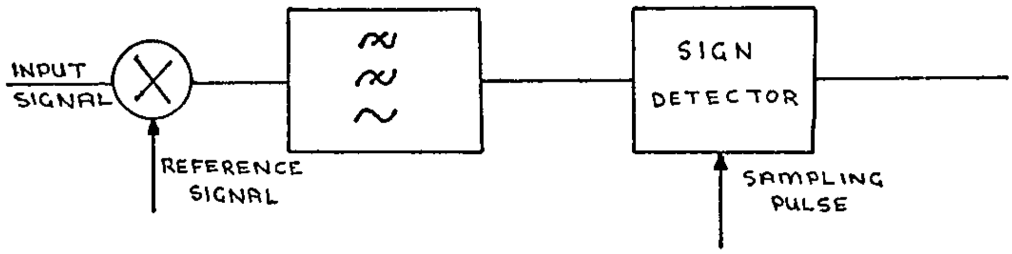
a) Coherent PSK

Figure 135 shows typical receivers for both Phase and Coherent detection of PSK - the analysis for both being the same (see Ref. 18). The probability that a digit may be in error (P_e) is given by :-

$$P_e = \tfrac{1}{2}\mathrm{erfc}(s)$$



a). Phase Detection



b). Coherent Detection

Fig.135. Receivers for PSK Systems

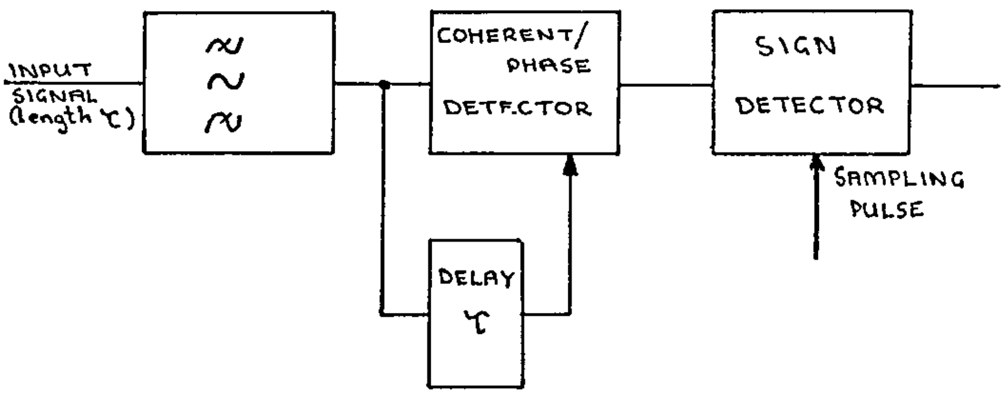


Fig.136. A Typical Receiver for DPSK

where s is the S/N ratio as defined in the appendix. For this case the reference waveform which must be generated locally is assumed noiseless. The resulting curves for bit error rate and the probability that the received telegram is false (see Appendix II) are shown on fig. 137.

b) DPSK

A typical receiving system for this is given in fig. 136. Here it is possible for the delayed channel noise to be correlated with the noise or the signal being received. Moreover, the rms noise values on the two channels may not be the same - due to the effects of the delay resonator. The probability of a bit error is given by (among other forms - see ref. 17 page 587) :-

$$P_e = Q(\sqrt{a},\sqrt{b}) - \frac{v^2}{1 + v^2} \exp\left[-\frac{a+b}{2}\right] I_o(ab)$$

where $Q(\sqrt{a},\sqrt{b})$ is the Marcum Q - Function (see below) and $I_o(z)$ is the modified Bessel Function of zeroth order.

$$Q(A,B) = \int_B^\infty x.\exp\left[-\frac{A^2 + x^2}{2}\right] I_o(Ax).dx$$

The subscript 1 denotes the direct channel and 2 the delayed channel. If ρ is the normalised cross covariance coefficient between the two channels then

$$a = \frac{I_s^2 (\sigma_1 - \sigma_2)^2}{4\sigma_1^2\sigma_2^2}$$

$$b = \frac{I_s^2 (\sigma_1+\sigma_2)^2}{4\sigma_1^2 \sigma_2^2}$$

$$v = \frac{1 + \rho}{1 - \rho}$$

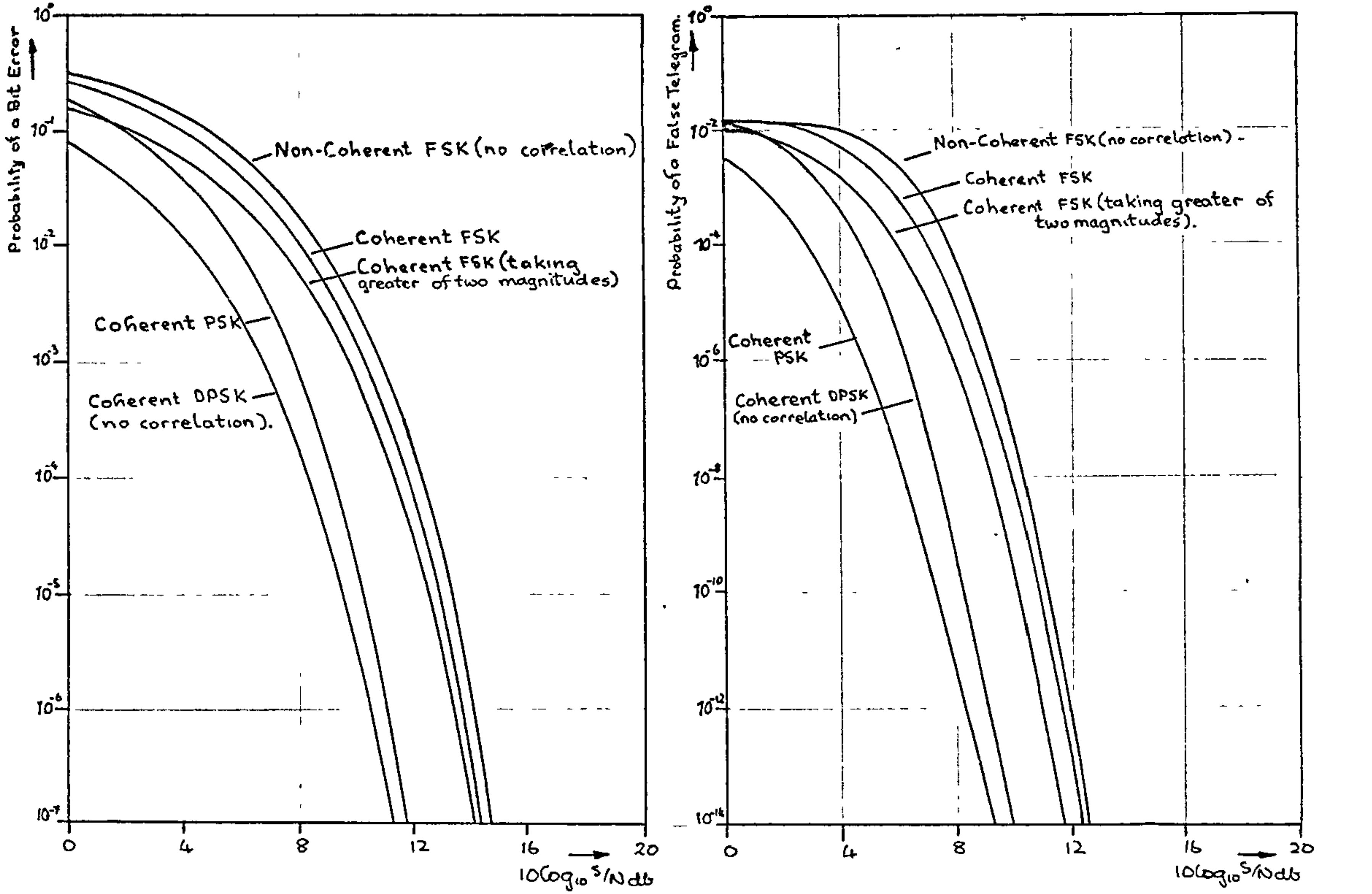


Fig. 137. Error Rates for Various Types of Modulation.

where I_s is the peak line current and σ_1 and σ_2 are the rms noise levels on the two channels. Curves are only plotted for the most likely case of $\sigma_1 = \sigma_2$. The curves are given in figure 138 and are for the bit error rate and the probability of the reception of a false telegram. P_e is derived using a method described in Ref. 17, page 315 ff.

12.3 Frequency Shift Keying

a) Coherent FSK

Figure 139 shows a typical receiver for this type of modulation, the probability of a bit error being given by:-

$$P_e = \tfrac{1}{2}\,\mathrm{erfc}(s/\sqrt{2}) \quad \ldots \quad \text{see ref. 21}$$

If the receiver is such that it chooses the larger of the two magnitudes for the output (i.e. does not take into account the algebraic sign) the probability of a digit error is given by:-

$$P_e' = 2.P_e\,(1 - P_e)$$

where P_e is as defined above.

b) Non-Coherent FSK

This is probably a far more practical proposition with FSK for track to train communications as no ideal reference waveform is required to be generated aboard the train. A block diagram of a typical receiver is given in fig. 140. Assuming that the noise at both filter outputs may be correlated, with normalised cross-covariance ρ, the digit error rate can be expressed as :-

$$P_e = Q(\sqrt{a},\sqrt{b}) \quad - \quad \frac{v^2}{1 + v^2}\ \exp\left[-\ \frac{a + b}{2}\right] I_o(\sqrt{ab})^{*}$$

* Again using the method given in Ref. 17, page 315 ff.

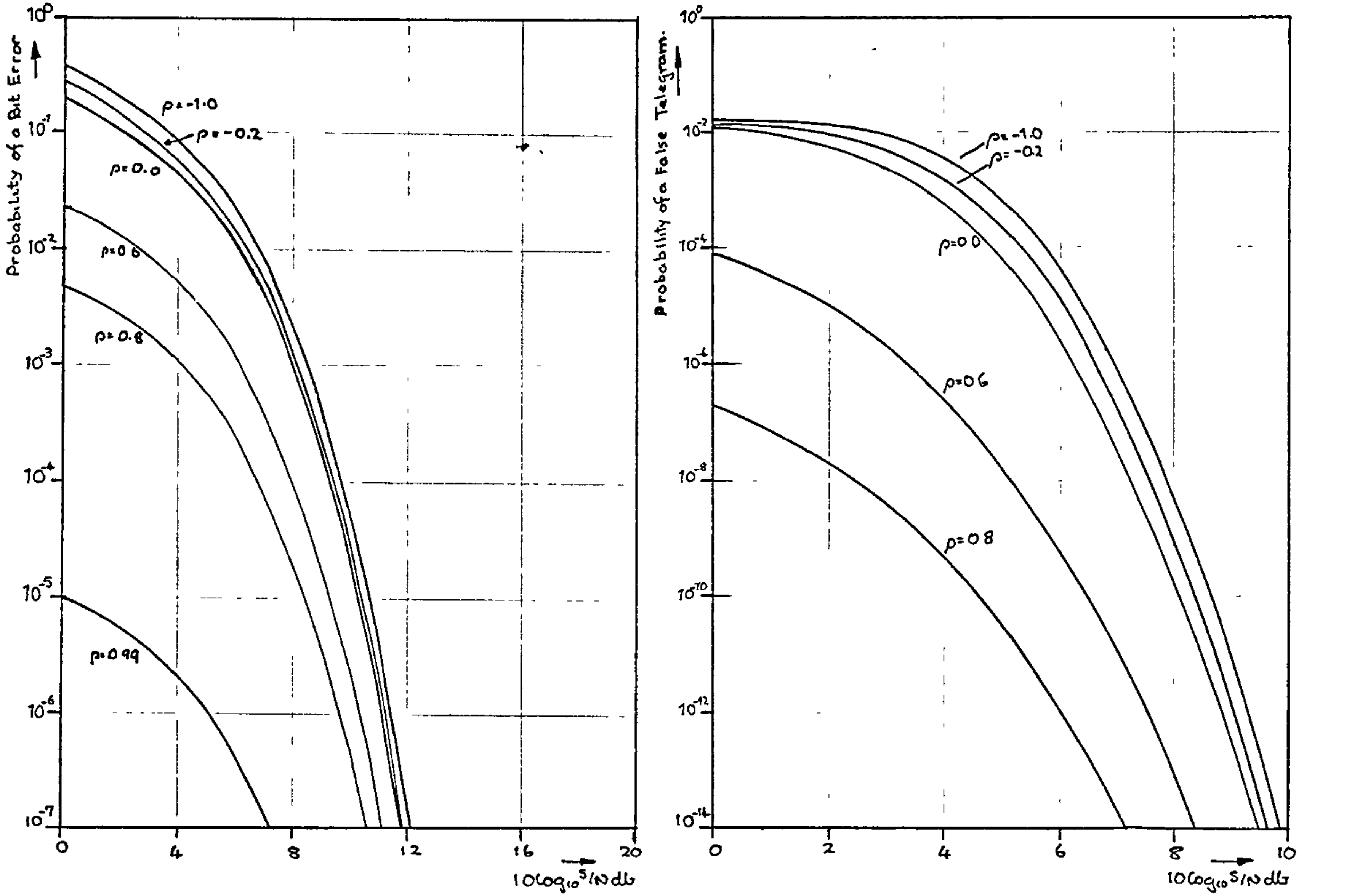


Fig. 138. Error Rates for DPSK with Correlated Delayed Channel Noise and Equal Noise RMS Values.

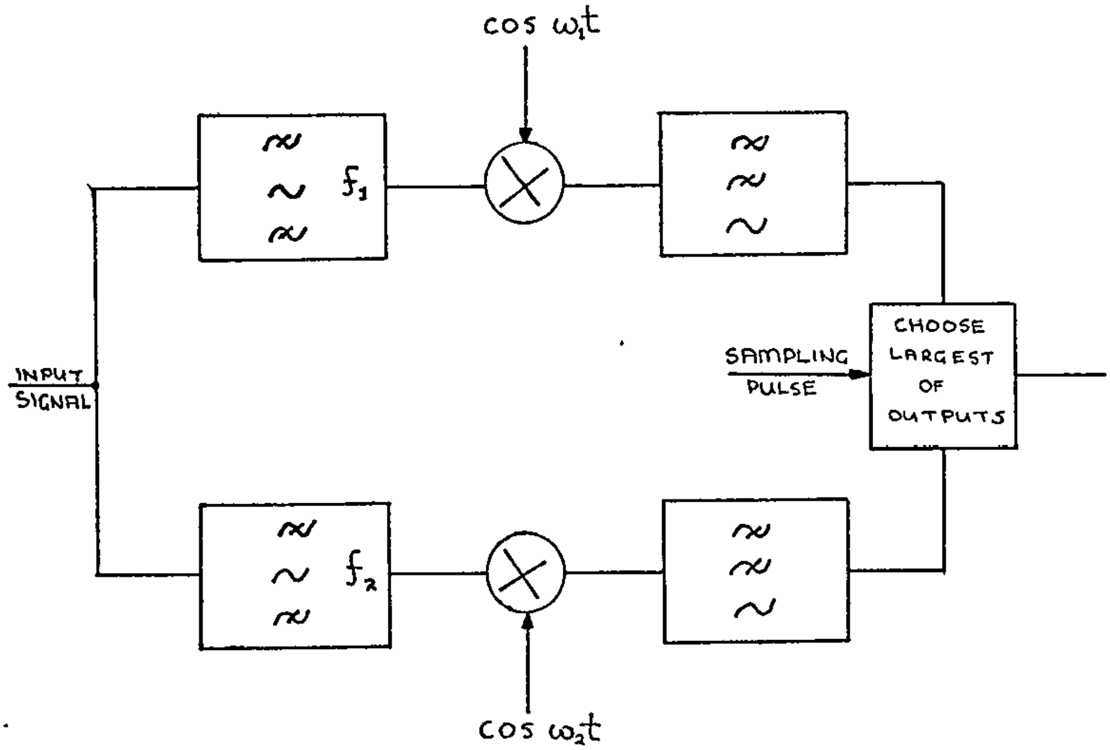


Fig.139. Receiver for Coherent FSK

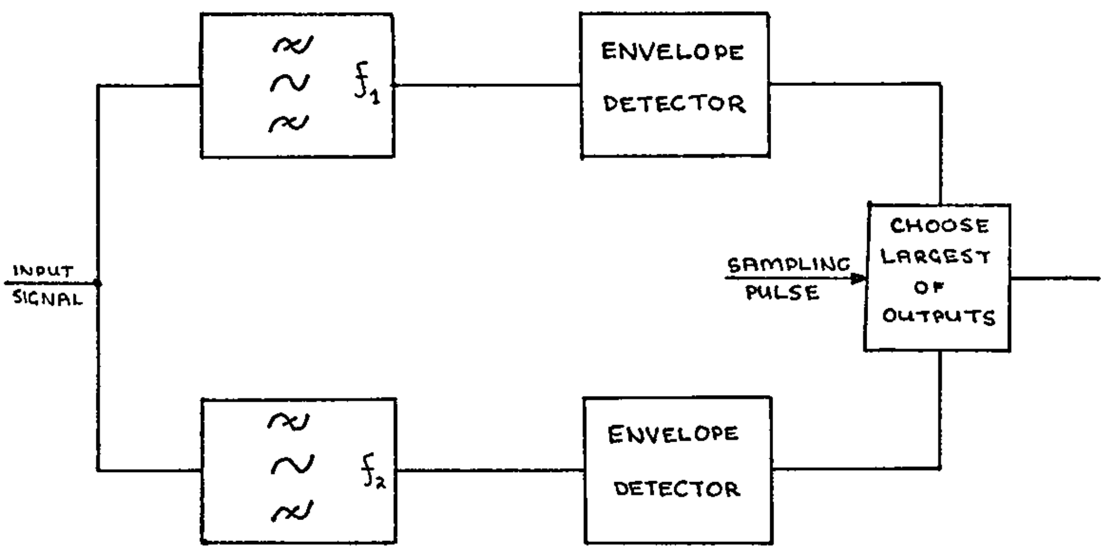


Fig.140. Receiver for Non-Coherent FSK

where

$$A = \frac{\sigma_1^2 - \sigma_2^2}{\left[(\sigma_1^2 + \sigma_2^2)^2 - 4\sigma_1^2\sigma_2^2\rho^2\right]^{1/2}}$$

$$V = \frac{1 + A}{1 - A}$$

and $$\begin{Bmatrix} a \\ b \end{Bmatrix} = \frac{1}{2}\left[\frac{(\sigma_1^2 + \sigma_2^2)\, I_s^2}{(\sigma_1^2+\sigma_2^2)^2-4\sigma_1^2\sigma_2^2\rho^2} \mp \frac{I_s^2}{\sqrt{(\sigma_1^2+\sigma_2^2)^2-4\sigma_1^2\sigma_2^2\rho^2}}\right]$$

The rms noise values are given by σ_1 and σ_2 for the two channels and I_s, $I_o(z)$ and Q(A,B) are as defined previously. The relevant curves are given in figures 141, assuming that the rms noise levels in each channel are the same but that various degrees of correlation exist between the noise on the two channels.

12.4 Discussion on the Error Rates for Modulation System

As can be seen from figs. 137 and 138, PSK and DPSK are superior to any form of FSK - at high S/N ratios the gain being 3 db for the same probability of error; this could be of vital importance where systems are being used under difficult conditions. The difference between PSK and DPSK is only really significant at low S/N ratios and is dependent on the relationship between the reference waveform and the incoming signal in DPSK. However, for various values of this correlation, DPSK can improve on normal PSK.

If modulation is to be used for the data transmission, and because of the reliability required, it would appear that it is desirable to use either PSK or DPSK. Because of the transpositions in the track conductors (see page 6) and the associated phase reversals it may be impractical to use either PSK or DPSK so that FSK must be considered as the alternative. It might,

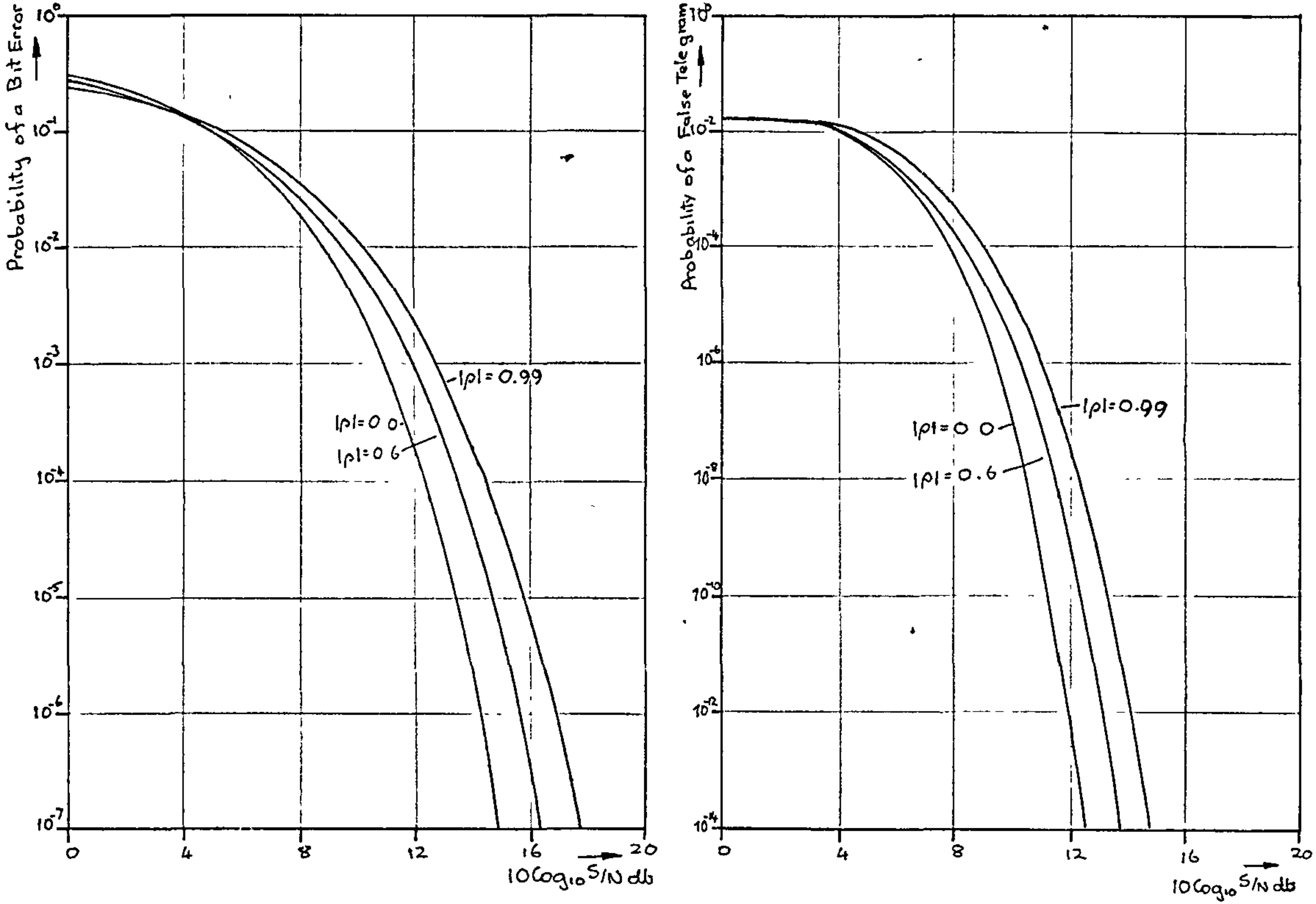


Fig. 141. Error Rates for Non-Coherent FSK for Various Degrees of Correlation between the Channels.

however, be possible to use some form of gating to inhibit reception as the transpositions are traversed and thus regain the advantages offered by PSK or DPSK. If FSK is used it would seem easiest to implement non-coherent FSK as no ideal reference waveform is required, the error rate of which tends to that of coherent FSK anyway at high signal to noise ratios (i.e. above about 10 db).

12.5 Telegram Coil Channels

The form of the input signal(s) to the receivers and assumed multiplicative demodulator is derived in Appendix 10. The filter bandwidths are assumed greater than 100 Hz - the maximum telegram pulse rate. Figure 142 shows a typical telegram coil signal. It is assumed that some form of synchronisation signal is available on the train so that the telegram pulses are always sampled at the same point on the signal envelope - for the case of the following curves this is assumed to be the maximum of the signal. The signal values used in this analysis are the worst encountered - i.e. at the extreme of the assumed $\pm 1''$ bogie movement. The error rate has been calculated assuming a signal is being received and that it is in error. From this is also derived (see Appendix 11) the probability that a telegram received is false - i.e. the error detecting digits are correct for the received information digits. An alternative to the above defined error rate is that of a signal being received when none is transmitted - this is because of the intermittent nature of this type of transmission system. Although this type of error could ruin the reception of a telegram, i.e. produce more than the 32 bits required at present,

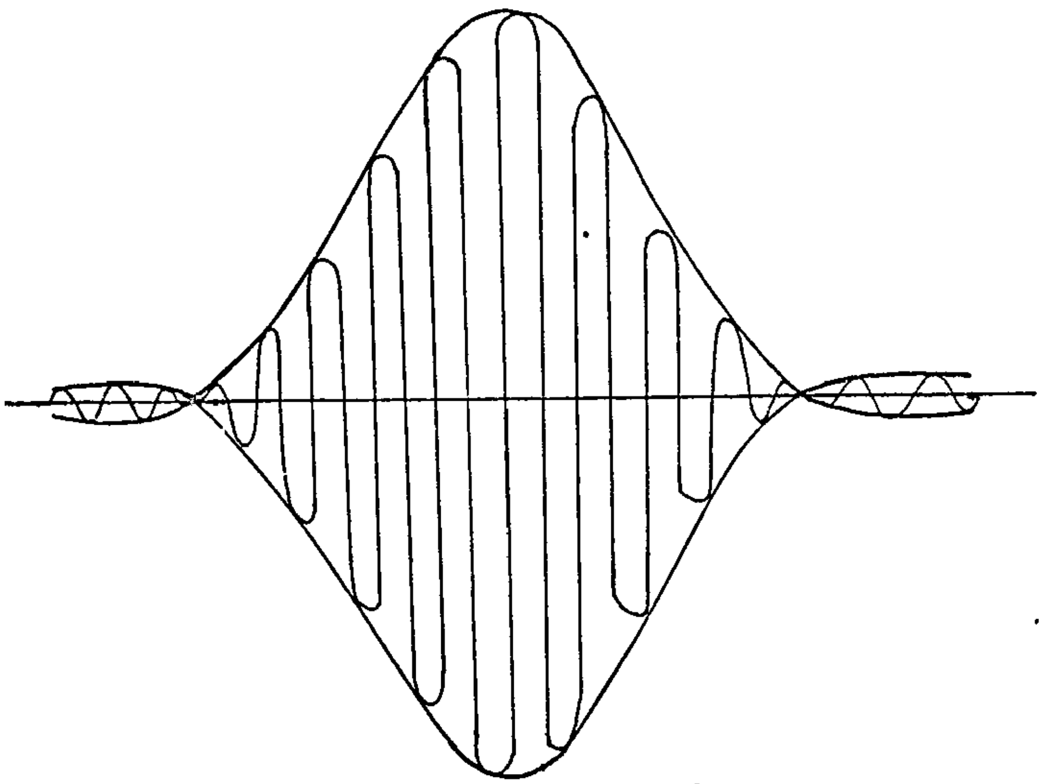


Fig. 142. A Typical Telegram Coil Pulse.

