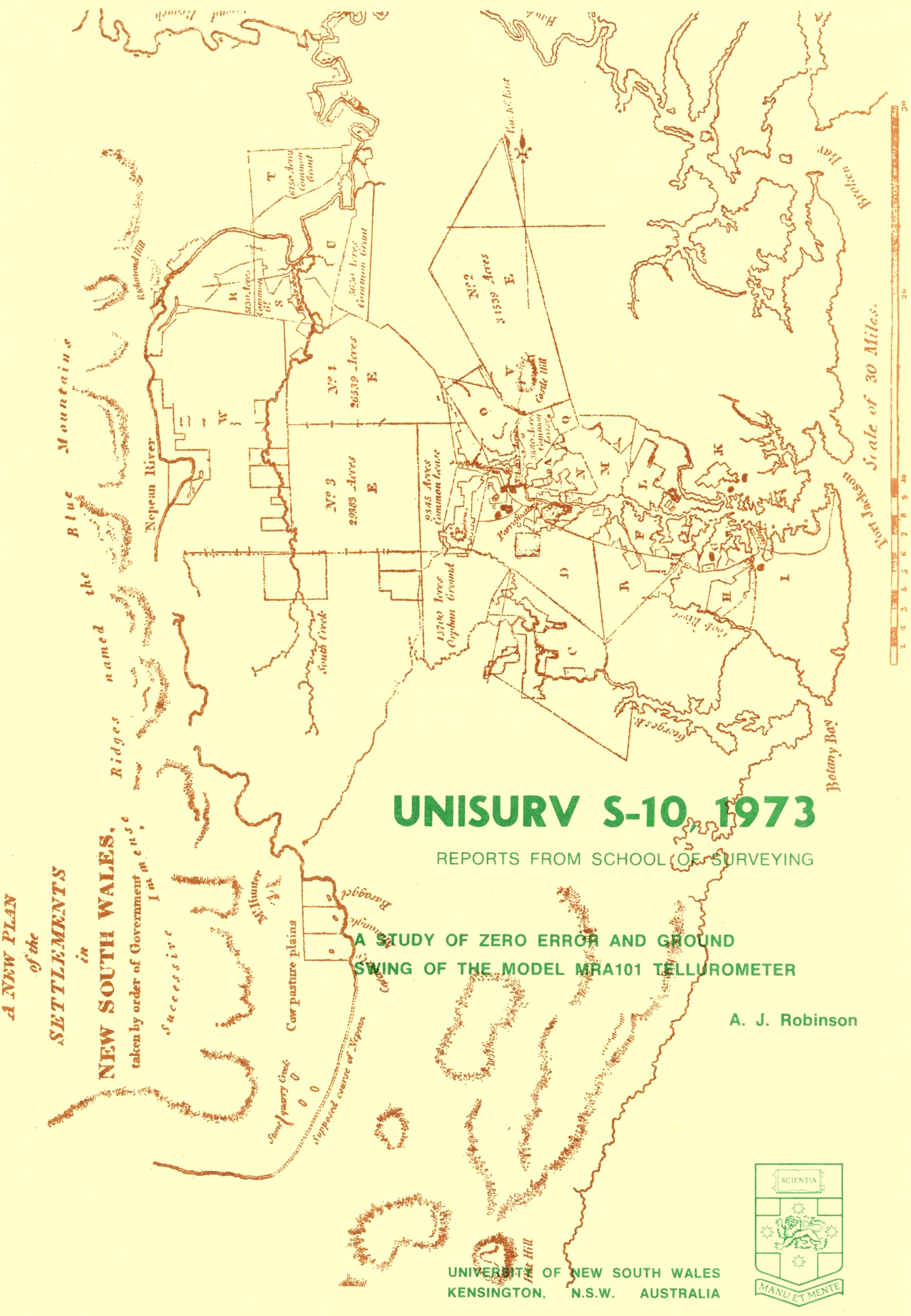


UNISURV S-10, 1973

REPORTS FROM SCHOOL OF SURVEYING

A STUDY OF ZERO ERROR AND GROUND SWING OF THE MODEL MRA101 TELLUROMETER

A. J. Robinson

UNIVERSITY OF NEW SOUTH WALES
KENSINGTON, N.S.W. AUSTRALIA

Reference to Districts.

A	Northern Boundaries
B	Liberty Plains
C	Banks Town
D	Parramatta
EEEE	Ground reserved for Govt. purposes
F	Concord
G	Petersham
H	Bulanaming
I	Sydney
K	Hunters Hills
L	Eastern Farms
M	Field of Mars
N	Ponds
O	Toongabbey
P	Prospect
Q	
R	Richmond Hill
S	Green Hills
T	Phillip
U	Nelson
V	Castle Hill
W	Evan

The cover map is a reproduction in part of a map noted as follows:

London: Published by John Booth, Duke Street, Portland Place, July 20th, 1810

Reproduced here by courtesy of The Mitchell Library, Sydney

UNISURV REPORT NO S10, 1973

A Study of Zero Error and Ground Swing of the Model MRA101 Tellurometer

A.J. Robinson

Received November 1973

School of Surveying,
The University of New South Wales,
P.O. Box 1,
Kensington, N.S.W. 2033. Australia.

National Library of Australia
Card No. and SBN
0 85839 015 9

"THE TELLUROMETER AT OVENS

MEASURING TO CALLAGHAN"

ABSTRACT

The tellurometer* system of measurement was developed at the South African Council for Industrial and Scientific Research (by T.L. Wadley in 1956), Wadley *(1957 and 1958)*. The introduction of this electromagnetic distance meter was one of the major contributions made to the surveying profession in this century. As is the case in the development of most electronic instruments, several different models of tellurometers were produced to take advantage of modern electronic technology and components. The range of tellurometers now available include the MRA1 and MRA2 which use a ten centimetre carrier wave length, the MRA3, MRA101 and MRA301 which use a three centimetre carrier wave length and the MRA4 which uses an eight millimetre carrier wave length. With the introduction of the model MRA4 tellurometer, the problems associated with ground swing and zero error were almost if not entirely eliminated, however, there are still large numbers of the three centimetre instruments in use today and a market still exists for these instruments, hence the work covered in this report is still very useful and will help users of the three centimetre model MRA101 tellurometer obtain better results with their instruments.

The treatment of zero error and ground swing as covered in this work is covered in two complete sections; however, of necessity some sections must overlap. A general description of the instruments in the tellurometer range is given followed

---

* The lower case spelling of tellurometer will be used throughout this work to conform with the suggestion as set out in the supplement of the Canadian Surveyor, Vol. XVIII, No. 4 September 1964, pp. 332-333.

by a description of the equipment used in the experiments. Several modifications were made to the tellurometer equipment as supplied by the manufacturer and these modifications are described. The zero error has been thoroughly investigated and the experiments and results are given in the early chapters. To test the zero error results, measurements made in the ground swing experiments were used.

The study of ground swing is introduced in Chapter 5 and an experiment involving the changing of instrument height from about 1.5 metres to 30.5 metres is discussed. Chapter 6 continues with a study of ground swing and an experiment involving the change of instrument height over a range of 0.3 metres in order to find critical height is fully described. The remaining work covers experiments on field techniques used to reduce the observed ground swing, namely tilting the instrument and shielding the instrument using natural shields. The effect of instrument tilt on zero error is also discussed which is part of the overlap of zero error and ground swing that is mentioned above.

The conclusion of this work sums up very generally the results of the experiments into ground swing and zero error and suggests areas in which further research should be carried out.

CONTENTS

1. GENERAL INTRODUCTION

1.1 INTRODUCTION

Early in 1966 the School of Surveying of the University of New South Wales purchased three model MRA101 tellurometers, the latest available in the tellurometer range. The earlier ten centimetre carrier wave length tellurometers model MRA1 and MRA2 had exhibited a zero error that was cyclic and dependent on the A reading according to Poder et al *(1960)* and Lilly *(1963)*. With the introduction of the three centimetre carrier wave length tellurometer Model MRA3 Yaskowich *(1965)*, Bosler *(1964)*, Bosler et al. *(1965)* showed that the zero error was cyclic and dependent on the A reading but with a reduced amplitude compared with the earlier instruments. The model MRA101 tellurometer makes use of a three centimetre carrier wave length and is not identical with the model MRA3. A thorough investigation was carried out on zero error over two base lines using two different techniques. In addition investigations on ground swing for this instrument were also carried out.

1.2 THE RANGE OF TELLUROMETERS

A brief description of all tellurometers follows, but if greater detail of a particular instrument is required reference may be made to the bibliography or enquiries made to the manufacturers.

1.2.1 Model MRA1

The first tellurometer produced, model MRA1, operated with a carrier wave length of ten centimetres, a beam width of 20°, and the measurement was made between two instruments referred to as the Master and Remote. The Master and Remote instruments of the model MRA1 were separate units and their functions could not be interchanged.

The crystals used to produce the measuring frequencies were not thermostatically controlled, hence a temperature versus frequency calibration was necessary. The instrument measured the distance in time units which were displayed on a cathode ray oscilloscope. The range of the instrument was from about 120 metres to about 50 kilometres (manufacturer's value); however longer distances than this were successfully measured *(Rimington 1957)*. Investigations carried out with the equipment over a base line of approximately 122 metres (400 feet) by the designers, showed that the electrical centre (the point from which measurements are made) almost coincided with the plumbing centre. A small correction of the order of 0.06 metres was applied to each measurement. Further investigations into zero error were carried out and it was found that the zero error was cyclic and dependent on the A reading. *(Poder et al, 1960, and Lilly 1963)*.

1.2.2 Model MRA2

The Model MRA2 was the next instrument to be produced in the tellurometer range. The overall bulk of the model MRA1 was reduced by the application of transistors in some of the circuitry and the vibrator power pack was eliminated. Another major change was the introduction of interchangeability of the Master and Remote functions, each unit could then be used as the Master or Remote. The Model MRA2 made use of the ten centimetre carrier wavelength and the beam width was maintained at 20°. The readout was also similar to the model MRA1, being in time units and also displayed on a cathode ray oscilloscope. The measuring centre of the Model MRA2 coincided with the plumbing centre, supposedly eliminating the zero error. Investigation of the zero error revealed that it had a finite value and that this zero error was also cyclic and dependent on the A reading *(Poder et al,* *1960 and Lilly, 1963)*. This was to be expected as there was no great change in design of the Model MRA2 from the design of the Model MRA1.

As mentioned above, the Model MRA1 and the Model MRA2 operated on a carrier wave length of ten centimetres. The ground effects, i.e. the scattering of the waves radiating from the instrument could be reduced if the wavelength of the carrier was reduced *(Wadley 1958)* and it was for this reason that the Model MRA3, which operated with a three centimetre carrier wave length was produced.

1.2.3 Model MRA3

The model MRA3 tellurometer also introduced a new readout system. The cathode ray oscilloscope of the earlier models was replaced by a digital readout system in either time units (nano seconds) or international metres for a refractive index of 1.000325. The model MRA3 tellurometer is fully transistorised and is available with a built-in power supply operating from nickel cadmium (alkaline) cells. The beam width has been reduced to 9° and this reduced beam width, together with the reduction in carrier wavelength has greatly reduced the magnitude of the ground swing and because of this the model MRA3 has found wide use. All components used in this instrument are tested to military specifications, making the instrument very reliable. The crystals are ovened making temperature frequency calibration unnecessary. The manufacturer recommends that the instrument be calibrated for zero error and research has shown that a cyclic zero error is present but the magnitude of this error is smaller than that of the models MRA1 and MRA2 *(Bosler 1964, Yaskowich 1965 and Bosler et al. 1965)*.

1.2.4 Model MRA101

The need for a commercial model of the tellurometer was felt and in 1965 the Model MRA101 was produced. This model was similar to the MRA3 but the components were not subjected to the rigid tests of military specifications. The instrument operates with a three centimetres carrier wavelength and is provided with a digital readout in metres. The instrument is fully transistorised, the beam width is 6° and power supply is by means of an external battery. A full description of the instrument will be given in Section 2.1.

1.2.5 Model MRA301

This Model was produced at the request of the U.S. Department of Defence for use by the Departments of Army, Navy and Air Force. This instrument is basicly the Model MRA3, but utilising the improved antenna system of the Model MRA101. The components have been more rigidly tested and the temperature range of operation has been increased. This instrument is designed and built to withstand the rugged conditions found in military use.

1.2.6 Model MRA4

When the carrier wavelength of the tellurometers was reduced from ten centimetres to three centimetres, a considerable reduction in ground swing resulted and the accuracy of measurement was increased. A further reduction in carrier wavelength from three centimetres to eight millimetres was made possible because better quality and additional electronic components were available, and as a result of this the model MRA4 was produced. This instrument uses an eight millimetres carrier wavelength, and a larger diameter reflector has reduced the beam width to 2° which has virtually eliminated ground swing. The MRA4 has a resolution of one millimetre and the quoted standard deviation (manufacturer) is

±(0.3 cm + 3 ppm.S.), (where S is the distance being measured). The electrical centre and the plumbing centre are coincident and the zero correction does not seem to vary with the A reading *(Marshall, 1967 and Hall, 1967).*

2. EQUIPMENT

2.1 THE OPERATING PRINCIPLE OF THE TELLUROMETER MODEL MRA101

The tellurometer Model MRA101 is a fully transistorised instrument with a nominal carrier wavelength of three centimetres and a beam width at the half power points of 6°. The instrument makes use of a resolver and phase discriminator to give a direct readout in metres for a refractive index of 1.000 325. The electronic principles of this instrument will not be given here as they are fully described by Wadley *(1957 and 1958)*. The operational procedures are described in Appendix 1. The carrier frequency, which is generated by a Klystron oscillator, lies in the range 10 050 Mega Hertz to 10 450 Mega Hertz (MHz). This carrier frequency is modulated by the pattern frequencies whose values are shown in Table 2.1 (Manufacturer's values).

	MASTER		REMOTE
A	7.492 377 MHz	A	7.493 377 MHz
E	5.993 902	E	5.992 902
D	7.342 529	D	7.341 529
C	7.477 392	C	7.467 392
B	7.490 879	B	7.489 879
		Remote Ref.	7.491 377

Table 2.1

Two frequency calibration tests were carried out at the University of New South Wales School of Electrical Engineering. The results of these calibrations are given in Appendix 2.

A subtraction process is carried out in the measuring procedure to give the decimal components of the distance. The components are called A, E, D, C and B and give the following components of the distance

A - 10 metres
E - 100 metres
D - 1 000 metres
C - 10 000 metres
B - 100 000 metres

2.1.1 Description of the Model MRA101

The instrument (see Figure 2.1) is portable, dimensions 38 x 36 x 18 centimetres, total weight being about 17 kilograms without the power supply which is a 12 volt DC external battery. When the instrument is removed from the transit case the only mechanical operations necessary before a measurement can be commenced are

(i) connection to the 12 volt DC battery
(ii) connection of the headset, and
(iii) fitting the small mirror assembly to the R.F. head.

The controls can be described by reference to figure 2.1.

1. Headset connection.
2. Oven lamp. This light cycles between the on and off position when the crystals have reached the operating temperature.
3. Warm up switch, allows low tension voltage to be applied to the power unit and the transistor circuits.
4. Operate switch. This controls the Klystron high tension power.
5. 5 amp fuse.
6. 12 volt 5-pin battery connector.
7. AFC switch. This two-position switch allows a voltage to be applied to the Klystron for the purpose of automatically controlling the carrier frequency

relative to that of the other instrument. This switch is used in the 'IN' position for master operation and the 'OUT' position for remote operation, this being the only change necessary to reverse the functions of the instruments from master to remote.

8. Speak/measure switch. This switch selects either the measuring circuit or the speak circuit.

9. The pattern switch is a 12-way switch which controls the pattern frequencies. There are six frequencies for the remote settings and five for the master.

10. The null meter. This meter is used in conjunction with the circular dial readout unit (11).

11. The readout unit. This consists of a circular dial divided into ten major divisions which are each further subdivided into another ten divisions. There is a vernier scale provided behind this main scale enabling the scale to be observed to three figures. There is also a zero lock which when engaged to the main scale, holds this scale fixed, allowing the inner knurled knob to be turned.

12. The Monitor Meter. This meter is used in conjunction with the five way monitor switch (13).

13. Monitor switch. This five way switch is used to indicate battery voltage (BATT), mixer current (OUTPUT), received signal strength (SIG), tuning accuracy (TUNE), and modulation levels of the crystals (MOD). These indications are shown on the monitor meter (12).

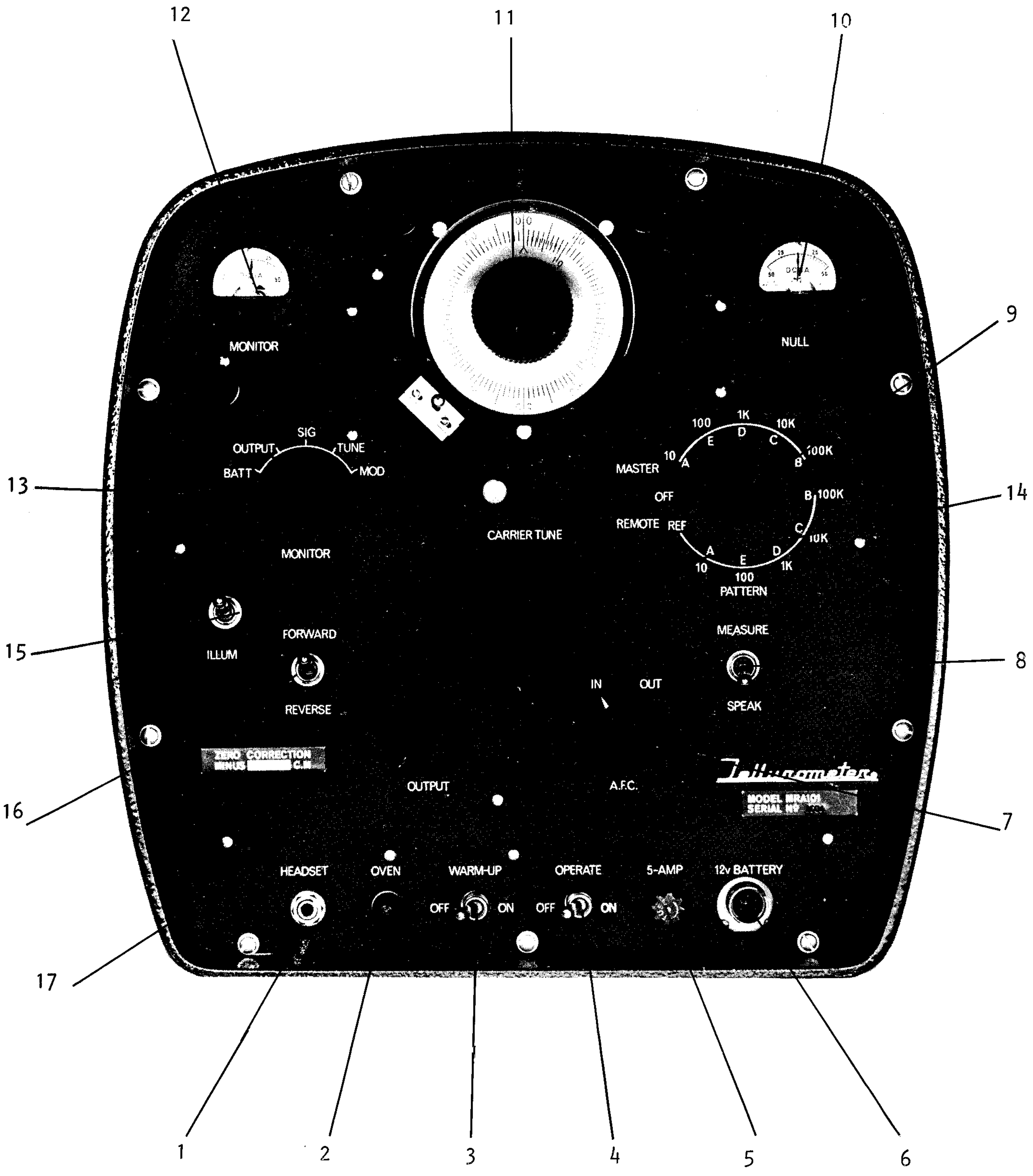
14. Carrier tune. This control knob is used to set a particular carrier frequency (Remote function) or to tune the Klystron to a particular remote setting (Master function). The particular setting is indicated by a number viewed in the small window above the knob. (See Figure 2.3)

15. Illumination. This switch controls the panel lights.
16. Forward, Reverse switch. This two-position switch is used to reverse the phase (i.e. change by 180°) of the measuring signal in the remote unit. Thus **eliminating instrumental error in the resolver circuit.**
17. Output. The output control is used in conjunction with the monitor meter when it is set to output. This control is adjusted for peak mixer current reading, which is in effect a measure of the output power from the Klystron.

The instructions for field operation of the instrument, field sheets and a reduction sheet are shown in Appendix 1.

2.1.2 Modifications

The tellurometer model MRA101 was modified slightly for use in the experiments. The carrier frequencies were shown by the numbers 0, 1, 2, 3, 4, 5, 6, and 7 (see Figure 2.2(a)) etched on a circular disc and viewed through a small window. Between each of these numbers there was a line indicating the ½ carrier settings but as no reference pointer was provided, a particular carrier frequency could not be set consistently on the instrument. The circular disc was removed and modified by etching additional marks on the disc. These marks consisted of a line through the number and a 'dot' placed to show the ¼ carrier settings. The number 0 was changed to 8 (see figure 2.2(b)). A knife edge pointer was placed behind the window in front of the scale so that a parallax free setting could be made on the graduated dial (see Figure 2.3). This modification was made so that the remote operator could set the same carrier tune setting throughout all measurements during the experiments. During the initial setting up of the instrument, difficulty


12
11
10
9
13
14
15
8
16
7
17
1
2
3
4
5
6
MONITOR
NULL
SIG
OUTPUT
TUNE
BATT
MOD
MONITOR
CARRIER TUNE
MASTER
OFF
REMOTE
REF
10
100
1K
10K
100K
A
E
D
C
B
PATTERN
ILLUM
FORWARD
REVERSE
MEASURE
SPEAK
IN
OUT
ZERO CORRECTION
MINUS C.M.
OUTPUT
A.F.C.
Tellurometer
MODEL MRA101
SERIAL NO
HEADSET
OVEN
WARM-UP
OFF
ON
OPERATE
OFF
ON
5-AMP
12v BATTERY

1

FIG 2.1

was experienced in pointing the instruments towards one another. A further modification was made in order to overcome this difficulty. A small sighting slot was cut in the metal plate, mounted on the bottom of the fibreglass case, in the direction of the antenna. Through this slot the other instrument could be viewed. This modification proved very useful in the setting up and centering of the instruments at each station of a short line.

It was planned to investigate the effect of tilting the instrument on the zero error and also to examine the change of ground swing when using the instrument on a line of known distance. The tripods provided with the instrument had Johnson heads which allow a tilting movement in a ball and socket device. This feature was not considered to be satisfactory for some of this experimental work for the following reasons:-

(1) The instrument is unstable at large instrument tilts because the centre of gravity of the instrument is high above the point of support.

(2) The plumbing centre changes when the angle of tilt is changed.

(3) When the Johnson head is released the instrument can move in all directions (except the vertical) so that the instrument cannot be replaced in its original position.

(4) The amount of tilt could not be measured easily.

A cradle was designed to allow the instrument to be rotated in azimuth and also to allow for a large tilt in the vertical plane. The cradle consisted of a U shaped frame attached to a levelling head with three footscrews. Figure 2.4 shows this cradle with the tellurometer clamped in position. The tops of the cradle were machined to take brass lugs fixed to the centre of each side of the fibre glass case of the tellurometer. A clamp was provided so that the instrument could be locked at a particular vertical angle. An azimuth clamp was also provided. The movement in azimuth and in the vertical plane can be seen in Figure 2.4.

In order to measure the amount of tilt a protractor was attached to the side of the tellurometer and a slot was cut in the corresponding side of the U shaped arm. A small fiducal mark was attached to the frame so that the tilt angle could be read off. The tilt can be read to 15 minutes of arc. As the fiducal mark is about one centimetre from the scale an observer must be very careful to avoid parallax. The cradle was provided with a spot bubble so that it could be levelled at each set up. To adjust the cradle so that at zero tilt the instrument was vertical, a theodolite was set to the side of the tellurometer and carefully levelled. The tellurometer was set to zero tilt and the front case of the tellurometer was brought into the vertical plane by means of the levelling screws of the cradle. The bubble was then adjusted and then kept with the particular tellurometer. It is interesting to note that Tellurometer (U.S.A.) have designed cradles very similar to the ones described above. The U.S.A. product appeared on the market after 1968 final year students at the University of New South Wales had used the cradles described here.

A further modification was made to the tripod to allow the instrument height to be changed by thirty centimetres. This is an attachment that is fixed to the top of a Wild tripod and consists of a circular tube which is allowed to slide in a circular clamp. The tube is graduated from 0 to 30 centimetres in five millimetre divisions and has a key way so that the azimuth of the tellurometer is not altered when the height of the tellurometer is changed (see Figure 2.5). This attachment was made especially for the critical height studies and has proved very successful although the height change is limited to thirty centimetres. The method of use will be discussed in Section 7.4.

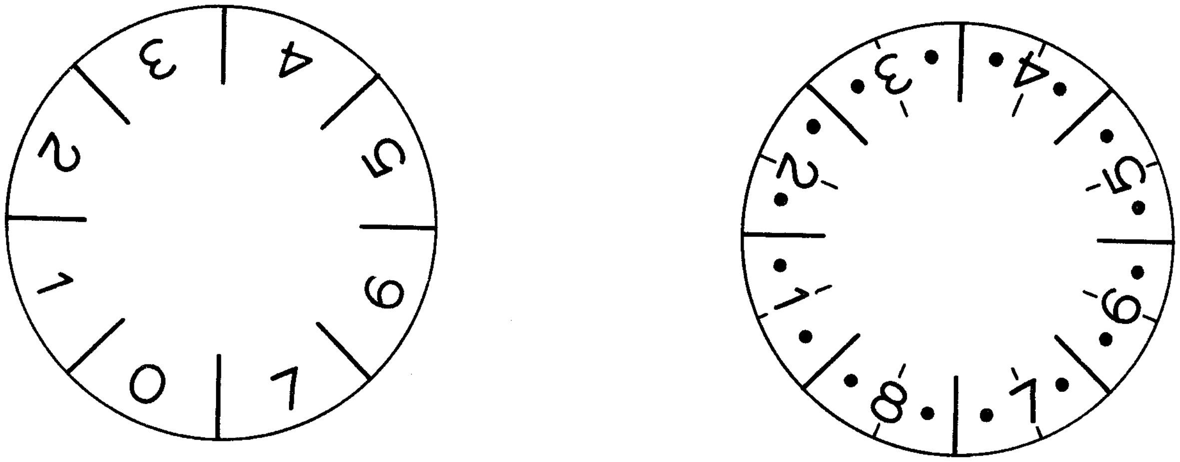
2.2 METEOROLOGICAL INSTRUMENTS

2.2.1 Aneroid Barometer

The barometers used to measure the atmospheric pressure, for refractive index determination, throughout the experimental work were "Baromech aneroid barometers". This barometer (see Figure 2.6) is of the contact type and is considered to be the best available. Pressure is read directly to 0.05 mm Hg. A full description of this barometer is given by Allman *(1968)*. Both before and after the barometers were used in the field they were calibrated against a Fortin Barometer housed in the Astronomical Laboratory of the School of Surveying. Any corrections so found were applied to the field readings before the refractive index was calculated.

2.2.2 Psychrometer

The psychrometer used to measure the dry and wet bulb temperature was a mechanically operated "Assmann's Aspiration Psychrometer" (see Figure 2.7). The thermometers are graduated to 1°C and readings were estimated to 0.2°C. The thermometers were calibrated by the National Standards Laboratory, Sydney, and the results of this calibration are shown in the report in Appendix 3. From the report it can be seen that the largest corrections are -0.5 deg.C at 0 deg.C and +0.3 deg.C at 25.3 deg.C.



(a) (b)

FIG. 2.2

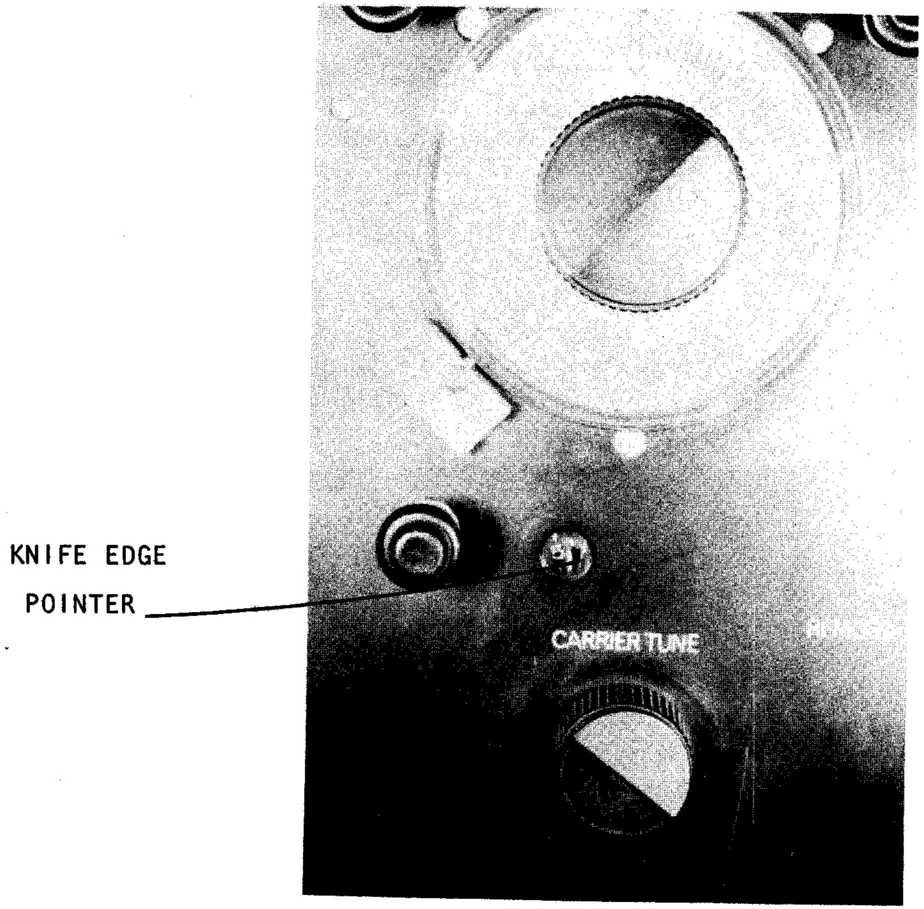


FIG. 2.3

FIG. 2.4

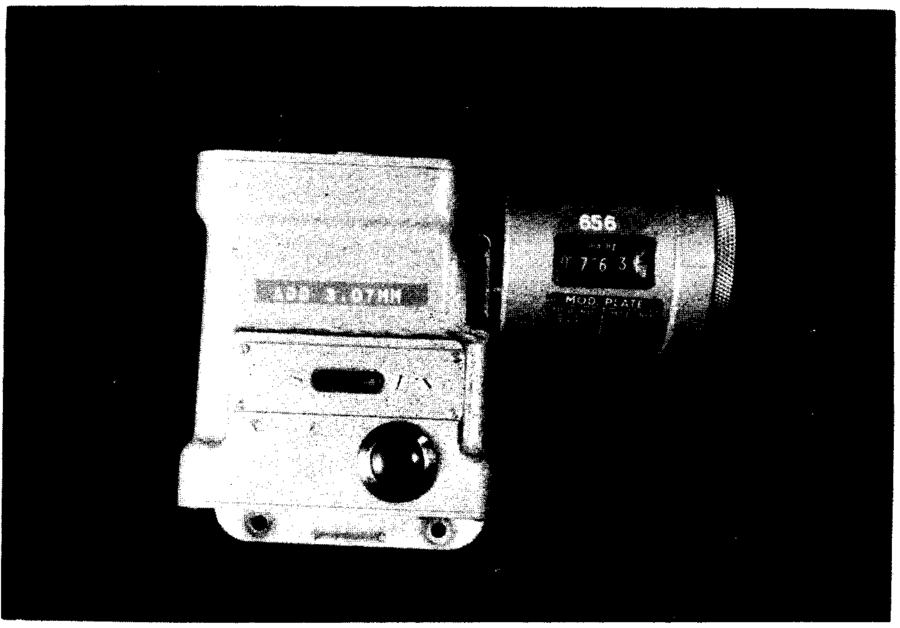


FIG. 2.6

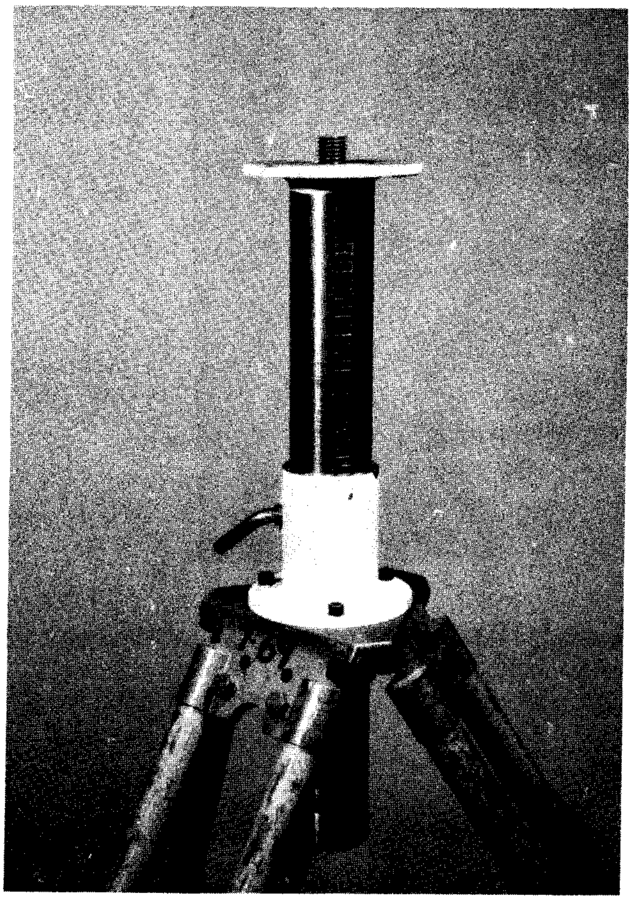


FIG. 2.5

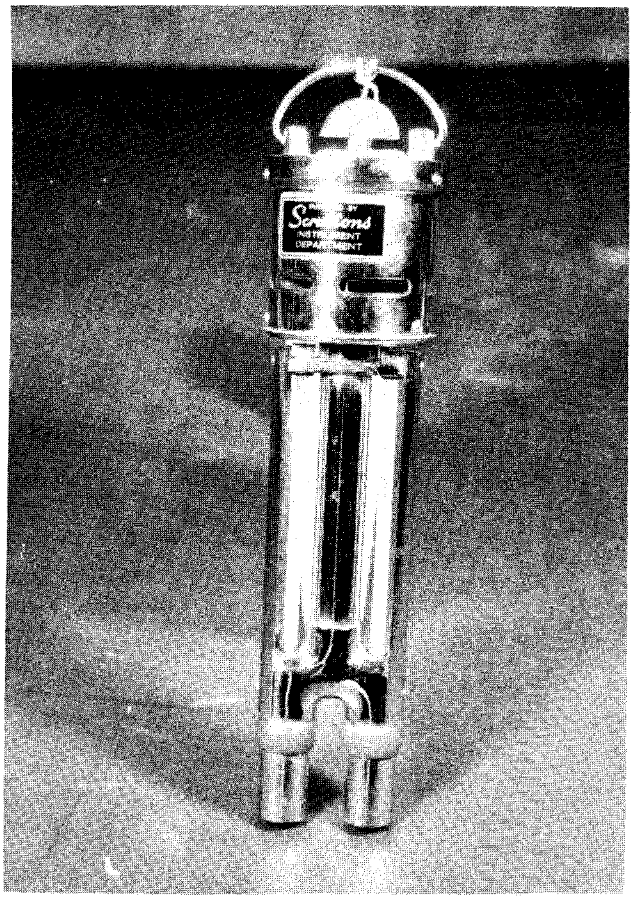


FIG. 2.7

3. TEST AREAS AND FIELD MEASUREMENTS

3.1 INTRODUCTION

Several experiments were contemplated when the University received the tellurometers. The manufacturer recommended that the instruments be calibrated for zero error and as previous instruments had exhibited a zero error that was cyclic *(Poder et al, 1960; Lilly, 1963; Yaskowich, 1965; Bosler, 1964 and Bosler et al, 1965)*, the zero error calibration was considered to be most important. Ground swing experiments were also contemplated over a short line which exhibited a reasonably constant surface condition.

3.2 THE TEST AREAS

3.2.1 Warwick Farm

The test area sought was a large open field of level topography, preferably with controlled public access. The intention was to measure a base line of about 200 metres, free from obstruction on both sides of the base. This area had to be close to Sydney because of difficulties of transporting staff and equipment.

The Australian Jockey Club offered the use of the No. 2 Polo Field at Warwick Farm, which is about 20 kilometres west of Sydney. This area (see Figures 3.1 and 3.4) is relatively level and is covered with grass about four to six centimetres high. Public access is controlled and the chosen base line is free from obstruction on either side with the exception of a tree and three fence posts about one metre high. The base line has an azimuth of 48° and is at an elevation of five metres above Standard Datum.

The terminal points, South Base and North Base are stainless steel pins set in a concrete block about 0.6 metres x 0.6 metres x 0.6 metres cast in situ and covered with a cast iron cover box. The base line was measured by the New South Wales Department of Lands. The equipment used for the measurement was Watts Standard Traversing Equipment which included a standardised 200 feet, $\frac{1}{8}$ inch invar band. The weather conditions for the measurement were calm, overcast, with very light rain and a temperature range of $20^{\circ}C$ to $22^{\circ}C$. The length between the terminal points was found to be 182.694 metres and is considered to be accurate to better than 1 part in 50,000.

At the northern end of the base line, nine additional marks were placed (see Figure 3.1), approximately one metre apart, to give a total of ten points which, when used in conjunction with South Base, gave ten base lines. These additional points were centre punch marks in tacks in 8 cm x 8 cm x 40 cm wooden pegs driven flush with the surface. Each time the nine auxiliary points were used the distances between them and North Base were measured. This precaution was taken in order to determine whether any of the pegs had been moved. The measured distances were then added to or subtracted from the base length in order to obtain the length of the auxiliary base line. The greatest difference between measurements from the same peg to North Base on different days was two millimetres.

3.2.2 Curl Curl

The test area at Curl Curl was chosen to calibrate the tellurometers over a base line whose length was not accurately known. This was done because many tellurometers users may not have the facility of an accurately known base line for instrument calibration. The base line was chosen along the beach front at Curl Curl to the north of Sydney (see Figure 3.2). A line was selected about 780 metres long, over gently undulating sand ridges covered with grass up to about 0.3 metres high. This area was well suited for the experiment as public access was limited and each station on the base line was easily accessible to the vehicles transporting the equipment. There were no obstructions along the length of the line and the ground swing for each measurement was not excessive. The maximum observed ground swing was 0.13 m and the minimum 0.08 m. The average value was 0.10 m. The terminal points and the four intermediate points (placed on line) were each marked by a centre punch mark in a tack in a 5 cm x 10 cm x 40 cm wooden survey peg driven flush with the ground. The six points so marked, A, B, C, D, E, and F gave the required base line AF and the five sections AB, BC, CD, DE, and EF. These marks were considered to be stable provided the six lines were measured on the same day. Peg A was found to be disturbed by about ten centimetres over one night but this did not affect the experiment as peg A was used in the new position for two further sets of measurements which were considered independently from observations on other days.

3.3 FIELD OBSERVATIONS

3.3.1 Tellurometer Measurements

Most tellurometer determinations of distance in this report were taken with the following procedure. The tellurometer was centred by means of a theodolite set at 90° to the line being measured. The instruments were directed towards one another by sighting through the small sighting slot and then a point on the screw used to hold the instrument on the tripod just below the tripod top was plumbed by means of the theodolite. This process was repeated until the other instrument was seen to lie in the centre of the field of view of the slot and the point on the screw was centred over the ground mark. This method was tested and the results showed that the instrument could be reset to within three millimetres. A conservative estimate of the standard deviation of centering of two millimetres (2 mm) was adopted. A determination of distance consisted of the mean of two measurements, one made with instrument No. 110 as Master, the other with instrument No. 11[illegible] as Master. Twenty fine readings were taken at ½ carrier tune settings. For each measurement the same remote carrier tune settings were used, thus giving true repetitive measurements.

3.3.2 Meteorological Observations.

Meteorological observations were taken before and after each set of fine readings at one end for the short line work and at both ends for the longer line work with the equipment described in Section 3.2. The refractive indices were then calculated from a nomogram, see figure 3.3, and the mean of the two refractive indices being accepted as the refractive index for the measurement. The range in the calculated refractive index for the work at the Warwick Farm base was 1.000 339 to 1.000 400. The largest correction from this source was 14 mm for the 183 m base line. The refractive index range at Curl Curl was of the same order being 1.000 308 to 1.000 387 but because the base line was much longer, viz. 780 m, this amounted to a correction of 48 mm.

3.4 CORRECTIONS

All the measurements determined by the tellurometers were corrected for -

1) Refractive Index
2) Slope
3) Sea Level
4) Arc to Arc

3.4.1 Refractive Index

As mentioned in Section 3.3.2 meteorological observations were taken in order that the refractive index for the particular measurement could be determined. The refractive indices were taken from a nomogram produced by the Trigonometrical Survey Office, Mowbray, Cape, South Africa (see Figure 3.3).

3.4.2. Slope

The slope reduction was calculated for all lines measured using the expression,

$$\text{slope correction} = -\frac{h^2}{2D} - \frac{h^4}{8D^3} - \dots\dots\dots\dots$$

where h = height difference between the terminals

and D = slope distance.

The difference in height was found by spirit levelling between the two instrument stations. A profile of the Warwick Farm base is shown in Figure 3.4 and the reduced levels (assumed datum) for the Curl Curl base are shown in Table 3.1.

Point	R.L. Metres (assumed)
A	30.00
B	28.83
C	28.18
D	28.00
E	28.24
F	28.90

Table 3.1

The slope corrections calculated using the above values was 2 mm for the Warwick Farm base provided the instruments were set at about the same instrument height and a correction of up to 5 mm for the Curl Curl base

3.4.3 Sea Level

As the tellurometer measurements were taken at elevations of about five metres above mean sea level the reduction to sea level correction was negligible.

3.4.4 Arc to Arc

The arc to arc correction for the tellurometer measurements was also negligible because of the short length of lines.

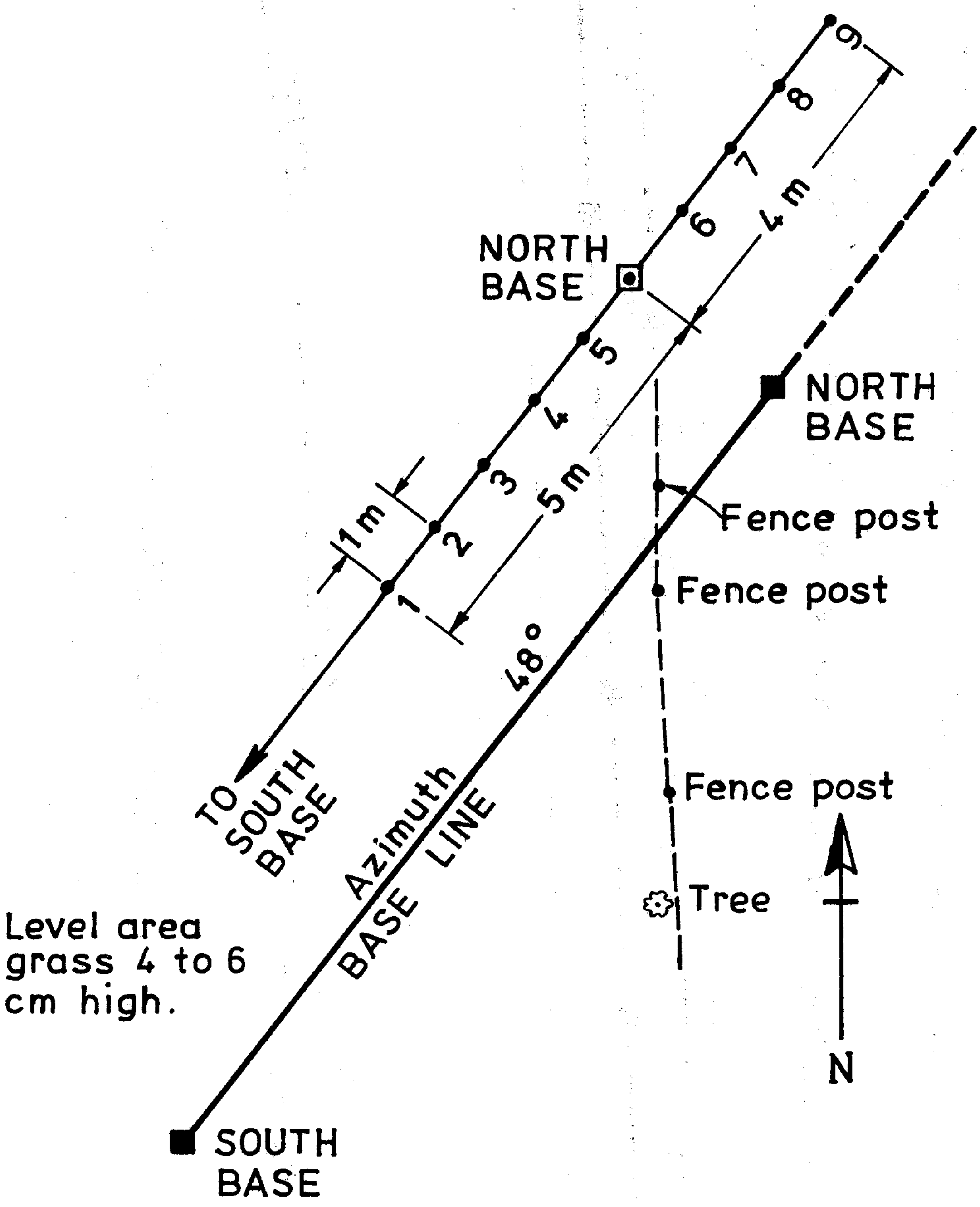


DIAGRAM OF BASE LINE - WARWICK FARM

FIG. 3·1

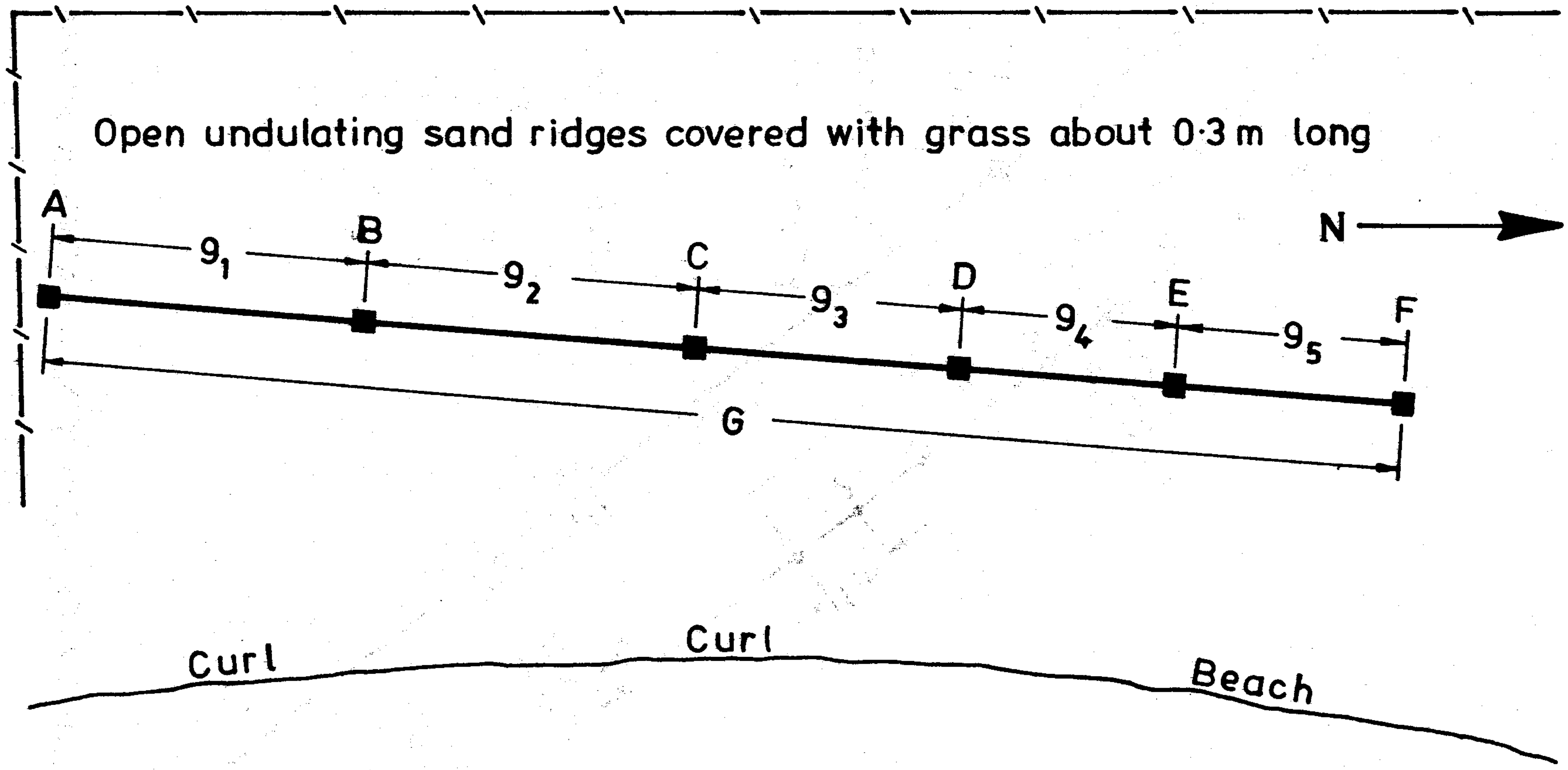
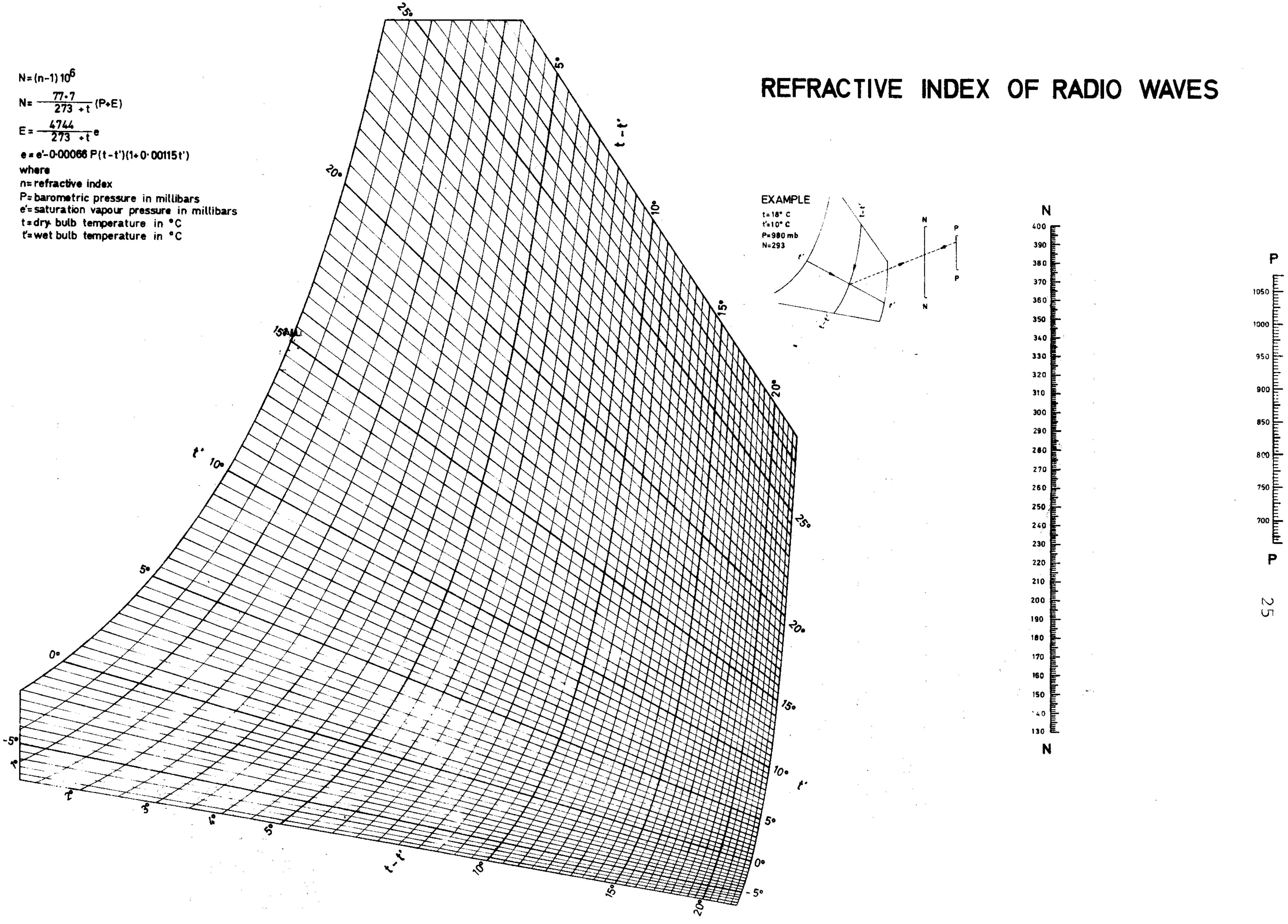


DIAGRAM OF BASE LINE — CURL CURL

FIG. 3·2

REFRACTIVE INDEX OF RADIO WAVES



$N = (n-1)\,10^6$

$N = \frac{77{\cdot}7}{273 + t}(P+E)$

$E = \frac{4744}{273 + t}e$

$e = e' - 0{\cdot}00066\,P(t-t')(1+0{\cdot}00115\,t')$

where

n = refractive index

P = barometric pressure in millibars

e' = saturation vapour pressure in millibars

t = dry bulb temperature in °C

t' = wet bulb temperature in °C

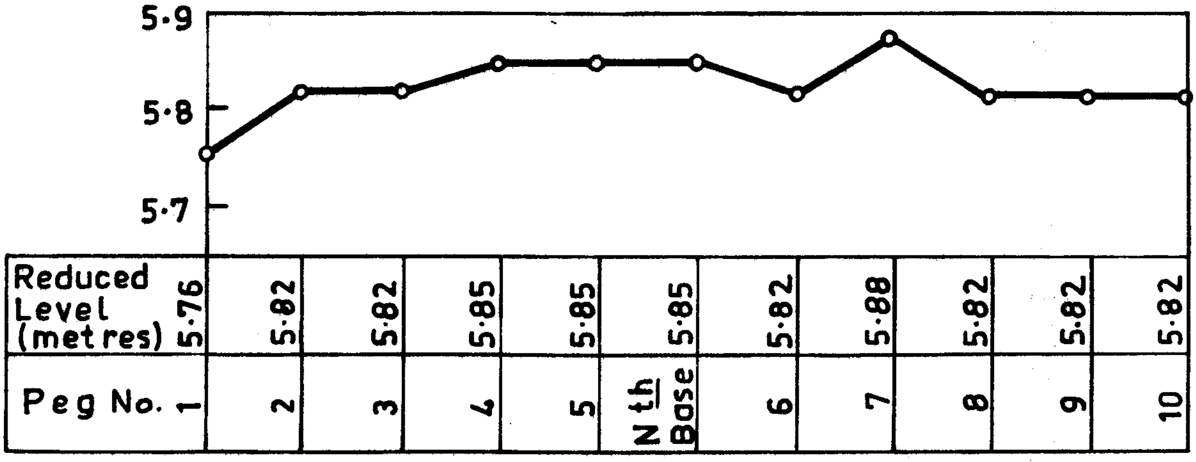
EXAMPLE

t = 18° C

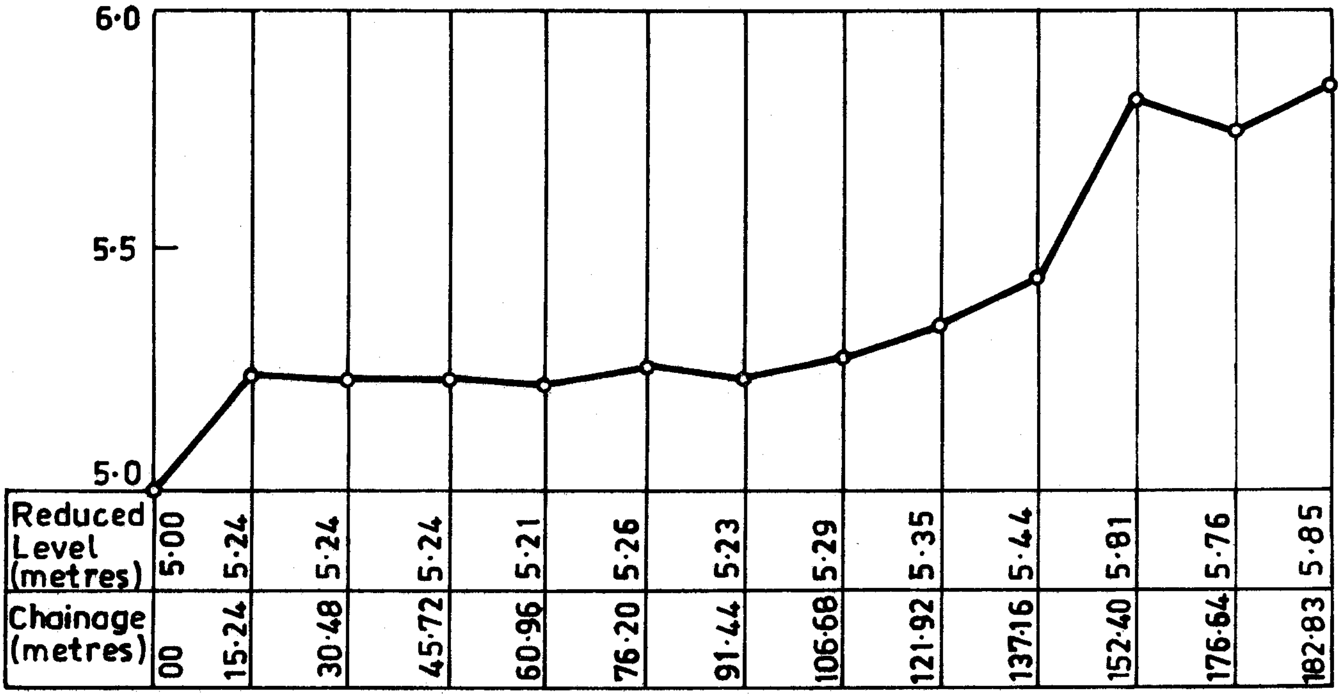
t' = 10° C

P = 980 mb

N = 293



Profile of Pegs at North Base



Profile of Warwick Farm Base Line

FIG. 3·4

4. ZERO CORRECTION

4.1 WARWICK FARM BASE

The five tellurometer measurements of each of the ten base lines at the Warwick Farm site are shown in Table 4.1. The accepted tellurometer length for the individual base lines is found from the mean of the five measurements. The adopted length (from invar band measurement) of each of the base lines is shown as the "adopted length" entry on the table. The difference between the tellurometer length and the adopted length gives the zero correction which is shown in the Table. The last entry in the table is the standard deviation of a single observation.

