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LIST OF PUBLICATIONS SUBMITTED

- (1) A SINGLE-BAND 0-20 Mcs IONOSPHERE RECORDER EMBODYING
SOME NEW TECHNIQUES
 - (2) A SINGLE-BAND IONOSPHERE RECORDER COVERING THE RANGE
0.1 TO 20 MEGACYCLES/SECOND
 - (3) VARIABLE-FREQUENCY CRYSTAL-CONTROLLED RECEIVERS AND
GENERATORS
 - (4) ELECTRONIC PRINCIPLES OF THE TELLUROMETER
 - (5) THE TELLUROMETER SYSTEM OF DISTANCE MEASUREMENT
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Introduction

The first National Institute for Telecommunications Research,

science of ra,

P.O. Box 10319, the G.W. telegraph receiver.

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JOHANNESBURG. It is assumed to be simply

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the 6th February 1959. The

more important purpose however was that of increasing the sensitivity of

The Registrar,

University of the Witwatersrand,

JOHANNESBURG.

Dear Sir,

I submit herewith 4 copies of the published work presented for approval, as a candidate for the Degree of D.Sc. in Engineering.

I hereby declare:

(i) That this is my own work.

(ii) That it has not been submitted for a degree well known super-
of another University.

Yours faithfully,

T.L. Wadley

T.L. Wadley: design and operation in

This flexibility is usually associated with one or both of two factors,

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factors have introduced in achievements in this

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Heterodyne Techniques in Specialised Radio Instrumentation

T.L. WADLEY - Candidate for Degree of D.Sc.

Introduction

The first historical application of the heterodyne method in the science of radio was that of the heterodyne C.W. telegraph receiver. The purpose of the method in this instance is often assumed to be simply that of deriving an audible tone from the high radio frequency. The more important purpose however was that of increasing the sensitivity of detection, as there is, even to this day no known method other than heterodyne methods of detecting weak radio waves without a large degree of preamplification. Furthermore in spite of modern methods of amplifying virtually all radio frequencies, "detection" is still usually performed at low level by heterodyne methods. In this connection it is interesting to note that modern parametric amplifiers and possibly masers in which limiting noise factors are achieved, are in principle heterodyne methods of detection.

The next major step in this development was the now well known super-heterodyne technique, in which the ability of heterodyne methods to provide almost unlimited selectivity was realised. Subsequently the development of heterodyne methods has been rather slow and unimpressive compared with the original developments. These subsequent developments are perhaps mainly concerned with achieving a flexibility of design and operation in various fields.

This flexibility is usually associated with one or both of two factors, firstly the provision of oscillators of high frequency relative to the frequencies to be used with consequent instability, and secondly the use of a number of oscillators in conjunction. In the radio frequency field these factors have introduced difficulties, and the main achievements in this field have been at relatively low or audio frequencies. Two examples may

be quoted/

be quoted, firstly the ubiquitous audio B.F.O., which nevertheless suffers from frequency instability unless very well designed, and also spurious signals arising from the multiple oscillators. Secondly the success of the carrier telephone engineer in applying multiple heterodyne techniques from an early stage of development of his subject, may be mentioned.

In the radio frequency field however success along similar lines has been slow. No beat radio frequency generator is in common use, and even double superheterodyne receivers have been slow to develop on account of the spurious effects which arise without skilful design.

In spite of these difficulties the present author has endeavoured to apply these methods to various instrumentation problems to achieve greater flexibility, particularly where the advantages to be gained by heterodyne methods appear too great to be ignored.

Application of Heterodyne Methods to Ionospheric Recorders

Papers submitted:

"A Single-band C-20 Mc/s Ionosphere Recorder Embodying Some New Techniques", Proc. Institute of Electrical Engineers, Vol. 96, Part III, No. 44, November 1949.

"A Single Band Ionosphere Recorder", C.S.I.R. Series ETR2, 1947.

In this application the transmitted pulses are derived by a radio frequency beat oscillator principle, to remove the need for bandswitching over the wide spectrum. The consequent instability of the radiated frequency is rendered of no account by tuning the associated receiver by means of multiple heterodyne methods to the same frequency as the transmitter. Common heterodyne oscillators are used for this purpose.

The spurious responses of the multiple heterodyne receiver have been minimised as far as necessary for the purpose, but as the recorder sweeps across the congested shortwave spectrum, anyway, the requirement here is not severe.

As the recorder is sweeping in frequency its instantaneous frequency

is immaterial/ ...

is immaterial and there is no stability requirement in this respect. However the associated photographic record requires accurate frequency calibration and this is provided by gating pulses derived by heterodyne methods from the harmonics of a calibrating crystal, beating with the aforementioned common oscillator.

These techniques were original although parallel development has taken place elsewhere. Recorders operating on these principles have been in continuous use for some 12 years in Southern Africa and the methods have been adopted in a number of designs in other countries.

Application of Heterodyne Techniques to the Crystal Control of Receivers and Generators

Paper submitted:

"Variable Frequency Crystal Controlled Receivers and Generators",
Transactions of the S.A. Institute of Electrical Engineers, Vol. 45,
No. 2, February 1954.

Following on from the above work, a receiver for general purpose communication was developed having some of the properties of the foregoing ionospheric receiver in so far as it operates without bandswitching across the whole spectrum.

In this case however the absolute stability of such a receiver is of prime importance, and the shortcoming of the wide band double super-heterodyne principle in this respect is overcome by interlocking the received frequency to a crystal harmonic spectrum by heterodyne methods similar to those used to lock to the ionospheric transmitter. The method of producing the required harmonic spectrum is similar to that used for calibrating purposes in the ionospheric recorder.

The spurious responses and signals usually associated with such a multiple heterodyne receiver, and which were of minor importance in the ionospheric recorder, have been completely eliminated in this design by means of suitable filtering techniques and attention to other design details.

The application/ ...

The application of the same heterodyne sequence in a reverse direction gives rise to a generator which is in effect a radio beat frequency oscillator, but whose stability is of a high order comparable to that of the associated crystal oscillator. As in the case of the audio B.F.O. careful design must be devoted to the elimination of unwanted components but the technique in this respect is not very different from that used in audio B.F.O. design.

These principles which are original have been applied to the control of frequency of the S.A.B.C. short wave transmitters at Paradys and the G.P.O. transmitters at Olifantsfontein.

Receivers operating on these principles are in use by the British Admiralty and other services.

Application of Heterodyne Techniques to the Precision Measurement of Distance by Radio

Papers submitted:

"Electronic Principles of the Tellurometer", Transactions of the S.A. Institute of Electrical Engineers, May 1958.

"The Tellurometer System of Distance Measurement", Empire Survey Review, Vol. XIV, Nos. 105, 106 and 107.

In this application use is made of the ability of heterodyne techniques to resolve the difficulties of the measurement of high frequency phase by an extension of the frequency interlocking methods previously referred to. Interrelated heterodyne methods are used at all stages of the Tellurometer techniques described.

Firstly these techniques are used to interlock the radiated and received frequencies at the measuring instruments at each end of the line as essential preliminary to the superimposition of the heterodyne phase measuring technique.

The ability to receive and transmit simultaneously from a common aerial system with continuous waves results from the common function of local oscillator and local transmitter.

The relay of the measuring modulations from the remote station in the presence of the incoming modulation is achieved by splitting the returned modulation into two waves by heterodyne methods.

The amplification and display of the high modulation frequency phase information is achieved with adequate stability in narrow band circuits by transforming this high frequency phase information to a low comparison frequency by the same heterodyne process required to return the measuring wave.

Finally use is made of difference frequencies and phases to resolve the ambiguities of the basic phase measurement.

These principles are original and have been applied to instruments which are presently being used for survey purposes in many parts of the world.

Conclusion

The author has over the past 13 years attempted to extend the use of heterodyne techniques to provide a solution to various instrumentation problems. Heterodyne techniques have from the beginnings of radio science provided powerful methods of achieving the desired ends in many applications and are often the only satisfactory methods available. Such methods are however not always easy to apply without unwanted effects, but the methods are becoming better understood and the essential design factors more firmly established.



THE INSTITUTION OF ELECTRICAL ENGINEERS

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SAVOY PLACE, LONDON, W.C.2

A SINGLE-BAND 0–20-Mc/s IONOSPHERE RECORDER EMBODYING SOME NEW TECHNIQUES

By

T. L. WADLEY

Reprint from

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or speakers*

A SINGLE-BAND 0-20-Mc/s IONOSPHERE RECORDER EMBODYING SOME NEW TECHNIQUES

By T. L. WADLEY.

(The paper was first received 16th October, 1948, and in revised form 16th May, 1949.)

SUMMARY

The paper describes briefly an ionosphere recorder developed in South Africa by the Telecommunications Research Laboratory of the Council for Scientific and Industrial Research. The first account of it was published in the *Transactions of the South African Institute of Electrical Engineers*, July 1947.

The equipment is considered to possess a number of advantages over previous designs. It is completely automatic and requires a minimum of routine attention. The mechanical moving parts have been reduced to one slowly-moving split-stator condenser, and there is no band-switching. Each record is photographed on a single frame of 16-mm film, thus reducing to a minimum the photographic work required. A panoramic display on a long-afterglow tube is provided. The frequency sweep occupies only 7 sec and enables rapidly changing phenomena to be observed or photographed. Another feature is a crystal-controlled frequency-calibrating circuit, which is independent of the sweeping mechanism and enables the limits of sweep to be set as desired within the range 0-20 Mc/s.

(1) INTRODUCTION

There are numerous methods of making ionospheric measurements, the most successful of which, particularly at the higher frequencies, are pulse sounding methods.

The main technical problem involved in the design of suitable equipment is to arrange a radio pulse transmitter and its associated receiver in such a way that the frequency may be continuously varied while the receiver tuning keeps in track with the transmitter frequency to an accuracy of a few kilocycles per second.

This may be done by purely mechanical means consisting of precision equipment manipulated by precision cams. A recorder of this nature is described by Higgs.¹

A very ingenious method of overcoming the difficulty consists of sweeping a continuous-wave transmitter through the receiver pass-band at a predetermined rate to produce a pulse and its associated reflections of the required dimensions. A recorder of this nature is described by Thomas and Chalmers.² This method, whilst possessing some advantages for special work, is considered to be inferior to a controlled pulse method for routine observations. Theoretically, the former method is capable of higher recording speeds, but practical mechanical considerations limit the recording speed to less than that achieved by some controlled pulse designs, which in any case can be made to equal the theoretical limit by suitable design.

Furthermore, the method gives rise to numerous practical difficulties, such as maintaining a constant pulse length. High-speed moving parts and considerable mechanical complication are features of this equipment.

A method of electrically interlocking the transmitter and receiver frequencies by means of a common local oscillator was devised by Gilliland.³ This method is a very satisfactory way of solving the difficulty and has formed the basis of many success-

ful designs, including the one at present under discussion and a previous design by Wadley and Fejer.⁴

The latter equipment, along with those described above, suffers from some degree of mechanical complexity with consequent decline in performance with time, due to wear, and requires regular maintenance and adjustment.

(2) NEW PRINCIPLE OF OPERATION

The equipment which is to be described in this paper is almost completely free of mechanical parts. The frequency is swept from a few hundred kilocycles per second to 20 Mc/s in a single band. There is only one moving part, namely the rotor of the main sweeping oscillator. This mechanical simplicity is obtained at the expense of increased electrical complication.

The principles involved were developed by the Telecommunications Research Laboratory of the South African Council for Scientific and Industrial Research, although similar equipment appears to have been developed at much the same time by Wells and George.⁵

(3) DETAILS OF OPERATION

The receiver is a double superheterodyne with a first intermediate frequency of 30 Mc/s and a second intermediate frequency of 900 kc/s. The transmitter may also be described as a double superheterodyne. The single-band operation is obtained by mixing two high frequencies, one variable and the other fixed, to obtain a beat frequency in a manner very similar to that employed in an ordinary audio beat-frequency oscillator, except that instead of being an audio frequency the beat is a radio frequency variable from zero to 20 Mc/s.

(4) THE TRANSMITTER

Referring to the block diagram, Fig. 1, there are three oscillators:

- (a) The main variable oscillator, 30-50 Mc/s.
- (b) A crystal-controlled oscillator, 29.1 Mc/s.
- (c) A pulsing oscillator, 900 kc/s.

The operation of the transmitter is then as follows. The output of the pulsing oscillator of 900 kc/s is mixed with that of the crystal oscillator of 29.1 Mc/s, and by suitable filtering the sideband 30 Mc/s is selected. The latter frequency is, of course, pulsing and is then mixed with the output of the main variable oscillator of 30-50 Mc/s to produce a difference frequency variable from zero to 20 Mc/s. This is also pulsing and is the frequency to be radiated. At this stage the level is a few volts, peak to peak. The pulse is now fed into an untuned r.f. amplifier of four stages with a band-pass up to 20 Mc/s. The level is raised in the final stage to about 2 000-3 000 volts, peak to peak, at an impedance of about 600 ohms. This is equivalent to about 1 kW. All stages in this amplifier operate as class A, for, since they are untuned, it is not possible for them to work as class C. The stages are pulsed into the class A condition in synchronism with the r.f. pulse, being normally completely cut off. The

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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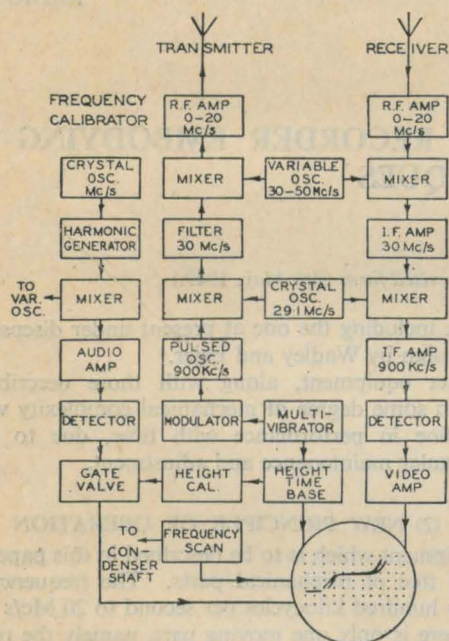


Fig. 1.—Block diagram of ionosphere recorder to illustrate general principle.

coupling circuits consist of low-pass filter sections of about 400–700 ohms impedance, depending on the individual valve capacitances. These filter sections cut off at 20 Mc/s. They are mid-shunt input and mid-series terminated, the valve input capacitances being about twice the output capacitance of the previous stages in each case. The output stage is connected via suitable transformers to the transmitting aerials, which are untuned and arranged to radiate upwards at all frequencies concerned.

Full technical details of these circuits have been published.⁶

(5) THE RECEIVER

The receiver consists first of an untuned r.f. stage with a suitable grid-blocking circuit for common aerial operation. This is followed by the first mixer, where the signal is mixed with the output of the main variable oscillator to produce a first intermediate frequency of 30 Mc/s. As before, this is independent of the radiation frequency, being exactly equal to the original 30-Mc/s pulse in the transmitter. After some amplification at this frequency, this 30 Mc/s is passed to the second mixer, where it is mixed with the output of the 29.1-Mc/s oscillator to give the second intermediate frequency of 900 kc/s. This intermediate frequency is exactly equal to that of the original 900-kc/s pulsed oscillator in the transmitter. After further amplification at this frequency the signal is demodulated, video-amplified and applied to the oscilloscopes. It will be noted that the stability of the whole system is related only to the stability of the 900-kc/s pulsed oscillator, being quite independent of the stability of the high-frequency oscillators. The reason for the crystal control of the 29.1 Mc/s is bound up with the frequency calibration. It will also be noted that the 900-kc/s and 30-Mc/s signals in the transmitter which correspond to the two receiver intermediate frequencies are both pulsed and therefore cause no interference during reception. The harmonic radiation of the transmitter is rather high, owing to the method of producing the beat frequency and to the amplification in the wide-band amplifiers, but it will be noted that the receiver is insensitive to anything but the fundamental. The harmonic radiation will add to the inter-

ference caused by the equipment, but owing to the short operating time this is not objectionable.

The bandwidth of the 30-Mc/s i.f. amplifier is a few hundred kilocycles per second, the main function of the selection at this point being to suppress the image at 28.2 Mc/s. The gain of this amplifier is about 10, this being sufficient to override the second mixer internal noise without raising the level high enough to cause undue cross-modulation effects due to strong unwanted signals within the first i.f. pass-band. The equipment operates without undue interference in the presence of strong local c.w. signals of some tens of millivolts per metre. Strong broadcast signals below 1 Mc/s of some hundreds of millivolts per metre have to be suitably suppressed by means of filters or, in this particular design, by means of the aerial transformers, which do not cover this band under normal operating conditions.

The second i.f. pass-band is about 30 kc/s, sufficient to accommodate the pulse width of about 70 microsec. The second i.f. stages have suitable slide-back circuits on the grids to enable the amplifier to operate while in the presence of strong c.w. signals. The detector and video stages are similarly arranged to slide back and pass only the pulses. This is necessary, as the sounder operates across the congested short-wave spectrum.

(6) HEIGHT TIME-BASE AND FREQUENCY SCAN

The height time-base is produced from a suitable multi-vibrator circuit in the usual way. The recurrence frequency is 100/sec. The frequency scan across the oscilloscope is derived from a long-time-constant sweep circuit which is triggered by a contact on the main condenser shaft. A complete sweep takes about 7 sec. The height calibration follows the usual practice.

(7) FREQUENCY CALIBRATOR

The method of frequency calibration is of some interest. The usual method of bringing up marks by means of a switch on the main condenser drive is unsatisfactory in many respects. In this equipment the frequency calibration is performed in the following way. A crystal-controlled 1-Mc/s oscillator feeds a mixer stage after suitable distortion of the waveform to give harmonics up to 50 Mc/s. The mixer is also fed from the main variable oscillator. The fixed 30-Mc/s frequency in the transmitter is to all intents crystal-controlled, i.e. it is the sum of the 29.1-Mc/s crystal-controlled and 900-kc/s uncontrolled oscillations. Thus, the variable-oscillator and radiation frequencies pass through multiples of 1 Mc/s simultaneously. The output of the mixer stage therefore contains an audio beat frequency at every 1-Mc/s increment in the radiation frequency. This audio beat is suitably amplified and finally rectified to produce a pulse at these 1-Mc/s intervals. This pulse is applied to a gating stage which allows the height calibration to pass through to the oscilloscope at these intervals. This results in vertical rows of height calibration marks being displayed on the oscilloscope every 1 Mc/s division of frequency. This method of calibration has the advantage of being quite independent of the main oscillator condenser, which need not be of high precision. The calibration is crystal-controlled and cannot be maladjusted. Furthermore, the limits of sweep may be set at will without affecting the frequency calibration. It will be noted that the second intermediate frequency is 900 kc/s and not 1 Mc/s, so as to avoid interference from the calibrator oscillator. Hence the odd figure of 29.1 Mc/s for the crystal-controlled high-frequency oscillator.

(8) DISPLAY

The display is on a long-afterglow tube in order that the complete picture may be examined visually when the equipment is switched to operate continuously. A small monitor tube with signal deflection is also provided. When switched to automatic

operation, a time switch brings up the filaments, then the h.t. and condenser drive motor. A 16-mm ciné camera is arranged to record one complete sweep, it being operated in synchronism with the condenser drive. One frame is exposed for the duration

of the sweep, i.e. about 7 sec. An electric clock with a mechanical counter geared to it is simultaneously photographed to record the hour and day. Normally the equipment makes one record every 20 minutes.

(9) AERIAL SYSTEM

The aerials consist of two concentric vertical rhombics with centre frequencies of 4 and 12 Mc/s respectively. These cover the band 1-20 Mc/s fairly effectively. They are fed by two air-cored transformers which are connected in series on the primary side. The high-frequency transformer primary resonates at about 8 Mc/s with the valve and stray capacitances of about $40\ \mu\text{F}$, whilst the low-frequency transformer primary resonates at about 3 Mc/s with a $100\text{-}\mu\text{F}$ condenser and strays. The unloaded primary impedance in each case falls to about 600 ohms at the end of each band. At the take-over frequency of 6 Mc/s the impedances are roughly equal and both aerials radiate equally. By arranging the correct phase of one relative to the other, by reversing the feeders if necessary, they do not interfere unduly. The secondaries are coupled as tightly as is physically possible with air-cored coils, the coupling coefficient being about 0.6. The aerials are fed push-pull at an impedance of about 1 000 ohms.

(10) GENERAL LAYOUT OF EQUIPMENT

The complete equipment is arranged on one chassis. This eliminates a multiplicity of chassis interconnections. There is also an almost complete absence of screening. This is possible owing to the low impedance of the various untuned stages and to the fact that the necessary amplification may be done at different frequencies in easy stages. The chassis is arranged vertically

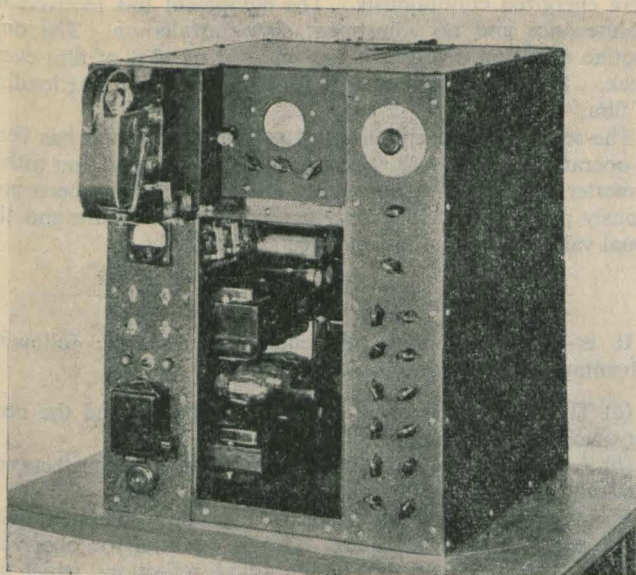


Fig. 2.—General view of equipment.

The photographic compartment is on the left, the monitor tube in the centre and frequency dial on the right. The power and switching circuits are on the lower left and all other circuits on the right.

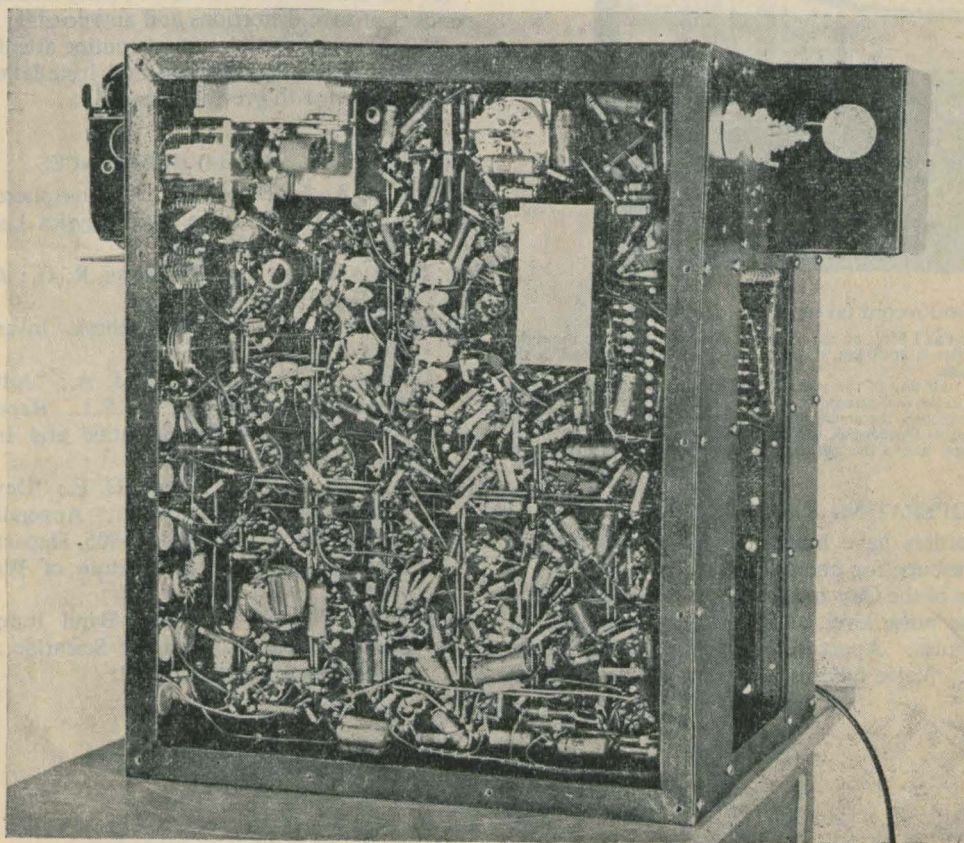


Fig. 3.—Side view of equipment with cover removed, showing accessibility of wiring and the main tuning condenser and drive motor on the top left.

with all valves inwards and wiring outwards on the side. This makes for easy access, particularly during the experimental stage. The equipment is intended to be semi-portable and has been built as compactly as possible, the overall size being 22 in $\times$ 22 in by 27 in high. Figs. 2 and 3 show general views of the equipment.

(11) RECORDS TAKEN BY EQUIPMENT

Fig. 4 illustrates typical records taken by the equipment.

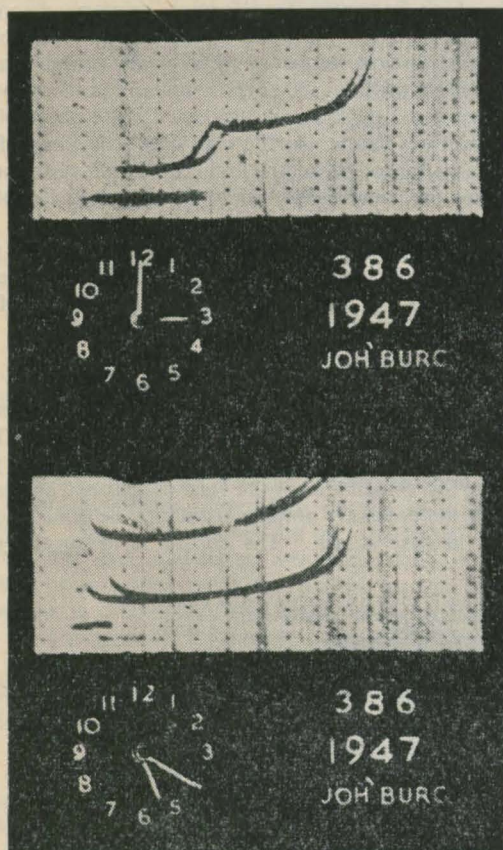


Fig. 4.—Typical record taken by the equipment.