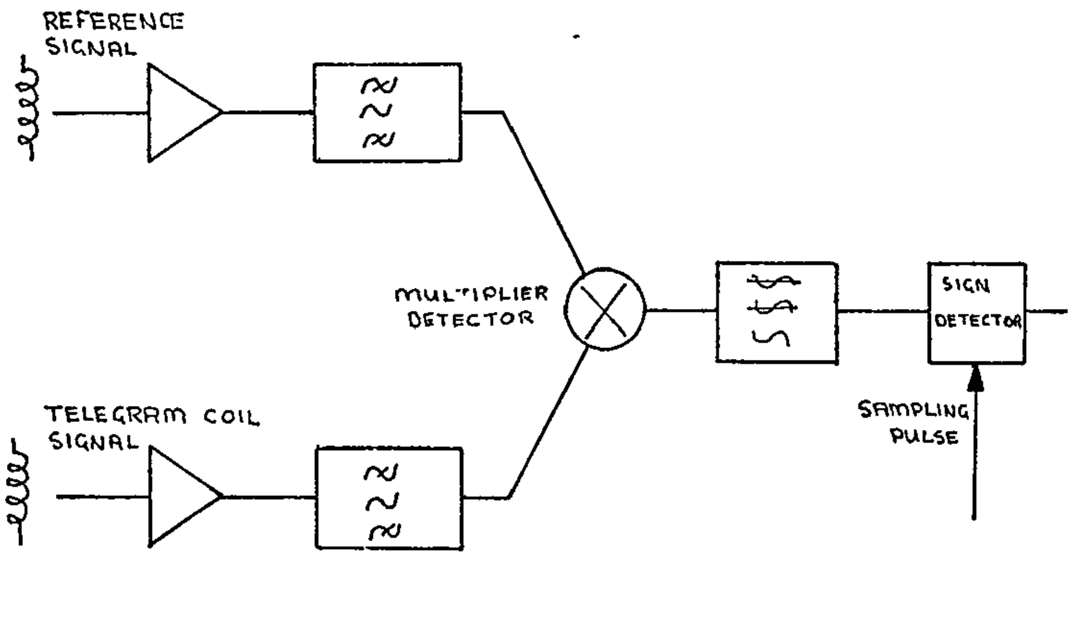


Fig. 143. The Assumed Telegram Coil Receiver.

the train receiver looks for 32 bits to be received between two transpositions. If the number received differs from this, a failure will be reported and the train will revert to complete manual control. However, it is very unlikely that a false telegram will be received due to this effect and it is felt that the error rates of importance are those that have been described previously. It is realised that this is not a full analysis but should suffice initially for a comparison between the two available telegram coil systems and with the various methods of modulation. The two telegram coil systems are the original BR system and the newly developed system described in this thesis.

Figures 144-146 for the BR system assume that the rms noise levels of the space-borne noise on each channel are the same whilst figures 147 and 148 for the new system take into account the effect of differing space-borne rms noise levels. The error rates have been evaluated for varying degrees of correlation between the space-borne noise on the various channels and for varying values of the ratio (k) of rms line noise current to rms space-borne noise levels (evaluated with respect to line currents). Values of k equal to 0, 0.1 and 1.0 have been examined although not all the curves are shown in this thesis. From practical measurements taken (see ref. 15) it was found that the induced aerial voltage due to line noise currents was very much less than that due to space-borne noise. Hence the curve for the ratio equal to 1 is rather hypothetical - a more appropriate value being 0.1.

From Appendix 13 it is shown that if one noise source is predominant, then the normalised cross-correlation coefficient tends to $\pm$ 1, whilst for a collection of random noise sources it can take a range of values according to the distribution, magnitude and directional properties of the noise sources. For partly correlated noise sources it can be inferred from the appendix that various values of cross-covariance can exist. Depending on the motion of the train - i.e. braking, accelerating or braking - the correlation between the noise sources may vary and thus also affect the error rates. Hence, all that can be hoped for from this study is to produce sets of curves that will provide limits for the error rates to be expected during normal operations. Whilst many curves can be plotted for the varying parameters, those included in this thesis are representative and give direct comparisons between the various systems.

12.6 Reception of Telegrams using only One Field Component from the Telegram Coils

This case is considered for both BR type coils and the new ones - using only the vertical field component. Figure 143 shows the form of the receiver assumed in making the analysis given in Appendix 10. This approximates to that used in the practical investigations in Derby. The detection is very similar to that of PSK - the transmission is virtually PSK. The probability of a single bit error is given by:-

$$P_e = Q(\sqrt{a},\sqrt{b}) - \frac{v^2}{1+v^2}\exp\left[-\frac{a+b}{2}\right].I_0(\sqrt{ab})$$

where a, b and v are defined in Appendix 10.

As explained in the appendix, the signal to noise ratio can be defined in two ways but only that defined by the PW signal is used here. If the received telegram coil pulse is not sampled at the maximum but some other value, then a somewhat lower S/N for this channel will result for a given error rate. The curves shown have been calculated for the condition of worst interference between the coils and the parallel wires, and vice versa, and between adjacent telegram coils.

The details of the coils examined for this type of system are:-

i) BR coils, 9" x 7", both pick-up heights 0.305 m above sleeper level and η/ϕ = 0.587.

ii) Loughborough type coil, 6" x 2", mounted on rail foot. This was assumed 3" (0.075m) below rail head with the pick-up coil the same distance above rail head (i.e. about 0.25 m above sleeper level). The reference signal pick-up coil was assumed as for the BR case. Here the calculation was for the worst case of the $\pm$1" movement and η/ϕ = 0.538 (for sleeper spacing - 0.76m) and η/ϕ = 0.529 for one metre spacing.

Evaluation of η/ϕ taking into account interfering signals between coils and track conductors is given in Appendix 12. Only the curves for sleeper spacing are shown for the Loughborough coils as the error rates for one metre spacing are virtually the same.

The error rate curves for the British Rail coils are shown in figs. 144 to 146. These curves show the effect of varying the magnitude of the line noise but keeping the space-borne noise constant. For values of k = 0 and 0.1 the error rates are almost identical but at low S/N ratios and k=1.0 there is a noticeable improvement. At higher S/N ratios (above about 12 db) all the curves seem to tend to the same asymptote. This

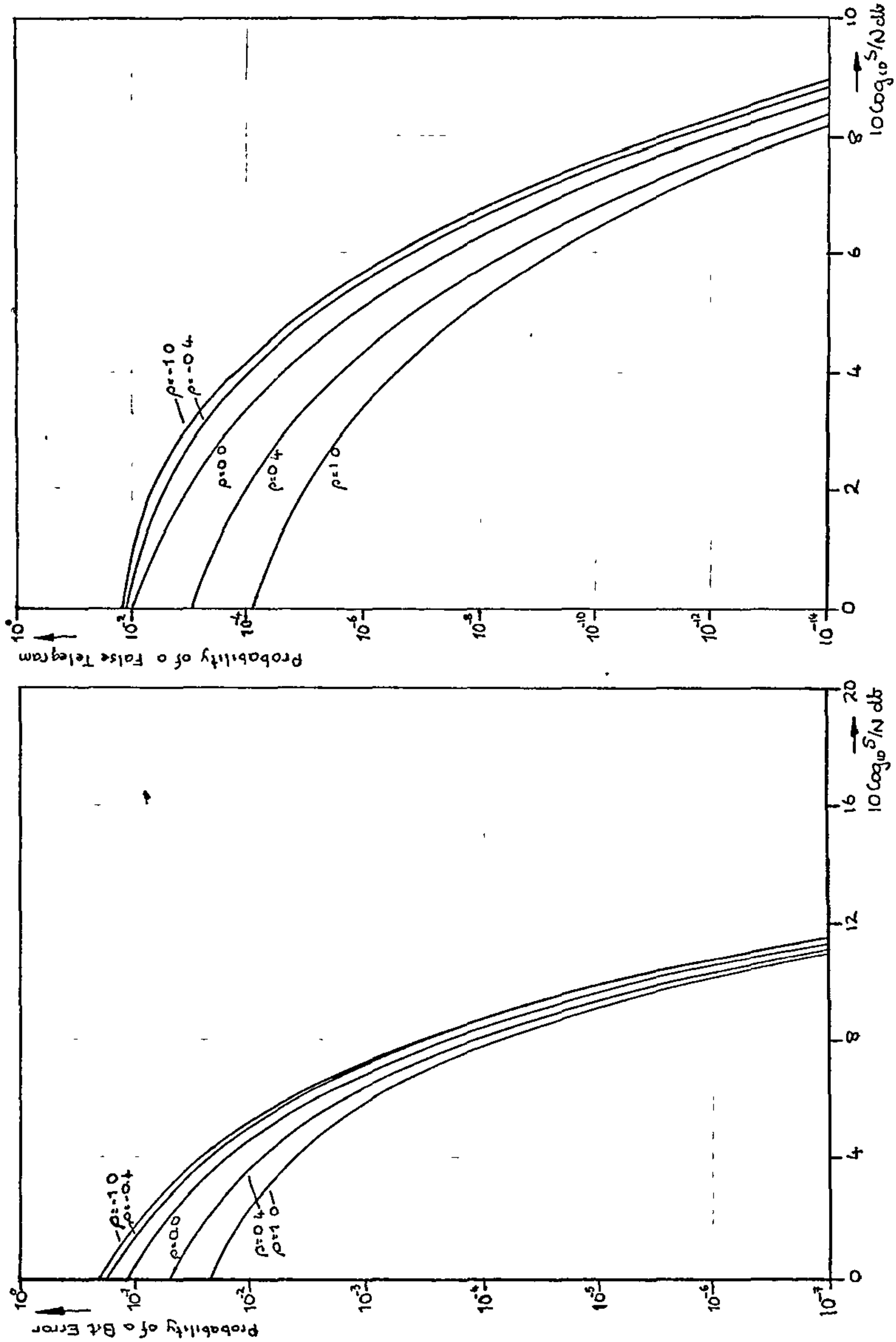


Fig. 144. Error Rates for BR Telegram Coils. Equal Space-Borne Noise both Channels, k=0.0.

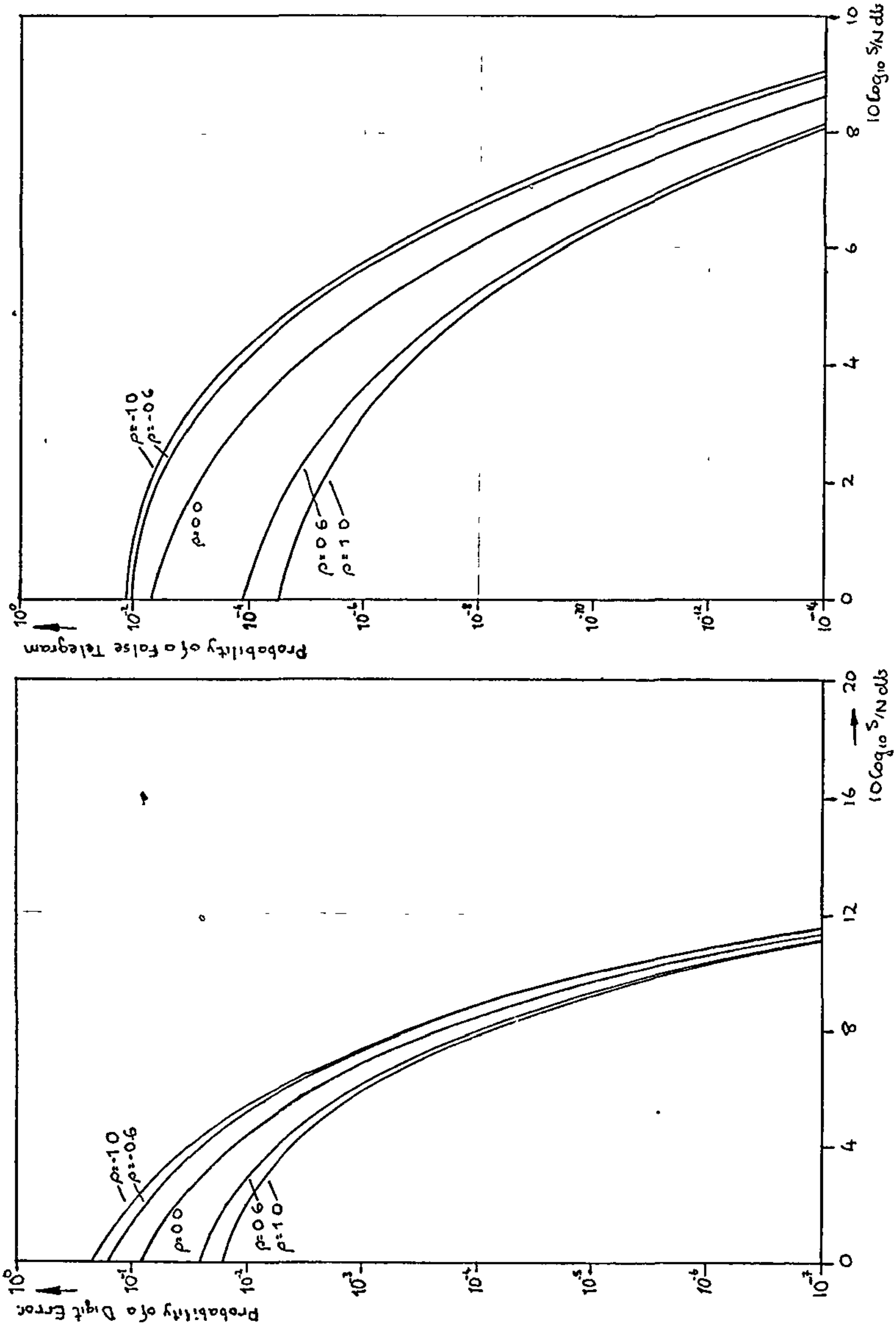
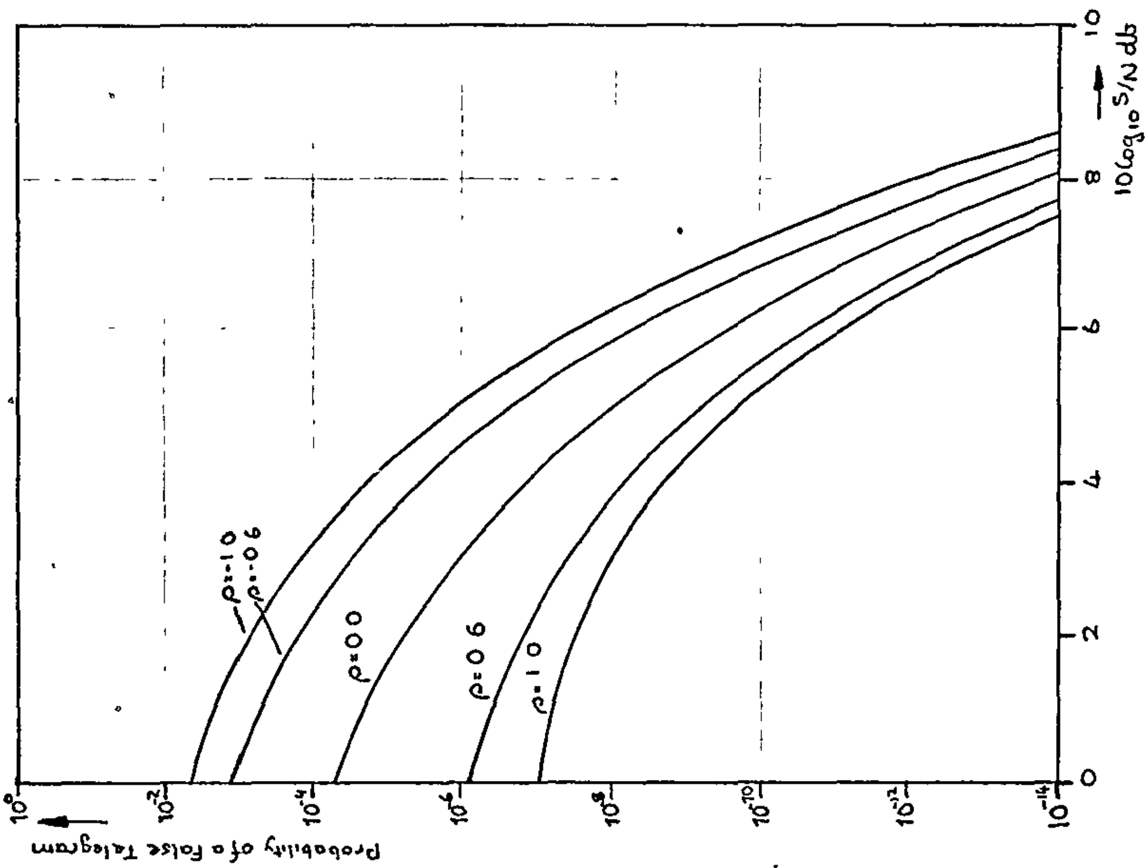


Fig. 145. Error Rates for BR Telegram Coils. Equal Space-

Borne Noise both Channels, k = C.1.



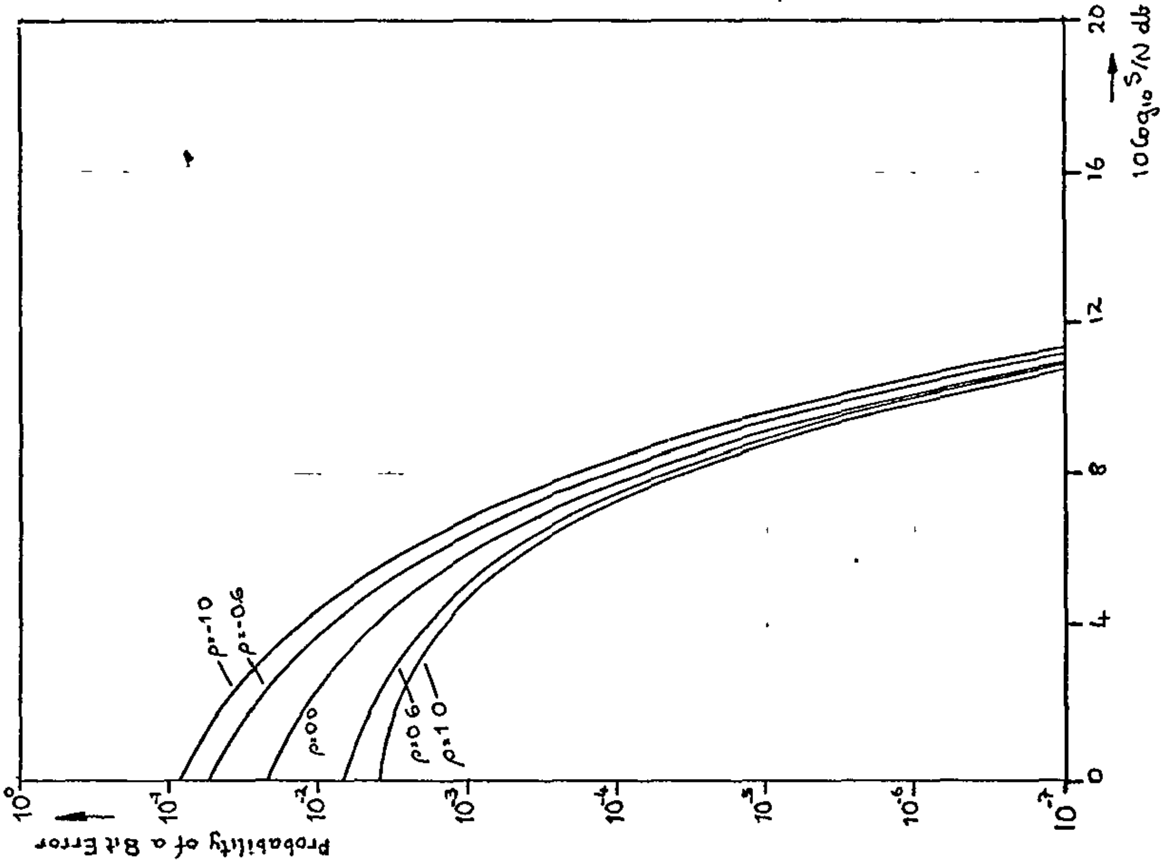


Fig. 146. Error Rates for BR Telegram Coils. Equal Space-Borne Noise both Channels, k = 1.0.

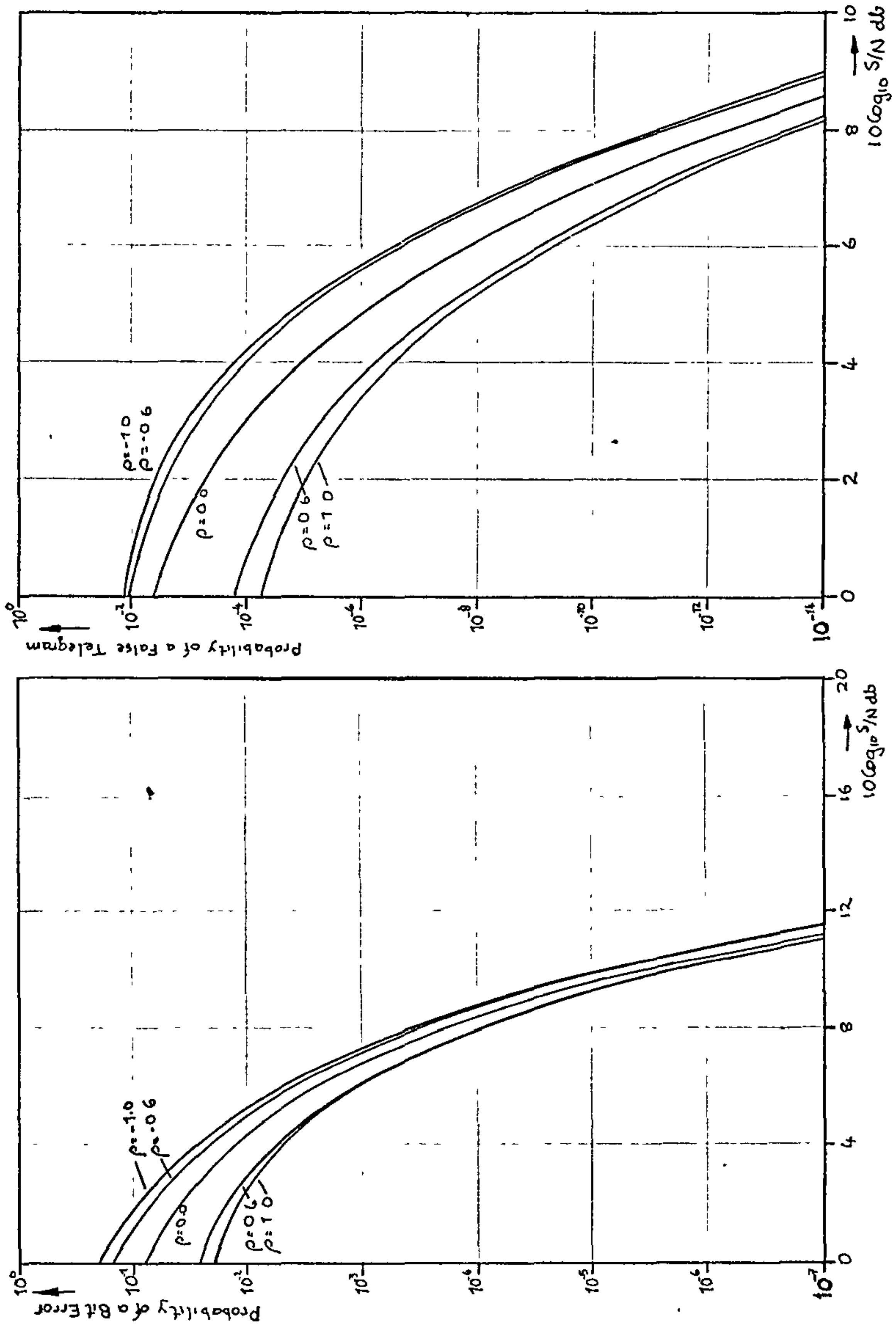


Fig. 147. Modified Telegram Coils Using only One Field Component.

Equal Values of RMS Space-borne Noise, k = 0.1.

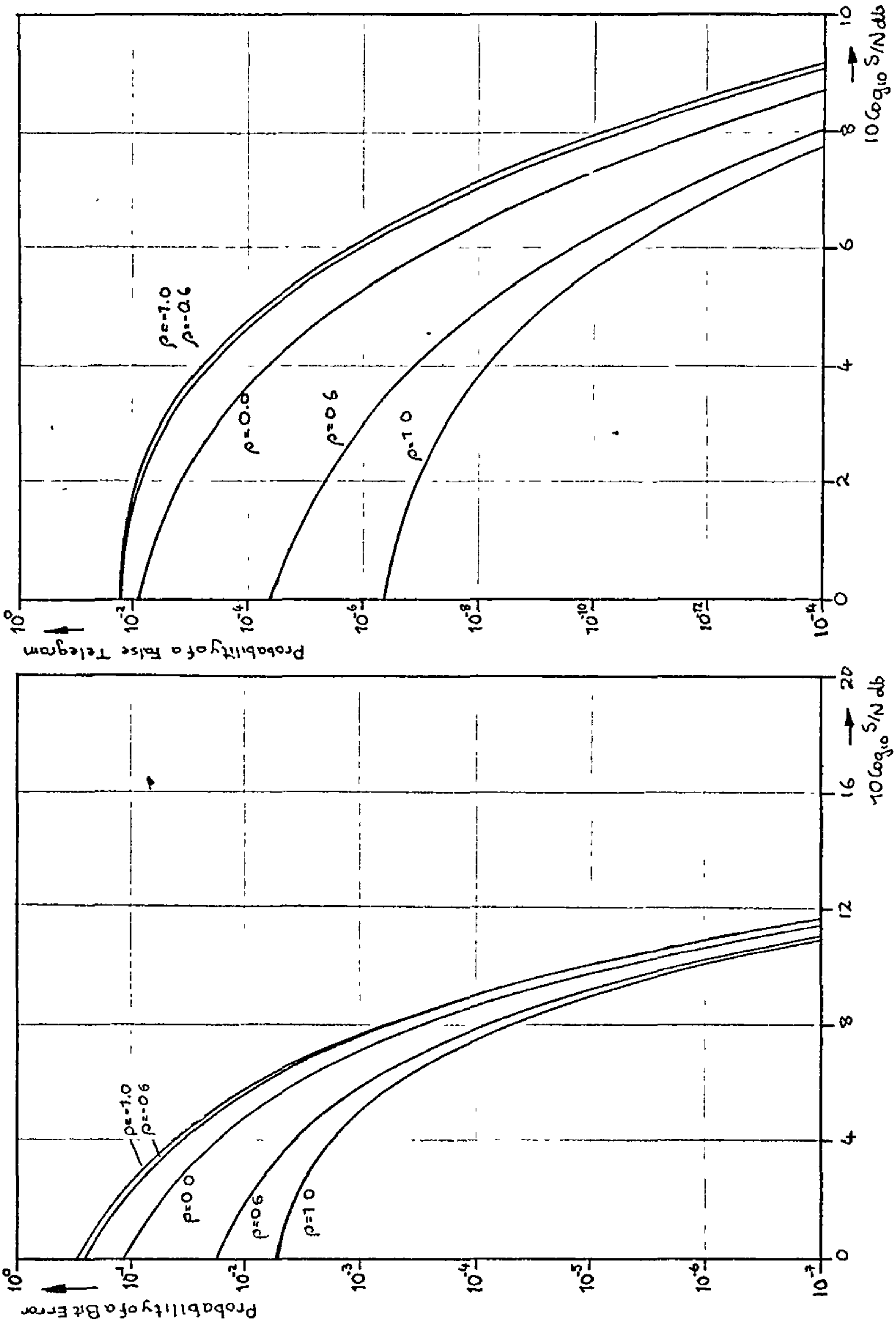


Fig. 148. Error Rates for Modified Telegram Coils Using Only One Field Component. Increased Space-borne Noise on Telegram Coil Channel (Double), k = 0.1.

improvement may at first seem surprising but as the current flows also through the coils, there is always a fixed relationship (0° or 180°) with the reference signal and so the line noise will aid decoding.