Figure 4.1 shows the zero correction graphed against the tellurometer A reading. It appears from the graph that the zero correction is cyclic and depends on the A reading. A least squares curve was fitted to the zero correction results according to the following theory.

Let y = the zero correction.

Then according to Figure 4.2

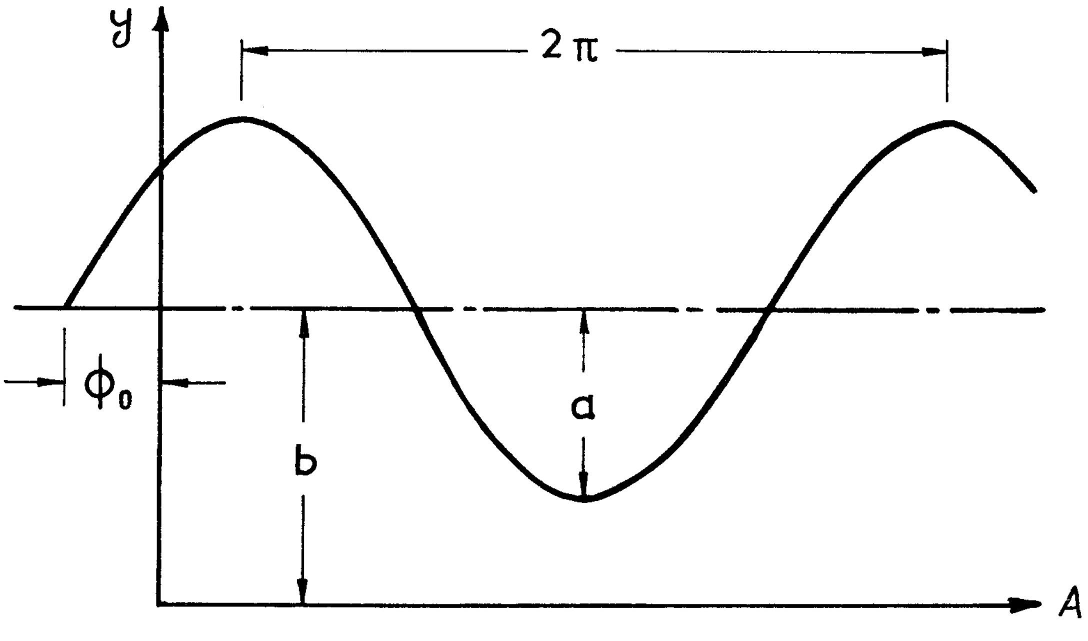


FIG. 4·2

$$y = -\{b + a \sin (\frac{2\Pi A}{10} + \phi_o)\} \qquad \ldots 4.$$

where b = constant

a = amplitude

ϕ_o = phase shift

and A = A reading of tellurometer in metres

From Table 4.1, $b = 34.60$ cm

This is the mean of the zero errors. See page 31 for explanation.

Differentiation of equation 4.1 with respect to a and ϕ_o gives

$$-\delta y = \sin (\frac{2\pi A}{10} + \phi_o)\ \delta a + a \cos (\frac{2\pi A}{10} + \phi_o)\ \delta\phi_o.$$

Let $\Delta y = y_m - y_c$

$\therefore\ \Delta y = P\delta a + Q\delta\phi_o$ where y_m = zero correction measured

y_c = zero correction calculated

$P = \sin (\frac{2\pi A}{10} + \phi_o)$

$Q = \cos (\frac{2\pi A}{10} + \phi_o)$

Now let $a = 1.0$ cm

$\phi_o = 80^o$ ... 1st approximation

then $y_c = -(34.60 + 1.0 \sin (\frac{2\pi A}{10} + 80^o))$

and $P = \sin (\frac{2\pi A}{10} + 80^o)$

$Q = \cos (\frac{2\pi A}{10} + 80^o)$

Using the values from tables 4.1 and 4.2 parametric equations of the form $P\delta a + Q\delta\phi_o - \Delta y = 0$ can be written as follows

$P\delta a$ A	$Q\delta\phi_o$ B	Abs C	Sum S
+0.99	+0.14	-0.19	+0.94
+0.88	-0.47	-0.30	+0.11
+0.45	-0.90	+0.24	-0.21
-0.17	-0.99	-0.35	-1.51
-0.71	-0.71	-0.80	-2.22
-0.99	-0.16	-0.10	-1.25
-0.89	+0.45	+0.23	-0.21
-0.46	+0.89	+0.71	+1.14
+0.17	+0.98	-0.33	+0.82
+0.71	+0.70	+0.87	+2.28
[AA]	[AB]	[AC]	[AS]
+5.007	+0.004	+0.413	+5.424
	[BB]	[BC]	[BS]
	+5.006	+1.850	+6.860

where [ ] indicates the sum of.

From these equations the normal equations can be formed.

$$+5.007\delta a + 0.004\delta\phi_o + 0.413 = 0$$
$$+0.004\delta a + 5.006\delta\phi_o + 1.850 = 0$$

Solution of the normal equation gives

$\delta a = -0.08$ and

$\delta\phi_o = -0.37.$

$$\text{Let } a_1 = a + \delta a = 1.00 - 0.08 = 0.92$$
$$\text{and } \phi_{o1} = \phi_o + \delta\phi_o = 80^\circ - 21^\circ = 59^\circ,$$

substituting these values in equation 4.1 gives

$$y = -\{34.6 + 0.92 \sin (\frac{2\pi A}{10} + 59^\circ)\} \text{ cm} \qquad \ldots 4.2$$

where y = zero correction.

Equation 4.2 has been calculated (see Table 4.3) and is shown in Figure 4.3 together with the original zero correction results.

Another method by which a curve can be fitted to the zero error results is given below. This method assumes that the change in A readings is a constant, in the case $\frac{2\pi}{10}$ i.e. 36°.

Let y be the observed zero correction at intervals of x where $x = \alpha + \frac{2\ell\pi}{n}$ where n is the total number of measurements,

$\ell = 0, 1 \ldots, n - 1$ and α = the first A reading, (in this case A = 0.058, i.e. $\frac{2\pi A}{10} \simeq 2^\circ$).

The curve is assumed to be sinusoidal of period 2π which can be represented by

$$y = -\{b + a \sin (x + \phi_o)\} \qquad \ldots (1)$$

where b, a and ϕ are unknown constants.

Expanding (1) gives

$$y = -\{b + a \sin x \cos \phi_o + a \cos x \sin \phi_o\} \qquad \ldots (2)$$

Put $a \sin \phi_o = X$ and $a \cos \phi_o = Y$ and substitute in (2) giving

$$y = -\{b + X \cos x + Y \sin x\}$$

Therefore correction equations will be of the form

$$v_i = -\{b + X\cos x + Y\sin x\} - (-y_i)$$

where $i = 1, 2, \ldots, n$

Forming normal equations

A	X	Y	abs	0
n	$[\cos x]$	$[\sin x]$	$-[y]$	
	$[\cos^2 x]$	$[\sin x \cos x]$	$+[y\cos x]$	
		$[\sin^2 x]$	$-[y\sin x]$	

It may be proved that $[\cos x] = [\sin x] = [\sin x \cos x] = 0$ and $[\cos x] = [\sin x] = {}^{n}/_{2}$ according to Whittaker and Robinson *(1944)*

$$\therefore\ b = \frac{[y]}{n} \qquad x = \frac{[y\cos x]}{[\cos^2 x]} \qquad Y = \frac{[y\sin x]}{[\sin^2 x]}$$

$$\text{then } \tan\phi_o = \frac{X}{Y} = \frac{[y\cos x]}{[y\sin x]}$$

$$a = \frac{X}{\sin\phi_o} = \frac{Y}{\cos\phi_o}$$

If the zero correction results from table 4.1 are considered and if the assumption is made that the A readings are 36^o apart then table 4.4 shows the calculations to give

$$X = \frac{(y\cos x)}{5} = \frac{4.15}{5} = 0.83$$

$$Y = \frac{(y\sin x)}{5} = \frac{2.65}{5} = 0.53$$

$$\tan \phi_o = \frac{X}{Y} \quad \therefore \quad \phi_o = 57^\circ.5$$

$$\text{and } a = 0.98$$

$$\text{and } b = \left(\frac{346.00}{10} \right) = 34.6$$

$$\text{i.e. } y = -\{34.6 + 0.98 \sin (\frac{2\pi A}{10} + 57^\circ.5)\} \text{ cm} \qquad \dots 4.3$$

If equation 4.3 is compared to equation 4.2 it can be seen that both the amplitude and phase angle are slightly different. This difference is very small and will not greatly affect the calculation of the zero correction. The difference is to be expected as the A readings used in the zero correction determination were not exactly 36° apart.

4.2 CURL CURL BASE

The method of zero error determination used on the Curl Curl base is particularly convenient when an accurately measured base line is not available for comparison. This method assumes that the zero error is a constant. The Curl Curl base line (AF, Figure 3.2) was divided into five sections so that the measured lengths of these sections and the length AF were not the same, i.e. the A reading on each line was different. This technique was used to sample the zero error over part of the A reading range (0 m to 10 m) of the instrument. The pegs defining these lines were considered to be stable for a day's measurement and the six lines were measured on the one day to give a "set" of results. To eliminate any systematic error of centering the six lines were measured five times, re-centering the instrument after each measurement. The tellurometers were not used consistently at the same end of the lines and the measurements of the lines were made in as varied weather conditions as possible. The five tellurometer measurements of the six base lines is shown in Table 4.5 The last entry in the Table is the zero error derived from the following theory.

Let the true length of the six lines be given by

$AF = G$

$AB = g_1$

$BC = g_2$

$CD = g_3$

$DE = g_4$

$EF = g_5$

Then $G = \sum_{i=1}^{5} g_i$ See Figure 3.2

Let the zero error of the tellurometer be constant and equal to Δ. The value for the **six** lines as indicated by the tellurometer would be

$(G + \Delta)$ and $(g_i + \Delta)$ $(i = 1, 5)$

$$\text{Then} \quad (G + \Delta) = \sum_{i=1}^{5} (g_i + \Delta) - (i - 1)\,\Delta.$$

$$\text{from which} \quad \Delta = \sum_{i=1}^{5} \frac{(g_i + \Delta) - (G + \Delta)}{(i - 1)}$$

A mean of the **five** values calculated as above gives a value of -0.324 metres for the zero correction.

4.3 TEST OF ZERO CORRECTION VALUES

The values of the zero correction can be summarised as follows (see Table 4.6).

1) Manufacturer's value -0.30 metres. This value is recommended by the manufacturer and is simply stated, no information is given as to how this value is calculated.

2) The cyclic value. This value was derived from the Warwick Farm base.

$$y = -\{0.346 + 0.009 \sin (\frac{2\pi A}{10} + 59^\circ)\} \text{ metres}$$

3) The constant value determined from the Curl Curl experiment as -0.324 metres.

The cyclic zero correction can be further simplified into two parts,

a) a constant value of -0.346 metres and

b) the cyclic value of $-(0.009 \sin (\frac{2\pi A}{10} + 59^\circ))$m.

The cyclic part has a maximum value of about one centimetre and as the average value of the standard deviations from the Warwick Farm measurements is 2.45 cm this cyclic part may be masked by the uncertainty of the measurements. In the testing of the zero corrections a further constant value of -0.346 metres (made up of the constant part of the cyclic value) is tested. The lines measured in the tower experiments, (see section 5.3) were used to test the various zero corrections. It should be noted that the use of these results is not conclusive as the range in A reading is from 2.8 metres to 5.4 metres. Reference to Figure 4.3 shows that if A readings (2.5 to 5.5) are used, then the relationship of the fitted curve to the actual curve is reasonably representative of the whole curve. The test of the four values of zero correction was conducted as follows. The standard deviations of the measurements were calculated from the differences between tellurometer distance, calculated using the four different zero corrections, and the adopted distance. The results of these calculations together with the zero correction used is shown in Table 4.6.

4.4 CONCLUSION

From the foregoing experiments and tests some very important conclusions can be drawn.

It is most important that users of the Model MRA101 tellurometers calibrate the instruments for zero correction.

The experiments show that the zero correction for this Model tellurometer is cyclic and dependent on the A reading, however the amplitude of the cyclic term is small and of the order of one centimetre. It can also be seen from Table 4.6 that application of the cyclic correction greatly reduces the standard deviation of the measurement from that calculated using the manufacturer's constant value. An important fact however is that if the cyclic component of the zero correction is ignored, then the standard deviation calculated is very similar to that value calculated using the complete cyclic expression. Theoretically it would be possible to make observations with the A readings satisfying the conditions of $(\frac{2\pi A}{10} + 59^{o}) = 0^{o}$ or 180^{o} i.e. $A = 3.36$m or 8.36m for these particular instruments. However, this presupposes a prior determination of the phase shift, but for normal use of these instruments this may well be impractical.

Reference to Table 4.6 shows that the standard deviation calculated from the Curl Curl experiment is an improvement on the value calculated from the manufacturer's zero correction. It must be pointed out that in the Curl Curl experiment the zero correction was assumed constant. For the whole and individual sections of the Curl Curl base line different A readings were used and thus the effect on the results by the cyclic component of the zero correction was considerably reduced.

Base line	1	v	2	v	3	v	4	v	5	v
Tellurometer measurements	178.011	+.044	179.003	+.041	180.029	+.029	181.019	+.034	182.004	+.038metres
	.040	+.015	.032	+.012	.046	+.012	.032	+.021	.027	+.015
	.066	-.011	.033	+.011	.044	+.014	.053	0	.046	-.004
	.080	-.025	.068	-.024	.086	-.028	.080	-.027	.076	-.034
	.078	-.023	.086	-.042	.084	-.026	.080	-.027	.057	-.015
Mean	178.055		179.044		180.058		181.053		182.042	
Adopted length	177.704		178.700		179.700		180.695		181.694	
Zero Correction	- 0.351		- 0.344		- 0.358		- 0.358		- 0.348	
Standard deviation of a single observation	±0.029		±0.033		±0.026		±0.027		±0.028	
Base line	Base	v	6	v	7	v	8	v	9	v
Tellurometer measurements	183.012	+.030	184.006	+.026	184.997	+.024	185.996	+.019	186.996	+.013metres
	.023	+.019	.012	+.020	.999	+.022	186.005	+.010	.992	+.017
	.048	-.006	.032	0	185.028	-.007	.013	+.002	187.002	+.007
	.061	-.019	.060	-.028	.043	-.022	.025	-.010	.027	-.018
	.065	-.023	.050	-.018	.038	-.017	.036	-.021	.029	-.020
Mean	183.042		184.032		185.021		186.015		187.009	
Adopted length	182.694		183.685		184.684		185.680		186.675	
Zero Correction	- 0.348		- 0.347		- 0.337		- 0.335		- 0.334	
Standard deviation of a single observation	±0.023		±0.024		±0.022		±0.015		±0.018	

Table 4.1

A reading	$\left(\frac{2\pi A}{10}+80^\circ\right)$	P	Q	y_c (cm)	y_m (cm)	$\Delta y=y_m-y_c$
0.058	82° 05'	+0.990	+0.138	35.59	35.78	+0.19
1.053	117 54	+0.884	-0.468	35.48	35.78	+0.30
2.042	153 31	+0.446	-0.895	35.05	34.81	-0.24
3.042	189 30	-0.165	-0.986	34.43	34.78	+0.35
4.032	225 09	-0.709	-0.705	33.89	34.69	+0.80
5.021	260 46	-0.987	-0.160	33.61	33.71	+0.10
6.015	296 32	-0.895	+0.447	33.71	33.48	-0.23
7.009	332 20	-0.464	+0.886	34.14	33.43	-0.71
8.055	9 59	+0.173	+0.985	34.77	35.10	+0.33
9.044	45 36	+0.714	+0.700	35.31	34.44	-0.87

Table 4.2

A reading	$\left(\frac{2\pi A}{10}+59^\circ\right)$	$\sin\left(\frac{2\pi A}{10}+59^\circ\right)$	$0.92\sin\left(\frac{2\pi A}{10}+59^\circ\right)$	$34.6+0.92\left(\frac{2\pi A}{10}+59^\circ\right)$
0.058	61 05	+0.875	+0.81	35.41
1.053	96 54	+0.993	+0.91	35.51
2.042	132 31	+0.737	+0.68	35.28
3.042	168 30	+0.199	+0.18	34.78
4.032	204 09	-0.409	-0.38	34.22
5.021	239 46	-0.864	-0.79	33.81
6.015	275 32	-0.995	-0.92	33.68
7.009	311 20	-0.751	-0.69	33.91
8.055	348 59	-0.191	-0.18	34.42
9.044	24 36	+0.416	+0.38	34.98

Table 4.3

i	y	x	sin x	cos x	y sin x	y cos x
1	35.78	2°	+0.035	+0.999	+ 1.25	+35.74
2	35.78	38°	+0.616	+0.788	+22.04	+28.19
3	34.81	74°	+0.961	+0.276	+33.45	+ 9.61
4	34.78	110°	+0.940	-0.342	+32.69	-11.89
5	34.69	146°	+0.559	-0.829	+19.39	-28.76
6	33.71	182°	-0.035	-0.999	- 1.18	-33.68
7	33.48	218°	-0.616	-0.788	-20.62	-26.38
8	33.43	254°	-0.961	-0.276	-32.13	- 9.23
9	35.10	290°	-0.940	+0.342	-32.99	+12.00
10	34.44	326°	-0.559	+0.829	-19.25	+28.55
$\sum$	346.00				+ 2.65	+ 4.15

Table 4.4

LINE	MEASUREMENT 1	MEASUREMENT 2	MEASUREMENT 3	MEASUREMENT 4	MEASUREMENT 5
A F $(G + \Delta)$	779.608 metre	779.608 m	779.600 m	779.738 m	779.772 m
A B $(g_1+\Delta)$	183.754	183.759	183.756	183.860	183.870
B C $(g_2+\Delta)$	190.380	190.380	190.380	190.382	190.402
C D $(g_3+\Delta)$	151.498	151.501	151.502	151.506	151.530
D E $(g_4+\Delta)$	126.990	126.988	126.994	126.987	127.038
E F $(g_5+\Delta)$	128.252	128.253	128.259	128.277	128.304
$\sum_{i=1}^{5} (g_i+\Delta)$	780.874	780.881	780.891	781.012	781.144
$(G+\Delta)$	779.608	779.608	779.600	779.738	779.772
$\sum_{i=1}^{5} (g_i+\Delta)-(G+\Delta)$	1.266	1.273	1.291	1.274	1.372
Δ	0.316	0.318	0.323	0.318	0.343

$$\therefore \quad \Delta = \frac{\sum_{i=1}^{5} (g_i+\Delta)-(G+\Delta)}{i-1}$$

Table 4.5

ZERO CORRECTION	STANDARD DEVIATION (from tower measurements)
-0.30 metres (manufacturers value)	±0.066 metres
$-(0.346+0.009\sin(\frac{2\pi A}{10}+59^{o}))$ m (cyclic value)	±0.029 m
-0.346 m (constant term of cyclic value)	±0.030 m
-0.324 m (constant value from Curl Curl base line)	±0.046 m

TABLE 4.6

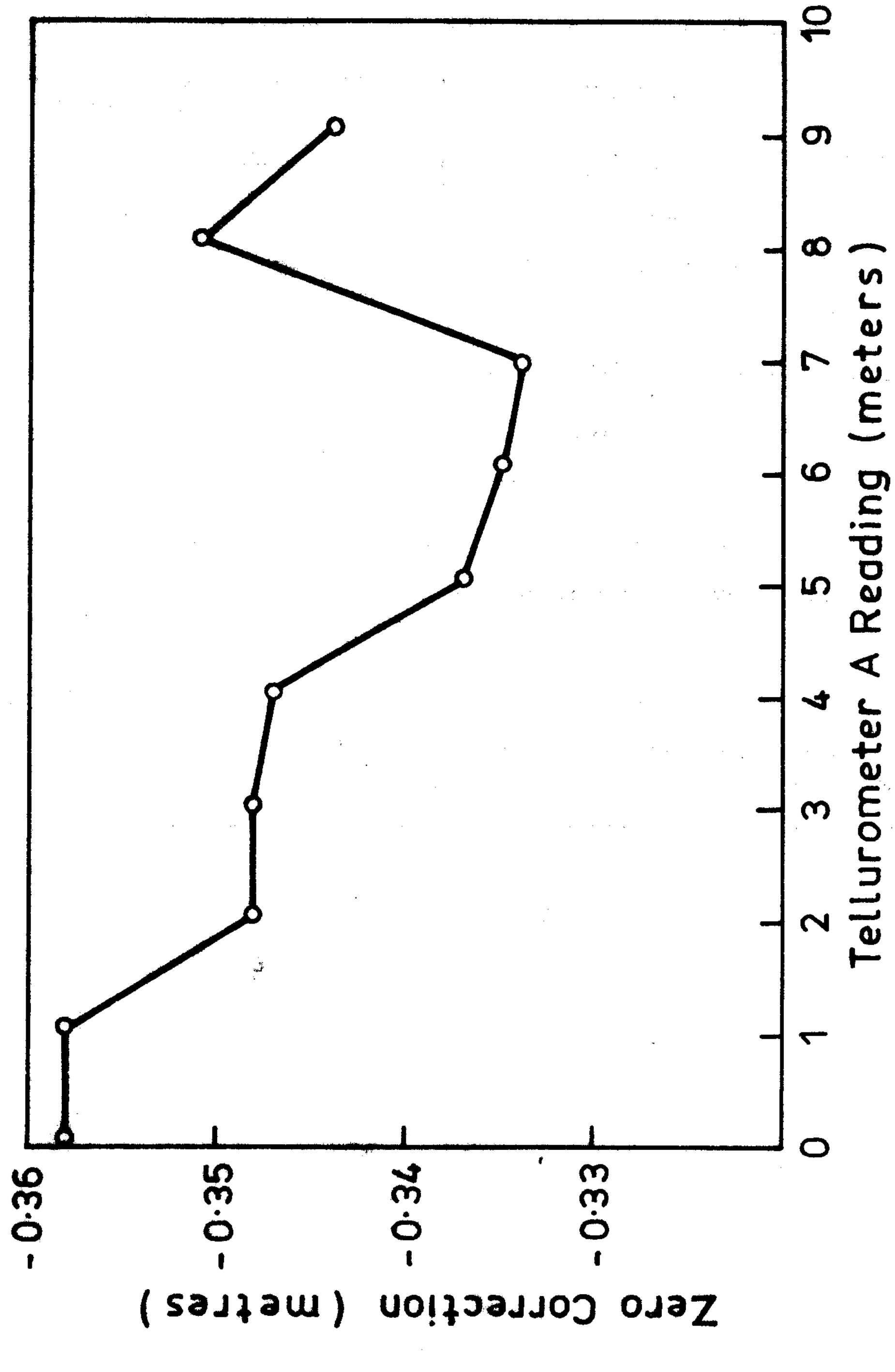
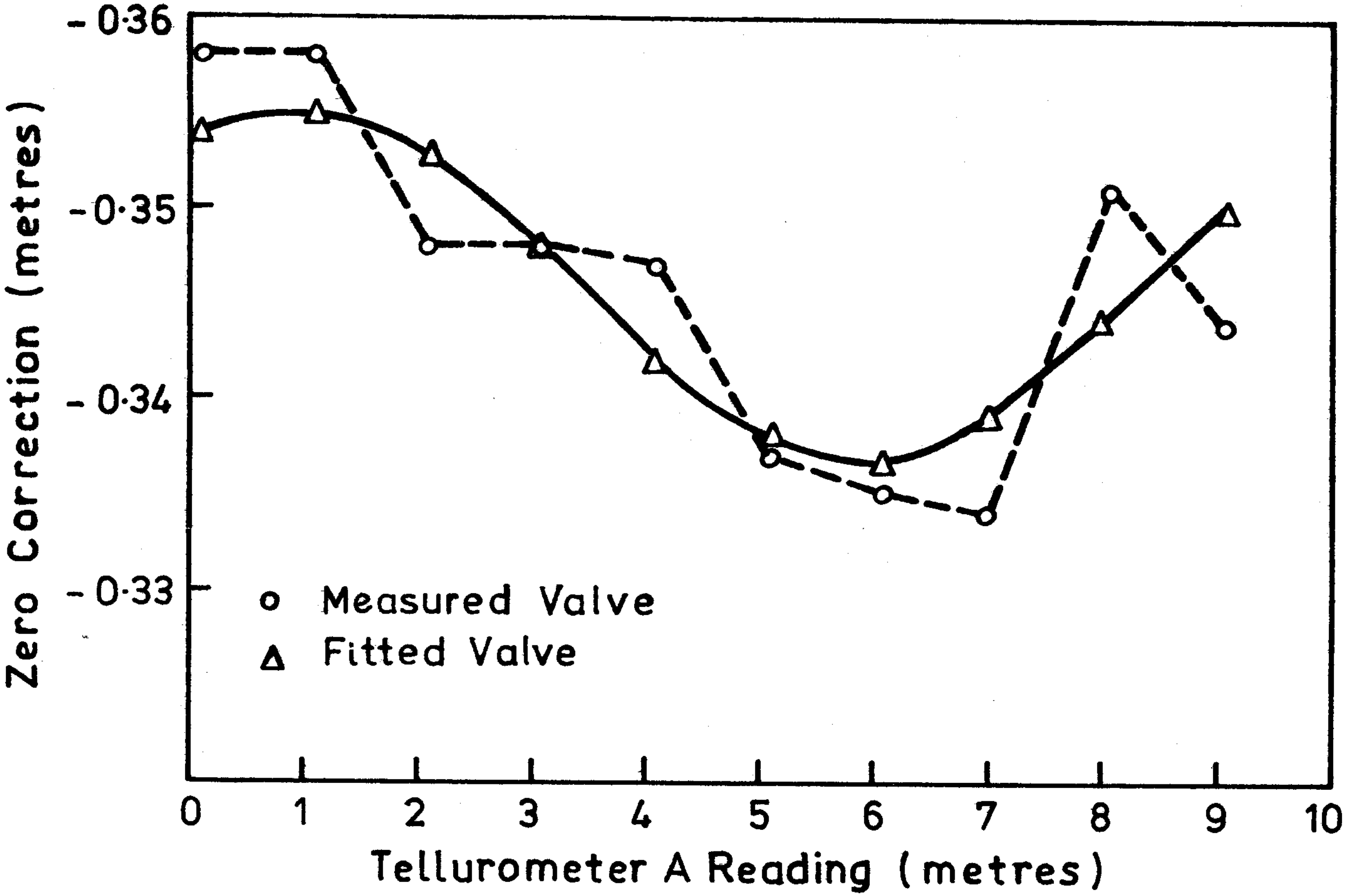

-0·36
-0·35
-0·34
-0·33
Zero Correction (metres)
0
1
2
3
4
5
6
7
8
9
10
Tellurometer A Reading (meters)

FIG. 4·1



A Least Squares Curve Fitted to the Zero Correction Results.

FIG. 4·3

5. GROUND SWING

5.1 DEFINITION

Micro waves are used as the carrier waves in the tellurometer and it is impossible to obtain a transmission free of spurious paths via ground reflections and reflections from other objects in the beam along the line being measured. The tellurometer is designed so that the carrier frequency can be varied over a range, of about 10 percentum in the earlier models (MRA 1 and MRA 2), and about 4 percentum (10 050 MHz to 10 450 MHz) in the model MRA 101. This variation in carrier frequency produces a periodic or quasiperiodic variation of distance, the amount of variation being dependent on the physical properties of the line being measured. This variation of distance is referred to as Tellurometer Ground Swing or in general ground swing.

5.2 GROUND SWING THEORY

The inventor of the tellurometer system of measurement, T.L. Wadley, has described in general terms the effects of ground swing on microwave measurements. This description has been supplemented by a mathematical analysis by Dr. J.A. Fejer *(Wadley 1958)*. This work dealt with the 10 centimetre instrument, namely the model MRA 1. It was considered necessary to examine this theory to see if in practice the theoretical conclusions hold. The instruments used in the test were the model MRA 101 tellurometers.

Dr. J.A. Fejer gives the error angle β in radians resulting from a number of relatively weak reflections as

$$\beta = - \Sigma a_i \cos \frac{2\pi\Delta d_i}{\lambda c} \cdot \sin \frac{2\pi\Delta d_i}{\lambda m} \qquad \ldots 5.1$$

where a_i = reflection coefficient
Δd_i = path difference
λc = carrier wave length
and λm = modulation wave length

There is a similar relationship for the return path. The sine component will be very similar to that of the forward path but the cosine component will be different because of the difference in the carrier frequency at the remote instrument. It is stressed at this point that the reflections must be relatively weak. It is stated by *Wadley (1958)* that the reflection coefficient is generally of the order of 10 percentum but over dry barren ground it may be as high as 40 percentum. Over water surfaces the reflection coefficient may be 40 percentum or more. *Poder (1962)* has suggested that over smooth water surfaces one can expect a high reflection coefficient of the order of 0.6 to 1.0. It can be seen from equation 5.1 that the sine component controls the amplitude of the error angle (providing the reflection coefficient is held fixed) and the cosine component determines the number of cycles for a particular path difference. To have a maximum amplitude, with a particular reflection coefficient

$\sin \frac{2\pi\Delta d}{\lambda m}$ must equal 1

i.e. $\frac{\Delta d}{\lambda m} = \frac{1}{4}$

i.e. $\Delta d = \frac{\lambda m}{4}$

$= 10$ metres

(λm for the model MRA 101 Tellurometer is 40 metres)

If $\Delta d = 10$ metres and the path difference is given by $\frac{2h^2}{D}$ where h = instrument height and D = distance

then $h^2 = \frac{10D}{2}$

For the Warwick Farm base line the length D is approximately 183 metres and if the instrument heights are about the same

then $h^2 = \frac{1830}{2}$

or $h \simeq 30$ metres

i.e. in order to reach a maximum value for the sine term over the length of 183 metres it is necessary to have an instrument height of 30 metres. Further examination of the sine terms shows that when $\Delta d = 0$ i.e. the instrument sighted with the antenna at ground level then sine $\frac{2\pi\Delta d}{\lambda m} = 0$, or the amplitude is zero, hence there is no ground swing. The carrier wave length of the MRA 101 can be varied from about 0.0298 metres to 0.0287 metres and inspection of the cosine term shows that one complete cycle will be developed if the path difference is equal to 0.78 metres. At a path difference greater than 0.78 metres one or more cycles are developed because of the cosine term, and the amplitude varies because of the sine term. At path differences of less than 0.78 metres a complete cycle of swing will not be developed.

A computer programme was written for the calculation of the error angle β as defined by equation 5.1. This programme calculated the error angle for the forward path using the modulation and carrier wave lengths of the master instrument, and the error angle for the return path using the modulation and carrier wave lengths of the remote instrument. The carrier wave lengths were derived from the carrier frequencies as shown in Appendix 2, with a frequency of 33 MHz being used as the difference frequency. The sum of these two error angles was converted to centimetres and accepted as the total error. The programme was designed so that varying reflection coefficients and path differences could be entered. This allowed error curves associated with a particular path difference and reflection coefficient to be calculated.

The output lists the reflection coefficient and path difference used in the calculation. The error angle, in centimetres, is shown for a particular carrier setting as a mathematical value and is also shown graphically as error angle plotted against carrier setting. (e.g. see Figure 5.7)

5.3 PRACTICAL EXPERIMENT

It has been shown above that for the sine term to have a maximum value for the Warwick Farm base line the instrument height had to be about 30 metres. Further it has been shown that one cycle of swing is developed if the path difference is 0.78 metres. To examine the effect of change of instrument height on the ground swing curve and to cover the range of instrument heights necessary to have a maximum sine term (in equation 5.1) the instrument height had to be varied up to a value of about 30 metres. To be able to vary the instrument height over such a large range two tubular steel towers 1.83 metres (6 feet) square by 29.26 metres (96 feet) high were erected over the base terminals of the Warwick Farm base line. Figure 5.1.

These towers had eight landings 3.66 metres (12 feet) apart so that instrument height could be varied from about 1.22 metres (4 feet) (at ground level) to 30.48 metres (100 feet) (at the top landing). Each of these landings consisted of a platform for the observer and a separate platform for the instrument figure 5.2, this provision allowed the observer to move without disturbing the instrument. It was most important that the towers should be stable and to aid in this stability each tower was guyed at 9.14, 18.29 and 27.43 metres (30, 60 and 90 feet respectively) from the ground on each of the four corners. This guying made the towers very stable even during strong wind gusts. The tellurometers were set up so that they were very close to the front of the towers. This was done so as to avoid any reflections from that part of the towers immediately in front of the instruments, see figure 5.2. During all the measurements the tellurometers were centred by means of a theodolite set on the ground at 90° to the base line. The method of plumbing was carried out in the following way.

A plastic scale about 40 centimetres long, and graduated in millimetres, was fixed over the base terminals as shown in figure 5.3, and a particular graduation, say 17 centimetres, was plumbed over the terminal point. The theodolite was then levelled very carefully and made to intersect the screw which holds the tellurometer to the tripod. The telescope was then lowered to read the scale, say, 23 centimetres, giving a correction of minus 6 centimetres to the distance. This method of plumbing was carried out on both towers during all tellurometer measurements. The greatest variation in plumbed position was caused during strong wind gusts, and amounted to 5 millimetres with the tellurometer moving about a mean position. As the true length of the base line was known a correction to this length could be determined by applying the corrections from both north and south base scale readings. Hence the true length of line being measured by the tellurometer was determined. Meteorological observations were taken at one end only and were taken at the mean height position.

The tellurometers and tripods were lifted to the required level using a pulley system, see figure 5.4. This proved very successful however some difficulties were experienced in hauling the 12 volt D.C. batteries to the required level. Extension leads 31 metres long were made up so that the battery could be left on the ground but the power loss in the long leads was too large and as a result this method proved unsuccessful. Hence the batteries were hauled to the required level using the pulley system.

For the experiment all distance combinations from one tower to the other tower were measured i.e. from each landing on the north tower distances were taken to the eight landings at the south tower. The measurements from equal towers landings were repeated. This gave a total of 53 measurements. The range in the fine readings i.e. the A reading, was from 3.0 metres (ground to ground) to 5.4 metres (south ground to north 8).

The notation used to describe the tower measurements is, the north tower is referred to as N, the south tower as S, and the heights as G for ground level and 1, 2.........8 for the eight landings, 8 being the top landing. The distances from north tower ground level, to the south tower positions are shown diagrammatically in figure 5.5. The path difference Δd, for all the combinations of measurements was calculated using the expression

$$\text{path difference} \simeq \frac{2H_1 H_2}{S}$$

where H_1 and H_2 are instrument heights and S is the horizontal distance between the points. (see figure 5.6)

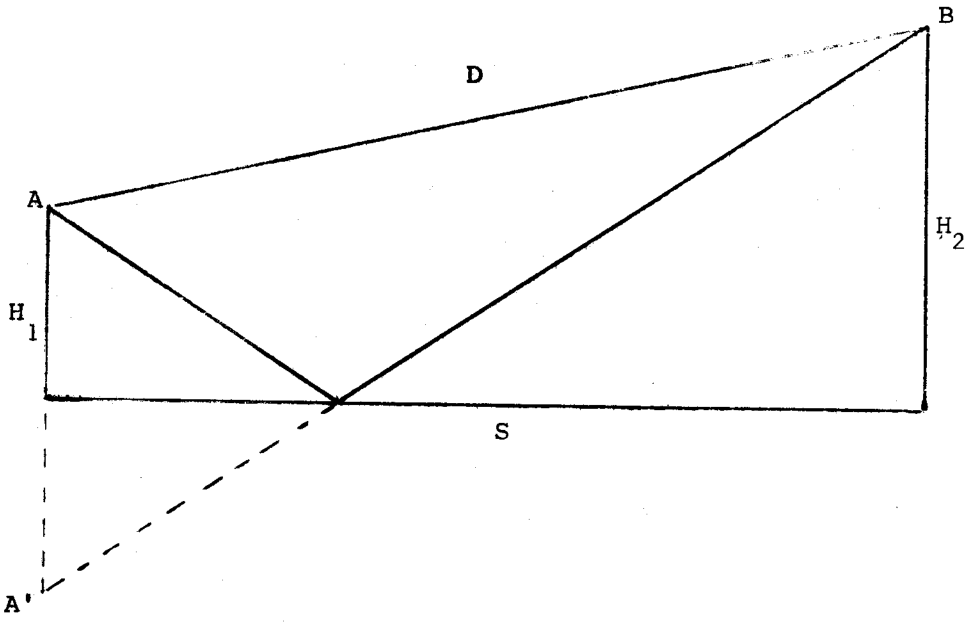


FIG. 5.6

In figure 5.6, let,

D = Direct path, AB

S = Horizontal Distance

R = Indirect Path, A'B.

The assumption is made that the surface between the line terminals is level.

$$D^2 = S^2 + (H_2 - H_1)^2$$

$$\therefore \quad D = \{S^2 + (H_2 - H_1)^2\}^{\frac{1}{2}}$$

Similarly $R = \{S^2 + (H_2 + H_1)^2\}^{\frac{1}{2}}$

$\therefore$ Path difference $R-D = \{S^2 + (H_2+H_1)^2\}^{\frac{1}{2}} - \{S^2 + (H_2-H_1)^2\}^{\frac{1}{2}}$

i.e. $\Delta d = \{S + \frac{1}{2}(S^2)^{-\frac{1}{2}}(H_1+H_2)^2\} - \{S + \frac{1}{2}(S^2)^{-\frac{1}{2}}(H_2-H_1)^2\}$ retaining terms up to the second power

$$\simeq \frac{(H_1 + H_2)^2}{2S} - \frac{(H_2 - H_1)^2}{2S}$$

$$\simeq \frac{1}{2S}\{4H_1H_2\}$$

$$\therefore \quad \Delta d \simeq \frac{2\,H_1H_2}{S} \qquad \ldots\ 5.2$$

If the ground surface between the line terminals is assumed to be evenly sloping and if the difference in elevation between the line terminals is ΔH then by similar reasoning the path difference Δd is given by

$$\Delta d \simeq \frac{2H_1H_2}{S} + \frac{2H_1\Delta H}{S} \qquad \ldots\ 5.3$$

The adopted lengths for all the lines measured on the towers and the path difference (from equation 5.2) are shown in table 5.1.

5.4 RESULTS

The ground swing curves, for all the tower measurements were calculated using equation 5.1 with varying reflection coefficients. A curve was also calculated using a path difference of 0.78 metres and a reflection coefficient of 0.2 in order to see if a full cycle of swing was developed as predicted in section 5.2. This curve is shown in figure 5.7 and it can be seen that a full cycle of swing is not completely developed. However this was to be expected as only the forward path was considered in section 5.2. A full cycle of swing would be developed with a slight increase in path difference. It should be noted that the line N3 to S1 has a path difference of 0.774 metres. The calculated swing curve for this line with a reflection coefficient of 0.2 is shown in figure 5.8, and it can be seen that a complete cycle of swing is not quite developed. The observed swing curves for these lines is shown in figures 5.9 and 5.10 with instrument No. 113 and instrument No. 110 as master respectively. It can be seen from figure 5.9 and 5.10 that the amplitudes of these swing curves are 0.20 and 0.175 metres respectively and that a full cycle of swing is not completely developed. The three curves have been plotted together and are shown in figure 5.11. It should be noted that when the observed swing curves were plotted the carrier settings were equally spaced to agree with the theoretical curve carrier settings, thus the curves may be slightly different to those shown in figure 5.9 and 5.10. The three swing curves as shown in figure 5.11 agree very closely with each other and it would appear that the theory is confirmed by the practice.

However this is not the case if the line N8 to S8 is considered. The theoretical curve is shown in figure 5.12. This curve has been calculated with a reflection coefficient of 0.20 and the amplitude is of the order of 1.00 metres, and many cycles of swing have been developed. Section 5.2 predicted that for a path difference of this magnitude the sine term would take the maximum value. The observed swing curves on line N8 to S8, measured twice, are shown in figures 5.13(a) and 5.13(b), for master instrument No. 113 and figures 5.13(c) and 5.13(d) for master instrument No. 110 and show that the amplitudes are 0.09, 0.08, 0.095 and 0.085 metres and further only one cycle of swing is developed. The line NG to SG was measured many times during the zero error experiments and the average ground swing was about 0.10 metres. The path difference for this line is 0.029 metres and a swing curve was calculated using a reflection coefficient of 0.2. This calculated curve is shown in figure 5.14, and is almost a straight line, the values range from -0.286 to -0.290 centimetres. The observed ground swing for the line N8 to S8 and the observed ground swing for the line NG to SG do not agree with the calculated ground swing curves for these lines. This disagreement may have been caused by the fact that the observed swing curves are in fact "antenna swing" curves.

Marshall (1967 page 3) states "on looking at figure (7.20) it can be seen that there is a possibility of double reflections between the main parabola, small reflector and edges of the wave guide. Although the amplitude of these double reflections is extremely small they nevertheless produce a signal which is out of phase with that following the correct path ..... this antenna swing can be made to vary about the correct reading or even through a complete cycle of error by varying the frequency or cavity tune. In practice, if a full range of cavity tune readings is taken the error is averaged out."

Fennell (1971) states that the manufacturers advise: "I should mention that the electrical centre of the MRA101 is on the centre line of the wave guide at about the point of the mixer diode. Although the electrical centre is always on the centre line it will move backwards and forwards from the mixer diode depending on the carrier frequency and the individual characteristics of the wave guide and reflector concerned. (my underlining). This is due to microwave reflections in the wave guide and antenna system".

Furthermore support for these statements is given by *Fradin (1961)* when discussing the differences between real and ideal reflectors, he states (page 394) "..... inaccuracies in manufacture (e.g., difference between form of reflector from ideal paraboloid, unevenness of surface, inexact location of radiators etc.) have an influence on the characteristics of paraboloids of revolution". And further, "the directional patterns for real radiators differ from those .... for ideal radiators".

Fradin (op. cit.) page 395 mentions briefly the formation of standing waves (double reflections) between the radiator and the reflector which cause "disturbance of the amplitude and of the phase relationship of the field in the reflector".

It would appear then; that since any reflected ray reaching the instruments, via the ground surface during the measurements of the line N8 to S8, would be very weak the observed swing curve is in fact an antenna swing curve. Further when considering the line NG to SG, as the path difference is small then the magnitude of the sine component of equation 5.1 will be small, hence the calculated ground swing curve will have a small amplitude, in fact, a value of 0.3 cm (figures 5.14). The observed swing curves for this line may also be antenna swing curves. This line, NG to SG, with a small path difference approximates the case in which $\Delta d = 0$ where no ground swing would be expected because

$$\Sigma\ a_i \sin \frac{2\pi\Delta d}{\lambda m} = 0$$

Values of the magnitude of antenna swing for the model MRA3 (NOTE. This tellurometer uses a different antenna system from the MRA101, 301 and 4) are of the order of 5cm to 20 cm and that for the model MRA4 are of the order of 6mm or 7mm. (*Marshall op. cit.*). From the observations taken on the Warwick Farm base line it would appear that for the particular instruments used, i.e. serial numbers 110 and 113 that the average value of antenna swing for the MRA101 tellurometers is in the range 8cm to 10cm.

5.5 CONCLUSION

The results of the calculated swing curves agree in certain cases only with the observed swing curves when a short line is considered. The agreement seems to occur when a full cycle is developed. The reason for an incomplete agreement between the theoretical and observed ground swing curves may also be due to the fact that multi-reflections are occurring and not single point reflections on which the theory depends.

The tower measurements indicate that when a large instrument height is used over a short line then, as the reflected signal is very weak, the observed swing curve may be due solely to antenna swing. This must also be considered when the path difference is very small. Both these conditions indicate that for the model MRA101 tellurometers the magnitude of antenna swing is about 0.08m to 0.10m.

The random relationship of the observed ground swing with path difference for the tower experiment can be seen from figure 5.15, which shows the observed ground swing in metres plotted against the path difference in metres.

FROM	TO	ADOPTED LENGTH (m)	PATH DIFFERENCE (m)	FROM	TO	ADOPTED LENGTH (m)	PATH DIFFERENCE (m)
NG	SG	182.710	0.029	N6	S5	182.552	5.312
N1	S1	.550	.347	N6	S4	.517	4.338
N2	S2	.564	.946	N6	S3	.519	3.363
N3	S3	.523	1.839	N6	S2	.545	2.397
N4	S4	.520	3.027	N6	S1	.561	1.416
N5	S5	.602	4.506	N6	SG	.610	.332
N6	S6	.514	6.284	N8	S8	.441	10.724
N7	S7	.497	8.363	N8	S7	.488	9.454
N2	S1	.593	.560	N7	S6	.539	7.239
N2	SG	.624	.131	N7	S5	.556	6.119
N1	SG	.603	.081	N7	S4	.529	4.998
N3	S2	.550	1.307	N7	S3	.536	3.874
N3	S1	.579	.774	N7	S2	.564	2.754
N3	SG	.598	.182	N7	S1	.582	1.631
N4	S3	.529	2.347	N7	SG	.616	.382
N4	S2	.564	1.668	N8	SG	.575	.432
N4	S1	.571	.988	N8	S1	.563	1.844
N4	SG	.591	.232	N8	S2	.553	3.113
N5	S4	.529	3.681	N8	S6	.512	8.184
N5	S3	.530	2.854	N8	S5	.549	6.917
N5	S2	.560	2.028	N8	S4	.509	5.650
N5	S1	.576	1.201	N8	S3	.516	4.380
N5	SG	.623	.281				

TABLE 5.1

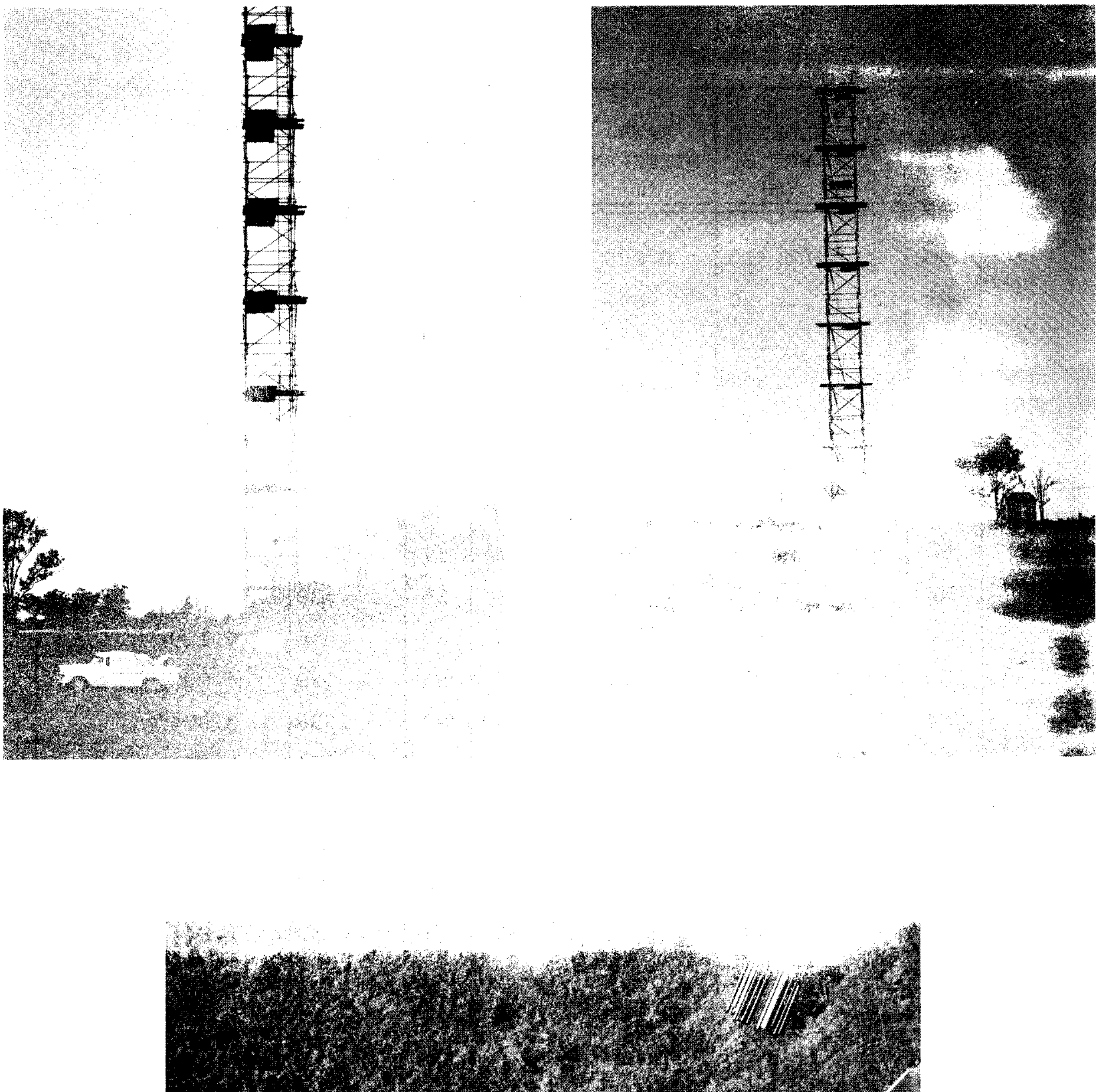


FIG. 5.1

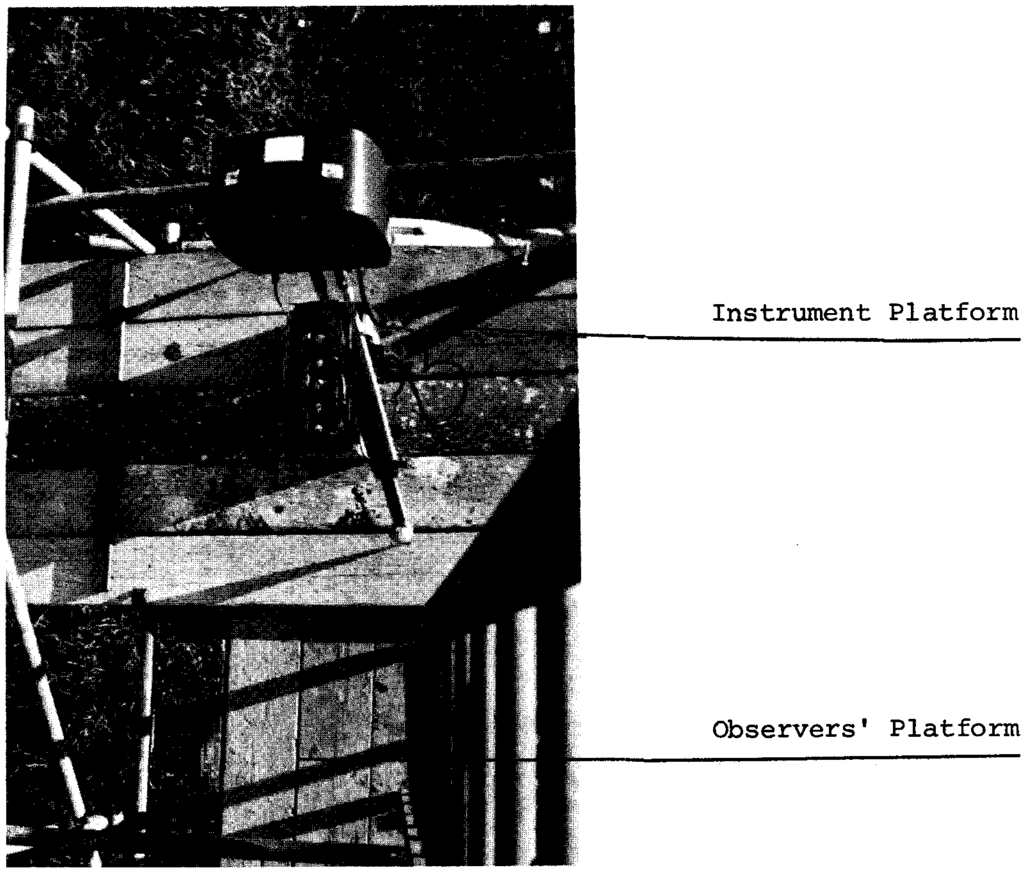


FIG. 5.2

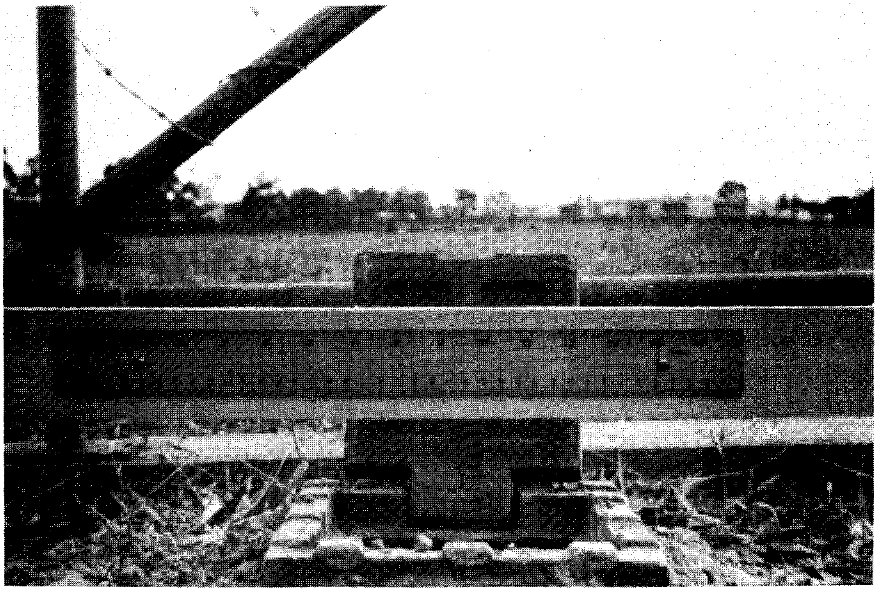


FIG. 5.3

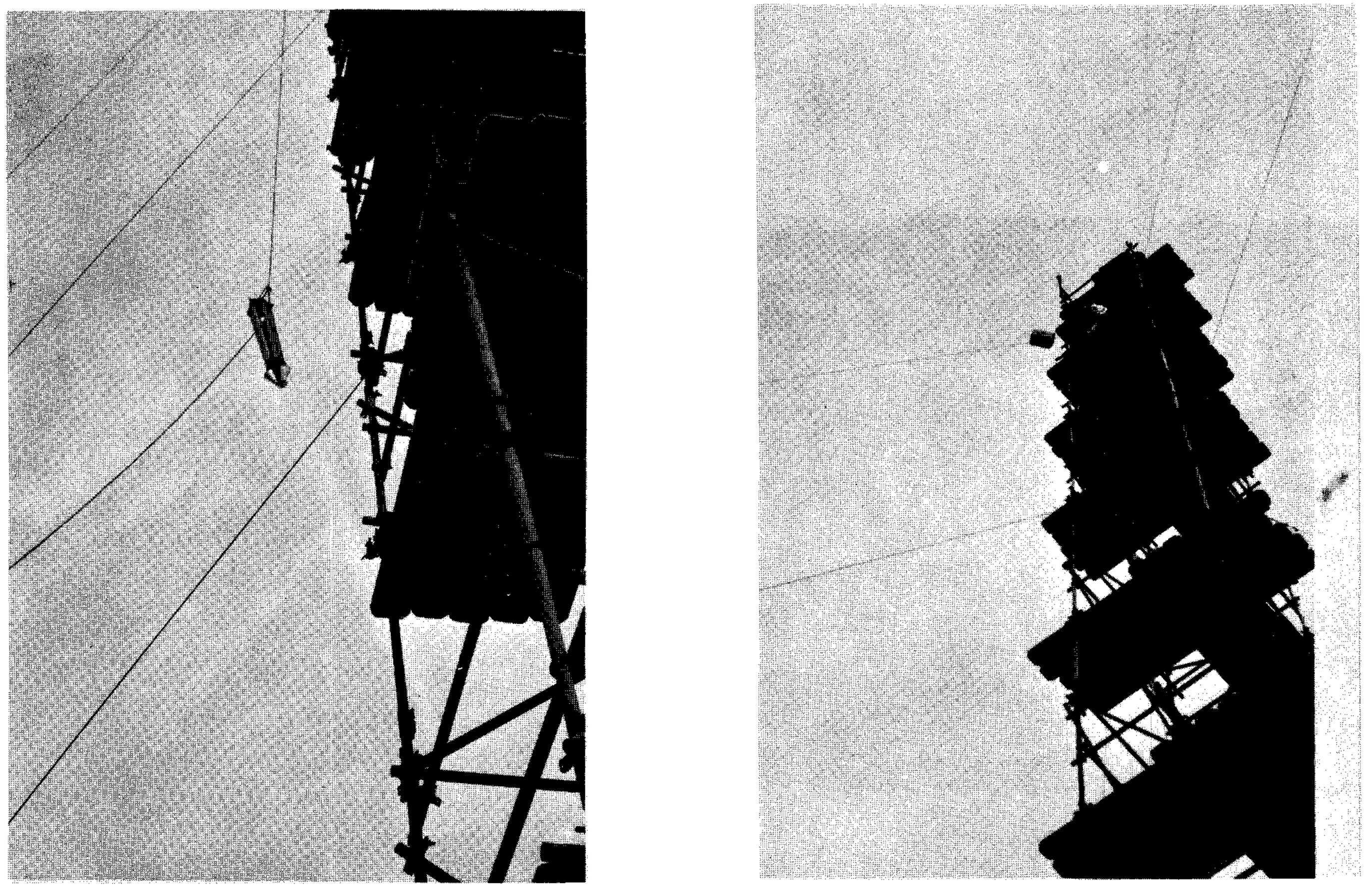
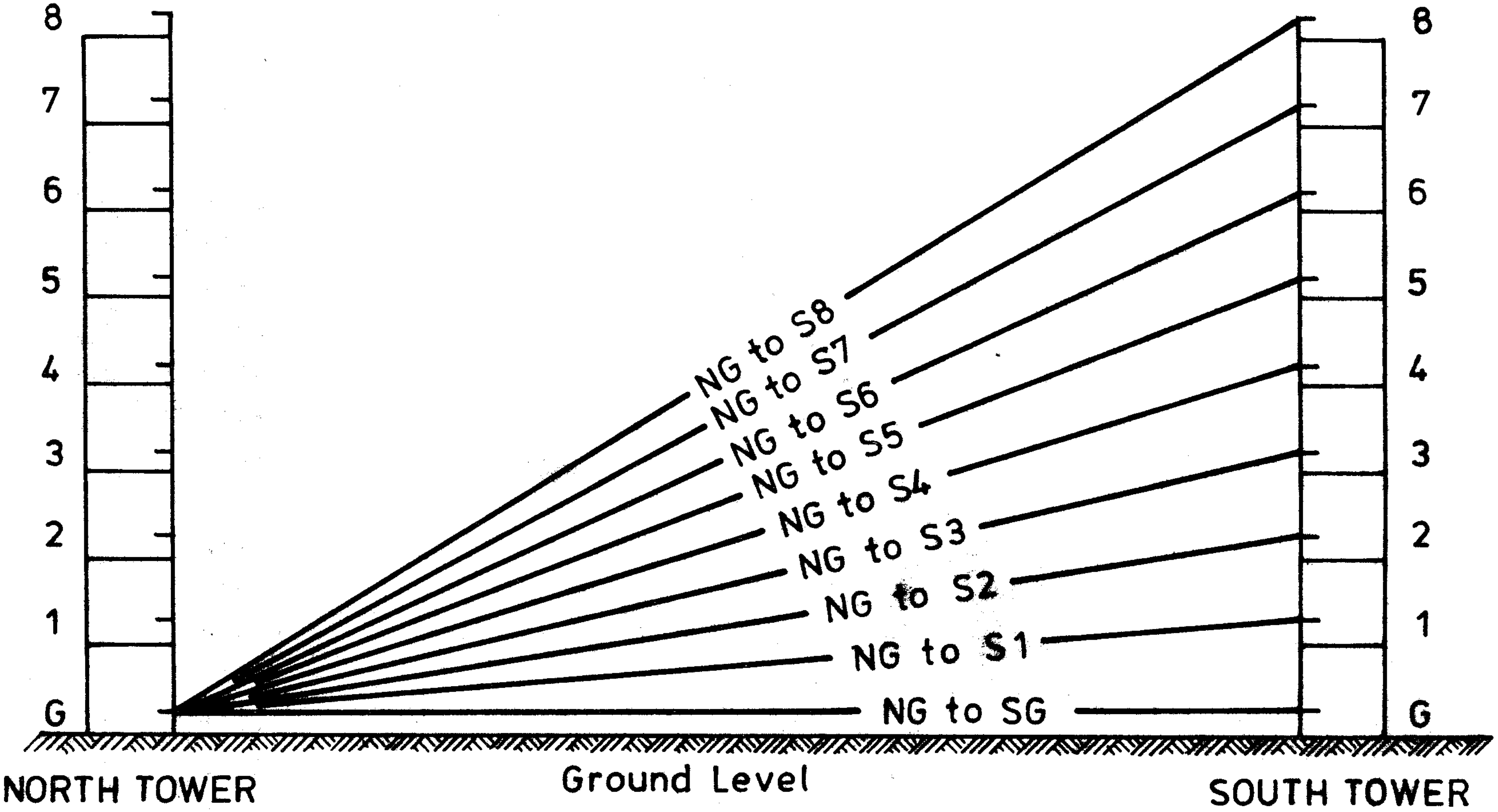