The frequency limits are set at 1 Mc/s on the left-hand side to 15 Mc/s on the right. The first height-calibration dot is at 50 km, the zero kilometre dot being lost in the main pulse and ground signals.

The counter registers the half day of the year. The year and place are indicated below. The upper picture, in the mid-afternoon, shows sporadic E, F1 and F2 layers respectively. On the lower picture the strong local broadcast stations may be seen at 4.3 Mc/s, 6.0 Mc/s and other frequencies, and considerable clutter from the upper short-wave bands around and above the critical frequency in the late afternoon is also apparent.

(12) OPERATING EXPERIENCE

Two of these recorders have been built. One has been in operation in Johannesburg for about 2 years (April 1949). It operates in the middle of the City and has given consistently good signals in spite of the noise level, and strong local signals. It operates every 20 minutes. Apart from valve failures there have been no breakdowns. Valve failures occur at the rate of about

one every few months, and are invariably due to open-circuited filaments, or more commonly, open-circuited cathodes. This is due to the switching cycle on the filaments, but it is regarded as preferable that the valves should fail on this account rather than from emission trouble as would perhaps occur if the filaments were energized continuously. The equipment has received no maintenance and no adjustment since installation. The only routine attention involved is the removal of 12 ft of film every week. The camera will operate for two months on one loading of film.

The second recorder is installed at Cape Town and has been in operation for one year. It was placed in full operation within a matter of minutes of unpacking, the aerials having been previously prepared. Apart from one component failure and the usual valve failures, it has operated satisfactorily.

(13) CONCLUSION

It is considered that this equipment has the following advantages over previous designs:

- (a) The elimination of all mechanical troubles and the need for precision-built components.
- (b) A complete solution to the problem of tracking between the transmitter and receiver.
- (c) The highest possible speed of operation consistent with good definition, i.e. 700 lines. This is essential for observing rapidly changing effects such as sporadic E-reflections, which are often observed to develop and disappear over periods of less than half a minute.
- (d) The ability to present a picture which can be viewed directly if necessary.
- (e) Accurate calibration in frequency and height which is independent of tube distortions and any possible maladjustments.
- (f) It requires a minimum of routine attention.
- (g) The cost of production and installation is less than has been achieved with previous designs.

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Thesis

TELECOMMUNICATIONS RESEARCH LABORATORY
TELEKOMMUNIKASIES NAVORSINGSLABORATORIUM

A SINGLE BAND IONOSPHERE RECORDER

COVERING THE RANGE
0.1 TO 20 MEGACYCLES/SECOND

By T. L. Wadley

PRETORIA
1947

SUID-AFRIKAANSE
WETENSKAPLIKE EN
NYWERHEIDNAVORSINGSRAAD

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A SINGLE BAND IONOSPHERE RECORDER COVERING THE RANGE 0.1 TO 20 MEGACYCLES/SECOND.

ABSTRACT.

This report describes an automatic ionosphere recorder which covers the range of 0.1 to 20 megacycles/second in a single band by a system of high frequency heterodyning and the use of wide band amplifiers. The system is arranged to be independent of the stability of high frequency oscillators by means of a double heterodyne in the transmitter as well as the receiver.

The equipment has a panoramic display with a sweep duration of 7 seconds, such that the height frequency curve may be viewed directly. The frequency calibration is crystal controlled and quite independent of the sweeping mechanism, which may be set to any desired limits of sweep.

The aerial systems consist of a pair of concentric vertical rhombics suitably coupled to the equipment by wide band transformers, which are arranged to transfer the power from one aerial to the other automatically as frequency proceeds up the band. Common aerial operation is employed on the transmitter and receiver.

GENERAL.

This equipment consists of an automatically operated radio pulse sounder covering the frequency range of 0.1 to 20 megacycles/second. It operates every twenty minutes and records a graph of height of the ionosphere layer against the frequency on a single frame of 16 mm film. A record of the time and the date is simultaneously photographed.

The frequency range 0.1 to 20 megacycles/second is covered in a single band by means of a heterodyning arrangement and the use of wide band R.F. amplifiers. The transmitter radiation frequency is derived by mixing a fixed 30 megacycles/second frequency with a variable 30 to 50 Mc/sec frequency.

The receiver consists of a double superheterodyne with a first I.F. of 30 Mc/sec and a second I.F. of 900 Kc/sec. The receiver is interlocked with the transmitter by arranging the variable oscillator 30 to 50 Mc/sec common to both. It performs the function of the first local oscillator in the receiver from which the first I.F. of 30 Mc/sec is derived. The second local oscillator operates at 29.1 Mc/sec, giving a second I.F. of 900 kilocycles. The stability of the whole system is ensured by deriving the 30 Mc/sec fixed transmitter frequency from the sum of the second receiver local oscillator 29.1 Mc/sec, and a 900 Kc/sec oscillator. The

stability of the system, therefore, relates back to the 900 Kc/sec oscillator and is quite independent of the stability of the two high frequency oscillators.

The transmitter amplifier consists of a number of untuned stages, with a bandpass of 20 Mc/sec. The receiver input consists of a similar untuned pre-amplifier.

The transmitter and receiver are arranged to operate on a common aerial system, or separately if desired. The aerial may consist of a simple untuned wire suitably disposed, or, for a permanent installation, a system of vertical rhombics is used, which is coupled to the equipment through suitable transformers.

The display is on a long afterglow cathode-ray oscillograph on which the height against frequency graph is built up by deflecting the spot vertically with a height time-base and horizontally in synchronism with the frequency change. The signals are applied so as to intensity modulate the beam. A complete frequency sweep occupies about 7 seconds and a persistent picture is maintained by the afterglow when the equipment is switched to run continuously. When photographing every twenty minutes, a single frame is exposed for one complete sweep, i.e. 7 seconds.

Height calibration is provided at 50 Km. intervals from a 3,000 cycle shock excited oscillation, which, after suitable shaping, is applied to the oscilloscope.

Frequency calibration is provided from the harmonics of a 1 Mc/sec crystal controlled oscillator. These harmonics are caused to beat with the main variable oscillator. A calibrating pulse is derived from the audio beat every 1 Mc/sec interval. This pulse causes the height calibration to be gated through to the oscilloscope so as to produce rows of height dots at 1 Mc/sec increments in frequency. In order to ensure that the main variable oscillator and radiation frequencies pass through the multiples of 1 Mc/sec simultaneously, the 29.1 local oscillator is crystal controlled.

An auxiliary A scan C.R.O. with signal deflection is provided for monitoring and tuning purposes.

Automatic time-switching is provided from a self-starting synchronous clock movement. The switching is arranged to bring up all the filaments for a 100 second warm-up period. The H.T. and variable oscillator condenser drive motor are then brought on and the equipment goes through one complete cycle. A 16 mm. camera records this sweep.

The time is recorded from a suitably illuminated non-selfstarting synchronous clock to which is geared a counter which registers the half-day of the year.

The complete equipment is contained in a rack of dimensions 22" $\times$ 22" $\times$ 27" high. It is very compact and is intended to be semi-

portable. With the exception of the power supplies and switching, all circuits are arranged on one panel. There are thus no chassis interconnections. This panel is arranged vertically with the valves inwards and the wiring outwards. The power supplies and switching are arranged on a similar panel on the other side of the equipment. All controls are brought out to the front. All parts of the equipment are accessible simply by removing the side dust covers.

DESCRIPTION OF THE EQUIPMENT.

For the purpose of description, the equipment may be divided into the following sections:—

- (a) Height time base.
- (b) Modulator pulser.
- (c) Transmitter driver.
- (d) Transmitter amplifier.
- (e) Receiver.
- (f) Frequency time base.
- (g) Height calibrator.
- (h) Frequency calibrator.
- (i) Calibration gate stage.
- (j) Main display oscilloscope.
- (k) Auxiliary A scan oscilloscope.
- (l) Aerial transformers.
- (m) Power supplies.
- (n) Automatic switching.

Circuit Diagrams.

Two diagrams are provided; a block diagram of the main circuits and a complete detailed circuit diagram. These are both arranged, as far as possible, in the same manner as the actual circuits in the equipment to simplify servicing. The diagrams are arranged as viewed from the outside, i.e. the wiring side in the case of both the main panel and power supplies. The valves are numbered in sequence corresponding to their position in each row and column. Valve pin connections are as shown.

Description of Block Diagram.

The various sections of the equipment are shown in dotted lines.

Height Time Base. (V.71, 72, 73, 74, 75 and 76.)

V.71 and 72 form a multivibrator. This provides a square synchronising wave to the height calibrator V.61 and to the modulator pulser V.41. From it is also derived a saw toothed wave which provides the height time base. This is phase inverted in V.73 and D.C. restored by V.74. V.75 and V.76 form a push pull amplifier and apply the height time base to the vertical oscilloscope deflection coils. The multivibrator also provides a black-out wave to the oscilloscope to remove the back trace.

Modulator Pulser. (V.41.)

V.41 produces a pulse of about 70 microseconds from the square multivibrator wave and provides a grid modulating voltage to the 900 Kc. oscillator V.21 and all stages of the transmitter amplifier.

Transmitter Driver. (V.11, 12, 13, 21, 22, 23, 31, 32 and 33.)

V.31 is a crystal controlled oscillator operating at 7.275 Mc/sec. V.32 multiplies this four times to 29.1 Mc/sec. V.21 is a pulsed 900 Kc. oscillator which is pulsed as described above. V.22 is a mixer stage which mixes 29.1 Mc/sec from V.32 and the 900 Kc/sec pulse from V.21. V.33 and V.23 are tuned stages which separate out the 30 Mc/sec pulse from the mixer. The output of V.23 is applied to the second mixer stage V.12, together with the variable oscillator frequency 30–50 Mc/sec from V.11. The output of this latter mixer contains the radiation frequency pulse 0–20 Mc/sec. This is separated and amplified by V.13 which is an untuned R.F. amplifier.

Transmitter Amplifier. (V.5, 6 and 7.)

This consists of three stages V.5, 6 and 7. The stages are untuned and have a bandpass up to 20 Mc/sec. The stages operate Class A, as being untuned it is not possible to operate Class C. This amplifier is normally biased beyond cut-off, and is pulsed into Class A condition in synchronism with the pulse, by the modulator. The output level is about 1 kW, and is applied straight to an untuned antenna.

Receiver. (V.14, 15, 16, 24, 25, 34, 35, 44, 45, 46 and 56.)

This consists firstly of an untuned R.F. stage V.16 connected directly to the aerial. This is followed by a mixer V.14 where the signal is mixed with the variable oscillator V.11, to give a first I.F. of 30 Mc/sec exactly equal to the original 30 Mc/sec in the transmitter. V.15 is the first I.F. amplifier. V.25 is the second mixer where the signal is mixed with the 29.1 Mc/sec oscillator V.32 to give a second I.F. of 900 Kc/sec. This is exactly equal to the original 900 Kc/sec pulsed oscillator in the transmitter. The latter is tuned to coincide exactly with the second I.F. The receiver is thus maintained in tune at all radiation frequencies. V.35, V.34 and V.44 are second I.F. amplifier stages. They are followed by the detector V.45 and video amplifier V.46. The noise level at V.46 is fed back to the A.V.C. tube V.24 to provide control on the three second I.F. stages. V.56 is the video output stage which applies the signals to intensity modulate the oscilloscope in the correct phase, that is to produce blacked-out signals on a bright line.

Frequency Time Base. (V.51, 52 and 53.)

V.51 forms part of a push pull circuit consisting of a long time constant charging network. The charging is initiated by a cam contact on the main variable oscillator condenser drive. A slow linearly in-

creasing voltage is produced and applied via the push pull amplifier V.52 and V.53 to the horizontal oscilloscope deflection coils.

Height Calibrator. (V.61, 62 and 63.)

V.61 is associated with a tuned circuit of frequency 3,000 cycles/second. This is shocked into oscillation by the square wave from the multivibrator. This oscillation is amplified by the overdriven stages V.62 (double triode) and thereby produces a square waveform. This is differentiated to produce pips. The latter are amplified and limited by the following stage V.63. They are then passed on to the calibration gating stage V.43.

Frequency Calibrator. (V.42, 54, 55, 64, 65, 66 and 74.)

V.54 is a crystal controlled oscillator operating at 1 Mc/second. V.42 is the 1 Mc/sec crystal. This 1 Mc/sec is fed at high level to the mixer stage V.55. Harmonics of 1 Mc/sec up to at least 50 Mc/sec are produced in this stage. V.55 is also fed from the main variable oscillator V.11. The output of V.55 contains audio beat notes as the variable oscillator frequency passes through harmonics of 1 Mc/sec. V.64, 65 and 66 are amplifier stages which bring the beat up to a suitable level. V.74 (half a double diode) rectifies this beat and produces a calibrating pulse.

Calibration Gate Stage. (V. 43.)

V.43 is a gating stage which is fed with the height calibration from V.63 and the frequency calibrating pulses from V.74. It causes the height calibration to be gated through to the oscilloscope cathode upon reception of the gating pulse. Rows of blacked-out height dots are thus produced at 1 Mc/sec intervals.

DETAILED CIRCUIT DESCRIPTION.

(a) Height Time Base. (V.71, 72, 73, 74, 75 and 76.)

V.71 and V.72 form a multivibrator operating on their screens as plates. The plates themselves are used to supply the required waveforms to the outside circuits. During the flyback period V.72 is conducting. V.71 is cut off due to the negative charge on the grid coupling condenser 0.005 microfarad. This charge is leaking away at a rate determined by the setting of the control C.51. V.71 eventually becomes conducting and the multivibrator reverses. V.72 becomes cut off. A square negative going wave is developed on the plate of V.71 and is fed as a synchronising wave to the height calibrator V.61 and the modulator V.41. It also supplies a brightening up voltage to the main C.R.O. cathode. A square positive going wave is developed on the screen of V.72, part of which supplies a brightening up voltage to the grid of the monitor C.R.O. The plate voltage of V.72 is normally near ground potential. As V.72 cuts off the condenser O.15 microfarad plate to ground starts charging

via 500 K. and 1 M. potentiometer to H.T. This rising voltage constitutes the height time base. Its rate is adjusted by C.62. The voltage is allowed to rise only a small fraction of the H.T. and the rise is therefore fairly linear. V.72 is held cut off by the charge on its grid condenser 0.03 microfarad. This charge is leaking away at a rate determined by the setting of C.52. V.72 eventually becomes conducting again and the multi-vibrator reverts to its original condition. C.52 determines the duration of the height sweep. The multivibrator can run free if desired, the P.R.F. being adjusted by C.51. It is, however, normally synchronised to the 100 cycle ripple on the power supply via cross-connection F on grid of V.72 to V.3 in the power pack. The saw-tooth time base wave on the plate of V.72 is applied direct to the grid of one push pull amplifier V.75, and the grid of the phase inverter V.73. The latter operates at a gain of unity, it having an un-bypassed cathode resistor equal to its plate resistor. The output of V.73 is applied to the other push pull amplifier V.76. The latter wave is D.C. restored by one diode of V.74 to a level set by the control C.61. C.61 is, therefore, the time base shift for the main C.R.O. The push pull amplifier V.75, V.76, has a common screen dropping resistor and common cathode resistor to assist in the balancing. The push pull plates have series resistors for voltage deflection of the monitor C.R.O., in addition to the current coils of the main C.R.O. The plate H.T. for these tubes is picked up at the deflection coil centre-tap on the main C.R.O. panel.

(b) Modulator Pulser. (V.41.)

V.41 is the modulator tube. It has its cathode and filaments at 400 volts negative with respect to ground. The filaments are supplied from a separate transformer. V.41 is normally conducting and drawing grid current as its grid is leaked to ground. (i.e. H.T. + relative to cathode.)

The tube is drawing heavy current and corresponding negative voltages are developed across the various sections 2K, 1K, and 12.5K of the plate load, which is located in the transmitter amplifier section. These voltages are sufficient to cut off each of the various transmitter amplifier stages to which they are applied as grid bias.

The negative going square wave from the multivibrator is applied to the grid of V.41 via 500 p.f. The modulator tube is thus caused to cut off sharply. The current flowing through the plate load is reduced to the current flowing through the 50K resistor, which shunts plate to cathode of the modulator tube. This sets up suitable Class A bias conditions on each of the transmitter amplifier stages. The charge on the 500 p.f. grid coupling condenser eventually leaks away at a rate determined by C.21, and the valve again conducts, restoring cut-off voltages to the amplifier stages. A modulating pulse is thus formed, the duration of which is controlled by C.21. It is normally set to about 70 microseconds.

(c) **Transmitter Driver.** (V.11, 12, 13, 21, 22, 23, 31, 32 and 33.)

V.31 is a crystal controlled oscillator operating at 7.275 Mc/sec. V.32 is a multiplier stage driven from V.31 with its plate circuit tuned to the fourth harmonic, i.e. 29.1 Mc/sec. This is applied as the second local oscillator to the receiver second mixer via the cross-connection B. It is also applied to the first transmitter mixer V.22, which is a pentagrid. The signal grid of the latter is supplied with a 900 Kc/sec pulse from V.21. V.21 is normally biased beyond cut-off, as its grid is connected via 20K leak resistor to the modulator plate load in the transmitter amplifier. V.21 is thus caused to produce a pulsed oscillation of 900 Kc/sec in synchronism with the modulator pulse. The 2M resistor from V.21 grid to H.T.+ ensures that the grid is brought to ground potential at the start of the pulse and not somewhat negative.

The mixer stage V.22 has its output sharply tuned to 30 Mc/sec. A pulse of this frequency is developed across it. This is followed by V.33 and V.23, which are stages similarly tuned to 30 Mc/sec. They do not amplify as the feed to each grid is tapped down the previous tuned circuit. These valves simply act as buffers between the three tuned circuits. The latter are required to suppress the original 29.1 Mc/sec and select the 30 Mc/sec pulse. The output of V.23, suitably matched down to low impedance, is coupled via a 10 p.f. condenser to the cathode of V.12, which is the second transmitter mixer stage.

V.11 is the main variable oscillator. It functions over the range 30 to 50 Mc/sec. The upper limit may be set on the trimmer condenser 20 p.f., and the lower limit on the padder condenser 500 p.f. The plates of the main condenser are shaped to give the desired frequency against rotation law in one 180° segment. This condenser is driven by an induction motor via a slipping clutch, which allows the condenser to be rotated independently by hand. Three sets of contacts are operated by a cam on the condenser shaft. The upper contact operates the camera, the middle contact applies negative bias to the main C.R.O. grid to eliminate the return sweep of the condenser, and the lower contact initiates the X sweep or frequency sweep on the main C.R.O. The main condenser shaft is brought through to the front panel where a calibrated dial indicates the frequency for manual operation.

The output of this oscillator V.11 is applied to the receiver first mixer V.14, via cross-connection A, and to the frequency calibrator mixer V.55, via cross-connection D. It is also applied to the plate of the second transmitter mixer V.12, which is a low impedance diode. The fixed 30 Mc/sec pulse is applied to its cathode. The difference frequency 0 to 20 Mc/sec appears across the cathode coupling condenser of 10 p.f. This 10 p.f. condenser forms the mid-shunt input component of a 700 ohm low pass filter. L.8 is the series element, and the grid capacity of V.13, also about 10 p.f., is the mid-shunt termination element. The

filter is terminated in a 700 ohm resistor. This filter, and all the subsequent coupling filters, cut off at about 20 Mc/sec. V.13 is the first wideband R.F. amplifier. The output is applied to the transmitter amplifier through a similar 700 ohm filter. The R.F. pulse level at this stage is about 10 volts peak to peak, being about 3 volts peak to peak at the diode output.

(d) Transmitter Amplifier. (V.5, 6 and 7.)

The three stages of this amplifier are all pulsed into Class A condition in synchronism with the pulse, as described in section (b). The 100 K resistor to H.T. between the 1 K and 2 K resistors in the bias circuit brings the operating point of V.5 to the correct position in relation to its cut-off voltage, as it requires rather more cut-off bias in proportion to its Class A bias than the latter stages. V.5 brings the level up to about 30 volts peak to peak on a 400 ohm coupling filter. This filter is mid-shut input as before, but is mid-series terminated, the grid capacity of V.6 forming the full shunt element and being about twice the output capacity of V.5. The 300 p.f. and 5 K grid coupling circuit on each stage is designed to couple the R.F. satisfactorily down to a few hundred kilocycles per second, and, at the same time, to apply the pulsed bias to the grids without distortion due to the by-passing effect of the coupling condenser.

The output of V.6 is into a 400 ohm filter similar to the previous one, the level at this stage being about 150 volts peak to peak. This feeds the final amplifier V.7 which operates with a Class A bias of about 75 volts. The screen voltage is 1,000 volts and is derived from the H.T. voltage of 2000, which is applied to the plate via the R.F. choke L.6. The peak plate current and swing is about 5 amps, which enables a peak to peak voltage of about 3,000 volts to be developed on a plate impedance of 600 ohms. The plate voltage thus swings from about 500 volts to 3,500 volts. The plate circuit is coupled via a 0.01 m.f.d. D.C. blocking condenser and L.5 R.F. choke to the aerial terminal, which should present an R.F. impedance of about 600 ohms to the final stage. The R.F. power level to the aerial is of the order of 1 kilowatt.

(e) Receiver. (V. 14, 15, 16, 24, 25, 34, 35, 44, 45, 46 and 56.)

The receiver consists, firstly, of an untuned R.F. stage V.16. It is connected direct to the aerial terminal with a shunt wave trap for broadcast frequencies and a short time constant R.C. coupling circuit. The transmitter output which is connected in parallel with the receiver input, causes V.16 to draw grid current until the 100 p.f. coupling condenser is charged to the peak transmitter voltage. V.16 continues to draw grid current to maintain this charge until the end of the pulse. The grid is then left 1,500 volts negative with respect to the cathode. This charge must leak away before any reflections are received. The time constant

is 2 microseconds and it thus takes perhaps 20 microseconds for this circuit to recover completely. V.16 must be capable of withstanding 3,000 volts on its grid, and a small transmitting tube is used for this purpose.

The output of V.16 is coupled via a 700 ohm filter as in the transmitter, to V.14 which is the first mixer stage. V.14 is fed from the variable oscillator V.11 via cross-connection A. The first I.F. of 30 Mc/sec is thus derived and applied via the tuned circuit L.11 to V.15, the first I.F. amplifier. The output of V.15 is similarly tuned to 30 Mc/sec and is applied to the signal grid of V.25, which is the second mixer stage. The oscillator grid is supplied via cross-connection B with 29.1 Mc/sec from V.32. The second I.F. of 900 Kc/sec is thus derived. This 900 Kc/sec is exactly equal to the original 900 Kc/sec pulse at V.21 in the transmitter.

The second I.F. consists of three stages which are all similar, V.35, V.34 and V.44. The bandpass is about 30 Kc/sec. The grid of each stage has a series R.C. circuit of 200 K and 50 p.f. This enables the amplifier to work through strong C.W. signals as the grid current drawn by each stage increases the bias voltage to prevent the amplifier saturating. The output of this I.F. amplifier is then applied to a diode detector V.45. The output of the detector passes through an I.F. filter consisting of three R.C. sections. At this stage, the signals are negative going. The pulses are separated from any D.C. level which may be present due to interfering stations, by the R.C. circuit 250 p.f. and 2 M on the grid of V. 46. The pulses and noise voltages are D.C. restored by the grid current of V. 46 which operates at zero bias. V.46 is a video amplifier. The signals on this plate are positive going. The mean D.C. level on the plate is a measure of the noise voltages present. This level is used to control the A.V.C. circuit to maintain a more or less constant noise level. The pulse amplitudes have relatively little effect on the A.V.C. as they are of short duration. This mean D.C. level is applied to the A.V.C. tube V.24 via cross-connection C. The D.C. is filtered out by the R.C. circuit 250K 0.1 m.f.d. and applied to the grid of V.24. This grid is also leaked to H.T. negative via the gain control C.22. V.24 is a cathode follower, with its cathode connected to all the cathodes of the second I.F. amplifier. C.22 is adjusted such that with no noise present, the grid of V.24 would be somewhat behind cut-off. The presence of noise causes the grid to rise positive, and V.24 to draw current. The I.F. cathodes rise positive and reduce the gain of the receiver to maintain a more or less constant noise level, as determined by the initial bias applied to V.24 by the gain control C.22.

The positive going output of V.46 is applied to the video output stage V.56. This is a double triode working with cathode near H.T. negative. The first section operates as a diode to D.C. restore the signal after coupling over from V.46. It restores the signals to H.T. negative.

It also suppresses the tendency of the pulse to back kick due to the differentiation prior to V.46. At this stage the signal is fed to Y_2 plate of the A-scan monitor C.R.O., and to the grid of the second half of V.56. The latter is forced biased somewhat behind cut-off and has no cathode by-pass. It thus has a large grid base and little gain. Its function is to remove the small noise peaks and pass only the pulses which are above the noise and to provide a signal of the correct polarity, i.e. negative going. Its plate load is connected directly to the grid of the main C.R.O. and thus the signals can only be negative with respect to ground. There is thus no tendency whatever to back kicks which are particularly objectional on a B-scan which is to be photographed. The pulses appear as black-out spots on a bright time base line.

(f) **Frequency Time Base.** (V. 51, 52 and 53.)

V.51 is the frequency time base charging stage. It has an un-bypassed cathode resistor to give it a grid base as wide as the following amplifiers. The tube is arranged as phase inverter of gain equal to unity, that is the amplified grid swing which appears across the plate load of 200 K is potentiometered down by the 2 M and 250 K resistors back to the original grid swing. The 4 m.f.d. charging condenser is connected from input to output of this stage. The grid is earthed during the main variable condenser return sweep by a contact on the cam as described previously. The other side of the 4 m.f.d. condenser is at a positive potential which may be set by C.31. At the beginning of the frequency sweep, the contact opens and the grid starts rising positive, being connected via 10 M to a variable H.T. point as set by C.32. As the grid rises positive, the other side of the condenser proceeds negative. The condenser thus presents an apparent capacity to the grid of 8 m.f.d. This, in conjunction with the 10 M resistor, gives a time constant of 80 seconds, and this determines the rate at which the grid rises positive relative to the voltage set up on C.32. The charging proceeds for a time of 6 to 10 seconds for a half rotation of the variable sweep condenser, and thus the rise is fairly linear. The push pull sweep across the 4 m.f.d. condenser is now applied to the grids of V.52 and V.53, which is the push pull X amplifier for the main C.R.O. These amplifiers have a common screen resistor and common cathode resistor. The voltage across the latter, in conjunction with the voltage on each side of the 4 m.f.d. condenser, determines the starting point and swing of each tube. The X sweep coils are connected from plate to plate. The starting point of the sweep may be set by C.31 and the rate of sweep by C.32. At the end of the sweep the cam contacts close again. V.51 grid returns to earth potential and the other side of the condenser 4 m.f.d. returns to its original potential in 2 to 3 seconds. During the return sweep the main C.R.O. is blacked out as described previously.