As line current noise is always much less than the space-borne noise, only the value of k=0.1 has been examined for the Loughborough coils. Curves are also given for increased telegram channel space-borne noise. This is because the Loughborough telegram coils lie close to the rail and may be affected more by traction current supplies and pick-up shoes. Comparing the curves for the BR and Loughborough coils it can be seen that using only the vertical field component there is hardly any difference in the predicted performances. This is because of the similar values of flux density encountered in the two systems, although it must be remembered that for the Loughborough telegram coils the worst possible value of flux density has been used in calculations - i.e. that at the extreme of the bogie movement. If this movement is not so large, then Loughborough coils have the advantage because of increased field strengths.

With increased space-borne noise it can be seen that for negative values of the normalised cross-covariance, the error rates have deteriorated whilst for positive values they have improved. This is due to the method of calculating the error rates - i.e. assuming that the two signals transmitted are in phase and that due to noise the decoding has predicted the opposite. If the latter was initially assumed then positive values of ρ would have shown the worst error rates. Thus, an average value of ρ must be taken, and for equal probability of 1's and 0's occurring this value would be zero.

12.7 Telegram Coil System Using Two Field Components

In calculating the error rates for this type of system a simplification has been made. As two bits are received simultaneously from a telegram coil then the noise on the two channels may be correlated. If the bit error rates for the two simultaneous channels are P_1 and P_2 (see end of Appendix 10) the average bit error rate has been defined as $\frac{1}{2}(P_1 + P_2)$. The term due to the possibility of correlation between the channels P_{12}, has been ignored for two reasons - i) it is not easily amenable to calculation and ii) it will in any case be smaller than either P_1 or P_2. The above definition has then been used to calculate the probability of a false telegram.

Figure 149 shows a block diagram of the receiver and decoder for this system and defines the channels used. Error rate curves are shown only for sleeper spacing - the error rates for one metre spacing being almost identical. Curves are given for channels TC1 and TC2 both being compared with the PW channel (figs. 150 and 151) and for channel TC1 with PW but channel TC2 with TC1 (figs. 152 and 153). The case for increased telegram channel space-borne noise is also shown. The cross-covariance between the noise on channel TC1 and its reference is ρ_1 and for TC2 is ρ_2. The curves depicted show the upper and lower error rates for the two channels plus an intermediate value $-\rho_1 = \rho_2 = 0$.

From the curves for the error rates it can be seen that at low S/N ratios and for average values of ρ_1 and ρ_2 that the system comparing channel TC2 with TC1 has slightly the better error rates. This is because the reference signal for channel

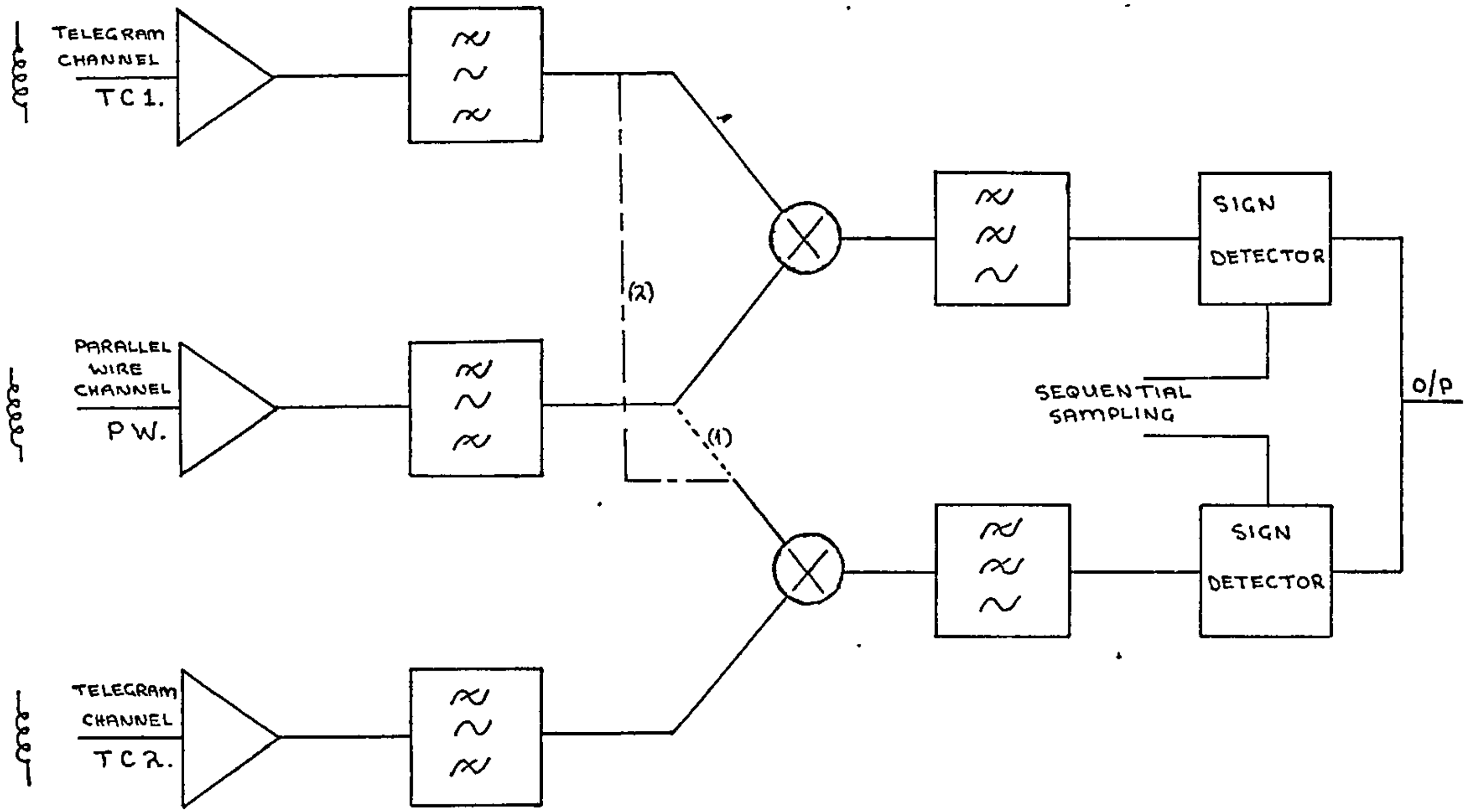


Fig. 149. Receiver for Two Bit Telegram Coils.

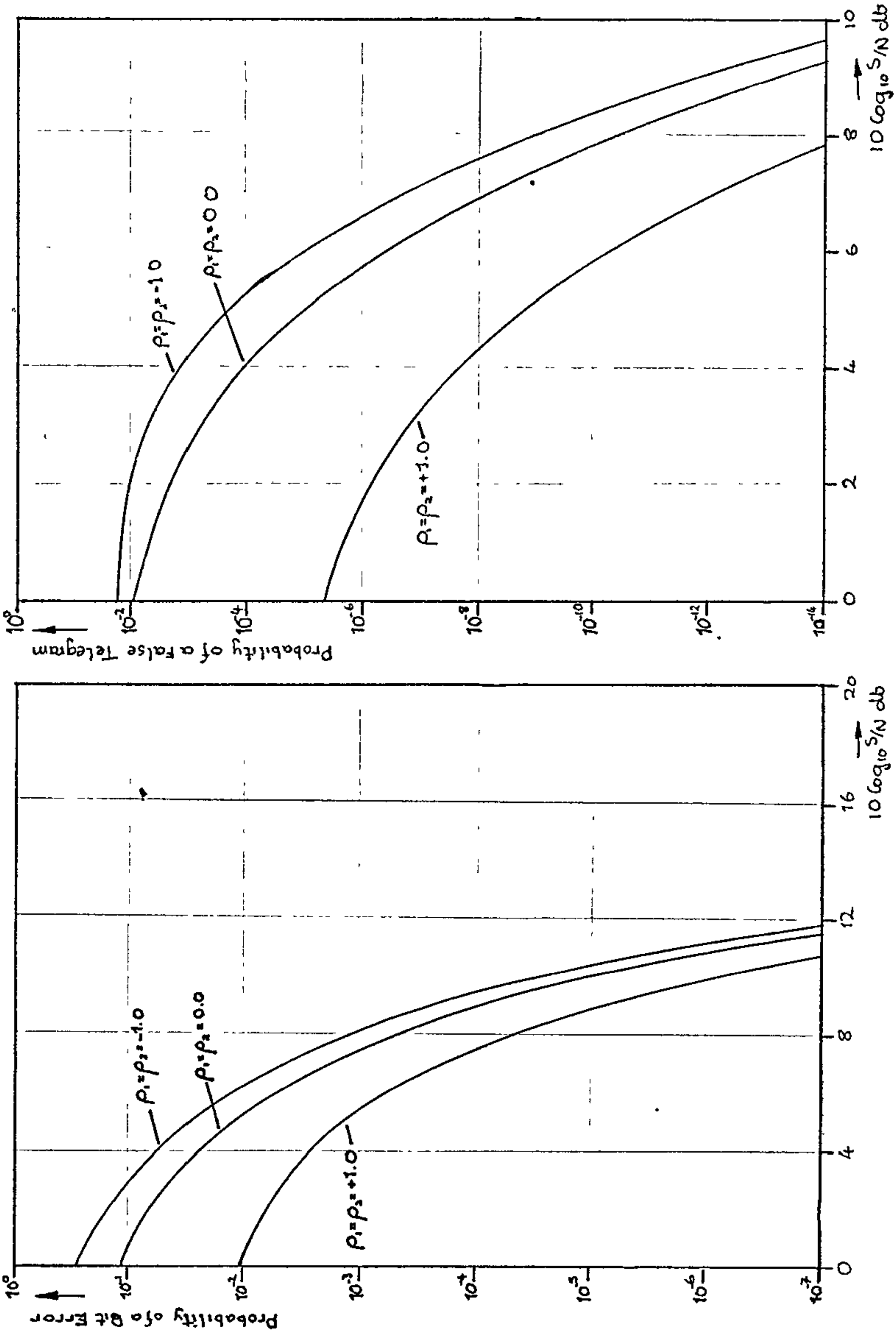
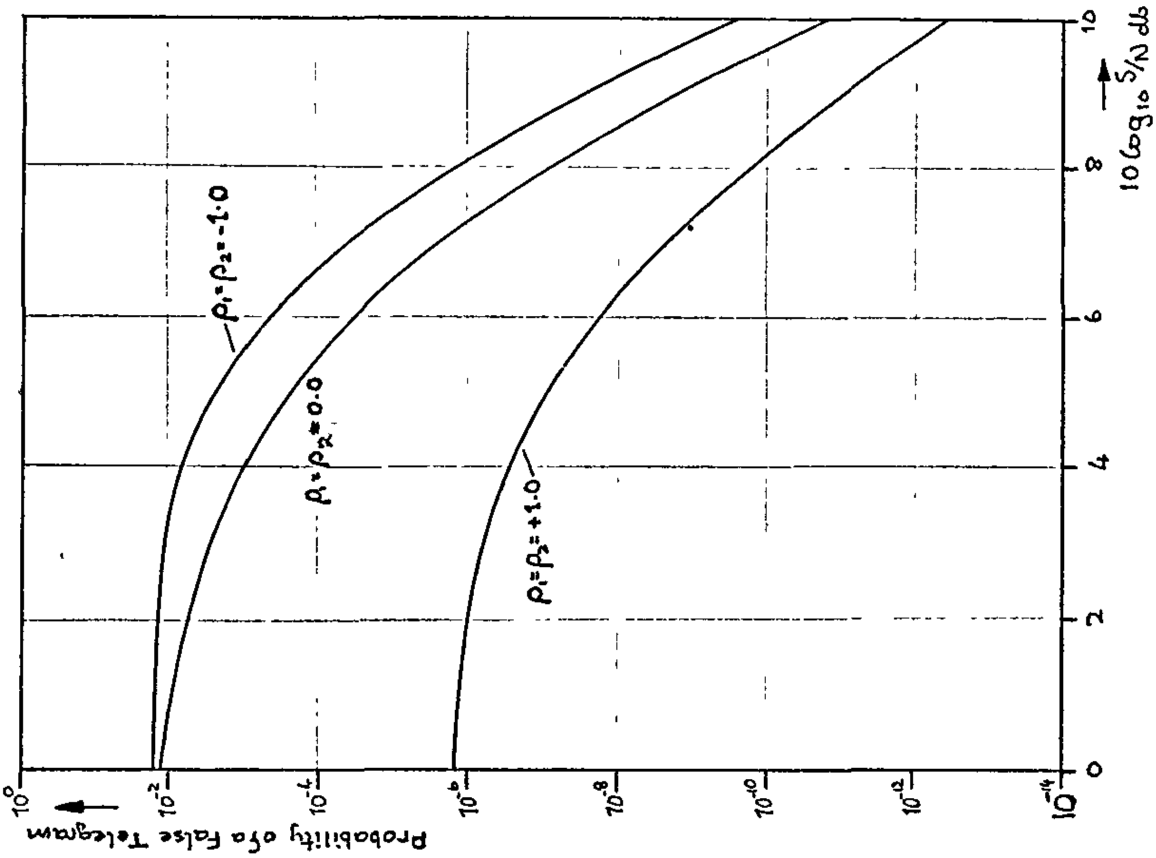


Fig. 15C. Error Rates for the Modified Telegram Coil System. Both Field Components Used and Compared with the PV Channel. Equal Space-borne Noise both Channels, k = 0.1.



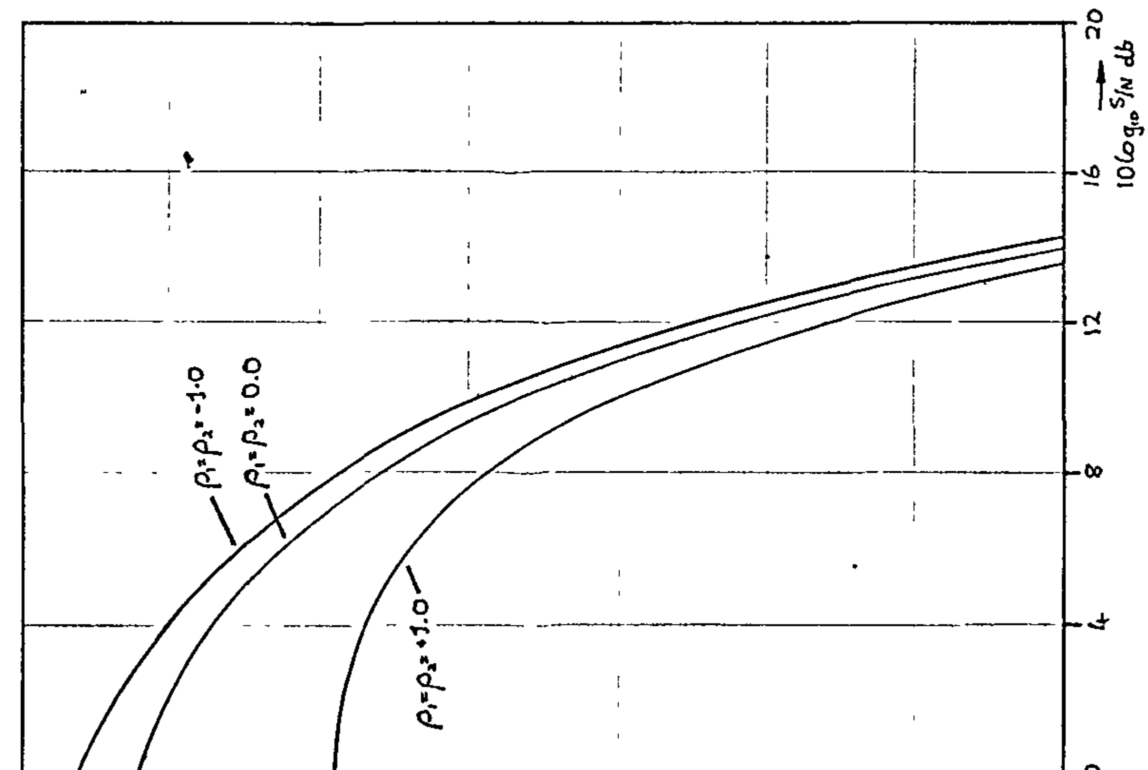


Fig. 151. Error Rates for the Modified Telegram Coil System.

Both Field Components Used and Compared with the PW Channel.

Increased Space-borne Noise (double) on the Telegram Coil Channels.

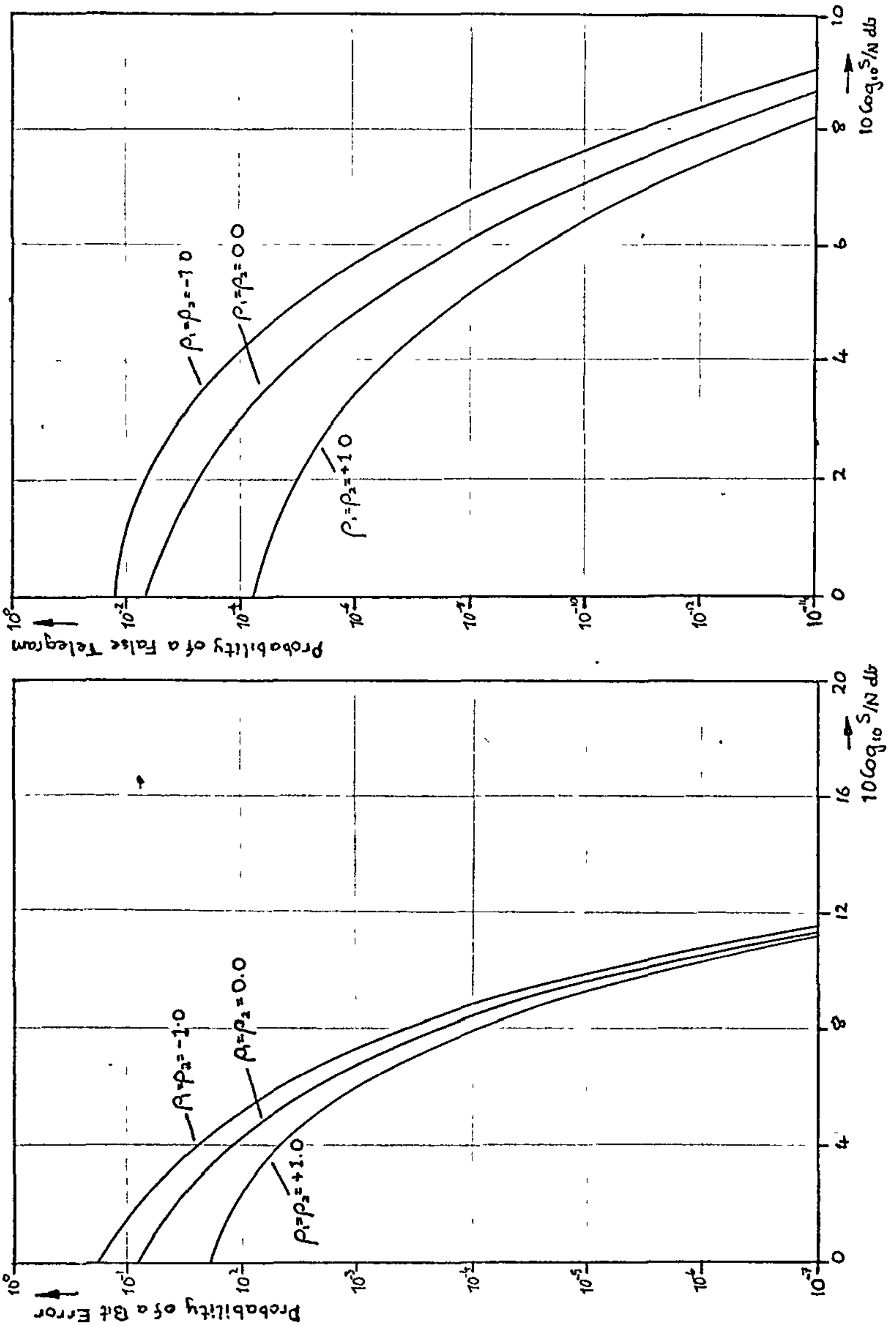


Fig. 152. Error Rates for the Modified Telegram Coil System Using Both Field Components with Channel TC1 Compared with F7 but TC2 with TC1. Equal Space-borne Noise on all Channels, k = 0.1.

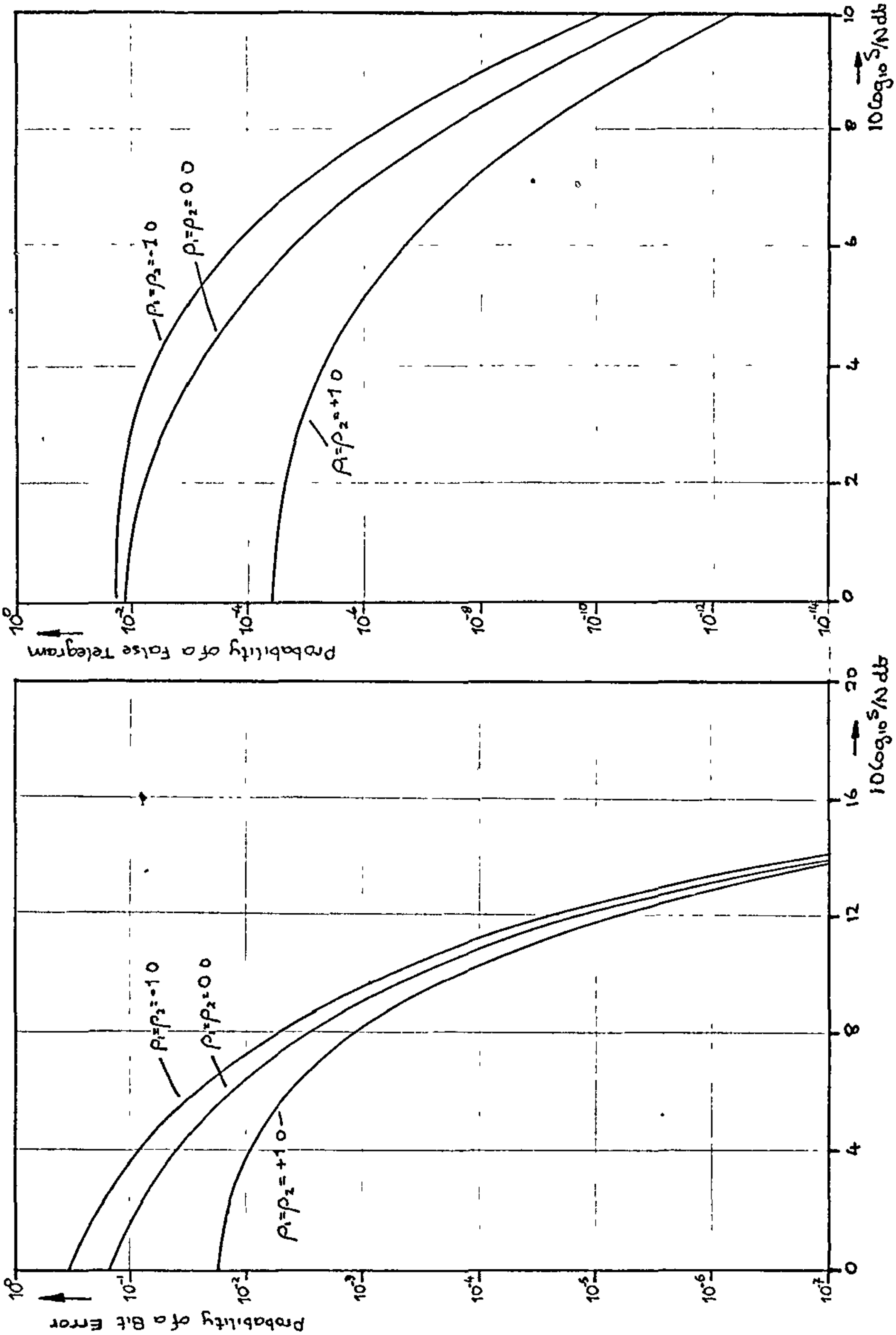


Fig. 153. Error Rates for the Modified Telegram Coil System Using Both Field Components with Channel TC1 Compared with PW but TC2 with TC1. Increased Space-borne Noise on Telegram Coil Channels.

TC2 is greater in magnitude than the PW signal. At higher signal to noise ratios however there would appear to be little advantage between the two methods of decoding - about 0.5 db. The main advantage of comparing channel TC2 with TC1 is the easier logic for laying the telegram coils (see section 7.4, page 45).

Comparing the error rates for the modified system and that only deriving one bit per telegram coil there appears to be little to recommend one over the other and so the choice must depend on other factors.

12.8 Telegram Coil System using Coils Both Sides of the Track

This system is identical to the above but with coils both sides of the track. The main difference is the way in which the magnetic field from the track conductors affects the horizontal field from the coils on opposite sides of the track. The average probability of error is defined as $\frac{1}{4}(P_1 + P_2 + P_3 + P_4)$, where P_1, P_2, P_3 and P_4 refer to the individual error rates on the telegram coil channels TC1, TC2, TC3 and TC4 respectively. All of the channels can be compared with the PW signal or the horizontal field from each coil can be compared with the vertical field from that coil. Other combinations are possible but are not dealt with here as they do not represent an easy way of determining the logic for laying the coils.

The results for this system are very similar to the previous one and are not shown here. This similarity is to be expected as P_1 and P_3 are equal and there only being a slight difference between P_2 and P_4.

As far as error rates are concerned there would appear to be no advantage with this system and the system must therefore be judged on other merits it offers.