FIG. 5.4



TOWER MEASUREMENTS
NORTH GROUND TO SOUTH STATIONS

FIG. 5·5

```
REFLECTION COEFFICIENT      PATH DIFF.
        0.200               0.780

CARRIER   B CMS-30
   1      -2.250
   2      -0.935
   3       2.564
   4       3.019
   5       4.399
   6       5.741
   7       6.893
   8       7.452
   9       7.294
  10       6.285
  11       4.640
  12       2.846
  13       0.285
  14      -2.078
  15      -4.480
  16      -6.173
  17      -7.022
  18      -7.378
  19      -7.096
  20      -6.665

CARRIER   B CMS-30
```

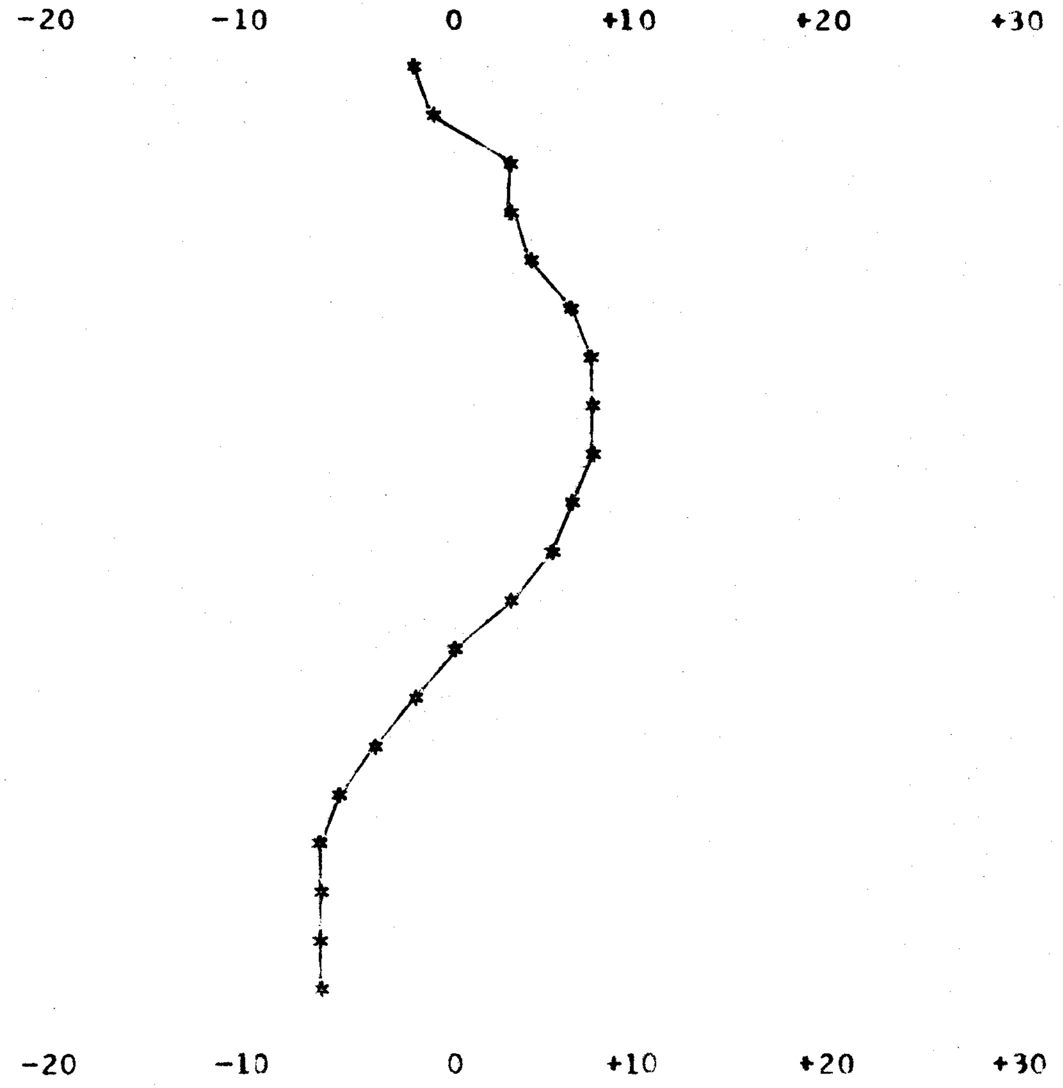


FIG. 5.7

```
REFLECTION COEFFICIENT     PATH DIFF.
         0.200              0.774

CARRIER   B CMS
   1     -7.444
   2     -7.326
   3     -5.933
   4     -5.629
   5     -4.485
   6     -2.921
   7     -0.826
   8      1.338
   9      3.708
  10      5.651
  11      6.901
  12      7.400
  13      7.246
  14      6.321
  15      4.548
  16      2.433
  17      0.666
  18     -0.661
  19     -4.152
  20     -5.007
CARRIER   B CMS
```

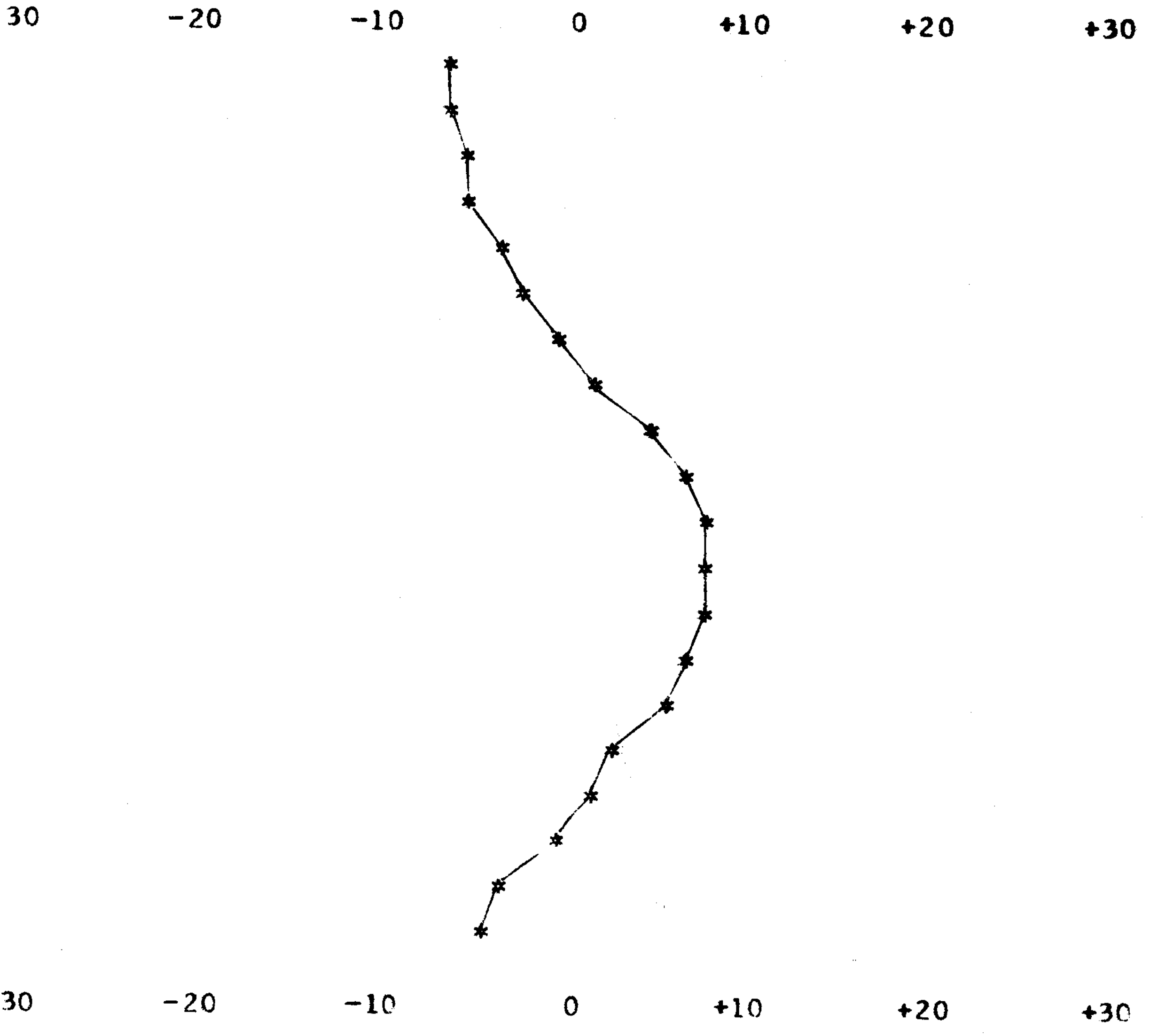


FIG. 5.8

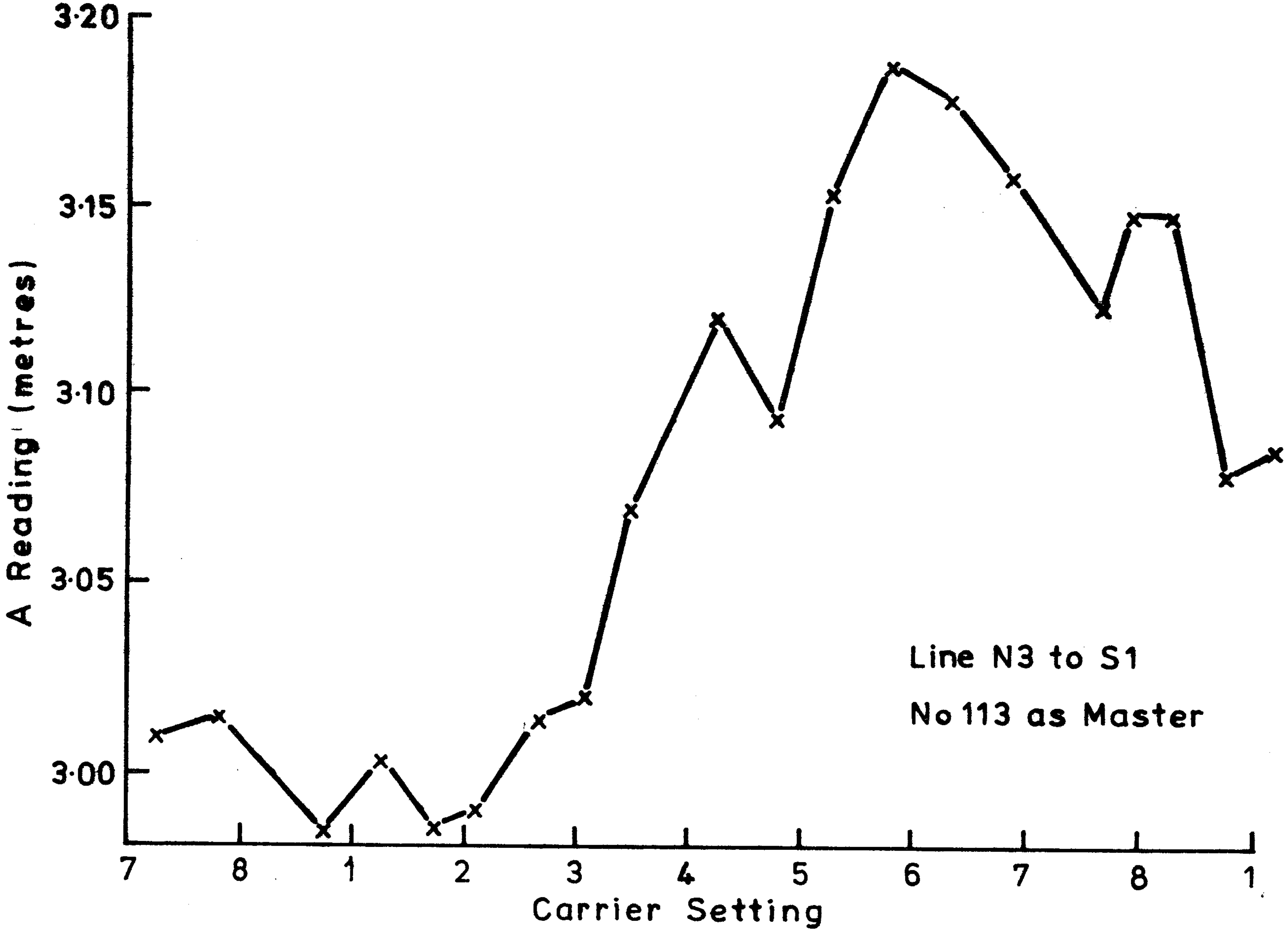

3·20
3·15
3·10
3·05
3·00
A Reading (metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
Line N3 to S1
No 113 as Master

FIG. 5·9

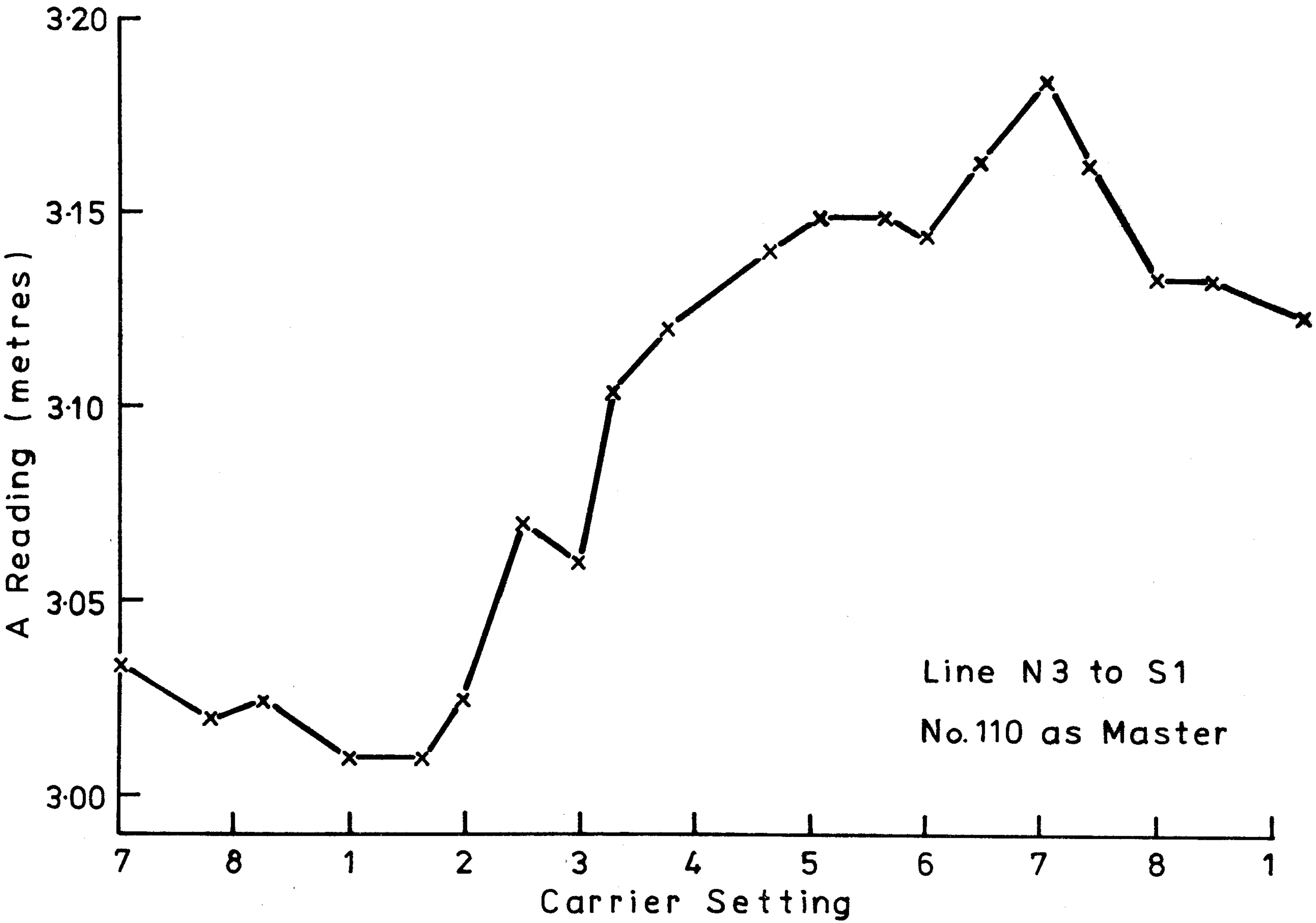

3·20
3·15
3·10
3·05
3·00
A Reading (metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
Line N3 to S1
No.110 as Master

FIG. 5·10

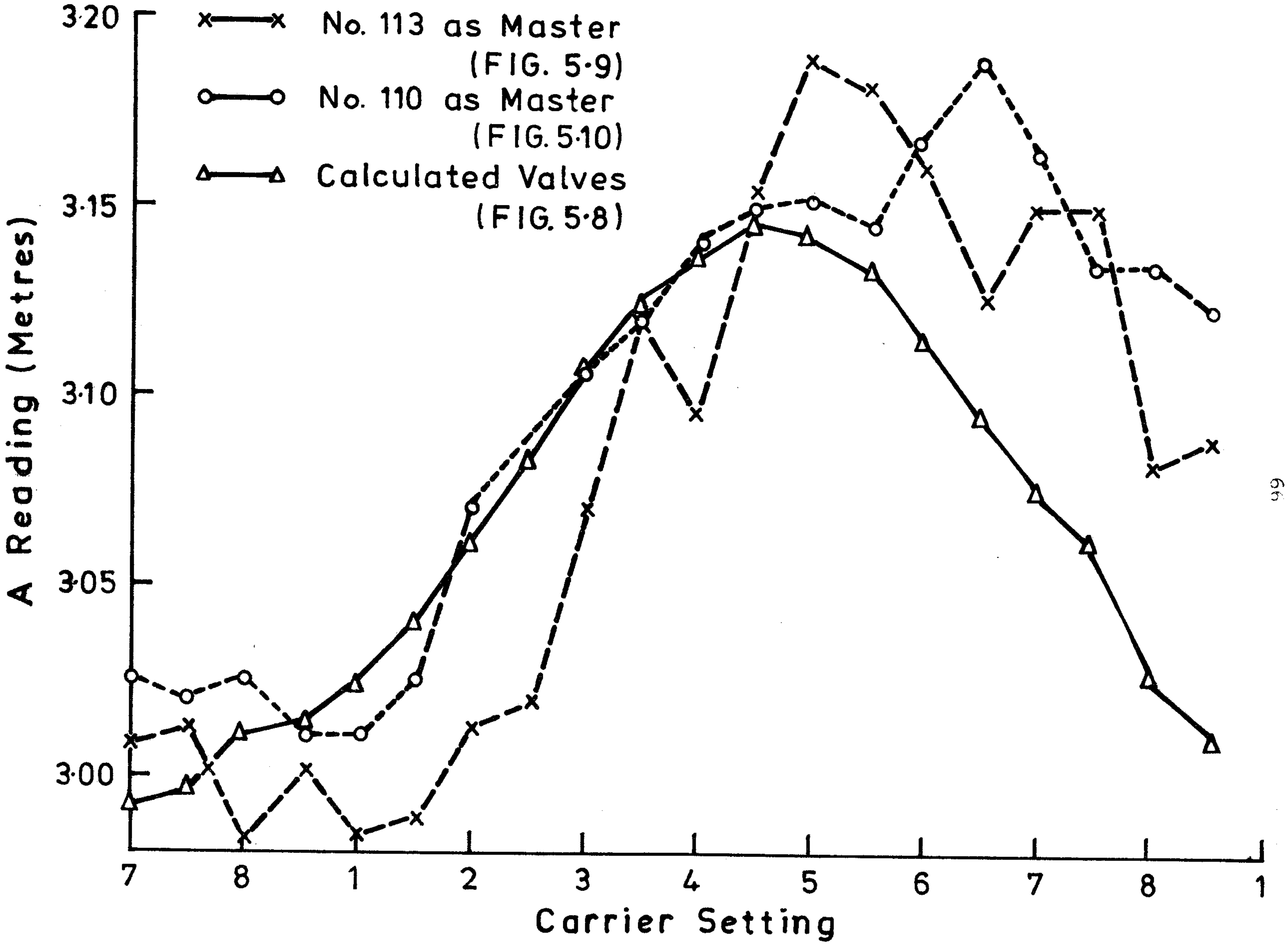
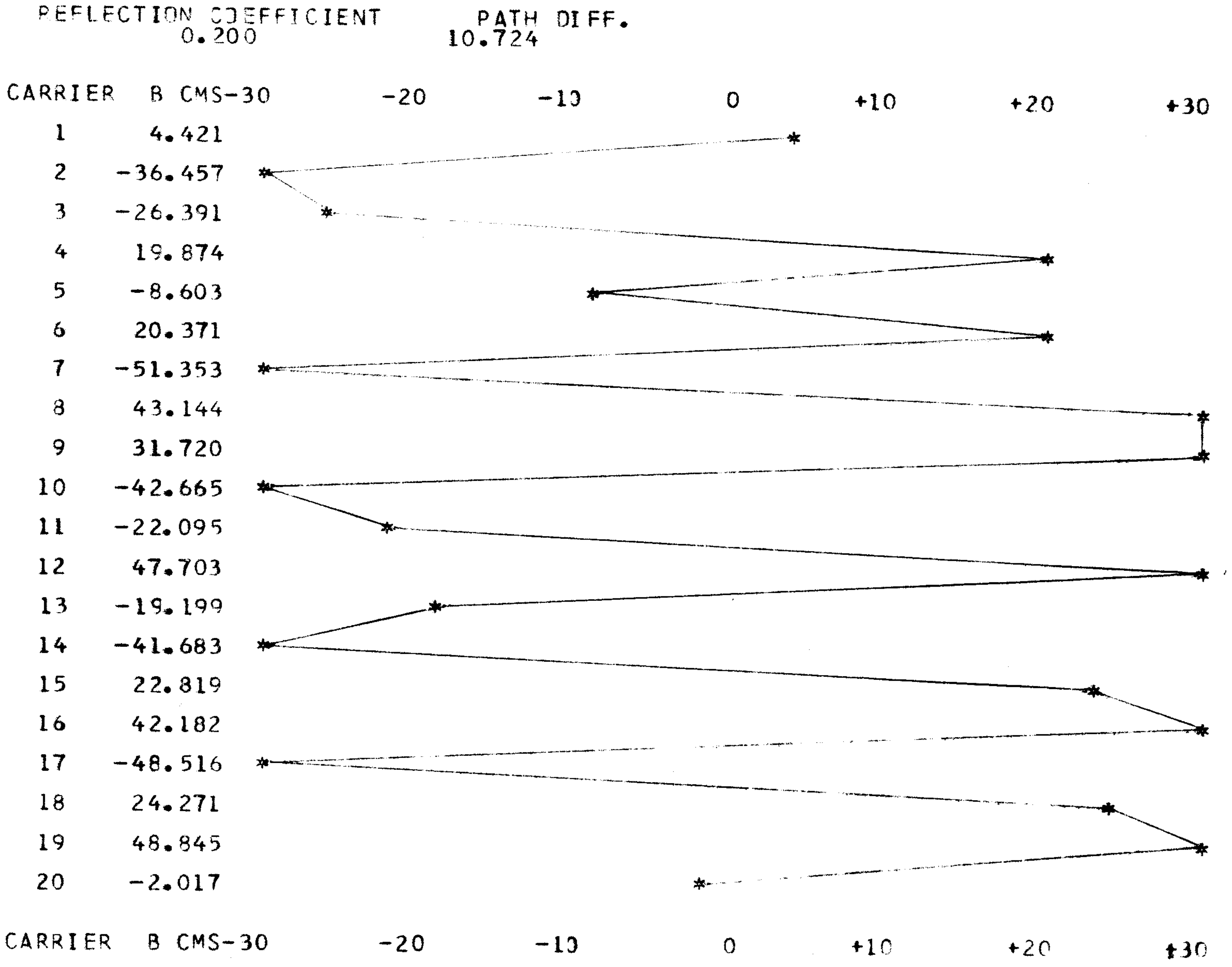

No. 113 as Master (FIG. 5·9)
No. 110 as Master (FIG. 5·10)
Calculated Valves (FIG. 5·8)
A Reading (Metres)
3·20
3·15
3·10
3·05
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 5·11



```
REFLECTION COEFFICIENT     PATH DIFF.
      0.200               10.724

CARRIER  B CMS-30        -20     -10      0     +10     +20     +30
   1      4.421
   2    -36.457
   3    -26.391
   4     19.874
   5     -8.603
   6     20.371
   7    -51.353
   8     43.144
   9     31.720
  10    -42.665
  11    -22.095
  12     47.703
  13    -19.199
  14    -41.683
  15     22.819
  16     42.182
  17    -48.516
  18     24.271
  19     48.845
  20     -2.017

CARRIER  B CMS-30        -20     -10      0     +10     +20     +30
```

FIG. 5.12

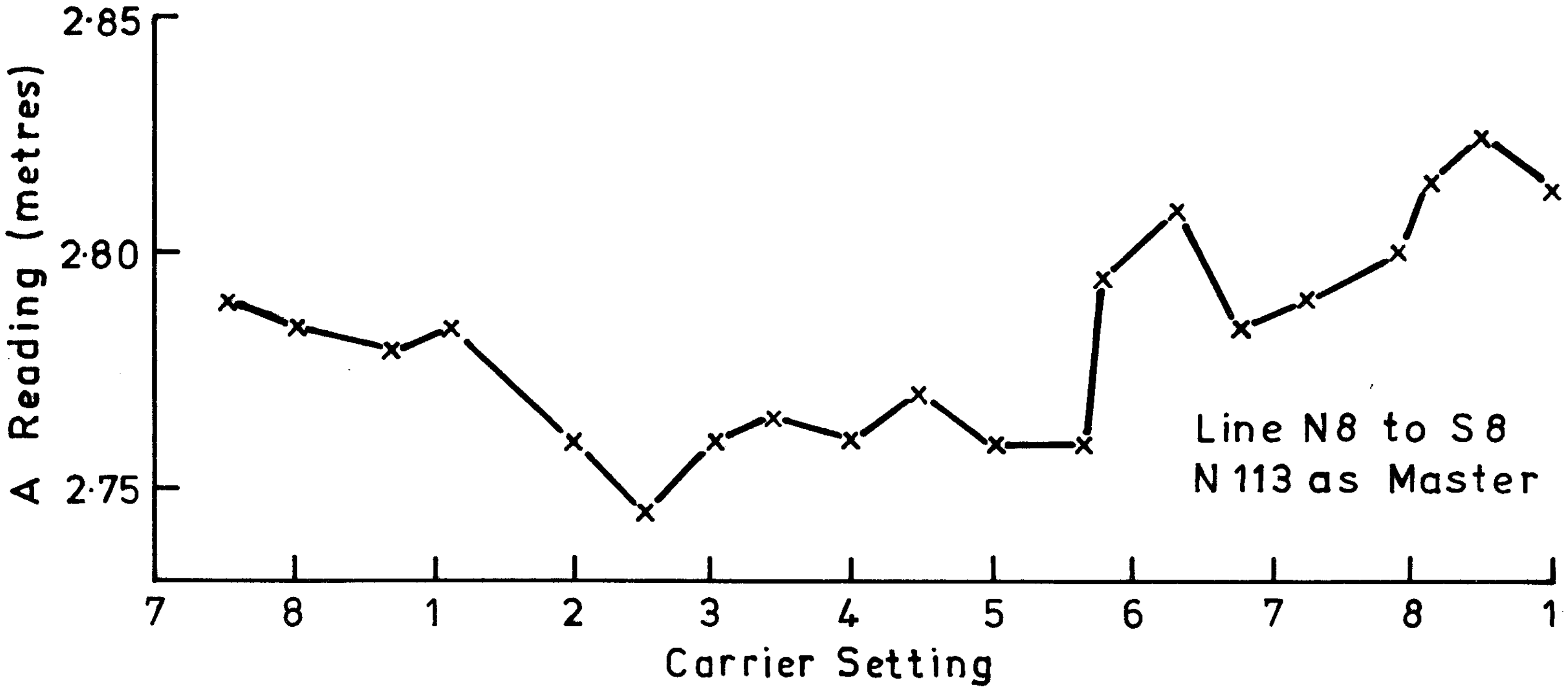

A Reading (metres)
2·85
2·80
2·75
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
Line N8 to S8
N 113 as Master

FIG. 5·13 (a)

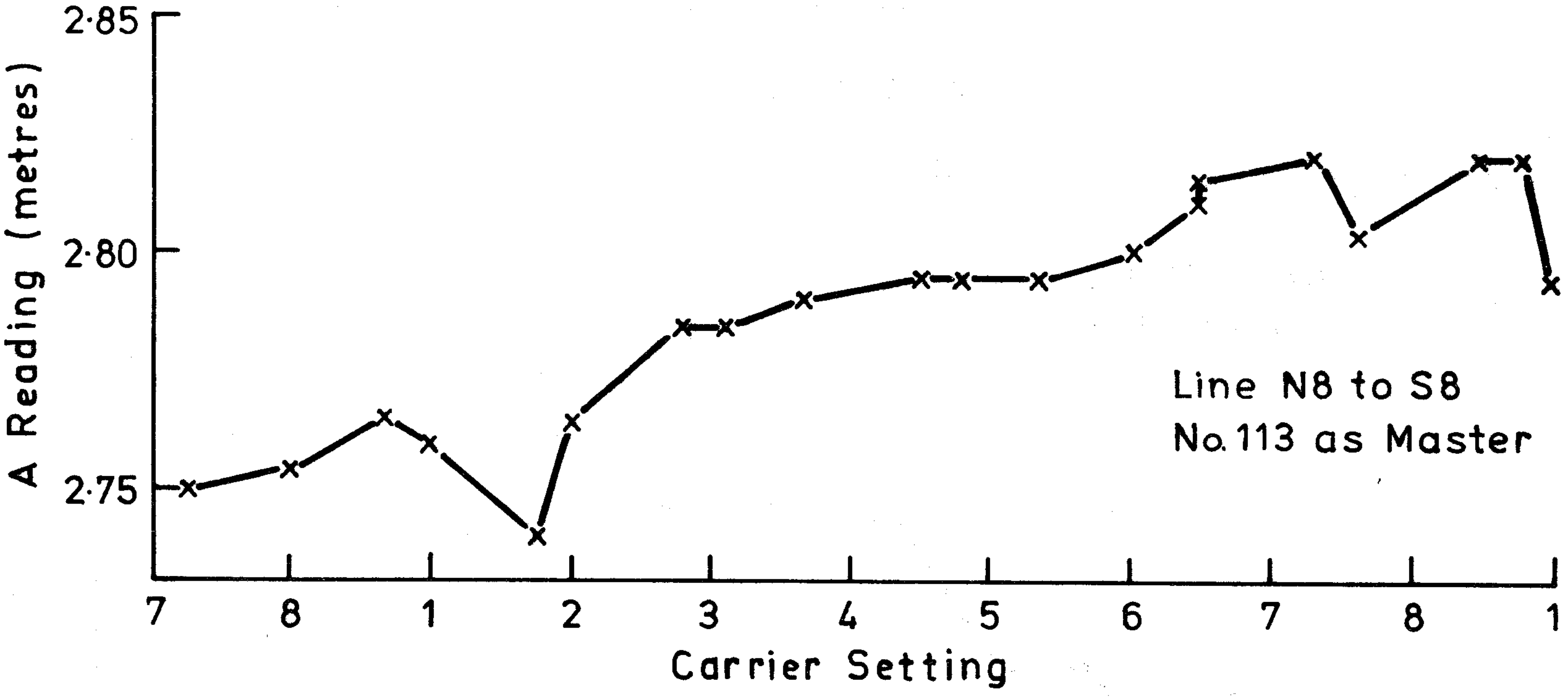

2·85
2·80
2·75
A Reading (metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
Line N8 to S8
No. 113 as Master

FIG. 5·13 (b).

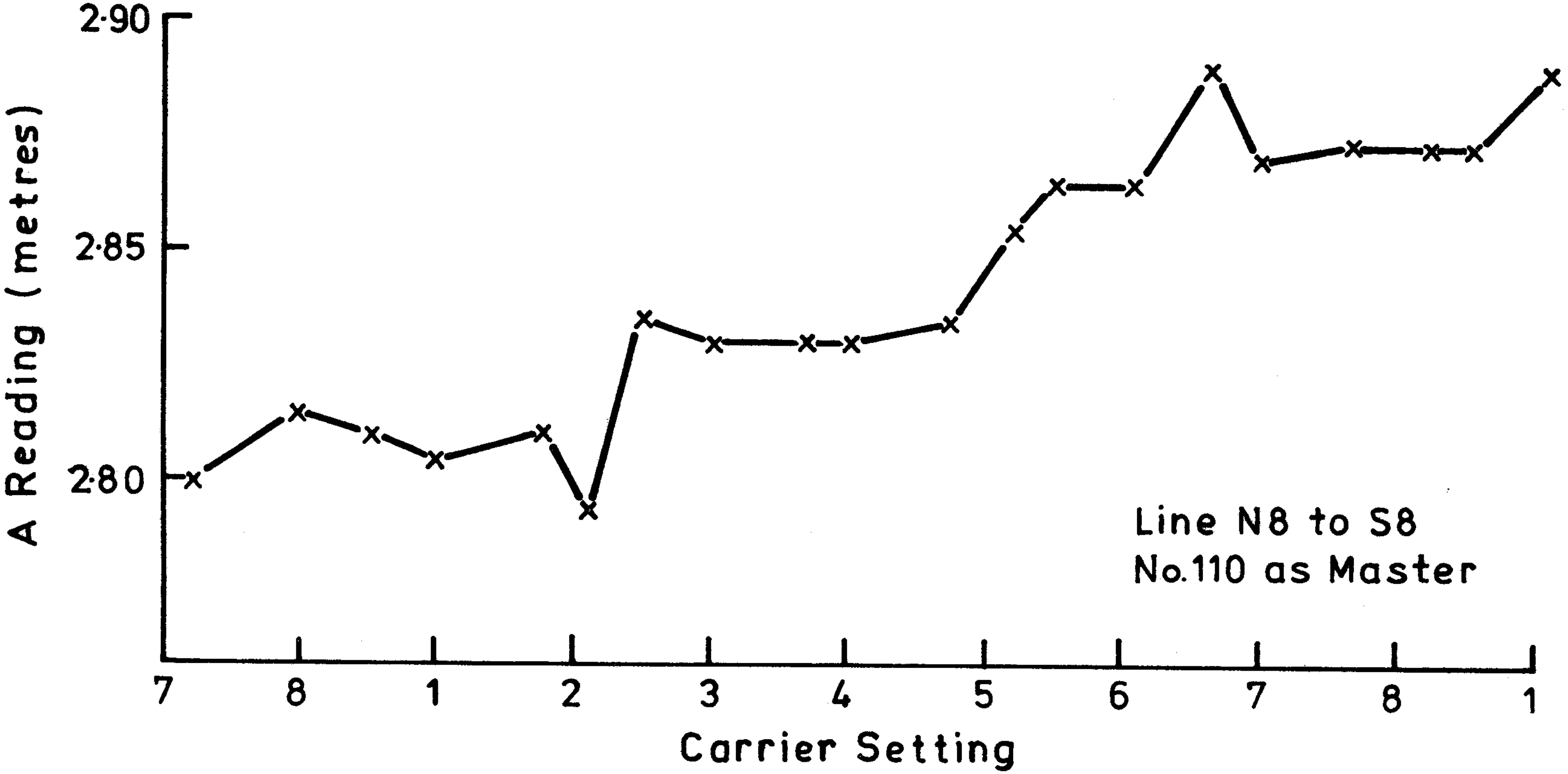

2·90
2·85
2·80
A Reading (metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
Line N8 to S8
No.110 as Master

FIG. 5·13 (c)

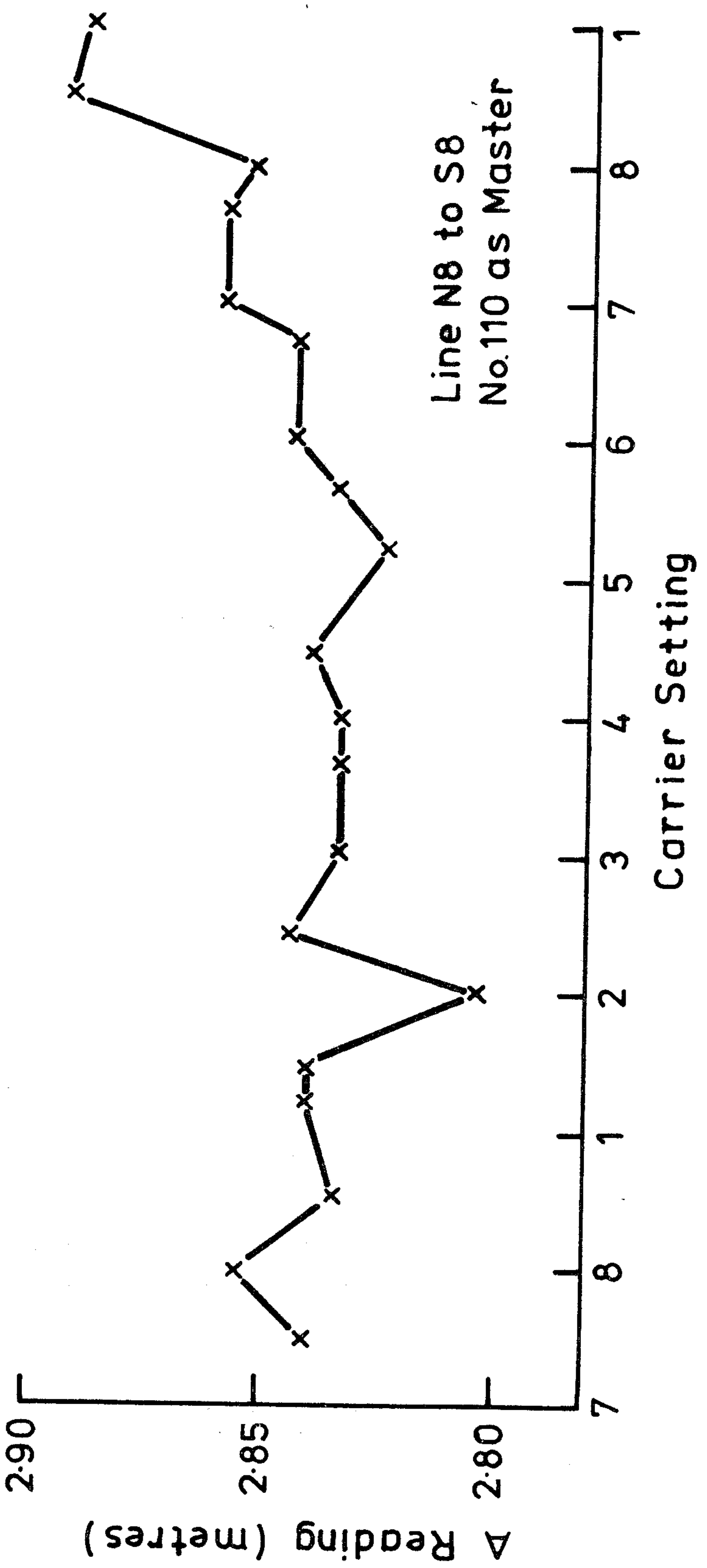

Line N8 to S8
No.110 as Master
A Reading (metres)
2·90
2·85
2·80
Carrier Setting
7
8
1
2
3
4
5
6
7
8
1

FIG. 5·13 (d)

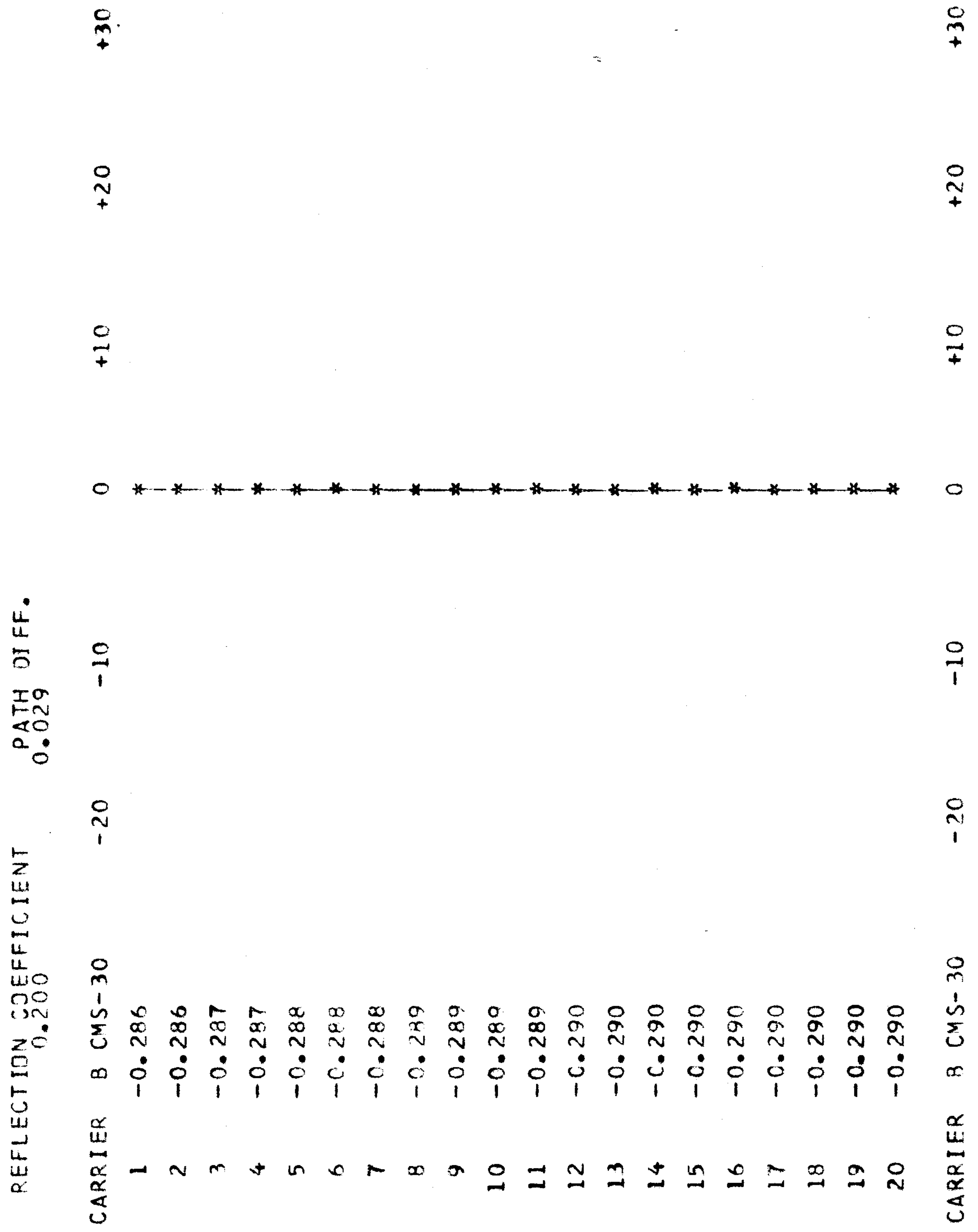

REFLECTION COEFFICIENT
0.200
PATH DIFF.
0.029
CARRIER
B CMS-30
-20
-10
0
+10
+20
+30
1 -0.286
2 -0.286
3 -0.287
4 -0.287
5 -0.288
6 -0.288
7 -0.288
8 -0.289
9 -0.289
10 -0.289
11 -0.289
12 -0.290
13 -0.290
14 -0.290
15 -0.290
16 -0.290
17 -0.290
18 -0.290
19 -0.290
20 -0.290
CARRIER
B CMS-30
-20
-10
0
+10
+20
+30

FIG. 5.14

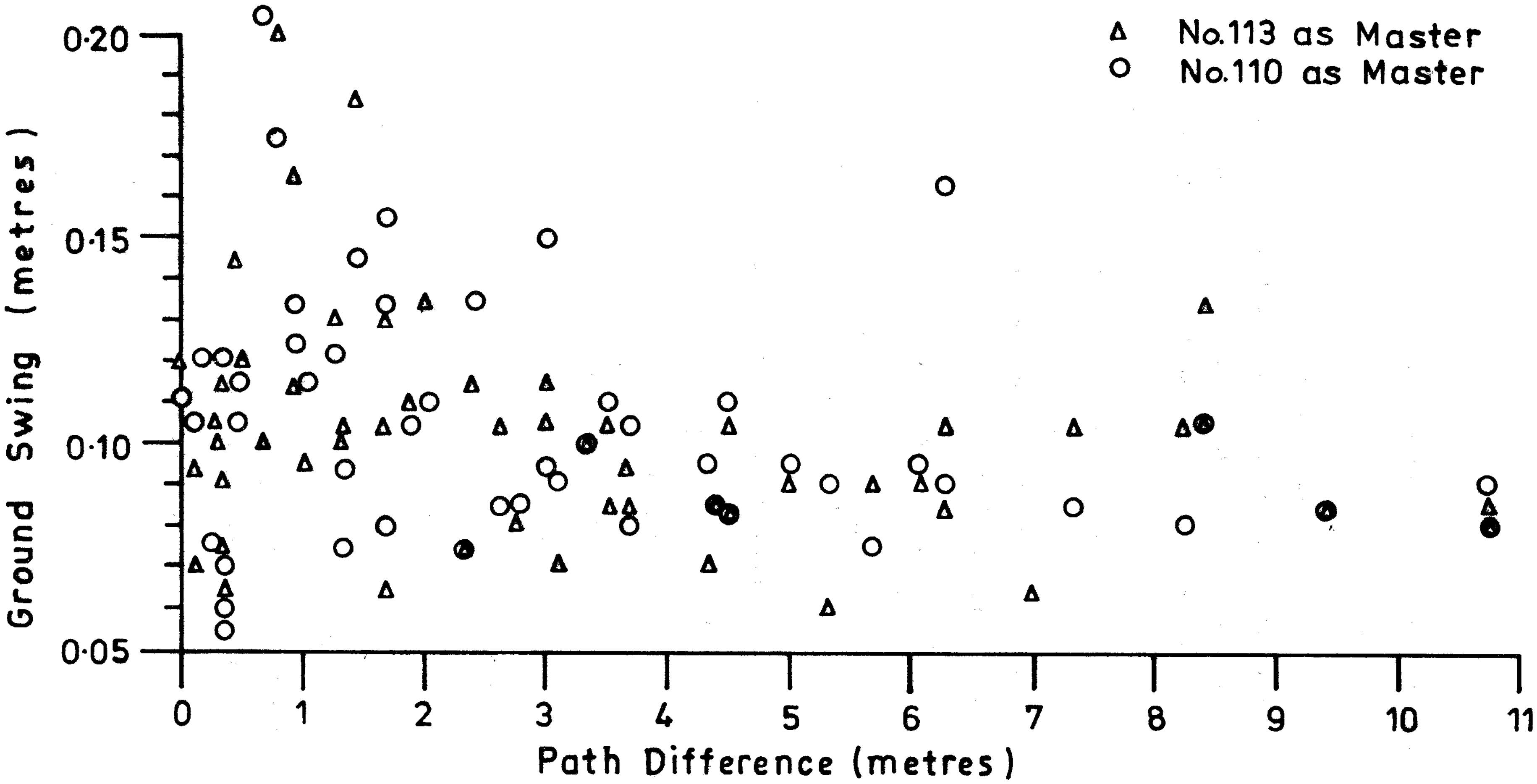

△ No.113 as Master
○ No.110 as Master
0·20
0·15
0·10
0·05
Ground Swing (metres)
0
1
2
3
4
5
6
7
8
9
10
11
Path Difference (metres)

FIG. 5·15

6. FURTHER THEORETICAL CONSIDERATIONS OF GROUND SWING

6.1 PODER'S THEORY

K. Poder (1962) made extensive studies of tellurometer ground swing and deduced a mathematical equation in order that ground swing for a particular line could be predicted and hence the phase error determined. Poder's work was intended to cover lines measured over highly reflecting surfaces such as smooth water. On lines of this nature tellurometer users had experienced difficulty in adopting a value for the length because of large ground swing and because the swing curve was not of the usual periodic or quasi periodic form.

Poder's equation is given by

$$X = \text{arc tan} \left(\frac{a_T \sin W_C Q \{\cos (\omega_C Q + r_T) + a_T\}}{1 + a_T^2 \cos W_C Q + \{(1 + \cos W_C Q)\, a_T \cos (\omega_C Q + r_T)\}} \right) \quad \ldots 6.1$$

where $a_T = a_T' \, D$ = tellurometer reflection coefficient

W_C = angular modulation frequency

Q = the excess transmission time = $c \, \Delta d$

r_T = change of phase at reflection surface $\simeq \pi$

ω_C = angular carrier frequency

C = velocity of electromagnetic waves in space

Δd = the excess path length

a_T' = reflection coefficient for a flat surface

D = divergence factor

c = subscript for "that of the other set"
(M for master, R for remote)

X = reflection phase error

The X in equation 6.1 is calculated for both the master X_M, and the remote XR, giving a total reflection error $X_T = X_M + X_R$. This error is referred to as the Poder error.

Gardiner-Hill (1963) described a method by which the Poder error could be calculated for a particular line providing the length of the line and the heights of the instrument were known. This procedure was used in a programme which calculated the Poder error for a particular line with a reflection coefficient that varied in 0.1 steps from 0.1 to 1.0. The output from this programme lists the two instrument heights H1 and H2, the distance and the reflection coefficient. The Poder error X sum, in centimetres, as well as the particular carrier frequency used to calculate the error are shown as mathematical values and the Poder error is shown graphically plotted against the carrier frequency.

6.2 KÜPFER'S WORK

Küpfer (1967) working with the Wild D150 Distomat extended the work of Poder and presented an alternative form of the Poder equation.

The Poder phase error ε as given by Küpfer is

$$\varepsilon = \text{arc tan}\ \frac{A \sin Z}{1-A(1-\cos Z)} \qquad \ldots\ 6.2$$

where

$$A = \frac{(\cos z + a_T)\ a_T}{1+ 2a_T\cos z + a_T^{2}}$$

where

$$Z = W_C Q$$

$$z = (\omega_C Q + r_T)$$

$$a_T = a_T'\ D$$

and note

$$Q = c\ \Delta d$$

If the expression for A is substituted in that for ε then equation 6.1 results.

This $\varepsilon(\Delta d)$ function is characterized by a fast and slow oscillation. The fast oscillation is the well known swing-curve and the carrier phase in the excess path represents its argument. The slow oscillation influences the form and intensity of the swing curves and the modulation phase in the excess path represents the argument. Both oscillations combine to form a $\varepsilon(\Delta d)$ function of the type shown in figure 6.1 (after Küpfer).

To examine more closely equation 6.2 it is important to look at the extreme values of the envelope of the fast oscillation. These are given by

$$\varepsilon \text{ ext } 1 = \text{arc tan} \left(\frac{a_T \cdot \sin Z}{a_T \cdot \cos Z.+1} \right)$$

and

$$\varepsilon \text{ ext } 2 = \text{arc tan} \left(\frac{a_T \cdot \sin Z}{a_T \cdot \cos Z-1} \right) \quad \ldots \textit{ Küpfer (op. cit.)}$$

Now that these extreme envelopes have been defined it is possible to consider special cases of a_T (the reflection coefficient) and of Z (the modulation phase in the excess path.) *Küpfer (1967)* page 7 and 8 gives some of these special cases. It is interesting to note that for the special case of small intensities of reflection a_T, then

$$A \simeq a_T \cdot \cos z < 0.1 \text{ if } a_T < 0.1$$

hence

$$\begin{aligned} \varepsilon &\simeq A \cdot \sin z \\ &\simeq a_T \cos z \sin Z \\ &\simeq a_T \cos \left(\frac{2\pi\Delta d}{\lambda c} + r_T\right) \sin \frac{2\pi\Delta d}{\lambda m} \end{aligned}$$

which is the Wadley expression as shown in Chapter 5, equation 5.1. (The difference being the r_T term which is the phase change at the reflection surface).

6.3 CRITICAL HEIGHT

It was shown in Chapter 5 that to develop a full cycle of swing over the Warwick Farm base line an excess path length of 0.78 metres was required. This can be generalised in the form that the number of cycles of swing, q, developed is given by

$$q = 1.33\ \Delta d.$$

That is to say, a minimum excess path of 0.78 metres is required to develop one or more cycles of swing. This requirement may be difficult to fulfil over short base lines and *Küpfer (op.cit.)* suggested that the height of the instruments be varied in order to produce a full cycle of swing. It should be noted that if this method is used then the carrier frequency is held fixed. The question is asked,

"What minimum height variation (both stations simultaneously) is required to get one or more swing periods?"

One cycle of swing will be developed if Δd is increased by the carrier wave length (λc).

i.e.

as $\Delta d \simeq \frac{2H^2}{D}$ assuming a level surface.

$D(\Delta d + \lambda c) \simeq 2(H + \Delta H)^2$ where Δh = minimum change

i.e.

$$\Delta h \simeq -H \pm \sqrt{H^2 + \frac{D\lambda c}{2}} \qquad \ldots\ 6.3$$

H = minimum height of height variation.

Δh = height variation for one full cycle of swing.

If the surface is not level between the two instruments then

$$\Delta h \simeq \frac{-(H_2+H_1)}{2} \pm \sqrt{\frac{(H_1+H_2)^2}{4} + \frac{D\lambda c}{2}} \qquad \ldots\ 6.4$$

where

Δh = height change to produce one full cycle of swing

H_1 and H_2 = instrument heights.

If the values for the Warwick Farm base line, D = 183 m and H = 1.35, are substituted in equation 6.3, then Δh = 0.78 metres. Further if the values of D = 183 m, H_1 = 1.35 m and H_2 = 2.20 are substituted in equation 6.4.

then Δh = 0.65 metres.

It is interesting to note that the value of the height change of 0.78 m for a level surface necessary to produce a full cycle of swing is similar to the path difference Δd necessary to produce a full cycle of swing by the carrier shift method over the Warwick Farm base line.

Küpfer (op.cit. page 9 and figure 13) has shown that when $z \simeq \pi$, or $(2n+1)\pi$, a critical phase state exists causing large negative peaks in the ground swing curve. It is therefore important to look at the instrument heights called critical heights that will give z a value of 180° and if possible avoid these heights in practice.

by definition $z \simeq (\frac{2\pi\Delta d}{\lambda c} + r_T)$

where $r_T \simeq \pi$

$\therefore \quad z = \pi(\frac{2\Delta d}{\lambda c} + 1)$

$z = \pi, 3\pi, 5\pi$ must be avoided.

i.e. when

$$\frac{2\Delta d}{\lambda c} = 2n \qquad n = 0,1,2,3$$

$$2\Delta d = 2(\frac{2h_c^2}{D})$$

$$= \frac{4h_c^2}{D} \qquad \text{where } h_c = \text{critical height}$$

or

$$hc = \sqrt{\frac{D\lambda_c n}{2}} \qquad \ldots 6.5$$

This has been derived for a level surface with equal instrument heights. If an even sloping surface is considered with equal instrument heights then

$$h_c = \pm\sqrt{\frac{\Delta H^2}{4} + \frac{D.n\lambda_c}{2}} - \frac{\Delta H}{2} \qquad n = 0.1.2.3 \qquad \ldots 6.6$$

The critical heights for the Warwick Farm base line calculated from equation 6.5 for the particular carrier frequencies and for n = 0 to 40 inclusive are shown in tables 6.1 to 6.4 inclusive. The critical heights as defined by equation 6.6 for the same conditions as above were calculated and are shown in tables 6.5 to 6.8 inclusive.

6.4 EXPERIMENT

An experiment was carried out at the Warwick Farm base line to study the effect of instrument height change on distance indication and also on ground swing curve production. The instrument height was changed through a maximum range of 0.30 metres. As shown in section 6.3 this height change is too small to produce a full cycle of swing, a change of 0.78 to 0.65 metres being necessary. The instrument height was varied over this 0.30 metres using the equipment described in section 2.1.3. The method of measurement used for the work is described below.

The instruments were set over the base terminals at similar heights above the ground with the height change apparatus set to its maximum value. The instruments were pointed towards each other and tuned in the conventional manner and the A forward fine reading taken for the particular carrier frequency setting. Each instrument was then lowered one centimetre and the null meter read according to the modified method of measurement as shown in Appendix 4. The instruments were then lowered another centimetre and the null meter recorded. This was repeated until the full range (30 centimetres) was completed. The instruments were then returned to the maximum height and the A reverse fine reading taken. The instrument was then lowered as above and a null meter reading was taken at each centimetre. The accepted value of the distance for each height and carrier frequency setting was the mean of the forward and reverse readings.