(g) **Height Calibrator.** (V.61, 62 and 63.)

V.61 has a tuned circuit of frequency 3 Kc/sec in its cathode. The tube is normally conducting as its grid is leaked to H.T. The negative going square wave from the multivibrator cuts the current off sharply in synchronism with the start of the time base sweep. The inductance discharges into the capacity of this tuned circuit and a damped oscillation of 3 Kc/sec is produced.

V.62, which is a double triode, amplifies squares and limits the 3 kilocycle wave. The series grid resistors in each stage allow the voltage to swing positive without drawing excessive grid current. This ensures that the squaring takes place in the correct phase relative to the square synchronising wave. The output of V.62 is differentiated by the 100 p.f. and 500 K R.C. circuit to give pips. The latter are amplified and limited by the first half of V.63, and then applied to the second half of V.63. This is a cathode follower which operates with its bias beyond cut off. Its function is to remove the negative going pips and pass only the positive going, the latter being the required 50 kilometer marks. The calibration marks tapped off 500 ohms of the cathode load are applied to the Y_1 plate of the A-scan monitor. The full cathode output is applied to the calibration gate stage V.43. Negative going calibration marks from the plate are also applied to V.43 for neutralising purposes as described below.

(h) **Frequency Calibrator.** (V.42, 54, 55, 64, 65, 66 and 74.)

V.42 is a 1 Mc/sec crystal which controls the oscillator stage V.54. The full output across the tuned plate circuit of the latter is applied via a 10 p.f. condenser to the first grid of V.55. The latter is a mixer stage. This grid circuit draws heavy grid current on the positive swings, charging the 10 p.f. condenser. This condenser discharges on the negative swings and a highly distorted waveform is produced, which contains a fair distribution of 1 Mc/sec harmonics up to at least 50 Mc/sec. The control grid of this mixer is fed from the main variable oscillator V.11 via cross-connection D. Audio beats thus occur in the plate circuit at 1 Mc/sec increments of the main variable oscillator frequency. These audio beats are amplified by the three similar stages V.64, V.65 and V.66. The band-pass of this audio amplifier is restricted to about 10 kilocycles by the R.C. coupling filters between stages. The output of this amplifier is coupled to one diode unit of V.74, and the audio beat is rectified to give a negative going calibrating pulse which is passed via cross-connection E to the calibration gate stage V.43. The duration of this pulse is determined by the 0.01 m.f.d. condenser and the setting of the control C.42, which is a 2 M variable resistor. It is thus of about $\frac{1}{50}$ second duration, with the leading edge of the pulse corresponding to the 1 Mc/sec division.

(i) Calibration Gate Stage. (V.43.)

V.43 is a double triode. The first section has the calibrating pulse on its grid via cross-connection E. This grid has a standing positive bias which is supplied from the cathode of V.65, along with the calibrating pulse. This positive bias prevents the tube from responding to noise and small spurious pulses from the frequency calibrator. Normally the tube is conducting and is D.C. coupled to the second triode section such that the latter is biased well behind cut off. The negative going calibrating pulse causes the first section to cut off completely and the bias of the second section to be brought just behind cut off. This second triode operates as a cathode follower. The height calibration pips are also supplied to its grid from V.63. The bias normally does not allow these pips to appear on the cathode, but during the calibration pulse the bias is such that positive height pips occur across the cathode load. The latter also constitutes the cathode resistor of the main C.R.O. and thus rows of blacked-out height pips occur on the main C.R.O. at 1 Mc/sec intervals. This cathode resistor is by-passed by a variable condenser which is control C.41. This causes the height pips to be lengthened out somewhat as they are otherwise too short to show on the long afterglow B-scan. The calibration width in height is thus set by C.41. A 4 p.f. condenser from the plate of V.63 to the cathode of V.43 neutralises the height calibration pips which tend to occur on the cathode due to grid capacity when the stage is biased right back. This is due to the cathode resistor being unavoidably high, as it also constitutes the bias resistor of the main C.R.O.

A negative going square wave is also applied at this point from the multivibrator V.71 via 0.1 m.f.d. and a 1 M resistor. This brightens up the main C.R.O. during the sweep and blacks it out during the return. The main C.R.O. brightness is adjusted by C.11, a 50 K potentiometer, which forms part of the cathode resistor. A forced bias current is supplied from a 4 M resistor to the 2,000 volt main C.R.O. H.T.

(j) Main Display Oscilloscope.

The main display C.R.O. is mounted within the frame together with the clock and day counter. The 16 mm. camera is on a swinging door on the front of the equipment. The main C.R.O. is a four inch long, afterglow tube, with magnetic deflection and focussing. The first anode operates at 400 volts, while current for the focussing coil is taken from the same point. C.12, which is located along with the intensity control on the front panel, is the focussing control. Signals are applied to the grid which operates from ground potential negative. Bias, calibration and black-out are applied to the cathode as described above. The final anode H.T. is 2,000 volts positive. Deflection is as described previously under sections (a) and (f).

(k) **Auxiliary A-Scan Oscilloscope.**

This consists of a three inch tube mounted within the frame on a front panel with its bias focus and shift controls immediately below it. The H.T. supply consists of the 400 volts negative and 400 volts positive supplies in series. The filament is operated from the special H.T. negative filament supply. Horizontal deflection is supplied from the height time-base, while the signals are applied to Y_2 and height calibration to Y_1 . A jack plug is provided in the Y_2 lead for monitoring purposes.

(l) **Aerial Transformers.**

These transformers are designed to enable the equipment to operate into a system of two vertical rhombic aerals, the first covering the band 1 to 5 Mc/secs, and the second 5 to 20 Mc/sec. The equipment normally operates with the transmitter output and receiver input in parallel. The two transformer primaries are in series. The high frequency transformer primary resonates at about 8 Mc/sec with the valve and stray capacities of about 40 p.f., whilst the low frequency transformer primary resonates at about 3 Mc/secs with the 100 p.f. condenser and strays. The unloaded primary impedance in each case falls to about 600 ohms at the end of each band. At the take-over frequency of 5 Mc/sec, the impedances are roughly equal and both aerals radiate equally. By arranging the correct phase of one relative to the other, by reversing the feeders if necessary, they do not interfere unduly. The secondaries are coupled as tightly as is physically possible with air cored coils, the coupling coefficient being about 0.6. The aerals are fed push pull at an impedance of about 1,000 ohms.

(m) **Power Supplies.**

H.T. Supplies.

There are three H.T. power supplies, as follows:—

- (1) The main 400 volt positive supply at 500 mA. This is derived from two identical supplies associated with V.3 and V.4. The filters are choke input. The rectifier filaments and H.T. windings are on separate transformers to simplify switching. These two supplies are finally commoned together on the distribution board on the main chassis.
- (2) A 400 volt negative supply. This is derived from a half wave rectifier V.2. and a suitable filter connected on to one of the H.T. transformers which supply the main positive H.T.
- (3) A 2,000 volt positive supply at 50 mA. This is derived from a half wave rectifier V.1. and after a simple filter consisting of a 500 ohm and 4 m.f.d. condenser, is applied

as the transmitter final H.T. A suitably by-passed milliammeter in the earth side of this supply indicates the final amplifier current.

After further filtering via 200 K and 2 m.f.d., this 2,000 volts is used to supply the main C.R.O. H.T. A 4 M resistor supplies current from this supply for the forced bias on the main C.R.O.

Filament Supplies.

There are three filament supplies, as follows:—

- (1) 6.3 volt 12 amps with one leg grounded.
- (2) 6.3 volt 6 amps with one leg connected to H.T. negative supply.
- (3) 24 volt 3 amps, which supplies the filament of the final transmitter amplifier.

Manual Switching.

All filaments are supplied from separate transformers and, for switching purposes, the primaries of all filament transformers are in parallel. Similarly, all transformers supplying H.T. are in parallel on their primary side. A filament and H.T. switch are provided in each of these circuits for manual switching. The filaments should be switched on at least a minute before the H.T. to enable the final transmitter amplifier to attain its full working temperature.

A third switch operates the variable oscillator condenser drive motor for manual operation of the equipment.

(n) Automatic Switching.

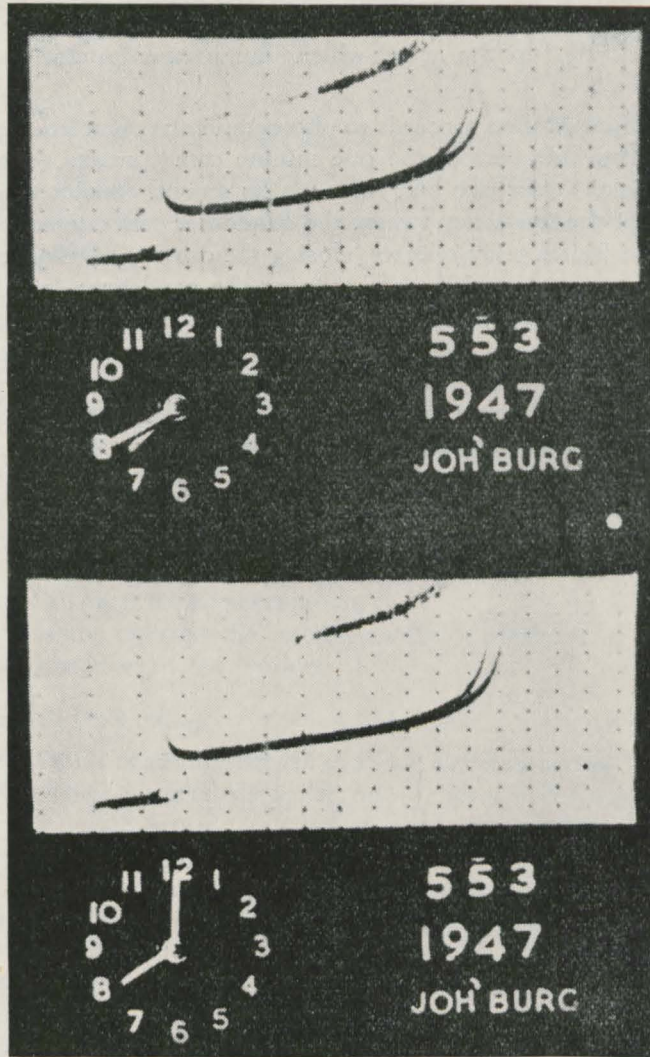
For automatic operation the three above switches are left open. A fourth switch which operates the synchronous motor in the time switch is closed after suitable setting, relative to the time of day. The time switch operates the equipment every twenty minutes, i.e. on the hour and at twenty minutes to, and past, the hour. The cam associated with the main condenser should be set in its operating position, that is anywhere within the condenser return sweep. The contacts will then be as shown in the diagram.

The sequence of operation is then as follows. The one minute cam in the time switch makes contact every minute, but no circuit is made. The twenty minute "A" cam makes a contact which operates the first relay. This brings up all the filaments, which are then allowed to warm up for a period of about 100 seconds. The intermediate operation of the one minute cam still does not complete any circuit. The twenty minute „B" cam then operates and on the next operation of the one minute cam, the second and third relays are operated. These switch on all H.T. transformers and the condenser drive motor respectively. The equipment then proceeds to complete the return sweep until the main condenser

is in the correct position for the start of the forward sweep. At this point the condenser cam contacts release. The lower contact starts the frequency time base as described above. The second contact removes the black-out bias from the main C.R.O. The upper contact operates the fourth relay. The latter operates the solenoid which opens the camera shutter and brings up the lamp, which illuminates the clock and day counter.

The equipment then proceeds to photograph one complete frequency sweep. During this period, the one minute cam contacts release, but relay four holds relays two and three via its second contact to ground. At the end of the frequency sweep, the condenser cam contacts operate again and the fourth relay releases, closing the camera. Relays two and three release, removing H.T. and stopping the condenser drive motor, which comes to rest somewhere in the condenser return sweep. The twenty minute "A" cam then releases the first relay which switches off the filaments. The twenty minute "B" cam contacts re-open somewhat after the release of the one minute cam contacts, the exact instant being of no importance. The equipment is then back to its original condition ready for the next photograph.

TYPICAL RECORDS TAKEN BY THE EQUIPMENT.
(Enlarged from 16 mm. film.)



The frequency limits in the above pictures are set at 1 Mc/sec on the left hand side to 17 Mc/sec on the right hand side, as indicated by the rows of calibration dots.

The first height calibration dot is 50 Kilometers, the first being lost in the main pulse and ground signals.

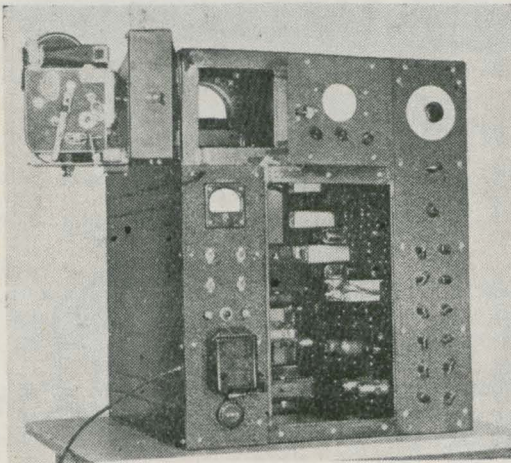
The counter registers the half-day of the year. The year and place are indicated below.

GENERAL VIEW OF RECORDER.



The equipment is mounted on top of its own specially made table which has a steel top. Working space is provided on each side, and storage space below for spares, film and test gear.

FRONT VIEW OF EQUIPMENT.



The camera is swung aside to show the main oscilloscope, with the clock and counter immediately below it.

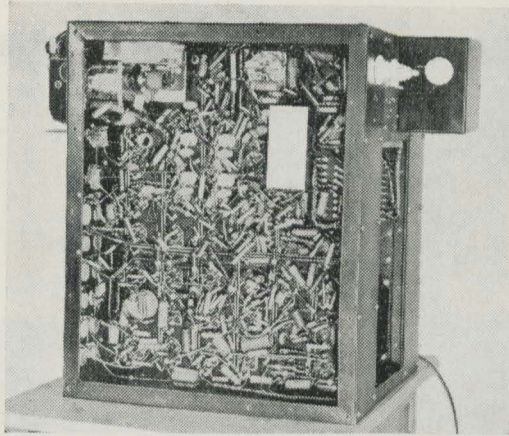
The monitor C.R.O. is in the centre.

The power switching panel is on the left and the various controls on the right hand panel.

The main tuning dial is to be seen on the top right.

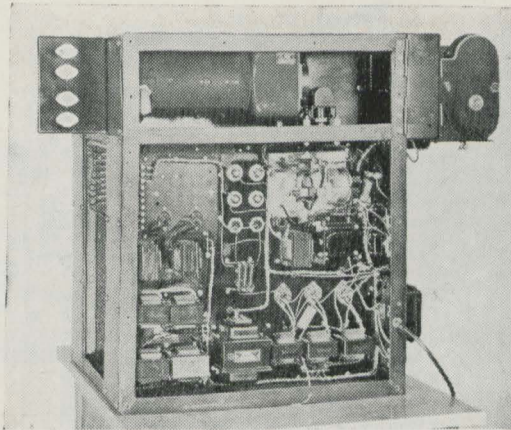
The valves may be seen projecting inwards within the frame.

RIGHT SIDE VIEW OF EQUIPMENT.
(With cover removed.)



The main oscillator condenser drive motor and cam may be seen in the top left hand corner. The wiring and valve bases are shown facing outwards. The various controls are shown from the back view on the left front panel. The terminal board may be seen on the right centre. The aerial transformers are contained in the box mounted on the rear of the equipment.

LEFT SIDE VIEW OF EQUIPMENT.
(With cover removed.)



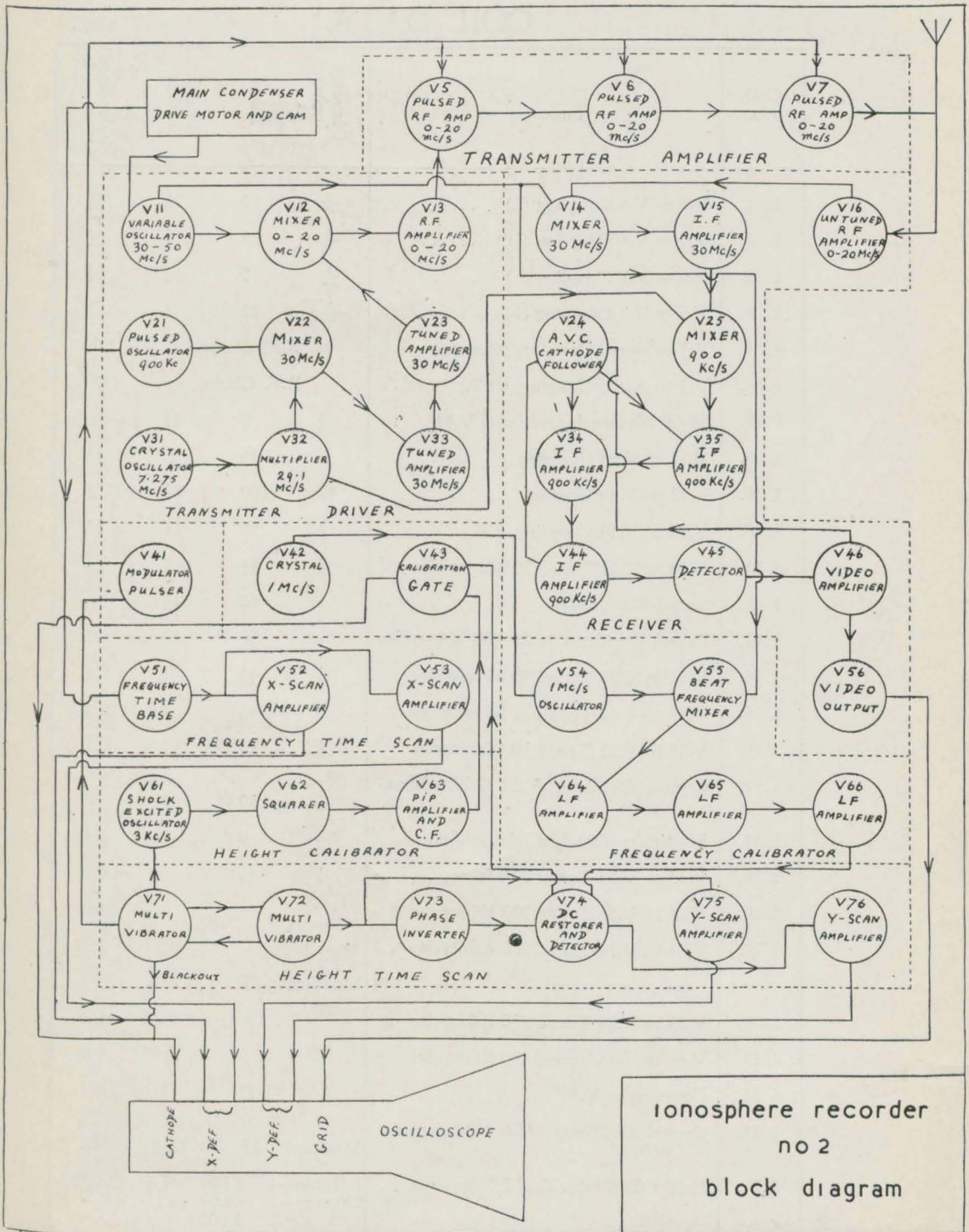
The main oscilloscope and clock assembly may be seen within the photographic box at the top.

Below are the various power circuits with the wiring facing outwards as on the other side.

The timing mechanism consisting of the cams and synchronous motor are seen mounted on a brass-plate on the right.

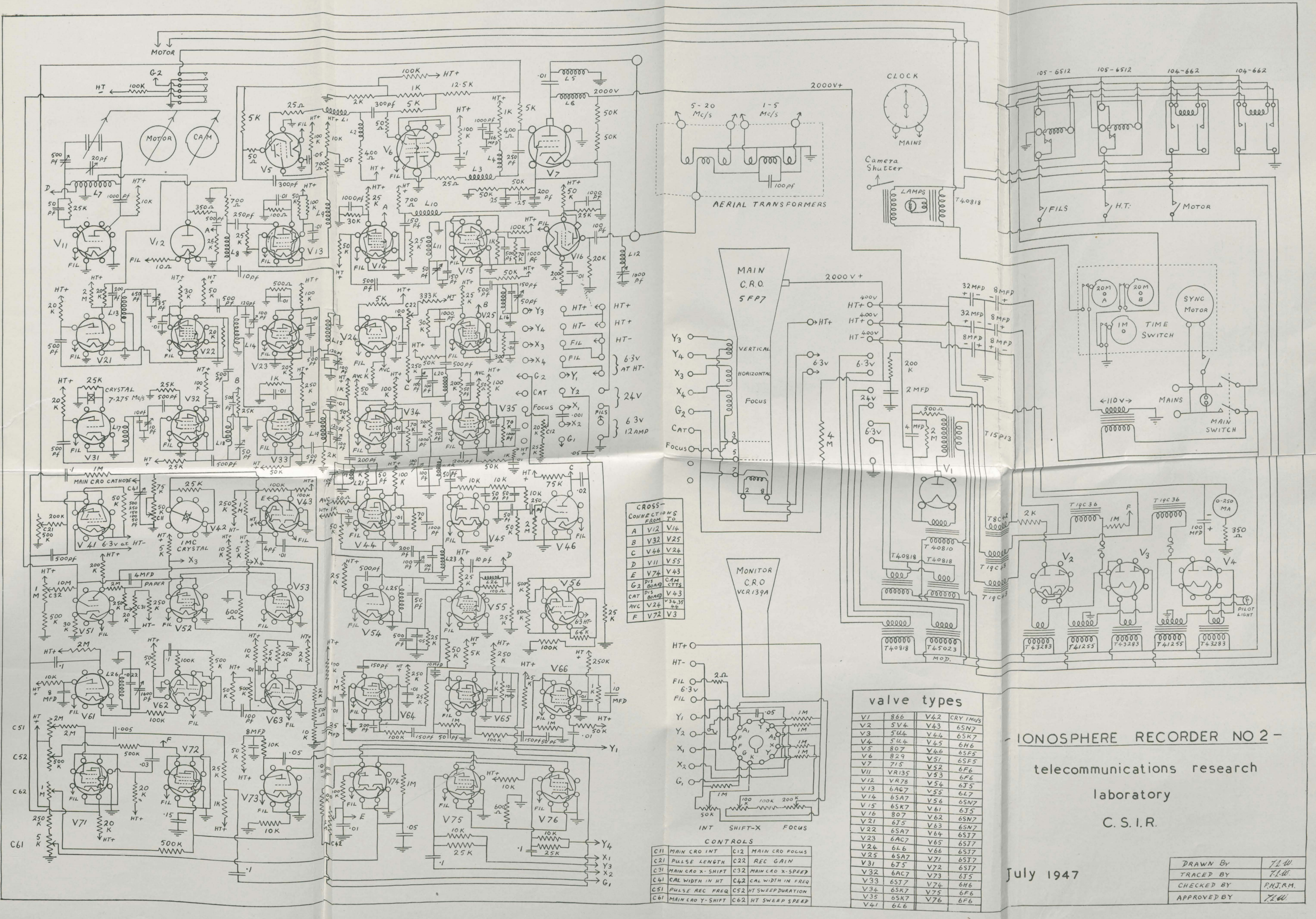
The high voltage rectifier and terminal board are mounted on the insulated board on the left.

The terminals to the rhombic aers may be seen on the aerial transformer box.