12.9 Discussion

Comparing the telegram coil systems deriving one bit per coil and the various forms of modulation it would appear that the error rates for telegram coils and PSK/DPSK are very similar - tending to the same asymptote at S/N ratios above about 10 db. At lower signal to noise ratios PSK is the better, the difference between DPSK and one bit telegram coils depending on the relationship between the various noise sources present. This similarity between these systems is to be expected because of the nature of decoding.

The error rates of the system deriving two bits of information per telegram coil (however the phase comparison is effected) vary between those of PSK/DPSK and FSK, depending on the magnitude of the space-borne noise on the telegram channels with relation to that on the PW signal. For equal values of rms space-borne noise on all channels the performance tends to that of PSK and DPSK above 10 db. For increased space-borne noise on the telegram coil channels (i.e. double that on the PW channel) the performance tends to that of FSK. For greater increases the telegram coil system is worse than FSK. For S/N ratios below 10 db the performance of the system is again closely tied to the relationship between the various noise sources. The above comments also equally apply to the system in 12.8.

At low values of S/N the error rate for a false telegram will tend to 0.156×10^{-1} or 1/64. This can be predicted from Appendix II because as the probability of a bit error decreases so the probability of the telegram being within the error detecting capabilities will decrease and will become small compared to unity.

12.10 Conclusions

In reaching conclusions from this chapter one must take into account the assumptions made, especially that of the noise being Gaussian and the restricted range of the calculations.

The results in this chapter show the similarity between PSK/DPSK and telegram coil systems using only one bit. For increased space-borne noise on the telegram coil channels, which is more likely for the modified system due to the proximity of the coils to the rail, for double the rms value the performance is about the same as FSK. For values in excess of this then modulation methods represent the best form for data transmission. An important factor with telegram coils is their severe limitation on the dynamic range of the system.

Further work on the error rates of systems would need to be done for more detailed conclusions but this can only be done experimentally because of the nature of the noise. This would have to involve trains running under actual running conditions and monitoring the performance of equipment. However, the results in this chapter show that there is very little basic difference between the systems discussed.

13. DISCUSSION, EXTENSION OF TELEGRAM COIL SYSTEMS AND CONCLUSIONS

This chapter contains some of the discussion of the practical work and the conclusions from the thesis. It also contains a short section comparing the relative costs of the two systems and possible other uses of telegram coils and field components.

13.1 Discussion

There were some problems with the experimental receiver built but these are likely to be inherent in any system using phase comparisons. The main problem was one of differential phase shifts between channels and was caused mainly by the filters. Another phase shift problem occurred when limiting took place in some of the amplifiers but this could easily be rectified by external limiting by zener diodes.

There is certainly an advantage in using some form of matching network with the telegram coils as the work in Section 10.3 shows. With the lattice network used it would seem unrealistic to accept a phase shift between the line current and telegram coil current greater than that already exhibited at 29 kHz when evaluating the telegram (about 20°). As the tendency now is to use higher frequencies, and if telegram coils are still used, then some other type of 'all-pass' matching network must be used. As already pointed out, the telegram could be split into several sections, each being individually matched but this is costly due to the extra number of capacitors and connections needed although the phase shift is considerably reduced per matching network, but not overall.

If telegram coils were only used one side of the track it would be better to feed half from each track conductor, thus giving a balanced loading and being easier to match into the line. It is also desirable to fix the telegram coils within $\pm\frac{1}{8}$" ($\pm$0.0032m) of their nominal position due to the susceptibility of this system to bogie movement. A similar tolerance should be adhered to for fixing of the pick-up coils. If only one component of field is required from these coils on the rail foot then, by offsetting the pick-up from the centre line of the rail larger values of flux-density will be encountered and hence increased values of R". The highest values of flux-density will always be produced by the vertical component of the field (B_z).

Because the signals from the telegram coils are received in parallel there are various ways in feeding them to the train-borne computer. Certainly with the parallel-serial converter (as used here) the telegram received in one direction is not the reverse of that received when traversing the telegram in the other direction. This means that a different form of coding would have to be used from that used at present to detect information such as a reverse telegram etc.

With the system used at present, and the parallel to serial converter, no information could be fed to a train-borne computer until all signals were present. This means that if the telegram coils are used on both rails they will need to be fairly accurately aligned, otherwise the channels on one side will be on the point of dropping away when those on the other side are just coming in. If this happens, due to the time delay of the pulse counting circuits either the wrong information will be fed in or none at all. This is further affected by line current attenuation which directly affects the flux densities, so that at the feed end of the line all channels may come in correctly but at the far end there could be problems. The gains of the vertical and horizontal channels are different (- the effective theshold) due to the differing values of flux density encountered in each case. The way in which the received signals are dealt with may well be determined by the computer design. A method of overcoming the above problem is to feed each channel into its own shift register store as it is received and then to clock the information out as desired.

The dynamic range of a system such as described is dependent on R" (although unbalanced line currents will upset this) for a fixed threshold. Table II gives predicted values of R" for various values of track conductor spacing and shows their degradation with increased conductor spacing. From results obtained - practically and theoretically - it is advantageous to have the coils 1.0 metres apart and Table II also shows the advantages of closer spaced track conductors. An improvement could be made on the dynamic range if, instead of a fixed threshold, a variable threshold dependent on the average value of the parallel wire (reference) signal was used for the telegram coil channel or the instantaneous value of the telegram coil channel is compared with that of the reference signal. The limiting value for this would be determined by the S/N ratio of the flux densities and the permissible error rates of the received signal(s). The values of R" found in practice are larger than those predicted, this is probably caused by the trolley movement not being as large as $\pm$ 1" horizontally and vertically, the values recorded being typical but allowing for some misalignment of telegram and pick-up coils.

TRACK CONDUCTOR SPACING	COIL SPACING / PARAMETER	0.76m.	1.0m
2'	R''_z	3.7 (7.4)	4.7 (14.5)
2'	R''_x	3.6 (23)	3.8 (28.6)
1'6"	R''_z	4.2 (7.4)	5.6 (14.5)
1'6"	R''_x	4.8 (23)	5.0 (28.6)
1'	R''_z	5.5 (7.4)	7.3 (14.5)
1'	R''_x	7.2 (23)	7.5 (28.6)
6"	R''_x	6.1 (7.4)	9.6 (14.5)
6"	R''_z	10.6 (23)	12.0 (28.6)

Table 11. Worst Values of R" for Various Track Conductor Spacings. (Values in Brackets are Neglecting Interference from the Track Conductors).

Induced longitudinal rail currents from the track conductors could also prohibit the use of the horizontal field if they were excessive (see section 11.5). The system finally used should, however, be compatible for all regions.

13.2 Economics

The following is only a very rough estimate of costs but, it is hoped, gives some idea of the difference in costs, even if it is only a percentage. The cost for a BR pick-up coil and a Loughborough pick-up coil is approximately the same. The fixing cost for one telegram pick-up coil per system would be about the same as a special bracket would be required for both, but if both sides of the track were used for the Loughborough system then fixing costs would be about doubled.

There would seem to be no reason why the cost of telegram coils for each system should be different. The advantage with BR telegram coils is that they can be bolted straight to wooden sleepers, although concrete speepers wouldneed a special fixing block. The Loughborough telegram coils, however, need special fixing blocks. This is probably not a disadvantage as they will probably be easy to fix to the rail and most of the cost with any telegram coils is in the labour laying them. The actual cost of the receivers used to just decode telegrams is somewhat difficult to estimate as no real attempt has been made to make the equipment for the new system 'fail safe'. To receive one bit of information from one telegram coil and decode it would be cheaper for the modified system, the cost to obtain two bits being about the same as the present B.R. receiver. However, to obtain all four bits of information at once from two telegram coils and provide a serial output the cost of the new receiver would be about 75% more than the present BR receiver. If a parallel-serial converter was not required and some simplification of the computer input resulted then the resulting cost of the new receiver might not be so much greater than the present BR receiver. The use of integrated circuits (digital and linear) probably help in keeping the cost of the receiver for Loughborough telegram coils down, as also does the use of active filters.

13.3 Possible Extension of Telegram Coils

The disadvantage with telegram coils is their fixed nature although they represent an admirable method for the transmission of fixed information. It is possible to use various control elements to vary their phase relationship with the track conductor signal. This could possibly be of use in the vicinity of junctions where the data for various routes is required. However cost of additional equipment is of prime importance. They are not suitable for all types of variable information, however, due to their discrete nature and would be of no use for control purposes in a moving block signalling system. If switched telegram coils are used, the equipment associated with them must meet the stringent safety requirements imposed by railway administrations when used to communicate vital signalling information.

13.4 Further Application of Field Components

As it is possible to use two field components from the telegram coils it is possible to use them without the track conductors by using one field component to produce the reference and the other one to contain information. If both sides of the track were used then 3 bits of information could be used, using one field component for the reference signal if the coils were reasonably well aligned per position. With this system there would be no interfering fields from track conductors, only from adjacent coils and those on the opposite side of the track, if any. The values of R" would be those given in Table 7 & 8. The coils could, in this way, be used in a simple system for conveying fixed information to a moving train such as speed restriction, gradients, route identification. The feed requirements would be relatively easy - a constant current source giving adequate S/N ratio and perhaps allowing a greater tolerance for bogie movement. Apart from using different field components from the coils it might be possible to use field components from the parallel wires themselves. There are three possible uses, these are:-

1. an alternative to transpositions
2. to provide fixed information, and
3. section ends.

Fig. 154 shows the vertical and lateral flux density variations in a direction transverse to the track conductors and for (1) and (2) by lateral displacement of the wires such that the maximum of the horizontal field is always used, for a bogie movement of $\pm$ 1" a maximum dynamic range for the system with a fixed threshold of 6:1 can be obtained (15.5 db). This figure takes into account the permissible line attenuation over one section providing the signals received are always sufficient to give an adequate S/N ratio. It should be borne in mind that the signal from the vertical field is about 40% less than that directly above the centre of the track conductors (but about the same as the horizontal field) and may require larger

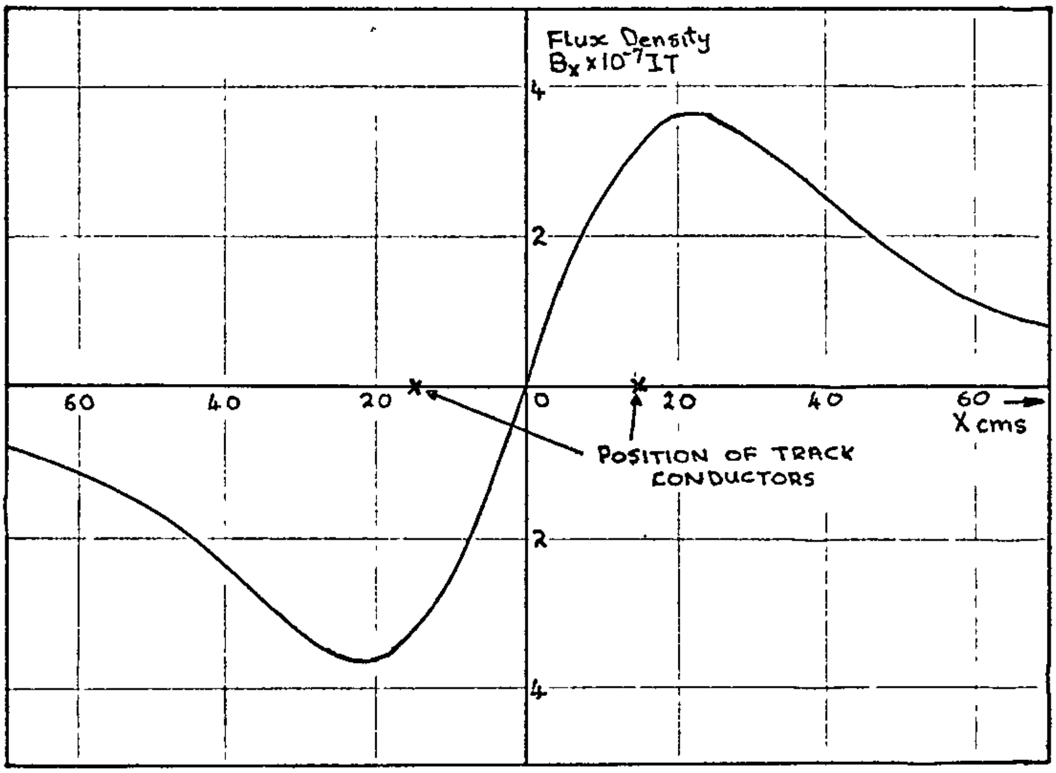
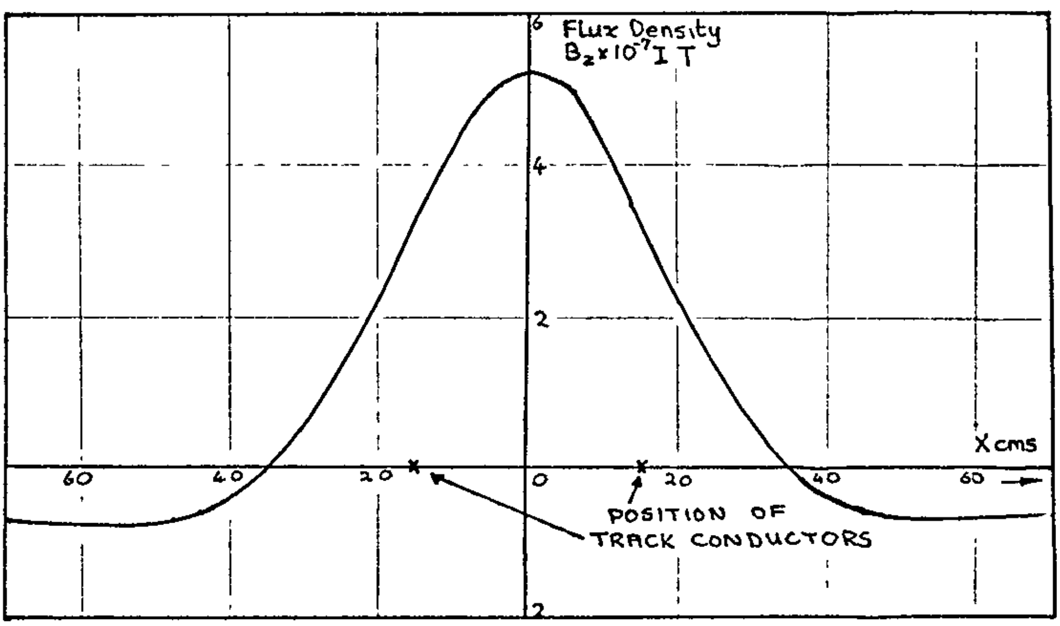


Fig. 154. Field Patterns from the Track Conductors for a Spacing of 0.30 m and a Pick-up Height of 0.30 m.



line currents. Alternatively the threshold on 'X' could be set by some average value of the received 'Z' signal - the dynamic range then being limited by receiving a signal giving an adequate S/N ratio. Due to the steep sides of the field pattern(s) and bogie movement the received signals will be amplitude modulated but, providing all information on the carrier is angle modulated, there should be no problem with reception.

Transpositions could be effected by laterally displacing the track conductors from the centre line of the track and noting the changes in phase of 'X' with respect to the 'Z' signal. Figure 155 gives possible configurations for the track conductors. This method would mean that the reception of the 'Z' signal, track to train and vice versa, is never interrupted and a transposition pulse obtained by noting the 'X' signal passing through a zero as it changes phase. The disadvantages is the use of lower flux densities and the fact that some signal will be lost in train-to-track communication, which is already at a very low level. However, the nulls in the vertical field pattern from the track conductors are eliminated giving a better data channel. The 'Y' field - i.e. in the direction of motion - which is absent over an entire transposition section occurs at a conventional transposition as the currents in the cross connections are in the same sense - see fig. 156 - and could be used to provide an additional transposition pulse, providing section ends do not upset the field patterns. The other disadvantage of this method is that conventional transpositions help reduce any longitudinally induced currents, whereas this method does not; transpositions and conventional

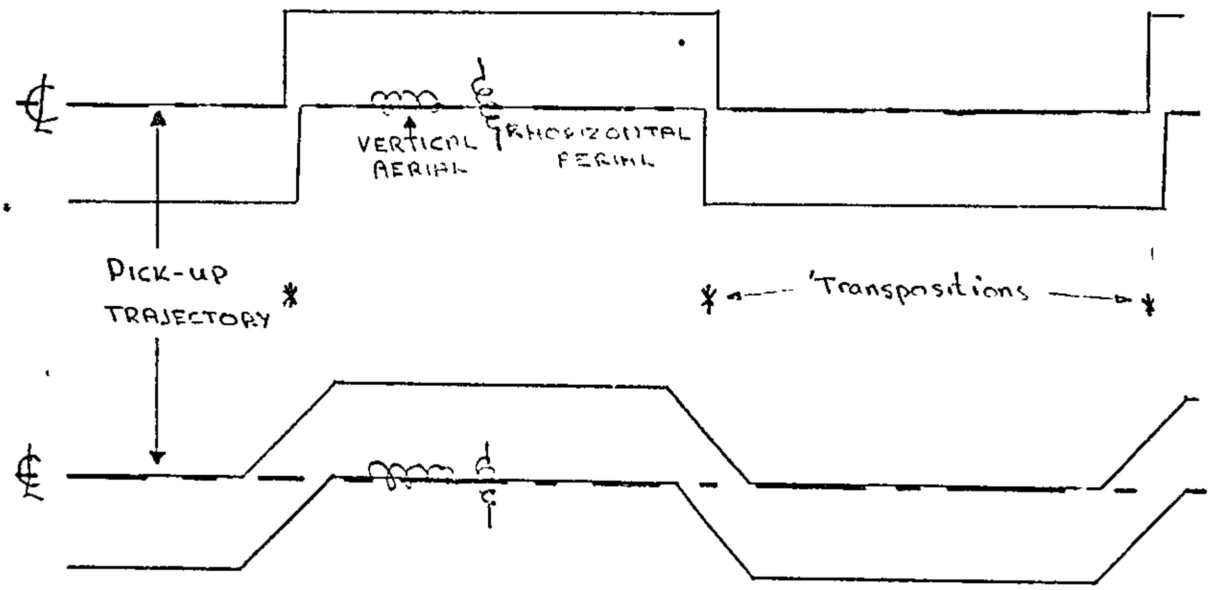


Fig. 155. Two Track Conductor Configurations for an Alternative Method for Transpositions.

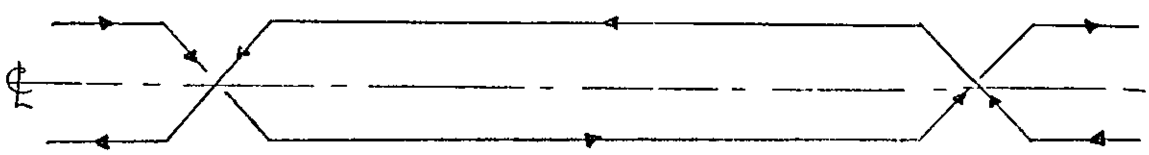


Fig. 156. Conventional Transpositions Showing Current Flow.

telegrams would have to be 'sited' and could be placed only on one side of the track.

Extra information could be achieved by using the conventional arrangement for track conductors but displacing the track conductors within a transposition section to give additional binary information - see fig. 157 for a possible track conductor configuration. This method would be suitable for fixed information such as gradients, distances and route identification but does not lend itself easily to the display of temporary changes of information. Again placing of telegram coils, if used, would be restricted.

A third possible use of field components from the track conductors is that of section ends - i.e. the end of one track loop and the beginning of the next. There are three requirements here, these are :-

1. continuity of safety carrier
2. the production of a section end pulse, and
3. the prevention of false information being received due to 'beating' of adjacent carrier frequencies in the two loops as the oscillators feeding them are not frequency locked.

One solution to this problem currently being tested by B.R. involves a telegram coil as shown in fig. 158, the following method not requiring one (fig. 159). The new section is placed off-centre of the track such that the null in the vertical field of the new section lies on the centre line of the old section (X). Y_1 and Y_2 are such as to prevent two fields interfering on one channel at a given time and to provide an overlap to keep continuity of carrier. Normally channel 2

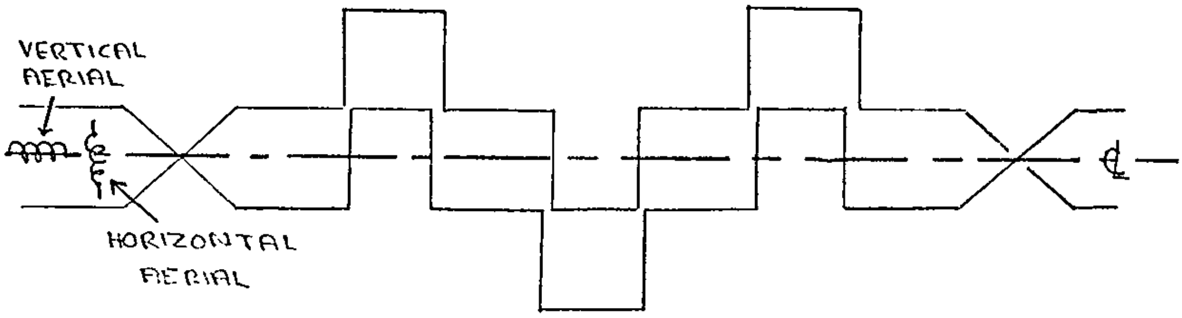


Fig. 157. Possible Method of Writing Binary Information into the Track Conductors.

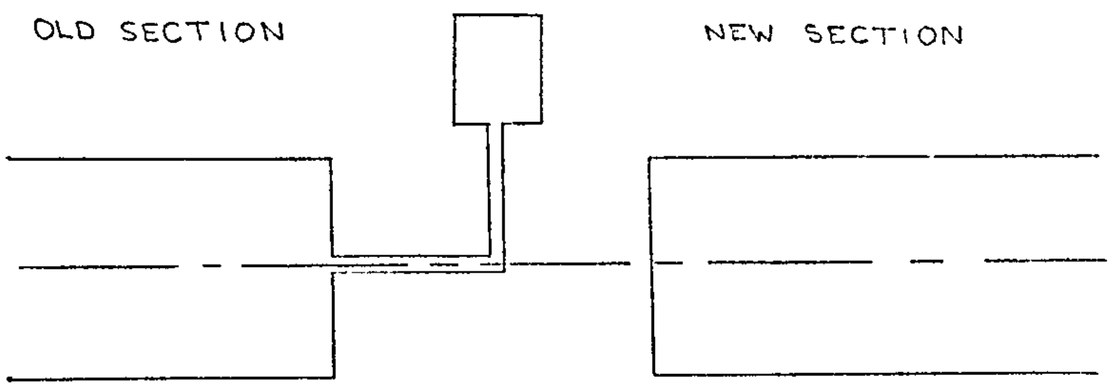


Fig. 158. Conventional End of Section.

receives little or no signal. As the end of the old section is reached, channel 2 first picks up the new section, and then after a distance of approximately (Y_1-Y_2) channel one 'drops' out. After a further distance Y_2, channel one picks up again followed shortly by channel 2 'dropping' out. Thus continuity is maintained, any beating effects virtually eliminated, and an end of section pulse can be obtained by noting that channel one 'drops' out and picks up again. This is used so that failure of a channel will read in a section end pulse and put the train computer in a more restrictive mode. Figure 160 shows the envelopes of the received signals. It is best to receive the 'X' signal at the feed end of a line due to it always being less in magnitude than the vertical signal.

13.5 Conclusions

The work described in this thesis shows the practical application of the initial investigations carried out. The period of time spent at Derby has certainly shown the problems prevalent in a railway environment and it is hoped that this experience has helped to provide a reasonable working system.

The modified telegram coil system giving extra information per coil certainly reduces the length of track needed for a telegram, especially if both sides of the track are used. The placing of the telegram coils on the rail foot is also advantageous as they are not restricted to sleeper spacing and are also less likely to be damaged by track maintenance equipment, e.g. tamping machines. On the other hand coils in this position are more of a nuisance when

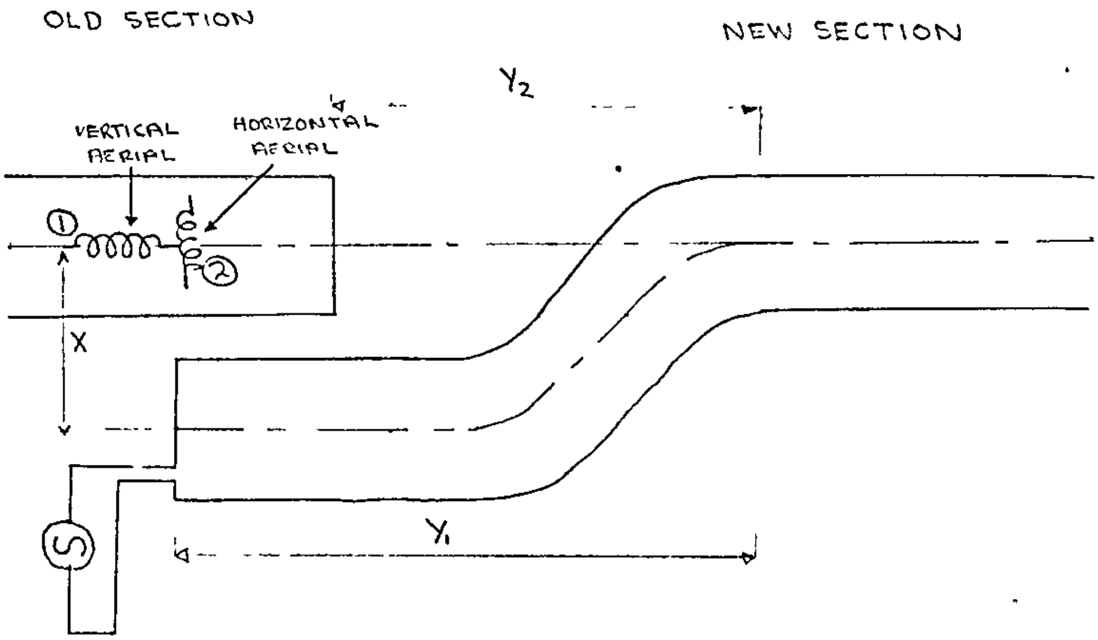


Fig. 159. Possible Alternative End of Section.