6.5 RESULTS

A graph of the indicated distance versus the height of the instrument is shown in figure 6.2. It can be seen that the minimum distance occurred at an instrument height of 1.60 metres. Graphs have also been drawn of indicated distance for a particular carrier frequency and instrument height for each instrument as master. See figure 6.3 for No. 110 as master and figure 6.4 for No. 113 as master. It can be seen from figures 6.3 and 6.4 that a critical height occurred at an instrument height of 1.60 metres. In order to further examine this area another height change experiment was carried out over the same base line for carrier frequencies of 8.0 to 4.0 and instrument heights of 1.65 to 1.55. This section was reobserved because it appeared to contain the critical height.

The observations were made as described above with the following modification. The carrier frequencies were changed by ½ settings (i.e. on a 20 fine reading basis) and the instrument heights were changed by 5 millimetre steps. The distance indication resulting from a particular carrier setting and instrument height is shown in figure 6.5 for instrument No. 110 as master and in figure 6.6 for instrument No. 113 as master. It can be seen from figures 6.5 and 6.6 that a critical height exists at an instrument height of about 1.585 metres which compares favourably with the height of 1.60 from the previous experiment.

It is interesting to note that the first critical height as predicted by equation 6,5 is, 1.65 metres (table 6.1) and the height as predicted by equation 6.6 is 1.278 (table 6.5). The observed critical height of 1.60 lies in between these values and this can be accounted for by the examination of the profile of the Warwick Farm Base Line, figure 3.4 which shows that the base line is neither evenly sloping, (this assumption was used in the derivation of equation 6.6), nor level, (assumption used in the derivation of equation 6.5). A close study of figures 6.3 and 6.4 reveals that the frequency shift method of measurement would sample the indicated distance across the contours (of distance). This gives the well known ground swing curve. In fact the ground swing curves for a particular instrument height can be obtained by taking the values of the indicated distance from the figure and plotting these for the carrier frequencies. If this is done the resulting curves are similar to the swing curves observed during the zero error measurements and the ground measurements taken as part of the tower measurements.

If the height change method is considered for a fixed carrier frequency for this particular experiment a sample would be taken along the contours (of distance). A full cycle of swing would not be obtained, in fact, the distance indication (against height for a particular carrier frequency) would vary only marginally around a certain value. This was to be expected as section 6.3 predicted that a height change of from 0.65m to 0.78m would be necessary to produce a full cycle of swing by the height change method over the Warwick Farm base line.

Examination of the instrument heights for the tower experiments shows that the measurement from N2 to S2 (instrument height of 9 metres) is a predicted critical height for n = 30 equation 6.5, and a predicted critical height for n = 33 equation 6.6. However, examination of the measurements of the line shows that although no difficulties were experienced with the measurement, the observed ground swing curve for instrument No. 113 as master exhibited a rather large negative peak, and that for instrument No. 110 as master has a similar form but with smaller magnitude. These curves are shown in figures 6.7 and 6.8. It is interesting to note that a repeated measurement taken 4 days later over this line under similar weather conditions did not display the negative peaks and the value of the ground swings were 10.5 and 9.5 centimetres for instrument No. 110 and 113 respectively. The predicted ground swing curve according to *Wadley (equation 5.1)* for this line is shown in figure 6.9, and it can be seen from this graph that there does not appear to be any indication of the existence of a critical height.

The predicted error curve according to Poder, equation 6.1, for this line is shown in figure 6.10 and one can see immediately the existence of the negative peak, possibly indicating a critical height. Note for both figure 6.9 and 6.10 a reflection coefficient of 0.20 was used. Further examination of the tower heights show that instrument height of 12.66 metres and 16.33 metres, i.e. measurements from S3 to N3 and from S4 to N4 respectively are also predicted critical heights from equation 6.6. However examination of the Poder Error curve shows these graphs to be "normal" (i.e. the graphs do not exhibit any abnormality in the form of large negative peaks). Also no difficulty was experienced with the measurements of both these lines. It is very interesting to note that as the value for n in equation 6.6 is increased from 50 to 150, the predicted critical heights occur at instrument heights which are separated at about one centimetre intervals. The tower measurements certainly did not support the predictions of a critical height occurring every centimetre. Consideration must be given to the fact that for the tower measurements the frequency change method of measurement was used and this in itself could have masked the effect of critical heights.

As mentioned in 6.1 the Poder phase error was programmed so that it could be calculated for the ground measurements and the tower measurements for the Warwick Farm base line. The output shows that for small reflection coefficients the Poder error for the ground measurements is less than 1 centimetre. Further, for the tower measurements and for reflection coefficients of 0.1 and 0.2 the Poder curve is very similar to the Wadley curve which was expected, see Section 6.2.

6.6 CONCLUSION

The results clearly show that certain instrument heights called critical heights exist, and at these heights the displayed distance can be in error by a large amount. If tellurometers are to be calibrated over a short base line then users must be very careful, and avoid these heights. These heights can be easily calculated using equation 6.3 for equal instrument heights over level ground and equation 6.4 for equal instrument heights over evenly sloping ground.

The *Küpfer (op. cit.)* technique of producing a cycle of swing over a short line, where the excess path length is small, by the change of height method cannot be fully examined here because of the limited height change available. This method may be difficult to use in the field because one would need a special tripod or would need to modify an existing tripod in a similar way so that described in 2.1.2 to provide a range of height shift necessary to produce a full cycle of swing.

CRITICAL HEIGHTS

DISTANCE = 182.694

FREQUENCY (MHZ)	N									
	1	2	3	4	5	6	7	8	9	10
10054	1.650	2.334	2.859	3.301	3.690	4.043	4.367	4.668	4.951	5.219
10065	1.650	2.333	2.857	3.299	3.688	4.040	4.364	4.666	4.949	5.216
10094	1.647	2.329	2.853	3.294	3.683	4.035	4.358	4.659	4.941	5.209
10098	1.647	2.329	2.852	3.294	3.682	4.034	4.357	4.658	4.940	5.208
10111	1.646	2.327	2.851	3.292	3.680	4.031	4.354	4.655	4.937	5.204
10126	1.645	2.326	2.848	3.289	3.677	4.028	4.351	4.651	4.934	5.200
10144	1.643	2.324	2.846	3.286	3.674	4.025	4.347	4.647	4.929	5.196
10162	1.642	2.322	2.843	3.283	3.671	4.021	4.343	4.643	4.925	5.191
10183	1.640	2.319	2.840	3.280	3.667	4.017	4.339	4.638	4.920	5.186
10204	1.638	2.317	2.838	3.276	3.663	4.013	4.334	4.634	4.915	5.181
10224	1.637	2.315	2.835	3.273	3.660	4.009	4.330	4.629	4.910	5.176
10241	1.635	2.313	2.832	3.271	3.657	4.006	4.327	4.625	4.906	5.171
10263	1.634	2.310	2.829	3.267	3.653	4.001	4.322	4.620	4.901	5.166
10282	1.632	2.308	2.827	3.264	3.649	3.998	4.318	4.616	4.896	5.161
10304	1.630	2.306	2.824	3.261	3.645	3.993	4.313	4.611	4.891	5.155
10324	1.629	2.303	2.821	3.257	3.642	3.989	4.309	4.607	4.886	5.150
10339	1.628	2.302	2.819	3.255	3.639	3.987	4.306	4.603	4.883	5.147
10350	1.627	2.300	2.817	3.253	3.637	3.984	4.304	4.601	4.880	5.144
10381	1.624	2.297	2.813	3.248	3.632	3.978	4.297	4.594	4.873	5.136
10390	1.624	2.296	2.812	3.247	3.630	3.977	4.295	4.592	4.871	5.134

TABLE 6.1

CRITICAL HEIGHTS

DISTANCE = 182.694

FREQUENCY (MHZ)	N									
	11	12	13	14	15	16	17	18	19	20
10054	5.474	5.717	5.951	6.175	6.392	6.602	6.805	7.002	7.194	7.381
10065	5.471	5.714	5.947	6.172	6.389	6.598	6.801	6.998	7.190	7.377
10094	5.463	5.706	5.939	6.163	6.379	6.589	6.791	6.988	7.180	7.366
10098	5.462	5.705	5.938	6.162	6.378	6.587	6.790	6.987	7.178	7.365
10111	5.458	5.701	5.934	6.158	6.374	6.583	6.786	6.982	7.174	7.360
10126	5.454	5.697	5.929	6.153	6.369	6.578	6.781	6.977	7.168	7.355
10144	5.449	5.692	5.924	6.148	6.364	6.572	6.775	6.971	7.162	7.348
10162	5.445	5.687	5.919	6.142	6.358	6.566	6.769	6.965	7.156	7.342
10183	5.439	5.681	5.913	6.136	6.351	6.560	6.762	6.958	7.148	7.334
10204	5.433	5.675	5.907	6.130	6.345	6.553	6.755	6.950	7.141	7.326
10224	5.428	5.669	5.901	6.124	6.339	6.547	6.748	6.944	7.134	7.319
10241	5.424	5.665	5.896	6.119	6.333	6.541	6.742	6.938	7.128	7.313
10263	5.418	5.659	5.890	6.112	6.327	6.534	6.735	6.930	7.120	7.305
10282	5.413	5.653	5.884	6.106	6.321	6.528	6.729	6.924	7.114	7.299
10304	5.407	5.647	5.878	6.100	6.314	6.521	6.722	6.917	7.106	7.291
10324	5.402	5.642	5.872	6.094	6.308	6.515	6.715	6.910	7.099	7.284
10339	5.398	5.638	5.868	6.090	6.303	6.510	6.710	6.905	7.094	7.278
10350	5.395	5.635	5.865	6.086	6.300	6.507	6.707	6.901	7.090	7.275
10381	5.387	5.626	5.856	6.077	6.291	6.497	6.697	6.891	7.080	7.264
10390	5.385	5.624	5.854	6.075	6.288	6.494	6.694	6.888	7.077	7.261

TABLE 6.2

CRITICAL HEIGHTS

DISTANCE = 182.694

FREQUENCY (MHZ)	N 21	22	23	24	25	26	27	28	29	30
10054	7.563	7.741	7.915	8.085	8.252	8.416	8.576	8.733	8.888	9.040
10065	7.559	7.737	7.911	8.081	8.248	8.411	8.571	8.728	8.883	9.035
10094	7.548	7.726	7.899	8.069	8.236	8.399	8.559	8.716	8.870	9.022
10098	7.547	7.724	7.898	8.068	8.234	8.397	8.557	8.714	8.868	9.020
10111	7.542	7.719	7.893	8.063	8.229	8.392	8.552	8.709	8.863	9.014
10126	7.536	7.714	7.887	8.057	8.223	8.386	8.545	8.702	8.856	9.008
10144	7.530	7.707	7.880	8.049	8.215	8.378	8.538	8.694	8.848	9.000
10162	7.523	7.700	7.873	8.042	8.208	8.371	8.530	8.687	8.840	8.992
10183	7.515	7.692	7.865	8.034	8.200	8.362	8.521	8.678	8.831	8.982
10204	7.507	7.648	7.857	8.026	8.191	8.353	8.513	8.669	8.822	8.973
10224	7.500	7.677	7.849	8.018	8.183	8.345	8.504	8.660	8.814	8.964
10241	7.494	7.670	7.843	8.011	8.176	8.338	8.497	8.653	8.806	8.957
10263	7.486	7.662	7.834	8.003	8.168	8.329	8.488	8.644	8.797	8.947
10232	7.479	7.655	7.827	7.995	8.160	8.322	8.480	8.636	8.789	8.939
10304	7.471	7.647	7.819	7.987	8.151	8.313	8.471	8.627	8.779	8.929
10324	7.464	7.639	7.811	7.979	8.143	8.305	8.463	8.618	8.771	8.921
10339	7.458	7.634	7.805	7.973	8.138	8.299	8.457	8.612	8.764	8.914
10350	7.454	7.630	7.801	7.969	8.133	8.294	8.452	8.607	8.760	8.910
10381	7.443	7.618	7.789	7.957	8.121	8.282	8.440	8.595	8.747	8.896
10390	7.440	7.615	7.786	7.954	8.118	8.278	8.436	8.591	8.743	8.892

TABLE 6.3

CRITICAL HEIGHTS

DISTANCE = 182.694

FREQUENCY (MHZ)	N									
	31	32	33	34	35	36	37	38	39	40
10054	9.189	9.336	9.481	9.623	9.764	9.902	10.039	10.174	10.307	10.438
10065	9.184	9.331	9.476	9.618	9.759	9.897	10.034	10.168	10.301	10.432
10094	9.171	9.318	9.462	9.604	9.745	9.883	10.019	10.154	10.286	10.417
10098	9.169	9.316	9.460	9.603	9.743	9.881	10.017	10.152	10.284	10.415
10111	9.163	9.310	9.454	9.596	9.736	9.875	10.011	10.145	10.278	10.409
10126	9.156	9.303	9.447	9.589	9.729	9.867	10.003	10.138	10.270	10.401
10144	9.148	9.295	9.439	9.581	9.721	9.858	9.994	10.129	10.261	10.392
10162	9.140	9.286	9.430	9.572	9.712	9.850	9.986	10.120	10.252	10.383
10183	9.131	9.277	9.421	9.562	9.702	9.840	9.975	10.109	10.241	10.372
10204	9.121	9.267	9.411	9.553	9.692	9.829	9.965	10.099	10.231	10.361
10224	9.112	9.258	9.402	9.543	9.682	9.820	9.955	10.089	10.221	10.351
10241	9.105	9.251	9.394	9.535	9.674	9.812	9.947	10.081	10.212	10.342
10263	9.095	9.241	9.384	9.525	9.664	9.801	9.936	10.070	10.201	10.331
10282	9.087	9.232	9.375	9.516	9.655	9.792	9.927	10.060	10.192	10.322
10304	9.077	9.222	9.365	9.506	9.645	9.782	9.917	10.050	10.181	10.311
10324	9.068	9.213	9.356	9.497	9.635	9.772	9.907	10.040	10.171	10.301
10339	9.062	9.207	9.349	9.490	9.628	9.765	9.900	10.033	10.164	10.293
10350	9.057	9.202	9.344	9.485	9.623	9.760	9.894	10.027	10.158	10.288
10381	9.043	9.188	9.330	9.471	9.609	9.745	9.880	10.012	10.143	10.272
10390	9.039	9.184	9.326	9.467	9.605	9.741	9.875	10.008	10.139	10.268

TABLE 6.4

DISTANCE = 182.694

CRITICAL HEIGHTS

FREQUENCY (MHZ)	N 1	2	3	4	5	6	7	8	9	10
10054	1.278	1.946	2.464	2.902	3.288	3.638	3.961	4.261	4.543	4.810
10065	1.277	1.945	2.462	2.900	3.286	3.636	3.958	4.258	4.540	4.807
10094	1.275	1.941	2.458	2.895	3.281	3.630	3.952	4.252	4.533	4.799
10098	1.274	1.941	2.457	2.894	3.280	3.630	3.951	4.251	4.532	4.798
10111	1.273	1.940	2.456	2.892	3.278	3.627	3.948	4.248	4.529	4.795
10126	1.272	1.938	2.454	2.890	3.275	3.624	3.945	4.244	4.525	4.791
10144	1.271	1.936	2.451	2.887	3.272	3.621	3.941	4.240	4.521	4.787
10162	1.269	1.934	2.449	2.884	3.269	3.617	3.938	4.236	4.517	4.782
10183	1.268	1.931	2.446	2.881	3.265	3.613	3.933	4.231	4.512	4.777
10204	1.266	1.929	2.443	2.877	3.261	3.609	3.929	4.227	4.507	4.771
10224	1.265	1.927	2.440	2.874	3.258	3.605	3.924	4.222	4.502	4.766
10241	1.263	1.925	2.438	2.872	3.255	3.602	3.921	4.218	4.498	4.762
10263	1.262	1.923	2.435	2.868	3.251	3.597	3.916	4.213	4.492	4.757
10282	1.260	1.920	2.432	2.865	3.247	3.594	3.912	4.209	4.488	4.752
10304	1.258	1.918	2.429	2.862	3.244	3.589	3.908	4.204	4.483	4.746
10324	1.257	1.916	2.426	2.859	3.240	3.586	3.903	4.200	4.478	4.741
10339	1.256	1.914	2.424	2.856	3.237	3.583	3.900	4.196	4.474	4.738
10350	1.255	1.913	2.423	2.854	3.236	3.581	3.898	4.194	4.472	4.735
10381	1.253	1.910	2.419	2.850	3.230	3.575	3.892	4.187	4.465	4.727
10390	1.252	1.909	2.417	2.848	3.229	3.573	3.890	4.185	4.462	4.725

TABLE 6.5

CRITICAL HEIGHTS

DISTANCE = 182.694

FREQUENCY (MHZ)	N 11	12	13	14	15	16	17	18	19	20
10054	5.064	5.306	5.539	5.763	5.980	6.189	6.392	6.588	6.780	6.967
10065	5.061	5.303	5.536	5.760	5.976	6.185	6.388	6.585	6.776	6.962
10094	5.053	5.295	5.527	5.751	5.967	6.176	6.378	6.575	6.766	6.952
10098	5.052	5.294	5.526	5.750	5.966	6.174	6.377	6.573	6.764	6.950
10111	5.048	5.290	5.522	5.746	5.962	6.170	6.372	6.569	6.760	6.946
10126	5.044	5.286	5.518	5.741	5.957	6.165	6.367	6.564	6.754	6.940
10144	5.039	5.281	5.513	5.736	5.951	6.159	6.361	6.557	6.748	6.934
10162	5.035	5.276	5.508	5.730	5.946	6.154	6.355	6.551	6.742	6.927
10183	5.029	5.270	5.502	5.724	5.939	6.147	6.348	6.544	6.734	6.920
10204	5.023	5.264	5.495	5.718	5.933	6.140	6.341	6.537	6.727	6.912
10224	5.018	5.259	5.490	5.712	5.926	6.134	6.335	6.530	6.720	6.905
10241	5.014	5.254	5.485	5.707	5.921	6.128	6.329	6.524	6.714	6.899
10263	5.008	5.248	5.478	5.700	5.914	6.121	6.322	6.517	6.706	6.891
10282	5.003	5.243	5.473	5.695	5.908	6.115	6.316	6.510	6.700	6.884
10304	4.997	5.237	5.467	5.688	5.902	6.108	6.309	6.503	6.692	6.877
10324	4.992	5.231	5.461	5.682	5.896	6.102	6.302	6.496	6.685	6.870
10339	4.988	5.227	5.457	5.678	5.891	6.097	6.297	6.491	6.680	6.864
10350	4.985	5.224	5.454	5.675	5.888	6.094	6.294	6.488	6.677	6.860
10381	4.977	5.216	5.445	5.666	5.878	6.084	6.284	6.477	6.666	6.850
10390	4.975	5.213	5.442	5.663	5.876	6.081	6.281	6.474	6.663	6.846

TABLE 6.6

CRITICAL HEIGHTS

DISTANCE = 182.694

FREQUENCY (MHZ)	N									
	21	22	23	24	25	26	27	28	29	30
10054	7.148	7.326	7.500	7.670	7.836	8.000	8.160	8.317	8.471	8.623
10065	7.144	7.322	7.496	7.665	7.832	7.995	8.155	8.312	8.466	8.618
10094	7.134	7.311	7.484	7.654	7.820	7.983	8.143	8.300	8.454	8.605
10098	7.132	7.309	7.483	7.652	7.818	7.981	8.141	8.298	8.452	8.603
10111	7.127	7.304	7.478	7.647	7.813	7.976	8.136	8.292	8.446	8.598
10126	7.122	7.299	7.472	7.641	7.807	7.970	8.129	8.286	8.440	8.591
10144	7.115	7.292	7.465	7.634	7.800	7.962	8.122	8.278	8.432	8.583
10162	7.108	7.285	7.458	7.627	7.792	7.955	8.114	8.270	8.424	8.575
10183	7.101	7.277	7.450	7.619	7.784	7.946	8.105	8.261	8.415	8.566
10204	7.093	7.269	7.442	7.610	7.776	7.938	8.097	8.253	8.406	8.556
10224	7.085	7.262	7.434	7.603	7.768	7.929	8.088	8.244	8.397	8.548
10241	7.079	7.255	7.427	7.596	7.761	7.923	8.081	8.237	8.390	8.540
10263	7.071	7.247	7.419	7.587	7.752	7.914	8.072	8.228	8.380	8.531
10282	7.064	7.240	7.412	7.580	7.745	7.906	8.064	8.220	8.372	8.522
10304	7.056	7.232	7.403	7.571	7.736	7.897	8.055	8.210	8.363	8.513
10324	7.049	7.224	7.396	7.564	7.728	7.889	8.047	8.202	8.354	8.504
10339	7.044	7.219	7.390	7.558	7.722	7.883	8.041	8.196	8.348	8.498
10350	7.040	7.215	7.386	7.554	7.718	7.879	8.036	8.191	8.343	8.493
10381	7.029	7.203	7.374	7.542	7.706	7.866	8.024	8.178	8.330	8.480
10390	7.025	7.200	7.371	7.538	7.702	7.863	8.020	8.175	8.327	8.476

TABLE 6.7

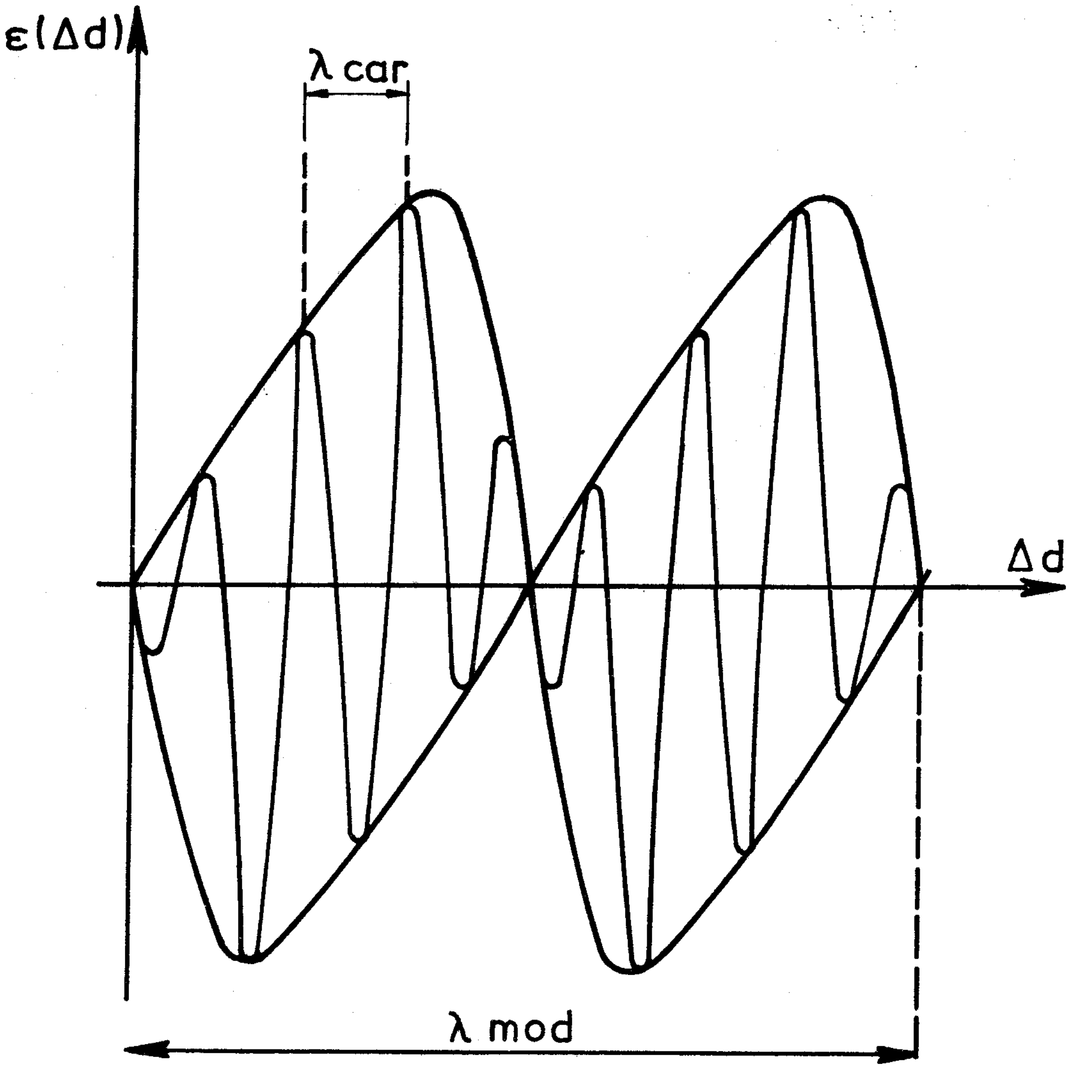
DISTANCE = 182.694

CRITICAL HEIGHTS

N

FREQUENCY (MHZ)	31	32	33	34	35	36	37	38	39	40
10054	8.772	8.919	9.064	9.206	9.347	9.485	9.621	9.756	9.889	10.020
10065	8.767	8.914	9.059	9.201	9.341	9.480	9.616	9.751	9.883	10.014
10094	8.754	8.901	9.045	9.187	9.327	9.465	9.602	9.736	9.869	9.999
10098	8.752	8.899	9.043	9.185	9.325	9.463	9.600	9.734	9.867	9.997
10111	8.746	8.893	9.037	9.179	9.319	9.457	9.593	9.727	9.860	9.991
10126	8.740	8.886	9.030	9.172	9.312	9.450	9.586	9.720	9.852	9.983
10144	8.732	8.878	9.022	9.164	9.303	9.441	9.577	9.711	9.843	9.974
10162	8.723	8.870	9.013	9.155	9.295	9.432	9.568	9.702	9.834	9.965
10183	8.714	8.860	9.004	9.145	9.285	9.422	9.558	9.692	9.824	9.954
10204	8.705	8.850	8.994	9.135	9.275	9.412	9.547	9.681	9.813	9.943
10224	8.696	8.841	8.985	9.126	9.265	9.402	9.538	9.671	9.803	9.933
10241	8.688	8.834	8.977	9.118	9.257	9.394	9.529	9.663	9.795	9.925
10263	8.678	8.824	8.967	9.108	9.247	9.384	9.519	9.652	9.784	9.913
10282	8.670	8.815	8.958	9.099	9.238	9.375	9.510	9.643	9.774	9.904
10304	8.660	8.805	8.948	9.089	9.228	9.364	9.499	9.632	9.763	9.893
10324	8.652	8.796	8.939	9.080	9.218	9.355	9.489	9.622	9.753	9.883
10339	8.645	8.790	8.932	9.073	9.211	9.348	9.482	9.615	9.746	9.875
10350	8.640	8.785	8.927	9.068	9.216	9.342	9.477	9.610	9.741	9.870
10381	8.627	8.771	8.913	9.054	9.192	9.328	9.462	9.595	9.725	9.855
10390	8.623	8.767	8.909	9.050	9.188	9.324	9.458	9.590	9.721	9.850

TABLE 6.8



Error Versus Excess Path
(after Küpfer)

FIG. 6·1

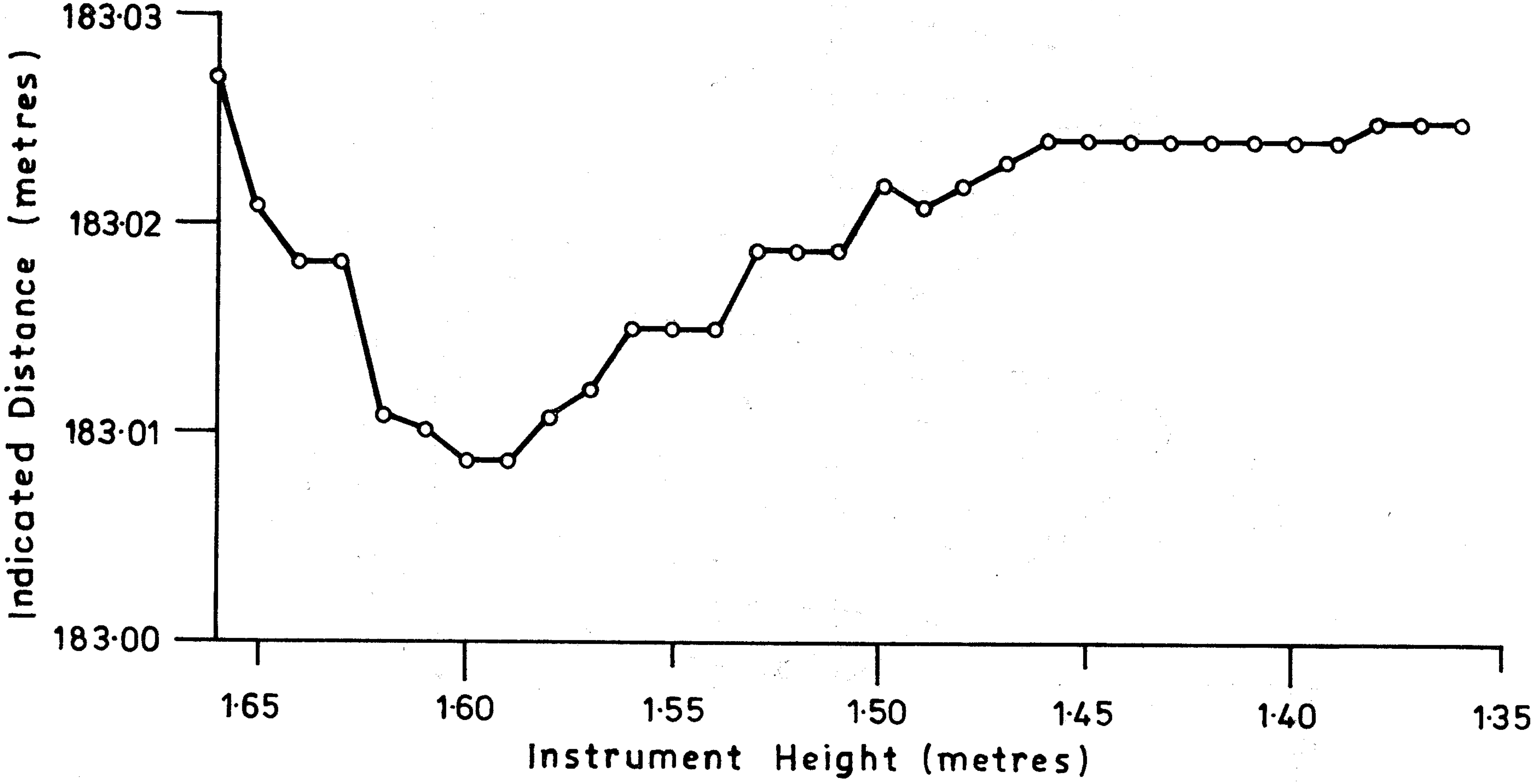
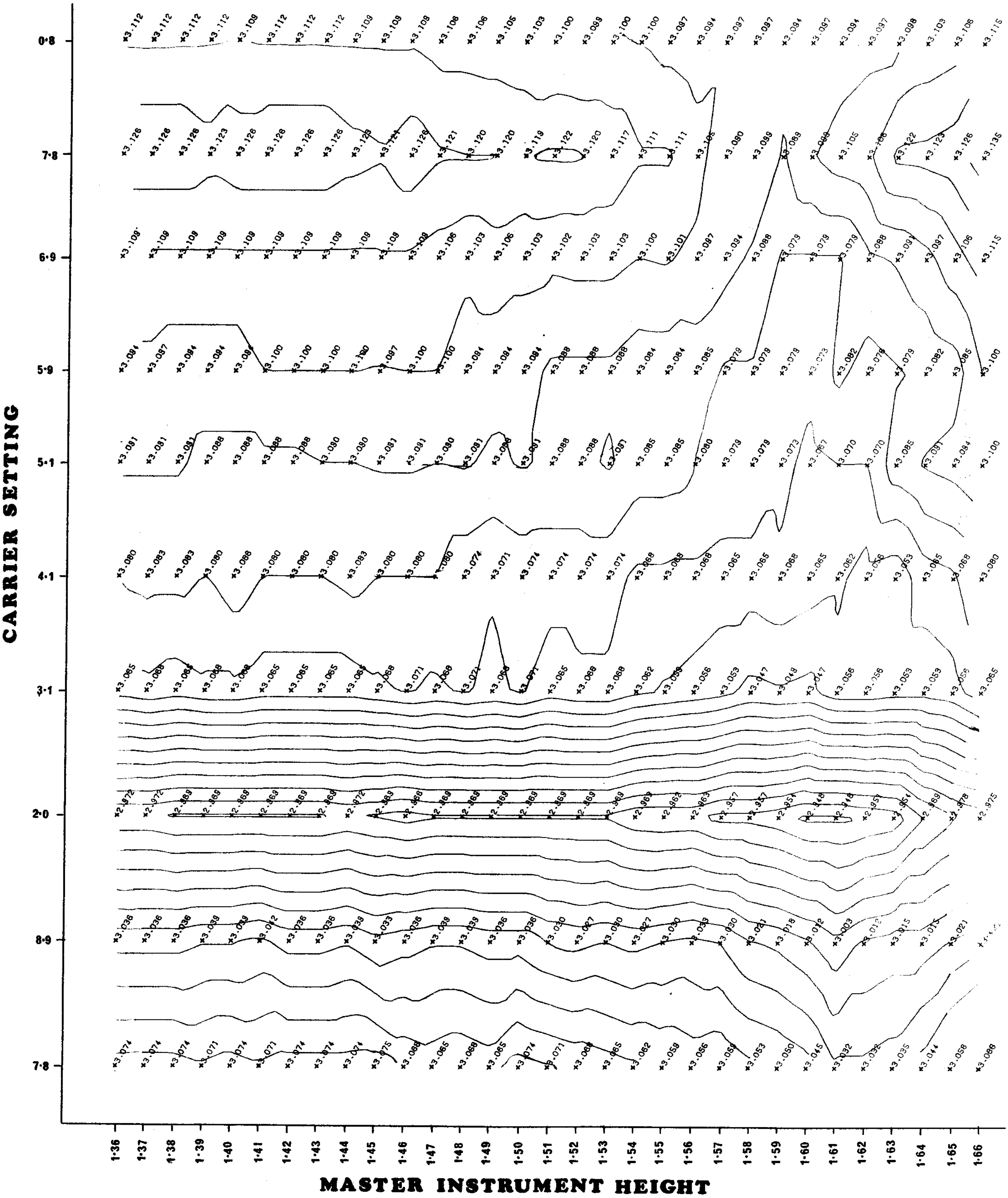

183·03
183·02
183·01
183·00
Indicated Distance (metres)
1·65
1·60
1·55
1·50
1·45
1·40
1·35
Instrument Height (metres)

FIG. 6·2

INSTRUMENT No 110 AS MASTER

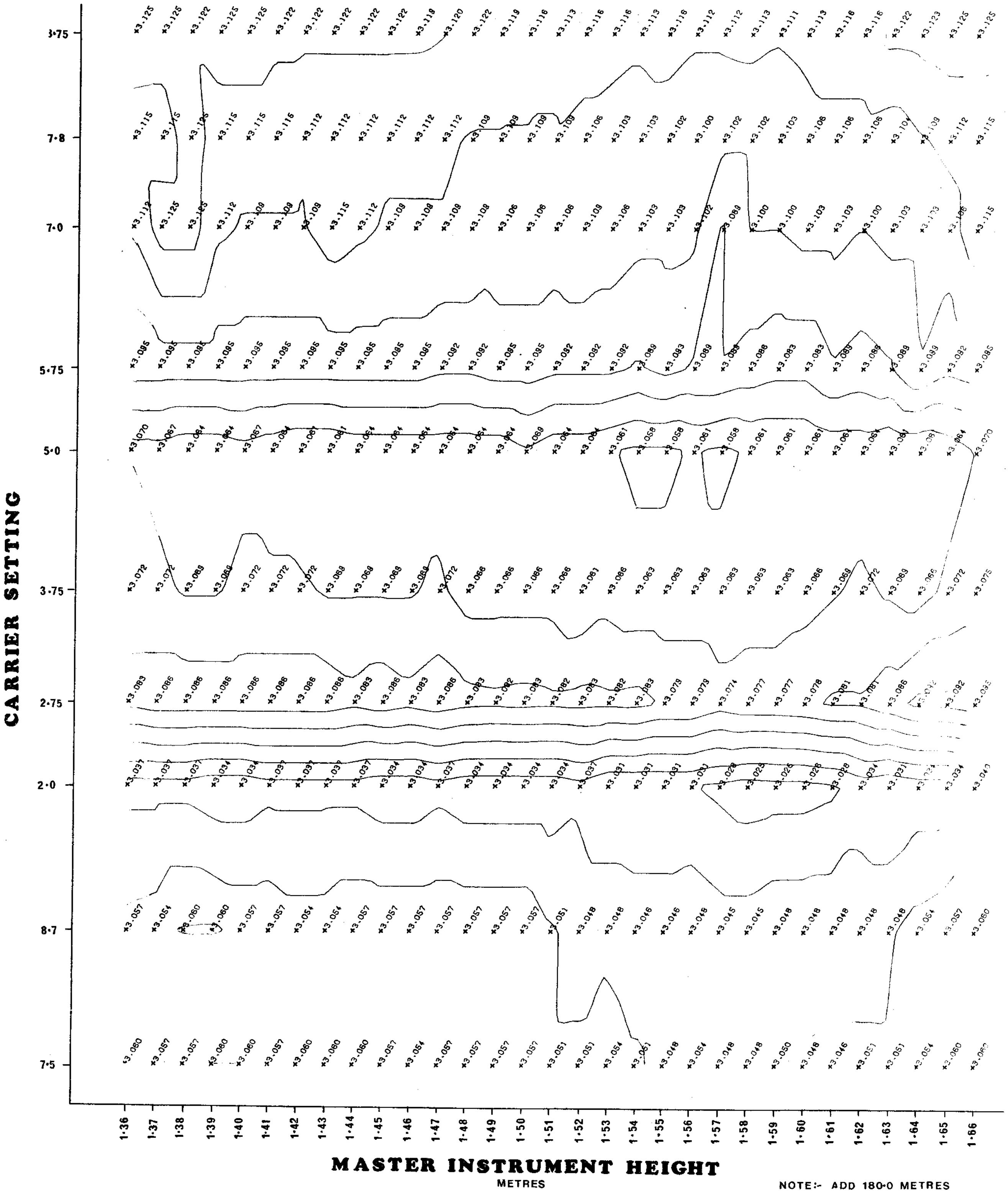


NOTE:- ADD 180·0 METRES
TO ALL DISTANCES

CENTIMETRE CONTOURS

fig. 6·3

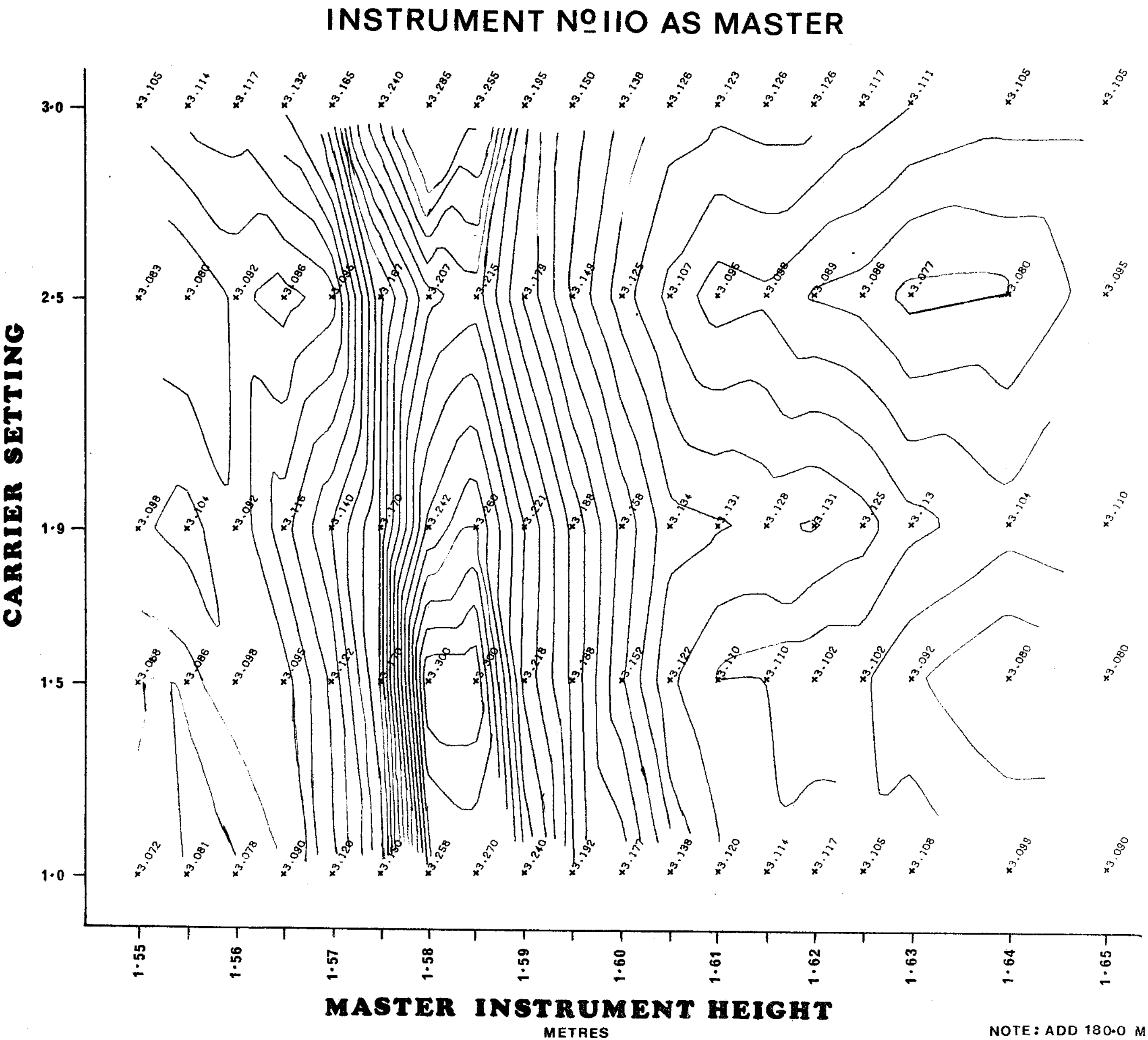
INSTRUMENT Nº113 AS MASTER



NOTE:- ADD 180·0 METRES
TO ALL DISTANCES

CENTIMETRE CONTOURS

fig. 6·4

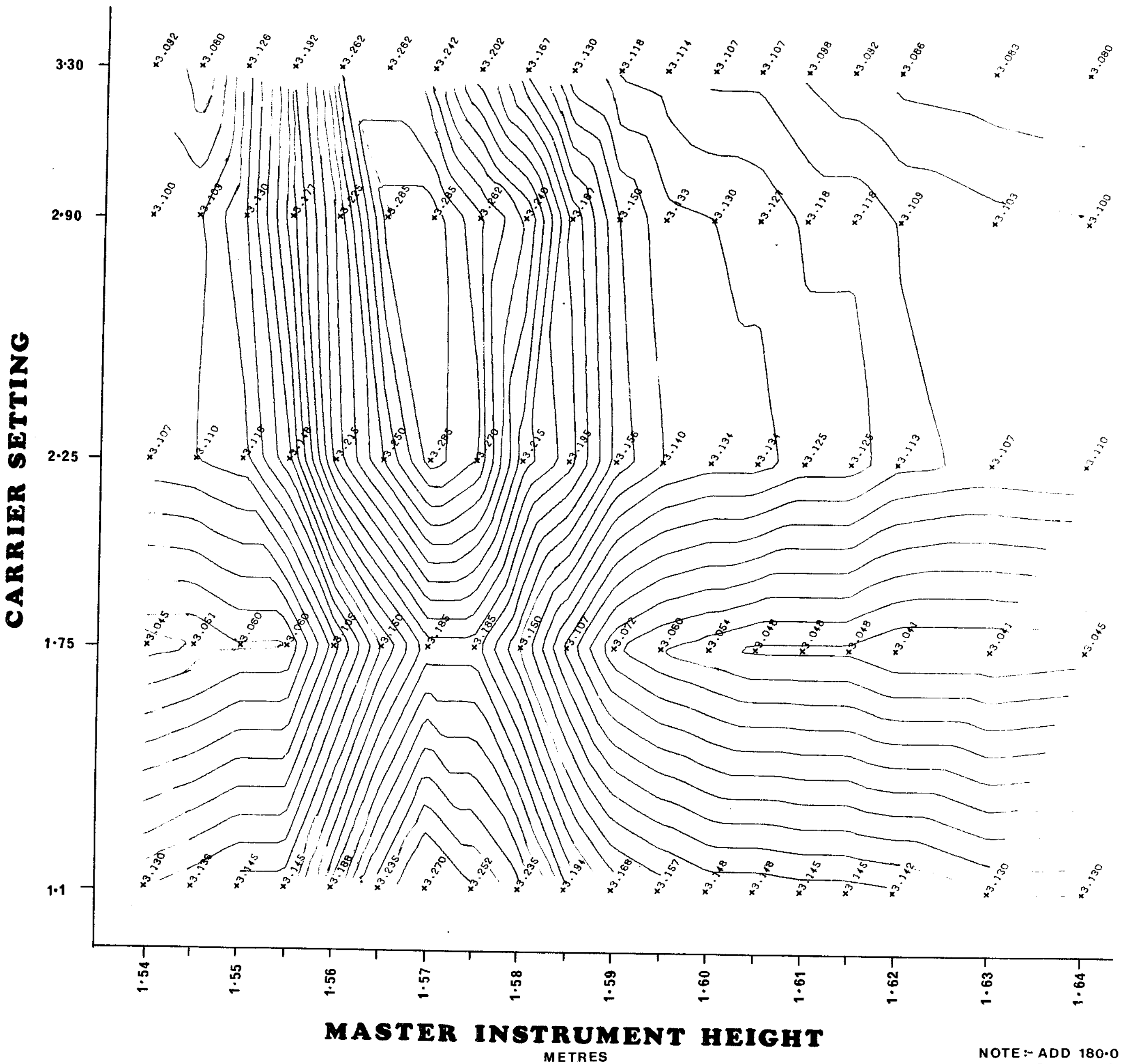


NOTE: ADD 180·0 METRES
TO ALL DISTANCES

CENTIMETRE CONTOURS

fig 6·5

INSTRUMENT Nº113 AS MASTER



NOTE:- ADD 180·0 METRE
TO ALL DISTANCES

CENTIMETRE CONTOURS

fig. 6·6

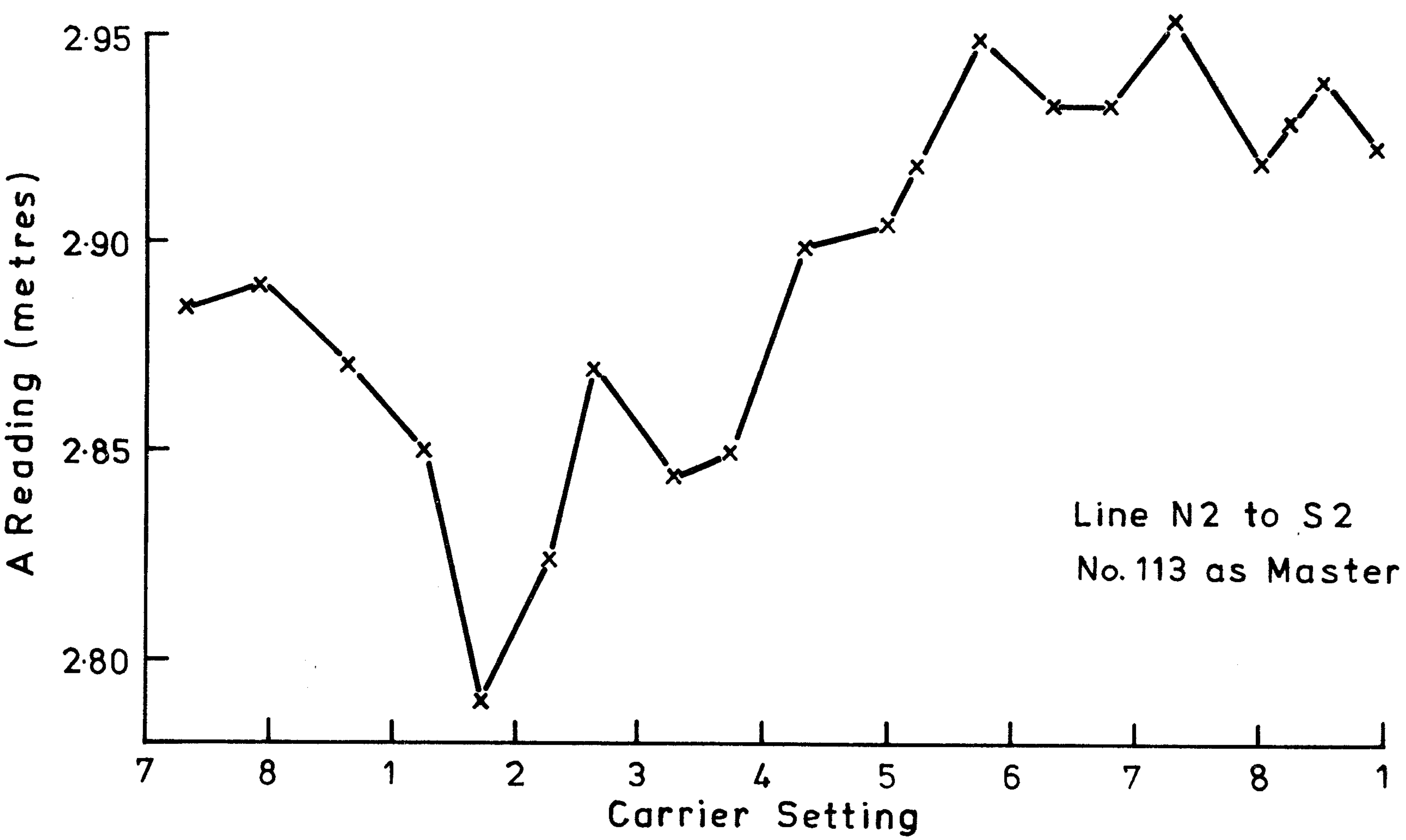

A Reading (metres)
2·95
2·90
2·85
2·80
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
Line N2 to S2
No. 113 as Master

FIG. 6·7

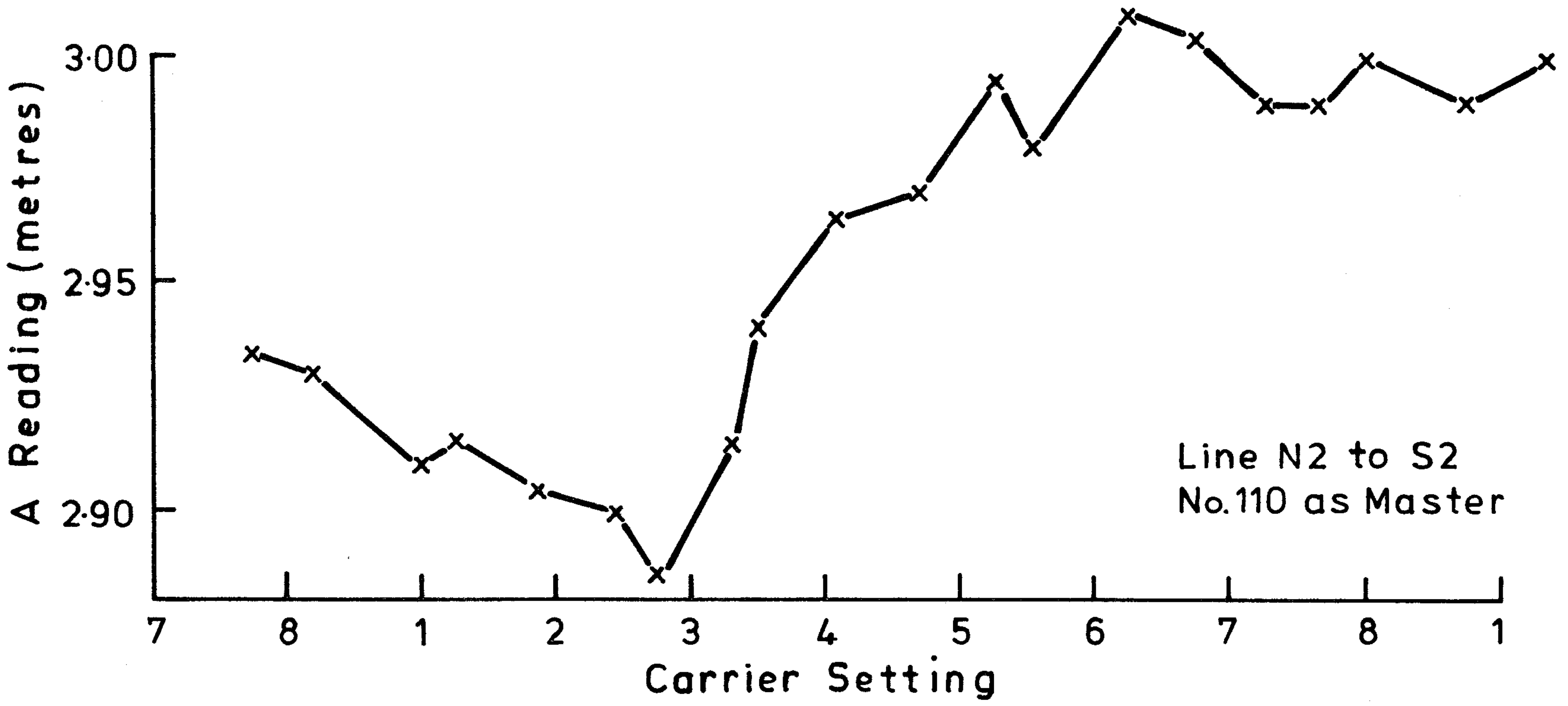
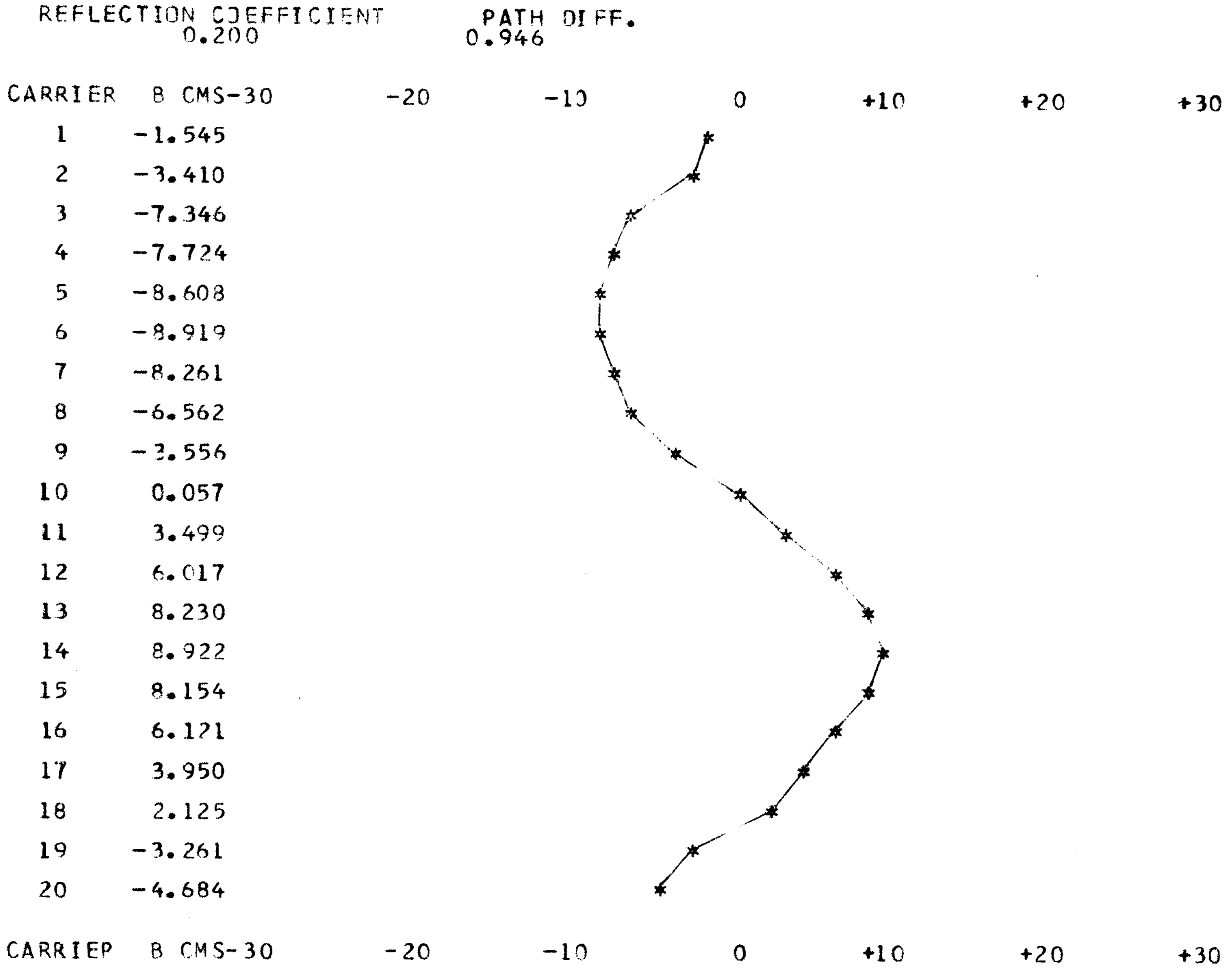

A Reading (metres)
3·00
2·95
2·90
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
Line N2 to S2
No.110 as Master

FIG. 6·8

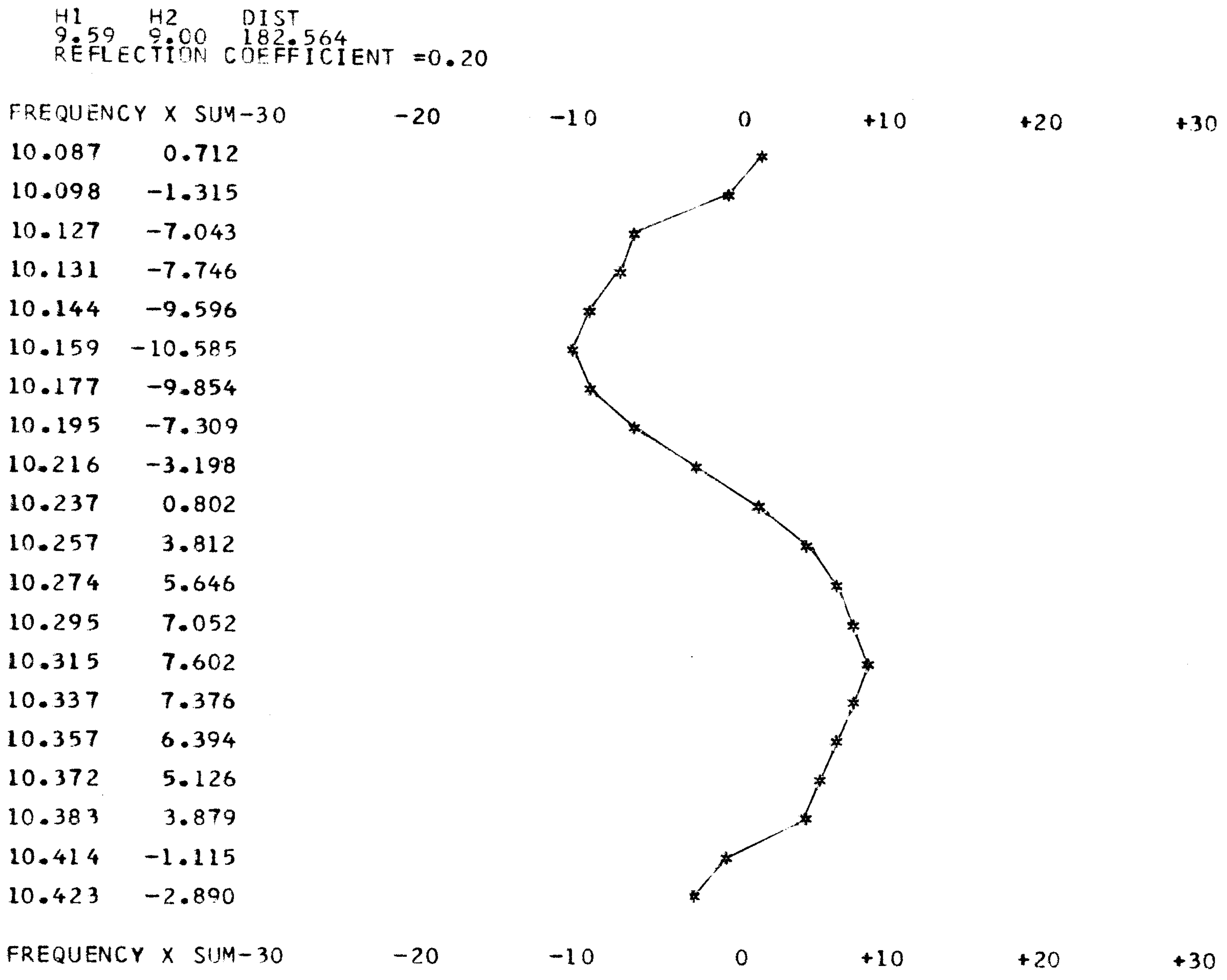


```
REFLECTION COEFFICIENT      PATH DIFF.
        0.200               0.946

CARRIER  B CMS-30     -20      -10      0      +10      +20      +30
   1      -1.545
   2      -3.410
   3      -7.346
   4      -7.724
   5      -8.608
   6      -8.919
   7      -8.261
   8      -6.562
   9      -3.556
  10       0.057
  11       3.499
  12       6.017
  13       8.230
  14       8.922
  15       8.154
  16       6.121
  17       3.950
  18       2.125
  19      -3.261
  20      -4.684

CARRIER  B CMS-30     -20      -10      0      +10      +20      +30
```

FIG. 6.9



```
H1    H2    DIST
9.59  9.00  182.564
REFLECTION COEFFICIENT =0.20

FREQUENCY X SUM-30       -20      -10       0      +10      +20      +30
10.087     0.712
10.098    -1.315
10.127    -7.043
10.131    -7.746
10.144    -9.596
10.159   -10.585
10.177    -9.854
10.195    -7.309
10.216    -3.198
10.237     0.802
10.257     3.812
10.274     5.646
10.295     7.052
10.315     7.602
10.337     7.376
10.357     6.394
10.372     5.126
10.383     3.879
10.414    -1.115
10.423    -2.890

FREQUENCY X SUM-30       -20      -10       0      +10      +20      +30
```

FIG. 6.10

7. INSTRUMENT TILT

7.1 INTRODUCTION

Most tellurometer users are familiar with the technique of tilting both master and remote instruments in the vertical plane, to reduce ground swing on lines that exhibit a large ground swing. The tilt range used in this experiment was from +6° to -6°, each instrument both master and remote being set to tilts at 1° intervals within this range. Measurements were taken at all combinations of tilts. Instrumental tilts of 6° are probably larger than would normally be used in the field and hence should cover all practical applications. The measurements for this experiment were taken on the Warwick Farm base line (see 3.2.1).