COIL DATA

Coil No.	Function	Diameter Inches	Turns	Length Inches	Inductance Microhenries
L. 1.	V.5 to V.6 Coupling (L)	$\frac{5}{16}$	50	$1\frac{1}{8}$	$6\frac{1}{2}$
L. 2.	V.5 to V.6 Coupling ($\frac{1}{2}$ L)	$\frac{5}{16}$	25	$\frac{1}{2}$	$3\frac{1}{4}$
L. 3.	V.6 to V.7 Coupling (L)	$\frac{5}{16}$	50	$1\frac{1}{8}$	$6\frac{1}{2}$
L. 4.	V.6 to V.7 Coupling ($\frac{1}{2}$ L)	$\frac{5}{16}$	25	$\frac{1}{2}$	$3\frac{1}{4}$
L. 5.	V.7 to Aerial Coupling (Ground) . .		R.F. Choke		2,500
L. 6.	V.7 to Aerial Coupling (H.T.)		R.F. Choke		1,000
L. 7.	30-50 Megacycle Oscillator V.11 . .	$\frac{1}{2}$	9	$1\frac{1}{2}$	0.3
L. 8.	V.12 to V.13 Coupling	$\frac{1}{2}$	36	1	11
L. 9.	V.13 to V.5 Coupling	$\frac{5}{16}$	100	$2\frac{1}{2}$	11
L.10.	V.16 to V.14 Coupling	$\frac{1}{2}$	36	1	11
L.11.	V.14 to V.15 Tuned 30 Megacycles . .	$\frac{1}{2}$	$4\frac{1}{2}$	1	0.1
L.12.	Aerial Wave Trap	1	60	$1\frac{1}{2}$	—
L.13.	Pulsed Oscillator V.21 900 Kilocycles	1	50	$1\frac{1}{4}$	50
L.14.	V.22 to V.33 Tuned 30 Megacycles . .	$\frac{1}{2}$	$4\frac{1}{2}$	1	0.1
L.15.	V.23 to V.12 Tuned 30 Megacycles . .	$\frac{1}{2}$	$4\frac{1}{2}$	1	0.1
L.16.	V.15 to V.25 Tuned 30 Megacycles . .	$\frac{1}{2}$	$4\frac{1}{2}$	1	0.1
L.17.	Crystal Oscillator V.31 7.275 Megacycles	$\frac{1}{2}$	30	$\frac{3}{4}$	—
L.18.	Multiplier V.32 29.1 Megacycles . .	$\frac{1}{2}$	9	1	0.4
L.19.	V.33 to V.23 Tuned 30 Megacycles . .	$\frac{1}{2}$	$4\frac{1}{2}$	1	0.1
L.20.	V.25 to V.26 Tuned 900 Kilocycles . .				166
L.21.	V.34 to V.44 Tuned 900 Kilocycles . .				166
		Modified	I.F.	Coils	
L.22.	V.35 to V.34 Tuned 900 Kilocycles . .				166
L.23.	V.44 to V.45 Tuned 900 Kilocycles . .				166
L.24.	Coupling to V.55	$\frac{5}{16}$	12	$\frac{3}{4}$	—
L.25.	Crystal Oscillator V.54 1 Megacycle/second		Modified	I.F.	Coil
L.26.	Height Calibrator Coil 3 Kilocycles . .		Inside—1 Outside—2	1,500 to 2,000 Full	$\frac{1}{2}$ 116,000



CROSS-CONNECTIONS FROM TO

A	V12	V14
B	V32	V25
C	V46	V24
D	V11	V55
E	V74	V43
G2	D13 BOARD	CAM CTS
CAT	D13 BOARD	V43
AVC	V24	V34-35
F	V72	V3

valve types

V1	866	V42	CRY 1Mc/s
V2	5V4	V43	6SN7
V3	5U4	V44	6SK7
V4	5U4	V45	6H6
V5	807	V46	6SF5
V6	829	V51	6SF5
V7	715	V52	6F6
V11	VR135	V53	6F6
V12	VR78	V54	6J5
V13	6AC7	V55	6L7
V14	6SA7	V56	6SN7
V15	6SK7	V61	6J5
V16	807	V62	6SN7
V21	6T5	V63	6SN7
V22	6SA7	V64	6SJ7
V23	6AC7	V65	6SJ7
V24	6L6	V66	6SJ7
V25	6SA7	V71	6SJ7
V31	6T5	V72	6SJ7
V32	6AC7	V73	6T5
V33	6SJ7	V74	6H6
V34	6SK7	V75	6F6
V35	6SK7	V76	6F6
V41	6L6		

CONTROLS

C11	MAIN CRO INT	C12	MAIN CRO FOCUS
C21	PULSE LENGTH	C22	REC GAIN
C31	MAIN CRO X-SHIFT	C32	MAIN CRO X-SPEED
C41	CAL WIDTH IN HT	C42	CAL WIDTH IN FREQ
C51	PULSE REC FREQ	C52	HT SWEEP DURATION
C61	MAIN CRO Y-SHIFT	C62	HT SWEEP SPEED

IONOSPHERE RECORDER NO 2 -
telecommunications research
laboratory
C. S. I. R.

July 1947

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VARIABLE-FREQUENCY CRYSTAL-CONTROLLED RECEIVERS AND GENERATORS

By T. L. Wadley

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VARIABLE-FREQUENCY CRYSTAL-CONTROLLED RECEIVERS AND GENERATORS

By T. L. WADLEY *

(This paper was presented to the Light Current Section of the Institute at a meeting on 11th August 1953)

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1. INTRODUCTION

The continually increasing use which is made of the limited radio-frequency spectrum has made increasing demands on the precision of radio equipment. In particular, the need for accurately controlling frequency has become necessary. The development of quartz crystal oscillators of high-frequency stability, for controlling the frequency of both a transmitter and the associated receiver to operate on a pre-determined channel, has provided an ideal solution.

However, for equipment in which flexibility of frequency is required, it has been usual to fall back on an *L.C.* oscillator, compensated for temperature. Using this technique it is difficult to meet modern requirements in respect of transmitter stability, and difficult in respect of receivers to exploit fully the selectivity of narrow-band filters. In addition, it is frequently necessary to provide auxiliary frequency-measuring equipment.

Various systems have been devised to apply the stability of crystal control to multifrequency equipment. Numerous crystals may be used directly or in various combinations. Such systems can become very complex when anything like complete flexibility is required, and are often confined to producing a number of fixed channels rather than a continuously variable device.

An attractive possibility is to make use of the harmonic spectrum of a single crystal. The problem is then to separate the required harmonic from the adjacent harmonics with sufficient suppression of the latter and to interpolate between the harmonics if necessary. One possibility is to synchronize an oscillator to the harmonic required. The ability of such an oscillator to remain locked to the required frequency depends upon the level of the synchronizing signal being high and its ability to discriminate against the adjacent signal depends upon the synchronizing signal being weak. These conflicting requirements make it impossible to design a satisfactory arrangement of this nature, without the use of something of the nature of an a.f.c. device which exploits the short-term stability of the tuned circuit. Difficulties then arise in ensuring that the device is brought into the required operating condition and remains there. It is also difficult to apply interpolation to such a system.

The basic problem of separating harmonics of this nature is one of filtering, however the selection may be performed. As in the case of the selectivity of a radio receiver, the solution to the basic problem lies in providing the necessary number of circuits in the filtering arrangements and, if necessary, in transforming the frequency at which the filtering is performed. The degree of adjacent channel suppression and width of filtering band may then be adjusted

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separately. This cannot be done with anything in the nature of a single circuit.

In the simplest arrangement a variable multi-element filter may be designed to cover the required range with the required bandpass, say, about equal to the spacing of the harmonics. The adjacent suppression required will then determine the number of elements.

By heterodyning the harmonic spectrum by means of a variable oscillator and mixer, the filter may be made of fixed frequency. The advantage of this heterodyning is two-fold, the filtering frequency becomes fixed and a more suitable choice of filtering frequency may be made. This is the basic principle of the devices which are to be described in this paper. This principle gives rise to harmonic-selecting devices to which interpolation between harmonics may easily be applied. The devices have effectively long scales, using mechanically simple dials. The calibration may be linear at all frequencies and the scales read directly in frequency. The principles may be applied to both frequency generators and receivers for a variety of purposes over any span of frequencies.

In the case of receivers the principle has been adapted to a multiple heterodyne receiver covering the span 0 to 30 Mc/sec based on a 1-Mc/sec crystal.

A generator based on the same principle covering 0 to 20 Mc/sec has been built based on a 100-ke/sec crystal.

2. GENERAL PRINCIPLES APPLIED TO GENERATORS

Fig. 1 refers to the general principle of selecting the harmonics.

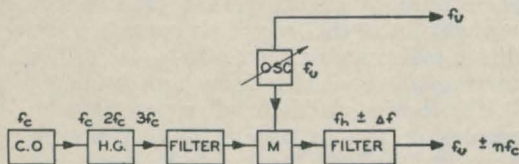


Fig. 1

The crystal oscillator of frequency f_c is followed by a harmonic generator which produces the harmonic spectrum $f_c, 2f_c, 3f_c$, etc., all of similar amplitude. The waveform of this spectrum is a short pulse of

recurrence equal to f_c and of duration less than a half cycle of the highest harmonic required. This is followed by a filter, which may be required to remove unwanted harmonics. The harmonic spectrum is then shifted in frequency by the mixer M_1 by means of the variable oscillator f_v and a harmonic which then lies within the band-

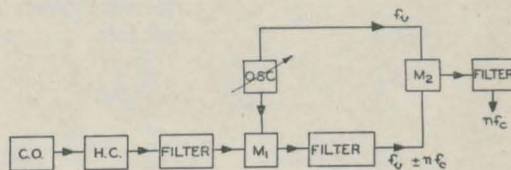


Fig. 2

pass of the filter in the mixer output is filtered out. The filter output is $f_v \pm nf_c$. The filtered harmonic thus occurs as the difference between this frequency and the frequency f_v of the variable oscillator. The harmonic which has been selected in this way may be made use of in a variety of ways.

In the simplest case the two frequencies f_v and $f_v \pm nf_c$ are applied to a second mixer M_2 as shown in Fig. 2 and the harmonic nf_c extracted by a suitable filter.

The choice of frequency to which the harmonic frequencies are heterodyned is determined by the following consideration. The number of filter sections required to produce a given suppression of the adjacent unwanted harmonic does not depend on the frequency chosen once the bandpass of the filter has been decided upon. This bandpass should be a large fraction of the harmonic spacing, perhaps even equal to the spacing, if the setting of the variable oscillator is not to be critical. The filter frequency may therefore be made as high as the circuit Q 's will allow and, if this frequency is made higher than the highest harmonic required, the image frequencies of the two mixers may be removed by low-pass filters, and the device will operate over as large a range as required by means of a single oscillator range.

To place the filter frequency within the harmonic range, or below the lowest harmonic required, would restrict the range of coverage to considerably less than a two-to-one interval if all filters were fixed or, alternatively, it would become necessary to make the two image filters variable and

ganged to the oscillator and perhaps switch ranges also, if a wide coverage were required.

In the devices to be described, a frequency higher than the highest harmonic is used for filtering with the advantages mentioned. Practical circuit Q 's limit the span of harmonics which can be selected to the order of 30 to 50 and perhaps 100 in the limiting case.

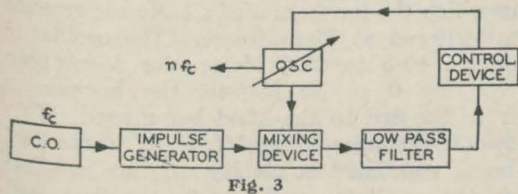


Fig. 3

This is sufficient for certain purposes and when a further subdivision of frequencies is required, methods of compounding the principle may be used as described later.

It is interesting to compare the system with the device known as the 'impulse-governed oscillator.'¹ The latter may be described as conforming to the general principle outlined above, in which the filtering frequency is centred around zero. This is shown in its simplest form in Fig. 3. The impulse generator following the crystal oscillator performs the same function as the harmonic generator, that is, produces a harmonic spectrum in which all harmonics are of similar amplitude. The oscillator to be impulse-governed corresponds to the variable oscillator. This is fed together with the impulse to the mixing device (phase discriminator) which corresponds to M_1 . The output of this, which in the steady state is at zero frequency, is fed via a quick-acting coupling circuit (low-pass filter of suitable cut off) to a control device which corresponds to M_2 in that it modulates (in the steady-state frequency controls) the oscillator. The advantage of the choice of zero as the filtering frequency is that in the steady state the image at the input to

the mixing device M_1 is coincident with the wanted channel, and the sidebands and the oscillator frequency in the output are coincident and therefore no input or output filtering is required or indeed possible. When the device is responding to disturbance of the oscillator constants, this coincidence breaks down but this is perhaps of no account. The bandpass of the coupling from the mixing device to control device determines the capture range in the same way as the bandpass of the harmonic filter determines the non-critical range of the variable oscillator and, similarly, a coupling from the mixing device to the control device, which is too fast-acting or which cuts off in frequency too slowly will result in the adjacent harmonics appearing in the output in strength, in the same way that they would occur as a result of too wide a harmonic filter or a filter with insufficient edge suppression. An advantage of the impulse-governed oscillator is that narrowness of the filter bandpass is not likely to be restricted by circuit Q 's and consequently a large number of harmonics may be selected in this way, although the range will be restricted to that of the oscillator unless it is bandswitched.

The above comparison is valid only in the steady state of the impulse-governed oscillator. In the state corresponding to the impulse-governed oscillator being unlocked, that is, when adjusted between harmonics, the system under discussion has no output. It is a passive device which has only one possible mode of operation for any adjustment.

The advantage of the system under discussion is that interpolation between the harmonics may easily be added as shown in Fig. 4. Furthermore, the harmonic which has been selected as in Fig. 1 may be applied to the control of a receiver indirectly without deriving the harmonic, to give certain advantages which will be described below.

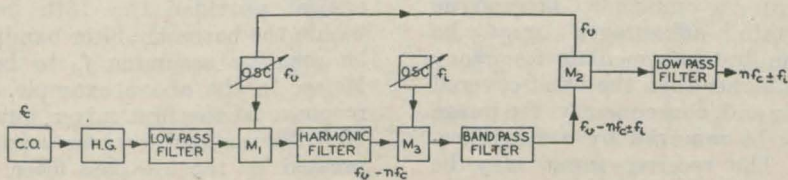


Fig. 4

Fig. 4 shows a mixer M_3 and interpolation oscillator of frequency f_i which shifts the frequency of the harmonic-filter output by a variable amount usually equal to the spacing between the harmonics. The following filter separates the shifted frequency from the other sideband and harmonic-filter frequency. The output of the device is then $nf_c \pm f_i$ depending upon which sideband is used.

All the filters in the system are fixed. The two variable oscillators are brought out to two dials, the calibration of f_v being in whole numbers intervals of f_c , and its setting to the required whole number need not be exact. The total scale length is the length of the interpolation dial multiplied by the number of harmonic intervals. The frequency scale on both dials may be made linear by quite easy shaping of the condensers, with the scale from zero to the required maximum.

The principle may be extended so that the interpolation oscillator f_i is replaced by a generator of the same nature as Fig. 4 in which all elements are of a correspondingly lower order and, if necessary, the process may be repeated indefinitely, say, on a decade system. The detailed design of such a system will be discussed later.

3. GENERAL PRINCIPLES APPLIED TO RECEIVERS

The generators described above may be used as the local oscillator of a normal heterodyne receiver, with obvious advantage to the stability and setability of the frequency scale. There is some difficulty in providing pre-selection in a receiver of this nature, unless the pre-selection is controlled separately from the main tuning, on account of the fact that the frequency law of the local oscillator is not suitable for ganging to *L.C.* circuits at the signal frequency, unless a somewhat complicated system is devised.

By integrating the general principles described with a multiple heterodyne receiver certain advantages may be obtained. The first intermediate frequency may be made higher than the band covered by the receiver and, consequently, the image response may be removed by a fixed low-pass filter. The receiver input may be aperiodic when this is desirable, otherwise

pre-selection may be provided in addition and switched in and adjusted separately.

The receivers to be described in this paper are of this nature. Figs. 5, 6 and 7 show three variations of the principle. That of Fig. 5 is considered the most useful and its design will be discussed in detail.

Referring to Fig. 5, the system in the dotted lines is seen to be that of Fig. 1 in which the harmonics of a 1-Mc/sec crystal are filtered at 37.5 Mc/sec. The oscillator covers 40.5 to 69.5 Mc/sec for a receiver covering 0 to 30 Mc/sec, the harmonics from the 3rd to the 32nd being used. The two frequencies, f_v and $f_v - nf_c$, instead of being combined to derive nf_c , are applied as the oscillator voltages to the first and second mixers of a multiple heterodyne. The first i.f. is 40 Mc/sec and has a bandpass somewhat wider than the spacing of the harmonics. The first mixer is preceded by a low-pass filter to remove the image response and the response to the 40-Mc/sec i.f. This is preceded by the necessary r.f. amplifiers and pre-selective circuits as required. The net effect of these two conversions is to transform the signal frequency by an exact integral number of Mc/sec. By way of example, consider a signal frequency say 15.4 Mc/sec. The 18th harmonic is used. f_v is set to 55.5 Mc/sec and the 18th harmonic is thus filtered at 37.5 Mc/sec. In the signal channel 55.5 Mc/sec heterodynes the incoming 15.4 Mc/sec to 40.1 Mc/sec which is within the first i.f. bandpass. The second conversion with 37.5 Mc/sec gives 2.6 Mc/sec. This is finally detected by a 2 to 3-Mc/sec interpolation receiver shown within the dotted lines. The signal frequency band 15 to 16 Mc/sec is transferred and actually inverted to 3 to 2 Mc/sec. This inversion is of no account and arises out of the fact that the harmonic-filter frequency is below the first i.f. This is done to avoid using the harmonic of zero order for the band 2 to 3 Mc/sec.

The setting of the oscillator f_v is not critical provided the 18th harmonic lies within the harmonic-filter bandpass, as may be seen by assuming f_v to be, say, 55.4 Mc/sec in the above example. The image response of the first mixer would be about 95.5 Mc/sec and can be adequately suppressed by the low-pass filter. The image response of the second mixer lies between

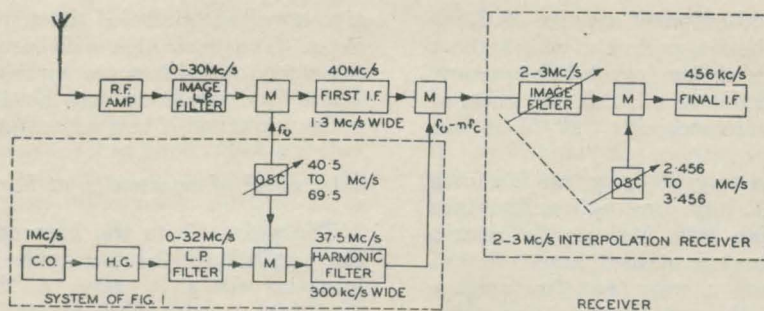


Fig. 5

34.5 and 35.5 Mc/sec and is removed by the first i.f. filter. The 2 to 3-Mc/sec interpolating receiver may be of any suitable design to give the final selectivity required. Its detailed design will be considered later. At this stage it might be noted that the final i.f. is open to choice and may be made as low as necessary, say, 100 kc/sec. This is

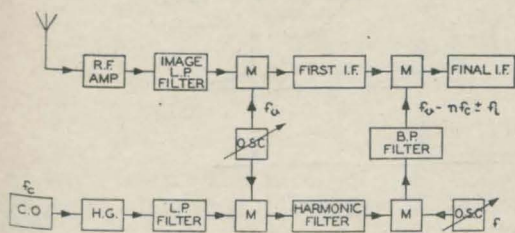


Fig. 6

an advantage shared with most multiple heterodyne receivers. The interpolation receiver may itself be a receiver of the nature of the whole of Fig. 5 of a lower order of frequency, if a finer degree of control is required, or the oscillator of the interpolation receiver may be a generator of the type described previously.

The receivers of Fig. 6 and 7 are variations of the receiver of Fig. 5. Fig. 6 may be described as a double heterodyne to which the interpolation arrangement of Fig. 4 has been applied. It has the disadvantage that the final i.f. must be considerably more than half the harmonic interval, that is, 500 kc/sec unless the first i.f. is narrow and variable. Even with a high final i.f. the design of the first i.f. for image protection of the second mix is difficult. The receiver of Fig. 7 may have a fairly low final i.f. as the second i.f. filter may be made as narrow as the harmonic filter but it is more than likely that harmonics of the interpolation oscillator in the signal channel would give trouble. The receivers of Fig. 6 and 7 will not be discussed further. That of Fig. 5 will form the basis of a detailed discussion.

4. DESIGN OF HARMONIC GENERATORS

Before dealing with the receiver in detail the design of the harmonic generators which is common to all equipment of this type will be discussed. To produce the harmonic spectrum with all harmonics approximately equal in amplitude requires

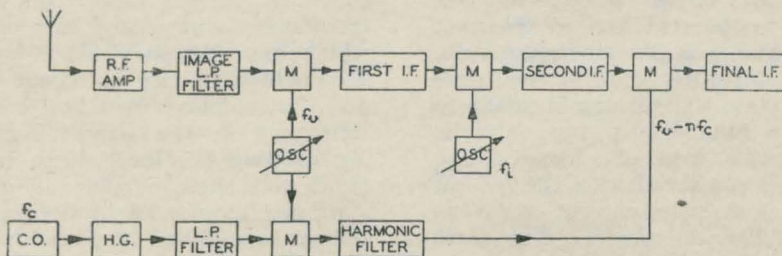


Fig. 7

in effect the production of a pulse of duration less than half a period of the highest at a recurrence of the crystal frequency. For the receiver described, this is a pulse of about 0.01 microseconds at 1-Mc/sec recurrence.

A very simple way of doing this is shown in Fig. 8. A high mutual-conductance pentode is driven from a sinusoidal source of sufficient swing via a short time-constant coupling, in such a way that the voltage passes through the grid base of the valve at the highest rate of change of the voltage wave. This corresponds to the point when $V \sin 2\pi f_c t$ is zero and the rate of change is $2\pi f_c V$ volts/sec. A peak voltage of, say, 50 volts gives a rate of change of

give a voltage pulse of the required dimensions. The back kick will be quite small if the screen constants are correctly adjusted. There is a tendency for the 4th harmonic to be weakened if this adjustment is wrong.

4.1 Level of harmonics at harmonic mixer

The pulses from the harmonic generator are applied to the harmonic mixer via a low-pass filter to remove the harmonic spectrum above the wanted maximum. The impedance of this filter should be higher than the impedance of the differentiating inductance at the highest frequency. This usually presents no problem as the pulse can in general be made at a far higher

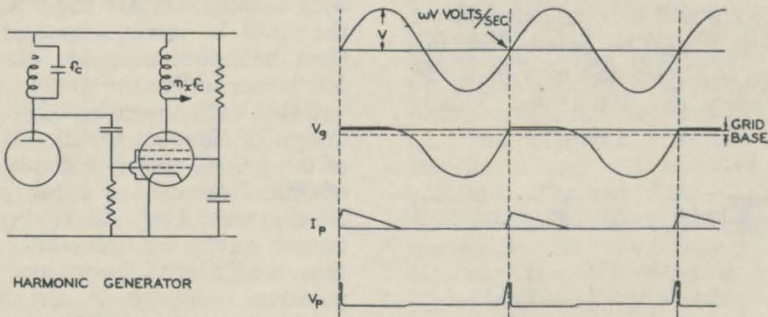


Fig. 8

3×10^8 volts/sec which would cause the grid voltage to swing through a grid base of 3 volts in 0.01 microsecond. The time constant of the grid circuit is adjusted to achieve this, a time constant of about one-fifth of the period being required. Values of 10 pf and 22 000 ohms are approximately correct for a 1-Mc/sec spectrum. After sweeping through the grid base the grid draws current for about a quarter cycle after which the valve cuts off relatively slowly at the peak of the voltage wave but returns again to the grid base at the next instant the wave is at its maximum rate. By suitably adjusting the screen time constant, the plate current can be made to cut off slowly immediately the valve is switched on, this rate of change being negligibly small compared with the rate of switching on. A plate-current wave as shown in the diagram results. The plate load is made inductive and this results in the differentiation of the current wave to

level than is required and kept suitably small by reducing this inductance, although in a receiver it is perhaps better to make the inductance a maximum and reduce the level by reducing the screen voltage of the harmonic generator, in order to avoid producing a higher harmonic current which may couple into the signal circuits.

The level of the pulse at the mixer grid must not be more than about one-third volt otherwise the non-linearity of the grid characteristic will distort this pulse and reintroduce the unwanted harmonic spectrum which the low-pass filter has removed. This will give rise to image components and harmonics at the harmonic-filter frequency in the harmonic-filter output. By keeping the level down to, say, one-third volt these effects will give rise to spurious frequencies in the harmonic-filter output some 60 to 70 db below the wanted harmonic. Reducing the level below one-third volt would improve this effect

but would give rise to spurious noise frequencies for the following reason. For the case of 30 harmonics, one-third volt pulse level corresponds to harmonics of about 10 millivolts each at the mixer grid. The equivalent noise level at the grid of a mixer of the type used, usually a pentagrid or similar, is a few microvolts, referred to a bandpass of, say, 10 kc/sec, which is representative of the final bandpass in which these effects will be observed in an average case. This noise level is thus some 70 db down on each harmonic and therefore the one-third volt level of the pulse represents a compromise between these two effects.

A conversion gain of 100 or more is required from the grid of the harmonic mixer to the output of the harmonic-filter circuits to produce a signal of useful level

are required to attenuate is well removed from their cut-off frequency. Resonant sections may be used when these frequencies cannot be well separated, although in general an extra section or two is preferable to an extra tuning adjustment. At frequencies up to about 30 Mc/sec satisfactory low-pass filters may be made with surge impedances up to 1 000 ohms using valve capacities only at the ends.

The bandpass filters required are usually fairly narrow compared with their centre frequency. This requirement can be most easily met by a number of inductively coupled circuits as shown in Fig. 9. These tuned circuits are inductively coupled to the adjacent coils only. Coupling to other sections is avoided by enclosing the filter in a screening tube, or long box of such a

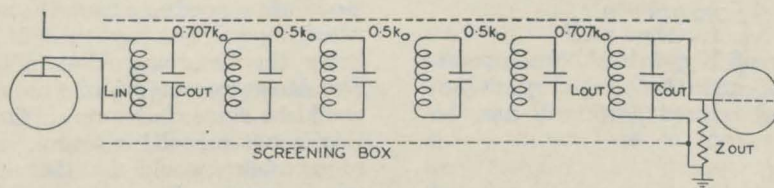


Fig. 9

in most cases. This involves perhaps two amplifiers following the mixer at higher frequencies and perhaps one at lower frequencies.

To reduce the effect of the reformed harmonic spectrum at about the harmonic-filtering frequency and also to simplify the design of the low-pass filter, the harmonic-filtering frequency can with advantage be placed between two harmonic frequencies, for example, 37.5 Mc/sec in the case of the receiver of Fig. 5.

4.2 Design of filters

Efficient filtering is essential at all stages of these devices. The degree of filtering required is often more than can be provided by simple coupling circuits, say, a coupled pair of tuned circuits between two mixers, particularly in cases where no amplifier is required between such mixers. In these cases multi-element filters are required with from perhaps four to seven sections.

Low-pass filters may be of the simplest type if the lowest frequency at which they

cross-section that the wave attenuation down it is high. This is achieved by making the cross-sectional dimensions comparable with the coil spacing. The attenuation of such a filter to frequencies well away from the operating frequency is extremely high, the effect of stray modes of coupling being small. This is important in the case of receiver designs as will be explained below.

Electrical design details for these filters are as follows:—

$$\text{If } k_0 = \frac{\text{bandpass}}{\text{centre/frequency}}$$

then end sections are coupled $0.707 k_0$ and intermediate couplings are $0.5 k_0$

$$Z_{in} = \frac{Z_{Cin}}{k_0}; \quad Z_{out} = \frac{Z_{Cout}}{k_0}; \quad \text{voltage transformation} = \sqrt{\frac{Z_{out}}{Z_{in}}}$$

where $Z_{Cin} = Z_{Lin}$ at the centre frequency.

The filter is terminated in a resistance $= Z_{out}$.

The input and output sections may be of any suitable impedance to meet the valve requirements. The intermediate sections may be any impedance provided the coefficient of coupling to adjacent sections is as shown. All coils should have as high a Q as possible to minimize insertion loss but in any case must have a Q greater than $\frac{2}{k_0}$.

More complicated filter designs can result in some economy of components but often require special care in adjustment. In the case of bandpass filters in which the band is wide relative to the centre frequency, more involved designs must be resorted to but, for most purposes in these applications, the above filters have proved simple and satisfactory.