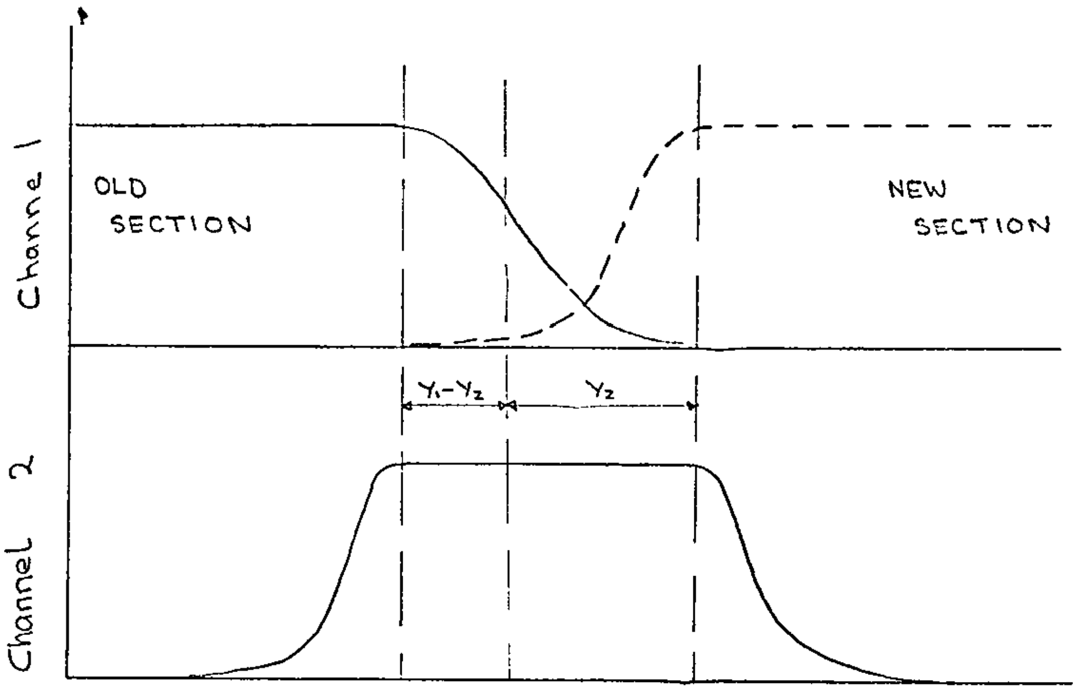


Fig. 160. Envelope of Received Signal.

replacing rails.

A system using small coils on the rail foot is certainly susceptible to bogie movement but with suitable siting of telegram coils (e.g. not on a junction) and positioning of pick-up coils this short-coming can be minimised. The dynamic range of systems using telegram coils seems adequate for the length of sections of track conductors envisaged at present, it being advantageous to use 1.0m spacings if possible. Unbalanced line currents might well reduce this range, but by matching the telegram into the balanced line this effect is virtually eliminated, only an earth fault being of concern. The coils might impose a minimum value of line current although the value of magnetic field produced by the parallel wires for the central pick-up coil is slightly less than the minimum experienced from the coils at an extreme of the bogie movement.

The inductance of telegrams connected into the track conductors causes a decrease in the velocity of propagation which also means a decrease of wavelengths on the line. This means that standing waves could be a problem on the line, especially for the new coils with their higher inductance. Section 10.3 certainly shows this effect and the advantages of matching telegrams into the track conductors.

The chapter on error rates shows that there is little basic difference between the use of telegram coils and the forms of modulation discussed. However, the position of coils on the rail foot and their proximity to conductor rails (e.g. the Southern Region) might limit their use but at present there is insufficient detailed knowledge about this source of interference and its effect on telegram coils.

Whilst telegram coils do have certain disadvantages they do represent an admirable method of transmitting limited amounts of fixed information and with high reliability. The system could be enhanced by using the extra data transmission facilities discussed in section 13.4.

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Appendix I.

To show the emf induced in a stationary coil situated in a low frequency magnetic field is proportional to the flux density cutting the coil.

Assuming there to be no radiation effects, the flux density from a coil in space carrying a low frequency current can be expressed as :-

$$B = k.f(x,y,z).I \qquad \text{where } I = I_o.e^{jwT}$$

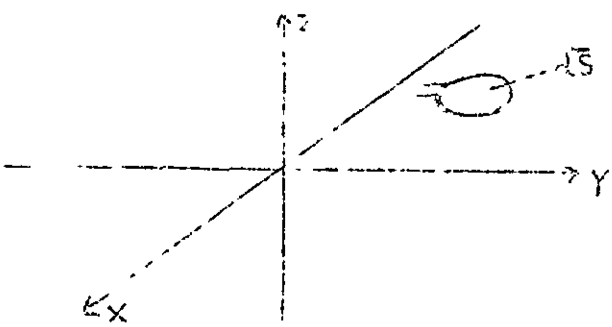
For a fixed point in space, i.e. x, y, and z are fixed

$$\text{then} \quad B \propto I$$

Now the emf induced in a small pick-up coil is given by :-

$$e = -\frac{\partial}{\partial t} \int_S \bar{B}.d\bar{S}$$

If the plane of the coil is in the x - y plane then dS is parallel to the z axis.



Now B.dS = B dS Cos θ (where θ is the angle between B and dS)

and $\bar{B} = \bar{B}_x + \bar{B}_y + \bar{B}_z$.

$$\therefore \quad \bar{B}.d\bar{S} = B_z dS$$

If the area of the pick-up coil remains constant then

$$e \propto \frac{\partial B_z}{\partial t} \propto \frac{\partial I}{\partial t}$$

therefore

$$e \propto \frac{\partial I}{\partial t} = \omega I$$

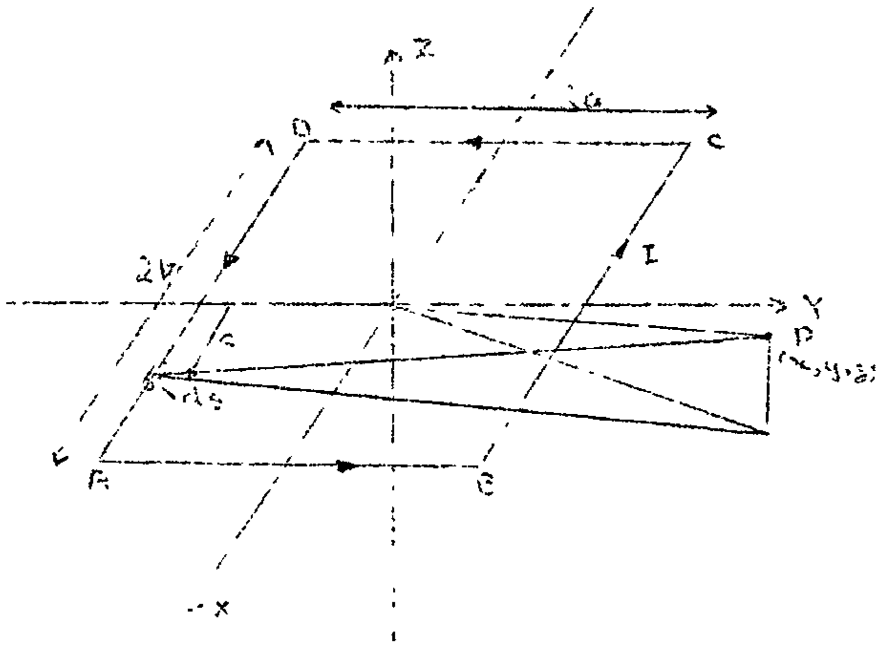
But ω is constant, hence $e \propto I$ but $B_z \propto I$.

therefore $e \propto B_z$

Hence the emf induced in the coil is a measure of the flux density perpendicular to the plane of the coil and it can therefore be used for measuring components of flux density.

Appendix 2.

Magnetic Field from a Rectangular Coil.



Consider each side of the rectangle separately and as being made up from small elements ds. The magnetic vector potential is given by :-

$$\overline{A} = \frac{u}{4\pi} \int \frac{Ie^{-j\beta r}\overline{ds}}{r}$$

But in this case $\beta r \ll 1$, therefore $e^{-j\beta r} = 1$. This means that the amplitude and phase of the current in the rectangular coil is essentially the same at any point.

Hence for AD

$$\overline{A}_x = \frac{uI}{4\pi} \int_{-b}^{+b} \frac{\overline{ds}}{\left[(y+a)^2 + (x-s)^2 + z^2\right]^{\frac{1}{2}}}$$

but $\overline{B} = \text{Curl } \overline{A}$

$$\therefore \bar{B} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \\ A_x & 0 & 0 \end{vmatrix}$$

therefore

$$\bar{B}_x = -\frac{\partial \bar{A}_x}{\partial y}, \quad \bar{B}_y = \frac{\partial \bar{A}_x}{\partial z}, \quad \bar{B}_x = 0$$

B_z Field Component.

$$\bar{B}_z(AD) = \hat{a}_z \cdot -\frac{uI}{4\pi}\int_{-b}^{b}\frac{-(y+a)\ ds}{\left[(y+a)^2 + (x-s)^2 + z^2\right]^{\frac{3}{2}}}$$

$$\text{let } (x-s) = \left[z^2 + (y+a)^2\right]^{\frac{1}{2}} \operatorname{Tan}\theta$$

$$\text{therefore } ds = -\left[z^2 + (y+a)^2\right]^{\frac{1}{2}} \operatorname{Sec}^2\theta\ d\theta$$

$$\therefore \bar{B}_z(AD) = \hat{a}_z \frac{uI(y+a)}{4\pi\,(z^2 + (y+a)^2)}\int_{s=-b}^{s=+b} \operatorname{Cos}\theta\ d\theta$$

$$\text{at } s = +b, \qquad \theta = \tan^{-1}\frac{x-b}{\left[z^2 + (y+a)^2\right]^{\frac{1}{2}}}$$

$$\text{at } s = -b, \qquad \theta = \tan^{-1}\frac{x+b}{\left[z^2 + (y+a)^2\right]^{\frac{1}{2}}}$$

$$\text{Hence } B_z = \hat{a}_z \cdot \frac{-uI\ (y+a)}{4\pi(z^2 + (y+a)^2)}\left[\operatorname{Sin}\left(\tan^{-1}\frac{x-b}{\left[z^2 + (y+a)^2\right]^{\frac{1}{2}}}\right)\right.$$

$$\left. - \operatorname{Sin}\left(\tan^{-1}\frac{x+b}{\left[z^2 + (y+a)^2\right]^{\frac{1}{2}}}\right)\right] \quad - (1)$$

$$\text{but } \operatorname{Sin}\left(\tan^{-1}\frac{x}{y}\right) = \frac{x}{(x^2 + y^2)^{\frac{1}{2}}}$$

and (1) simplifies to give :-

$$\bar{B}_z = \hat{a}_z \cdot \frac{uI(y+a)}{4\pi(z^2 + (y+a)^2)}\left[\frac{x+b}{\left[z^2 + (y+a)^2 + (x+b)^2\right]^{\frac{1}{2}}}\right.$$

$$\left. - \frac{x-b}{\left[z^2 + (y+a)^2 + (x-b)^2\right]^{\frac{1}{2}}}\right]$$

Similarly the B_z components of field due to the current in the remaining sides are :-

$$\overline{B}_z(BC) = \hat{a}_z \cdot \frac{uI(y-a)}{4\pi(z^2 + (y-a)^2} \left[\frac{x-b}{\left[z^2 + (y-a)^2 + (x-b)^2\right]^{\frac{1}{2}}} - \frac{x+b}{\left[z^2 + (y-a)^2 + (x+b)^2\right]^{\frac{1}{2}}} \right]$$

$$\overline{B}_{z(AB)} = \hat{a}_z \cdot \frac{uI(x-b)}{4\pi(z^2 + (x-b)^2)} \left[\frac{y-a}{\left[z^2 + (y-a)^2 + (x-b)^2\right]^{\frac{1}{2}}} - \frac{y+a}{\left[z^2 + (y+a)^2 + (x-b)^2\right]^{\frac{1}{2}}} \right]$$

$$\overline{B}_{z(CD)} = \hat{a}_z \cdot \frac{uI(x+b)}{4\pi(z^2 + (x+b)^2)} \left[\frac{y+a}{\left[z^2 + (y+a)^2 + (x+b)^2\right]^{\frac{1}{2}}} - \frac{y-a}{\left[z^2 + (y-a)^2 + (x+b)^2\right]^{\frac{1}{2}}} \right]$$

The total field is then given by :-

$$\underline{\overline{B}_z = \overline{B}_z(AD) + \overline{B}_z(BC) + \overline{B}_z(AB) + \overline{B}_z(CD)}$$

The sign of $B_z(..)$ is determined by the right hand corkscrew rule. This can be checked as each field at $x = 0$ and $y = 0$ is positive for the given direction of current.

<u>B_y Field Component.</u>

Here only the sides AD and BC produce a field in this direction. From above

$$\overline{B}_y = \frac{\partial \overline{A}x}{\partial z}$$

In the same way as B_z was derived the following expressions are obtained.

$$\overline{B}_y(AD) = \hat{a}_y \cdot \frac{uIz}{4\pi(z^2 + (y+a)^2)} \left[\frac{x-b}{\left[z^2 + (y+a)^2 + (x-b)^2\right]^{\frac{1}{2}}} - \frac{x+b}{\left[z^2 + (y+a)^2 + (x+b)^2\right]^{\frac{1}{2}}} \right]$$

$$\overline{B}_y(BC) = \hat{a}_y \cdot \frac{uIz}{4\pi\,(z^2 + (y-a)^2)} \left[\frac{x + b}{\left[z^2 + (y-a)^2 + (x+b)^2\right]^{\frac{1}{2}}} - \frac{x - b}{\left[z^2 + (y-a)^2 + (x-b)^2\right]^{\frac{1}{2}}} \right]$$

The total 'y' field is then given by :-

$$\underline{\overline{B}_y = \overline{B}_y(AD) + \overline{B}_y(BC)}$$

$\underline{B_x \text{ field component}}$.

Again only two sides contribute to this field - AB and CD. Using $\overline{B}_x = \frac{\partial \overline{A}y}{\partial z}$ and by a process similar to the above,

$$\overline{B}_x(AB) = \hat{a}_x \cdot \frac{uIz}{4\pi(z^2 + (x-b)^2\,)} \left[\frac{y + a}{\left[z^2 + (y+a)^2 + (x-b)^2\right]^{\frac{1}{2}}} - \frac{y - a}{\left[z^2 + (y-a)^2 + (x-b)^2\right]^{\frac{1}{2}}} \right]$$

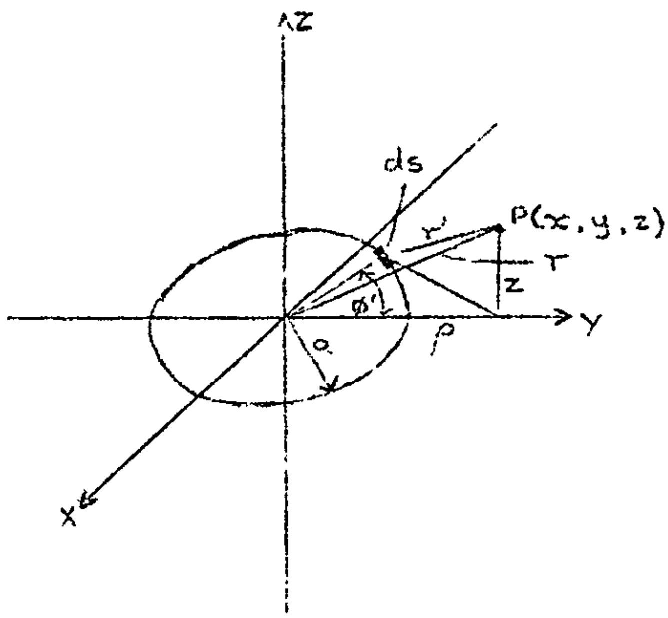
$$\overline{B}_x(CD) = \hat{a}_x \cdot \frac{uIz}{4\pi(z^2 + (x+b)^2)} \left[\frac{y - a}{\left[\,z^2 + (y-a)^2 + (x+b)^2\right]^{\frac{1}{2}}} - \frac{y + a}{\left[z^2 + (y+a)^2 + (x+b)^2\right]^{\frac{1}{2}}} \right]$$

And the total field is then given by :-

$$\underline{\overline{B}_x = \overline{B}_x(AB) + \overline{B}_x(CD)}$$

Appendix 3.

Magnetic Field produced by a Circular Coil.



Starting again with the magnetic vector potential for a low frequency current, i.e.

$$\overline{A} = \frac{u}{4\pi}\int \frac{I\overline{ds}}{r'}$$

on substituting the known parameters shown in the diagram,

$$\overline{A} = \frac{uI}{4\pi}\int_0^{2\pi} \frac{a\overline{d\phi'}}{(z^2 + \rho^2 + a^2 - 2a\rho\cos\phi')^{\frac{1}{2}}} \cdot \hat{a}_{\phi'} \qquad (\overline{ds} = a\overline{d\phi})$$

The point P can be considered as lying in the y-z plane for a circular coil without any loss of generality. This simplifies the expression for A slightly.

The unit vector $a_{\phi'}$ can now be expressed in terms of the unit vectors of the coordinate system,

$$a_{\phi'} = a_\phi \cos\phi' + a_\rho \sin\phi'$$

$\overline{A}$ thus appears to have both a $a_{\phi'}$ and a_ρ component but the integration can be carried out to show that $\overline{A}_\rho = 0$. This should be obvious since $\overline{I}\rho = 0$.

Therefore $\overline{A}_\phi = \hat{a}_\phi . \frac{uIa}{4\pi\rho} \int_0^{2\pi} \frac{\cos\phi' \, d\phi'}{(z^2 + \rho^2 + a^2 - 2a\rho\cos\phi')^{\frac{1}{2}}}$

Using the definition $\overline{B} = \text{Curl } \overline{A}$ and expanding.

$$\overline{B}_z = \hat{a}_z . \quad \frac{1}{\rho} \frac{\partial(\rho A\phi)}{\partial\rho}$$

Thus,

$$\overline{B}_z = \hat{a}_z . \quad \frac{uI}{4\pi}\left[\int_0^{2\pi} \frac{a\cos\phi' \, d\phi'}{(z^2 + \rho^2 + a^2 - 2a\rho\cos\phi')^{\frac{1}{2}}} \right.$$

$$\left. - \int_0^{2\pi} \frac{a\cos\phi'(\rho \; 2a\cos\phi') \, d\phi'}{(z^2 + \rho^2 + a^2 - 2a\rho\cos\phi')} \right]$$

By introducing two new variables, $\beta = \frac{\pi - \phi'}{2}$ and

$k^2 = \frac{4a\rho}{(a+\rho)^2 + z^2}$ the equations can be rearranged and

simplified to yield the following :-

$$\overline{B}_z = \hat{a}_z . \quad \frac{uI}{2\pi} \quad \frac{1}{((a+p)^2 + z^2)^{\frac{1}{2}}} \left[\int_0^{\frac{\pi}{2}} \frac{d\beta}{(1 - k^2\sin^2\beta)^{\frac{1}{2}}} \right.$$

$$\left. + \frac{a^2 - \rho^2 - z^2}{(a - \rho)^2 + z^2} \int_0^{\frac{\pi}{2}} (1 - k^2\sin^2\beta)^{\frac{1}{2}} d\beta \right]$$

Let $K = \int_0^{\frac{\pi}{2}} \frac{d\beta}{(1 - k^2\sin^2\beta)^{\frac{1}{2}}}$ and $E = \int_0^{\frac{\pi}{2}} (1 - k^2\sin^2\beta)^{\frac{1}{2}} d\beta$

then K and E are complete elliptic integrals of the first and second kind respectively.

Hence,

$$\overline{B}_z = \frac{uI}{2\pi} \quad \frac{1}{((a+\rho)^2 + z^2)^{\frac{1}{2}}} \left[K + \frac{a^2 - \rho^2 - z^2}{(a-\rho)^2 + z^2} \quad E \right] . \hat{a}_z$$

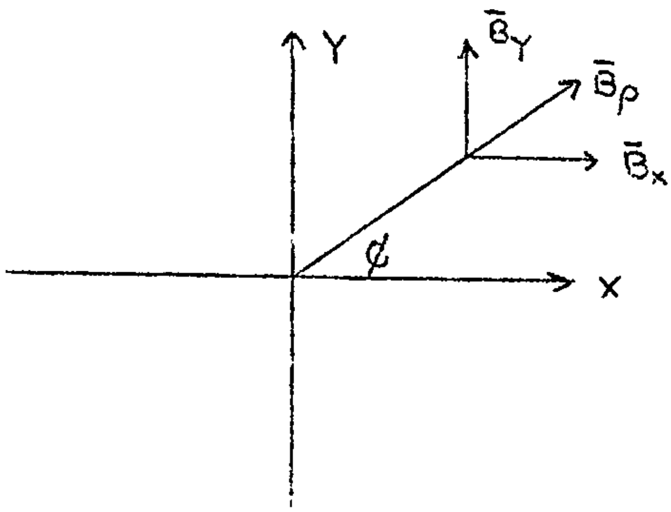
Using a similar analysis,

$$\overline{B}_\rho = \hat{a}_\rho . \frac{uI}{2\pi\rho} \quad \frac{z}{((a+\rho)^2 + z^2)^{\frac{1}{2}}} \left[- K + \frac{a^2 + \rho^2 + z^2}{(a-\rho)^2 + z^2} . \; E \right]$$

Using x, y, and z components to simplify measurements, then

$$\overline{B}_y = \overline{B}_\rho \operatorname{Sin} \phi$$

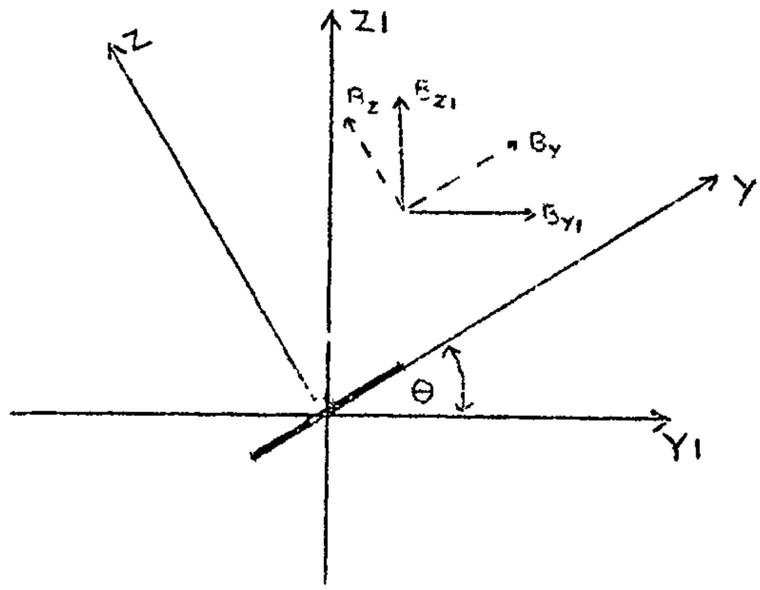
and $$\overline{B}_x = \overline{B}_\rho \operatorname{Cos} \phi$$



Appendix 4.

Magnetic Fields Produced by Tilted Coils.

Consider the coil tilted in the manner shown in the diagram below.



By using the transformations

$$y = Z_1 \text{ Sin } \theta + Y_1 \text{ Cos } \theta$$

and $$z = Z_1 \text{ Cos } \theta - Y_1 \text{ Sin } \theta$$

a change of axes can be accomplished giving the field components, B_x, B_y and B_z in terms of Y_1 and Z_1. The field components with respect to the new set of axes are then given by :-

$$B_{Z1} = B_z \text{ Cos } \theta + B_y \text{ Sin } \theta$$

$$B_{Y1} = B_y \text{ Cos } \theta - B_z \text{ Sin } \theta$$

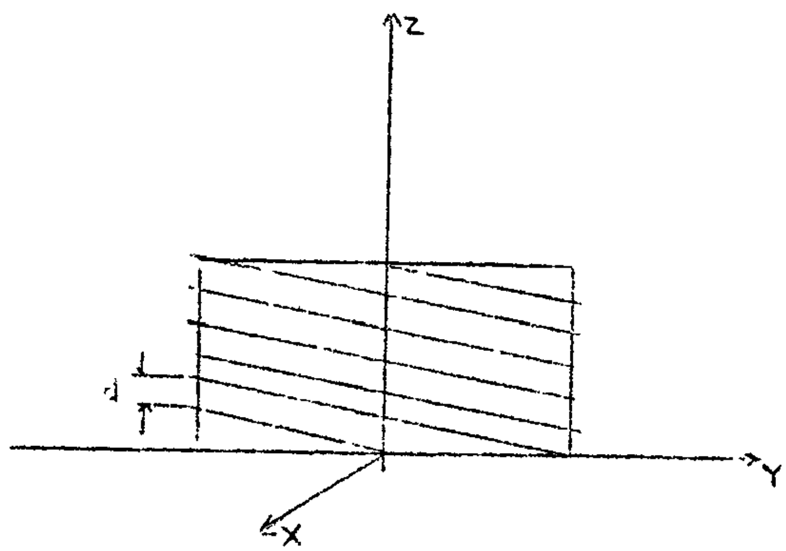
$$B_{X1} = B_x$$

Field components from coils tilted in a different arrangement than shown above can be obtained by suitable change of axes.

Appendix 5.

Field Components from Multi-turn Coils.

If the coils are made from thin wire and are closely wound, the resulting coil, to a good approximation, can be considered as made up from an equal number of parallel turns. The diagram shown below depicts an enlarged coil with total number of turns N.



If a field component from one turn is given by f(x,y,z), the total field at some given point in space is made up fro, the summation of all the parallel turns of wire, i.e.

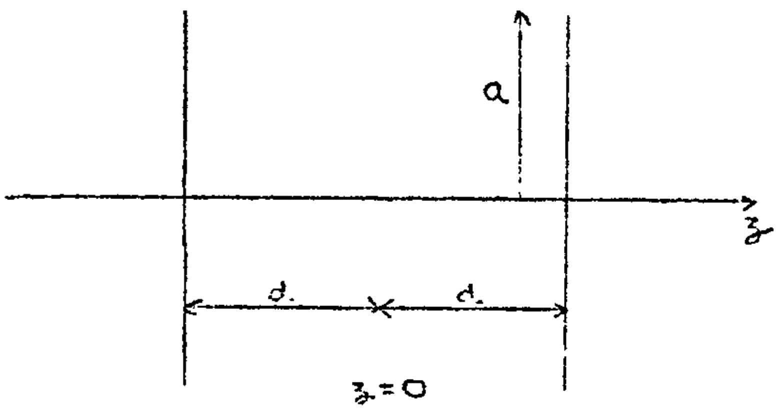
$$B = \sum \text{ of all parallel turns}$$

or :-

$$\underline{B = \sum_{n=o}^{N} f(x,y,z-nd)}$$

Appendix 6.

The Field Produced by Helmholtz Coils.



The field on the axis between the two coils is given by :-

$$H_z(z,0) = \frac{a^2 I}{2}\left[\frac{1}{\left[a^2 + (z+d)^2\right]^{3/2}} + \frac{1}{\left[a^2 + (z-d)^2\right]^{3/2}}\right]$$

$$= \frac{a^2 I}{2(a^2 + d^2)^{3/2}}\left\{\left[1 + \frac{z(z+2d)}{a^2 + d^2}\right]^{-3/2} + \left[1 + \frac{z(z-2d)}{a^2 + d^2}\right]^{-3/2}\right]$$

Using the Binomial expansion -

$$(1 + u)^{-3/2} = 1 - \frac{3u}{2} + \frac{15u^2}{8} \quad \ldots\ldots\ldots\ldots\ldots$$

Substituting this in the above equation

$$H_z(z,0) = \frac{a^2 I}{2(a^2 + d^2)^{3/2}}\left[\ 2 + C_2 z^2 + C_4 z^4 \ \ldots\ldots\ \right]$$

in which $\quad C_2 = \dfrac{15d^2 - 3(a^2 + d^2)}{(a^2 + d^2)^2}$

but,

$$H_z''(z,0) = \frac{a^2 I}{2(a^2 + d^2)^{3/2}}\left[2C_2 + 4.3.C_4 z^2 + \ldots\ldots\ldots\ldots\right]$$

which $= \dfrac{a^2 I}{(a^2 + d^2)^{3/2}} C_2$ if z and r are sufficiently small.