7.2 MEASURING PROCEDURE

7.2.1 Method of Measurement

The modified method of measurement as described in Appendix 4, was used throughout this experiment. The tellurometers were mounted in the cradles as described in 2.1.2 so that they could be set to a particular tilt value. The instruments were set over the base terminals and levelled. The remote was set to the desired tilt and held fixed at this setting for the twenty carrier frequency values. The master instrument was set to a particular tilt and the null meter centred and the displayed distance recorded. The master instrument was then set at one degree intervals in the tilt range at +6° to -6° and the null meter value for each setting was recorded. This process was repeated for the reverse mode on each carrier frequency setting. To obtain a distance for a particular tilt combination the mean of the readings taken on the twenty different carrier frequencies both forward and reverse was used.

Meteorological readings were taken to monitor the refractive index throughout the measurements. All measurements were then reduced for slope and refractive index. The difference between maximum and minimum refractive index on this 183 metre line only amounted to three millimetres during the period of the measurements.

7.2.2 Alignment of the Instruments

During the initial set-up and orientation of the master and remote tellurometers it is sometimes necessary to use a compass bearing or some other method to align the instruments towards one another when the terminals are not intervisible. When voice contact has been made the instruments can be aligned more closely by moving each in turn until a maximum indication is shown for signal strength on the monitor meter. When signal maximising has been completed both operators proceed with the measurement assuming correct alignment, i.e. each instrument pointing towards the other. Due to reflections the above method may not give true alignment but practice has shown this method to be acceptable *(Kerr, 1951, pp. 436 & 437).*

7.3 AMOUNT OF TILT

On a line where ground swing is excessive, i.e. exceeds an acceptable value, tellurometer users usually adopt one of several methods to reduce the ground swing. One such method is to tilt the instrument upwards in the vertical plane by a pre-determined amount after the instruments have been aligned. The amount by which the instrument is tilted depends on several factors, some are described below.

7.3.1 Length of Line

This is most important because the line may be of such a length that when the instrument is tilted the signal strength falls to a low value making a measurement impossible. With these circumstances tilting the instrument is unsatisfactory and usually the solution is to move one of the instruments to an eccentric station such that the new line defined by the new instrument positions is not as greatly affected by ground swing.

7.3.2 The Radiation Diagram

The Tellurometer MRA101 is fitted with a Cassegrain antenna system with the main reflector 33 centimetres in diameter and the cassegrain reflector 6 centimetres in diameter. The radiation diagram of one of the instruments was measured by Dr. B. Vu of the School of Electrical Engineering, University of New South Wales, in both the vertical plane and the horizonatal plane. The results of these measurements is shown in Figures 7.1 and 7.2. The radiation diagram in the vertical plane is most important when considering vertical tilts. Both radiation diagrams follow the well-known pattern for this type of antenna. It is assumed that the radiation diagram for the other instrument used in the experiment will be of the same shape.

7.3.3 The Line Profile

The profile of the line governs the angle at which the reflected signal arrives at the antenna. The reflected signal is usually that formed from multi-path propagation, the exception being a signal reflected from a highly reflecting surface such as water, ice or snow. The angle of arrival of the reflected signal will cause a change in the ratio of the amplitude of the direct to the indirect ray.

7.4 EFFECT OF TILT ON GROUND SWING

The effect of tilt on the measurement can be studied by consideration of 7.3.2 and 7.3.3. Let it be assumed that a line profile will give at the antenna of the receiver the conditions as shown in Figure 7.3 for conventional pointing. Let the amplitude of the direct ray be D and that of the indirect ray be I. The ratio of I to D is given by a_1, i.e. $a_1 = \frac{I}{D}$. Note, the grazing angle in Figure 7.3 is α and the conditions shown are for a single point reflection. The value of a_1 will be close to unity if the angle α is small. When the instrument is tilted the conditions change to those shown in Figure 7.4. The grazing angle α remains the same and the angle of tilt is shown as t. The ratio $^{I_1}/_{D_1}$ is now given by a_2. Generally $a_1 > a_2$ which results in a reduction of ground swing. If single point reflection is considered on the Warwick Farm base then the indirect ray will arrive about 1^{O} below the direct ray, i.e., a grazing angle of 1^{O}. The value for 1^{O} has been used to calculate the factor a_1 and a_2 from an enlarged copy of Figure 7.1, for some combinations of tilt used in the experiment. The value of a_1 for 0^{0} tilt and the value of a_2 for equal amounts of tilt of master and remote are shown in Table 7.1.

Master and Remote Setting	a_1	a_2
0^o	0.99	
-1^o		.98
-2^o		.97
-3^o		.95
-4^o		.93
-5^o		.89
-6^o		.82
$+1^o$		.99
$+2^o$		.98
$+3^o$		.97
$+4^o$		.95
$+5^o$		.93
$+6^o$		0.89

TABLE 7.1

The values in Table 7.1 show that although $a_1 > a_2$ there is not a substantial reduction in the values of a_2 when compared to a_1. It is significant to note that for values of tilt from 0^o to $+3^o$ the values for a_1 and a_2 differ only by 3%.

In practice the amount of tilt used will vary with each line and with individual observers. A value of tilt of 2^o has been recommended by Küpfer from the results of experimental work using the Wild Distomat 150 *(Küpfer, 1967)*. Küpfer (op. cit. page 24) states that the value of 2^o is the optimum value and found in experiments that this gave -

a) reduced sensitivity to ground reflections for MOST lines.

b) unchanged sensitivity to ground reflections for some lines, and

c) increased sensitivity to ground reflection in "no case".

The ground swing curves for tilt combinations of $+6^\circ$ remote and $+6^\circ$ master to -6° remote and -6° master and equal tilts of master and remote within this range are shown in Figures 7.5 to 7.17. The values of ground swing for some of the tilt combinations are shown in Table 7.2.

Tilt Combination	Ground Swing
$+6^\circ/+6^\circ$	12.5 cm
$+5^\circ/+5^\circ$	27 cm
$+4^\circ/+4^\circ$	12 cm
$+3^\circ/+3^\circ$	11.5 cm
$+2^\circ/+2^\circ$	8.5 cm
$+1^\circ/+1^\circ$	9 cm
0/0	10 cm
$-1^\circ/-1^\circ$	9 cm
$-2^\circ/-2^\circ$	11 cm
$-3^\circ/-3^\circ$	9.5 cm
$-4^\circ/-4^\circ$	9.5 cm
$-5^\circ/-5^\circ$	12 cm
$-6^\circ/-6^\circ$	20.5 cm

TABLE 7.2

The range in ground swing for the Warwick Farm base line measurements used in the zero error determination were of the order of 8 cm to 13 cm. It was discussed in section 5.4 that antenna swing could amount to 8 cm to 10 cm hence the lower value above could be antenna swing. The results in table 7.2 and the corresponding swing curves in figure 7.5 to 7.17 show that as the tilt was increased, the ground swing was reduced for tilts of $+1^\circ/+1^\circ$ and $+2^\circ/+2^\circ$ but then increased for values $+3^\circ/+3^\circ$ to $+6^\circ/+6^\circ$. The reduction for the values up to $+2^\circ/+2^\circ$ support Küpfer's (op. cit.) value of $+2^\circ$ as the optimum value of tilt.

Because the ground swing was small on the line during conventional measurements and because the reduction in ground swing, as a consequence of instrument tilt, is minimal, care should be exercised in drawing firm conclusions from these results. The ground swing curves for the tilt values of $+1^{\circ}/+1^{\circ}$ and $+2^{\circ}/+2^{\circ}$ may in fact be antenna swing curves. Further, the measurement made at the larger instrument tilt values on certain carrier frequencies were unstable.

7.5 EFFECT OF TILT ON ZERO ERROR

The reduced measurements of all tilt combinations are shown in Table 7.3. Figure 7.18 shows these readings plotted with lines of equal zero error drawn (as contour lines). The true distance is shown as a heavy line. The readings in Table 7.3 denoted by an asterisk do not contain the mean of readings on all carrier frequencies. At the higher carrier frequencies (10.3 to 10.4 GHz) the null meter was unstable, at times oscillating between its total range of +50 to -50 (null meter scale). Because of this instability the readings for these carrier settings were not included in the calculation of the means of the fine readings. Some difficulties were experienced on the master instrument during the -4° tilt setting and at one stage the signal was lost. The effect of instrument tilt of both master and remote can be seen from Figure 7.18 and Table 7.3. A study reveals that within the tilt range of $+3^{\circ}$ to -3° the indicated distance is not greatly changed from the level value. This range of tilts would be those normally used in the field and this range also includes the value of 2° as recommended by Küpfer (op. cit.) as being the optimum value.

Whenever an observer must tilt the instrument outside this range of ±3° to values of about 6° then the results show that the distance is altered and users must calibrate for these tilts. Care must also be taken when using large tilts because of the tuning difficulties that were experienced during the experimental measurements. Figure 7.18 shows that when the master instrument is held in the level position and the remote instrument is tilted then the displayed distance is not altered significantly. This indicates that tilts of the master instrument are more significant than those of the remote. With the Cassegrain Antenna of the Model MRA101 Tellurometer it would appear that rays striking the parabolic dish are reflected towards the focal point of the parabola but this point is also one of the foci of the cassegrain reflector which is an hyperbola. This means that the rays on reflection from the hyperbola will pass down the wave guide as shown in Figures 7.19 and 7.20 (Figure 7.20 after Marshall).

When the instrument is tilted upwards or downwards at an angle of say t°, then the phase centre point is shifted upwards or downwards because the point of tilt is not about the phase centre point. As a result of the vertical displacement of the phase centre point, an additional error is introduced into the indicated distance. If the distance between the phase centre point and the point of tilt is b, then the error according to Küpfer (op. cit. and 1971) is given by error $e = 2b\ |t^{\circ}|$, the factor 2 is included because both instruments are tilted. Let b = 15 centimetres for the MRA101 tellurometer then Table 7.4 shows the correction to be applied for the range of tilts used in the experiment.

t = 1°	e = 0.5 centimetres
2°	1.1 cm
3°	1.6 cm
4°	2.1 cm
5°	2.6 cm
6°	3.1 cm

TABLE 7.4

However, examination of the results of the tilt experiment as shown in Table 7.3 shows that the indicated distances do not decrease as the tilts are increased, in fact the indicated distances increase from the 0° position. The effect of this error is certainly being masked by the fact that

i) multi-reflections are taking place along the line,
ii) reflections are taking place at the antenna, (antenna swing?)
iii) the instrument has only centimetre resolution,
and iv) indicated distance is obtained from a ground swing curve i.e. from a number of fine readings.

7.6 CONCLUSION

It can be seen from the results that the effect of instrument tilt on ground swing as tested in this section over the Warwick Farm base line is inconclusive as far as ground swing reduction is concerned. The ground swing on this base line was not excessive as both the tower and zero error experiments have shown and the tilt experiment did not reduce this by any great magnitude. The swing graphs, Figures 5.5 to 5.17 for the tilt measurements are similar to the swing graphs from the other work mentioned above.

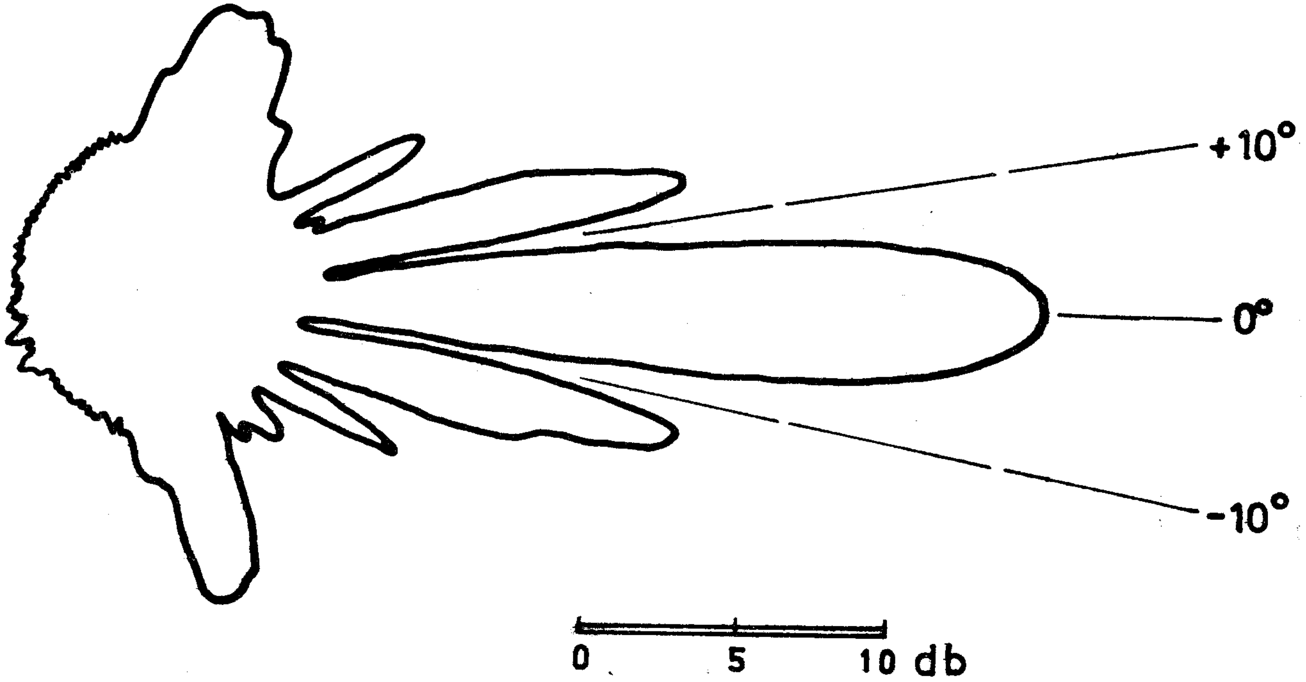
Table 7.3 and Figure 7.18 show that the zero error determined from normal aligning techniques is changed when the instruments are tilted. It is important to note that within the tilt range of +3° to -3° (both master and remote) no great difference was recorded in the zero correction. However at tilts greater than this a further correction must be applied to the indicated distance. If the zero error calibration is carried out with both instruments tilted (say upwards at 3°) and users intend to use this instrument position for ALL measurements then no additional correction need be applied. This technique may in fact reduce the effective range of the instrument and users may prefer to use conventional pointing methods for measurements with acceptable ground swing and a tilting techniques for lines with large ground swing. If this is the case then each instrument must be calibrated because the effect of multi-reflection at the antenna and the antenna itself, mask the theoretical correction that could be expected to be applied.

All distances in metres

		← M A S T E R →												
		-6°	-5°	-4°	-3°	-2°	-1°	0°	+1°	+2°	+3°	+4°	+5°	+6°
← R E M O T E →	+6°	183.13*	183.15	183.14	183.16	183.14	183.15	183.12	183.15	183.15	183.16	183.22	183.26	183.26
	+5°	3.00*	3.12	3.12	3.14	3.12	3.12	3.08	3.12	3.12	3.14	3.18	3.25	3.25
	+4°	3.04*	3.08	3.09	3.08	3.08	3.08	3.05	3.07	3.06	3.07	3.11	3.17	3.22
	+3°	3.01*	3.06	3.07	3.06	3.05	3.06	3.04	3.05	3.05	3.06	3.10	3.16	3.19
	+2°	2.99*	3.05	3.06	3.06	3.05	3.05	3.04	3.05	3.05	3.06	3.10	3.14	3.18
	+1°	2.98	3.05	3.06	3.06	3.05	3.05	3.04	3.05	3.05	3.06	3.11	3.14	3.18
	0°	2.99	3.05	3.06	3.05	3.06	3.06	3.05	3.05	3.05	3.06	3.11	3.16	3.18
	-1°	3.00	3.06	3.06	3.05	3.06	3.06	3.04	3.06	3.06	3.07	3.11	3.16	3.18
	-2°	3.00	3.06	3.07	3.05	3.06	3.06	3.04	3.06	3.06	3.07	3.11	3.16	3.18
	-3°	3.01	3.06	3.06	3.06	3.06	3.06	3.04	3.06	3.06	3.07	3.11	3.16	3.18
	-4°	3.01	3.06	3.06	3.06	3.06	3.06	3.04	3.06	3.06	3.08	3.12	3.17	3.18
	-5°	3.01	3.06	3.07	3.06	3.06	3.06	3.04	3.06	3.06	3.07	3.12	3.18	3.20
	-6°	3.01	3.07	3.07	3.06	3.06	3.07	3.05	3.06	3.06	3.09	3.16	3.21	3.22

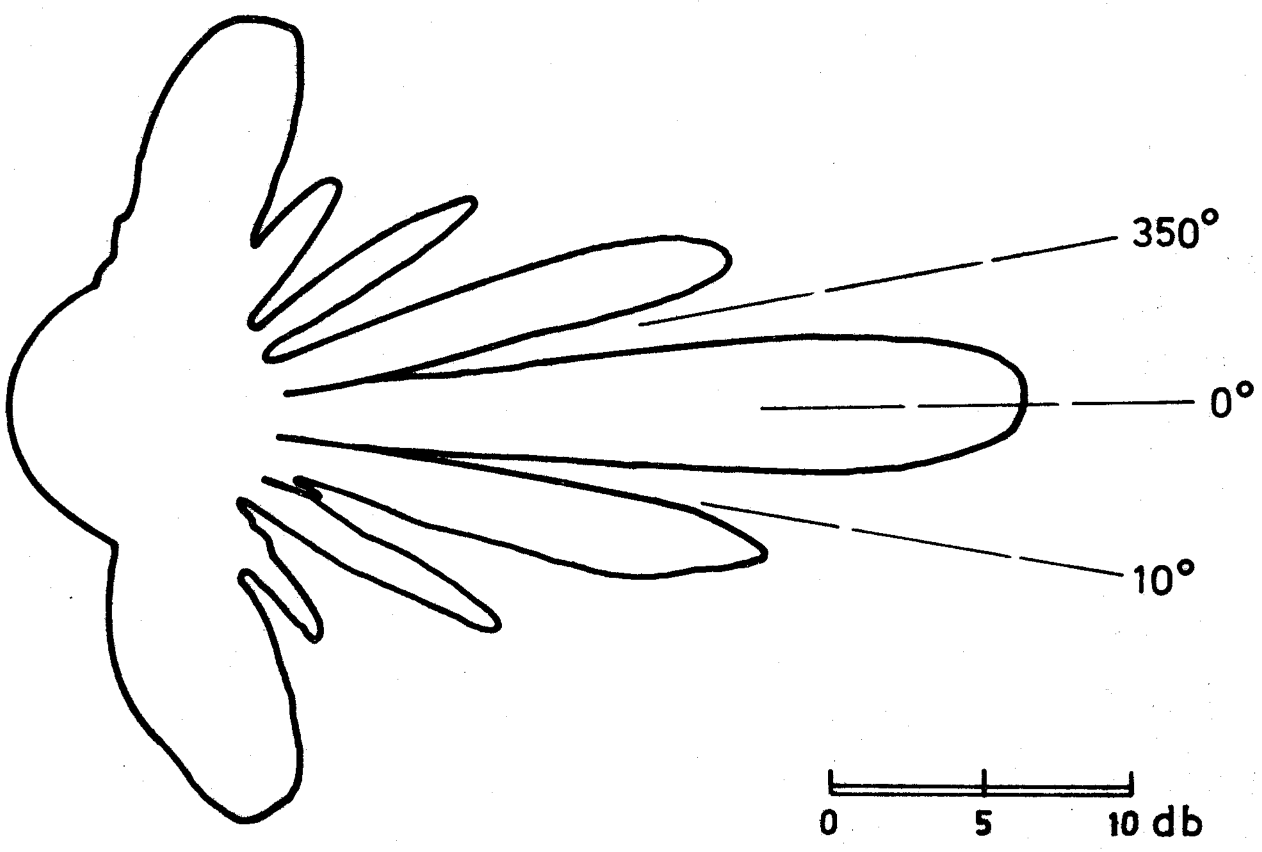
ADOPTED DISTANCE = 183.06

TABLE 7.3



Radiation Diagram:— Vertical Plane
(10·1 GH_z)

FIG. 7·1



Radiation Diagram:— Horizontal Plane
($10{\cdot}1\ GH_z$)

FIG. 7·2

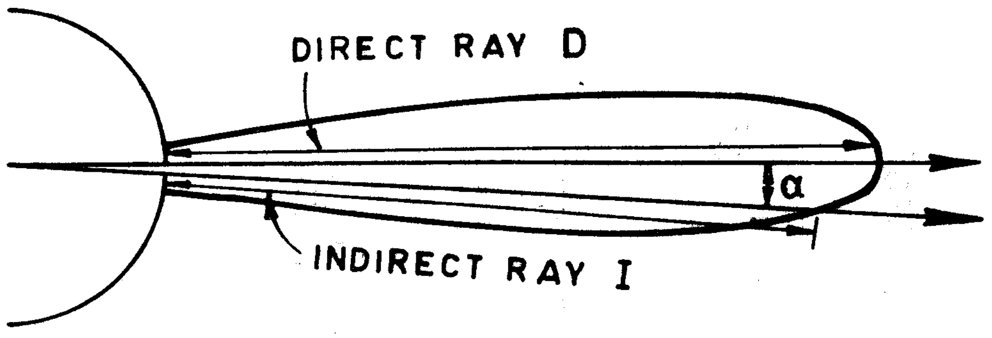


FIG. 7·3

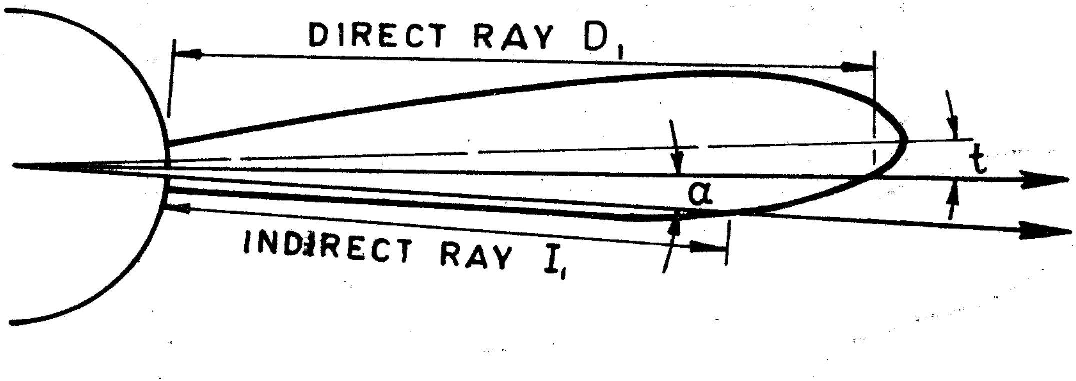


FIG. 7·4

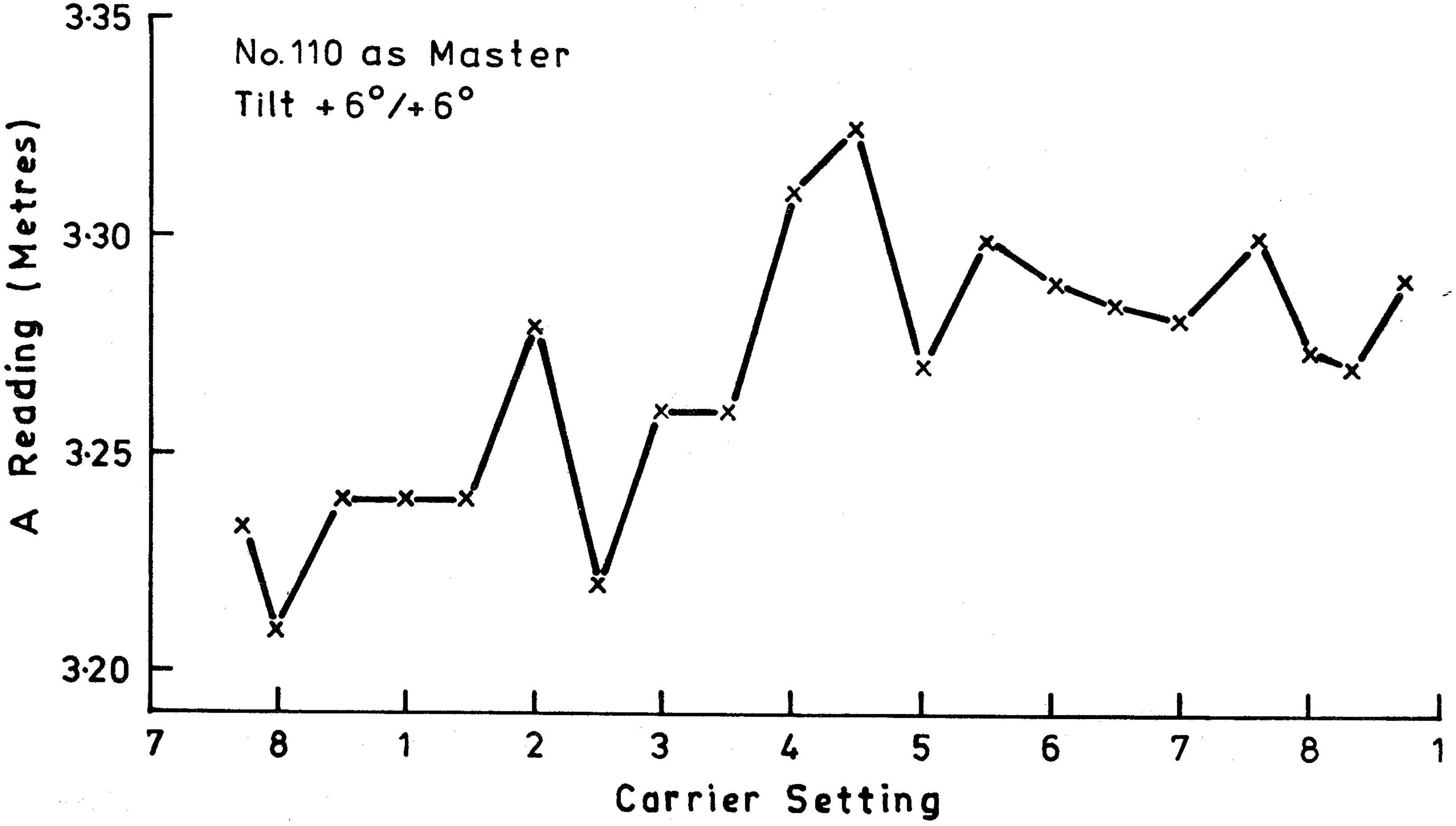

No.110 as Master
Tilt +6°/+6°
A Reading (Metres)
3·35
3·30
3·25
3·20
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·5

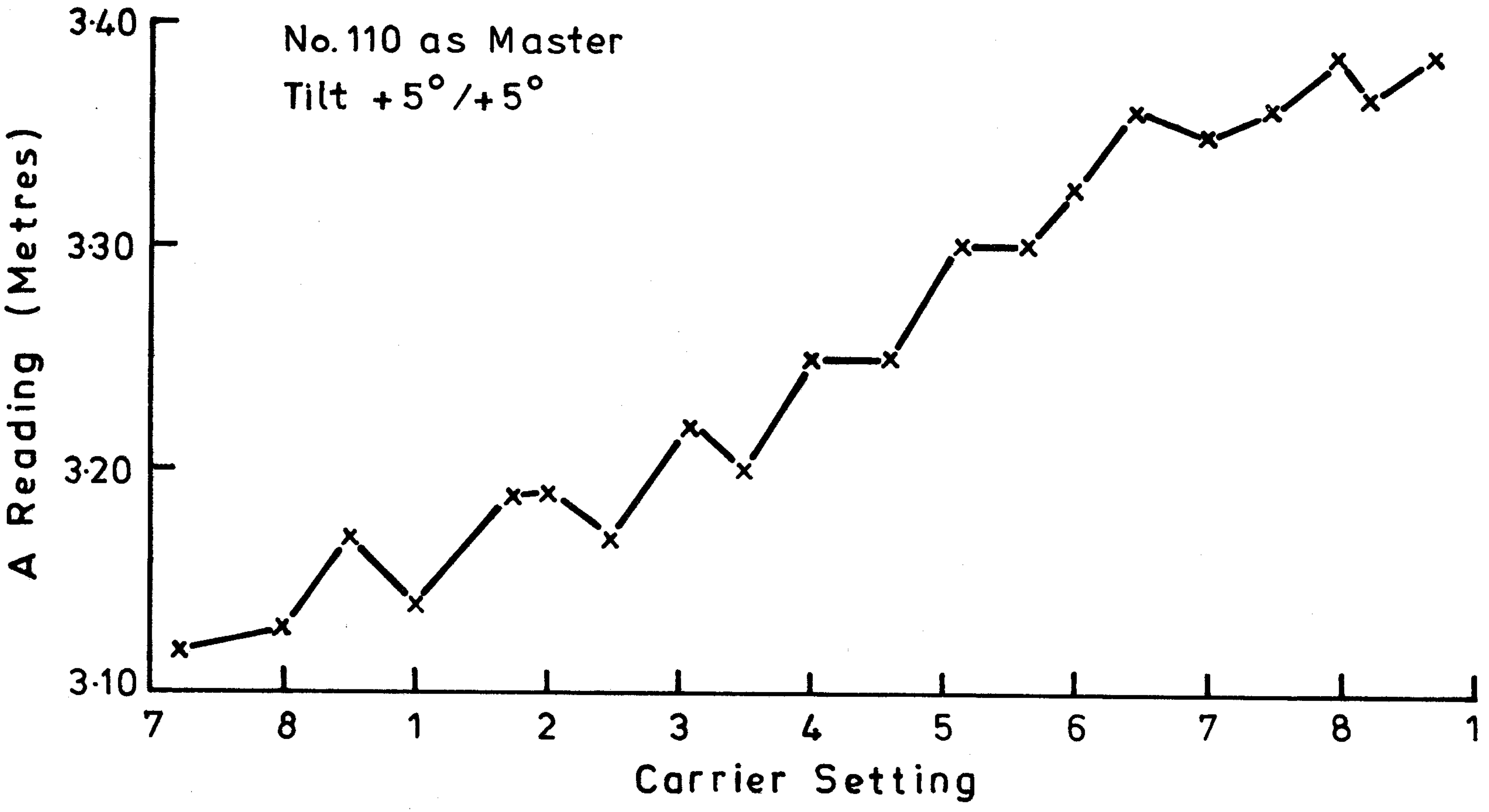

No. 110 as Master
Tilt +5°/+5°
3·40
3·30
3·20
3·10
A Reading (Metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·6

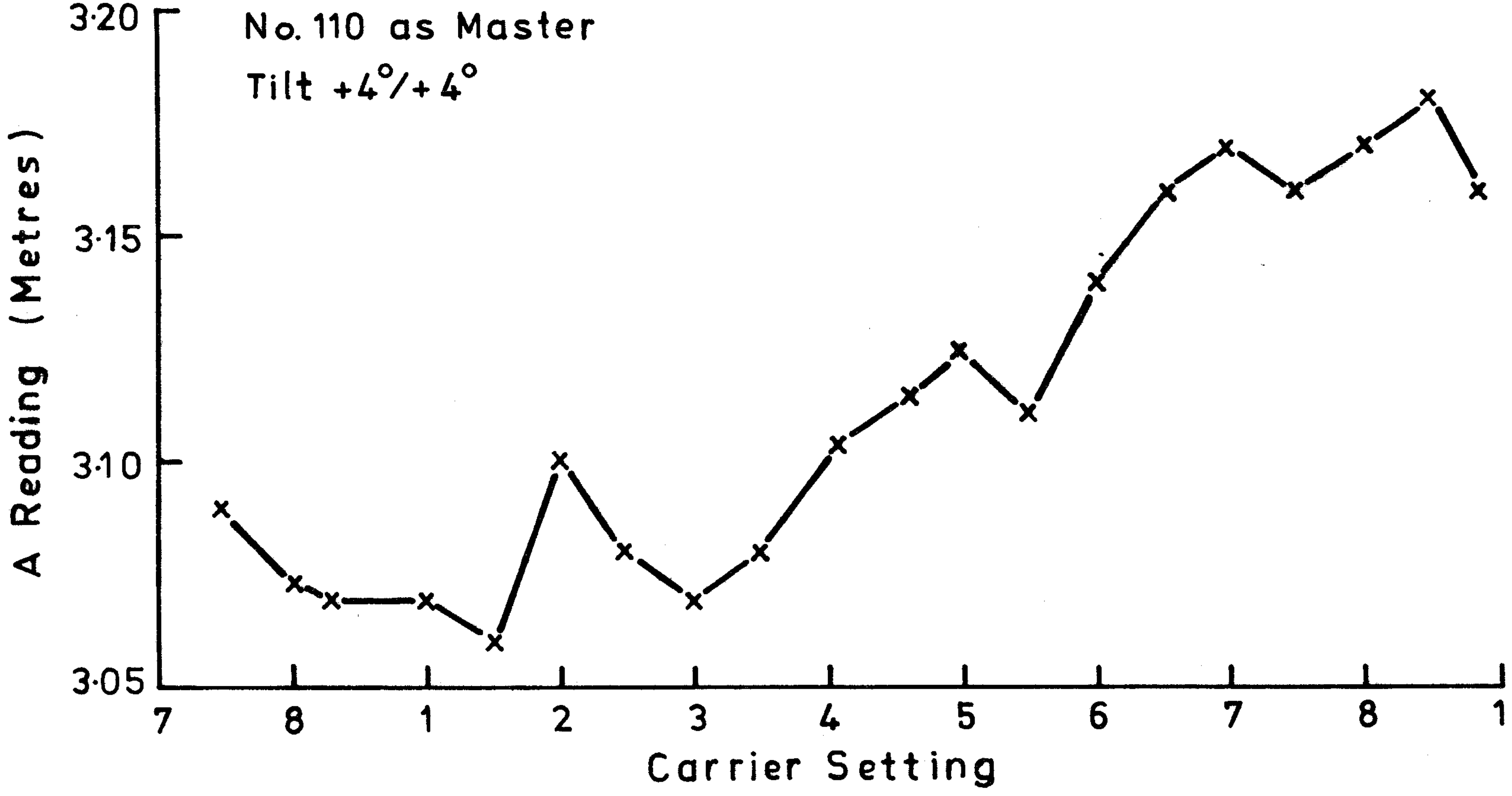

No. 110 as Master
Tilt +4°/+4°
A Reading (Metres)
3·20
3·15
3·10
3·05
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·7

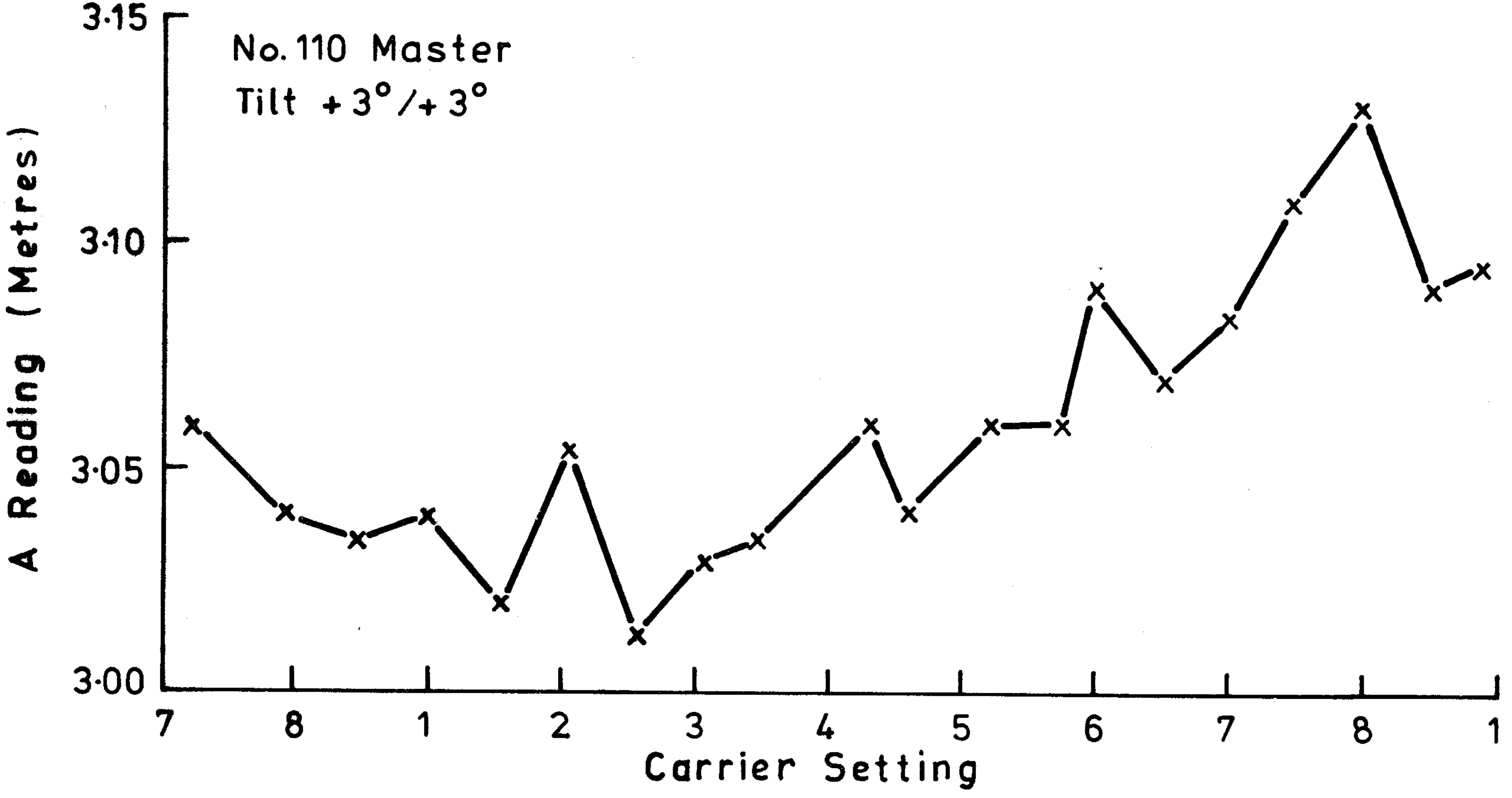

No. 110 Master
Tilt +3°/+3°
A Reading (Metres)
3·15
3·10
3·05
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·8

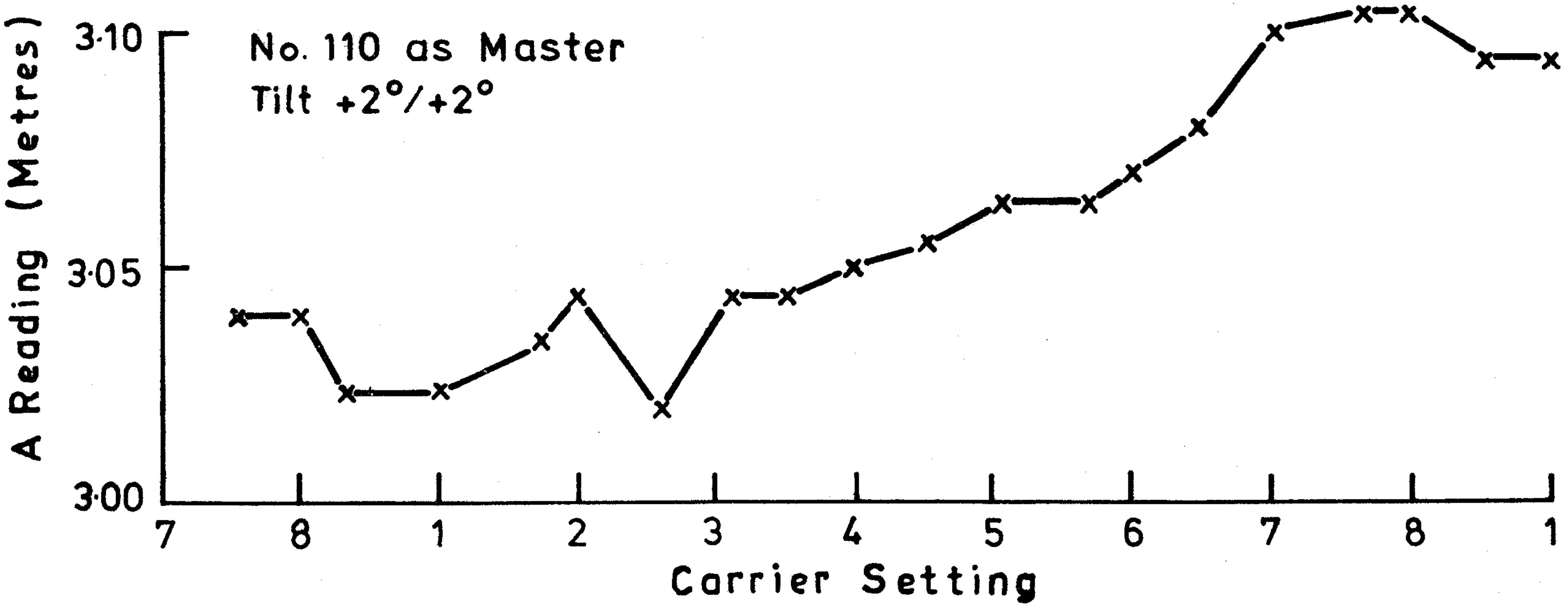

No. 110 as Master
Tilt +2°/+2°
A Reading (Metres)
3·10
3·05
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·9

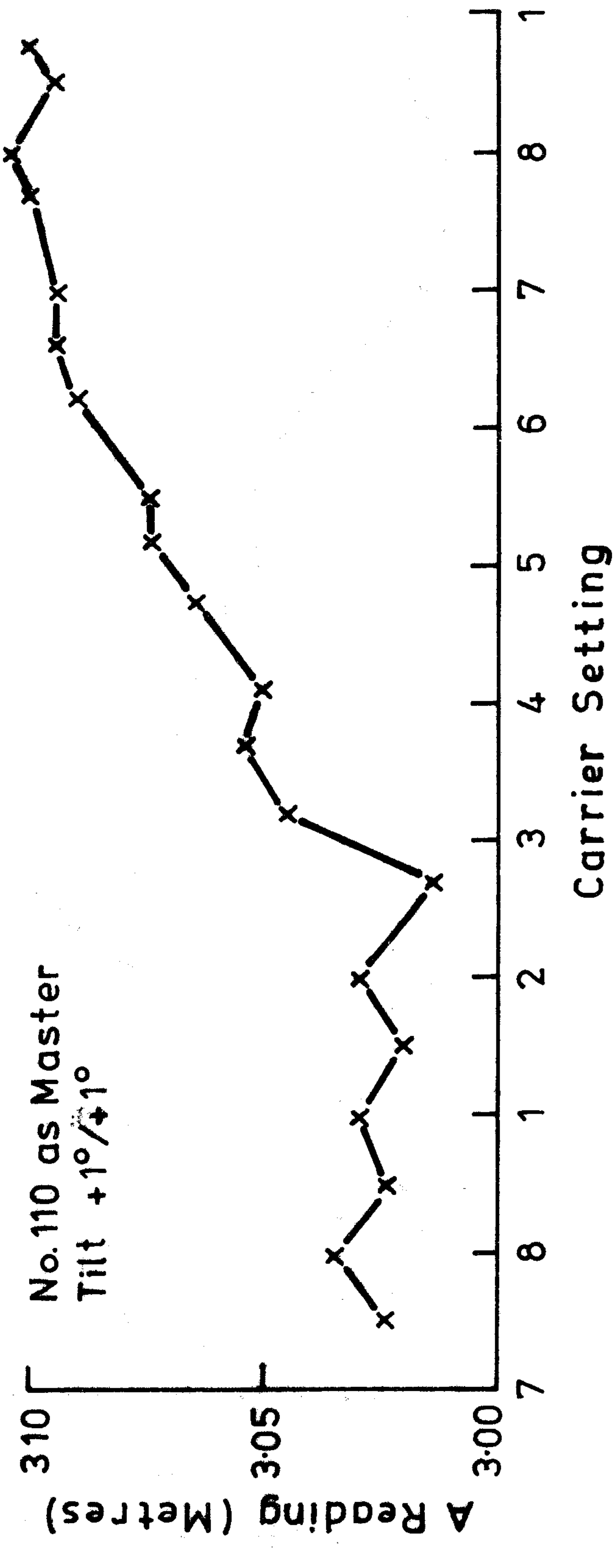

No. 110 as Master
Tilt +1°/+1°
A Reading (Metres)
310
3·05
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·10

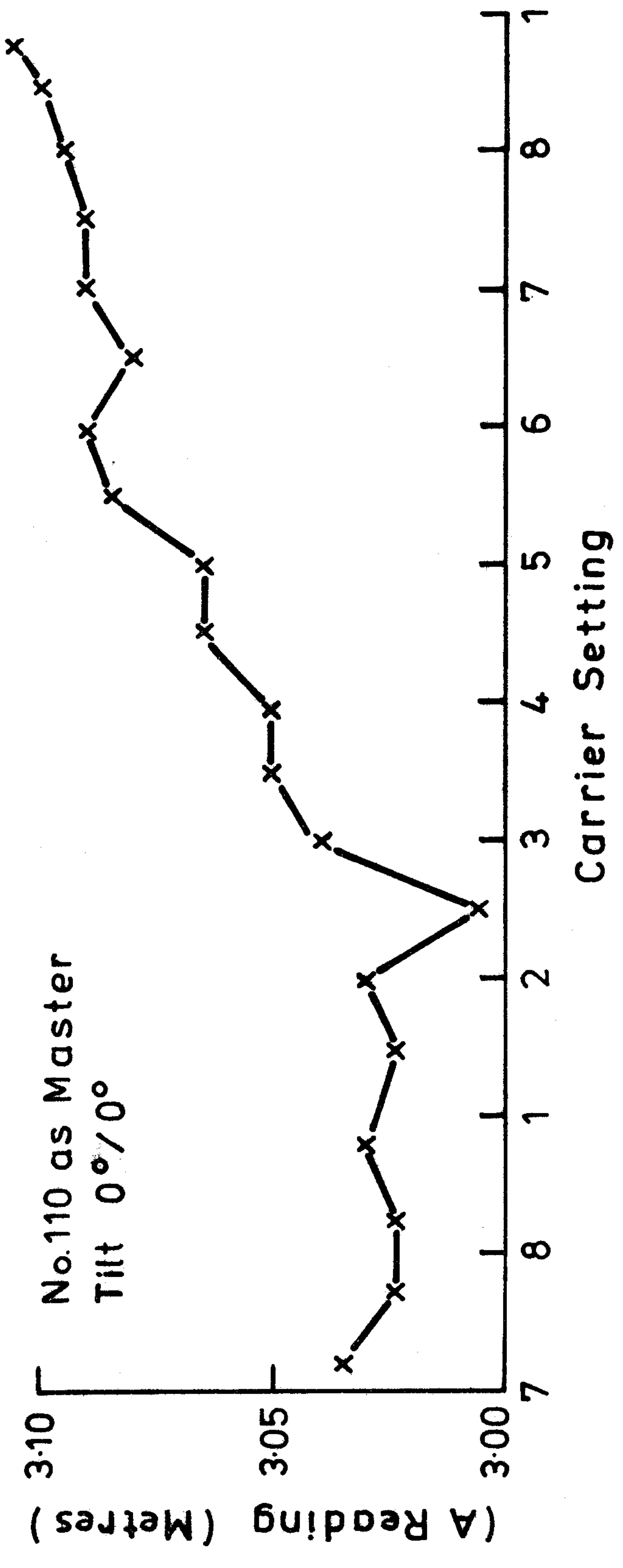

No.110 as Master
Tilt 0°/0°
(A Reading (Metres)
3·10
3·05
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·11

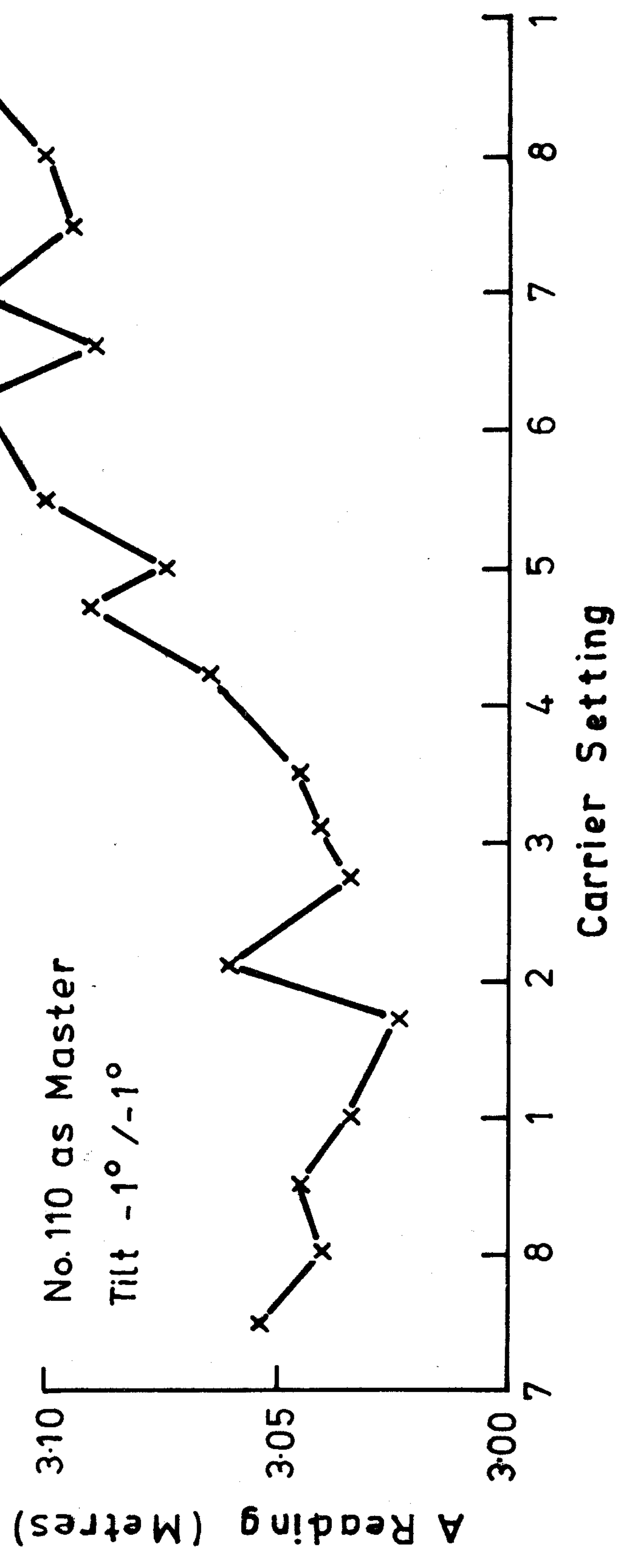

No. 110 as Master
Tilt -1°/-1°
A Reading (Metres)
3·10
3·05
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·12

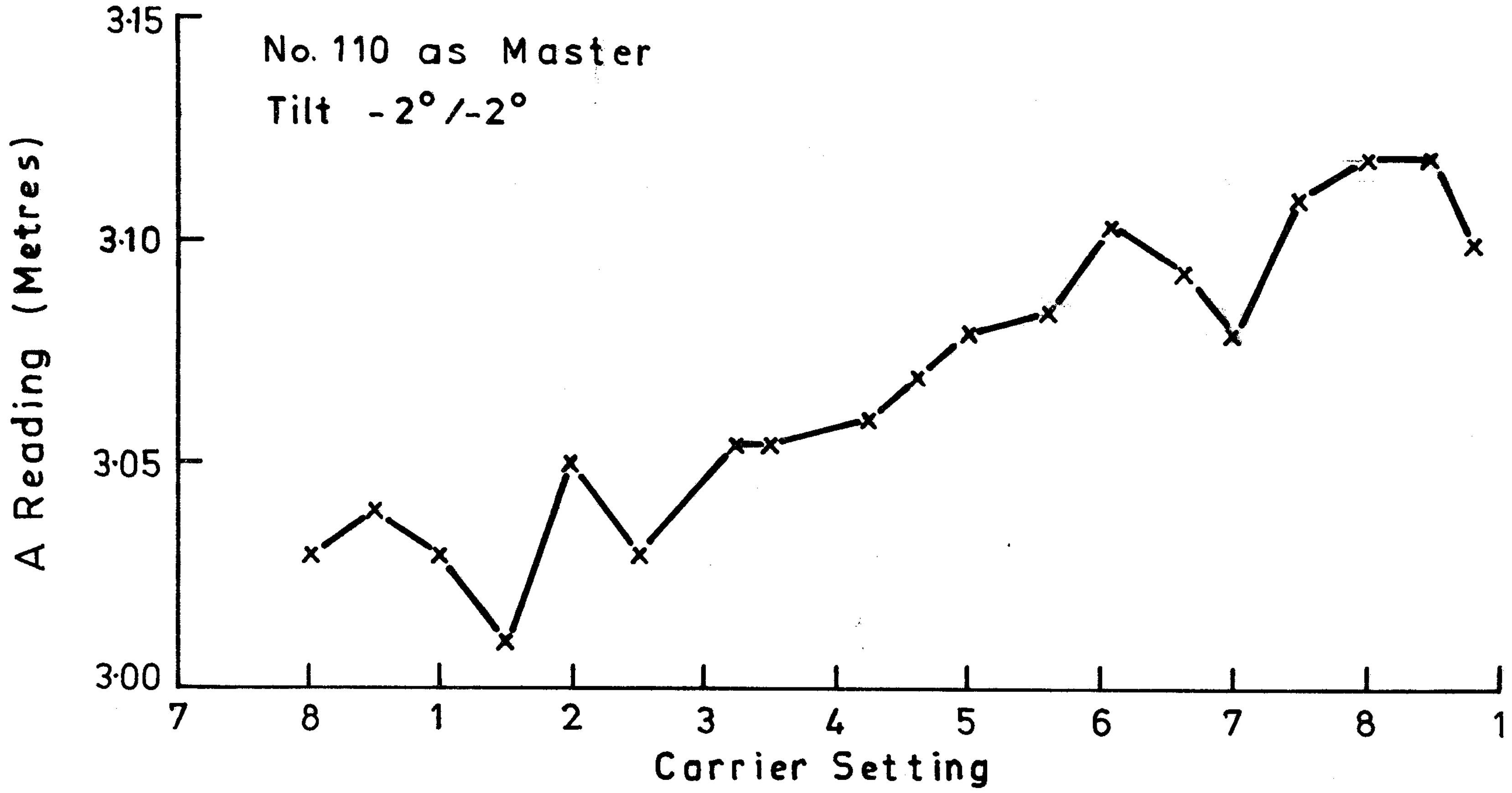

No. 110 as Master
Tilt -2°/-2°
A Reading (Metres)
3·15
3·10
3·05
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·13