5. DETAILED CONSIDERATION OF RECEIVER DESIGN

The receiver of Fig. 5 has been investigated in detail and the necessary design precautions and requirements will now be discussed.

5.1 Selection of frequencies and filter performance required

The range covered (0 to 30 Mc/sec) represents the requirement of a general purpose short-wave receiver. The band 0 to 1 Mc/sec is included although the filtering arrangements have broken down as will be explained later but, nevertheless, its inclusion is quite useful. No attempt, however, is made to provide high performance at these low frequencies.

The first i.f. is 40 Mc/sec. This is well removed from the top r.f. frequency of 30 Mc/sec and the signal-image filter can be easily designed to have at least 60-db suppression at 40 Mc/sec. Its bandpass of 1.3 Mc/sec is designed to accommodate the 1 Mc/sec-wide signal channel plus 300 kc/sec tolerance for the setting of the first oscillator.

The harmonic-filter frequency of 37.5 Mc/sec is below the first i.f. and the harmonics 3 to 32 are used. Placing this frequency above the first i.f., that is, 42.5 Mc/sec, would involve the use of the harmonics -2, -1, 0, 1, 2 up to 27 Mc/sec. Some difficulty then arises in separating the first harmonic from that of order zero, that is, the oscillator frequency. The

oscillator is very much stronger than each harmonic at the harmonic mixer unless a balanced mix is used. In this case the difficulty, although relieved, would still exist.

The harmonic-image filter must pass 32 Mc/sec and suppress 37.5 Mc/sec by some 60 db. Some further protection against 37 and 38 Mc/sec is provided by the choice of 37.5 Mc/sec as the filtering frequency. This image filter is not quite as easy as the signal-image filter as the frequencies involved represent the minimum for a simple low-pass design for reasonable number of sections. Hence the original choice of 40 Mc/sec for the first i.f.

The choice of interpolation frequency 2 to 3 Mc/sec arises from a number of reasons. The possible alternative 1 to 2 Mc/sec would give trouble with intermodulation products from the second mixer, which may exist up to 1.3 Mc/sec, this being the bandpass of the first i.f. filter. The image protection of the second mixer would be somewhat more difficult although this is not a real limitation. The severest requirement would be the adjacent harmonic suppression required from the harmonic filter, as these harmonics would have to be down some 120 db at least on the required harmonic otherwise they would demodulate against the required harmonic to give a blocking signal at one end of the interpolation scale. With the interpolation frequency 2 to 3 Mc/sec the adjacent Mc/sec harmonics need only be down some 60 to 80 db to avoid the formation of spurious channels on adjacent r.f. signals removed 1 Mc/sec from the main signal. These channels receive a further slight protection as they exist outside the edge of the first i.f. filter. The harmonic-filter suppression at the harmonic two removed from the required harmonic must then be down some 120 db or more and this can be achieved fairly easily.

The choice of interpolation frequency 1.5 to 2.5 Mc/sec is possible but would lead to less elegant scales.

The final i.f. frequency in this design was chosen as 456 kc/sec simply to make use of standard i.f. transformers. In this case two loosely coupled circuits at the 2 to 3 Mc/sec image filter are sufficient to make the image due to the final mix down some 70 db. A standard three-gang condenser is used in

the interpolation section for this purpose. The interpolation oscillator frequency coverage follows from the above.

There are a multitude of other possible designs for the interpolation section. Two of these may be mentioned. A final i.f. of 750 kc/sec or so would enable a fixed 2 to 3 Mc/sec image filter to be used, with possible advantage in, say, a panoramic receiver with a 1-Mc/sec display. Some trouble would perhaps arise with intermodulation products in the third mixer. The other possibility is to use a lower i.f. of, say, 100 kc/sec with its obvious advantages, although this would involve perhaps three sections of image protection at the 2 to 3-Mc/sec filter.

The design of the first i.f. filter is usually set by the requirement that it must effectively prevent the first oscillator voltage appearing in the second mixer on the band 1 to 2 Mc/sec, that is, when the first oscillator is set to 41.5 Mc/sec approximately. This cannot be done on the band 0 to 1-Mc/sec as the first oscillator at 40.5 Mc/sec then lies within one edge of the first i.f. filter. This explains the remarks on this point referred to above. This effect gives rise to spurious signals on this band but the band is nevertheless included in this design for what it is worth. The effect may be minimised by a balanced first mix, although this was not done in the design under discussion. For the band 1 to 2-Mc/sec this suppression at 41.5 Mc/sec should be as high as is economically practical, say, about 40 to 60 db down. If this requirement is met, other requirements of this filter, that is, image protection of the second mixer will be more than adequate.

5.2 Spurious signals

The generation of spurious signals is a feature of all multiple heterodyne receivers which must be carefully considered in the design of such receivers. In addition to these other spurious signals peculiar to the receiver under discussion must be guarded against.

The most common source of these signals arises from the fundamental or harmonics of any one oscillator breaking into any mixer other than that with which it is associated, to heterodyne with the fundamental or harmonics of the oscillator

associated with this mixer to give a frequency equal to that to which the following circuits are sensitive. The combinations in which these can exist are almost without number and the harmonics concerned often extend into the hundreds and even thousands of Mc/sec. The level at which these signals can cause trouble can be of the order of microvolts or less, at the mixer concerned.

These spurious signals can be completely eliminated once their cause is fully understood. The first requirement is that each oscillator and its associated mixer be placed, together with any amplifier and components associated with the input or output in a separate screened compartment. Secondly, these compartments must be connected via the necessary filters which transmit only the band of frequencies required. Spurious modes of coupling between the elements of the filter must be avoided. For instance, an ordinary i.f. transformer can have a spurious mode of coupling which constitutes a high-pass filter to some very high frequency in which the shunt inductances of the condenser leads are coupled via stray capacity. The screened multi-section filters described in paragraph 4.2 are very effective in eliminating such effects. Thirdly, the power leads to each compartment must be filtered by single-section low-pass filters, with particular attention to the very high frequency efficiency of such filters.

The first and second mixers of this receiver are more susceptible to this trouble than the third mixer as their oscillator frequencies are of the same order. Nevertheless, in this receiver, a spurious mode of coupling from the second to third mix arose due to a parallel resonance of the fixed capacity on the 2 to 3-Mc/sec variable condensers, with the inductance of the rotor and stator plates, to give a band-pass coupling with stray capacities to 37.5 Mc/sec in a certain position of the plates. This 37.5 Mc/sec gave spurious signals in the third mix with a harmonic between the 11th and 16th of the interpolation oscillator. Re-distribution of the components to give a low-pass mode to the spurious coupling removed the trouble.

These spurious signals, if they do occur in this receiver, can always be shifted away from the channel to which the receiver is tuned by a re-setting of the first oscillator.

A more difficult sort of spurious signal peculiar to this receiver occurs at the zero and 1 000-kc/sec mark on the interpolation dial. This can arise from a number of causes although the effect is the same. Firstly, inadequate performance of the harmonic filter at the second and third harmonic removed from the wanted harmonic as explained in section 5.1. This can occur as a result of bad bonding of the longitudinal joints of the filter screen, destroying the wave-attenuating property of the screen, even although the design of the filter is adequate. A second cause is direct leakage of the second and third harmonic from the crystal oscillator and harmonic generator section into the third mix. This is unlikely with good power filtering and general screening. A third cause is direct leakage of the harmonic spectrum into the input of the receiver or first mixer. The same remark applies to this. Fourthly, the harmonic spectrum can couple into the first mix via the harmonic mixer as they are fed from the same oscillator. This effect can cause considerable trouble in the design. Its elimination requires the use of a pentagrid mixer for the harmonic mixer, with small coupling between grids, and electron coupling with a broad-band circuit from the plate of the first oscillator to the harmonic mixer whilst the signal mixer is supplied from the oscillator tuned circuit in the cathode. Fifthly, the frequency components 39.5 Mc/sec and 40.5 Mc/sec which are generated in the harmonic mixer can couple into the first i.f. filter or first mixer. This can be eliminated by the measures under case four and by avoiding coupling between the input of the harmonic-filter and the first i.f.-filter.

When all these points have been attended to, this source of trouble disappears with the possible exception of direct break through from the crystal oscillator when the receiver is set to 1 Mc/sec.

5.3 *Spurious channels*

Spurious channels of the nature of true image channels arising at any signal mixer can, in this receiver, be reduced to negligible proportions and are usually difficult to detect at all. Spurious channels can also arise due to the spurious frequency com-

ponents in the output of the harmonic filter as explained in Section 4.1. These channels, which arise in the second mix, will be as much down on the main channel as these spurious frequencies are down on the wanted harmonic, that is, some 60 to 70 db. These channels move with respect to the main channel as the first oscillator is displaced. This, in fact, applies to any spurious effect in either the first or second mixer with the exception of cross-modulation effects in so far as a shift of the first oscillator constitutes a shift of the first i.f., without any corresponding shift of the main channel. These remarks, however, do not apply to any effect in the third mixer, for example, direct-image or second-harmonic conversion.

A broad noise channel can also occur as a result of the noise components of the harmonic filter which will also be down some 70 db on the main channel.

5.4 *Cross-modulations, intermodulations and levels*

It is often convenient to work the input stages of this receiver aperiodic when conditions permit. This is particularly attractive in this receiver due to lack of image troubles. Also with modern valves quite satisfactory noise figures can be obtained for this purpose. Aperiodic or alternatively wide-band pre-amplifiers are often used extensively in suitably sited receiving stations, and hence favour the use of an aperiodic input.

The design of the receiver for this purpose must be considered particularly in regard to cross-modulations and intermodulations as affected by the level at which each mixer works.

Intermodulations are unlikely to arise at the third mix on account of the frequency bands involved, nor are they likely at the second mix for the same reason explained in Section 5.1. They will, however, occur at the first mixer when the input is a periodic. Cross-modulations, except adjacent channel cross-modulation, is unlikely at the third mix on account of the relatively narrow band of the 2 to 3-Mc/sec image filtering, more likely at the second mix on account of its wider band of 1.3 Mc/sec and will occur at the first mixer as a result of any very powerful transmission in any part of the spectrum.

The third mix may therefore be at relatively high level, that is to say, a reasonable gain may be provided from second to third mix although, of course, no amplifier is called for. The first and second mix should, however, work at as low a level as possible. Again very little more than unity should be provided from the first mix to the second mix. This can be simply met as the bandpass filter has a fairly low impedance for the bandpass required and little gain is possible. The r.f. gain should be must sufficient for the r.f. tube noise to over-ride all the following mixers. High mutual-conductance tubes are used for the r.f. stage, which has a gain of about 4, and also for the first and second mix which consequently have relatively low noise levels. The third mixer is a pentagrid.

The equivalent noise resistance of the whole chain is about 2 000 ohms, that of the r.f. tube itself being about 1 200 ohms. Noise figures with the input aperiodic can therefore, with a 400-ohm input, be better than 10 db at all frequencies.

5.5 R.F. tuned circuits

Some degree of r.f. pre-selection must be provided for general purpose use on account of cross-modulation and intermodulation effects. Intermodulation products must give rise to the first i.f. of 40 Mc/sec approximately and, in general, the two r.f. frequencies which might cause intermodulation are well removed from each other, except when both are in the region of 20 Mc/sec. A high degree of pre-selection is therefore not necessary on this account, if it can be assumed that field strengths at 20 Mc/sec are rarely excessive.

The difficulty of ganging in pre-selection has been mentioned in Section 3. In the design under discussion a single-stage of pre-selection is provided in the grid of the r.f. amplifier only. This requires no ganging on a second section and consequently can be peaked for maximum performance in much the same way as an aerial trim adjustment. This tuned input also enables the noise figure to be brought near the thermal limit at any suitable input impedance. A noise figure of about 2 or 3 db is achieved at the lower frequencies and about 6 db at the highest.

On account of cross-modulation effects, more pre-selection would perhaps be desirable, although the complication would be increased. The cross-modulation performance of this receiver at frequencies well removed from the main channel is worse than a receiver with more pre-selection, although its performance for near channel cross-modulation is perhaps better than most, as most receivers tend to have excessive r.f. gain at some parts of the band. The problem of cross-modulation can be very troublesome under circumstances where it is essential to work transmitters and receivers in close proximity. This problem often calls for special pre-first stage tuners of involved design. As a precaution against the receiver becoming unworkable in a strong wanted or unwanted field, an aerial attenuator has been included. This is apparently a modern practice. Its use of course will lower the noise figure but this often is of no account when external noise and interference is high or signals are strong.

5.6 Overall performance of receiver

The overall performance of the receiver which has been described is as follows:—

Coverage—0 to 30 Mc/sec with the band 0 to 1 Mc/sec included, although the performance on this band is not equal to that on the rest of the coverage.

Stability—From cold to 2 hours after switching on, the drift is not more than 200 cycles/sec at the lower frequencies and 500 cycles/sec at the highest frequency

Stability—Frequency scales linear and settable to 1 kc/sec at any frequency

Spurious signals—Not higher than the internal noise except the breakthrough of the crystal at 1 Mc/sec

Spurious channels—All image channels and other spurious channels down at least 60 to 70 db on the main channel

Sensitivity—10 db or better with the input untuned at an impedance of 400 ohms.

With the input tuned at 70-ohms impedance the sensitivity is 2 to 3 db at the lower frequencies and 6 db or better at the highest frequency.

With an interpolation coverage of 1 to 2 Mc/sec the harmonic filter 1 at 43.5 Mc/sec follows, as does the first oscillator coverage. The harmonic series 2 to 21 Mc/sec is used as a result. This is an advantage of a 1 to 2-Mc/sec interpolation as against a 0 to 1-Mc/sec interpolation, as the first harmonic, which is difficult to separate from the oscillator frequency is avoided. A further advantage is that any given output frequency is derived from a harmonic differing at least 1 Mc/sec from it. Otherwise the output may equal or differ very little from the original harmonic used with possible trouble due to the output leaking into mixer 1 which works at a fairly low level, that is, about 10 millivolts. A further advantage is that it avoids the harmonic-filter frequency lying within the band of filter 3 with possible coupling trouble.

In the second section the harmonic spectrum 18th to 37th of 50 kc/sec is used which, together with the oscillator 3 covering 100 to 150 kc/sec, gives the required interpolation 1 to 2 Mc/sec. The oscillator 3 is made 100 to 150 kc/sec rather than say 50 to 100 kc/sec to avoid any harmonic lying within its span, that is, second harmonic of 50 kc at 100 kc/sec. The mix at mixer 3 is a subtraction to help lower the harmonic order used. Filter 5 is nominally 2 Mc/sec and oscillator 2 nominally 3 to 4 Mc/sec, the small discrepancy arising from incidental causes. The harmonic filter 4 frequency of 2.175 Mc/sec follows from the above. This frequency is as before placed between two harmonics, hence the odd figure and part of the above discrepancy. This harmonic filter frequency is rather close to the top harmonic frequency of 1.850 Mc/sec and consequently the harmonic low-pass filter design is near the limit. The frequency of filter 2 follows.

6.3 Levels and spurious signals

The same considerations apply to the level of each spectrum at each harmonic mix as in the case of the receiver. The level of each feed to a mixer which is at a lower frequency than the following filter must not be too high, to avoid harmonics of this feed appearing in the following filter. This applies to oscillator 3 into mixer 3, filter 5 into mixer 4, and oscillator 2 into

mixer 5. In all these cases the harmonic order involved is quite high and no great difficulty is experienced in this respect, as long as this possibility is appreciated and also suitable valves are used, for example, pentagrids or similar.

6.4 Filters and screening

The screening requirements are not as severe as in the case of the receiver as all circuits work at fairly high level. All filters are screened and are of the nature described in Section 4.2. Harmonic filters consist of six sections and all other filters five sections.

6.5 Overall performance

The output of the device with the necessary output amplifier is about 1 volt at 70 ohms. The overall stability equals that of the crystal itself at any frequency above about 1 Mc/sec. It operates quite effectively down to zero frequency and the interpolation scale may be checked by a zero beat with all dials at zero, and also at the other end of the scale at minus fifty and plus fifty on the last two dials.

All scales are linear, the minor divisions being 250 cycles at any frequency. The readability of dials is perhaps 50 or 100 cycles.

Spurious output frequencies are down 60 db on the main signal in respect of all components away from the main signal and 70 db or more on components which may beat with the main signal. The noise level is also some 70 db down, referred to a 10-kc/sec bandpass.

6.6 Contemplated design

The above design is somewhat complicated for transmitter drive purposes. A simpler design of a one-stage generator is contemplated of the nature of Fig. 4, in which the coverage is 2 to 5 Mc/sec based on a harmonic spectrum of 100 kc/sec. The stability of such a system could perhaps be very nearly that of the crystal, the interpolation oscillator being 200 to 300 kc/sec. On the grounds of stability it is possibly uneconomic to go further than this, but on the grounds of readability of scales a factor of about 8 would be lost compared with the above generator when deriving a frequency

near 20 Mc/sec, that is, the interpolation dial would lose a factor of 2 and a multiplication of 4 would be required in the transmitter.

The harmonic-filtering frequency would be in the region of, say, 7 Mc/sec, with a bandpass of, say, 50 kc/sec. This design is perhaps a bit difficult but modern core materials should ease this difficulty. The possibility of a spurious mix of the second harmonic of the harmonic-filter frequency would have to be taken into account as mentioned in Section 6.2.

The setting accuracy could be allowed for in the following manner. An auxiliary interpolation oscillator of no great stability could be switched into circuit in place of the interpolation oscillator, while the output of the whole device is used to set the frequency of the main interpolation oscillator on, say, the tenth harmonic of the latter. For example, to set up, say, 3.456 700 Mc/sec, the interpolation oscillator must be set to 256 700 kc/sec. If the whole instrument with the aid of the auxiliary oscillator be set to generate 2.567 Mc/sec, the zero beat with the tenth harmonic of 256 700 kc/sec may be used to set the main interpolation oscillator with the aid of a build-in detector and phone jack. The main interpolation oscillator is then switched back and the first dial set to 3.4 Mc/sec. This system would of course be of no assistance in checking the frequency while the trans-

mitter is running but could be done at any time the transmitter is idle.

7. CONCLUSION

Problems of adequate frequency control of flexible equipment to meet modern requirements are continually confronting the radio engineer to-day. The methods described are capable of easing these problems, although the exact form in which they should be applied to any particular requirement requires further investigation. The technique is not easy but none of the associated problems are insuperable. Equipment employing these methods can be mechanically simple and robust and are extremely simple to operate efficiently. The difficulties of their design they share with all other methods directed to the same ends.

8. ACKNOWLEDGMENT

The author wishes to thank the Council for Scientific and Industrial Research for permission to present this paper and to demonstrate the equipment.

9. REFERENCE

1. Impulse governed oscillator. *Philips Transmission*, Century House, Shaftesbury Avenue, London.

DISCUSSION

A. BIRRELL (Associate Member): The application of the principles described by Mr Wadley makes possible the design of a receiver which possesses ideal characteristics for communication purposes:—

- a High accuracy of frequency setting
- b High stability (virtually crystal stability)
- c Continuous frequency coverage without bandswitching
- d Constant calibrated bandspread of 1 Mc/sec.

Other receivers are available in which these characteristics are obtained by the use of multiple crystals and considerable mechanical and electrical complexity. The simplicity of Mr Wadley's receiver from a manufacturing and maintenance point of view compared to such receivers is a revelation.

For the specialized diversity receivers employed on commercial radio telephony and telegraphy circuits it is felt that the application of the frequency generator as the first heterodyning oscillator of the receiver, is preferable to the application of the principles outlined, directly to the receiver.

It is in the application to transmitter frequency control, as a frequency generator that these principles are likely to be most valuable. The international frequency tolerance generally applicable to services operating between 4 000 and 30 000 kc/sec is ± 30 parts in 10^6 . While stability much greater than this can be achieved by the use of crystal control the difficulty of producing crystals whose specified frequency is well within this tolerance (say, ± 15 parts in the 10^6) is difficult and expensive.

Some interesting monitoring records compiled during 1950 and 1951 by the British Post Office revealed that in 1950, 46.9 per cent of all stations checked showed departures greater than ± 30 parts in 10^6 from nominal frequency, and that for 1951 this was 43.7 per cent.

The required bandwidth for teleprinter operation on frequency shift keying at 20 Mc/sec using a deviation of 425 c/sec is 1 870 c/sec plus the tolerance of 1 200 c/sec. It is probable that in the future a further decrease in tolerances is likely for the efficient utilization of the frequency spectrum. This would require still more accurate control of transmitter and receiver frequency stabilities.

Modern transmitters are usually self-contained with crystal oscillators having ten switch-selected crystal frequencies. This is very inflexible on a large station, and with the present scramble for frequencies it is essential that when a clear frequency has been found by monitoring, it should be immediately occupied. This is not possible with fixed crystal control. In an attempt to solve the first difficulty, the British Post Office have developed an extremely simple aperiodic crystal oscillator, which uses crystals produced to a very rigid specification and which without temperature control can meet a tolerance of ± 15 parts in 10^6 . These oscillators are provided in centralized banks on the basis of one per registered station frequency and are fed by coaxial cable to any desired transmitter. The second problem of a variable oscillator of high stability is under consideration by the British Post Office. A prototype generator requires common equipment producing some 37, frequently oddly related frequencies from a standard source of 100 kc/sec. These frequencies are fed into five modulators to produce any integral multiple of 4 kc/sec between 3 and 7 Mc/sec with interpolation of 4 kc/sec provided by a variable oscillator. The disadvantages of this system are—

- a physical size and complexity of the equipment
- b the fact that the frequencies are not built up according to a simple system, and require the use of decade switches which are set up to indicate the desired frequency, and indicate the mixing fre-

quency inputs to the various modulators on a lamp display panel. These frequencies are then fed into the five modulators for the synthesis of the desired frequency. The interpolation oscillator is set up to interpolate the final 4 kc/sec.

A commercially available variable oscillator uses twelve crystals and an interpolation oscillator covering 150 kc/sec to give a continuous coverage from 3.45 to 6.9 Mc/sec by using the upper and lower side bands generated with each crystal frequency.

Other systems of frequency synthesis exist, but generally suffer from complexity, and the fact that the setting up procedure is not direct.

The essential simplicity of a frequency generator operating on the principles outlined by Mr Wadley, and covering from 2 to 7 Mc/sec with a first 100 kc/sec harmonic selection dial and a second dial interpolating 100 kc/sec is obvious when compared with the systems mentioned above. Adequate stability could be obtained by overing the interpolation oscillator and using a high-stability 100 kc/sec master frequency for the whole station. The setting-up accuracy could be ingeniously obtained as outlined in the paper, without necessity for high calibration accuracy of the interpolation oscillator, or by the use of a separate frequency generator to check the tenth harmonic of the interpolation oscillator. The latter method would seem to be preferable for a large station as it would also allow for the checking of the frequency during operation. Such an oscillator could also be readily applied to the control of commercial diversity receivers. The restriction of the range to 7 Mc/sec which is approaching the design limit for a 100-kc/sec harmonic series would be no disadvantage, as frequency doubling and quadrupling is common in such receivers, and also in most transmitters, to restrict the crystal frequency range when crystal frequency control is employed.

A duplicate of the prototype receiver constructed at the Telecommunications Research Laboratories by a post office engineer under Mr Wadley's supervision, has been in use for about two years. This receiver with its high setting accuracy

compared to conventional receivers, has proved invaluable on our commercial services as a check receiver, and we consider that such receivers would be extremely useful for monitoring services.

A three-dial frequency generator constructed by Mr Wadley has been in use on one of the Post Office transmitters for several months. The generator frequency is doubled in the transmitter and setting accuracies of the order of ± 200 c/sec on the final frequency can be obtained without reference to frequency measurement. The internal crystal and the interpolation oscillator in this generator are un-ovened but after warm up, stabilities of the order of ± 20 c/sec are obtained. This generator in its present form more than meets the stability requirements for international services, but the calibration and setting accuracy is too low at the lower frequencies. This could be overcome very simply by the setting-up procedure outlined in the paper, but it is felt that it would be highly desirable if a calibration and setting up accuracy of ± 20 c/sec could be obtained in the interpolation oscillator, to allow direct setting up to within tolerance at any frequency.

The Post Office as a result of tests on this generator, has decided to employ frequency generators operating on these principles for the drives to all transmitters which will be installed at the new International transmitting station at Olifantsfontein. The principles may later be extended to receiver control at the International receiving station at Derdepoort, instead of using crystal control on spot frequencies with its attendant disadvantages. The total requirements of both stations would be in the order of 50 units. It is proposed that these generators will be produced by the Post Office, after the development and testing of a prototype.

The general adoption of these principles would undoubtedly lead to improved utilization of the frequency spectrum and considerable economies in outlay on crystals, which would only be used on fixed frequency transmitters.

Mr Wadley is to be congratulated on the contribution which his development of these principles makes to the art of frequency control in radio equipment.

B. J. STEVENS : I should like to congratulate Mr Wadley on his excellent paper, and even more on the development which forms its subject.

Communications engineers have been trying for many years to develop a variable-frequency oscillator which would attain the stability of a reasonably good crystal-controlled instrument, and which could be used to control the frequency of transmitters.

While inductance-capacity types of variable frequency oscillators have been developed which would be sufficiently stable for most applications, there are certain instances where the conventional *L.C.* oscillators, cannot meet stability figures of better than 1 part in 100 000. I refer particularly to the need for a variable-frequency-drive oscillator for use with short-wave transmitters in the high-frequency broadcast bands. These bands are now so congested that it has become almost impossible to find a clear channel, and it is becoming more and more necessary to resort to shared frequency working.

An analysis of the results of monitoring by Commonwealth countries of the 6, 7 and 9 Mc/s international h.f. broadcasting bands between 16.00 and 20.00 G.M.T. for the month of January 1953, reveals that in the 6-Mc/s band, which is 250 kc/sec wide, 56 stations were identified in Zone 1, and 61 stations in Zone 3. In addition, some 24 stations were identified outside the band. The maximum number of h.f. broadcasting stations identified in any zone was thus of the order of 85, which gives a spectrum space of under 3 kc/sec per transmission, a very unsatisfactory state of affairs when at least 10 kc/sec is required for music transmissions.

In the 7-Mc/s band, which is 200 kc/s wide, 49 stations were identified in Zone 1 and 56 in Zone 3, with some 30 additional stations identified outside the band. The maximum number of transmission identified in Zone 3 was of the order of 86, which again gives a spectrum width per transmission of approximately 2.3 kc/sec.