Now $H_z(z,\rho)$ can be expressed as a series (see Bibliography 5 p. 300), therefore,

$$H_z(z,\rho) = H_z(z,0) - H_z''(z,0)\left[\frac{\rho^2}{2}\right]$$

$$= H_z(z,0) - \frac{a^2 I}{(a^2 + d^2)^{3/2}} C_2\left[\frac{\rho^2}{2}\right]$$

If the dimensions are now suitably chosen to make $C_2 = 0$, i.e. $a = 2d$

then

$$H_z(z,\rho) = H_z(z,0)$$

i.e.

$$H_z(z,\rho) = \frac{a^2 I}{2(a^2 + d^2)^{3/2}}\left[2 + C_4 z^4 \;\ldots\ldots\ldots\right]$$

Neglecting the term in z^4,

$$H_z(z,\rho) = \frac{4d^2 I}{(5d^2)^{3/2}}$$

To the same approximation $H\rho(z,\rho) = 0$.

This design makes possible the production of homogeneous magnetic fields. Hence,

$$\underline{B_z(z,\rho) = \frac{4ud^2 I}{(5d^2)^{3/2}}} \quad \text{for values close to the axis.}$$

Appendix 7.

Fields from Scale Models of the Coils.

(i) Circular Coils.

The 'rho' component of field from a circular coil is given by :-

$$B_\rho = \frac{\mu_0 I z}{2\pi\rho\left[(a+\rho)^2 + z^2\right]^{\frac{1}{2}}} \left[-K + \frac{a^2 + \rho^2 + z^2}{(a-\rho)^2 + z^2} E \right]$$

(see Appendix 3).

The elliptic integer parameter k is given by :-

$$k^2 = \frac{4a\rho}{(a+\rho)^2 + z^2}$$

If all the dimensions are scaled down by a factor n, and the new variables denoted by a prime, then

$$k'^2 = \frac{4\,\frac{a}{n}\,\frac{\rho}{n}}{\left(\frac{a}{n} + \frac{\rho}{n}\right)^2 + \frac{z^2}{n^2}} =$$

$$\frac{4a\rho}{(a+\rho)^2 + z^2} = k^2$$

Hence the value of the elliptic integrals remain unaltered by linear scaling.

The 'rho prime' component of field is then given by :-

$$B'_\rho = \frac{\mu_0 I}{2\pi} \frac{\frac{z}{n}}{\frac{\rho}{n}\left[\left(\frac{a}{n} + \frac{\rho}{n}\right)^2 + \frac{z^2}{n^2}\right]^{\frac{1}{2}}} \left[-K + \frac{\frac{a^2}{n^2} + \frac{\rho^2}{n^2} + \frac{z^2}{n^2}}{\left(\frac{a}{n} - \frac{\rho}{n}\right)^2 + \frac{z^2}{n^2}} \cdot E \right]$$

$$= \frac{\mu_0 I n z}{2\pi\rho\left[(a+\rho)^2 + z^2\right]^{\frac{1}{2}}} \left[-K + \frac{a^2 + \rho^2 + z^2}{(a-\rho)^2 + z^2} \cdot E \right]$$

$$= n\,B_\rho$$

Thus, if the current is also scaled by a factor n, the magnitude of the field is the same as before linear scaling. A similar analysis can be effected for the B_z field of a circular coil and the same results are obtained,

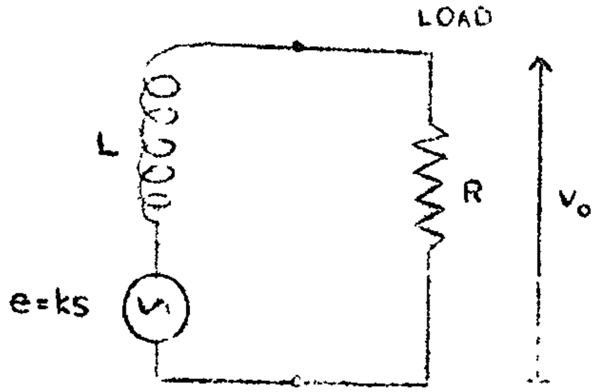
(2) Rectangular Coils.

A similar process on the expressions for the field components of rectangular coils also yields the same results.

Hence it is possible by linear scaling of all dimensions and the current to produce an exact model of the coils and the parallel wires of the proposed system.

APPENDIX 8

Consider the pick-up coil as a signal generator, whose emf is proportional to frequency, in series with an inductance.



Where $s = j\omega$

Now,

$$V_O = \frac{R}{R+sL} ks$$

If $R << sL$,

$$V_O \doteqdot \frac{Rk}{L} \quad \text{(i.e. independent of frequency)}$$

At 30 kHz the average reactance of a pick-up coil ($L \doteqdot 410\mu H$) is about 78Ω. The output voltage is also dependent on R so that R must be as large as possible to give a nearly constant output voltage. A value of $R = 47\Omega$ was taken as a compromise.

APPENDIX 9

P.W. Input Signal

Assuming a low input impedance amplifier such that over the frequency range considered the receiver sees a virtually constant input voltage regardless of frequency. Let the conversion factor from line current to flux density be η and the flux density/induced aerial voltage factor and receiver gain be K.

The receiver output voltage is then given by :-

$v_o = K\eta I$ where I is the line current plus noise.

As the receiver is band-pass, one can assume that the receiver picks up only narrow band noise.

Let the signal current be $\hat{I}_s \cos \omega_o t$ and the narrow band line noise be $x(t)\cos \omega_o t - y(t) \sin \omega_o t$

Then, so far, v_o is given by

$$v_o = K\eta\left[(\hat{I}_s + x(t)) \cos \omega_o t - y(t)\sin \omega_o t\right]$$

To this must be added any 'space-borne' noise which, in terms of its flux density can be written as

$$x_o(t) \cos \omega_o t - y_o(t) \sin \omega_o t$$

Total output voltage is then given by :-

$$v_o = K\eta \left[(\hat{I}_s + x(t))\cos \omega_o t - y(t)\sin \omega_o t\right] + K\left[x_o(t)\cos\omega_o t - y_o(t) \sin \omega_o t\right]$$

which by writing

$$x' = x(t) + x_o(t)/\eta, \; y' = y(t) + y_o(t)/\eta$$

is

$$v_o = K\eta \left[(\hat{I}_s + x') \cos \omega_o t - y' \sin \omega_o t\right]$$

and $\overline{[x'(t)]^2} = \overline{[y'(t)]^2} = \sigma'^2$

and the signal to noise ratio is defined as

$$S^2 = \frac{\hat{I}_s^2}{2\sigma'^2}$$

Space-borne and line noise are assumed uncorrelated

APPENDIX 10

P.W. and T.C. Input Signal

Assuming input conditions as in Appendix 9 but with ϕ the line current/flux density conversion factor and K_1 the flux density/induced aerial voltage and receiver gain for the telegram coil channel.

The output voltage of the TC receiver can be written in the form

$$v_o' = K_1 \phi \left(I_s + x''(t)\right) \cos \omega_o t - y''(t) \sin \omega_o t$$

where
$$x''(t) = x(t) + x_1(t)/\phi$$
$$y''(t) = y(t) + y_1(t)/\phi$$

$x(t)$ and $y(t)$ are assumed as in Appendix 9 and $x_1(t)$, $y_1(t)$ are associated with the space-borne noise associated with the T.C. channel and are correlated with $x_o(t)$, $y_o(t)$ as defined in Appendix 9.

$$\overline{x_1^2(t)} = \overline{y_1^2(t)} = \sigma_1^2$$

Using a multiplier detector (PW signal + TC signal), and low pass filter, and assuming sampling at maximum of TC signal, the probability of receiving a wrong bit is given by (using ref. 17 p 587)

$$P(f) = Q(\sqrt{a},\sqrt{b}) - \frac{v^2}{1+v^2} \exp\left\{-\frac{a+b}{2}\right\} . I_o\left(\sqrt{ab}\right)$$

and
$$A = \frac{\sigma^2 + \sigma_1 \sigma_o \rho}{(\sigma^2 + \sigma_o{}^2)^{\frac{1}{2}} (\sigma^2 + \sigma_1{}^2)^{\frac{1}{2}}} \quad , \quad v = \frac{1+A}{1-A}$$

$$\left\{ \begin{matrix} a \\ b \end{matrix} \right\} = \frac{I_s{}^2}{4} \left[\frac{1}{\sigma^2 + \sigma_o{}^2} + \frac{1}{\sigma^2 + \sigma_1{}^2} \mp \frac{2}{(\sigma^2 + \sigma_o{}^2)^{\frac{1}{2}} (\sigma^2 + \sigma_1{}^2)^{\frac{1}{2}}} \right]$$

and ρ is the normalised auto-covariance between the two space-borne noises.

The S/N ratio can be defined in terms of either the TC channel or the PW channel and in either case is directly expressable in terms of line current.

This is defined as

$$S^2 = \frac{I_s^{\,2}}{2(\sigma^2+\sigma_o^{\,2})} \quad - \text{ PW}$$

or

$$S^2 = \frac{I_s^{\,2}}{2(\sigma^2+\sigma_1^{\,2})} \quad - \text{ TC}$$

let $\sigma_1^{\,2} = \omega.\sigma_o^{\,2}$, then $\eta^2\omega\sigma_o^{\,2} = \phi^2\sigma_1^{\,2}$

also let $\sigma^2 = k\sigma_o^{\,2}$, then

$$S^2 = \frac{I_s^{\,2}}{2\sigma_o^{\,2}(1+k)} \quad \text{or} \quad \frac{I_s^{\,2}}{2\sigma_o^{\,2}(k+(\frac{\eta}{\phi})^2\omega)}$$

For calculations the S/N is taken as that from the P. wires. From η and ϕ must be subtracted the value of the interfering fields between coils and wires (Appendix 12). By alteration of the various parameters above, calculation of the error rate for any channel compared with another can be effected - e.g. substitution for σ_1 by σ_2 for channel TC2 compared with the PW signal.

APPENDIX II

Probability of a False Telegram

Let a telegram consist of N digits of which e are for error detecting purposes. Assuming a Hamming distance of d, then for d or more errors there is the possibility of a false, but valid, telegram being received.

Probability of being within error code detecting capabilities is, assuming a bit error rate P_e,

$$= \sum_{k=0}^{d-1} \binom{N}{k} . P_e^k . (1-P_e)^{N-k} = P$$

Probability of being outside code capability (i.e., $\geq$ d-1 errors)

$$= 1 - P$$

If there are e error correcting digits only one combination is correct for a given telegram, and assuming the digits received are uncorrelated, there is a chance of $1/2^e$ of the error correcting digits being correct.

$\therefore$ prob. of detection is $(1-P)\left(\frac{2^e-1}{2^e}\right)$

(i.e. outside the code capability)

Total probability of detecting an error, in or outside code capability $= P + (1-P)(1-1/2^e)$

$\therefore$ Probability of not detecting the error - i.e. possibility of receiving a false telegram is

$$1 - P + (1-P)(1-1/2^e)$$

$$= \frac{1-P}{2^e}$$

APPENDIX 12

Effects of Interference

Let ϕ be the conversion for the P. wires from line current to flux density and K the receiver gain from field induced voltage to amplifier gain, the output of the receiver can be given by

$$V_o = K\phi I + Kb \qquad (I = I(\text{sig.}) + I(\text{line noise}))$$

where b is 'space-borne' noise. If there is an interfering field from a neighbouring coil with current to flux density conversion factor E

$$V_o = K\phi I - KEI + Kb$$

$$= K\phi' \ I + b/\phi' \quad \text{where } \phi' = \phi - E$$

i.e. conversion factor = theoretical interference free factor - interference factor.

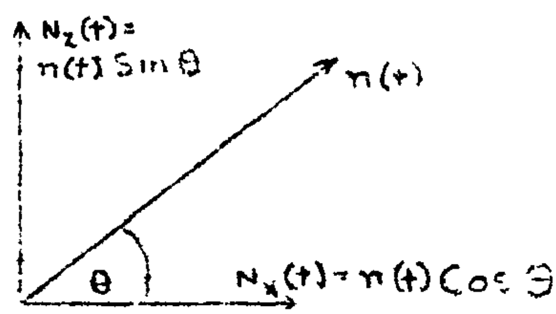
A similar analysis can be done for the telegram coils including interference from P. wires and adjacent coils. For the worst possible case the line current/flux density conversion factors the individual interference factors just have to be subtracted from the interference free value.

APPENDIX 13

The Correlation between the Quadrature Components of a Magnetic Field produced by a Collection of Noise Sources.

A random noise source is assumed producing a magnetic field in space, the noise being Gaussian and narrow band (the receiver containing the filters). This resultant vector is resolved into two components which are in quadrature, and correspond to those used in telegram transmission employing telegram coils.

Let a noise source generate a magnetic field in space and which can be represented by a vector $\overline{n}(t)$ with direction θ.



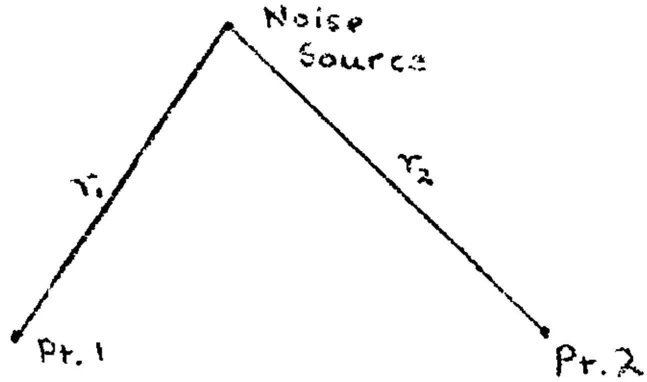
Assuming the noise to be narrow band, this can then be written as :-

$$n(t) = x(t) \cos \omega_o t - y(t) \sin \omega_o t$$

where

$$\overline{x^2(t)} = \overline{y^2(t)} = \sigma^2$$

It is then possible to write down expressions for $N_Z(t)$ and $N_X(t)$. If all distances are now assumed much less than a wavelength - i.e. radiation effects can be neglected, the value of the magnetic induction field can be considered at two points remote from the source.



In the induction field the signal falls off as $\frac{1}{r^2}$

Hence the two components at Pt. 1 are :-

$$\frac{N_Z(t)}{r_1^2} \quad \text{and} \quad \frac{N_X(t)}{r_1^2}$$

and at point two are :-

$$\frac{N_Z(t)}{r_2^2} \quad \text{and} \quad \frac{N_X(t)}{r_2^2}$$

Now, considering an assembly of noise sources producing magnetic fields $n_1(t)$ - - - $n_n(t)$, in the directions θ_1 - - - - θ_n respectively, where

$$n_k(t) = x_k(t) \cos \omega_o t - y_k(t) \sin \omega_o t$$

and $\overline{x^2_k(t)} = \overline{y^2_k(t)} = \sigma_k^2$

The two components can then be represented at pt. 1 by :-

$$N_{1X}(t) = \sum_{k=1}^{n} \frac{1}{r_{k1}^2} n_k(t) \cos \theta_k$$

$$N_{1Z}(t) = \sum_{k=1}^{n} \frac{1}{r_{k1}^2} n_k(t) \sin \theta_k$$

where r_{kj} denotes the distance from the k^{th} noise source ($k=1, \ldots, n$) at point j ($j=1$ or 2).

Similarly for pt. 2,

$$N_{2X}(t) = \sum_{k=1}^{n} \frac{1}{r_{k2}^2} n_k(t) \cos \theta_k$$

and $$N_{2Z}(t) = \sum_{k=1}^{n} \frac{1}{r_{k2}^2} n_k(t) \sin \theta_k$$

If Pt. 2 is assumed the position for the parallel wire pick-up coil and Pt. 1 for the telogram coil pick-ups, the products of interest are :-

$$N_{1Z}(t) \times N_{2Z}(t),\ N_{1X}(t) \times N_{2Z}(t) \text{ and } N_{1Z}(t) \times N_{1X}(t)$$

Now a signal can be written in the form

$$e = \text{Re} \{ z(t).e^{j\omega_o t} \} \quad \text{(see Ref. 18, page 76)}$$

When calculating the above products, the normalised cross covariance function is defined as (see Ref. 17, page 317) :-

$$\sigma_1 \sigma_2 \rho = \overline{\tfrac{1}{2}(z_1 - \bar{z}_1)^{*}(z_2 - \bar{z}_2)} \quad \text{(writing } z_k \text{ for } z_k(t))$$

which can be written in terms of $x_k(t)$ and $y_k(t)$ and gives (letting $x_k(t) = x_k$ and $y_k(t) = \ \ _k$)

$$\sigma_1 \sigma_2 \rho = \tfrac{1}{2}\, \overline{x_1 x_2' + y_1 y_2}$$

Using the above definition for the product $N_{1Z}(t) \times N_{2Z}(t)$, the cross covariance can be written down as :-

$$\rho(1Z2Z) = \pm \frac{\overline{\tfrac{1}{2} \cdot \left(\sum_{k=1}^{n} \frac{x_k \sin \theta_k}{r_{k1}^2} \right)\left(\sum_{k=1}^{n} \frac{x_k \sin \theta_k}{r_{k2}^2} \right) + \left(\sum_{k=1}^{n} \frac{y_k \sin \theta_k}{r_{k1}^2} \right)\left(\sum_{k=1}^{n} \frac{y_k \sin \theta_k}{r_{k2}^2} \right)}}{\left(\sum_{k=1}^{n} \frac{\sigma_k^2 \sin^2 \theta_k}{r_{k1}^4} \right)^{\frac{1}{2}} \left(\sum_{k=1}^{n} \frac{\sigma_k^2 \sin^2 \theta_k}{r_{k2}^4} \right)^{\frac{1}{2}}}$$

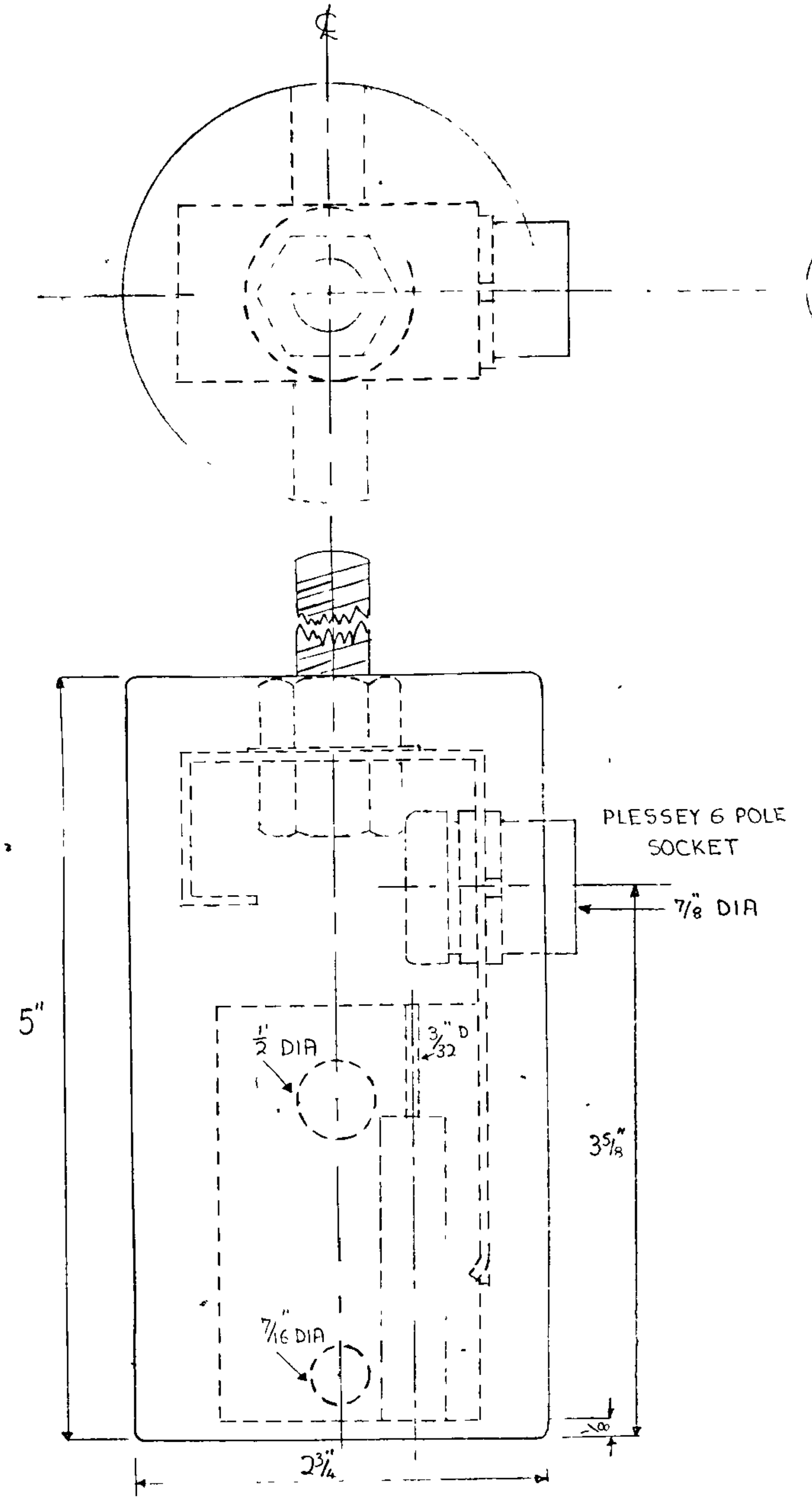
If all the noise sources are assumed completely random, then all products such as $\overline{x_k x_m}$ and $\overline{y_k y_m}$ (where $k \neq m$) are zero, then

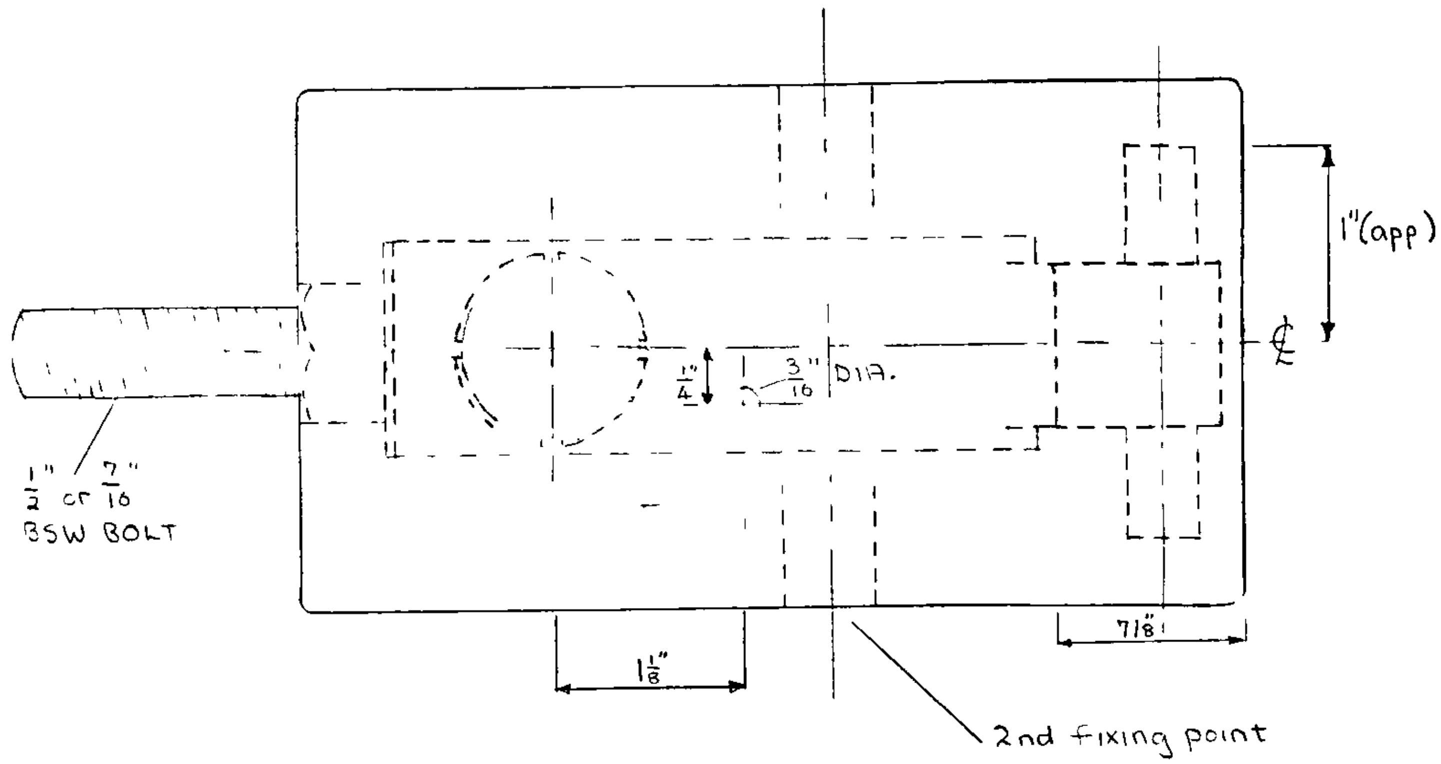
$$\rho(1Z2Z) = \pm \frac{\displaystyle\sum_{k=1}^{n} \frac{\sigma_k^{\,2} \sin^2 \theta_k}{r_{k1}^{\,2} r_{k2}^{\,2}}}{\left(\displaystyle\sum_{k=1}^{n} \frac{\sigma_k^{\,2} \sin^2 \theta_k}{r_{k1}^{\,4}}\right)^{\frac{1}{2}} \cdot \left(\displaystyle\sum_{k=1}^{n} \frac{\sigma_k^{\,2} \sin^2 \theta_k}{r_{k2}^{\,4}}\right)^{\frac{1}{2}}}$$

If one noise source is predominant, i.e. $\sigma_1^{\,2} \gg \sigma_2^{\,2}, \sigma_3^{\,2} \ldots\ldots \sigma_n^{\,2}$, then

$$\rho(1Z2Z) \rightarrow \pm \frac{\dfrac{\sigma_1^{\,2} \sin^2 \theta_1}{r_{11}^{\,2}\, r_{21}^{\,2}}}{\dfrac{\sigma_1 \sin \theta_1}{r_{11}^{\,2}} \cdot \dfrac{\sigma_1 \sin \theta_1}{r_{12}^{\,2}}} = \pm 1$$