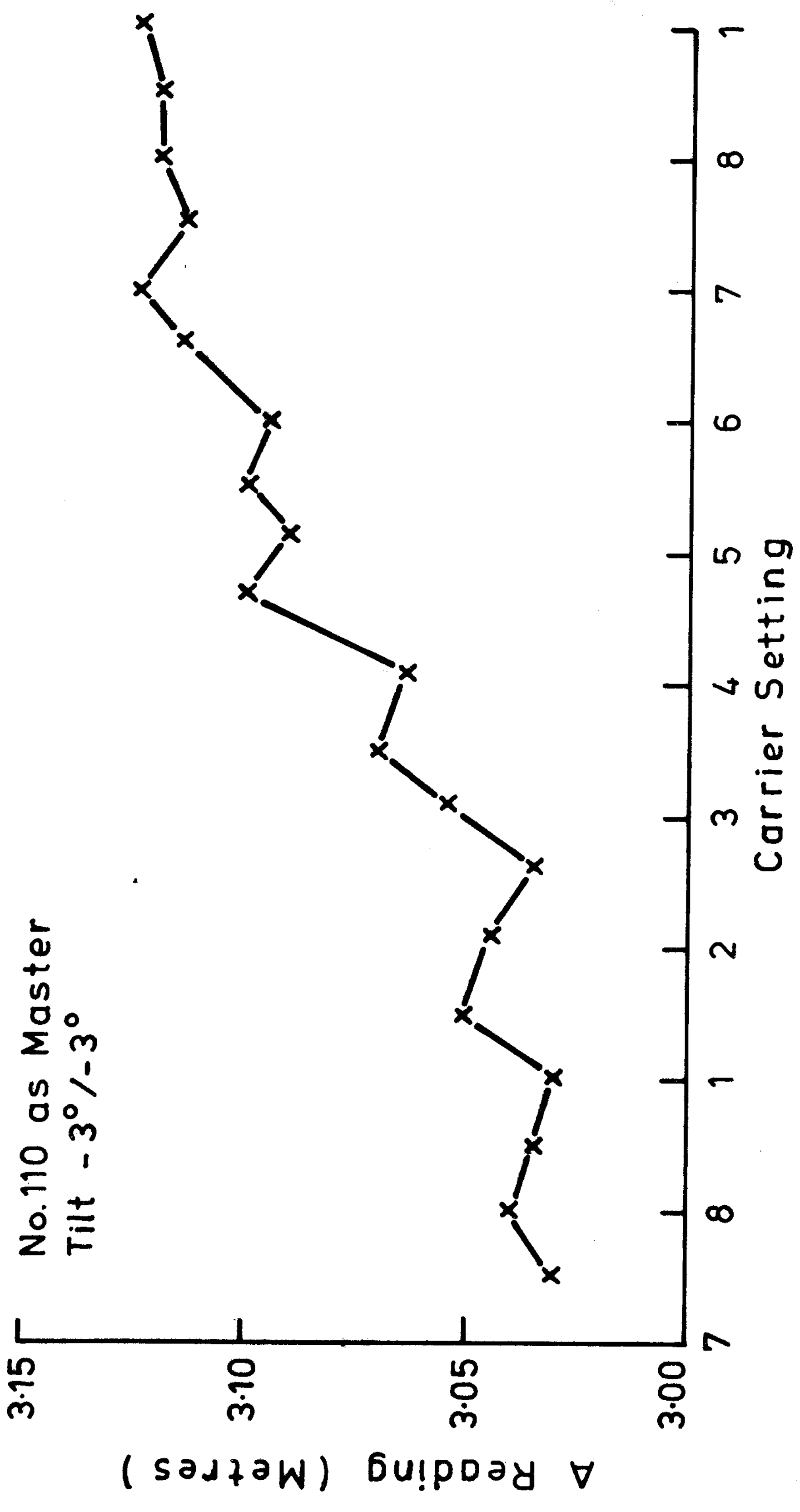

No.110 as Master
Tilt -3°/-3°
3·15
3·10
3·05
3·00
A Reading (Metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·14

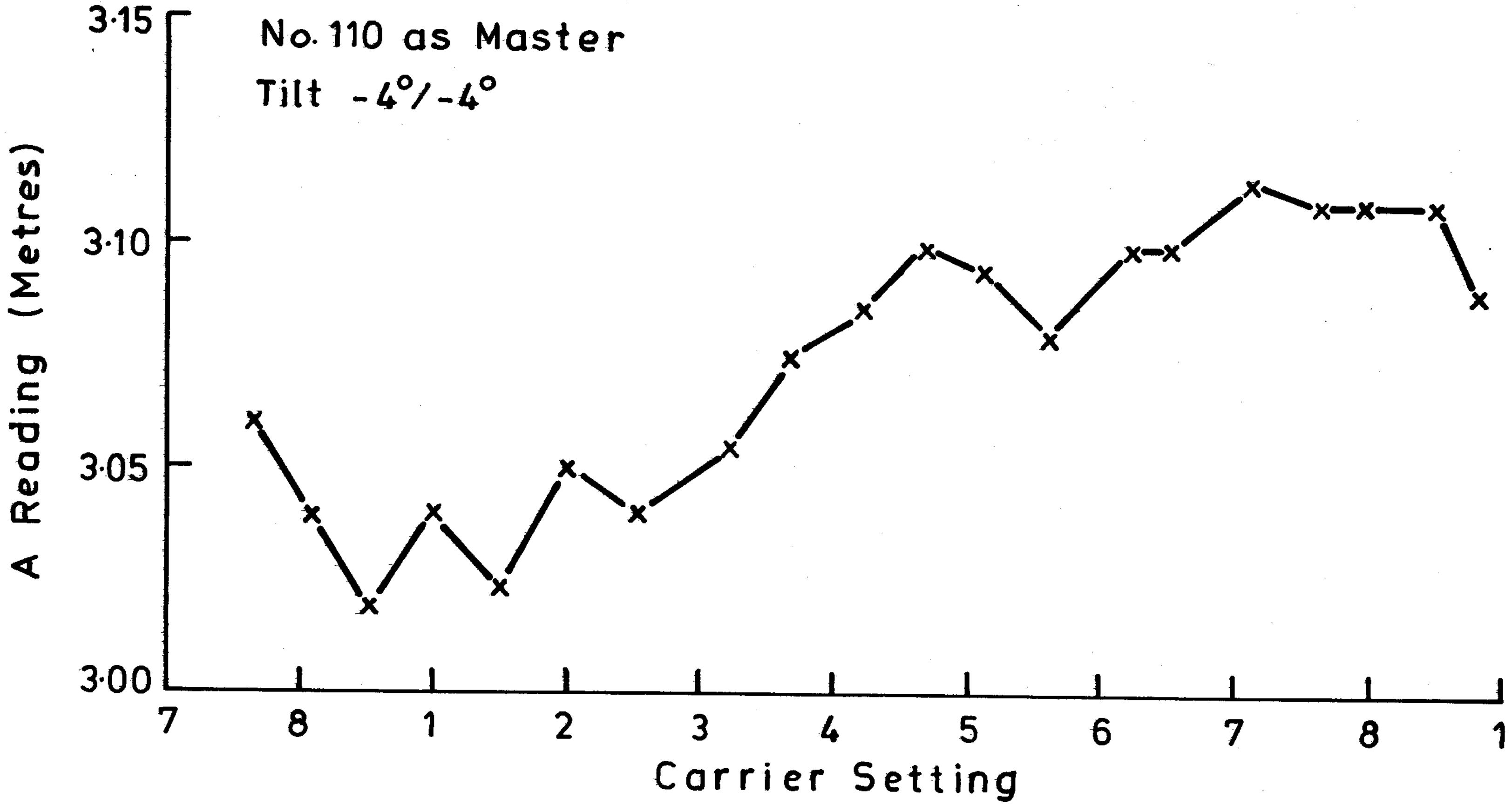

No. 110 as Master
Tilt -4°/-4°
3·15
3·10
3·05
3·00
A Reading (Metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·15

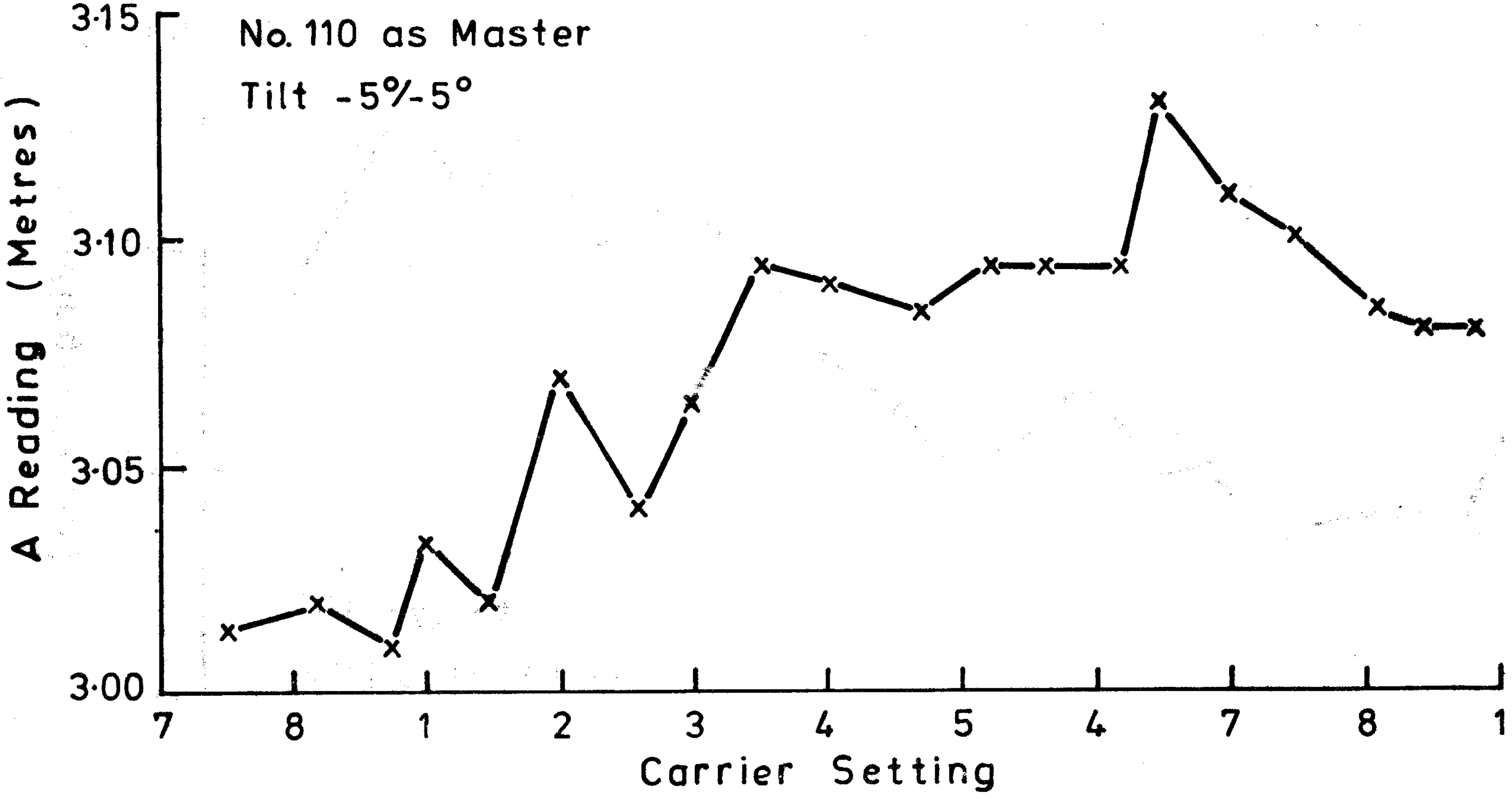

No. 110 as Master
Tilt -5%-5°
A Reading (Metres)
3·15
3·10
3·05
3·00
7
8
1
2
3
4
5
4
7
8
1
Carrier Setting

FIG. 7·16

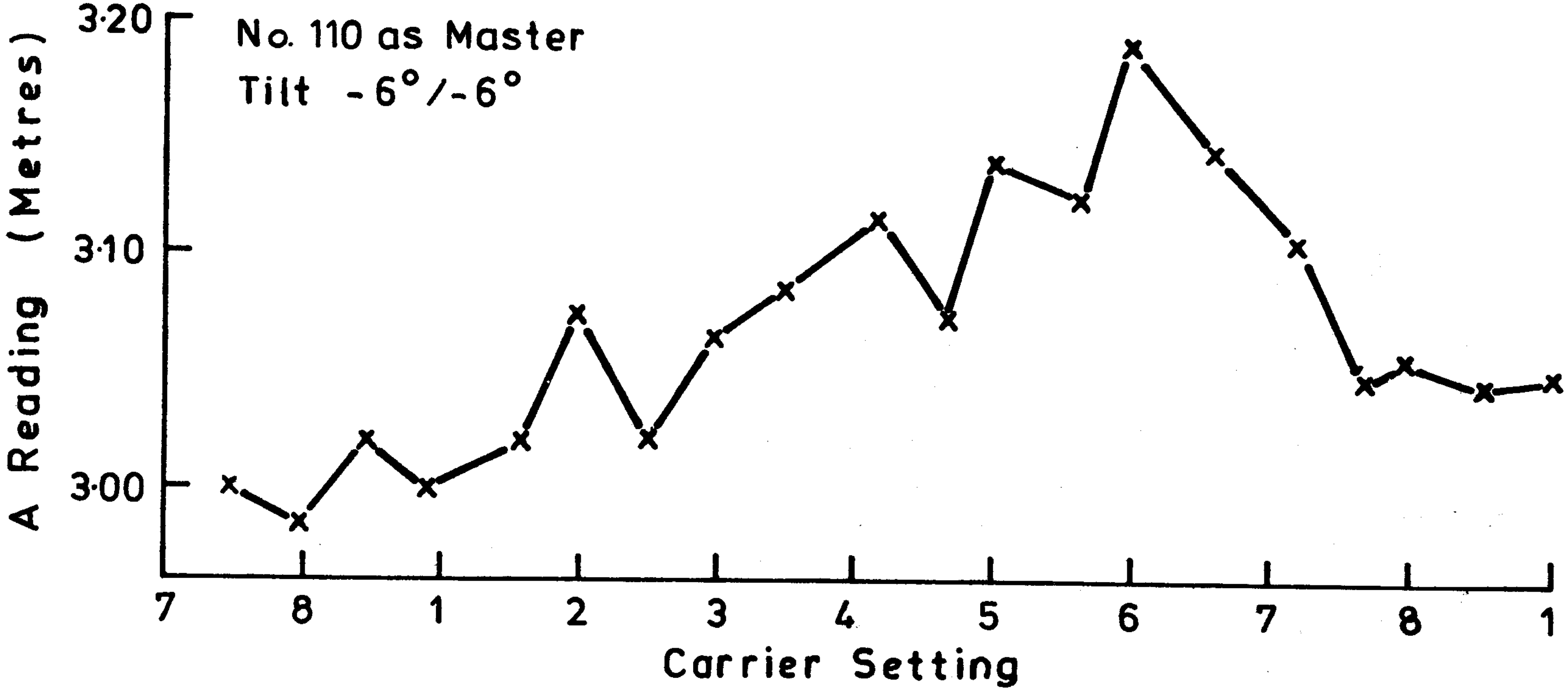
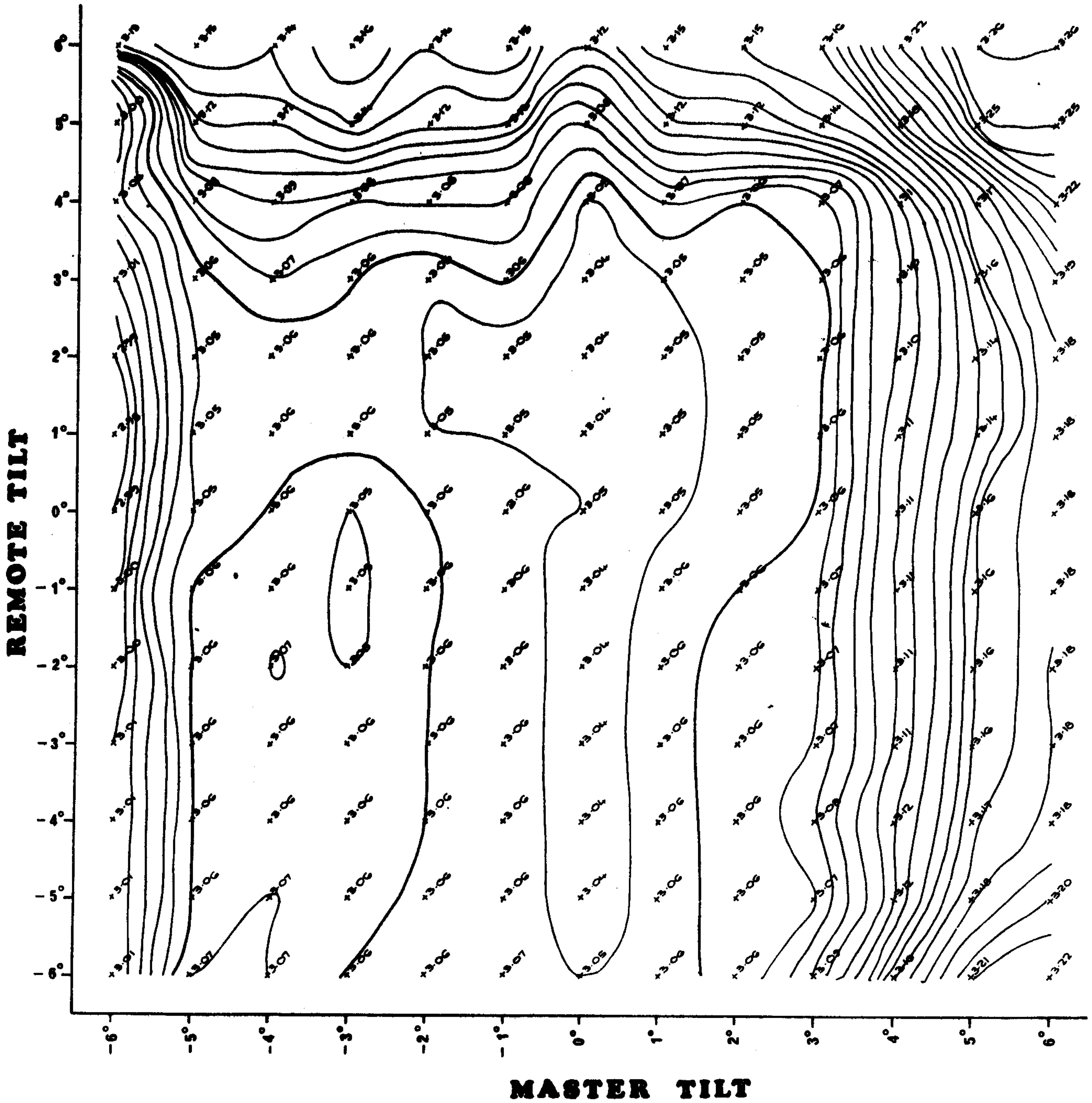

No. 110 as Master
Tilt -6°/-6°
A Reading (Metres)
3·20
3·10
3·00
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 7·17



NOTE:- ADD 180·0 METRES
TO ALL DISTANCES

CENTIMETRE CONTOURS

fig. 7·18

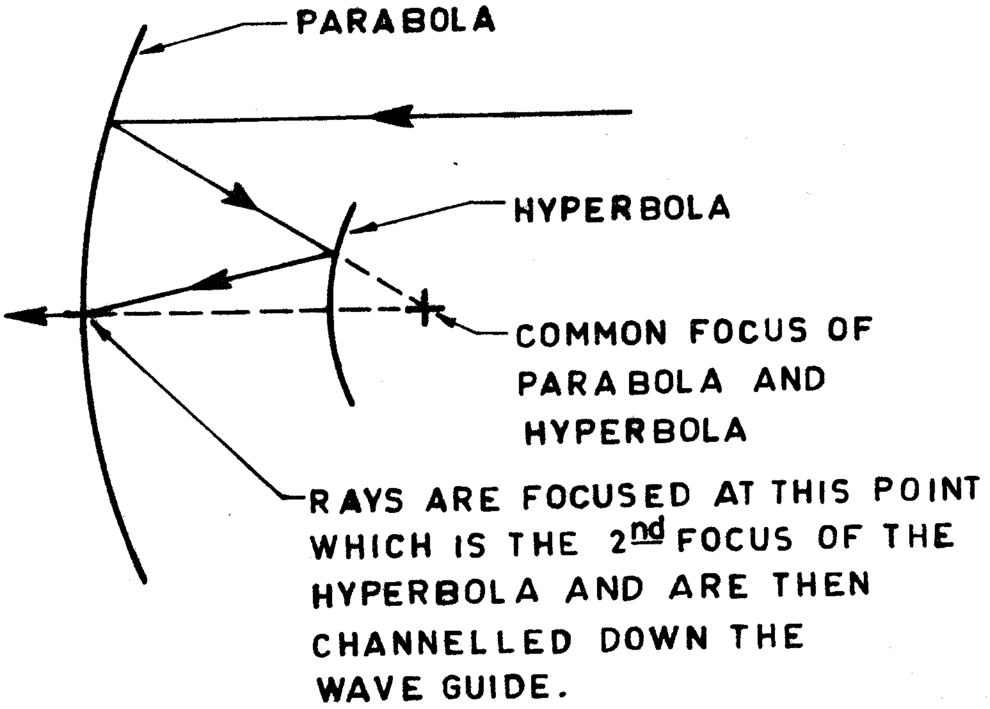


FIG. 7·19

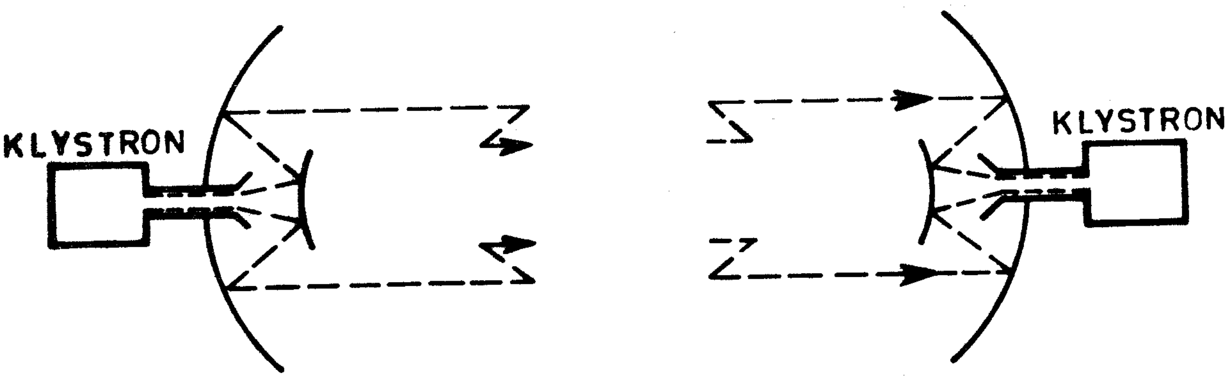


FIG. 7·20
(After Marshall)

8. GROUND SWING REDUCTION USING NATURAL SHIELDS

8.1 INTRODUCTION

Many tellurometer observers are familiar with the technique of reducing the amount of ground swing on a line which has large ground swing (i.e. above an accepted value) by setting behind a hill or lowering the instrument. This shielding technique makes use of the natural conditions that are available as distinct from those techniques where artificial screens are used, *(Chrzanowski 1968)*. *Kelsey (1959)* was the first to demonstrate this method and he made use of the ground surface as well as stone walls and also the bonnet of a motor vehicle. Care must be taken to see that the artificial shields and the natural shields do not themselves act as reflectors.

8.2 BATHURST MEASUREMENTS

The University of New South Wales, School of Surveying, has a Survey Camp site in the Bathurst area of N.S.W. The small triangulation network used by the School has been connected to the State (of New South Wales) Trigonometric Survey by theodolite observations and tellurometer distances. The scale of the U.N.S.W. triangulation scheme is also based on tellurometer measurements. The area around the Bathurst district is ideally suited for triangulation work because of the Great Dividing Range in the east and the hilly nature of the country to the west. (See figure 8.1(a) and 8.1(b)).

One line that was measured for the connection was the line Callaghan (U.N.S.W. station) to OVENS (State Trig. station). The profile of this line is shown in figure 8.2. It can be seen that the line is about 22 kilometres long and that the hills on which the occupied stations are, rise sharply from the valley floor. Because of the shape of the profile a large ground swing was expected and also many swing cycles were expected to be developed. The measurement was made in September 1970 in the afternoon after rain and the grass cover in the vicinity of the station Callaghan was about 5 centimetres high and wet. The instrument was set at normal height i.e. about 1.3 metres. The ground swing curve for the measurements taken with instrument Nos. 113 at Callaghan, and 114 at Ovens, as master are shown in figures 8.3 and 8.4 respectively. The ground swing (maximum value minus minimum value) for each of these measurements is 1.195 metres and 1.365 metres respectively. These values are high when compared with the average value of about 0.13 metres generally obtained from this equipment. A second measurement of the line was carried out this time re-siting the instrument at an eccentric station positioned behind the crest at Callaghan such that the lower portion of the transmission was shielded by the ground surface. The ground swing from this measurement made on 10 carrier tune settings was 0.135 metres and 0.220 metres for master instruments nos. 113 and 114 respectively. This is almost a ten times reduction of the ground swing. The ground swing curves are shown in figures 8.5 and 8.6.

The reduced distances from both measurements are -

(i)	large ground swing	22413.08
(ii)	reduced ground swing	22413.18

The difference of 0.10 metres gives an internal agreement of 1:224 000. Figures 8.3, 8.4, 8.5 and 8.6 show that in the case of the large ground swing several cycles were developed and in the reduced ground swing case only one cycle was developed.

It has been mentioned above that scale for the U.N.S.W. triangulation scheme was obtained from tellurometer measurements. The distance between stations Bald and Bayliss, 4901.26 m, was measured with ground swings of 0.45 and 0.38 metres for instrument nos. 110 and 113 respectively. Figure 8.7 shows these two ground swing curves. It can be seen that several cycles were developed. One student exercise at the survey camp is to measure the distance Bald, Bayliss with the tellurometer. However, as the stations are also occupied by students observing horizontal directions the tellurometers were set forward of both stations on line. At the new instrument position there was less shielding effect from the ground surface and as a result the ground swing on the new line was expected to be higher than that obtained on the old line. Ground swings up to 1.20 metres were obtained on this line, which at the time of measurement was covered with grass about 5 centimetres high and very wet. A further measurement was taken over the line with the tellurometer set at Bayliss, 10 metres towards Bald and set at Bald 28 metres away from Bayliss, thus at the station Bald the ground surface shielded the lower part of the beam. Ten fine readings were taken on this measurement and the ground swings were 0.095 and 0.105 metres for instrument nos. 114 and 113. See figure 8.8. The reduced distance for this measurement agreed exactly with that obtained from the control measurement.

8.3 EXPERIMENTAL MEASUREMENT

In view of the fact that a large reduction was obtained in the ground swing on the line Bald Bayliss it was decided to carry out a series of measurements on this line from stations, on line, with varying amounts of shielding. At station Bald ten auxiliary stations, numbered 1 to 11 (no. 8 being Bald) were marked on line such that some stations would have no shielding and others would have maximum shielding. A profile of the stations is shown in figure 8.9 to natural scale. Figure 8.9 also includes the inclination to Bayliss and further the 6^{o} cone (to half power points) of transmission. It should be noted that for this series of measurements only ten (10) fine readings were taken and these fine readings were taken at station Bald. To monitor the refractive index for the proposed measurements, meteorological readings were taken at each instrument before and after each set of fine readings. Thus the refractive index for a particular set of fine readings was taken as the mean of four refractive indexes, two from each end.

8.3.1 Measurement Sequence

A sequence of measurements was designed so that each set of measurements could be referred to the previous set and to avoid the systematic effect of centering, the instrument at Bald was re-centred after each measurement. A set consisted of measuring three of the lines twice in the following way: line 2, line 6, line 10; line 10, line 6, line 2. As the refractive index was monitored at both stations the effect of a change in the refractive index on the measurements could be calculated and further if the error in the determination of refractive index is considered to be linear, this measurement sequence would eliminate the effect of this error. This precaution was taken although it is realised that a small change in the refractive index has little effect over this distance.

The full sequence of measurements is as follows -

2	6	10	10	6	2
2	4	6	6	4	2
6	8	10	10	8	6
1	2	3	3	2	1
3	4	5	5	4	3
5	6	7	7	6	5
7	8	9	9	8	7
9	10	11	11	10	9

From the previous tellurometer measurements taken on this line it was anticipated that the ground swing of the lines 1 to 7, with very little shielding would be large, say 1.0 metres, and that on lines 8 to 11 with some shielding would be of the order of 0.20 metres. Station 1 was selected to be very close to the brow of the hill and one can see from the profile that the shielding effects on lines 1 to 6 are similar, hence one would expect similar ground swing curves for these lines.

8.4 RESULTS

These measurements were made in late December 1970 during a very dry period and the grass cover at both stations was completely different to that in September. At Bald the grass was about 0.7 metres high and the line had to be cleared of saffron thistle which was up to 1 metre high. The grass at Bayliss was about 0.5 metres high and like that at Bald, completely dry. The valley floor and the side slopes of the hill were similarly covered with dry long grass. The temperature (dry bulb) for the measurements was a maximum of 37°C and a minimum of 22°C compared with a range of about 5°C to 10°C during the September measurements. Because the ground conditions were very different from those of September the previous large ground swings were not expected to be observed.

Table 8.1 shows the ground swings for the 48 measurements.

Line	G/S metres	Line	G/S metres	Line	G/S metres	Line	G/S metres
1	0.20	4	0.23	6	0.30	9	0.13
	0.15		0.28		0.28		0.11
2	0.28		0.27		0.22		0.12
	0.11		0.24		0.22		0.11
	0.24	5	0.31	7	0.15	10	0.10
	0.30		0.26		0.16		0.11
	0.12		0.21		0.22		0.09
	0.24		0.16		0.22		0.10
3	0.21	6	0.37	8	0.20		0.11
	0.25		0.35		0.22		0.10
	0.22		0.32		0.13	11	0.09
	0.24		0.30		0.15		0.11

TABLE 8.1

It can be seen from table 8.1 that the maximum ground swing occurred on line 6 and not on line 1 as one would expect, also the magnitude of this ground swing 0.37 metres is less than expected. Several of the lines were measured by students in September 1971 and again in September 1972. During the 1971 measurements the weather conditions ranged from fine sunshine to cold conditions with some rain. The 1972 measurements were taken in ideal weather conditions, i.e. warm, fine, sunny days.

Tables 8.2 and 8.3 show the range in ground swing from the 1971 and 1972 measurements respectively.

Line		1	2	3	4	5	6	7	8	9	10	11
Ground	Max	.41*	.71	.56	.71	.72	.60	.48		.39	.26*	.25
Swing	Min	.16*	.28	.28	.27	.26	.18*	.30		.36	.15	.16
metres												

*rain and wet weather

1971 RESULTS

TABLE 8.2

Line		1	2	3	4	5	6	7	8
Ground Swing metres	Max	.28	.40	.44	.73	.38	.40	.46	.22
	Min	.13	.21	.22	.22	.26	.38	.28	.15

1972 RESULTS

TABLE 8.3

8.4.1 Reduced Distance

The reduced distances to station Bald for the 48 measurements are shown in table 8.4. The standard deviation for a single observation and for the mean are shown. The mean value being 4901.24 m. It should be noted that the measurements made on line 1 to 6 inclusive have much larger residuals than those from lines 7 to 11 inclusive. Table 8.5 shows the 48 measurements again reduced to station Bald but with each set fitted to the set taken before it i.e. the 2nd set of measurements 2, 4, 6, 6, 4, 2 has been fitted to the 1st set 2, 6, 10, 10, 6, 2. The standard deviation of a single observation and of the mean is also shown. The mean value for these observations is 4901.29 m. The accepted value for the distance Bald to Bayliss is 4901.26 metres. Again it can be seen that the residuals for the lines 1 to 6 inclusive are much larger than those for 7 to 11 inclusive.

It is important to note that the magnitude of the residuals is related to the magnitude of the ground swing, thus supporting the technique of shielding part of the transmission to reduce ground swing.

8.4.2 Calculated Ground Swing

Ground swing curves were calculated, for lines 1 to 8 inclusive, according to Poder's theory, equation 6.1. The curves for line 1, which are typical, are shown in figures 8.10 to 8.19. These curves exhibit positive peaks for reflection coefficients up to 0.4 and for reflections coefficients greater than this the positive peaks are predominant with some negative values. The curves with reflection coefficients of 0.1, 0.2 and 0.3 are "reasonably typical" of the observed ground swing curves but for values exceeding this the calculated curves are in no way similar to the observed curves. It must be noted that equation 6.1 was based on the assumption that single point reflection existed and further this reflection was very strong. In view of this and also that the curves with large reflection coefficients did not approximate the observed ground swing curves it appears that multi reflections occurred on the measured lines, hence equation 6.1 is not applicable. Curves were not calculated for line 9, 10 and 11 because the crest of the hill at Bald acted as a shield making equation 6.1 unsuited for these lines.

8.5 CONCLUSION

The results revealed that the physical ground conditions have an effect on the observed ground swing. Changes in the physical conditions can cause a considerable change in the magnitude of the reflection coefficient which is described by Reed et., al. *(1966 page 33)* as "a complex quantity being a function of the dielectric constant and conductivity of the reflection surface, the frequency and polarisation of the propagated wave and the grazing angle." The actual value or change in the value of the magnitude of the reflection coefficient is difficult to calculate because the accuracy of the calculation depends on the "accuracy with which the primary parameters conductivity, permittivity, and permeability are known", Reed et., al. *(op. cit. pp. 90-1)*.

However, for carrier wave of 10 cm or less, Kerr *(1951 page 435)* states "the critical factor in determining specular reflection is the roughness of the surface, not the conductivity and dielectric constant of the surface", but on page 423 he states "a satisfactory quantitative explanation of roughness has not been found".

From this it can be seen that an analysis of the magnitude of the reflection coefficient would be extremely difficult. Experiments have been carried out into the variation of the magnitude of the reflection coefficient for horizontal and vertical polarised radiation over land and sea surfaces. The results of these experiments show considerable difference between the theoretical and observed values of the magnitude of the reflection coefficient for 3 cm radiation. *(see Kerr (1951 pp. 424, 433)).*

However the polarisation of the MRA101 tellurometer radiation is 45° with the transmitted wave and the received wave separated by 90°. *(Wadley, 1958)* As there has been no research conducted on the magnitude of the reflection coefficient for radiation with 45° polarisation, Poder *(1962, p. 4)* suggests that the reflection coefficient can be found "by splitting the incident signal in two components (vertical and horizontal) and then multiply each of them with the respective reflection coefficient, and then find the sum of their projections on the plane of the receiving antenna". The uncertainties in horizontal and vertical polarised waves between experimental and theoretical values must therefore be compounded for 45° polarisation.

The change in the physical conditions between September 1970, when the lines were covered with short wet grass, and December 1970 when the grass was long and dry must have caused a change in the magnitude of the reflection coefficient. It should be noted however that the grass was wet for some of the 1971 measurements and the observed ground swings were not excessive.

We will see a more dramatic reduction in ground swing by shielding when the amplitude of the ground swing on the unshielded line is large as evidenced by the measurements on the line Ovens to Callaghan where the ground swing amplitude was reduced by about 85 per centum.

For lines which show a small amplitude in their ground swing the shielding effect is less dramatic, although the percentage reduction in amplitude is still considerable. For the line Bald to Bayliss the reduction was between 45 and 80 per centum.

Line	Distance	ν	$\nu\nu10^4$	Line	Distance	ν	$\nu\nu10^4$
1	4901.14	-.10	100	6	4901.20	-.04	16
	.13	-.09	81		.14	-.10	100
2	.29	+.05	25		.26	+.02	4
	.28	+.04	16		.27	+.03	9
	.25	+.01	1	7	.27	+.03	9
	.20	-.04	16		.23	-.01	1
	.19	-.05	25		.26	+.02	4
	.17	-.07	49		.26	+.02	4
3	.24	-.01	1	8	.25	+.01	1
	.20	-.04	16		.17	-.07	49
	.12	-.12	144		.27	+.03	9
	.15	-.09	81		.26	+.02	4
4	.27	+.03	9	9	.29	+.05	25
	.19	-.05	25		.28	+.04	16
	.13	-.11	121		.28	+.04	16
	.27	+.03	9		.27	+.03	9
5	.17	-.07	49	10	.29	+.05	25
	.20	-.04	16		.29	+.05	25
	.24	±0	0		.25	+.01	1
	.26	+.02	4		.23	-.01	1
6	.32	+.08	64		.28	+.04	16
	.33	+.09	81		.27	+.03	9
	.27	+.03	9	11	.26	+.02	4
	.25	+.01	1		.23	-.01	1
						Σ +0.93 -1.12	
							Σ1301

MEAN = 4901.24

$\sigma_{\text{single obs.}} = \pm 0.052$

$\sigma_{\text{mean}} = \pm 0.008$

UNFITTED VALUES

TABLE 8.4

Line	Distance	ν	$\nu\nu\ 10^4$	Line	Distance	ν	$\nu\nu 10^4$
1	4901.24	-.05	25	6	4901.28	-.01	1
	.24	-.05	25		.26	-.03	9
2	.29	± 0	0		.32	+.03	9
	.28	-.01	1		.32	+.04	16
	.29	± 0	0	7	.32	+.03	9
	.28	-.01	1		.29	± 0	0
	.29	± 0	0		.32	+.03	9
	.28	-.01	1		.29	± 0	0
3	.34	+.05	25	8	.33	+.04	16
	.31	+.02	4		.29	± 0	0
	.30	+.01	1		.33	+.04	16
	.13	-.16	256		.29	± 0	0
4	.31	+.02	4	9	.34	+.05	25
	.25	-.04	16		.30	+.01	1
	.31	+.02	4		.29	± 0	0
	.25	-.04	16		.28	-.01	1
5	.42	+.13	169	10	.29	± 0	0
	.24	-.05	25		.29	± 0	0
	.30	+.01	1		.33	+.04	16
	.32	+.03	9		.35	+.06	36
6	.32	+.03	9		.26	-.03	9
	.33	+.04	16		.25	-.04	16
	.31	+.02	4	11	.27	-.02	4
	.32	+.03	9		.25	-.04	16
						$\Sigma^{+0.78}_{-0.60}$	
							Σ830

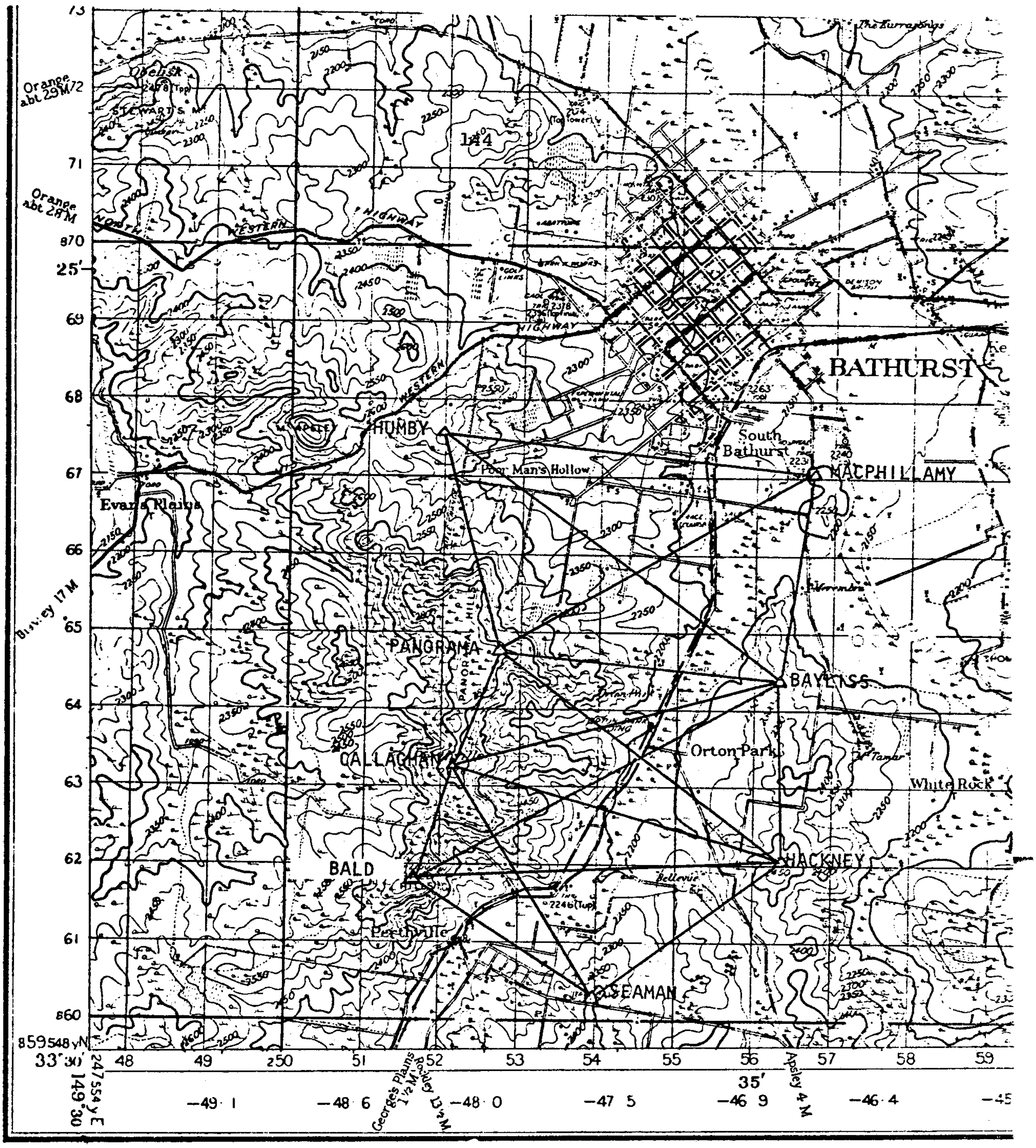
MEAN = 4901.29

$\sigma_{\text{single obs.}} = \pm 0.042$

$\sigma_{\text{mean}} = \pm 0.006$

FITTED VALUES

TABLE 8.5



Prepared by Australian Section Imperial General Staff

The framework of this Map depends entirely upon the Main Geodetic Triangulation of NSW supplemented by topographical triangulation by the Australian Survey Corps Polyconic Projection
Elevations in feet. Standard Datum, Sydney.
Surveyed in 1933 by Australian Survey Corps with aid of Air Photos by Royal Australian Air Force

Bridge (wood except where shown as masonry or iron) M or I
Culvert ....
Water Hole ....
Swamp or Marsh ....
Creek ....
Watercourse (non perennial) ....
Water channel ....
Railway (double line) .... STATIONS
Railway (single line) ....

Origin of Longitude, Sydney Observatory, 151°12'17"85

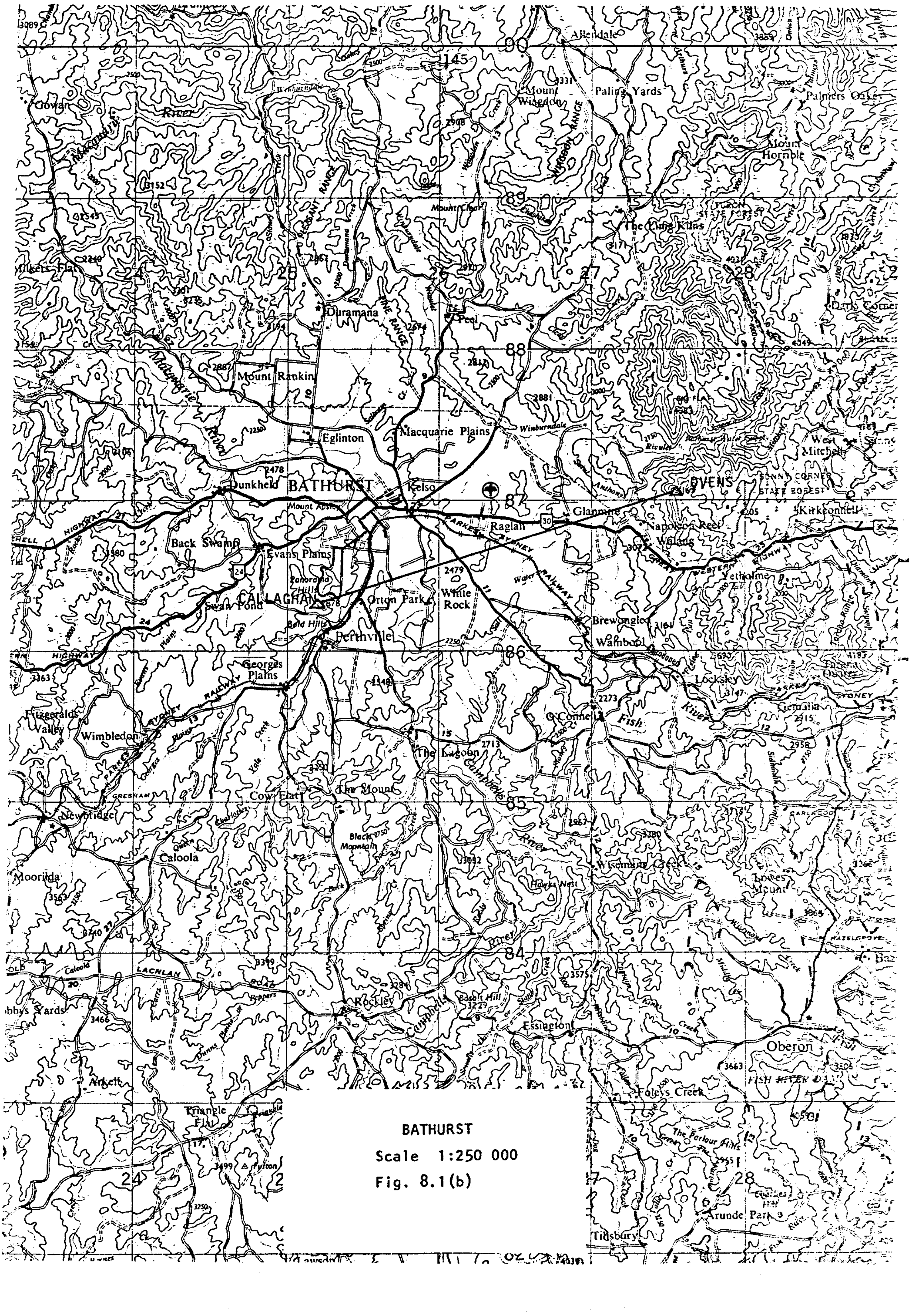
AHQ/A2-6/0704 P.

BATHURST

Scale 1:63 360

Fig. 8.1(a)

By Authority



BATHURST

Scale 1:250 000

Fig. 8.1(b)

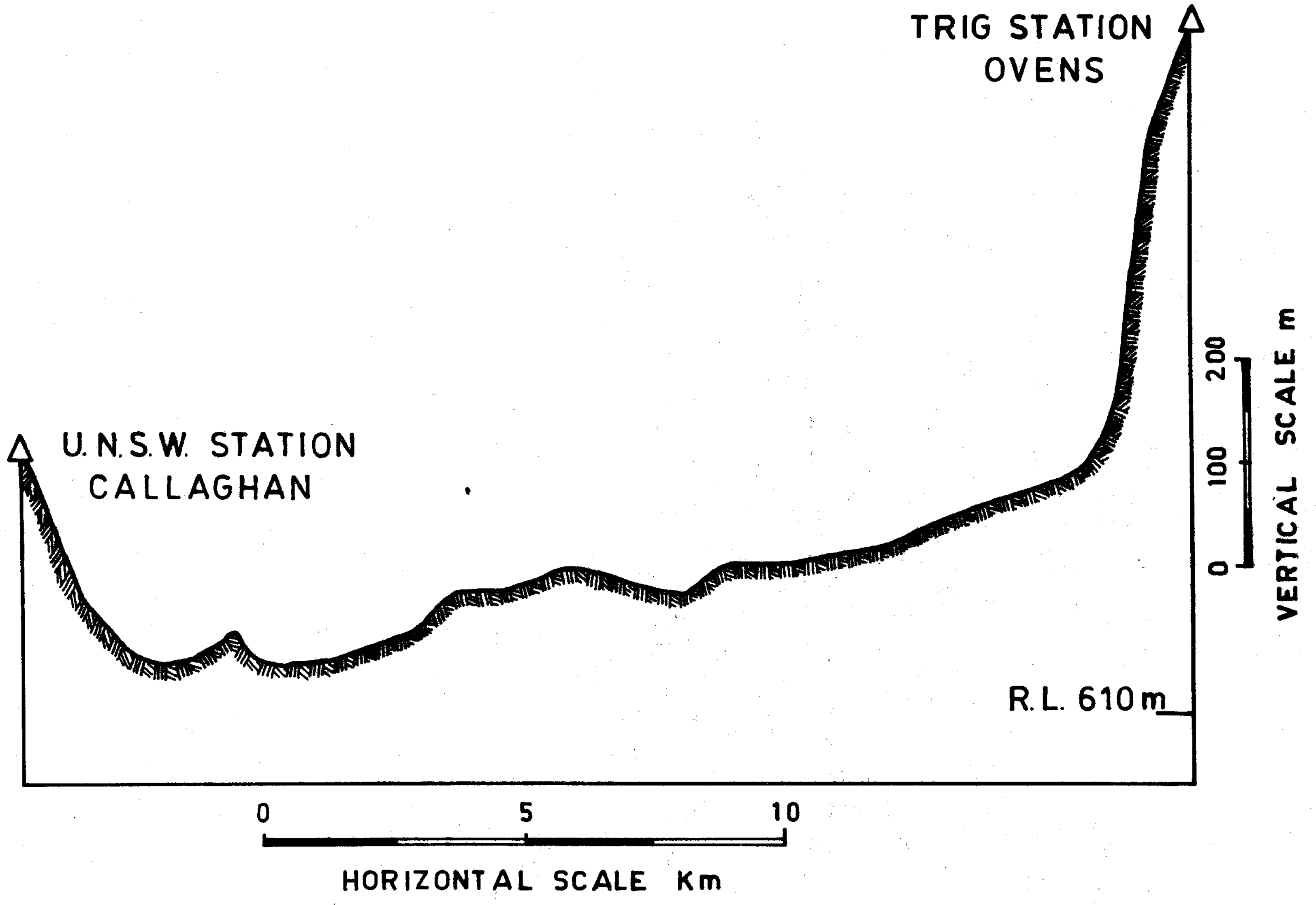

TRIG STATION
OVENS
U.N.S.W. STATION
CALLAGHAN
200
100
0
VERTICAL SCALE m
R.L. 610 m
0
5
10
HORIZONTAL SCALE Km

FIG. 8·2

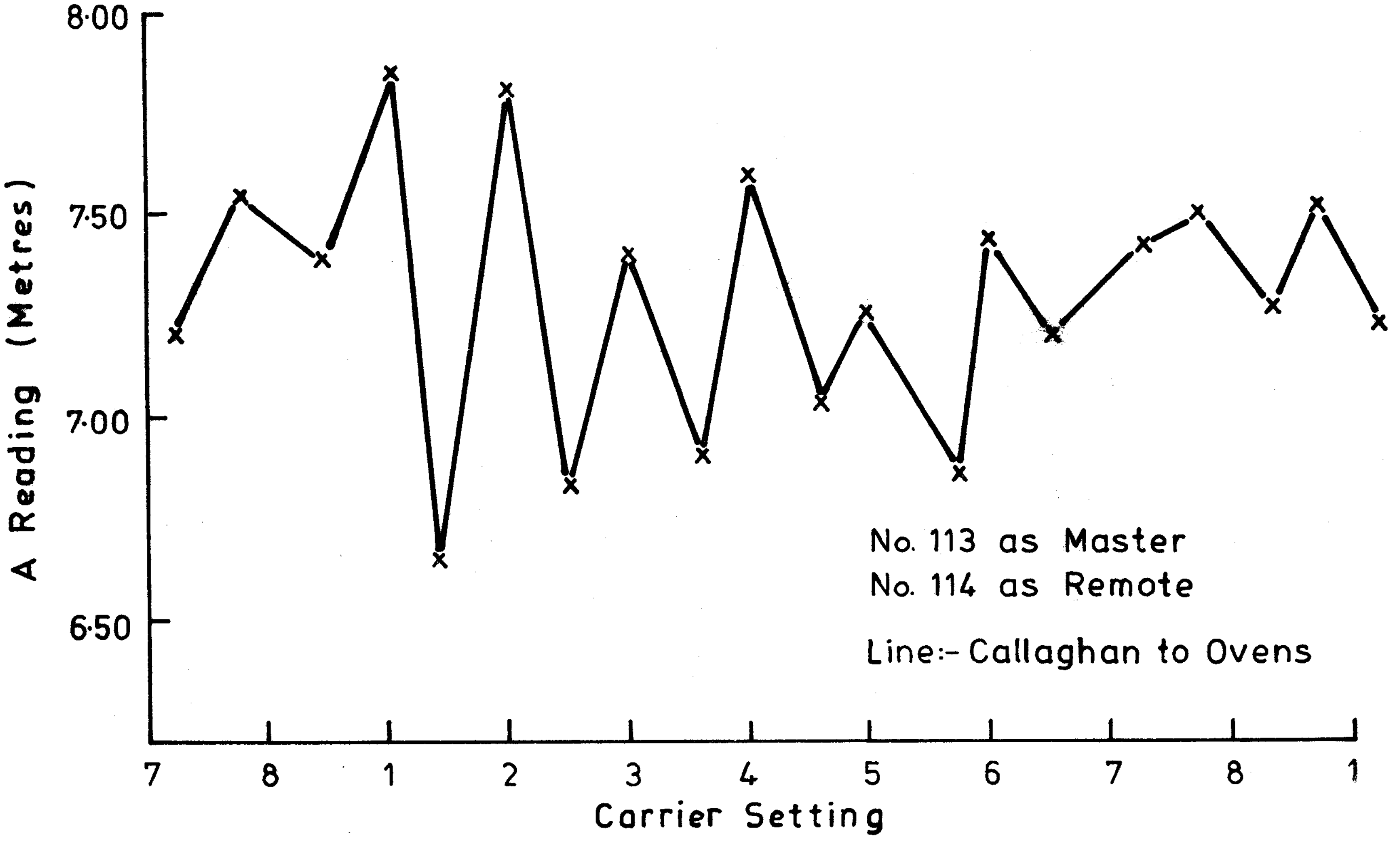

8·00
7·50
7·00
6·50
A Reading (Metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
No. 113 as Master
No. 114 as Remote
Line:- Callaghan to Ovens

FIG. 8·3

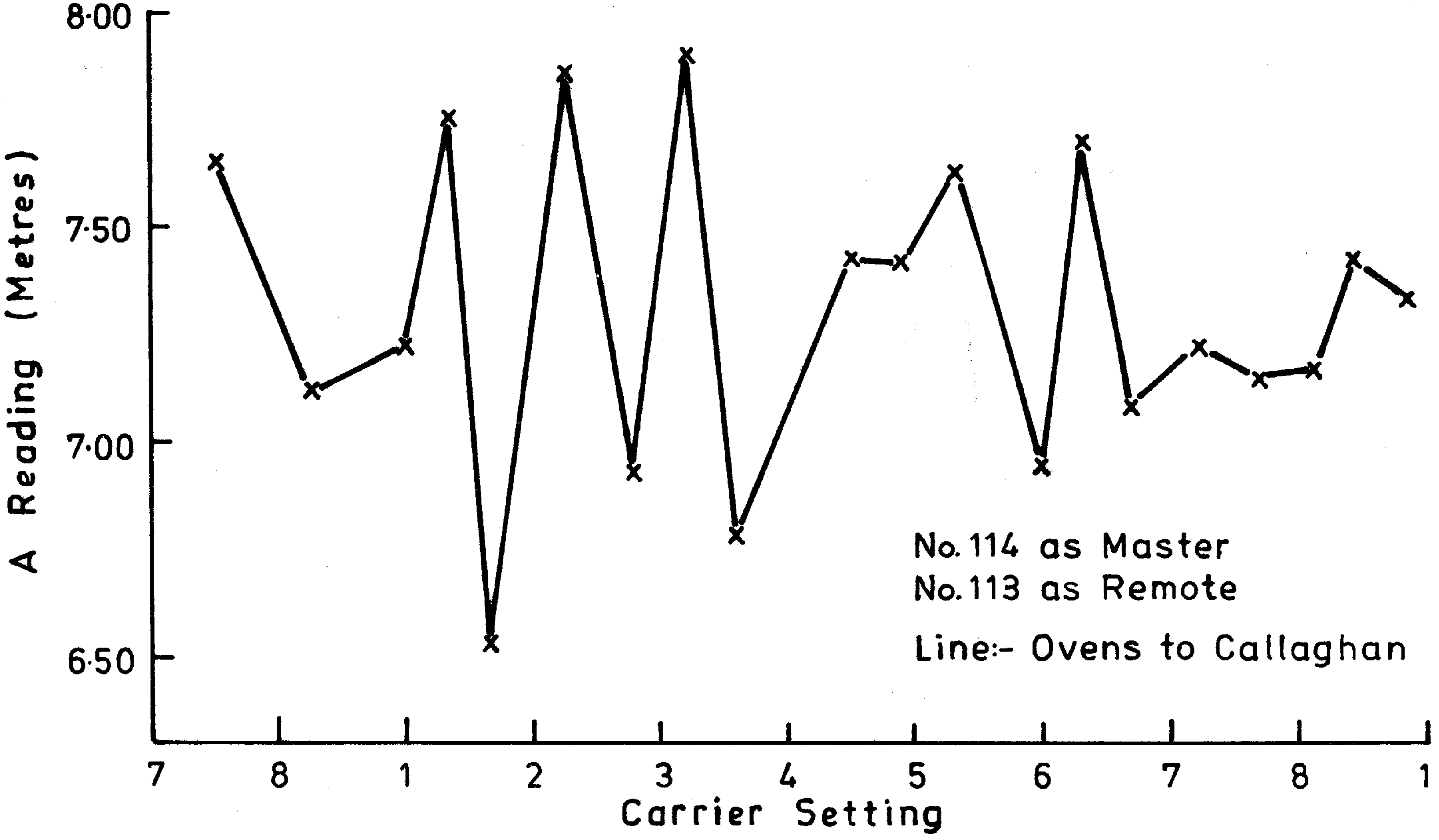

8·00
7·50
7·00
6·50
A Reading (Metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
No. 114 as Master
No. 113 as Remote
Line:- Ovens to Callaghan

FIG. 8·4

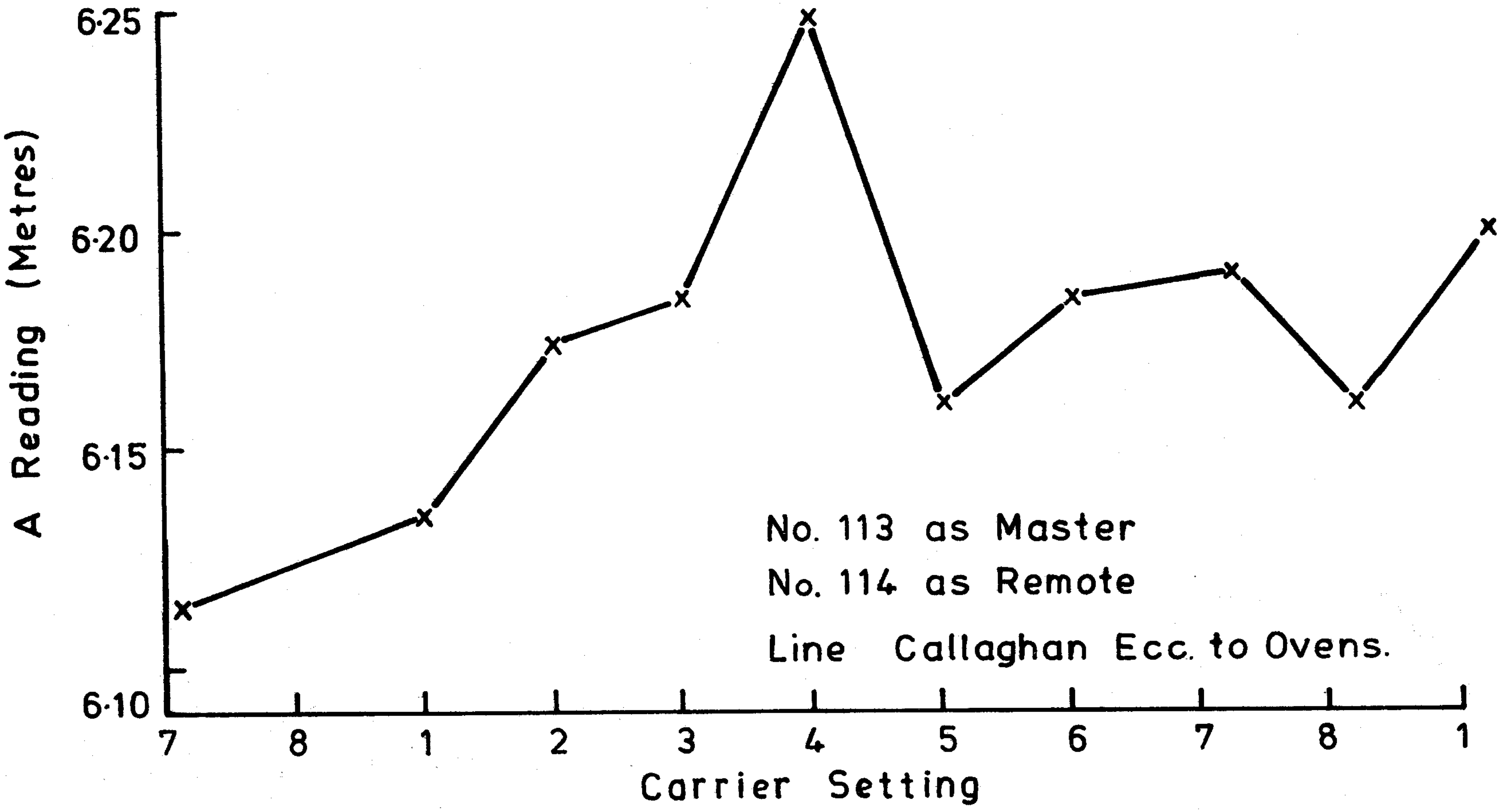

6·25
6·20
6·15
6·10
A Reading (Metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting
No. 113 as Master
No. 114 as Remote
Line Callaghan Ecc. to Ovens.