The 9 Mc/s band, 275 kc/s wide, contained 49 identified transmissions in Zone 1, 55 in Zone 3 with 20 additional transmissions outside the band. The maximum number of stations identified in any zone

was thus 75, which gives a spectrum space of under 3.7 kc/s per transmission.

The South African Broadcasting Corporation (S.A.B.C.) in establishing its proposed new short-wave centre at Bloemfontein, is thus faced with the choice of either trying to find a number of clear channels for operation (an almost impossible task) or of operating on the same frequencies as those used by distant stations. The latter solution, while open to many objections, is the only alternative. However, this method of finding spectrum space by frequency sharing requires that our transmitter carrier frequencies be adjusted to the same values as those of the distant stations, which necessitates the use of variable-frequency drive oscillators. An additional requirement is that our carrier frequencies be sufficiently stable as to remain within a few cycles per second of the other stations, otherwise the transmissions would be marred by low-frequency heterodynes. Since most h.f. broadcast transmitters to-day are controlled by relatively stable drive oscillators (usually) crystal controlled—it should be possible to operate under these conditions fairly satisfactorily—provided that the S.A.B.C.'s drive oscillators are capable of being set to the required frequencies and that they will have a short-time stability of at least one part in a million.

These requirements of relatively high stability, together with an ability to be set to any particular frequency, cannot be met by the conventional *L.C.* oscillator, and the S.A.B.C. was at a loss for a satisfactory solution to the problem when Mr Wadley came to our aid with his radically new design, which should prove completely satisfactory for the purpose.

I must therefore thank Mr Wadley and the Telecommunications Research Laboratory, not only for an excellent paper, but for the development of a piece of equipment which will be of great assistance to us in establishing the proposed S.A.B.C. short-wave centre at Bloemfontein.

H. DAINTY: I would like to make a few comments regarding some of the practical problems encountered during the course of constructing receivers to Mr Wadley's design, and based on a prototype

provided by the Telecommunications Research Laboratory of the C.S.I.R. As a matter of interest, I will also give a brief description of the latest prototype made, and which is exhibited here to-night.

In the first place, the prototype receiver provided was duplicated without difficulty. The layout of the following receivers was then radically altered in order to make for ease of production. Ordinarily during the normal process of evolving a production sample, one expects to make changes until the final stage is reached. During the development of the conventional type of receiver, radical changes are made without difficulty, but in the case of the Wadley receiver, major changes have to be carefully considered.

The reason for this may have been gathered from Mr Wadley's paper—the necessity for very careful screening and isolation between certain sections of the receiver. This is of paramount importance, if proper performance without the presence of spurious signals is to be secured. Spurious signals can be eliminated to the point where they are inaudible, provided the right technique is employed. This technique, if I may say so, is somewhat foreign to those of us more used to handling and thinking in terms of the conventional type of receiver. However, once a proper appreciation of the design problems of the Wadley-type receiver is arrived at, and the right technique employed, the solution follows.

During the course of the development of the latest model Wadley receiver, the difficulties encountered with spurious signals proved to be extremely frustrating. It was found that the spurious signals present were due to ineffective screening and by-passing, r.f. leaks via power connections to shield compartments, and the generation of spurious responses in the second mixer due to the application of an unnecessarily high harmonic level.

The combination of all these faults at one time proved to be harrowing experience to the initiated—once the causes had been traced step by step the technique for their prevention and elimination was soon acquired. These points are mentioned, because while the application of Mr Wadley's principles to receiver construction does present some problems, the ease by which they may be surmounted depends on

experience. The problems mentioned are peculiar to the designer and manufacturer and will not recur to plague the serviceman.

In spite of the apparent complexity of the Wadley receiver, it is quite easy to manufacture. The more or less complete absence of the usual multiplicity of r.f. tuning inductors and associated switch decks, padders, trimmers, etc., goes a long way towards making for easy production. Apart from the filters, the r.f. inductors which do exist in the receiver are the five simple tapped coils in the r.f. stage grid circuit and the three coils associated with the input of the 2/3 Mc/sec interpolation section of the receiver. The filters are easily constructed. The fact that the receiver is divided into units which may be assembled and wired separately, is also an advantage. The amount of metal fabrication involved is somewhat more than normally required, but this does not represent a production problem. Cast-aluminium compartments and chassis with built-in filter boxes may be employed in the future.

The receiver exhibited is easy to service—all sections are easy to get at and components are conventional. Adjustments are perfectly straightforward, most of them being required in the 2/3-Mc/sec interpolation section which to all intents and purposes is a straightforward superheterodyne, with mixer/oscillator, two 456-kc/sec i.f. stages, detector and two-stage audio amplifier. The signal and harmonic image filters are not adjustable, and the 40-Mc/sec i.f. and 37.5-Mc/sec harmonic filters are slug tuned. It is not anticipated that these filters will need adjustment in the normal course of events. The performance of the harmonic generator chain starting from the 1-Mc/sec crystal stage through to the output at the second mixer grid, can be checked with the aid of an r.f. voltmeter. The use of a crystal diode in series with the test leads of the usual 20 000-ohm per volt test meter serves admirably for this purpose.

The first oscillator in the receiver covers the range 40.5/69.5 Mc/sec, the tuning of which is controlled by the megacycle dial. The required stability of this circuit is easily attained without any special treatment. In any event the overall receiver calibration accuracy is not dependent on this section of the circuit. The tuning of the

megacycle dial is quite broad and is merely peaked for noise or signal at the required megacycle point, either by ear or with the aid of the signal-level meter.

The calibration accuracy of the receiver is dependent on the 2/3 Mc/sec interpolation section of the receiver, the tuned input circuits of which are controlled by the kilocycle dial. These circuits are easy to stabilize and calibrate accurately because of the narrow tuning range. The calibration accuracy claimed for this receiver is within 1 kc/sec at any frequency, and stability within 500 cycles per second from switch on, after any period and at any frequency.

It will be appreciated that such performance is most uncommon, and can be realized in the conventional receiver only at very considerable expense. In this connection, while final cost and selling figures for the Wadley receiver are not yet available, indications are that these figures will be very modest for a receiver of its class, and will certainly be quite well below imported types with anything like comparative performance.

The latest type Wadley receiver exhibited has seventeen tubes of the miniature B7G base series, and one octal base rectifier. Six of the tubes are associated with the harmonic generator, the balance being accounted for by the r.f. stage, first mixer, first oscillator, second mixer, third mixer, 2/465-kc/sec i.f. stages, diode detector/a.g.c. rectifier/noise limiter, b.f.o. and two stages of audio. No attempt has been made to provide an elaborate audio system the output of the audio amplifier being of the order of 1 watt to the built-in speaker.

Apart from the tuning dials, the following controls are provided:—r.f. input attenuator r.f. trimmer and associated switch for selecting broad band or tuned input, i.f. and audio gain controls, b.f.o. pitch control and on/off switch, a.g.c. and automatic noise limiter switches, and variable selectivity control.

The signal level indicator is a microammeter in series with the diode detector load. It provides a ready means for reading signal level, and incidentally, also serves as a built-in means for checking overall receiver performance. For example, with no antenna connected and full i.f. gain 10 microamps is registered with untuned input and about 25 microamps with tuned input. As most of the noise in the receiver emanates from

the r.f. stage, these figures will not be attained if all sections of the receiver are not performing satisfactorily. As a matter of further interest 0.6 of a microvolt input at 15.5 Mc/sec will result in 25 microamps of detector current (about 16.5 volts across the diode load).

A resume of the receiver performance and features is as follows:—

Frequency range—1.30 Mc/sec. The band 0 to 1 Mc/sec is included and is useful over at least portion of this range.

The frequency scale of the dials is directly calibrated, is bandspread over an equivalent of 37 ft, and is linear with frequency. Calibration accuracy is within 1 kc/sec

Stability—Within 500 cycles per second after switch on, for any period and at any frequency

Sensitivity—10db or less at 400 ohm untuned, and 6 db tuned

S.F. bandpass—5 kc/sec normal, 3 kc/sec at broad crystal and continuously variable down to 160 cycles/sec at narrow crystal position

Image channels—Down 60 db or more.

As may be imagined, the receiver described has a character (if one can describe it so) all of its own. Its appeal grows with use, and I predict that it is a receiver which will become a firm favourite with operators. To those not accustomed to operating a receiver with such a high degree of accuracy, the unflinching performance in this respect will be a revelation. It has other uses, for example it makes a very useful laboratory tool.

In conclusion I would like to pay tribute to the S.A. Council for Scientific and Industrial Research for making the design of the T.R.L. crystal-controlled receiver available for manufacture by South African industry and to pay tribute to Mr Wadley for his extremely valuable contribution to the State of the art.

T. C. B. VLOK (Associate Member): It gives me great pleasure to contribute to the discussion on Mr Wadley's fine effort. I have handled a receiver based on the principle demonstrated to-night and can say that the frequency selection is somewhat startling to one who is accustomed to main

dial plus vernier (and its calibration). My only criticism is that, for receiver application, the final stage still depends on the frequency stability of an *L.C.* oscillator, but over a band of 1 Mc/sec as the width specification frequency stability is only a mild problem. I hope members will agree that much publicity must be given to this new technique so that the application can become widespread and become a useful tool in the practice of radio.

The Defence Department were sufficiently impressed with this new departure that it has sponsored the production of six prototypes.

T. G. E. COCKBAIN (Associate): I have been fortunate enough to have had the opportunity of conducting some tests with a receiver using the Wadley principle. These tests were conducted mainly in the field, using the receiver in a mobile radio station. For this reason I shall confine my remarks to the application of the principle to receivers.

The receiver under test was produced by a South African commercial firm for prototype trials, and as it was one of the first, was not perhaps as elegant in appearance as the later models, which look very impressive. Its true worth became apparent as soon as we started to use it for communications, however, and the following points became clear:—

- a The apparatus is easy to use
- b The excellent frequency accuracy, and consequent re-setability of the receiver simplified operating procedure, and saved time and temper, particularly when conditions were poor
- c The absence of tricky setting-up procedures to ensure accuracy of the tuning scales was very welcome, particularly after some sad experiences with three other types of high-accuracy receivers
- d The stability of the receiver, even from cold, was outstanding.

In amplification of the above remarks, let me say that a side-by-side test was conducted with the Wadley receiver and one of the very expensive American receivers which makes a special point of its extremely accurate calibration. This receiver covers the normal communications band in steps

of one megacycle, switched by successive half-turns of a conventional bandswitch. A slide-rule type dial covers the first interpolation, and an engraved scale showing integral kc/sec is attached to the main tuning knob, being read against an adjustable pointer. This pointer is set by calibrating the tuning dial against a built-in 100-kc/sec crystal oscillator.

In practice, the Wadley receiver, in spite of the fact that its dial calibrations are spaced 5 kc/sec apart, proved at least equal to this comparison receiver in accuracy, and every bit as good in sensitivity. The short-term and long-term stability of the Wadley appeared to be superior especially from cold. Once the slight differences in operating technique required for the Wadley were mastered by the operators, they expressed a preference for it, and used it normally for schedule operating. The Wadley proved a lot easier and more consistent in its frequency accuracy, due in part to the fact that the comparison receiver gave a certain amount of trouble in setting up, due to crystal oscillator drift and b.f.o. setting. Thus it is fairly safe to say that the practical accuracy to be expected from the Wadley would be better than that of the comparison receiver. Only one really noticeable defect was present in the Wadley receiver tested, namely, that a frequency shift could be noticed due to loading of the input, when a nearby transmitter was keyed. (It should be mentioned that the transmitter was not supplied off the same power as the Wadley). This took the form of a slow chirp, continuing for more than a second, until a new stable operating point was reached. The magnitude of this frequency shift was of the order of 250 cycles per second. The comparison receiver did not suffer a similar shift. I am informed that this trouble will be ironed out in the later models.

The delightful mechanical simplicity of the Wadley receiver compares favourably with other high-precision receivers, in particular with the very complex mechanical arrangements on the comparison receiver used. In addition, no large batch of crystals is required to provide the precision megacycle bands, and simplified controls render it an easy receiver to use. For these reasons, the Wadley appears to be a much cheaper receiver to produce, especially in quantity.

Maintenance would probably be considerably simpler and less costly, while the apparent stability of the calibration leads one to believe that it could be run for long periods without much attention. The ease with which this design lends itself to adaptation to panoramic reception, makes it quite attractive as a military receiver. On balance, therefore, the application of the Wadley principle to communications receivers has everything to recommend it, and I hope that some enterprise will produce these receivers in quantity. The only factor militating against such a happy development, as I see it, may be the lack of a quantity market in this country, and therefore I hope that some steps will be taken to enable the overseas market to be exploited.

With the advent of this reasonably cheap high-accuracy, high stability receiver, I should like to see some effort put into the development of an adaptor for frequency-shift reception, employing straightforward filters, thereby eliminating the present complex discriminator-type adaptors.

PROFESSOR G. R. BOZZOLI (Vice-President): The Institute is fortunate in having been given the opportunity of first making public the details of this remarkable receiver and Mr Wadley deserves no little praise for his achievement. There is little doubt that both his receiver, and its offspring, the continuously variable signal generator of crystal stability will find many uses both in laboratories and in communications. As a laboratory instrument, the signal generator has no equal. Any of us who have used signal generators both of the cheaper general purpose type and of the more expensive specialized type have felt the lack of adequate calibrated bandspread and the shortfall in stability of frequency, both long and short term. This instrument will probably fall between the two in price and far surpass the more expensive in performance. It will place within the reach of University laboratories a secondary standard of frequency of great versatility.

The success of the device, whether a receiver or a generator, clearly lies in the care taken over filtering and shielding. Owing to the high frequencies normally involved, capacitances used are often of the

same order as valve stray capacitances. This immediately raises the question of servicing and valve replacement. The author has not discussed servicing although he has dealt fully with spurious responses and I would be very interested to know with what ease service could be carried out. It would seem to me that should a fault manifest itself by the appearance of an unwanted signal or heterodyne whistle, the serviceman might find considerable difficulty in locating the cause and removing it. Has the author considered the advisability of drawing up comprehensive instructions for the location of such defects? Such instructions would probably need to be a small treatise on the combination frequencies possible. The serviceman would also probably have to include in his kit, suitable frequency-measuring equipment.

V. R. KRAUSE (Associate Member): I should like to add my congratulations to Mr Wadley for his remarkable, original and even historic contribution to the art.

I feel that the full benefits and repercussions of his contribution cannot at present be appreciated. It is impossible to foresee all the possible applications for this valuable new tool. The idea is so different from the usual that, as in the case of the transistor, we are required to think along different lines from the conventional and to use new thought approaches, to fully appreciate the potentialities of the system.

With regard to the application of the system to receivers, which was the main application discussed in the paper, Mr Wadley's development has given us an ideal method of setting the frequency of the receiver to the required incoming signal. In eliminating the wave change system common to more conventional systems we are presented with a very real advantage. However, in a really first class communications receiver of the general coverage type, it is a considerable advantage, for obvious reasons, such as noise considerations, to have one or possibly two stages of pre-selection. The tuning of the preselector stages over such wide ranges as required in a general coverage receiver must, at present, be done by conventional *L.C.* circuits which bring us back to the wave-change switch. It is a pity that we have not

a parallel development to Mr Wadley's wide-band oscillator system, which could be applied effectively to the tuning of the input signals.

These remarks, of course, do not apply when the receiver is to be used for fixed frequency point-to-point service, for example in diversity applications. In this case wide bands of frequency coverage are not usually required and r.f. pre-amplification is a relatively simple matter. The problem arises when high performance is required under the flexible conditions usually imposed upon general coverage communications receivers.

With regard to spurious responses and beat troubles which are common to multiple heterodyne systems, it is desired to draw attention to the Mixer Harmonic Chart, by Thomas T. Brown, published in the mid-June 1953 issue of *Electronics*. This chart simplifies the identification of beats produced by the various harmonic combinations of two frequencies. No doubt a similar form of chart or charts could be developed in a reasonably short time to be especially applicable to the present problem. Such a chart would probably prove of considerable value in identifying quickly any spurious response, particularly during development. It might prove helpful with one of the problems described by Prof Bozzoli in connection with servicing.

In the case of the system being applied to generators for the primary control of the frequency of large transmitters, a possible difficulty is foreseen. Under these circumstances the generator will probably be operating in a field of high intensity (and complexity) caused by the transmitters. Should the output frequencies of the transmitters be of the same order as the frequency of any of the signals within the various oscillator-mixer chains, then difficulties might arise. The careful shielding and filtering used within the equipment to adequately control the spurious responses generated within the various sections of the equipment, while proving adequate for that purpose, might not be capable of dealing with the intense external fields.

This type of trouble, it is felt, will be encountered only occasionally as it will often be the case that the frequencies of the transmitters will not be sufficiently near oscillator or mixer frequencies to form

new and undesirable signals. It is felt, however, that a very real and serious problem may be presented under some circumstances.

G. ff. BELLAIRS (Associate Member): This paper describes the successful outcome of a remarkable piece of original research. Mr Wadley's technique has solved the old problem of the communications engineer, which may be described as the development of a 'rubber crystal' which could be squeezed to provide a number of alternative frequencies, each, however, having full crystal stability. The author has achieved an equivalent result in a neat and practical manner, and I think that his technique is likely to become standard practice in the construction of communication type receivers in the future.

I must confess that I am not too happy when I read of a new development unless I can form a mental picture of the processes involved. I was not able to do this while reading the paper as presented by the author, and I feel that there may be others

present who also have experienced some difficulty in visualizing exactly what takes place in this ingenious receiver. I have, therefore, drawn out a frequency diagram, using the symbolism generally employed in depicting the frequency translations of a carrier telephone system. In the diagram the frequencies are shown on the horizontal scale, and the rest of the diagram shows the various frequency spectra occurring in the receiver of Fig. 5 in the paper. Part A of Fig. A shows the frequency spectrum of the 1-Mc/sec crystal X accompanied by the harmonic series spaced at megacycle intervals extending up about 32 Mc/sec beyond which point the low-pass filter has suppressed all higher harmonics. This may be regarded as a 'fence-post' spectrum. Part B of the figure shows the frequency S of the signal to be received, the frequency V of the variable valve oscillator and the sum and difference products $V + S$ and $V - S$. The pass-band of the first i.f. filter is also shown and it will be observed that V must be positioned very roughly so that $V - S$ falls within the band of this filter. Part C of the figure shows the result of inter-

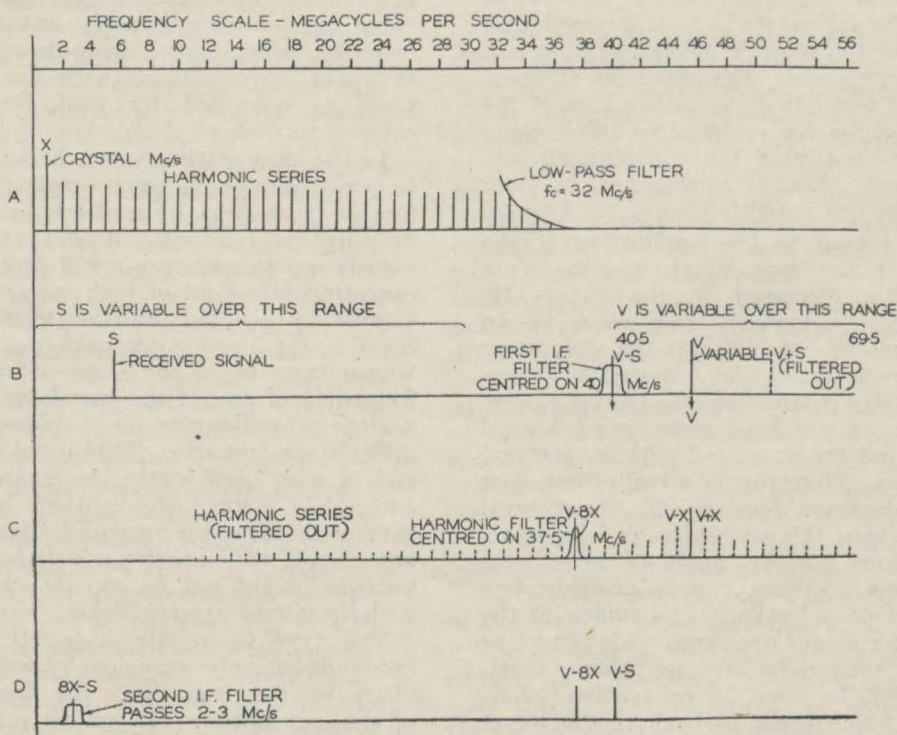


Fig. A

modulating the valve oscillator frequency V with the 'fence-post' spectrum of Part A. The result is a double 'fence-post' spectrum centred on the frequency V . In this figure is also shown the pass-band of the harmonic filter centred on 37.5 Mc/sec. It will be noticed that in the example chosen, one of the lines of the 'fence-post' spectrum (namely that corresponding to $V - 8X$) falls within the pass-band of this filter. All the remaining lines in the spectrum are filtered out and suppressed. Part D of Fig. A shows that the object of the foregoing manoeuvres is the production of the two difference frequencies $V - S$ and $V - 8X$ respectively. These two are intermodulated and, disregarding the sum product which is filtered out, we are left with the difference product which is $8X - S$. V does not enter into this result and it will, therefore, be noticed that the effect has been to move S in frequency by an integral number of megacycles. The product $8X - S$ passes through the second i.f. filter to the interpolation receiver, where it is treated in the ordinary way.

I must confess that the operation of the generator shown in Fig. 10 proved too much

for my powers of mental appreciation! I feel it would be very helpful if the author could produce some form of frequency diagram for this generator, possibly on the lines employed in Fig. A.

T. L. WADLEY (*in reply*): The possibility of intense fields from transmitters causing trouble within a generator is a very real one which must be taken into account in the design of the screening of the equipment.

Trouble in this respect is anticipated only at the input of the harmonic mixer, as all other circuits are at relatively high level. In the case of a generator covering up to 7 Mc/sec at present under development, the harmonic filtering is performed at 8.250 Mc/sec, and a powerful field within 50 kc/sec of this might cause trouble. The leakage signal at the harmonic mixer input would have to be not more than about 10 to 30 microvolts. It should be possible with suitable screening to keep below this level.

In the case of an individual transmitter interfering with itself, the difficulty could be overcome by a shift of this filtering frequency by re-adjustment.

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Thesis

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ELECTRONIC PRINCIPLES OF THE TELLUROMETER

by

T. L. WADLEY (Associate Member.)

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1. INTRODUCTION

1.1 General

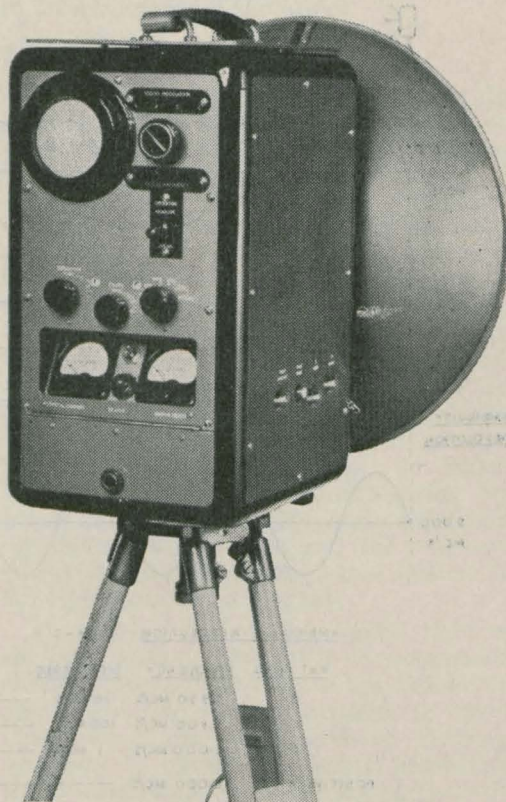
An operational description of the Tellurometer system of distance measurement has been published¹ but gives only the minimum of electronic detail for a broad understanding of the system. This paper is intended to supplement the operational description and will be confined to the electronic aspects only.

1.2 The operational requirements

The requirements which the Tellurometer was designed to meet were as follows:—

The instruments were required to be fully portable and capable of measuring distances between points for geodetic or other purposes within line of sight of each other, at distances from a few miles up to 20 miles apart to an accuracy of not less than 1 part in 100 000 and not ambiguous to less than one or two miles.

The performance of the instrument meets this requirement. Working ranges up to 30 miles and occasionally greater distances are achieved in suitable topography. The



The Master Tellurometer operating panel. The telephone handset and power cable are stored in the lower compartment.

accuracy attained is stated to be 3 parts per million plus 2 inches, or somewhat greater or less depending upon topographical and climatic conditions, and the system is unambiguous to 10 mile intervals.

It is doubtful whether accuracies much greater than this can be achieved over distances of this order, due to the meteorological limitations described¹, and the useful design limits of the instrumental technique are set by this consideration.

1.3 Timing accuracy required

To achieve accuracies of this order it is therefore necessary to determine the transit time of waves over a forward and return path to an order of accuracy of at least 1 millimicrosecond. One millimicrosecond corresponds to the transit time in both directions due to about 6 inches of the path, which is about 1 part in 100 000 of 10 miles. Allowing

for the possibility of greater accuracy in the range 10-30 miles, and the minimum required accuracy down to one or two miles, the timing accuracy must be perhaps 1/5 of a millimicrosecond. With present techniques it is not possible to use pulse methods, although such methods would have considerable advantage in avoiding stray reflection effects. Even assuming suitable pulse techniques to be available, the weight and power consumption of such equipment would be prohibitive for portable use and the stability of the pulse delays in the various circuits would be a source of design difficulty.