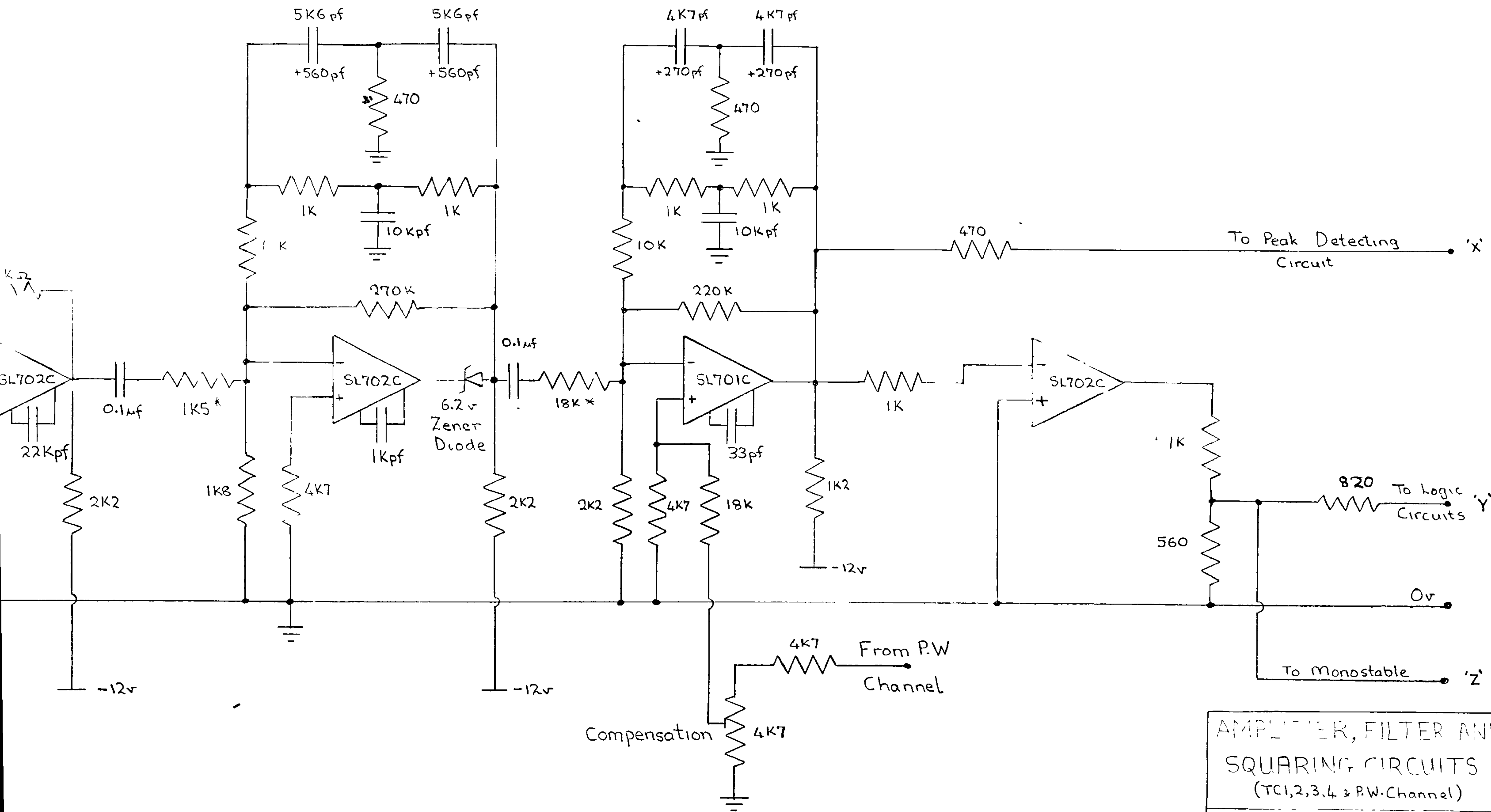
If, on the other hand, $n \rightarrow \infty$, i.e. an infinite number of noise sources, it can be shown that ρ may take any value between +1 and -1 depending on the physical distribution of the noise sources and the direction of the associated magnetic fields. This can also be shown to be the case for various degrees of correlation between the various noise sources except for full correlation when $\rho(1z2z)$ again tends to ± 1. A similar analysis can also be done for the other products required and the same conclusions can be drawn.





EXPERIMENTAL PICK-UP COIL AND ENCAPSULATION	
MODIFIED TELEGRAM COIL SYSTEM	
DRAWN CVS.	DATE 14 SEPT. 1969

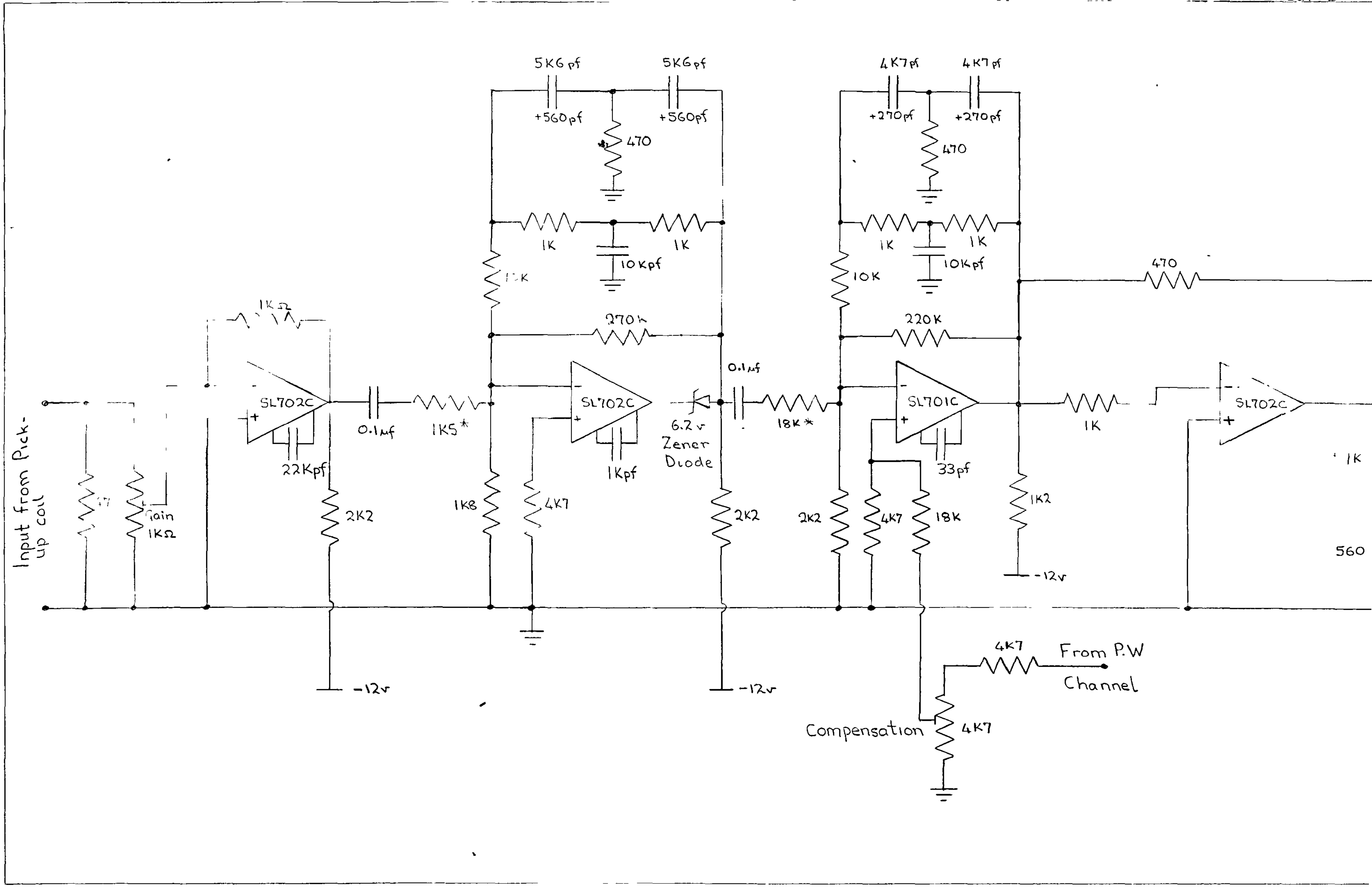
APPENDIX A

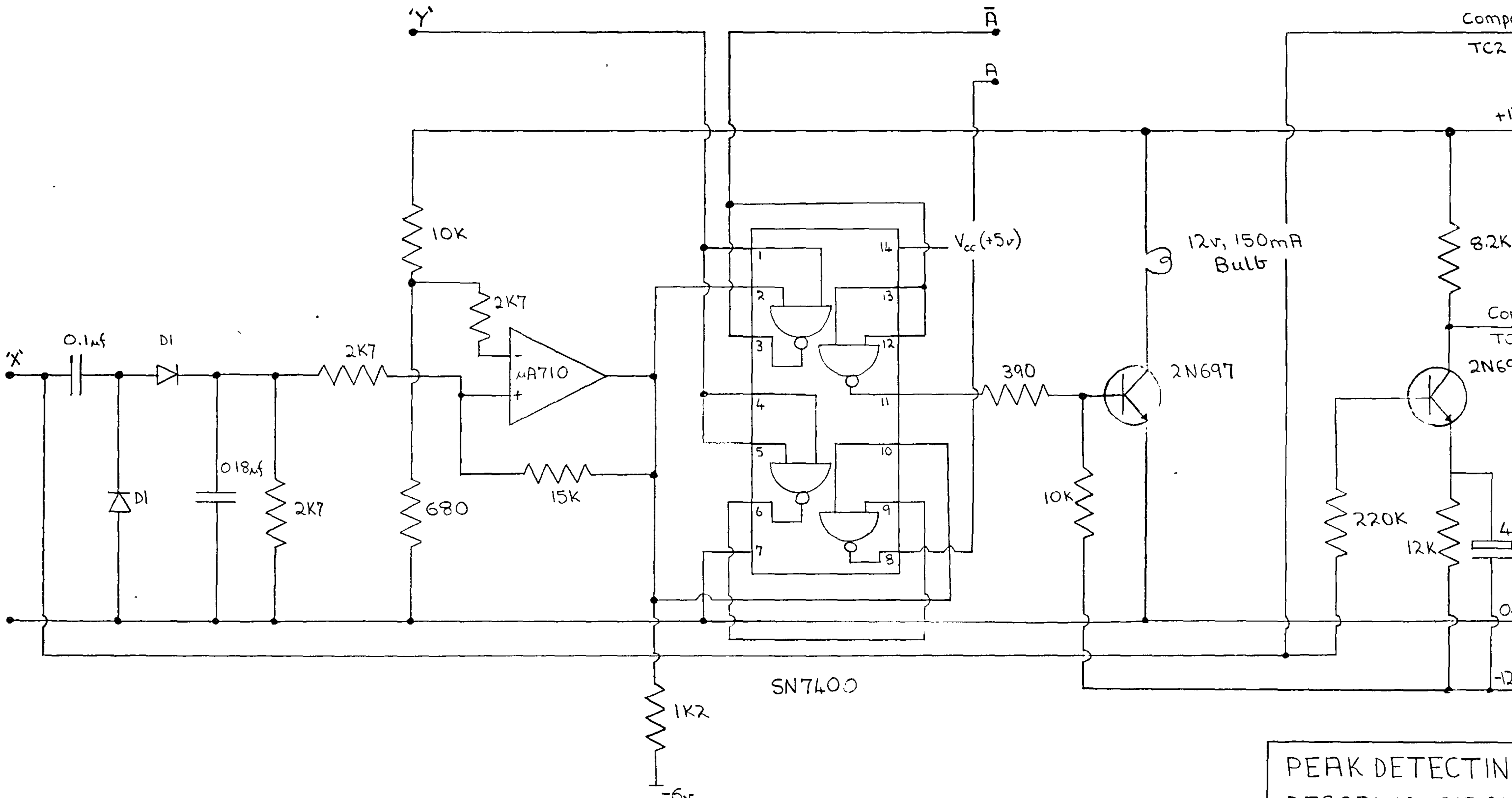


AMPLIFIER, FILTER AND SQUARING CIRCUITS (TC1,2,3,4 & P.W. Channel)

MODIFIED TELEGRAM COIL SYSTEM

DRAWN	DATE
CVS	13 SEPT 1969


5K6pf
5K6pf
+560pf
+560pf
470
4K7pf
4K7pf
+270pf
+270pf
470
1K
1K
10Kpf
1K
1K
10Kpf
10K
10K
470
1KΩ
270K
220K
0.1μf
SL702C
0.1μf
1K5*
SL702C
6.2v
Zener
Diode
18K*
SL701C
1K
SL702C
22Kpf
1Kpf
33pf
1K
Input from Pick-up coil
Gain
1KΩ
2K2
1K8
4K7
2K2
2K2
4K7
18K
1K2
560
-12v
-12v
-12v
-12v
4K7
From P.W
Channel
Compensation
4K7

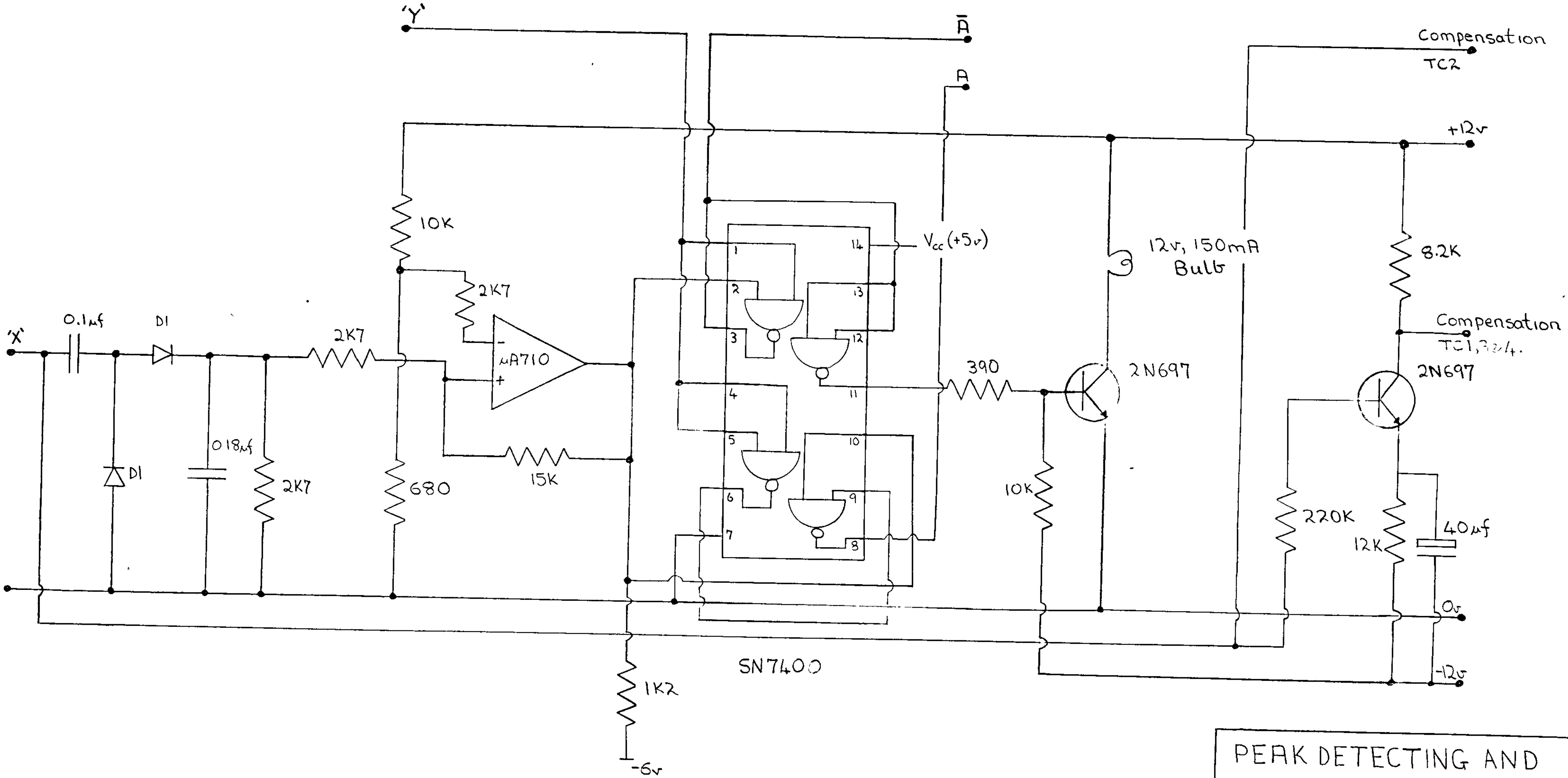


PEAK DETECTING / DECODING CIRCU (PW Channel Only)

MODIFIED TELEGRAM SYSTEM

DRAWN	DATE
C.V.S	1:

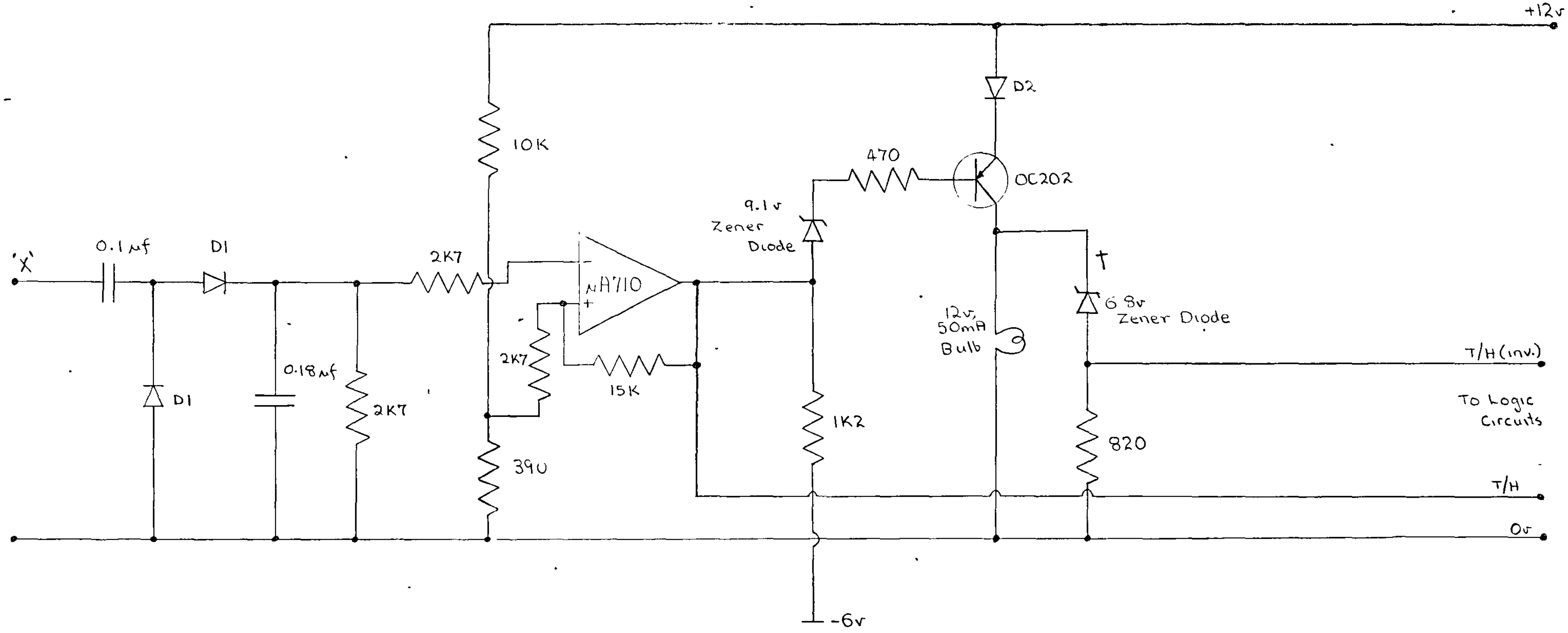
APPENDIX C



PEAK DETECTING AND DECODING CIRCUITS
(PW Channel Only)

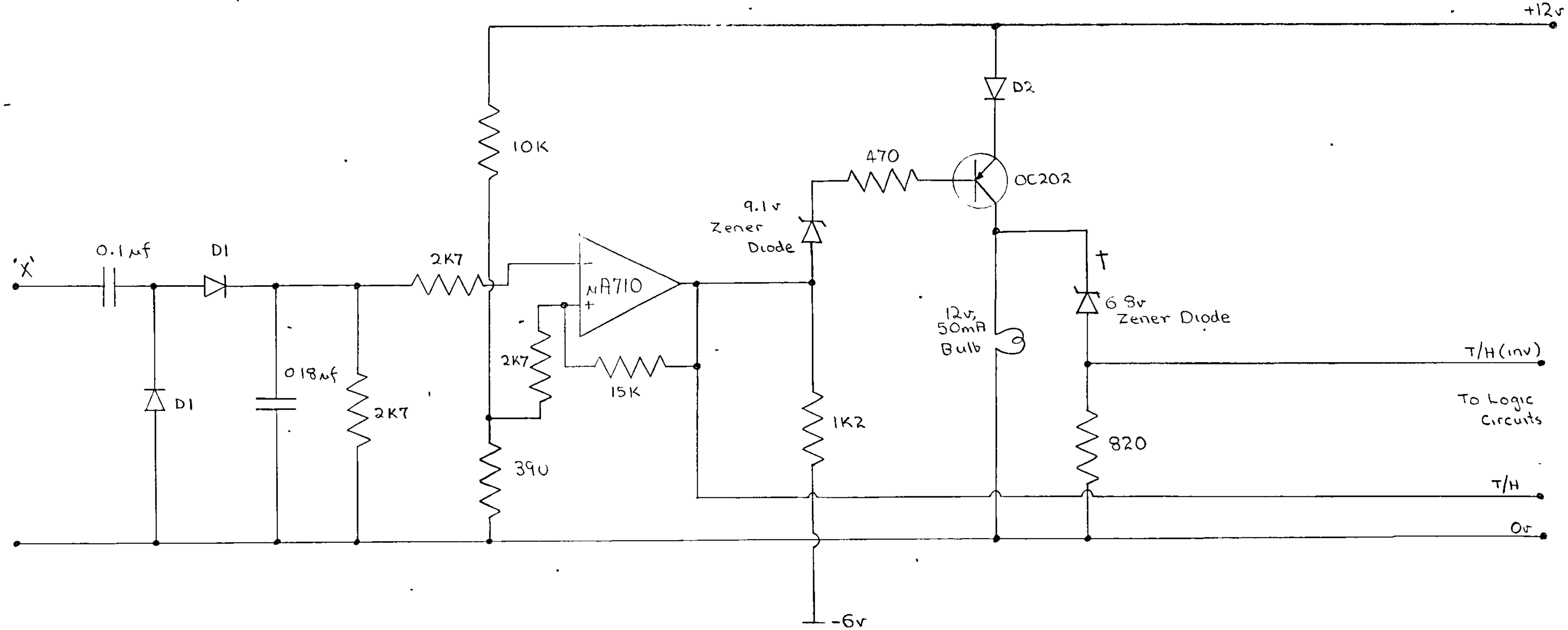
MODIFIED TELEGRAM COIL SYSTEM

DRAWN	DATE
C.V.S	12 OCT 1969



† - Omitted on TC2 . TC4
D1 - Germanium Diod s
D2 - Silicon Diod .

PEAK DETECTION LAMP DRIVER CIR (TC1, 2, 3 & 4 Channels On	
MODIFIED TELEGRAM C SYSTEM	
DRAWN CVS	DATE 3 OCT



† - Omitted on TC2 . TC4
D1 - Germanium Diodes
D2 - Silicon Diode

PEAK DETECTION AND LAMP DRIVER CIRCUITS (TC1,2,3 & 4 Channels Only)	
MODIFIED TELEGRAM COIL SYSTEM	
DRAWN CVS	DATE 3 OCT 1969

SN7474 Sampling Pulse Generator
'1' Set
A
PW
$\bar{A}$
N.H.
N.L.
'Z'
B1
M/S
TC 1
'T/H'
'T/H (INV)'
B2
TC 2
B3
TC 3
B4
TC 4
DTμL951
R
C
S/T
Green Lamp
Blue Lamp
G.L.
B.L.
'0'
'1'
'1's'
'0's'
Serial Output
SN7420
N8875A
Phase Comparison
Pulse Counting
FCL 101
Threshold
SN7410 - Sampling Gates
D1
D2
D3
D4
N8815A
SN7402
SW2
SN7400
SW1
Initiate Sampling Circuit
DECODING LOGIC AND PARALLEL TO SERIAL CONVERTER
MODIFIED TELEGRAM COIL SYSTEM
DRAWN C.V.S
DATE 9 OCT. 1969
M/S - Monostable
S/T - Schmitt Trigger
N.L. - Normally Low
N.H. - Normally High

PART II

AUTOMATION ON THE RAILWAYS

1. Introduction

Railways have often been criticised for lagging far behind the state of technology and in many cases it has been quite justified. This has been caused by lack of money, foresight and planning, i.e., poor management - and lack of technically qualified people in the right jobs to bring in new ideas and implement them. On the other hand railways will always, generally, tend to lag a little behind technology, especially in signalling, due to the stringent safety requirements to which they must adhere. It is probably for this reason that their safety record is second to none in passenger transport.

In the very early days of railways they kept up with technology by their development and use of the relay and the telegraph. However, the appearance of the electronic valve changed the situation. The valve, by its very nature, tends to be fragile and in a railway environment, especially on a locomotive, would probably not have a very long life. This, coupled with the relative difficulty of obtaining suitable power supplies on a steam locomotive and the desire for "fail-safe" working of equipment, is where railways and electronics parted.

Events now seem to have turned full circle and most railway authorities seem to be looking at electronics (Reference 1) and what modern technology can offer. Why is this? With the steam locomotive fast disappearing the possibilities for further automation are manifold. From early days it was realised that forms of control minimising human error and judgement were desirable. The first form of control was the mechanical signal in its various forms. This represented a one way communication

- apart from the driver throwing "a message" out at a station wrapped around a lump of coal. This single 'go' channel was very soon realised to be inadequate and a return channel using the track circuit and axle counter were developed and thus provided a two way communication but with very limited information capacity. With higher train speeds and loads and the desire for higher efficiency in the use of men and equipment, further attempts at automation were inevitable and greater concentrations occurred. The entirely mechanical signal box gave way to the electro-mechanical box and finally to the modern signal boxes of today with route setting and train description to cope with present traffic - but what about tomorrow?

What has happened in the past has only been the translation of previous ideas into the hardware of a new technology, mechanical interlocking to electro-mechanical interlocking (i.e. relays). The principles of signalling have remained basically the same and not much regard has been paid to modern technology in exploiting new ideas and maybe changes in the basic philosophies of signalling and control of trains. With the state of technology at the moment and the investigation into other concepts of signalling (References 2-4), it would seem that a mere translation of ideas is not what is required, but a complete rethink. The technologies of transistors, core storage devices, integrated circuits, MSI, coding etc. open up hitherto unobtainable possibilities. This opportunity should not, and must not, be passed by. Here one has the possibility of creating systems whereby movements of trains can be more closely controlled together with the possible interaction of signalling and the motive power units themselves (i.e. the diesel and electric traction motors), and hence providing still higher degrees of safety.