FIG. 8·5

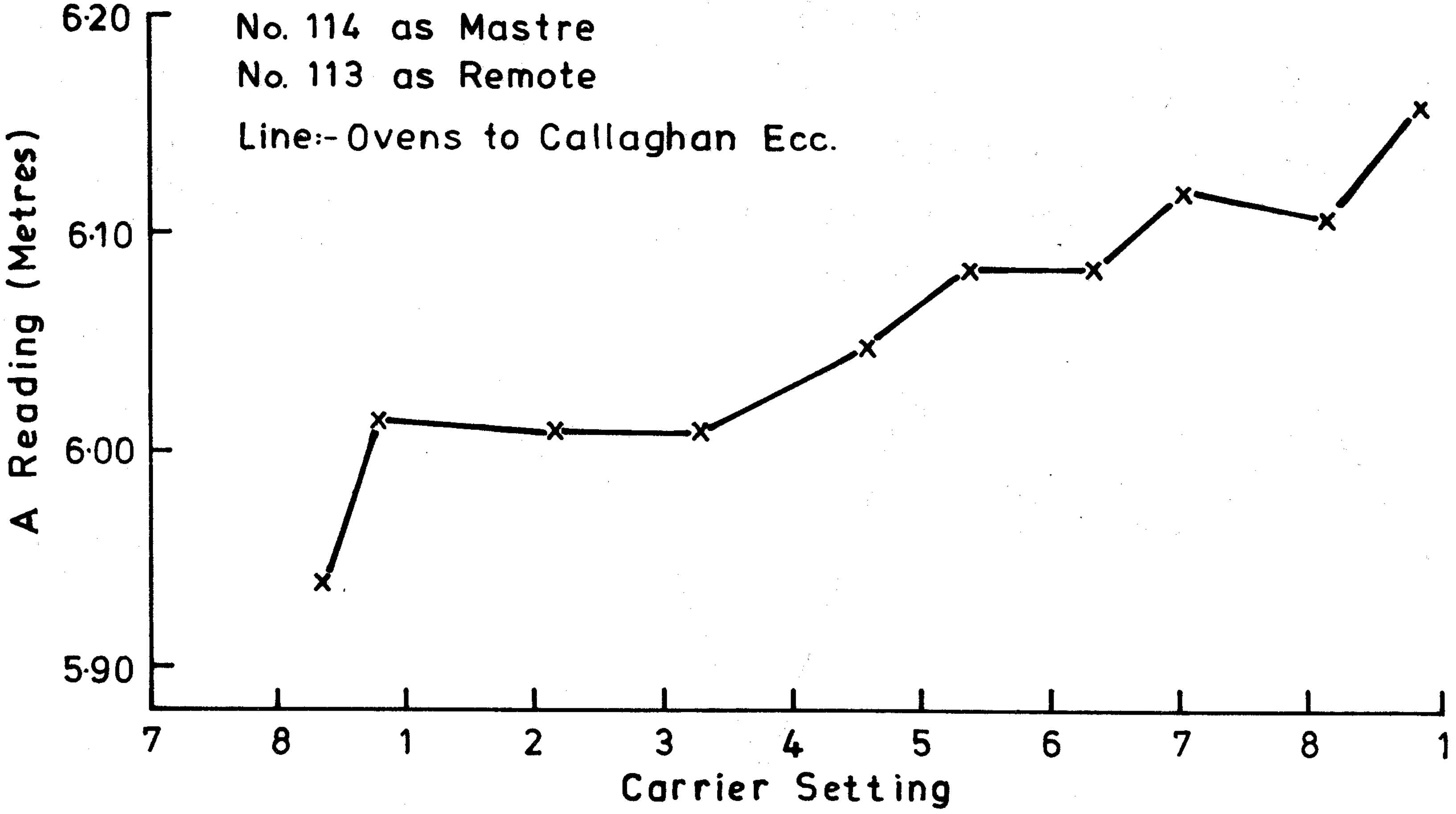

No. 114 as Mastre
No. 113 as Remote
Line:- Ovens to Callaghan Ecc.
A Reading (Metres)
6·20
6·10
6·00
5·90
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 8·6

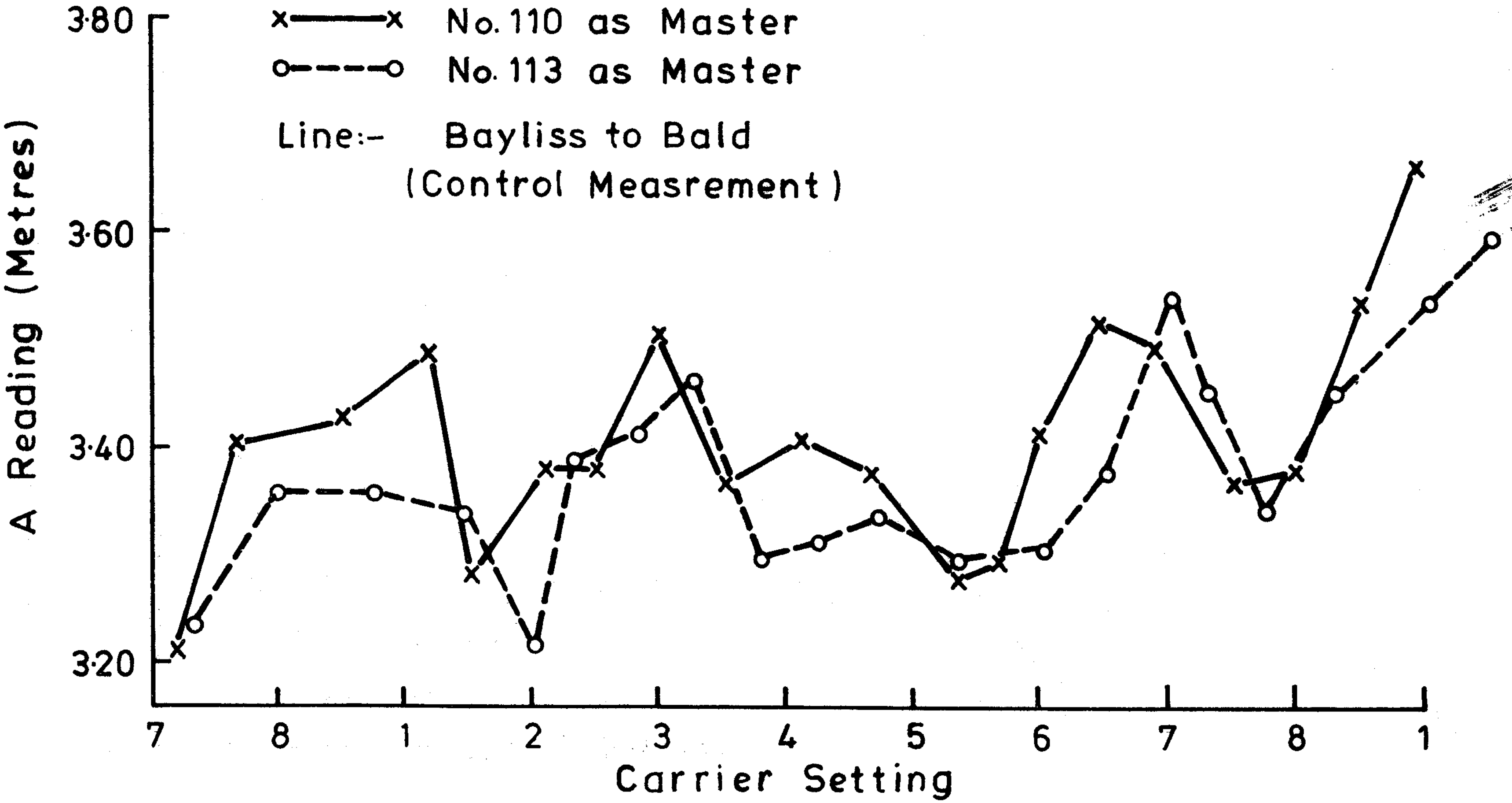

No. 110 as Master
No. 113 as Master
Line:- Bayliss to Bald
(Control Measrement)
A Reading (Metres)
3·80
3·60
3·40
3·20
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 8·7

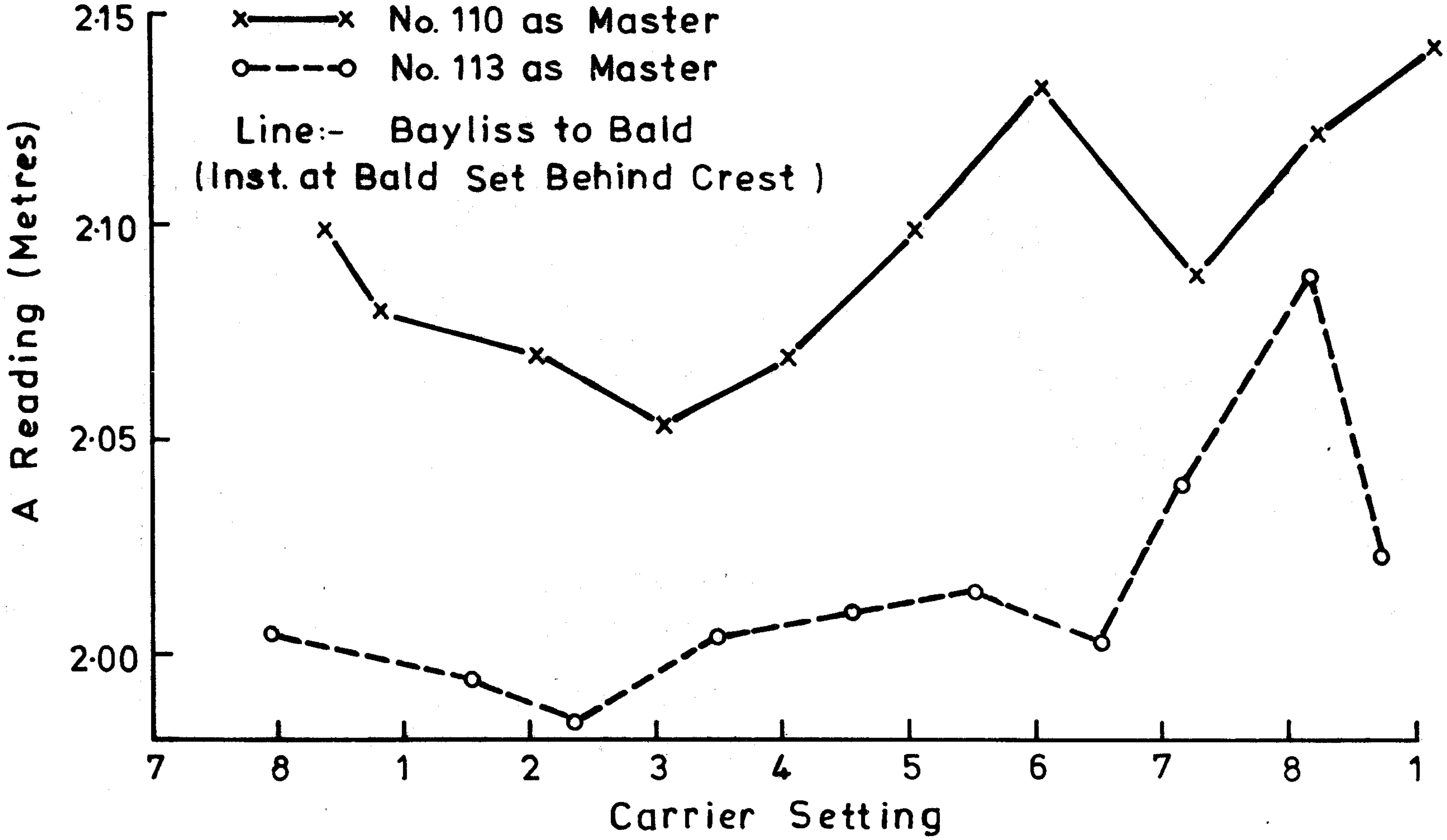
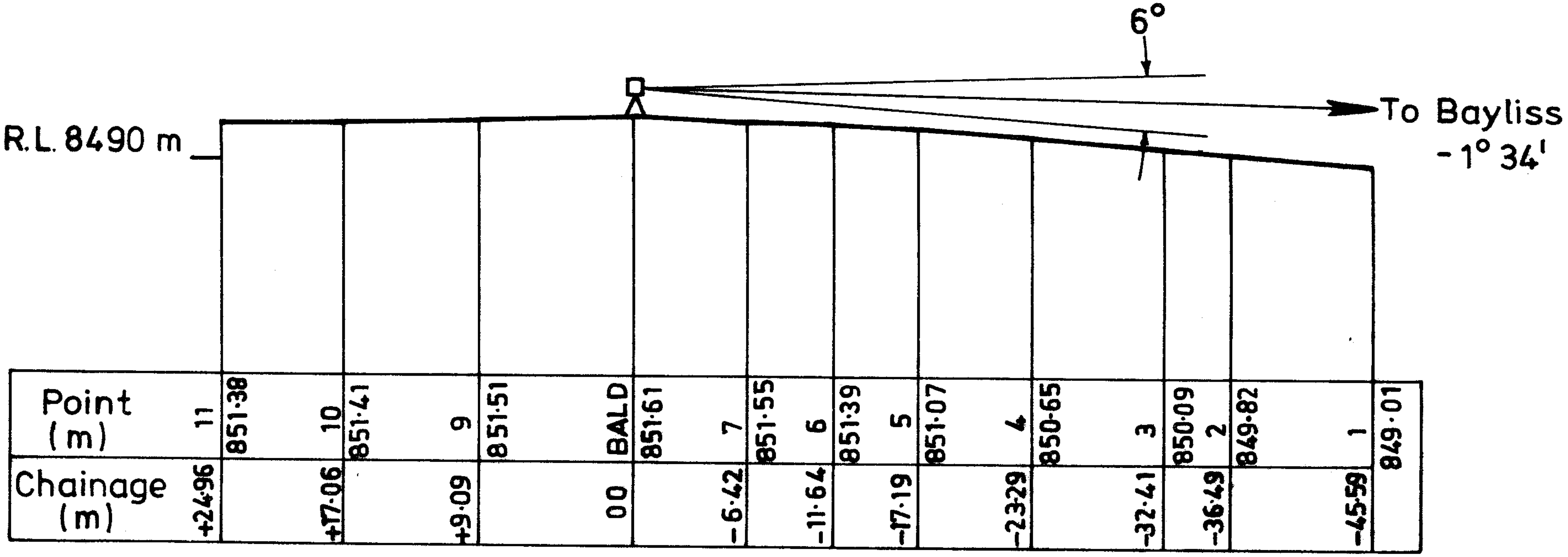
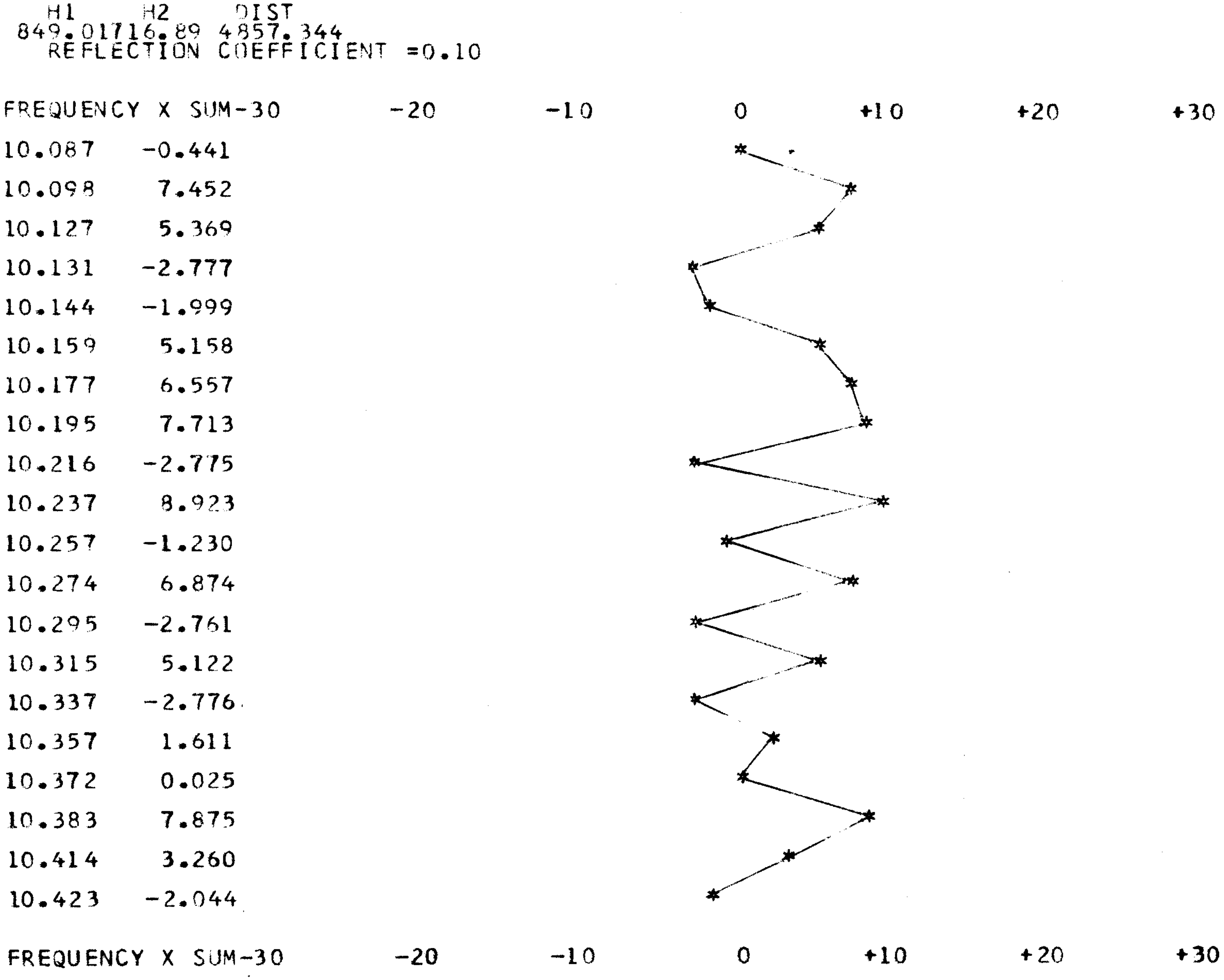

No. 110 as Master
No. 113 as Master
Line:- Bayliss to Bald
(Inst. at Bald Set Behind Crest)
2·15
2·10
2·05
2·00
A Reading (Metres)
7
8
1
2
3
4
5
6
7
8
1
Carrier Setting

FIG. 8·8



Profile at Station Bald
(Tellurometer 6° Cone of Transmission is Shown)

FIG. 8·9



```
 H1    H2     DIST
849.01716.89 4857.344
 REFLECTION COEFFICIENT =0.10

FREQUENCY X SUM-30        -20        -10        0        +10        +20        +30
10.087   -0.441
10.098    7.452
10.127    5.369
10.131   -2.777
10.144   -1.999
10.159    5.158
10.177    6.557
10.195    7.713
10.216   -2.775
10.237    8.923
10.257   -1.230
10.274    6.874
10.295   -2.761
10.315    5.122
10.337   -2.776
10.357    1.611
10.372    0.025
10.383    7.875
10.414    3.260
10.423   -2.044

FREQUENCY X SUM-30        -20        -10        0        +10        +20        +30
```

FIG. 8.10

```
   H1      H2     DIST
849.01716.89 4857.344
   REFLECTION COEFFICIENT =0.20

FREQUENCY X SUM-30
10.087   -0.337
10.098   19.496
10.127   13.719
10.131    0.790
10.144   -2.180
10.159   13.131
10.177   16.985
10.195   20.231
10.216    0.587
10.237   23.674
10.257   -1.561
10.274   17.870
10.295    0.044
10.315   13.046
10.337    0.887
10.357    4.017
10.372    0.537
10.383   20.689
10.414    8.094
10.423   -2.183

FREQUENCY X SUM-30
```

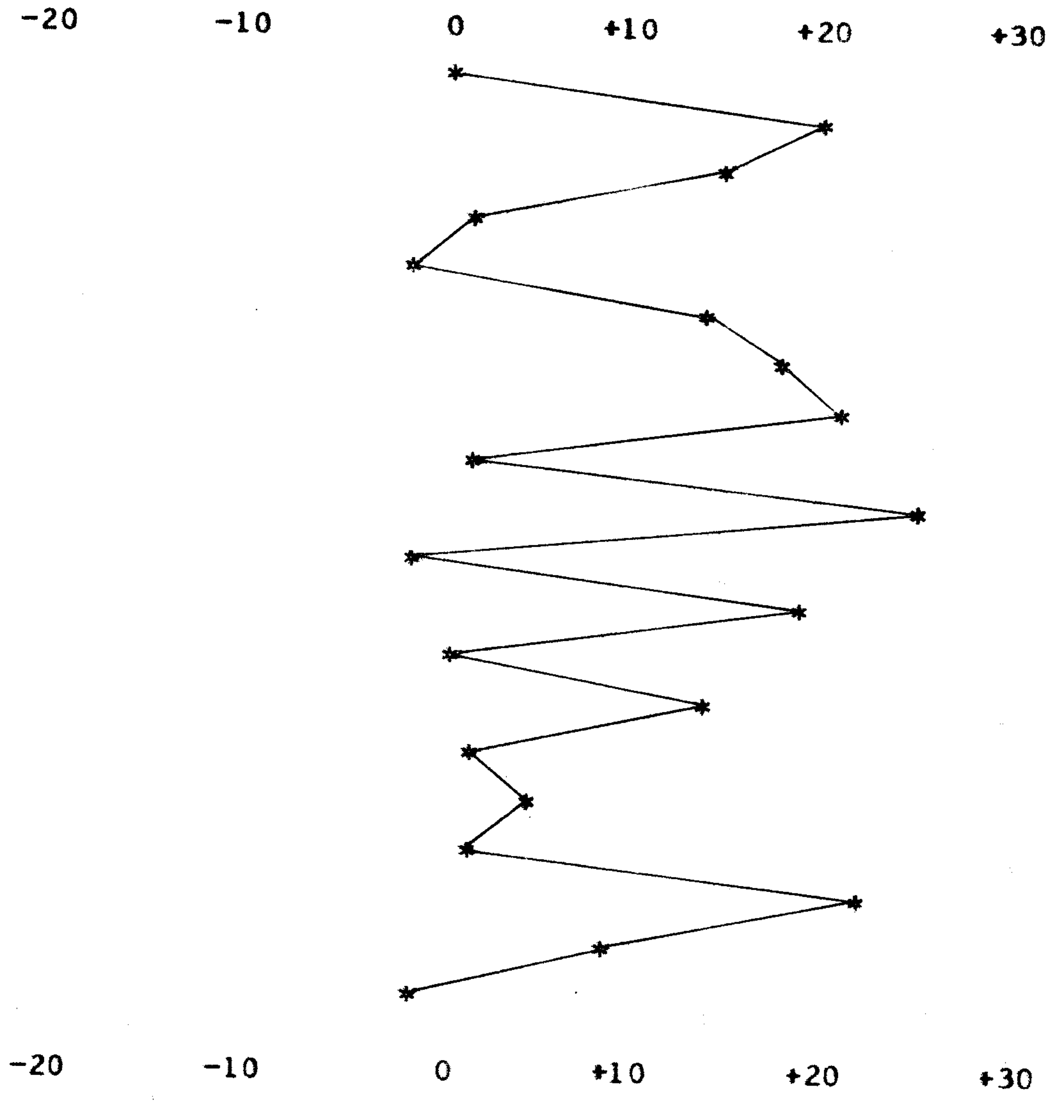


FIG. 8.11

```
  H1      H2     DIST
849.01716.89 4857.344
  REFLECTION COEFFICIENT =0.30

FREQUENCY X SUM-30
10.087     0.224
10.098    36.021
10.127    25.141
10.131    11.079
10.144    -0.663
10.159    24.014
10.177    31.286
10.195    37.405
10.216    10.434
10.237    43.664
10.257    -1.119
10.274    32.956
10.295     8.679
10.315    23.873
10.337    11.381
10.357     7.261
10.372     1.481
10.383    38.268
10.414    14.610
10.423    -0.532
FREQUENCY X SUM-30
```

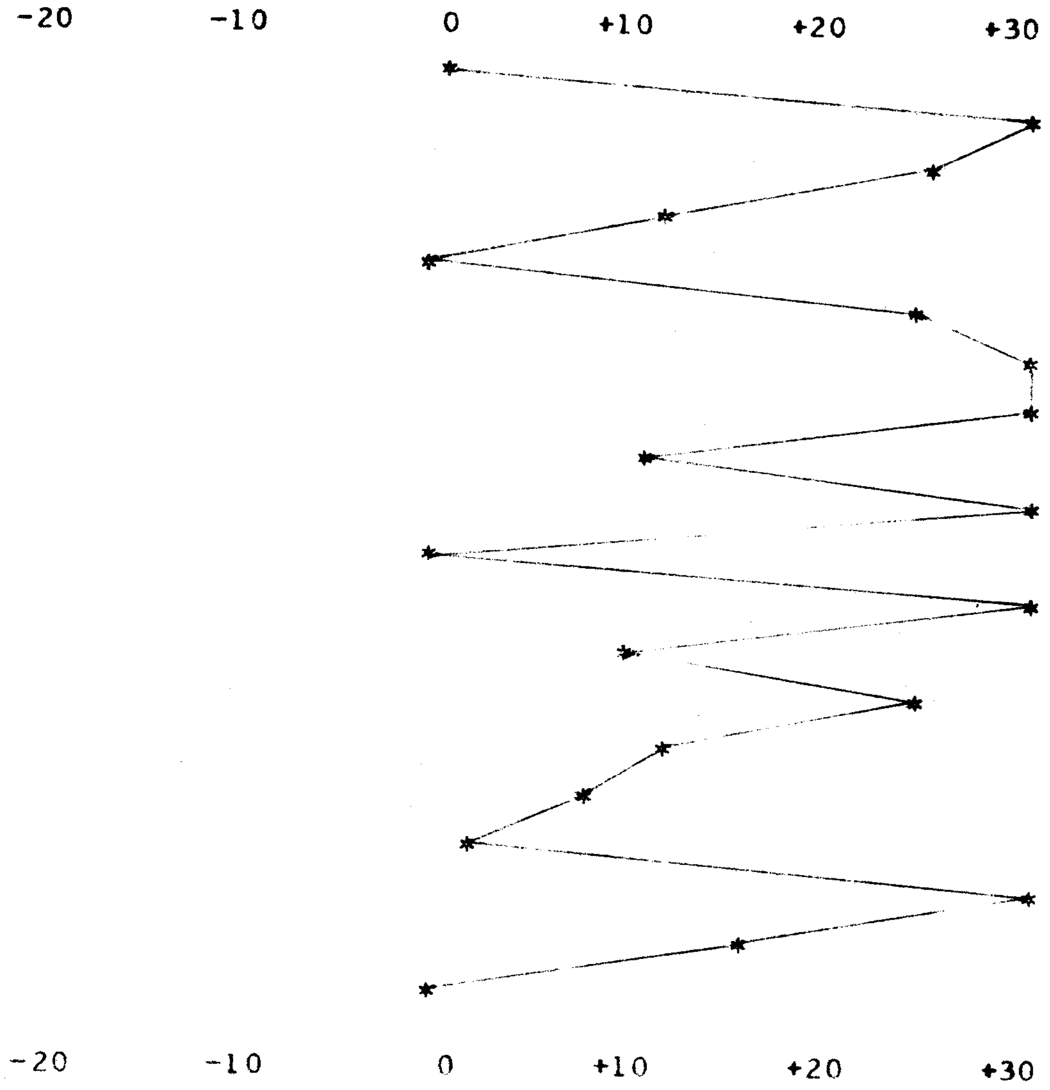


FIG. 8.12

```
  H1      H2      DIST
849.01716.89 4857.344
  REFLECTION COEFFICIENT =0.40

FREQUENCY X SUM-30
10.087    1.137
10.098   56.982
10.127   39.924
10.131   28.495
10.144    2.432
10.159   38.107
10.177   49.610
10.195   59.114
10.216   27.154
10.237   68.917
10.257   -0.058
10.274   52.224
10.295   23.475
10.315   37.905
10.337   29.116
10.357   11.448
10.372    2.792
10.383   60.437
10.414   23.067
10.423    2.796

FREQUENCY X SUM-30
```

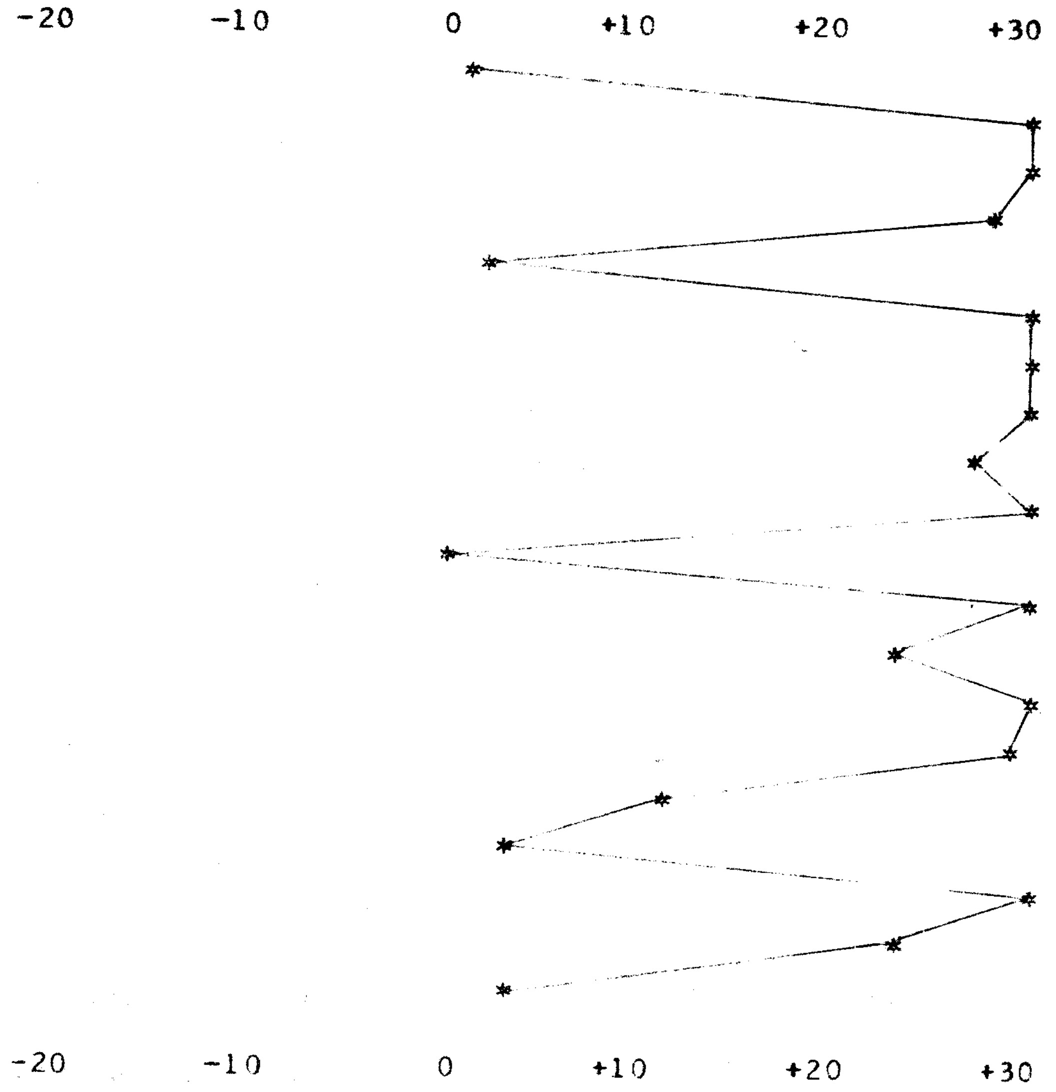


FIG. 8.13

```
  H1      H2     DIST
849.01716.89 4857.344
  REFLECTION COEFFICIENT =0.50

FREQUENCY X SUM-30
10.087     2.296
10.098    82.387
10.127    58.728
10.131    53.340
10.144     7.082
10.159    56.097
10.177    72.343
10.195    85.234
10.216    51.100
10.237    97.966
10.257     1.476
10.274    75.939
10.295    44.879
10.315    55.830
10.337    54.366
10.357    16.858
10.372     4.426
10.383    86.987
10.414    34.073
10.423     7.794

FREQUENCY X SUM-30
```

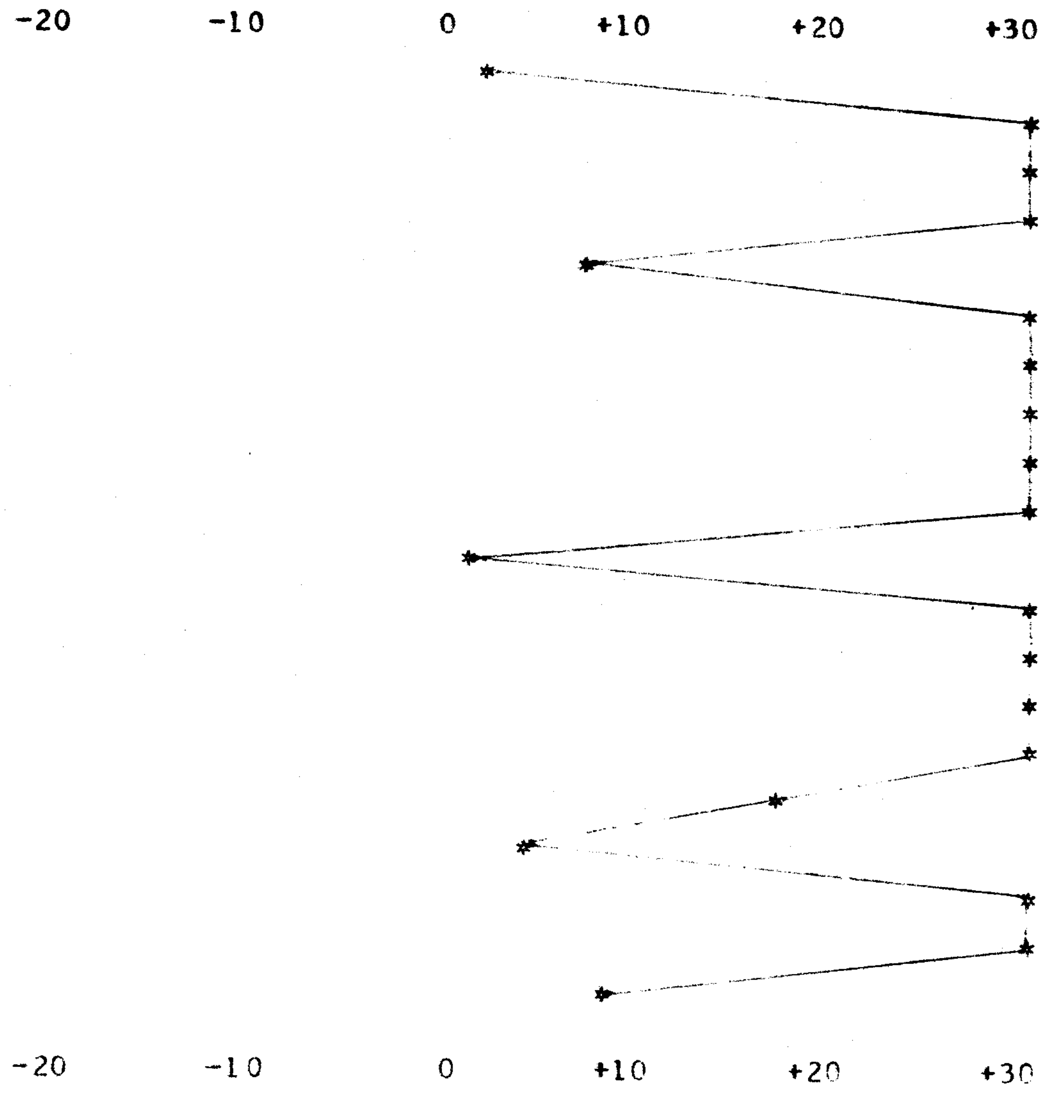


FIG. 8.14

```
  H1      H2      DIST
849.01716.89 4857.344
  REFLECTION COEFFICIENT =0.60

FREQUENCY X SUM-30
10.087     3.616
10.098   112.202
10.127    82.779
10.131    85.564
10.144    13.556
10.159    79.289
10.177   100.096
10.195   115.526
10.216    82.427
10.237   129.819
10.257     3.381
10.274   104.499
10.295    73.503
10.315    78.957
10.337    86.981
10.357    24.168
10.372     6.410
10.383   117.548
10.414    48.949
10.423    14.773

FREQUENCY X SUM-30
```

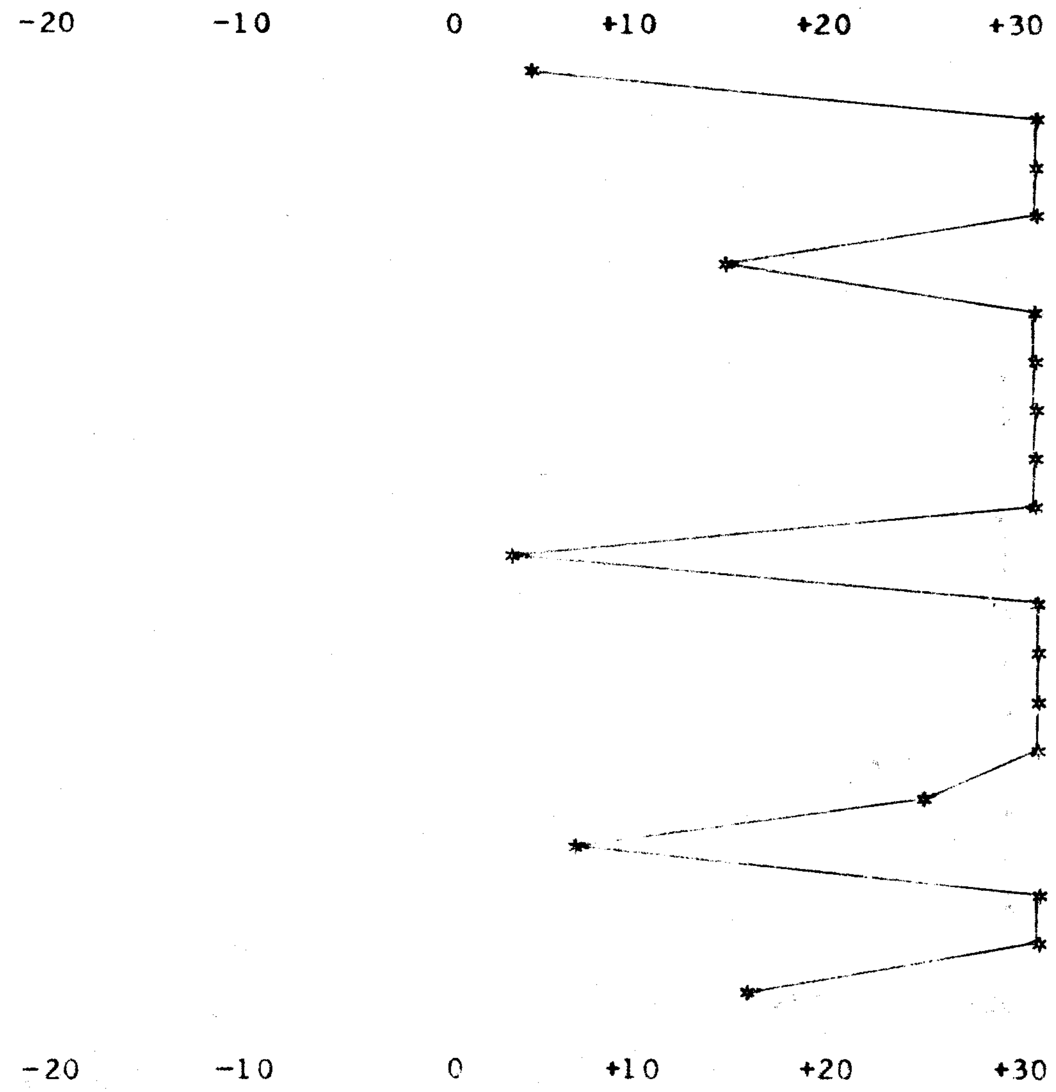


FIG. 8.15

```
  H1     H2     DIST
849.01716.89 4857.344
  REFLECTION COEFFICIENT =0.70

FREQUENCY X SUM-30
10.087     5.062
10.098   146.076
10.127   113.967
10.131   124.396
10.144    22.903
10.159   109.792
10.177   133.469
10.195   149.397
10.216   120.765
10.237   163.045
10.257     5.667
10.274   138.149
10.295   110.038
10.315   109.412
10.337   126.007
10.357    35.061
10.372     8.942
10.383   151.390
10.414    70.553
10.423    24.894

FREQUENCY X SUM-30
```

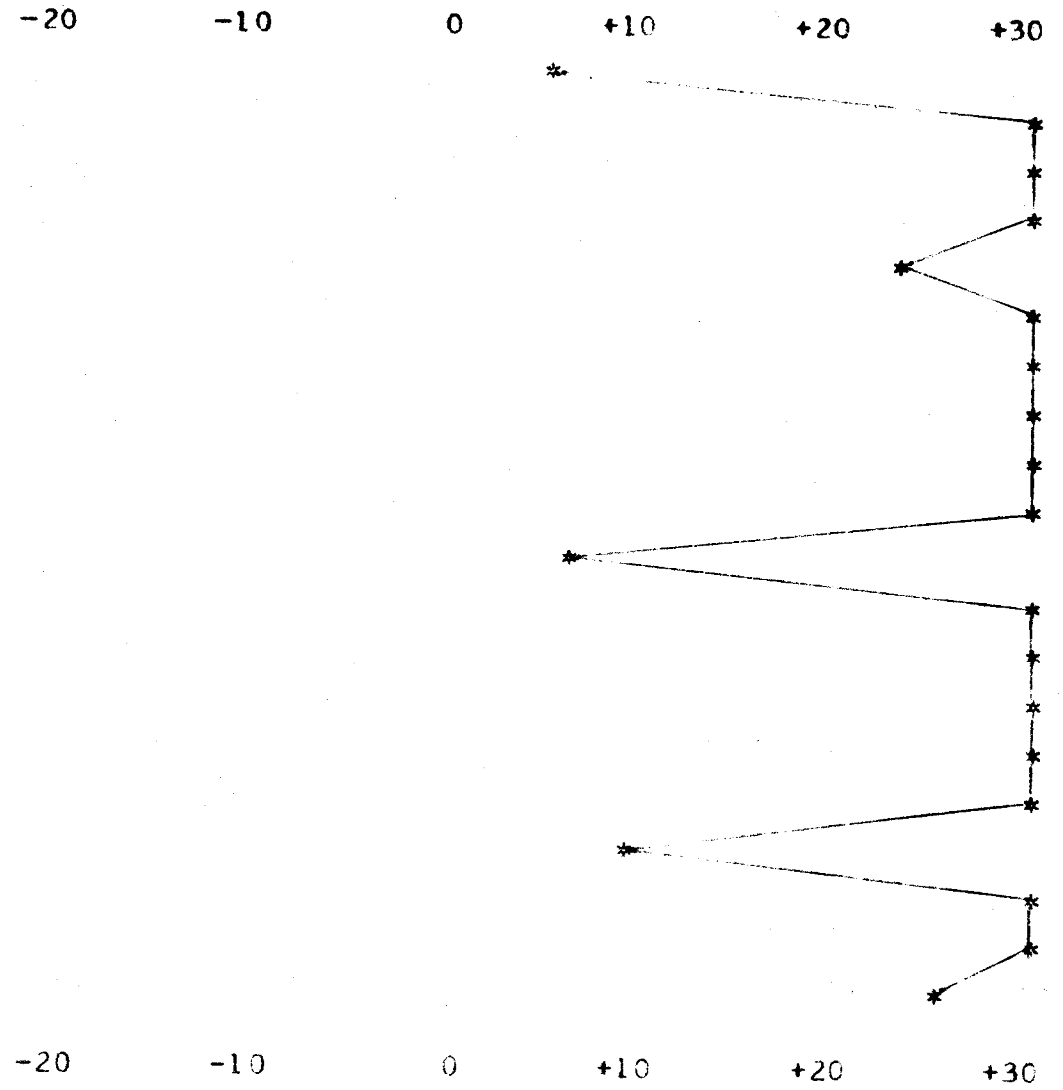
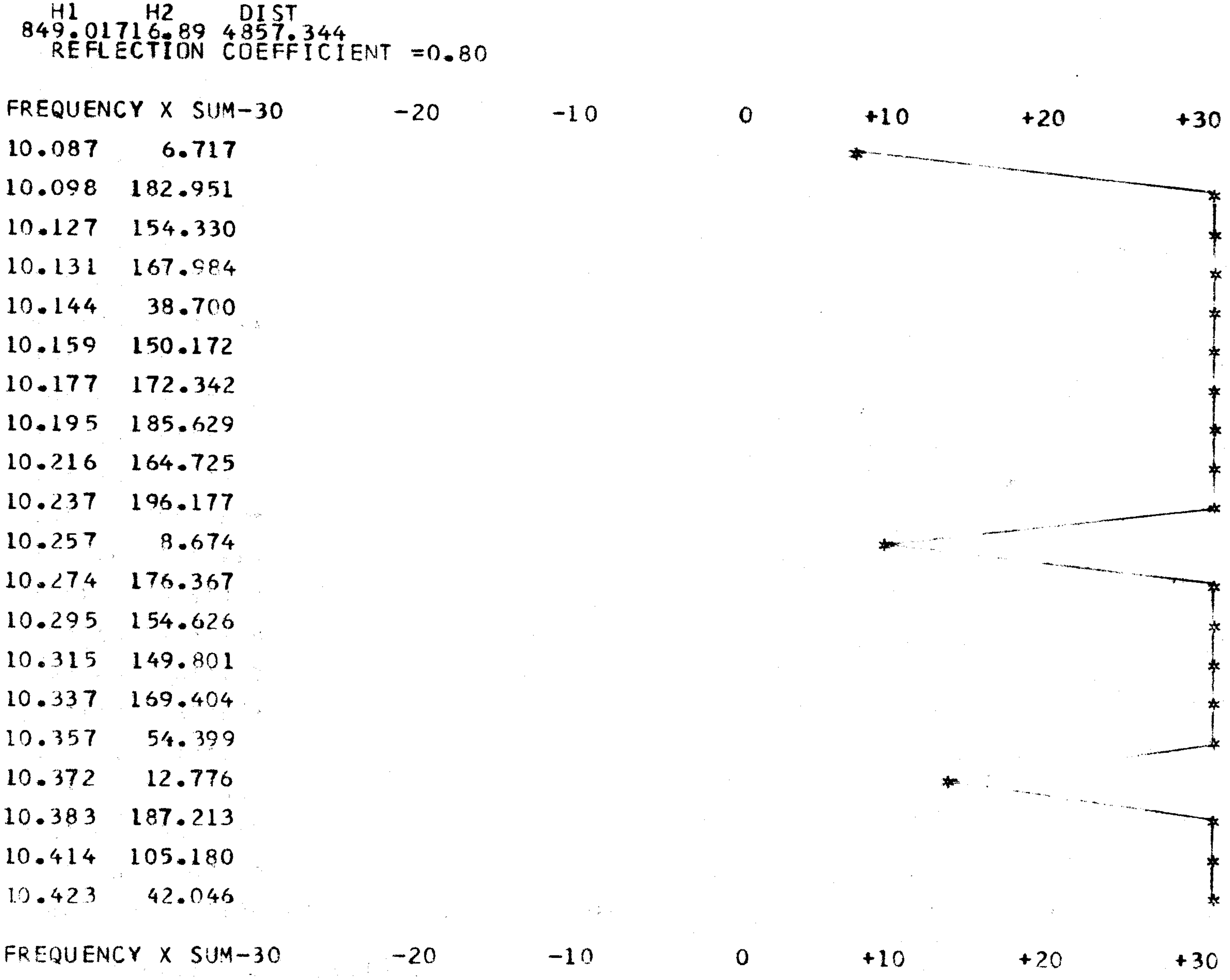


FIG. 8.16



```
  H1      H2     DIST
849.01716.89 4857.344
  REFLECTION COEFFICIENT =0.80

FREQUENCY X SUM-30       -20       -10        0       +10       +20       +30
10.087    6.717
10.098  182.951
10.127  154.330
10.131  167.984
10.144   38.700
10.159  150.172
10.177  172.342
10.195  185.629
10.216  164.725
10.237  196.177
10.257    8.674
10.274  176.367
10.295  154.626
10.315  149.801
10.337  169.404
10.357   54.399
10.372   12.776
10.383  187.213
10.414  105.180
10.423   42.046

FREQUENCY X SUM-30       -20       -10        0       +10       +20       +30
```

FIG. 8.17

```
    H1      H2     DIST
849.01716.89 4857.344
    REFLECTION COEFFICIENT =0.90

FREQUENCY  X SUM-30       -20        -10         0        +10        +20        +30
10.087     9.254
10.098   220.871
10.127   203.870
10.131   213.411
10.144    77.194
10.159   201.143
10.177   214.879
10.195   222.335
10.216   211.510
10.237   227.944
10.257    14.510
10.274   217.190
10.295   205.381
10.315   200.900
10.337   214.227
10.357   101.200
10.372    21.862
10.383   223.194
10.414   165.313
10.423    83.389

FREQUENCY  X SUM-30       -20        -10         0        +10        +20        +30
```

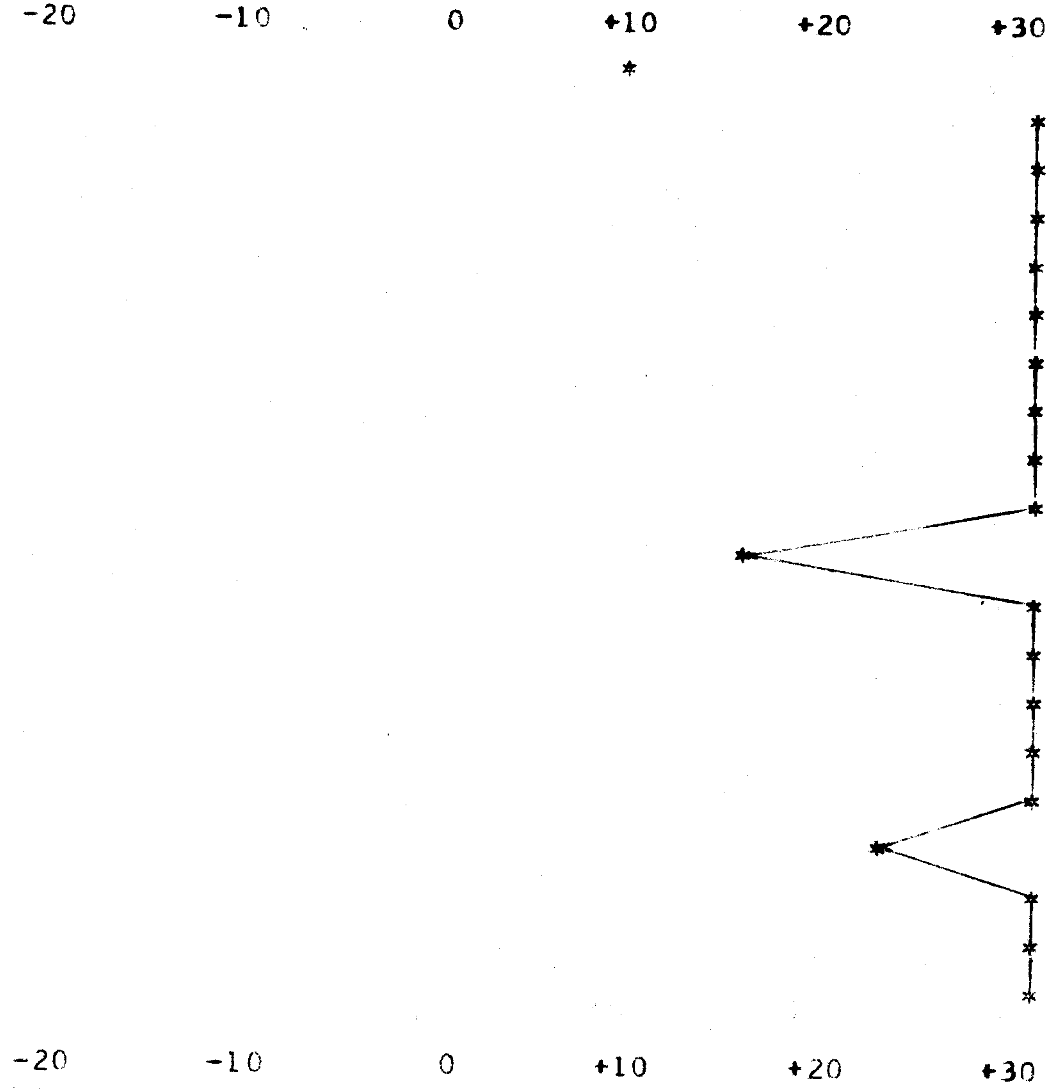


FIG. 8.18

```
   H1      H2      DIST
 849.01716.89 4857.344
   REFLECTION COEFFICIENT =1.00

FREQUENCY X SUM-30         -20        -10         0        +10        +20        +30
10.087   217.672                                                                   *
10.098   257.402                                                                   *
10.127   257.322                                                                   *
10.131   257.369                                                                   *
10.144   256.124                                                                   *
10.159   257.309                                                                   *
10.177   257.375                                                                   *
10.195   257.409                                                                   *
10.216   257.361                                                                   *
10.237   257.434                                                                   *
10.257   244.289                                                                   *
10.274   257.386                                                                   *
10.295   257.332                                                                   *
10.315   257.308                                                                   *
10.337   257.373                                                                   *
10.357   256.535                                                                   *
10.372   250.348                                                                   *
10.383   257.413                                                                   *
10.414   257.113                                                                   *
10.423   256.257                                                                   *

FREQUENCY X SUM-30         -20        -10         0        +10        +20        +30
```

FIG. 8.19

9. FINAL CONCLUSION

This work clearly shows that users of the model MRA101 tellurometer must calibrate their instruments for zero error. The zero error of this tellurometer is cyclic and dependent on the A reading but the magnitude of the cyclic term is of the order of one centimetre and the overall effect of the cyclic component can be masked by the fact that the instrument has centimetre resolution and the accepted distance is taken from a ground swing curve. Tests taken on measurements with a range in A readings from about 2.5 to 5.5 show that the addition of the cyclic term in the zero correction expression only marginally reduces the standard deviation of a measurement.

If a calibration base of known length is not available then the technique of measuring a line (of unknown length) and then measuring the line in sections proved a reliable method. It is recommended that when this method is used in practice, the line should be divided into nine sections so that the total of ten lines covers the range in the A readings. The resulting zero correction will then represent a mean value and should minimise the cyclic effects.

Care must be exercised when applying a zero correction derived from conventional pointing if the observers tilt the instruments in the vertical plane during the measurements in order to reduce the ground swing. The experimental work shows that for tilts up to 3° the zero correction does not differ greatly from the value for conventional pointing, but beyond this range the zero correction changes greatly. The experiment supported the tilt value of 2° suggested by Küpfer *(1967)* to be the ideal tilt for the reduction of ground swing.

The experiments conducted into ground swing show how difficult it is to predict the ground swing for a particular line. The theoretical expression by Wadley *(1958)* was supported over the short base line for medium instrument heights but at large instrument heights the resulting ground swing was most probably due to antenna swing. It is also interesting to note that over the short base line (183 m) at normal instrument heights (giving small path differences) the observed ground swing was probably antenna swing. Extreme care must be exercised when using short base lines for zero error calibration to ensure that the instruments are not set up at critical heights. At critical heights the effect of ground swing can cause large anomolies in the displayed distance, yet when studying the ground swing curve no anomalies appear to exist. Tables were calculated showing the expected critical heights over the 183 m base for a level surface and for an even sloping surface. The actual observed critical height fell between these two predicted values for the first critical height.

The monumental work of Poder *(1962)* into reflections dealt mainly with lines over highly reflecting surfaces and as a result its application to this work was very limited. Poder error curves were calculated and used wherever possible.

The effect of instrument tilt on ground swing was examined and the results indicated that if both instruments are tilted upward to a value of about 3° then the ground swing is reduced, however, as the ground swing on the original line was small no firm conclusions can be drawn from these experimental results.

The technique of using artificial shields to reduce ground swing on lines exhibiting large ground swing values is clearly demonstrated on the lines measured in the Bathurst area of N.S.W. The results of a detailed experiment into the effect of natural shields on one of the Bathurst lines revealed a considerable reduction in the amplitude of the ground swing even though the unshielded line did not exhibit a large amplitude ground swing curve.