2. THE BROAD PRINCIPLES

2.1 The general principle

The technique adopted in the Tellurometer system makes use of phase measurements in

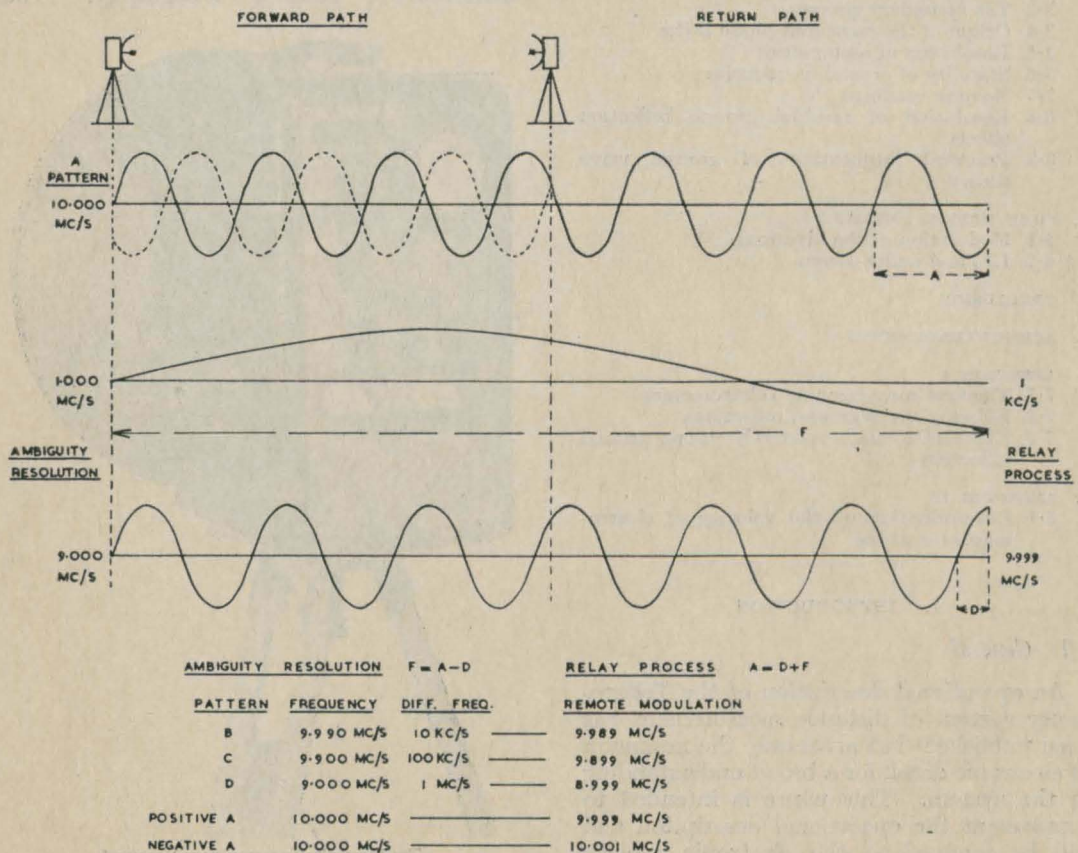


Fig. 1—Diagram illustrating the method of resolving ambiguities and also illustrating the relay process

which this order of timing accuracy may be relatively easily achieved. A carrier frequency, modulated by various pattern frequencies, is radiated from a master instrument. A similar carrier radiated back from a remote instrument, modulated by different but related signals, is detected at the master, and the outgoing and incoming phases are compared. This is illustrated in Fig. 1. A measuring modulation referred to as the A pattern is represented by the solid sinusoidal curve of the first diagram. This wave is shown as proceeding from the Master instrument to the Remote whence it is returned without change of phase back to the Master instrument, as indicated by the dotted curve. For convenience the return path is also shown as a continuation of the solid curve and the relative phase of the outgoing and incoming modulation at the Master instrument is then represented by the phase delay A as shown. This is referred to as the A pattern phase and its value measures the transit time across the double path. This value is of course ambiguous as the whole number of phase rotations is unknown.

In the simple case represented by the diagram this ambiguity could be resolved by providing a measuring pattern of one tenth the frequency as represented by the second diagram, the phase reading F providing the information that there are six unresolved whole rotations of the A pattern.

For various reasons, as explained below, this is not done. Instead a modulation of nine-tenths of the A pattern frequency, which may be referred to as the D pattern is provided, as illustrated by the third diagram. It will be seen that the phase difference between the A and D pattern at any point along the diagram is equal to the phase F of the wave of one-tenth frequency. It should be noted that the A and D patterns are not applied simultaneously but in succession and the F value arrived at by arithmetic subtraction.

2.2 Choice of pattern frequency

Assuming that phase may be measured to the order of 1° without undue difficulty, it is apparent that a pattern frequency of the order of 10 Mc/s is required, 1° of phase shift corresponding to about $\frac{1}{3}$ millimicrosecond. In practice a main pattern frequency of exactly 10 Mc/s is used and the measure-

ment made in terms of decimal system of time. The alternative practice of using an odd frequency to give exact units of distance is regarded as less attractive for the following reasons.

The odd frequencies required would be difficult to set up to the required accuracy without complex equipment whereas 10 Mc/s standard signals are readily available.

The corrections necessary may be applied without confusion before conversion to practical units of distance, which in survey practice are many and varied and sometimes contain local correction factors due to slightly differing standards.

Furthermore, the use of time units avoids the assumption of a velocity for electromagnetic waves, which may be subject to adjustment as its value is more accurately determined. It is also possible that units of time may be used directly as units of distance to avoid inconsistency in the definition of distance units and varying standards in different parts of the world.

2.3 Choice of carrier frequency

It would of course be possible to make the necessary phase measurements directly on radiated waves of 10 Mc/s. Such waves, however, travel along the ground with a velocity which is very much dependant upon ground constants and the necessary accuracy could not be obtained. Higher frequency waves are obviously more suitable as the waves along or near the ground become progressively more detached from the ground as the frequency is increased. Furthermore, coherent reflections from the ground or other objects become less likely due to scattering of the higher frequencies and absorption effects. Also, as higher frequencies are used, greater beaming becomes more easily possible, stray reflections are more easily avoided and the scattered energy is more highly attenuated relative to the highly beamed direct ray.

From this point of view visible light or similar radiations have much to recommend them. However, such waves are difficult to detect and are more susceptible to direct absorption. Also the excessive beaming necessary to obtain the desired sensitivity can be operationally undesirable particularly when it is necessary to work from unsteady supports.

Generally speaking, therefore, the highest radio frequencies which can be coherently generated and detected are probably most suitable. The Tellurometer system as at present engineered works on 3 000 Mc/s or 10 cm wavelength. At these frequencies the necessary radio technique is well developed and easily applied and the advantage of high frequency is obtained in good measure. The advantages of still higher frequencies accrue rather slowly, relative to the difficulties such as frequency stability, the need to change from coaxial to waveguide technique with possible increase of weight, poorer detector sensitivity and lower generator efficiencies. Nevertheless there is little doubt that such instruments will operate on higher frequencies in time to come, possibly in the 8 mm region. Care, however, must be taken in this region to avoid selective absorption and an anomalous velocity of propagation due to molecular effects.

Thus whilst 3 000 Mc/s is not necessarily an ideal frequency from all points of view it does represent at the present stage of development of the technique a good compromise. Ground reflected signals are in general substantially weaker than the direct signals, and the relatively wide beam of some 10° makes lining up very simple, the instruments are simple to tune, stable in operation, light in weight and have reasonably low power consumption.

2.4 *The modulation process*

In the Tellurometer system the pattern frequency is modulated upon the carrier frequency. In principle, of course, it is possible to make phase measurements upon the carrier frequency itself, even though this be 3 000 Mc/s. At very short range this is a useful technique and such instruments can be made to give accuracies of the order of a fraction of a millimetre. There are a number of reasons for not doing this in a geodetic instrument. Firstly, at extended range the carrier phase stability would break up due to the excessive resolution, and the method would thus fail at some range perhaps within the useful operational range under some meteorological conditions. Secondly, the high resolution which in itself would be meaningless due to refractive index uncertainties would require a number of extra steps to resolve its ambiguities. From a design point of view it is far easier to modulate with an

accurately controlled frequency than it is to control a carrier of this order. In effect of course a modulation process is simply a carrier process carried out on more than one carrier frequency simultaneously, wherein the difference frequencies and phases are of interest, the carrier frequencies and phases being unimportant and their stability of no account. This point may be appreciated by referring again to the process illustrated by Fig. 1. In this case the two high frequencies represent a carrier and one of its sidebands respectively, the modulation phases arising as the difference phases of the high frequencies. In this case, however, the waves exist simultaneously and their difference phases and frequencies arise physically as a result of the physical subtractions of the modulation and demodulation processes. Furthermore in the Tellurometer system the arbitrary carrier frequencies are made use of to enable the effects of stray reflections to be eliminated and although in principle a similar technique must be possible, using a variable carrier only, an extremely laborious computing process would be necessary to make use of it.

In the Tellurometer system the carrier is frequency modulated by the pattern frequency. There are two reasons for this. Firstly, centimetric generators such as the small klystrons used in the instrument are extremely easy to frequency modulate and secondly, as will be seen in the detailed description below, frequency modulation is more satisfactory in the heterodyne process used if the detectors tend toward linearity.

In principle, single sideband modulation is the simplest theoretical modulation that could be applied to the problem but it is not used because of practical difficulties.

2.5 *The heterodyne process*

It is evident that in techniques of this nature the modulation frequencies cannot be handled by straightforward processes of modulation, demodulation, remodulation, etc., on account of the impractical wide band-passes required and the phase instability with varying temperature and aging effects. In this system, therefore, use is made of heterodyne methods for the detection and amplification of the measuring pattern frequencies. All amplifier circuits, display circuits and relaying circuits are designed to operate at a low comparison

frequency although they carry the phase information derived from high measuring frequency waves. The measuring waves immediately upon reception at receiving dipoles are converted to lower frequencies in the first detector circuits.

2.6 *The relaying process*

These heterodyne processes apply firstly to relaying the measuring pattern from the Remote station. Here again Fig. 1 may be used to illustrate the process. In this case the outgoing 10 Mc/s A pattern modulation is represented as before and the other pair of waves have frequencies as indicated on the right hand side of the diagram for the Relay Process. By the same arguments as before the A pattern phase at any point along the double transmission path can be represented as the sum of the phase of two waves of frequencies 9.999 Mc/s and 1 kc/s. If from the Remote station such waves are substituted for the return transmission, the A pattern phase information is effectively retransmitted provided the phase relationship of the three waves as illustrated is preserved. Physically this is quite simply performed by radiating a modulation frequency of 9.999 Mc/s from the Remote transmitter in an arbitrary phase relationship and deriving the low frequency 1 kc/s comparison wave by heterodyning the incoming and outgoing high modulation frequencies. The remote receiver amplifier circuits are thus called upon to handle only the low comparison frequency of 1 kc/s and this wave after amplification and suitable treatment as described below is impressed on the Remote transmitter together with the 9.999 Mc/s modulation. On account of the low frequency this can be done with little or no phase shift.

2.7 *The phase indicating process*

The two returned modulation waves on arrival at the Master station could be added by a heterodyne process to recover the A pattern frequency of 10 Mc/s for the purpose of comparing its phase with the outgoing modulation. However, it is well known that if two equal high frequencies which are to be phase compared, are heterodyned down to a low frequency by means of a common conversion frequency applied in the same phase in each instance, the resulting low frequencies have the same phase relationship

as the original high frequencies. For the purpose of this argument then assuming this common conversion frequency to be the 9.999 Mc/s wave itself and subtracting this from each of the above A pattern waves, the phase comparison may be made between the difference frequency of the outgoing 10 Mc/s and incoming 9.999 Mc/s on the one hand and the returned 1 kc/s incoming wave on the other.

As in the case of the Remote stations the receiving circuits of the Master station need then handle only the low frequency comparison waves.

3. DETAILED ELECTRONIC PRINCIPLE

3.1 *The basic communication system*

This system is common to both the measuring function and speech communication, the latter being a practical necessity between Master and Remote stations.

With reference to Fig. 2, at each station a transmitting centimetric klystron feeds a dipole situated at the focus of the reflecting mirror of some 18 inches aperture. These dipoles are inclined at 45° to the horizontal. At right angles to these transmitting dipoles receiving dipoles are situated to give go and return polarizations mutually at right angles. This system ensures no loss of power on using a common receiving and transmitting mirror, the oblique polarization possibly aids the suppression of ground reflections in some conditions and the two stations have identical symmetrical aerial systems.

The receiving dipoles excite centimetric crystal detectors situated just in front of the mirror focus and are coupled thereto via the necessary balancing stubs and matching line. The latter are formed in concentric line moulded into an integral part with the dipole boss.

At each station the transmitting klystron also performs the function of the local oscillator. A small fixed capacitive coupling at the base of the dipoles within the moulding provides the necessary drive to the crystal detector. The detector current is about $\frac{1}{2}$ to 1 mA and constitutes in addition a monitor on the local transmitter.

The klystrons at each end are arranged to differ in frequency by 33 Mc/s, which is the intermediate frequency at each receiver. The system is thus automatically in tune

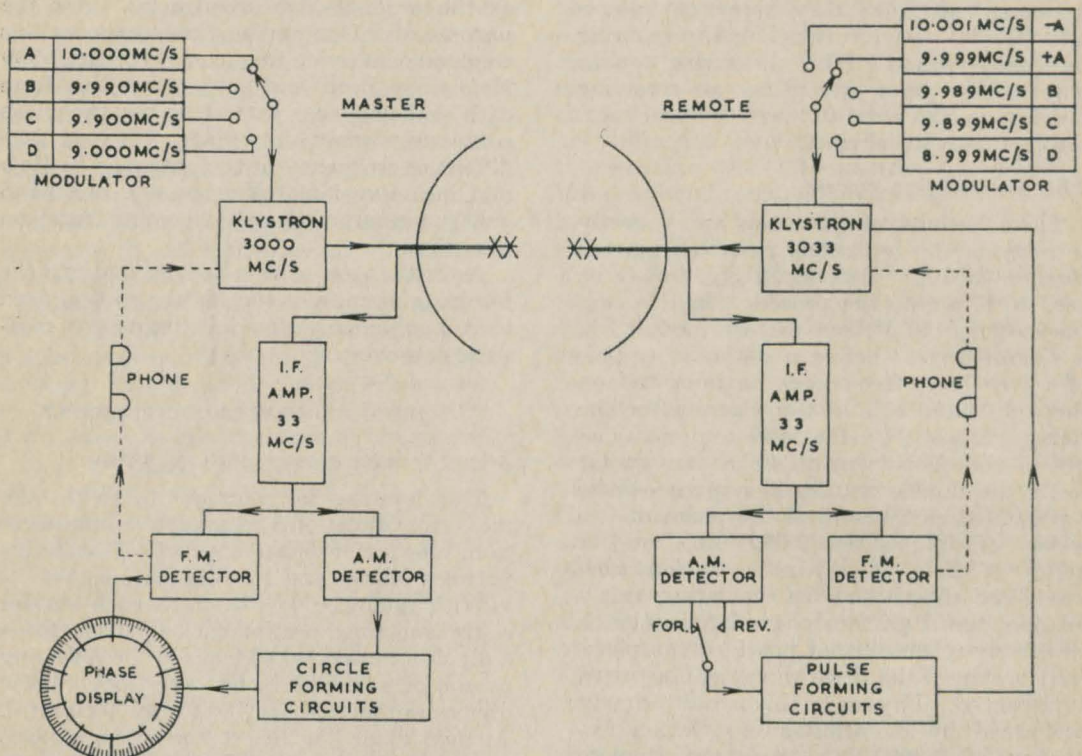


Fig. 2—Block diagram of the Tellurometer System. The centimetric mixers are contained in the dipole assembly and are not shown on the diagram

both ways simultaneously and can be tuned from either end. The klystrons are frequency modulated by the speech signals from microphones at each end and frequency discriminators after each I.F. drive the earphones. The speech is thus duplex with side tone automatically arising from the common klystron function to give the feel of an ordinary telephone.

The use of what is in effect a straight-forward double detection superheterodyne receiver in this manner is of course not essential for either the communicating or measuring process. The high sensitivity of such a receiver is, however, an advantage which cannot be obtained without the use of coherent carrier waves.

The intermediate frequency of 33 Mc/s is chosen to avoid near harmonics of the pattern frequencies but otherwise the I.F. design follows normal radar or centimetric practice having a bandpass of some 500 kc/s.

No attempt is made to reject the image frequencies, as the R.F. system must be

kept as wide band as possible to avoid phase troubles at the high measuring frequencies. The image response detracts slightly from the noise figure attainable. The noise figure is probably also adversely affected by klystron noise, as the klystron is tightly coupled into the aerial system to give the necessary bandpass for the measuring frequencies. Nevertheless adequate sensitivity is easily obtained using a nominal radiated power of 100 milliwatts from a conventional local oscillator type klystron.

3.2 The primary measuring process

The primary measuring process involves a frequency modulation of low modulation index of the Master klystron at 10.000 Mc/s in the case of the A pattern and the Remote klystron at a frequency of 9.999 Mc/s. At each crystal detector a similar heterodyne process takes place resulting in the 33 Mc/s I.F. developing an amplitude modulation of a frequency of 1 kc/s, that is the difference frequency between the modulations. Other

components of the heterodyne process lie outside the I.F. bandpass and are of no account.

Fig. 3 is a spectrum diagram illustrating the process. The two carriers are shown as heterodyning to give the I.F. frequency itself, as in the unmodulated condition. The two lower sidebands of the modulations give rise to the upper sideband of the I.F. frequency and the two upper sidebands the lower sideband of the I.F. frequency, displaced in each case 1 kc/s from the I.F. frequency.

It should be noted that the I.F. is thus amplitude modulated, not frequency modulated, due to the phase relationship of the original sidebands.

A more intuitive method of appreciating the process would be as follows. The two modulating frequencies for the purpose of this argument may be regarded as the same frequency, with their phase relationship changing slowly at the beat frequency. The I.F. is thus frequency modulated at, say, 10 Mc/s but the deviation is varying from double the deviation of either R.F. to zero deviation as the phase changes. At zero deviation the I.F. is virtually unmodulated and has its full undisturbed amplitude. As the deviation increases energy is removed from the carrier to appear as sidebands of the F.M. process lying ± 10 Mc/s from the carrier. The latter lie outside the I.F. bandpass and thus the amplitude of the wave within the I.F. diminishes and in fact undergoes a sinusoidal amplitude change at the beat frequency, the peak of this A.M. wave being equal to the original unmodulated condition and occurring at the instant when the modulations are in phase.

The first argument on a spectrum basis would obviously still apply if the R.F.'s were amplitude modulated, as a reversal of

the phase of the two upper sidebands would result in the same I.F. spectrum within the bandpass. This is strictly true only if the detector is quadratic. If the detector is strictly linear, no beat modulation at all would arise with primary amplitude modulations, as the stronger carrier frequencies inhibit the mixing of the weaker sidebands or, expressed more simply, the amplitude of a local oscillator does not affect the conversion process if a detector is strictly linear. In this case the I.F. would be simply amplitude modulated at the 10 Mc/s of the distant transmitter, the component within the bandpass having no modulation.

In the case of primary frequency modulations the intuitive argument is independent of the nature of the detector characteristic and in practice this is the case. The depth of amplitude modulation is a function of the deviations only and not the detector characteristic. On the basis of the spectrum argument it is difficult to see why this should be so.

The underlying explanation is that in the case of primary frequency modulations the intermixing of spectral frequencies as described above does not take place in a truly linear detector. The actual intermixing is a complex process involving the second harmonics of the local carrier, the result of the process insofar as it affects components within the I.F. bandpass, being identical with the original argument based on a quadratic detector. However, in the case of primary amplitude modulation although a similar complex process takes place, components arise which cancel each other, whereas the same components in the case of primary frequency modulation reinforce each other.

These processes will be discussed in more detail below but at this stage it may be

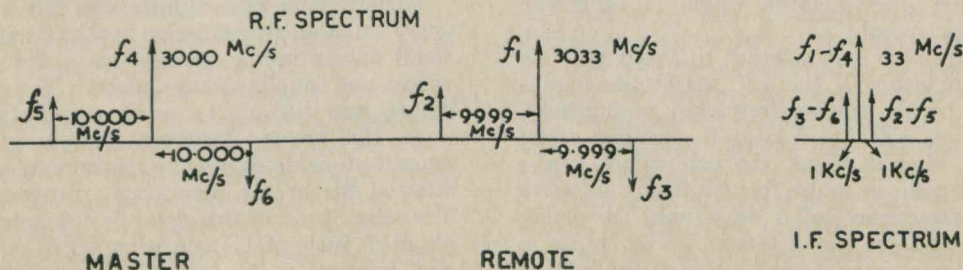


Fig. 3—Diagram illustrating the heterodyne mechanism of the primary measuring process as it occurs at both Master and Remote instruments

noted that the foregoing arguments are the reason for the use of primary F.M. Practical centimetric detectors have characteristics lying somewhere between quadratic and linear, and thus F.M. is preferable to A.M., apart from its ease of generation with klystrons.

The comparison frequencies of 1 kc/s by which the I.F.'s are modulated at each instrument carry over the modulation phase of the primary modulations and will rotate in phase relative to one another with changes in the length of the go and return paths in terms of the modulation wavelengths.

Amplitude detectors following each I.F. amplifier detect these 1 kc/s comparison frequencies.

3.3 *The secondary process*

This secondary process involves the transfer of the comparison wave from the Remote station to the Master station, where their relative phase is compared. The time delay associated with this transfer produces a small phase shift at the comparison frequency. It is this phase shift that makes the Master modulation frequency the pattern frequency, as the 10 Mc/s has been returned in the form of 9.999 Mc/s and 1 kc/s. If the comparison frequency were returned in the opposite direction then the frequency of 9.999 Mc/s would become the pattern frequency.

The method of transferring the comparison frequency from the Remote to the Master station makes use of the fact that although the primary process involves the frequency modulation of the klystrons at the measuring frequencies, the I.F. frequencies are not frequency modulated and consequently a further frequency modulation of the Remote klystron by the comparison frequency at the Remote station may be detected at the Master stations by means of a frequency discriminator after the I.F. amplifier, in fact the discriminator which is otherwise used for speech.

In practice and in order to avoid possible contamination of the I.F. amplitude modulation by the further frequency modulation, and *vice versa*, and also to achieve some circuit simplification, the comparison wave is returned as a pulse formed from this wave at a recurrence of 1 kc/s and frequency modulated on the klystron. This pulse is then displayed as a small intensity modulated break in a circular trace, the circle being

formed on an oscilloscope from the Master comparison wave.

3.4 *Origin of the measured phase shifts*

As the I.F. bandpass of 500 kc/s is very wide relative to the 1 kc/s modulation frequency which it carries, the phase shift of the modulation is very small and very stable with respect to tuning adjustments and ageing effects of components. Similar phase shifts occur in both instruments and tend to cancel out in the display. The pulse is formed at the Remote station at the instant the wave passes through zero voltage and this process and the subsequent modulation upon the klystron involves very small or at any rate constant and stable delays. The subsequent amplification of the pulse at the Master station does involve a small sensible delay but the I.F. bandpass is adequate to ensure that this is constant. In addition some deliberate phase shifts are introduced at the comparison frequencies to restrict the post detection bandpass to 10 kc/s to improve the display but again these are small and cancel.

Small phase shifts occur in the R.F. system between the point at which the transmitter to receiver coupling takes place and the crystal detector. These phase shifts would be at the measuring frequency itself but are kept small by keeping the lengths to a minimum and the circuits as wide band as possible, that is some few hundred Mc/s. Here again these phase shifts are cancelled as they occur at both stations.

All the foregoing constitute the internal phase shifts and their sum total is small and quite constant provided the comparison frequency is maintained more or less constant. In the complete technique they are all cancelled out as will be discussed below, the main requirement being that they should be reasonably small and constant.

The external phase shifts are due to the delay in the transmission path itself and small delays in the dipoles up to the point where the coupling takes place. The latter delays are difficult to predict and depend upon the precise focussing details. Their magnitude is determined experimentally and allowed for in the mounting arrangements. The magnitude of this delay is equivalent to about 1 inch of transmission path at each end relative to the nominal optical focus of the mirror. The instrument is, therefore,

mounted about 1 inch behind the directrix plane of the parabola.

The delays in the transmission path itself, which it is required to measure, may then be examined as follows:—

Let f_m be the Master modulation frequency (say 10·000 Mc/s)
 f_r be the Remote modulation frequency (say 9·999 Mc/s)
 f_c be the comparison frequency (say 1 kc/s).

Let T seconds be the total delay in the go and return paths and $T/2$ the delay in each direction.

The sense of the phase indication is such that the delays in the comparison frequency path are positive and cause the marking pulse to rotate clockwise, showing increasing range as this delay is increased.

The phase indication due to the comparison frequency delay alone is therefore $+2\pi f_c T/2$.

Considering the delay in the forward path, if the f_m be higher than f_r , then as the path delay increases the comparison frequency at the Remote station retards phase angle, the phase indication due to the forward path alone being thus $+2\pi f_m T/2$.

Similarly the comparison frequency at the Master station derived from the returned primary wave f_r advances in phase with increasing path delay. As this wave forms the circular display, its effect is in the opposite sense to the returned comparison wave and the phase indication due to the returned primary wave alone is thus $+2\pi f_r T/2$.

The total indicated phase is thus:—

$$2\pi T/2[f_m + f_r + f_c] \quad (+A \text{ pattern})$$

As however $f_c = f_m - f_r$

This becomes $+2\pi f_m T$ the pattern frequency being equal to the master modulation frequency alone.

The elimination of internal zero error is then based on the following technique:—

The Remote modulation frequency f_r is changed from 9·999 Mc/s to 10·001 Mc/s. The sense of the phase changes with increasing path delay in the comparison frequencies derived from the primary modulations therefore reverses, whereas the indicated phase due to the comparison frequency path delay alone remains the same.

The above expression for the total indicated phase therefore becomes:

$$2\pi T/2[-f_m - f_r + f_c] \quad (-A \text{ pattern})$$

$$= -2\pi f_m T \text{ putting } f_c = f_r - f_m \text{ as before.}$$

This phase indication therefore rotates backwards with increasing distance.

If there is an internal phase error in the complete system equal to, say, θ this adds to each phase indication in the same sense the difference phase $+A$ minus $-A$ becoming:
 $2\pi f_m T + \theta - [-2\pi f_m T + \theta]$
 $= 2\pi f_m T$ which gives a 20 Mc/s pattern free of all internal instrumental error.

3·5 Resolution of ambiguities

The resolution of ambiguities could be achieved by providing lower pattern frequencies using low modulation frequencies, i.e. 1 Mc/s, 100 kc/s, 10 kc/s. However, if these frequencies were applied directly to the klystrons the system would not work, except in the case of a 1 Mc/s pattern, as the complete system of sidebands would then lie within the I.F. bandpass and no amplitude modulation would arise.

Phase indications relative to these lower patterns are therefore obtained as difference phases with respect to the 10 Mc/s phase. This also has the advantage of eliminating internal phase errors as the phases which are subtracted each contain the internal phase error θ .