Although this article is basically about signalling the other areas of railway automation must not be forgotten - i.e. passenger control (commuter and suburban railways) automatic fare collection, automatic coupling, wagon identification, data collection and transmission. However, as far as train movements are concerned, most of these are fringe effects and it is automatic train control that will have the greatest effect on railway operation. Already partial effects of automation have been felt - A.W.S., Indusi System (Reference 5), colour light signals, automatic route setting and recently Southern Region A.W.S. (Ref. 6). This last item represents quite a large step forward with the use of much more electronics (apart from one or two isolated cases e.g. the Henley Scheme, Ref.7). However, as equipment is further built up it should conform to an overall national plan (excluding underground railways and rapid transit systems) - even international if possible (cf. work of U.I.C.). This is especially important for countries with international borders, and also for Britain with the possible construction of the channel tunnel to facilitate the through running of trains. Any changeover can obviously not occur 'overnight' and this period will probably have its troubles which can be minimised by careful pre-thought and design. During this period new systems may have to be built partially on to the old to maintain continuity of services but eventually the new must supercede the old, except where design is otherwise.

Another point not yet mentioned is, what is the final aim of automation? Is this the driverless train or is it to merely supervise the driver? What would be the psychological aspect of a driverless train for passengers? The work at the moment seems to be tending towards a supervised driver system -this not only increases the present safety standards but also allows the driver to maintain his driving skill. On the other hand, for a fully automatic railway at least one man is still required on the train to take care of any emergencies besides the normal functions of ticket control etc. Is the final aim also centralised train control? The final answer to this must surely be "Yes" although it is probably the final step of the automation process.

2. <u>The Need for Automation</u>

The main reason for automation is economic, although closely linked with this is the desire for better operating possibilities and the ability to compete with other forms of transport, e.g. road and air. Much of the railway's assets are fixed, i.e. the bulk of the capital of the railways is in fixed installations, and hence the desire to use these to the full. The assets are mainly the trackwork, the signalling, motive power, rolling stock, and buildings. Standards of service have to be maintained and improved,yet the costs must in turn be minimised. This can only be achieved by better utilisation of assets.

There is also the need, through automation, of optimum control of train movements. Included in this are the problems of minimising train delays, keeping to timetable with minimum energy consumption, minimising travelling times and generally reducing the effects of human control where possible. This in turn releases personnel for other duties or reduces labour charges. The possibility of human error is also reduced and hence safety standards are increased which is a prerequisite for high speed working. Another need directly connected with high speed working is the desire to provide advance information for the control of the motive power unit - either for driver supervision or complete automation. This is because of the much longer braking distances required by high speed trains and the desire to relieve the driver from observing every line side instruction (e.g. signals, whistle boards, etc.) which becomes increasingly tiring and hence unreliable at high speeds. This information is to aid the driver in taking decisions and to supervise him, i.e. to make sure the train is within the speed limit prevailing abd its braking capabilities. These are especially important in bad weather conditions and places of high density working.

3. The Requirements of Automation

The previous section outlined the need for automation, this section deals with the requirements imposed by it on staff and equipment. It is probably true that anything can be done - but at a price. This would seem to be so for automation on the railways but cost is an overriding factor in how far technical development can go. As mentioned in the introduction, the main impetus for automation must be the close control of train movements. This immediately involves signalling and information transmission which are the keys to the whole situation. No matter how good rolling stock and locomotives are, the system is only as good as its signal system allows. The present signalling system is inflexible because it consists of fixed distances between track-side signals. A much more flexible system is that known as moving block, the fundamentals of which are more fully discussed in the next section. However, this type of signalling system does require more information flow than the present system and also requires a very reliable communication channel.

The positioning of the equipment for automation (at the trackside or on the locomotive) depends on the type of railway system - underground and commuter service or main line railway - and the information flow (see section 5). Whichever system is used certain minimum safety requirements must be met and it is to be hoped that all new developments will not only maintain the present safety and reliability standards but also improve them. What does this mean for the equipment? Probably the utmost standard in railway signalling is safety which is achieved by 'fail safe' working. Attitudes to this will probably have to change, for whilst 'fail safe' is a very desirable principle, the question remains as to whether every failure in electronic equipment can be made 'fail safe'. Every failure mode must be examined beforehand and every effort should be made to make all possible failures tend towards the 'safe-side'. With the reliability of modern components what they are, one must ask - if the probability of a wrong-side failure with 'fail safe' relay technology is 1 : n, is not a wrong-side failure of "fail safe biased (i.e. not entirely fail-safe) equipment of 1 : 10n not as good, or even better than for the relay technique, if the overall failure rate for the new equipment is also 1 : n (i.e. right-side failures of 9 : 10n)? This, of course, is a question which has no "Yes" or "No" answer but one which must be borne in mind and at some time in the none too distant future be thoroughly examined. The problem then arises of constructing 'fail-safe' units with none 'fail-safe' building blocks and this may have to use special switching techniques. However, the construction of equipment must be such that units are easily interchangeable in order to minimise the effects of failures.

But what of the actual process of automating? How should this be done and what should each step do? It is certain that complete automation will not appear suddenly and the design of equipment must be so that it can be introduced in stages, although the full benefit from it will not be derived until later. Every step must be needed and not rendered superfluous after the introduction of the next or other units and all equipment must be compatible although, due to the time delays between different installations, different technologies may be used. The locomotive equipment naturally must conform with the above but what effect should an equipment failure have? This should always tend to have a more restrictive effect, i.e. bringing the train speed down or to a standstill if necessary whether the train is fully automatic or not. During a change-over period, two signal systems may have to coexist and if a failure occurs on, say, high speed equipment it seems logical to bring the speed of the particular train down to within the capabilities of the conventional signalling equipment. During any change-over period it must also be possible to use non-equipped trains, although their use would prohibit the full use of the new system. Eventually the old system must be discarded but it can be argued that an emergency stand-by system is necessary. This could consist of a skeleton form of a conventional signalling system which is activated by a defective section.or by the passage of a defective train. This system would have low capacity but would permit train operation. Again, whether two systems can be kept depends on costs.

The information channel must certainly have extra capacity to cope with any future developments and all data transmission must be such that no additional information is required for a change from supervised driver to full automation, if needed. This would mean that all the information for full automation is available in the train and probably all that has to be done is to install the actual control devices between the control signals and the mechanical/electrical train controls.

Apart from these requirements on equipment there must be changes in the need for personnel and possible re-training. For drivers there must obviously be re-training on driving with the new equipment and system and the actions to be taken in cases of failure or emergency. New attitudes will have to be taken by the drivers and they must have absolute trust in their equipment. But what about other staff? Automation will need specialists in the fields of electronics, cybernetics, information and data processing who will largely replace the signal engineer and controllers of today. Some people can be re-trained for newly created jobs but the right man should be used where the job demands it. These are all things which take time and something at which an early start has to be made. There will most likely be problems that must be sorted out with the unions over new methods of working and redundancies. However, no matter what may happen with automation the human being will still be the highest supervisory organ but with all his actions highly scrutinised.

4. New Signalling Concepts

Conventional signalling consists of fixed space blocks and the principles on which this is implemented are well known and will not be further discussed here. The modern four aspect signalling represents an advance on the other forms of signalling. It represents a digital type of moving space block system with limited capacity, the maximum only being approached at the higher speeds. With increasing the number of aspects the capacity can be improved but here a cost factor comes in. As the number of aspects increases the system quickly approaches a genuine moving space block. Is the only new signalling system one where the distance between successive trains is equal to the maximum braking distance needed by the fastest train in the system? No, there are other signal concepts - all of which are dependent on distance keeping - a fundamental requirement - but the distance is not always constant as shown below.

There are five basic types of moving block. Letting

S = minimum spacing of trains

V_A = speed of leading train

V_B = speed of trailing train

f = braking constant (deceleration)

V_m = maximum line speed

where $0 \leq V_A,\ V_B \leq V_M$

1. Relative Moving Block (R.M.B.)

$$S = \frac{(V_A - V_B)^2}{2f}$$

2. Pure Moving Block (P.M.B.)

$$S = V_B^2/2f$$

3. Moving Time Block (M.T.B.)

$$S = \frac{V_M}{2f} \cdot V_B$$

4. Moving Space Block (M.S.B.)

$$S = V_M^2/2f$$

5. Multi-Valued Moving Block (M.V.M.B.)

$$1. \quad S = \frac{V_M^2}{2f} \quad \text{- steady state}$$

$$2. \quad S = \frac{V_B^2}{2f} \quad \text{- approaching target}$$

These above definitions are ideal and have to be modified in practice to include such items as train length, system measurement tolerances and overrun distances (which ideally should be speed dependent). From the above definitions it can be seen that the distance between two trains is a function of at the most three variables of the group V_A, V_B, V_M and f, subject to the condition that $V_A, V_B \leq V_M$. V_A, V_B and f are then the basic parameters of the train which has to be controlled. Method 1 is the system which will give greatest capacity and is basically the method used when driving on the road. However, for technical reasons when effecting the measurements and calculations, this method is not suited to railway operation. There is also another difficulty with this system and that is the inclusion of trains with different braking characteristics. For these reasons this method is no further discussed.

Method 2 is derived from the first one by assuming the leading train to have an infinite braking rate (i.e. it can come to a standstill instantaneously). This them appears as a fixed obstacle for the following train. This eases calculations but still involves a squaring process. Moving Time Block (3) aims at keeping a fixed time interval between trains (dependent only on maximum permissible line speed). The braking distance is then proportional to the train speed and is relatively simple to calculate. M.S.B. keeps the distance between trains equal to the maximum braking distance and represents the limit of an infinite aspect signalling system. Method 5 employs both the ideas in 2 and 4 but the equipment for the calculations is more complex due to having to make a choice as to which condition applies besides the actual calculations.

These are then the basic concepts for a new signalling system, any final choice having to be based on the relative merits of each system. Of the possible systems (excluding R.M.B.), pure moving block provides the highest capacity but only below the maximum line speed. M.T.B. permits an almost constant line capacity over a wide range of speeds. M.V.M.B. also provides high capacity but the control system is more complicated. It is for these reasons that a moving time block is preferable (see also References 2 - 4) although some modification at low speeds is probably needed to improve the line capacity.

5. Information Exchange Required

This is one of the most important questions for automation and one around which most of the discussion revolves. Connected with this question is also that of where most of the equipment should be situated - track-side or locomotive carried. This last item also determines most of the data flow required.

What does seem certain is that the train needs to know no more and no less than what the driver already knows. This information is acquired by the driver before and during a journey. How is it acquired and where does it come from? The information will be taken in by the driver through his eyes and ears and will come from timetable and route manuals issued before a journey, his observance of wayside commands and his knowledge of the capabilities of the train itself. This, in turn, is then acted upon through the skill and experience of the driver. In other words, the information is collected from various sources, digested and then acted upon by some control organ as would be in any automatic system.

For underground and local commuter railways it has been suggested (Reference 2) that a mainly trackside orientated system is best. This is because of the large number of vehicles and motive power units, the frequent coupling and uncoupling of trains and the uniform characteristics of all the trains. This also reduces the amount of train carried equipment to a minimum and the amount of standby equipment needed. In any case, for a very high density service running over relatively short distances both track-side and train-borne equipment failure will have serious disruptive effects on services. With the very uniform train characteristics, this type of system needs very simple control commands.

On the other hand, there is the main line railway with its variety of traffic, high track mileage and large variance of braking capabilities. Here mainly train-borne equipment is probably better because of the much longer track sections involved with one control unit and the larger variety of information which is train variable. Also, the failure of one set of locomotive equipment will not have such a disruptive effect on other services such as would occur with a line-side set due to the possibility of other routes for following trains.

Apart from these, there is the problem of how do we make sure the train receives the information transmitted to it and not that for another one. This requires the transmission system to be place or train selective and means that the systems are not truly continuous but intermittent, although periods between message receptions are at the most a few seconds. For a place selective system the requirement is that a train can only pass one influence point at a time whilst for a train selective system train address codes must be used. For a place selective system codes have to be used to address the locality but the code is not required by the train. However, a train selective system is more flexible and more suitable for a moving block signalling system.

So far, only information required by the train has been mentioned. There obviously must be feedback for the system to function although this information is probably minimal but of vital importance. In fact it is this feedback of information that permits a recording of the train's position. This is then not altered until the next reply from the train - no reply being assumed a failure and the train becomes a fixed obstacle for following trains until the defect is cleared.

Figs. 1 and 2 represent two basic control systems and depict the information flow right up to a completely centralised control system with automatic route setting. They are only representative of the two types of possible control system

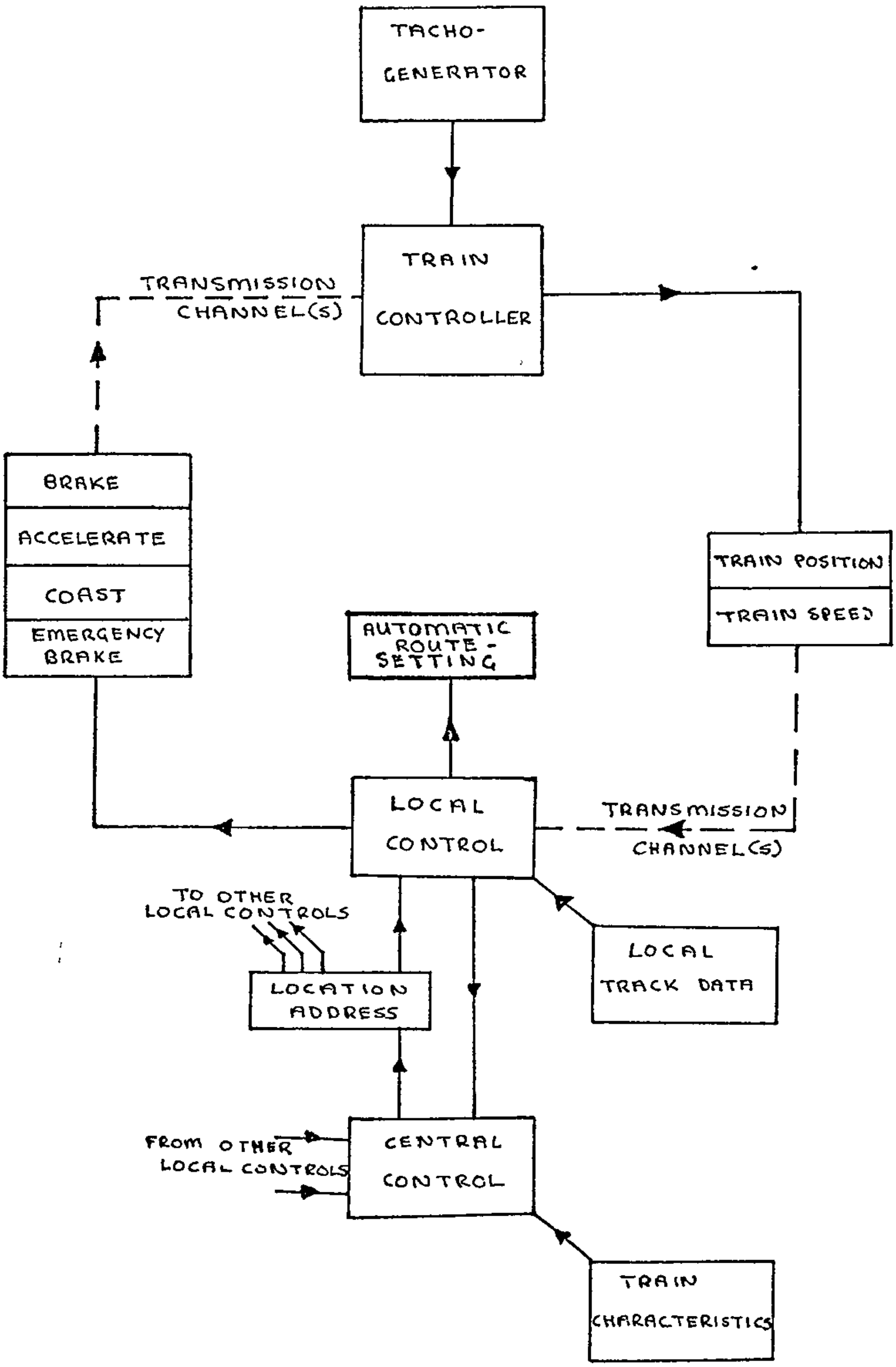


FIG. 1. BASIC COMMAND TRAIN CONTROL SYSTEM.

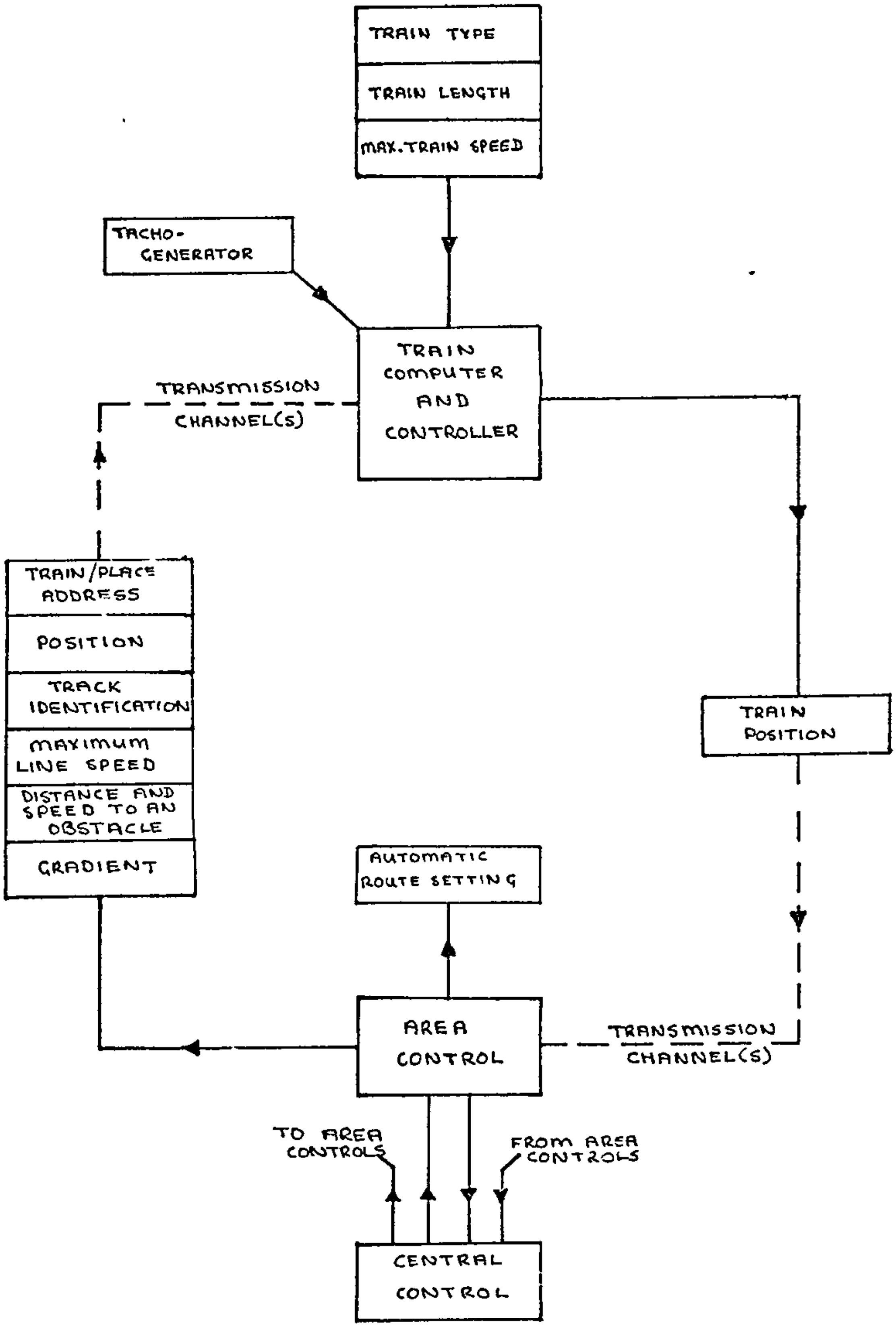


Fig. 2. HIGHER ORDER TRAIN CONTROL SYSTEM.

which are distinguished by the commands issued to the train, with possible additional commands such as the degree of braking (e.g. $\frac{1}{4}$, $\frac{1}{2}$, full). Fig. 1 represents what is a basic command system, i.e. the commands are the primary commands needed to activate the control devices on the train and hence minimise train-borne equipment. However, more information must be supplied to central and local control centres as all the information must be evaluated there. This needs more complex track-side equipment and is a system more suitable for underground and local railways. The second figure represents a system much more suitable for main line railways where it is desired to have locomotive-concentrated equipment. The information transmitted is the basic parameters needed to evaluate the essential control commands - brake, accelerate and coast. Other information regarding the nature of the train must also be provided and for a system of this type be fed in at the commencement of the journey.

All the information in both systems mentioned above must occur somewhere in the systems although at different points and must lead to the same end result. This information can be subdivided into two groups, as shown below, and will probably help to determine its transmission.

FIXED INFORMATION	VARIABLE INFORMATION
Track Identification	Brake (normal and emergency)
Maximum Line Speed (inc. temporary speed restrictions)	Accelerate
	Coast
Gradient	Variable Obstacles (distance to and speed at including preceding trains)
Fixed Obstacles (distance to and target speed)	
Position or Locality	Signal Aspects (if required)
Whistle and Test Commands	

In addition to the above information there is also the need for a speech link between driver and control points for any special information exchange or for passenger information. This could eventually lead to public telephones on board the train but this is certainly not an immediate goal.

If urban and main line railways are to run over the same tracks then there may be a case for using one system for both types of railway rather than having to interlace two systems which would certainly be uneconomic.

6. Possible Communication Links

Various types of control systems and communication channels have been suggested and tried and some of the salient features are mentioned here (for further details see References 8 - 12). Probably, the actual transmission channel has the most effect on the system, rather than the other way round as it determines largely when transmission is possible and how many trains it can influence per unit of time. The most obvious form of communication is of course radio. It is easy to install and requires nothing to be laid in the track. The main disadvantage of radio is that it is highly influenced by weather and geographical conditions and hence is unsuitable for providing a high integrity communication link, which is required for a railway control system. However, it could provide additional speech links if required. The overhead catenary system has also been examined as a possible communication channel either by direct contact or inductive coupling. As far as direct contact is concerned this is very dependent on contact resistance and ice and snow on the line. For contact and inductive coupling, the lines suffer from large fluctuations in impedance from one section to another. This makes feed arrangements and transmission difficult as well as the very non-directional properties of such a system. The same discussion also applies to the use of the 'third' rail as a communication system. Another disadvantage of using such media is that the whole railway network may not be electrified and hence another form of transmission channel must be used elsewhere which is contrary to the principle of wanting a uniform system.

Another clear alternative is the use of the rails themselves using inductive coupling. However, as far as long distances are concerned they represent a poor medium due to high rail attenuation and dependency on block sections and axle short circuits. The frequency band is restricted to that below about 5 kHz and distances of about 2-3 km - hence the information capacity tends to be low. Methods have been suggested by Form (Reference 13) which use the rail attenuation to good advantage by dividing it up into short loops and using frequencies of the order of 20 kHz but more track side equipment is needed. However, it has the advantage that the system is actuated by the axle short circuit as in conventional track circuiting. This system is of course unsuitable for use with steel sleepers. At the other end of the frequency spectrum there have been trials with microwaves. These tests have either been in the form of 'leaky' waveguides or the use of surface waves (see Reference 14 - 16). An additional use of surface waves has been their use for obstacle detection on the track. These installations tend to be rather expensive but with the advance of semiconductor tecnnology the cost of generators and receivers will have been greatly reduced.

The final system is the 'track conductor' system and for main line railways is probably the best solution at the moment. The frequency range is from 30 kHz - 150 kHz with the possibility of loops up to about 12 km. long. It is independent of block sections, axle short circuits and can be made virtually independent of weather conditions and type of sleeper. Also, with this type of system it is easy to build in to it inherent position markers. With this system there is also the choice of long or short loops but for a fully controlled railway system it would seem that long loops are the better. Long loops also mean less track side control points and that equipment can be located in easily accessible places such as stations which is better for maintenance or alteration of fixed data.

After deciding on a particular communication channel there is then the problem of where the information storage should occur. It has been suggested (Refs. 10 and 17) that information regarding timetable, stopping places etc. could be stored on the train in the form of punched tape or cards. This would, however, seem to be rather inflexible if disturbances occur such as deviation from timetable, route change or locomotive failure. It could be argued that extra tapes or cards could be kept on the train but they could never cope with all possibilities and in any case possible human errors could creep in here. This would minimise data transmission but a central control would have to be able to compare the train performance with the expected performance in order to perform optimum train control and automatic route setting. It would therefore appear that storage of timetable information and so on must be accomplished at a central control and that train automation and route setting must be considered as a single entity. Track features and other fixed data could be stored locally and if required by the train equipment can be transmitted by some form of modulation. An alternative for fixed information transmission are small coils (telegram coils) wound in series with the track conductors and producing either a signal in-phase or out-of-phase with the conductor signal (see Ref. 18 or Part I of this thesis). All variable information is probably best transmitted by some form of modulation (which is not amplitude dependent) although it would be conceivable to use switched telegram coils.

How should such a system be built up? It must of course be built up from the existing system. The first step would seem to be the provision of advance information to high speed trains to supervise high speed working and braking distances. It is to be hoped, that during this period more and more trains will be fitted with the control equipment so that supervision of slow trains also becomes possible. After this it should be possible to introduce regulation according to timetable, introduction of centralised control (with automatic route setting) and for moving block working the abandonment of lineside signals.

7. In Conclusion

Several partially or fully automatic systems are already in use and of these probably the best known are the London Transport Victoria Line, the Japanese Tokaido Line (see Reference 19), the Munich-Ausburg high speed track (Reference 20) and more recently the Bay Area Rapid Transit System. Other similar systems are on trial such as the B.R. system at Derby, those in various mines in Germany as well as those in Belgium, Switzerland and France.

Automation will certainly lend itself to making railway systems more flexible than what exist at present. It can also provide extra benefits such as better level crossing protection, permanent way gang protection and permanent speech communication with a moving train. However, while full automation is desirable on main lines, it may well be that only partial automation is economically viable on secondary lines although operation must still be compatible with that on main lines.

Whilst most major problems have been solved, one major one still remains. This is the problem of obstacle detection. Various forms of guided wave radar have been tried but so far no reliable, inexpensive system has been developed. Obstacles in the path of a moving train are obviously a hazard and for the present may be another valid reason for retaining a driver in the cab.

Whatever may happen in the future, automation will certainly play a bigger and bigger role in railway operations. However, at the same time trends in transport must be borne in mind and automation must not be done just for automation's sake.

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