The change in the amplitude of the ground swing curve was apparently caused by a change in the magnitude of the reflection coefficient. Changes in the magnitude of the reflection coefficient are very difficult to predict and research has shown a considerable difference between practical and theoretical values of the magnitude of reflection coefficient for horizontal and vertical polarised radiation. As the tellurometer has 45^{o} polarised radiation the situation is made more difficult and it is suggested that future research should be concentrated in this area.

REFERENCES

ALLMAN, J.S. 1968. "An analysis of the reliability of barometric elevations". *UNISURV Report No. 5.* The University of New South Wales.

ANGUS-LEPPAN, P.V. (ed.) 1968. "Proceedings of REF-EDM Conference". *The University of New South Wales.*

BAKKELID, S. 1962. "Preliminary Results of Studies of some Tellurometer Problems". *Geodetic Publication No. 13.* Oslo, Norway.

BEDSTED, O. 1962. "A note on the Cyclic Error". *Proceedings of the 1962 Tellurometer Symposium.* Oxford.

BOMFORD, G. 1962. "Geodesy". Second Edition. Clarendon Press

BOMFORD, G. 1971. "Geodesy". Third Edition. Clarendon Press.

BOSSLER, J.D. 1964. "A study of the Zero Error in the Model MRA 3 Tellurometer". Unpublished Thesis, *The Ohio State University.*

BOSSLER, J.D. & LAURILA, S.H. 1965. "Zero Error of MRA 3 Tellurometer". *Bulletin Geodesique.* June.

BULLINGTON, K. 1954. "Reflection Coefficients of Irregular Terrain". *Institute of Radio Engineers Proceedings.* Vol. 42. July to December.

BURNSIDE, C.D. 1971. "Electromagnetic Distance Measurement". Crosby Lockwood.

CHRZANOWSKI, A. & WILSON, P. 1966. "Underground Measurements with the Tellurometer". *Canadian Surveyor.* Vol. XX. No. 2. June.

CHRZANOWSKI, A. 1968. Private Communication.

DENISON, E.W. 1971. "Report of International Association of Geodesy Special Study Group". No. 1.19 on Electromagnetic Distance Measurement. 1967 to 1971.

DENISON, E.W. **1967**	"Report of International Association of Geodesy Special Study Group No. 19 on Electromagnetic Distance Measurement". 1963 - 1967.
FENNELL, C.W. **1971**	Private Correspondence. (*C.W. Fennell of D.R. Johnston & Co. "Stanhill 33"*, Queens Rd. Melbourne. 3004. Victoria. Australian Agents for Tellurometer).
FRADIN, A.Z. **1961**	"Microwave Antennas". Pergamon Press. London.
FROME, K.D. & **ESSEN, L.** **1969**	"The Velocity of Light and Radio Waves". Academic Press.
GARDINER-HILL, R.C. **1963**	"Refinements of Precise Distance Measurement by Tellurometer". *Paper No. 30. Commonwealth Survey Officers Conference.* Cambridge.
HALL, M.J. **1967**	"Field Performance of the Tellurometer Model MRA 4". *The Plessey Group.*
HEBBLETHWAITE, D.H. **1966**	"An Investigation into Tellurometer Ground Swing". Unpublished. *University of New South Wales.*
INTERNATIONAL ASSOCIATION OF GEODESY **1965**	"Electromagnetic Distance Measurement". A Symposium held in Oxford under the auspices of Special Study Group No. 19. September. Hilger & Watts Ltd. London.
HOAR, G.J. **1969**	"An Investigation into Ground Reflection errors affecting the Tellurometer MRA 101". *The University of New South Wales.* Unpublished.
JONES, P.B. **1968**	"Review of Recent Developments in Electronic Distance Measuring Apparatus". Proceedings of REF-EDM Conference. *The University of New South Wales.*
KELSEY, K. **1959**	"A Method for Reducing Ground Swing on Tellurometer Measurements". *Empire Survey Review*, Vol. XV. No. 112, April.
KERR, D.E. **1951**	"Propagation of Short Radio Waves". McGraw Hill Book Co. Inc.

KÜPFER, H.P.
1967
"How to Increase Accuracy in EDM". *International Union of Geodesy and Geophysics. International Association of Geodesy.* Lucerne. Switzerland.

KÜPFER, H.P.
1971
Private correcpondence.

LAURILA, S.H.
1963
"Electronic Surveying: Accuracy of the Tellurometer over Short Distances" *Journal of the Surveying and Mapping Division. Proceedings of American Society of Civil Engineers.* 89. No. SU 3. October.

LAURILA, S.H.
1965
"Expected Instrument Accuracy of Microwave Distancers". Report No. 64. Reports of the Department of Geodetic Science. *The Ohio State University.*

LILLY, J.E.
1963
"Tellurometer Cyclic Zero Error". *13th General Conference of International Union of Geodesy and Geophysics. International Association of Geodesy.* Berkley.

McLELLAN, C.D.
1961
"The Tellurometer in Geodetic Surveying". *Canadian Surveyor.* Vol. XV. No. 7, March.

MARSHALL, A.G.
1967
"Factors Affecting the Instrumental Accuracy of Tellurometers and Design Improvements Introduced to Minimize Errors". *The Third South African National Survey Conference.* Johannesburg.

PODER, K.
LENN, C.J. &
ANDERSON, O.B.
1960
"Some Preliminary Results and Considerations of Tellurometer Investigations". *International Union of Geodesy and Geophysics, General Assembly.* Helsinki.

PODER, K.
1962
"Reflections". *Proceedings of the 1962 Tellurometer Symposium.*

PODER, K. &
ANDERSON, O.B.
1963
"Results and Experience of Electronic Distance Measurement 1960 - 1963". *International Union of Geodesy and Geophysics. XIIIth General Assembly.* København.

POLING, A.C.
1961
Tellurometer Mannual. Coast and Geodetic Survey, United States Department of Commerce, Publication 62-1 (Revised 1961).

REED, H.R. &
RUSSELL, C.M.
1966
"Ultra High Frequency Propagation". Science Paperbacks and Chapman and Hall Ltd.

RIMINGTON, G.R.L.
1957
Report on Tellurometer Tests. *Australian Surveyor.* Vol. 16. No. 8. December.

ROBINSON, A.J.
1968
"Zero Error of the Model MRA 101 Tellurometer". Proceedings of REF-EDM Conference. *The University of New South Wales.*

ROBINSON, A.J.
1969
"Field Calibration of the Model MRA 101 Tellurometer". *Australian Surveyor.* Vol. 22. No. 8. December.

SAASTAMOINEN, J.J.
(ed.)
1967
"Surveyors Guide to Electromagnetic Distance Measurement". University of Toronto Press.

TELLUROMETER
1965
Instruction Manual for the Operation and Maintenance of Tellurometer Model MRA 101. September.

URBAN, V.F.
1961
"Tellurometer Surveys". *Technical Publications No. 2.* Department of the Surveyor General, Southern Rhodesia.

WADLEY, T.L.
1957
"The Tellurometer System of Distance Measurement". *Empire Survey Review.* No. 105 and No. 106.

WADLEY, T.L.
1958
"Electronic Principles of the Tellurometer". *The Transactions of the South African Institute of Electrical Engineers.* May.

WEBLEY, J.A.
1965
"The Tellurometer Model MRA 101". *International Association of Geodesy. A Symposium: Electromagnetic Distance Measurement.* Oxford.

WHITTAKER, E.T. &
ROBINSON, G.
1944.
"The Calculus of observations: a treatise on numerical mathematics". Blackie. London 4th Edition.

WRIGHT, J.W. **1967**	"Tests on MRA 3 and MRA 101 Tellurometers in Southern Nigeria. *Conference of Commonwealth Survey Officers.* Cambridge.
YASKOWICH, S.A. **1963**	"Tellurometer Ground Swing on Geodetic Lines". *International Association of Geodesy. International Union of Geodesy and Geophysics. XIIIth General Conference.* Berkley 1963.
YASKOWICH, S.A. **1965**	"Tellurometer Zero Error". *International Association of Geodesy. A Symposium: Electromagnetic Distance Measurement.* Oxford.

ACKNOWLEDGEMENTS

The tellurometer MRA101 must have an observer at both the master and remote instruments. Many staff members from the School of Surveying, and several of my fellow surveyors operated the remote instrument during the experimental measurements. These people gave generously of their time and for this I am most grateful.

The Australian Jockey Club of New South Wales gave permission to use the No. 2 Polo Field at Warwick Farm. Unlimited access was given to this area and on several occasions normal activities were transferred to other grounds so as not to interfere with the continuity of the experiments. For this I express my thanks.

Dr. A. Chrzanowski, of the University of New Brunswick, Canada, gave considerable encouragement and assistance when he was a Visiting Professor at the University of New South Wales.

Mr. J. Reen of the Research Laboratories of the Post Master General's Department was responsible for my attendance at Operation Euroka in Queensland. This was a most interesting project and I thank Mr. Reen for his interest in the tellurometer experiments.

Finally I would like to express my sincere thanks to Professor G.G. Bennett of the University of New South Wales who gave most generously of his time and gave me encouragement during the course of this report.

APPENDIX 1

OPERATING INSTRUCTIONS, RECORDING FORMS AND REDUCTION FORM.

1.1 Operating Instructions

The operating instructions provided by the manufacturer in the handbook were found to be confusing and because of this a more compact set of instructions was written. Of necessity an initial setting up procedure must be agreed upon by the operators. The system adopted in all measurements by the School of Surveying based on the author's experience is also given.

1.2 Initial Set up for Master and Remote Instruments

Before measurements are commenced operators must agree on

(i) Time at which contact is to be established.
(ii) Which instrument is going to be master.
(iii) Compass bearing on which to base initial orientation.

1.2.1 On arrival at instrument station.

1. Mount instrument on tripod, and point antenna in general direction of the other instrument. (Accurately centre instrument).
2. Fit the small-mirror assembly to the R.F.Head.
3. Connect the battery supply cable to the battery terminals (note red lead to +ve terminal) and plug the cable into the 12v. battery socket on the instrument. Allow 15 to 25 minutes for the oven lamp to cycle.
4. Plug in headset.
5. When oven lamp is cycling, switch warm up switch to on.
6. After about 30 seconds set operate switch to on.

7. Set Monitor switch to Batt. Reading (on monitor meter) should be 20 to 25.
8. Set Monitor switch to Output Carrier tune to 4. } Reading (on monitor meter) should be 15 to 50.
9. Set Monitor switch to Mod and speak/measure switch to measure. Switch to all patterns in turn, reading on monitor meter should be 45 on all patterns except E which should read 35.
10. Set Monitor switch to sig, speak/measure to speak.

1.3 Master function

The action required to be carried out and the position of the switches for the coarse readings and the fine readings is shown in table 1. The numbers for each instruction of the master function correspond to the numbers for the remote function.

1.4 Remote Function

The action required to be carried out and the position of the switches for the coarse and fine readings are shown in table 2.

1.5 Field Recording Sheet and Reduction Form

The field recording sheet suggested by the manufacturer was also found to be inadequate and two new sheets were designed. One sheet for 10 fine readings and the other for 20 fine readings. Examples of each of these are included.

A tellurometer reduction sheet has also been designed and is included for completeness.

	MASTER (coarse readings) ACTION	AFC	Monitor	speak/ measure	forward/ reverse	pattern
1.	Set carrier at 3, increase carrier setting until max. deflection on monitor. Speech contact now possible	IN	SIG	speak	for	Master A
2.	Instruct remote to adjust direction of inst. Repeat with Master, get max. reading on monitor.					
	Adj. output control for max. mixer current reading on monitor.	OUT	Output	speak	for	Master A
3.	Adj. carrier tune for a zero ± 5 reading on monitor. (equal & opp. rots. of control give same movement to needle).	IN	Tune	speak	for	Master A
4.	Instruct remote to switch to measure.	IN	SIG	speak	for	Master A
5.	Engage zero lock and rotate readout control for a correct null (control and meter needle move in same direction).	IN	SIG	meas.	for	Master A
6.	Instruct remote to switch to remote A and release zero lock.	IN	SIG	speak	for	Master A
7.	Rotate readout control for a correct null and record reading in Coarse A.	IN	SIG	meas.	for	Master A
8.	Switch to Master E. Rotate readout control for a correct null, record in Coarse E.	IN	SIG	meas.	for	Master E
9.	" " D " " " " " D.	"	"	"	"	Master D
10.	" " C " " " " " C.	"	"	"	"	Master C
11.	" " B " " " " " B.	"	"	"	"	Master B
	MASTER (fine readings)					
12.	Instruct remote to set carrier tune to 1 and take first met. readings.	IN	SIG	speak	for	Master A
13.	Set carrier of Master to 7 and adj. for max. output.	OUT	Output	speak	for	Master A
14.	Increase carrier until max. deflection on monitor, speech can now be heard.	IN	SIG	speak	"	"
15.	Check max. output on monitor. Read and record value.	OUT	Output	"	"	"
16.	Adj. carrier for fine tune. Zero ± 5 on monitor.	IN	tune	"	"	"
17.	Instruct remote to go to Measure, Remote Ref., Forward. Engage zero lock.	IN	SIG	meas.	"	"
18.	Rotate readout control for correct null.	"	"	"	"	"
19.	Instruct remote to go to Remote A.	"	"	speak	"	"
20.	Release zero lock. Obtain correct null. Record A FORWARD, carrier setting.	"	"	meas.	"	"
21.	Instruct remote to go to Remote Ref., Reverse. Engage zero lock.	"	"	speak	"	"
22.	Rotate readout control and get correct null.	"	"	meas.	"	"
23.	Instruct remote to switch to Remote A.	"	"	speak	"	"
24.	Release zero lock and get correct null. Record A REVERSE.	"	"	meas.	"	"
25.	Instruct remote to go up 1 carrier setting.	"	"	speak	"	"
26.	Repeat steps 12. to 25. with carrier settings 2, 3, ...7, 8, 1, 2.					
27.	Take second met. readings when fine readings have been completed.					
28.	Take second set of coarse readings (as above).					
29.	Instrument functions are now reversed and the above procedure for coarse and fine readings repeated for second measurement of distance.					

TABLE 1.

	REMOTE (coarse readings) ACTION	AFC	Monitor	speak/ measure	forward/ reverse	pattern
1.	Set carrier tune to 5. Adj. for max. output.	OUT	Output	speak	for	Remote Ref.
	Set monitor to SIG. Watch for max. deflection of monitor. Speech can now be heard.	OUT	SIG	speak	for	R.R.
2.	When instructed adj. instrument for max. deflection of monitor.	"	"	"	"	"
3.	No action.					
4.	When instructed, switch to Measure.	"	"	meas.	"	"
5.	No action.					
6.	When instructed, switch to Remote A.	"	"	"	"	Remote A
7.	No action.					
8.	When 1 Kc/s signal in headset is interrupted, switch to Remote E.	"	"	"	"	Remote E
9.	" " " " " " " D.	"	"	"	"	" D
10.	" " " " " " " C.	"	"	"	"	" C
11.	" " " " " " " B.	"	"	"	"	" B
	REMOTE (fine readings)					
12.	When instructed, set carrier to 1 and adj. for max. output. Set Speak Remote Ref.	OUT	Output	speak	for	Remote Ref.
13.	Switch to SIG, wait, when instructed take first met. readings.	"	SIG	"	"	"
14.	Watch monitor. Max. reading indicates contact. Speech can now be heard.	"	"	"	"	"
15.	No action.					
16.	No action.					
17.	When instructed, switch to, Measure, Remote Ref., Forward.	"	"	meas.	"	"
18.	No action.					
19.	When instructed, switch to Remote A.	"	"	"	"	Remote A
20.	No action.					
21.	When instructed, switch to Reverse, Remote Ref.	"	"	"	rev	Remote Ref.
22.	No action.					
23.	When instructed, switch to Remote A.	"	"	"	"	Remote A
24.	No action.					
25.	When instructed, go up 1 carrier setting, adj. for max. output. Set, Speak, Remote Ref., Forward	"	Output	speak	for	Remote Ref.
26.	Repeat steps 12. to 25. with carrier settings 2, 3, ...7, 8, 1, 2.					
27.	Take second met. readings when fine readings have been completed.					
28.	Take second set of coarse readings (as above).					
29.	Instrument functions are now reversed and the above procedure for coarse and fine readings repeated for second measurement of distance.					

TABLE 2.

UNIVERSITY OF NEW SOUTH WALES

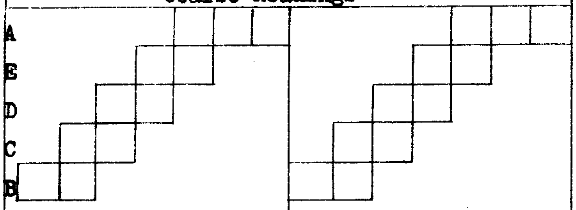
SCHOOL OF SURVEYING

TELLUROMETER FIELD SHEET

Survey ______ Date ______ Page ______

Master No.	Remote No.
Observer	Observer
Station	Station
Height of Inst.	Height of Target
Height of Target	Height of Target
Weather	Weather

Coarse Readings



coarse figure / carrier	coarse figure / carrier

Start carrier	Fine Reading output	forward	reverse	Finish MEAN
			Total	
			Arithmetic Mean	

MET. READINGS

time	dry t		wet t'		dep t-t'		Barometer			
	c	f	c	f	c	f	Read.	Cor	Cr'd	N
R										
R										
M										
R										
M										
R										
									mean	

Adopted length ______

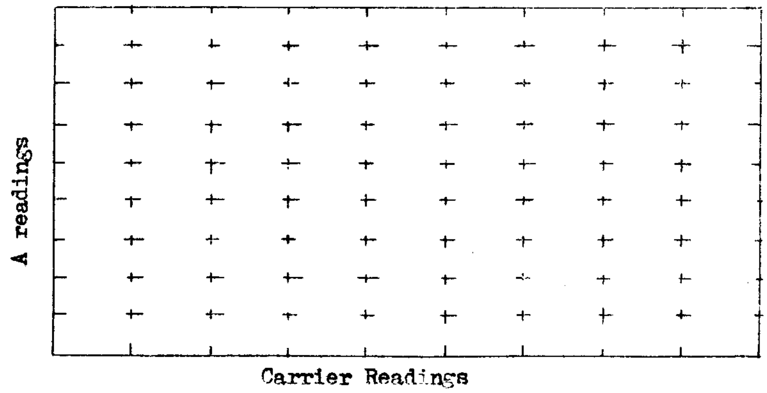
Zero Error ______

Uncorrected length ______

$\underline{n} = 1.000$ ______

SLOPE DISTANCE = ... $\times \dfrac{1.000325}{1.000}$ ______

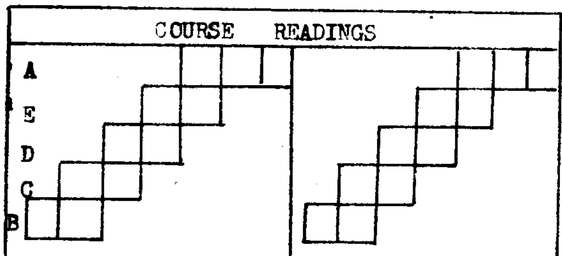
Ground Swing Curve



Instruction No. ________ Survey ________________ Date ________

Master No. ________	Remote No. ________
Observer ________	Observer ________
Station ________	Station ________
H.I. ________	H.I. ________
Target ________	Target ________
Weather ________	Weather ________
________	________

COURSE READINGS



________ m	________ m
course figure carrier.	course figure carrier.

Start		FINE READINGS		Finish
carrier	output	forward	reverse	MEAN
			TOTAL	
			ARITHMETIC MEAN	

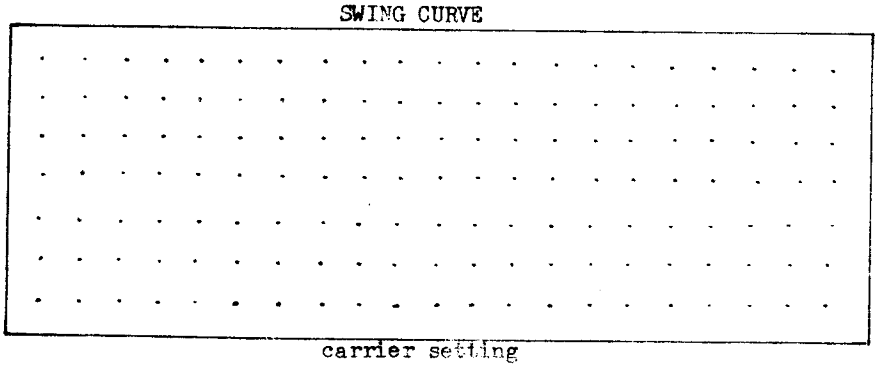
	Psychrometer				Barometer		
	time	dry t	wet t'	dep t−t'	read	cor	cor^{d} read
R							
R							
M							
R							
M							
R							
mean					mean		

N from graph ________
R.I. n=1.000 ________

Final Uncorrected Length ________

FINAL DISTANCE. × $\frac{1.000\ 325}{1.000}$ = ________

SWING CURVE



UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF SURVEYING

Tellurometer Reduction Sheet

Survey...................... Date............ Page..........

Slope Distance.D.................. metres.

Line from.................. to............

Station Reduced Level...................... ....

Instrument Height ....

Instrument Reduced Level h1................ h2............

h2................ h1............

h = h1 - h2................ h1 + h2............

$H = \frac{h1 + h2}{2}$............

Slope Correction $\frac{-h^2}{2D} - \frac{h^4}{8D^3}$ -............

Sea Level Correction $\frac{-DH}{(R+H)}$ -............

Arc Correction. +............

Total Corrections. ....

Slope Distance D. ....

SEA LEVEL DISTANCE ....

APPENDIX 2

CALIBRATION OF FREQUENCIES

1.1 Equipment

The equipment used to measure the carrier frequencies and the modulation frequencies of the tellurometers used in the work were housed in the Sydney County Council Testing Laboratory at the School of Electrical Engineering, University of New South Wales.

1.2 Modulation Frequencies

The modulation frequencies were measured in 1967 and 1969, these results are shown in table 1 together with the manufacturers value.

Special "take off" points have been provided on the main circuit board of the tellurometer so that these frequencies can be measured. The central panel has to be removed and connections made to the terminals labelled TJ3 and TJ17 (Tellurometer 1965 page 37). The earth connection TJ17 was found to be difficult to use so a "general earth" (the instrument chassis) connection was used. As the power output from the pattern frequencies was very low the signal was amplified by use of a videoamplifier before being compared to the known frequeny in the Hewlett Packard Frequency Counter. This known frequency is compared twice every day with the Sydney County Council standard.

1.3 Carrier Frequencies

The reason for measuring the carrier frequencies was to calibrate the instrument so that the carrier settings (1,2,3, etc.) used in the experiments could be associated with actual frequencies.

The instruments were set up about 4 feet in front of a horn which was connected to a 3 centimetre wavemeter (Hewlett Packard type X532B) and the frequency read directly with the above meter and checked by measuring the 100th harmonic on the frequency counter. When changing the carrier frequency the output was maximised as is done in the field.

The results are shown in table 2, values are in MHz.

Examination of the results of the modulation frequency measurements for both instruments reveals that for the patterns E,D,C and B there is reasonable agreement between the measured values and those set by the manufacturer. These patterns are used in conjunction with the A pattern to resolve the ambiguities in the distance and would need to have large differences from the standard values in order to introduce errors into the coarse readings.

The measured values for the master A pattern of both instruments show an agreement to -5ppm (parts per million) with a maximum difference over the two year period of 5 ppm. The values for the remote A and remote ref patterns of instrument NO. 110 show an agreement to within 11 ppm and a maximum change over the two year period of 10 ppm bringing the values to within 2 ppm of standard. However, the remote A pattern of instrument No. 113 for the 1966 measurement showed a difference of -42 ppm from that value set by the manufacturer. This value was adjusted to standard by the manufacturer and the 1969 measurement revealed an increase of +8 ppm. The remote ref pattern for this instrument remained stable at a value 2 ppm higher than standard.

MODULATION FREQUENCIES MHz

	Instrument No. 110		Instrument No. 113		
PATTERN	1967	1969	1967	1969	Manufacturer's Values
A MASTER	7.492 381	7.492 377	7.492 380	7.492 372	7.492 377
E do	5.993 903	5.993 901	5.993 896	5.993 906	5.993 902
D do	7.342 532	7.342 532	7.342 533	7.342 540	7.342 529
C do	7.477 390	7.477 382	7.477 389	7.477 391	7.477 392
B do	7.490 876	7.490 878	7.490 847	7.490 894	7.490 879
B REMOTE	7.489 875	7.489 879	7.489 860	7.489 860	7.489 879
C do	7.476 384	7.476 379	7.476 390	7.476 391	7.476 392
D do	7.341 529	7.341 534	7.341 537	7.341 537	7.341 529
E do	5.992 906	5.992 904	5.992 899	5.992 902	5.992 902
A do	7.493 388	7.493 378	7.493 335	7.493 385	7.493 377
REMOTE REF.	7.491 386	7.491 379	7.491 379	7.491 379	7.491 377

TABLE 1.

CARRIER FREQUENCY MHz

YEAR	1967		1969	
Carrier Setting	110	113	110	113
7.5	10,055	10,054	10,056	10,044
8.0	067	064	073	062
8.5	078	093	088	082
1.0	091	098	098	094
1.5	109	110	113	113
2.0	132	126	144	123
2.5	155	143	160	147
3.0	166	161	177	167
3.5	180	183	189	189
4.0	198	204	205	204
4.5	219	238	231	220
5.0	239	240	253	238
5.5	260	263	272	267
6.0	278	281	285	282
6.5	287	304	306	304
7.0	321	324	331	322
7.5	338	339	355	338
8.0	360	358	371	360
8.5	378	381	382	379
1.0	392	398	402	387
1.5	414	415	422	420
1.8		425		429
2.0	432		435	

TABLE 2

APPENDIX 3

CALIBRATION OF THERMOMETERS

CSIRO

NATIONAL STANDARDS LABORATORY — DIVISION OF PHYSICS

UNIVERSITY GROUNDS, CITY ROAD, CHIPPENDALE, N.S.W. TELEPHONE 680566. TELEGRAMS CORESEARCH SYDNEY

MB:EAS
B15/2//349

13th March 1967

Department of Civil Engineering,
University of New South Wales,
P.O. Box 1,
KENSINGTON. NSW

Attention: Mr Robinson

Dear Sir:

Enclosed herewith are Reports (ref.: N.S.L. 27955 and 27956) on Celsius scale thermometers Nos. PT16273 and PT16274 respectively, submitted to this Laboratory for test.

Yours faithfully

(R.G. Giovanelli)
CHIEF OF THE DIVISION

COMMONWEALTH OF AUSTRALIA

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION

PK

NATIONAL STANDARDS LABORATORY

REPORT ON THERMOMETER

Thermometer No.: PT16273.

Type: Mercury in glass, solid stem.

Range: -20° to 50° C.

Immersion: Not marked,
Tested: To the reading, vertical

Divided to 1 degC.

Limit of accuracy: ± 0.2 degC.

The corrections to the thermometer have been determined relative to the International Practical Temperature Scale by reference to Commonwealth standards of measurement of temperature. The results of the comparison are given in the table.

Temperature reading	Observed correction to thermometer reading	Temperature
0.10° C	-0.10 degC	0.00° C ± 0.20 degC
10.00	-0.20	9.80 "
15.00	-0.10	14.90 "
25.00	+0.05	25.05 "
35.00	+0.05	35.05 "
0.15	-0.15	0.00 "

/2....

Reference:
N.S.L. 27955
S.B.15/2// 349

Checked by: Date: 10th March 1967

R. G. GIOVANELLI
Chief, Division of Physics

Continued

CONTINUATION OF REPORT ON THERMOMETER No. PT16273.

NOTES

Note 1. **Limit of Accuracy.** The statement of limits incorporated in the third column of the table indicates the accuracy to which the corrected readings may be considered reliable. The limits have been estimated on the basis of a 99% confidence level, i.e., there is considered to be only one chance in a hundred that the stated result is in error, due to all causes, by more than the limits given.

Note 2. **Immersion:** If the thermometer is used under conditions in which the temperature of its liquid column differs from that obtaining at the time of test it may be necessary to apply a further correction for the expansion (or contraction) of the liquid column.

Note 3. **Test Procedure.** When a thermometer is heated and re-cooled to its initial temperature the bulb does not return immediately to its initial volume. In order to subject the thermometer to, as far as possible, reproducible conditions the test procedures outlined below were followed.

(a) Care was taken that each test temperature was the maximum to which the thermometer had been exposed up to that stage of the test.

(b) Following the calibration of the thermometer at the highest test temperature the thermometer was left at room temperature for at least 24 hours before the correction given in the last line of the table was determined.

The agreement of the corrections in the first and last lines of the table shows that the thermometer is satisfactory (to within the limits of accuracy given) for use up to the highest temperature at which the test has been made.

If a temperature is to be measured to the accuracy quoted in the third column of the table, the thermometer should be used only after an adequate time has elapsed since its last heating to a higher temperature.

----o----

Reference: N.S.L. 27955
S.B.15/2// 349

Checked by. Date: 10th March 1967

R. G. GIOVANELLI
Chief, Division of Physics

COMMONWEALTH OF AUSTRALIA

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION

PK

NATIONAL STANDARDS LABORATORY

REPORT ON THERMOMETER

Thermometer No.: PT16274.

Type: Mercury in glass, solid stem.

Range: -20° to 50° C.

Immersion: Not marked,
Tested: To the reading, vertical

Divided to 1 degC.

Limit of accuracy: ± 0.2 degC.

The corrections to the thermometer have been determined relative to the International Practical Temperature Scale by reference to Commonwealth standards of measurement of temperature. The results of the comparison are given in the table.

Temperature reading	Observed correction to thermometer reading	Temperature
0.50° C	-0.50 degC	0.00° C ± 0.20 degC
10.00	+0.15	10.15 "
15.00	+0.25	15.25 "
25.00	+0.30	25.30 "
35.00	0.00	35.00 "
0.45	-0.45	0.00 "

/2....

Reference: N.S.L. 27956
S.B.15/2// 349

Checked by: Date: 10th March 1967

R. G. GIOVANELLI
Chief, Division of Physics

Continued

CONTINUATION OF REPORT ON THERMOMETER No. PT16274.

NOTES

Note 1. **Limit of Accuracy.** The statement of limits incorporated in the third column of the table indicates the accuracy to which the corrected readings may be considered reliable. The limits have been estimated on the basis of a 99% confidence level, i.e., there is considered to be only one chance in a hundred that the stated result is in error, due to all causes, by more than the limits given.

Note 2. **Immersion:** If the thermometer is used under conditions in which the temperature of its liquid column differs from that obtaining at the time of test it may be necessary to apply a further correction for the expansion (or contraction) of the liquid column.

Note 3. **Test Procedure.** When a thermometer is heated and re-cooled to its initial temperature the bulb does not return immediately to its initial volume. In order to subject the thermometer to, as far as possible, reproducible conditions the test procedures outlined below were followed.

(a) Care was taken that each test temperature was the maximum to which the thermometer had been exposed up to that stage of the test.

(b) Following the calibration of the thermometer at the highest test temperature the thermometer was left at room temperature for at least 24 hours before the correction given in the last line of the table was determined.

The agreement of the corrections in the first and last lines of the table shows that the thermometer is satisfactory (to within the limits of accuracy given) for use up to the highest temperature at which the test has been made.

If a temperature is to be measured to the accuracy quoted in the third column of the table, the thermometer should be used only after an adequate time has elapsed since its last heating to a higher temperature.

-----o-----

Reference: N.S.L. 27956
S.B.15/2// 349

Checked by. Date: 10th March 1967

R. G. GIOVANELLI
Chief, Division of Physics

APPENDIX 4

MODIFIED METHOD OF MEASUREMENT

4.1 Conventional Method

The conventional method of reading the tellurometer model MRA101 is to null a meter by means of a resolver. This gives a value of the distance, in metres, for the particular carrier frequency. The actual measuring procedure for pattern A, fine reading, is given as an example (Instruments are assumed to be tuned) as follows:-

The pattern switch for the remote instrument is set to remote reference and that of the master to master A. The zero lock on the readout dial of the master is engaged. This zero lock holds the graduated dial on a reading of zero and prevents the graduated dial from moving when the resolver is turned. The null meter is now centred by means of the resolver. (A null in the correct direction is assumed). The remote is instructed to switch to remote A. This causes the zero setting on the null meter to move. The zero lock is released and the null meter is centred by means of the resolver and now the graduated dial moves with the resolver. The reading on the graduated dial is recorded. This measuring process is repeated for the reverse function and also for a series of carrier frequencies to give the desired number of fine readings.

4.2 The Null Meter

The null meter is graduated as shown in figure 1. A central graduation is marked 0 and the meter is evenly graduated with ten graduations each side of the zero. The value of each graduation is 5 units. When the meter is nulled the needle is in coincidence with the central graduation.

4.3 Modified Method

In several experiments with the model MRA101 Tellurometer it was necessary to take a large number of measurements from the one set up. The variation of distance between these measurements was small so the above method of measurement was modified.

The method is described as follows:- When a measurement is taken the needle on the null meter is set to zero. Now if the distance is changed (i.e. either decreased or increased) the needle will move off centre. If the new reading on the null meter is recorded (as null meter units left or right), then provided the null meter has been calibrated, the new distance reading can be deduced quite easily by application of the correction shown in table 1.

In the series of measurements taken using this method, the first fine reading in the forward mode was taken using the conventional method and recorded as an indicated distance. The length being measured was then changed (by tilting, height change etc.) and as a result the needle of the null meter moved from the central position. The new position of the needle was recorded as null meter units left or right, hence the new distance could be deduced. The above process was repeated for the reverse function of the instruments and the whole series again repeated for a change of carrier frequency. This method proved to be most useful and also reduced the time for a series of measuremen

4.4 Calibration of the Null Meter

The calibration of the null meter was carried out as follows:

The tellurometers were set up at the terminals of the line on which the experiments were to be made and the process of a normal measurement was carried out. The null meter was set to zero and the readout noted. The needle (of the null meter) was then set to each of the 10 graduations left and right in turn and the readout (distance) was recorded. This process was repeated in the reverse function and on three different carrier frequencies covering the total carrier range. The mean of the six readings for each graduation was used to deduce a correction (in distance) for the particular graduation. The null meter of Instrument No. 113 was calibrated as above with Instrument No. 110 as master. Instrument No. 110 was then used in the master mode with No. 113 as remote so that the null meter could be calibrated. The results of the calibration are shown in table 1. It can be seen that near the zero setting, the value of one division which represents 5 units is about 3 centimetres and therefore if one estimates the null meter reading to one unit then the distance is being estimated to about 0.6 centimetres.

4.5 Experiment

The modified method of measurement was used to monitor distance decrease during a large experiment, conducted in part, into the effects of bushfires on radio communication systems.

Operation Euroka was the code name for a mass fire-firestorm experiment held on October 23rd 1969 at a site 3 kilometres from Langley Homestead, 40 kilometres from the Bruce Highway and about 240 kilometres north west of Rockhampton, Queensland, Australia. The 20 hectare area of the experimental site contained 6000 tonnes of dry brigalow timber stacked in 30 windrows, about 8 metres wide with an 8 metre separation distance between the windrows. Around this area was a cleared area of about 120 hectares beyond which was a further area of 1200 hectares of felled timber.

Two lines about 735 metres long were selected across the burn site so that one line passed about 1.3 metres and the other about 2.5 metres above the tops of the windrows. A profile of the line is shown in figure 2 and it can be seen that there is a cleared area of about 137 metres between each instrument and the windrows. This area was a safety area and no personnel were allowed in this area during the burn. To gain the instrument heights necessary to give the clearances stated above, one tellurometer was set at ground level and another tellurometer was set on a landing of a tower erected for communication experiments by the Post Master General's Department at the southern end of the line. The tellurometer at the northern end was positioned so that both instruments at the southern end could be seen and at an instrument height of about 2.5 metres. The northern instrument could then measure to either instrument at the southern end to give the two lines.

The intention was to monitor the one way distance, from the northern end, on the lower line during the burn, until contact was lost or became difficult due to the heated atmosphere, then switch to the upper line and continue to monitor the distance. This continual monitoring was done using the modified method of measurement.

4.6 Measurement and Calibration

The two lines were measured using conventional methods before the burn and were reduced for slope and refractive index. These lines were used as base lines for additional survey work necessary to "fix" the position of several camera stations and towers around the burn site. The null meter of instrument No. 113 was calibrated, with both instrument No. 110 and No. 114 as remotes, on master carrier settings of 8.0, 4.0 and 1.8, in the manner described in 4.4. The results are similar to those shown in Table 1.

Immediately prior to the ignition both tellurometer lines were measured on 7 carrier settings in order to verify that the instruments were functioning correctly. The tellurometers on the lower line were tuned with the master instrument reading a carrier setting of 4 (about 10.198 GHz). The forward and reverse A fine readings were taken and from ignition the null meter deflections were recorded. Meteorological readings were taken during the first hour of the burn at the master stations but these readings were not representative of the whole line. At time B+60 minutes the upper line was observed and the variations monitored for seventeen minutes. At B+77 minutes the lower line was again observed and the null meter monitored until B+92 minutes.

On the following day both lines were measured using the conventional method. Some of the windrows were still smouldering but there was not enough heat in the ashes to worry personnel walking between the windrows.

4.7 Results

No difficulty was experienced in measuring the lines either before or after the burn although on two carrier settings on the preburn measurement some tuning difficulties were experienced. The reduced distances for the pre-burn and post-burn measurement agreed to within 0.02 metres. The distance decrease on the lower line for the first 60 minutes of the burn is shown in figure 3. It can be seen from this figure that the greatest distance decrease occurred at time B+43 minutes, which would be the time of greatest heat intensity over the fire area. Other experiments conducted at the site also gave the time of B+43 as the greatest heat period.*

At time B+60 minutes when the higher line was observed, no difficulty was experienced during the measurement and the distance as recorded was the same as that recorded for the preburn measurement. However over the next 17 minutes this line showed a decrease of about 0.01 metres. From B+77 minutes to B+92 minutes the lower line was again monitored and its length remained stable at about 0.01 metres short. No tellurometer measurements were taken after B+92 minutes.

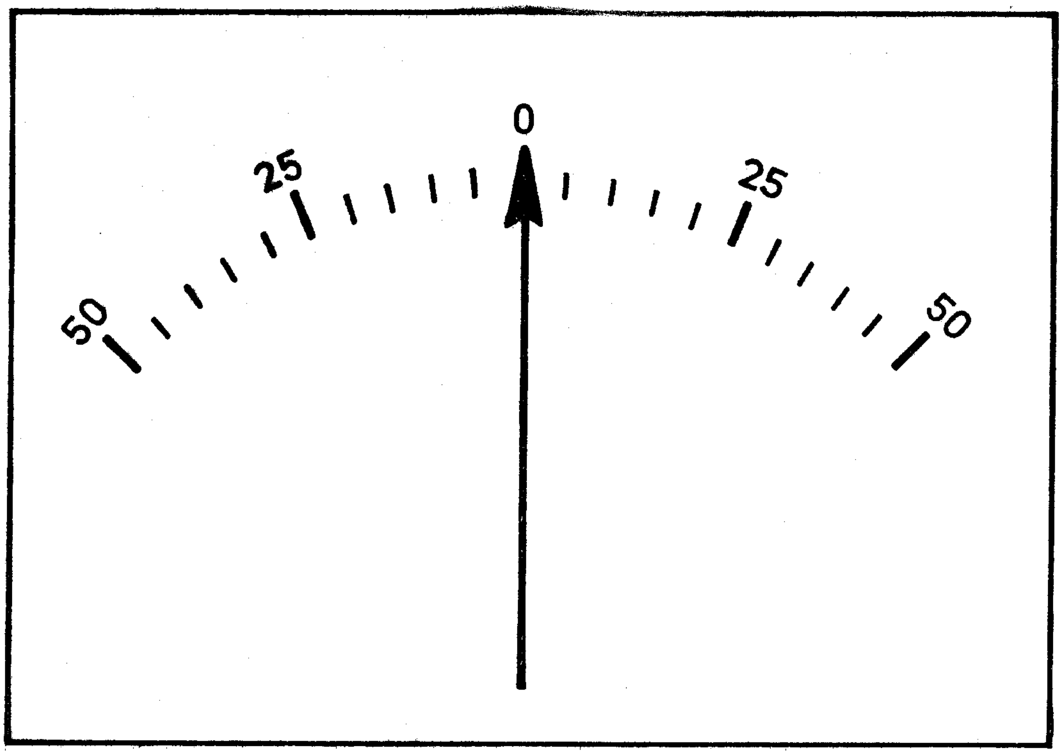
4.8 Conclusion

The results show very clearly that, as expected, the distance decreased during the burn and from this decrease the time of maximum heat intensity could be found. No tune was lost during the burn on the lower line and it is assumed that the upper line would have yielded a similar result. If tellurometers are to be used in future experiments of this nature it is recommended that the lines be such that they pass very close to the top of the windrows so that the direct transmission passes through the section of greatest heat.

* Operation Euroka. An Australian Mass Fire Experiment. Preliminary Report. *Williams, D.W., Adams, J.S., Batten, J.J., Whitty, F.G. and Richardson, G.T. 1969.*

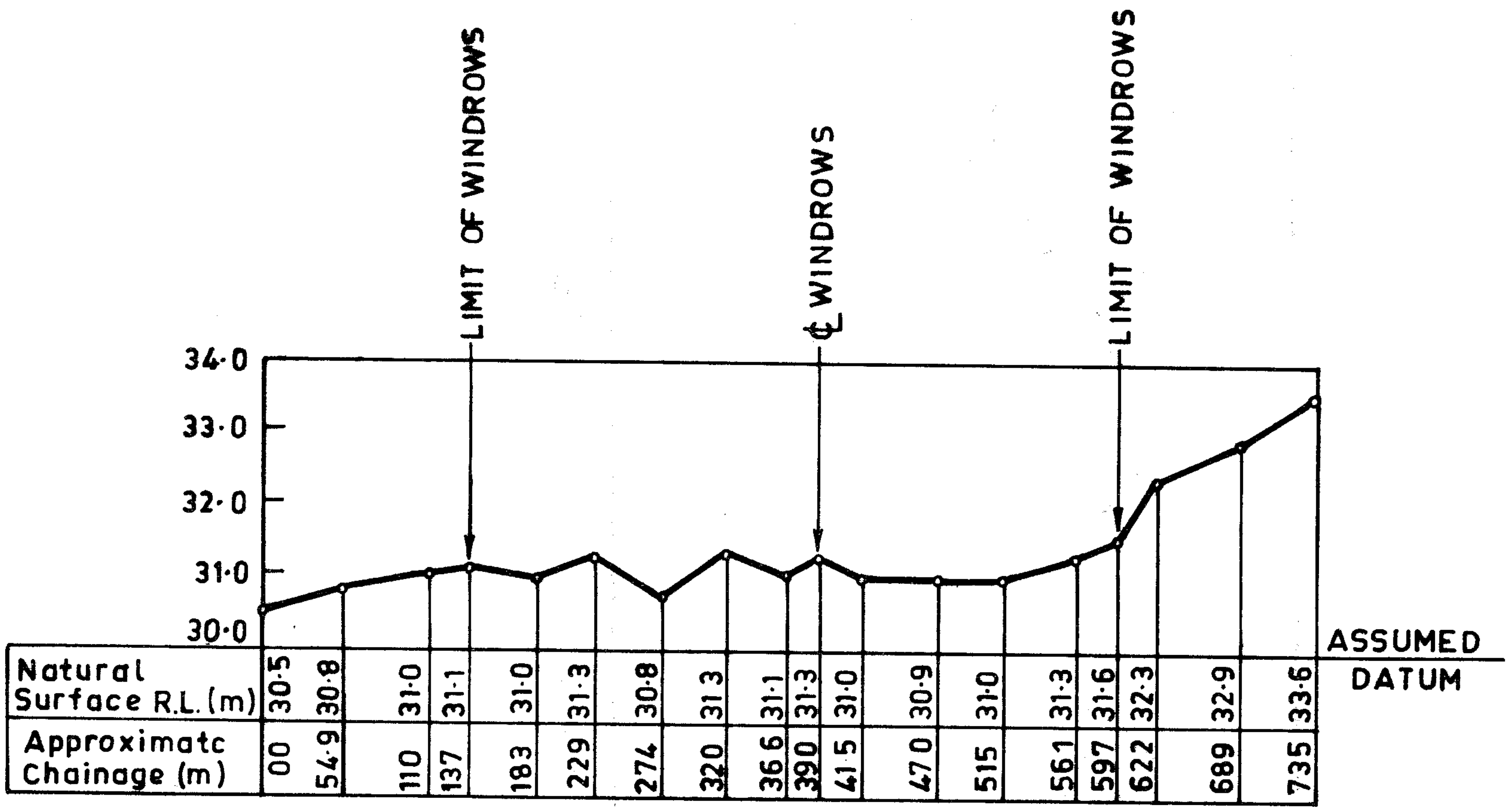
	Null Meter graduations LEFT											Null Meter graduations RIGHT									
	50	45	40	35	30	25	20	15	10	5	0	5	10	15	20	25	30	35	40	45	50
113 as Master 110 as Remote	40	38	32.5	27	22	18.5	14	10	6.5	3		3	7	10.5	14	18.5	23	28	34	40	48
110 as Master 113 as Remote	37	32	27.5	23	19	15.5	12.5	9	6	3		3	6	9	12	15	18.5	23	28	33	38.5
	Correction to indicated distance + centimetres											Correction to indicated distance - centimetres									

TABLE 1.



NULL METER

FIG. 1.



Profile of ground Surface along Tellurometer Line
Operation Euroka. Queensland.

FIG. 2.

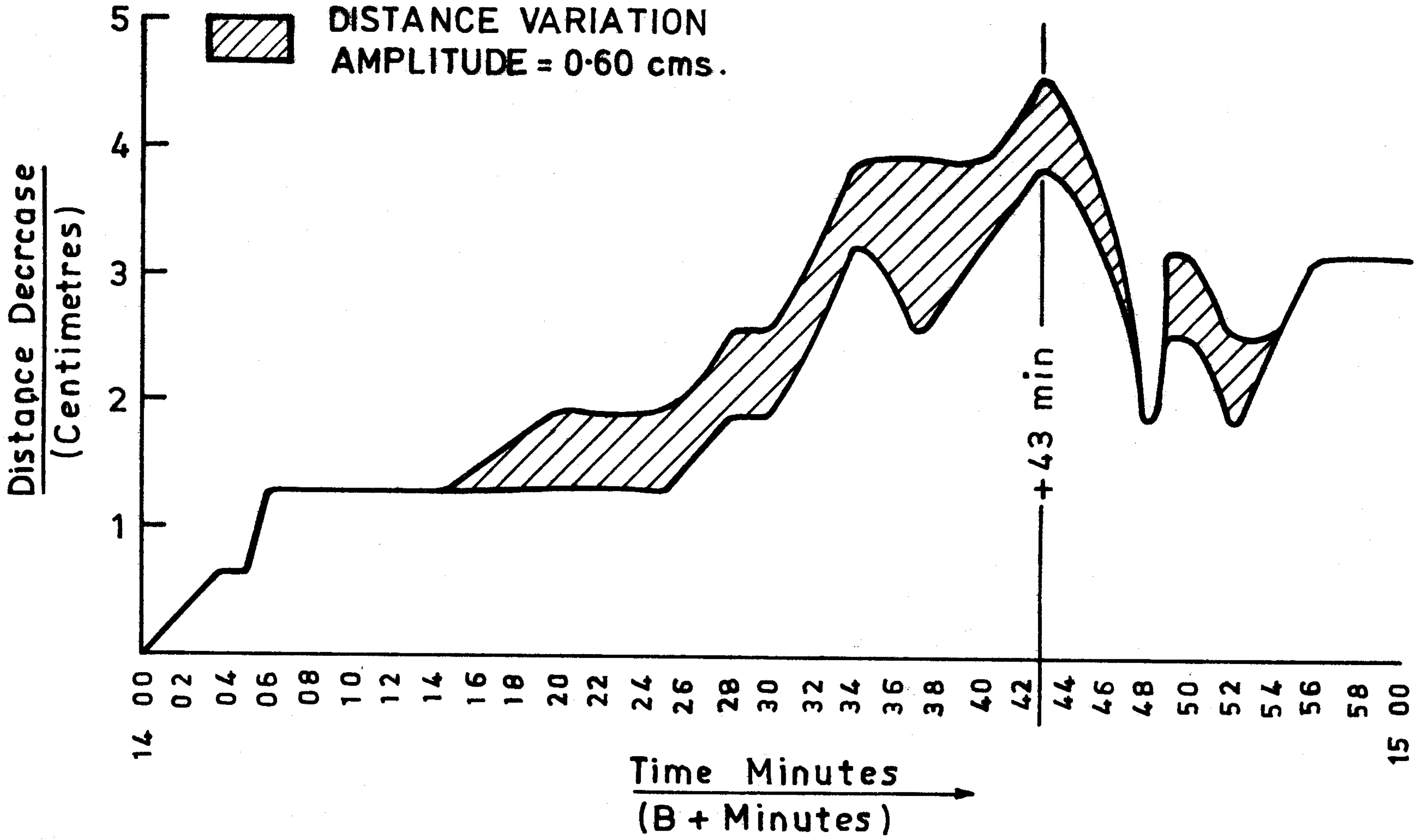
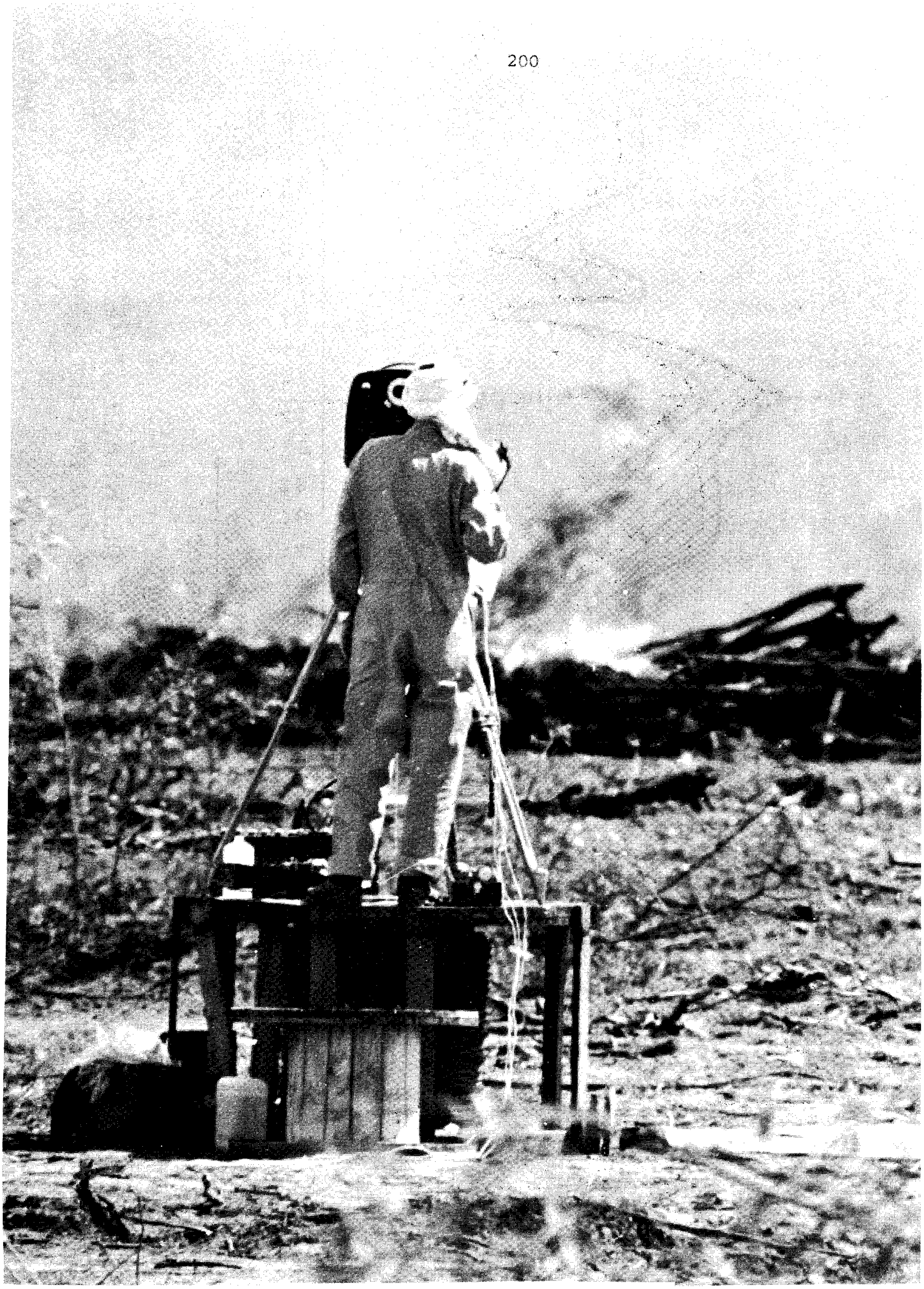


FIG. 3.

GRAPH SHOWING DISTANCE DECREASE / TIME
TELLUROMETER MRA 101 FREQUENCY 10·198 GHz (Approximate)



"THE TELLUROMETER DURING THE BURN
AT OPERATION EUROKA"

BIOGRAPHICAL NOTES

A.J. Robinson at present holds the appointment of Lecturer in the School of Surveying, University of New South Wales, to which he was appointed in 1968. He received an Honours Degree in Surveying from the University of New South Wales in 1962. After graduation Mr. Robinson was registered as a Surveyor by the New South Wales Board of Surveyors and was employed by the Department of Lands as a staff surveyor from 1962 to 1966. During this period he worked in both rural and urban areas of New South Wales. Mr. Robinson joined the University of New South Wales in 1966 as a Teaching Fellow and began research into Electromagnetic Distance Measuring systems. This is his main field of research and he has published several papers on this topic. He is also interested in field astronomy.

Publications from

THE SCHOOL OF SURVEYING, THE UNIVERSITY OF NEW SOUTH WALES

P.O. Box 1, Kensington, New South Wales, 2033

AUSTRALIA

Reports

1. *	The discrimination of radio time signals in Australia *G.G. Bennett*		UNICIV Rep. D-1	(G1)
2. *	A comparator for the accurate measurement of differential barometric pressure *J.S. Allman*	9pp	UNICIV Rep. D-3	(G2)
3.	The establishment of geodetic gravity networks in South Australia *R.S. Mather*	26pp	UNICIV Rep. R-17	(G3)
4.	The extension of the gravity field in South Australia *R.S. Mather*	26pp	UNICIV Rep. R-19	(G4)
5. *	An analysis of the reliability of barometric elevations *J.S. Allman*	335pp	UNISURV Rep. 5	(S1)
6. *	The free air geoid for South Australia and its relation to the equipotential surfaces of the earth's gravitational field *R.S. Mather*	491pp	UNISURV Rep. 6	(S2)
7. *	Control for mapping (Proceedings of Conference, May 1967) *P.V. Angus-Leppan (Editor)*	329pp	UNISURV Rep. 7	(G5)
8. *	The teaching of field astronomy *G.G. Bennett & J.G. Freislich*	30pp	UNISURV Rep. 8	(G6)
9. *	Photogrammetric pointing accuracy as a function of properties of the visual image *J.C. Trinder*	64pp	UNISURV Rep. 9	(G7)
10.*	An experimental determination of refraction over an icefield *P.V. Angus-Leppan*	23pp	UNISURV Rep. 10	(G8)
11.*	The non-regularised geoid and its relation to the telluroid and regularised geoids *R.S. Mather*	49pp	UNISURV Rep. 11	(G9)
12.*	The least squares adjustment of gyro-theodolite observations *G.G. Bennett*	53pp	UNISURV Rep. 12	(G10)
13.	The free air geoid for Australia from gravity data available in 1968 *R.S. Mather*	38pp	UNISURV Rep. 13	(G11)
14.	Verification of geoidal solutions by the adjustment of control networks using geocentric Cartesian co-ordinate systems *R.S. Mather*	42pp	UNISURV Rep. 14	(G12)

*	Out of Print	
G	General Series	Price: $4
S	Special Series (Limited printing)	Price: $20

Publications from the School of Surveying (contd.)

Reports (contd.)

15.* New methods of observation with the Wild GAKI gyro-theodolite
G.G. Bennett 68pp UNISURV Rep. 15 (G13)

16.* Theoretical and practical study of a gyroscopic attachment for a theodolite
G.G. Bennett 343pp UNISURV Rep. 16 (S3)

17.* Accuracy of monocular pointing to blurred photogrammetric signals
J.C. Trinder 231pp UNISURV Rep. 17 (S4)

18. The computation of three dimensional Cartesian co-ordinates of terrestrial networks by the use of local astronomic vector systems
A. Stolz 47pp UNISURV Rep. 18 (G14)

19. The Australian geodetic datum in earth space
R.S. Mather 130pp UNISURV Rep. 19 (G15)

20. The effect of the geoid on the Australian geodetic network
J.G. Fryer 221pp UNISURV Rep. 20 (S5)

21. The registration and cadastral survey of native-held rural land in the Territory of Papua and New Guinea
G.F. Toft 441pp UNISURV Rep. 21 (S6)

22. Communications from Australia to Section V, International Association of Geodesy, XV General Assembly, International Union of Geodesy & Geophysics, Moscow 1971
R.S. Mather et al 72pp UNISURV Rep. 22 (G16)

23. The dynamics of temperature in surveying steel and invar measuring bands
A.H. Campbell 195pp UNISURV Rep. S7

24. Three-D Cartesian co-ordinates of part of the Australian geodetic network by the use of local astronomic vector systems
A. Stolz UNISURV Rep. S8

25. Papers on Four-dimensional Geodesy, Network Adjustments and Sea Surface Topography
R.S. Mather, H.L. Mitchell, A. Stolz 73pp UNISURV Rep. G17

26. Papers on photogrammetry, co-ordinate systems for survey integration, geopotential networks and linear measurement
L. Berlin, G.J.F. Holden, P.V. Angus-Leppan, H.L. Mitchell and A. Campbell 80pp UNISURV Rep. G18

27. Aspects of Four-dimensional Geodesy
R.S. Mather, P.V. Angus-Leppan, A. Stolz and I. Lloyd
100pp UNISURV Rep. G19

28. Relations between Mean Sea Level and Geodetic Levelling in Australia
H.L. Mitchell UNISURV Rep. S9

29. A Study of Zero Error and Ground Swing of the Tellurometer MRA101
A.J. Robinson UNISURV Rep. S10

Publications from the School of Surveying (contd.)

Reports (contd.)

*	Out of print	
G	General Series	Price: $ 4
S	Special Series (Limited Printing)	Price: $20

Proceedings

Proceedings of conferences on refraction effects in geodesy & electronic distance measurement
P.V. Angus-Leppan (Editor) 264pp Price: $10

Monographs

1. The theory and geodetic use of some common projections (2nd Edition)
   R.S. Mather 125pp Price: $ 3

2. The analysis of the earth's gravity field
   R.S. Mather 172pp Price: $ 3