Modulation frequencies to give positive patterns, that is the Master frequency above the Remote frequency, as follows are applied:

Master	Remote	
9·990 Mc/s	9·989 Mc/s	B pattern
9·900 "	9·899 "	C pattern
9·000 "	8·999 "	D pattern.

3·6 Stability of crystal frequencies

As the pattern frequencies are independent of the Remote modulation frequencies the stability of the latter are of no account. However, as the comparison frequency must be kept near 1 kc/s, the Remote crystals are adjusted in the field if necessary to give this difference with respect to the Master crystal, by reference to a calibrating oscillator at 1 kc/s. Deviations up to 10 c/s from this frequency can then be accepted as the display and amplifying circuits can accommodate this without error.

The Master A crystal must then be maintained or calibrated to within the accuracy required in the length measurement. An accuracy of 1 p.p.m. or better, that is 10 c/s

or better, can easily be achieved by temperature calibration or ovening.

The other Master crystals must be maintained to an accuracy of such that there is no breakdown in the ambiguity resolution process. As the ambiguity is broken down in 10/1 steps, the maximum phase error permitted in these patterns is, say, 2 or 3 per cent of a complete phase rotation. This corresponds to about 10 p.p.m. over a line of 20 to 30 miles length and these crystals must therefore be maintained to this accuracy. Greater line length requires a corresponding increase of accuracy from these crystals.

3.7 *Reverse readings*

Reverse readings are provided on the positive and negative patterns to eliminate centring errors in the display. For this purpose the phase of the comparison frequency issuing from the Remote detector is reversed by reversing the polarity of the detector diode.

3.8 *Resolution of residual ground reflection effects*

Using radio beams with reasonable aerial apertures it is not possible to obtain a transmission path free of spurious paths via a ground reflection or from other objects in the beam. In general, at 10 cm wavelength the amplitude of such reflections is found to be perhaps 10 per cent of the direct ray, or rather less in most cases, although exceptional cases have been encountered giving up to a 40 per cent reflection over flat barren ground. Over water surfaces a 40 per cent reflection is perhaps the rule rather than the exception, depending upon the state of the surface. The 45° polarization of the radiators is intended to minimise this effect over smooth conducting surfaces at shallow incidence, as the reflected wave is then polarized at right angles to the distant dipole. Whether any advantage is obtained in practice due to this is not known. The advantage is probably little in most cases but quite substantial over flat smooth water.

Higher carrier frequencies would be advantageous in reducing these reflections, both on account of the greater directivity obtainable and the greater scattering produced by a given degree of surface roughness.

The procedure for minimising these effects is to take a series of phase indications on

successive carrier frequencies, the mean of these indications giving a close approximation to the true direct path. Only the *A* pattern is so treated. The coarse pattern differences are relatively free of such errors, as the difference in path lengths involved is unlikely to be sufficient to perturb the coarse indications. As the carrier frequency is changed the readings swing about the true reading, but the four patterns *A*, *B*, *C* and *D* swing more or less in sympathy as their frequencies are close.

The following is a simplified description of this process. A detailed mathematical analysis of the process is given by Dr J. A. Fejer in an accompanying appendix.

Consider the transmission in one direction only and let the modulation be represented by a single sideband only, differing from the carrier frequency by the modulation frequency. Let the indirect ray consist of only one reflection, which must be weaker than the direct ray.

Referring to Fig. 4(a) let the vector *C* represent the carrier due to the direct ray as received at the Remote instrument at an instant of time. Let *S*, for simplicity regarded as the same amplitude as *C*, be the vector as received at the same instant representing the sideband which was in phase with the carrier when transmitted from the Master instrument. The phase angle θ , plus an unresolved number of whole rotations, is then a measure of the delay time along the path in terms of the modulation frequency and via the heterodyne process is the phase angle which is measured.

Let *c* and *s* represent the carrier and sideband of lesser amplitude as received over an indirect path. These are displaced, relative to the direct vectors, due to the different delay time in terms of the carrier wavelength, but if the path delay is substantially the same relative to the modulation frequency wavelength the angle between them is again approximately θ . Adding the two carrier vectors and two sideband vectors the resultant phase angle is still θ . Thus reflections, no matter how strong, cause little error if the path lengths are substantially the same. They do, however, cause a weakening or strengthening of the received signals, that is, one may be either in a lobe minimum or lobe maximum due to the ground reflection.

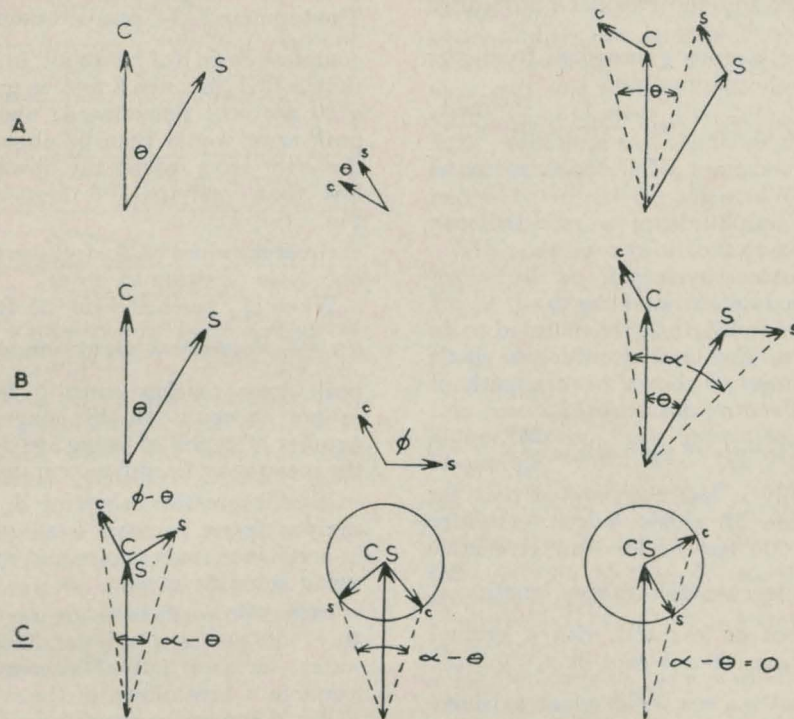


Fig. 4—Vector diagrams illustrating ground wave effects: (a) Refers to a ground wave of little excess length; (b) Refers to a ground wave of large excess length; (c) Illustrates the cyclic variation of the error angle

Fig. 4(b) shows the same vectors where the path differences are appreciable at the modulation wavelength. Here the carrier c is shown in a different phase relationship and the sideband displaced an angle ϕ due to the different path length. The resultant angle α between the sums is then seen to be considerably in error, the error angle being $\alpha - \theta$.

In Fig. 4(c) the direct carrier and sideband vectors have been redrawn in phase to simplify the argument, the error triangles remaining the same shape as before, the error angle $\alpha - \theta$ being as before and the angle between c and s being $\phi - \theta$ due to the rotation of S relative to C .

If the carrier wavelength is changed, the phase relationship of C and S remains constant and also the phase relationship between c and s but the latter two vectors rotate relative to C and S , the error angle being the angle between the two dotted vectors $\alpha - \theta$. The number of rotations is equal to the number of wavelengths of the carrier removed or added to the path difference by virtue of the change of carrier

wavelength.

It will be seen that the error angle goes through a cyclic change being equal to zero, in some positions, or positive or negative in other positions, the mean error angle being more or less zero if a number of cycles of 'swing' are developed.

A similar diagram may be drawn for the return path and a number of different reflection paths may be represented by similar diagrams. The period of these latter swings will be different and they may be phased differently but the sum of all will be periodic or quasiperiodic. In practice, due to the complexity of the reflected signal path, the phase plotted against frequency may assume a random distribution but the mean phase will give a good approximation to the true phase, provided the direct ray is substantially greater in amplitude than the combination of reflected rays.

3.9 Practical implications of ground wave theory

It is necessary to form some idea of the practical magnitude of the ground swings

that will arise and the residual errors after applying the technique.

Taking the simple expression from the appendix for the error angle:

$$\text{Error angle} = \Sigma a_i \cos \frac{2\pi \Delta_d}{\lambda_c} \sin \frac{2\pi \Delta_d}{\lambda_m}$$

which is derived from a full double sideband treatment. Where:

a_i is the amplitude of a reflected ray relative to the direct ray

λ_c the carrier wavelength

λ_m the modulation wavelength

Δ_d the excess length in the reflected path.

Referring to Fig. 5(a) in which a single ground reflection is shown over a path of length d and centre clearance h .

The excess length of the path is $\frac{2h^2}{d}$.

Operationally it has been stated that for a line of some 20 miles length, a centre clearance of 200 feet or less can give little error. In this case the excess length $\frac{2h^2}{d}$ is about 1 foot or less and with a ground reflection of, say, 30 per cent or $a_i=0.3$ the peak error, putting $\cos \frac{2\pi \Delta_d}{\lambda_c}$ equal to unity becomes:

$$\text{Error angle} = 0.3 \sin \frac{2\pi \cdot 1 \text{ ft}}{100 \text{ ft}}$$

which is about 0.15 of a foot in the indicated range, due to the forward path alone and therefore perhaps 0.3 of a foot total error as shown in Fig. 5(b). Only a fraction of a cycle of swing is developed due to the small excess length. The maximum carrier frequency deviation available is some 300 Mc/s or, say, 10 per cent of the carrier frequency.

The term $\cos \frac{2\pi \Delta_d}{\lambda_c}$ can be taken through one complete cycle if Δ_d is about $10\lambda_c$ or greater, that is if Δ_d is some 3 feet or greater. With a 30 per cent reflection as above, the total peak error would then be about 1 foot, and the error after taking the mean of the cycle less than perhaps 0.3 foot as shown in Fig. 5(c).

Greater values of Δ_d will cause more than one cycle of swing to occur.

When Δ_d reaches some 25 feet the term $\sin \frac{2\pi \Delta_d}{\lambda_m}$ reaches a maximum and the total peak error reaches some 5 feet, which it cannot exceed. At this stage, however, a number of cycles of swing are developed and the mean may be quite accurately estimated.

If still greater values of Δ_d are reached the peak error becomes less again and so on in a cyclic manner, more and more cycles of swing being developed.

Reflection coefficients greater than perhaps 40 or 50 per cent are not likely even over water surfaces but if encountered would result in a breakdown of the whole method.

Fig. 6 shows the amplitude distribution of ground swings taken from a large number of measurements in different conditions of topography.

It is seen that 50 per cent of measurements have peak ground swings of 0.4 foot or less. This is due to the fact that most lines of any substantial length are fairly shallow and little swing can arise. However, it is probable that the measured swings on shallow lines are not so much due to high reflection coefficients but to relatively large excess

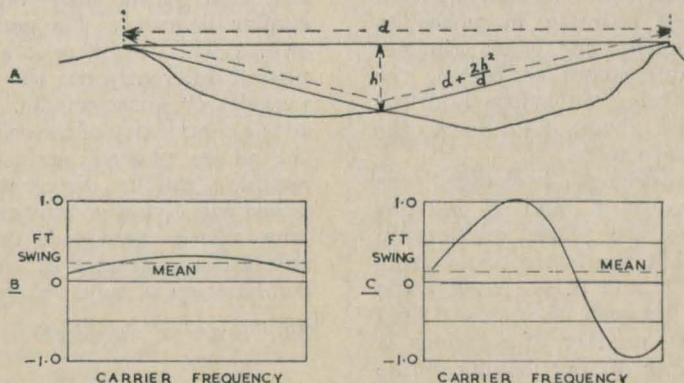


Fig. 5—(a) Diagram illustrating the excess length as a function of distance and ground clearance; (b) Refers to the swing with a ground wave of small excess length, say 1 foot; (c) Refers to the swing with a ground wave of excess length some 3 feet

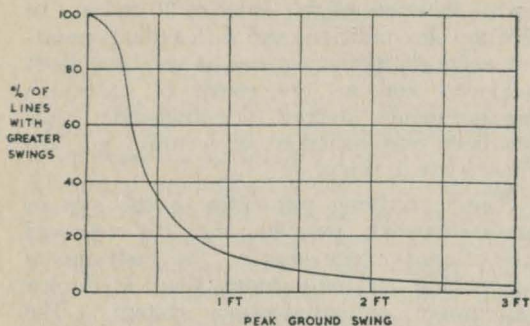


Fig. 6—Frequency of occurrence of various ground swing amplitudes derived from practical measurements

lengths of waves which are scattered from points on the ground well off to the side of the path of the direct ray and that the amplitude of these reflections is quite small. Numerous small scattered reflections must be involved and the frequency changes cause the statistical relationship between them to vary rapidly to give a mean value of phase which is probably better than the simple analysis above, based on a single strong reflection, would indicate.

4. SOME DESIGN DETAILS

4.1 Modulation of the klystrons

The klystrons must be coupled as tightly as possible to the transmitting dipole to give the maximum klystron bandpass of some 30 to 50 Mc/s.

The frequency deviations must be more or less equal at both klystrons and the modulation index must be somewhat less than unity, as discussed in detail in the appendix. Overmodulation is indicated by an excessive second harmonic and obvious distortion of the display circle.

It is also important that the klystrons be free of amplitude modulation at the modulation frequencies. This means that the klystron should have adequate bandpass and that the reflector voltage be reasonably well centred for each adjustment of cavity volume.

The effect of unwanted amplitude modulation is to cause errors in the phase reading. In the existing design these errors are apparent only with the reflector tuned to one edge or the other and reach a magnitude of the order of one foot. Attempts to modulate at much higher frequencies than

10 Mc/s, without adequate bandpass, produce severe errors due to these effects and the phase indications become very sensitive to reflector setting. If the detectors are run at a very low level of local excitation these errors disappear as the detection becomes truly quadratic and the mode of modulation is unimportant. However, to attain the necessary sensitivity this cannot be done in practice.

The possible origin of these effects may be explained as follows. Referring back to Fig. 3 the upper I.F. sideband was described as arising from the difference frequency $f_2 - f_5$ and this is true of quadratic detection. However, in the more complex detection, as the detector tends towards linearity or to higher power than quadratic, this same frequency will arise as the product $2f_1 - f_3 - f_5$, and similarly with the other sidebands. This process was determined by independent experiment to exceed the quadratic process ($f_2 - f_5$) by a factor of 3 in amplitude with the crystal detector running at a d.c. current of 0.7 mA due to the local excitation.

In the case of pure F.M. the sidebands resulting from both processes are in phase and thus indistinguishable. In the case of pure A.M. the results of these processes are subtractive. A modulation which contains both F.M. and A.M. in arbitrary phase relationship will give I.F. sideband phasing which will depend upon which detector process predominates and hence errors will arise which depend upon the nature of the detection at each end and which cannot be assumed to be identical.

It has been experimentally determined that these errors do not cancel out, as do other internal errors, when the technique of negative patterns is applied but the full explanation of the phenomenon has not been determined. For practical design purposes, however, the important fact is that modulation frequencies higher than can be comfortably accommodated by the klystron bandpass should not be attempted, in spite of the fact that it is possible to produce modulation sidebands well outside the nominal bandpass.

4.2 I.F. and audio design

The I.F. bandpass of 500 kc/s is determined mainly by klystron stability, although this full bandpass is useful but not essential to

accommodate the pulse modulation. The audio signals at 1 kc/s are restricted at both ends, however, to a 10 kc/s post detection bandpass to improve the circle signal-to-noise ratio and to stabilize the Remote relaying process. Greater restriction of bandpass would be possible although perhaps not desirable on account of phase instability.

The pulse deviation on the Remote klystron must be accurately adjusted to remain within the I.F. bandpass, otherwise the pulse will be reproduced in both A.M. detectors as a result of detection by the skirt of the I.F. response. This effect will occur even with correct deviation, if the instruments are detuned slightly. The effect causes a small distortion of the display circle at the Master instrument, and at the Remote instrument it will interfere with the pulse forming circuits. If the audio bandpass is too wide a regenerative effect can set in and give a series of mark pulses. However, with the audio bandpass restricted to 10 kc/s no regeneration takes place and the display is stable, although slightly distorted when off tune, as must be expected. It is apparent that any attempt to return the 1 kc/s wave as a C.W. instead of a pulse, would lead to great practical difficulties on account of the above effects, in spite of the fact that in principle it is possible, given flat topped I.F. responses, perfect A.M. and F.M. detection and with the instrument exactly tuned.

An important design consideration is to ensure that the I.F. tuning is independent of A.V.C. level, otherwise the discriminator centring will vary with signal strength and it will be impossible to tune correctly for both F.M. and A.M. detectors at all ranges.

It is also important of course that both Master and Remote I.F. frequencies be adjusted to accurate frequency standards, or at any rate to the same standard if they are to work together satisfactorily.

5. CONCLUSION

The Tellurometer system, which has been described, is capable of achieving timing accuracies greater than is necessary to fulfill the original operational requirement. The claimed accuracy of the system in average climatic and topographical conditions is 2 inches $\pm$ 3 p.p.m. on a single measurement

up to distances of the order of 30 miles. In favourable conditions and with skilled operating accuracy perhaps twice as good has been achieved and as the result of extensive measurements overall trigonometric scale has been established to an accuracy not less than some 1 p.p.m.

The underlying principles of the system are somewhat complex but its practical execution is very simple, the instruments amounting to little more than a duplex microwave communication system. The system is such that it is relatively free of errors due to design or adjustment defects and in general if it is working at all the measurements are accurate, the finer points of design adjustment and operation being necessary to achieve only the ultimate in accuracy.

The instrumental technique is thought to be capable of very nearly exhausting the limit of accuracy due to uncertainties in the distribution of the meteorological conditions along the path. Further development of the system in the direction of higher carrier and modulation frequencies is unlikely to produce much improvement in operational results at the longer ranges. Such development, however, will improve accuracy at shorter ranges of the order of a few hundred feet up to a mile or two and at longer ranges may improve the ease of measurement due to lessened ground wave effects but insofar as the majority of overland lines are relatively free of ground effects with the present design not much improvement in this respect need be attained.

6. ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of Dr J. A. Fejer who was responsible for the preparation of the full mathematical treatment of the Tellurometer principles which are given in the accompanying appendix and also to thank the Council for Scientific and Industrial Research for permission to publish this paper.

REFERENCE

- (1) WADLEY, T. L. The Tellurometer System of Distance Measurement; Empire Survey Review, Nos. 105, 106, and 107, Volume XIV, July and October, 1957, and January, 1958.

7. APPENDIX

7.1 *The first conversion in Tellurometers*

In the first conversion process of a Tellurometer, a strong local frequency modulated signal is heterodyned with a received frequency modulated signal. The products of this heterodyne process are signals of constant amplitude at linear combinations of the two 'instantaneous' input frequencies. These linear combination frequencies themselves vary in time resulting in frequency modulated signals. Only one of these combinations, the difference frequency, is in the neighbourhood of the receiver intermediate frequency.

Let the two signals be proportional to

$$\exp[j(\omega + m \sin \Omega t)] \\ \exp[j(\omega' + m' \sin \Omega' t)]$$

where t is the time, ω and ω' the two circular carrier frequencies and Ω , Ω' the circular modulation frequencies. Let $\omega > \omega'$ and $\Omega > \Omega'$. Then the signal at the difference frequency will be proportional to $v = \exp[j(\omega t - \omega' t + m \sin \Omega t - m' \sin \Omega' t)]$ (1)

Using the relation

$$\begin{aligned} n = +\infty \\ \exp(jx \sin \theta) = \sum J_n(x) \exp(jn\theta) \\ n = -\infty \end{aligned}$$

(1) may be re-written in terms of the Bessel functions J_n as

$$v = \exp[j(\omega - \omega')t] \sum_{m=-\infty}^{+\infty} J_n(m) \exp(jn\Omega t) \sum_{m'=-\infty}^{+\infty} J_{n'}(m') \exp(jn'\Omega' t)$$

$$J_n(-m') \exp(jv\Omega' t) \dots \dots \dots (2)$$

Using the identities $J_n = (-1)^n J_{-n}$ and $J_n(x) = (-1)^n J_n(-x)$ which are valid for integral n and writing $\Omega - \Omega' = p$, v may be evaluated by multiplying term by term the two series resulting from the summations indicated in (2). Collecting only the terms with frequencies

$\omega - \omega'$, $\omega - \omega' \pm p$, $\omega - \omega' \pm 2p$, etc., which fall within the bandwidth of the I.F. amplifier, one obtains

$$v = J_0(m)J_0(m') \exp[j(\omega - \omega')t] + J_1(m)J_1(m') \{ \exp[j(\omega - \omega' + p)t] + \exp[j(\omega - \omega' - p)t] \} + J_2(m)J_2(m') \{ \exp[j(\omega - \omega' + 2p)t] + \exp[j(\omega - \omega' - 2p)t] \} + \dots \dots \dots (3)$$

Equation (3) shows that the signal at the intermediate frequency $\omega - \omega'$ is amplitude modulated at the difference frequency $p = \Omega - \Omega'$ between the two modulation frequencies and its harmonics. The percentage modulation at the fundamental

frequency p is $[J_1(m)J_1(m')]/[J_0(m)J_0(m')]$ while the percentage second harmonic distortion of this modulation is $[J_2(m)J_2(m')]/[J_1(m)J_1(m')]$. The higher harmonics can be ignored in comparison with the second harmonic for low modulation indices.

For $m = m' = 1$ one obtains about 27 per cent modulation with 6 per cent second harmonic distortion, while for $m = m' = 0.5$ about 7 per cent modulation with 1.3 per cent second harmonic distortion is obtained. Tellurometers are usually adjusted to operate somewhere between these two limits.

7.2 *The effect of relatively weak ground reflections in Tellurometer measurements*

Considering the forward path alone the first conversion occurs at the remote station. Let the signals generated at the master and remote station be

$$\exp[j(\omega t + m \sin \Omega t)] \\ \exp[j(\omega' t + m' \sin \Omega' t)]$$

Let the signal come partly by the direct path which delays it by a time T_0 and partly by a number of indirect paths involving reflection by the ground which delay it by times $T_0 + T_i$, $i = 1, 2, \dots$ and let the amplitude of signals arriving by indirect paths have amplitudes which are smaller by factors a_i than the amplitude of the direct signal. The received signal is then proportional to $\exp\{j[\omega(t - T_0) + m \sin \Omega(t - T_0)]\} + \sum_i a_i \exp\{j[\omega(t - T_0 - T_i) + m \sin \Omega(t - T_0 - T_i)]\} \dots \dots \dots (4)$

If the received signals are relatively weak, it is reasonable to assume that the signal produced at the mixer output is the sum of the signals which would be produced by each part of the received signal (4) and considering carrier and first order sidebands only and applying equation (3), the mixer output is proportional to

$$[J_0(m)]^2 \{ \exp[j\omega(t - T_0) - j\omega' t] + \sum_i a_i \exp[j\omega(t - T_0 - T_i) - j\omega' t] \} + [J_1(m)]^2 \{ \exp[j(\omega - \omega' + p)t - j\omega T_0 - j\Omega T_0] + \sum_i a_i \exp[j(\omega - \omega' + p)t - j(\omega + \Omega)(T_0 + T_i)] \} + [J_1(m)]^2 \{ \exp[j(\omega - \omega' - p)t - j\omega T_0 - j\Omega T_0] + \sum_i a_i \exp[j(\omega - \omega' - p)t - j(\omega - \Omega)(T_0 + T_i)] \}$$

By taking out common factors and dividing all the three terms by the first one (this does not change the relative phases and amplitudes of carrier and sidebands) one obtains

$$\frac{1 + \{[J_1(m)]^2/[J_0(m)]^2\} \{ \exp(jpt - j\Omega T_0) \frac{1 + \sum_i a_i \exp[-j(\omega + \Omega)T_i]}{1 + \sum_i a_i \exp(-j\omega T_i)} + \exp(-jpt + j\Omega T_0) \frac{1 + \sum_i a_i \exp[-j(\omega - \Omega)T_i]}{1 + \sum_i a_i \exp(-j\omega T_i)} \}}{1 + \sum_i a_i \exp(-j\omega T_i)} \quad (5)$$

The signal represented by (5) is not purely amplitude modulated except when all the a_i are zero. In that case the amplitude modulation is delayed by ΩT_0 .

The last bracketed expression in (5) is proportional to the complex ratio of the 'instantaneous' combined sideband amplitude to the carrier amplitude and has the form of $M \exp(j\Psi) + N \exp(-j\Psi)$ where $\Psi = jpt - j\Omega T_0$

$$M = \frac{1 + \sum_i a_i \exp[-j(\omega + \Omega)T_i]}{1 + \sum_i a_i \exp(-j\omega T_i)} \\ N = \frac{1 + \sum_i a_i \exp[-j(\omega - \Omega)T_i]}{1 + \sum_i a_i \exp(-j\omega T_i)} \quad (6)$$

It can be shown that a part of this bracketed expression given by

$$\{ \operatorname{Re}[(M+N)/2] + \operatorname{Im}[(M-N)/2] \} \exp(j\Psi) + \{ \operatorname{Re}[(M+N)/2] - \operatorname{Im}[(M-N)/2] \} \exp(-j\Psi)$$

represents the amplitude modulated component. The error β in the phase of the amplitude modulation is therefore $\beta = \arctan \{ j^{-1} \operatorname{Im}[(M-N)/2] / \operatorname{Re}[(M+N)/2] \}$... (7)

If the a_i in expression (5) are relatively small it is easily shown that

$$\operatorname{Re}[(M+N)/2] \sim 1 \\ j^{-1} \operatorname{Im}[(M-N)/2] \sim - \sum_i a_i \cos(\omega T_i) \sin(\Omega T_i)$$

and substituting these values into (6)

$$\beta \sim - \sum_i a_i \cos \omega T_i \sin \Omega T_i \quad \dots \quad (8)$$

or expressed in terms of the path delay Δd_i , carrier wavelength λ_c and modulation wavelength λ_m

$$\beta = - \sum_i a_i \cos(2\pi \Delta d_i / \lambda_c) \sin(2\pi \Delta d_i / \lambda_m) \quad (9)$$

Expression (8) shows that if the excess delays ΩT_i in the modulation phase of the indirect rays are sufficiently small then the error β will be small even if the amplitudes a_i of the ground reflections are substantial. This corresponds to the case in which the path differences between direct and reflected rays are much smaller than the wave length of the modulation frequency.

If the path differences are not small compared to the modulation wave length then they must be very much longer than the wave length of the carrier so that the ωT_i are very large. In this case the contribution

of each reflected wave to β is a cosine function of the circular carrier frequency ω with a period $\Delta \omega = 2\pi/T_i$ or expressed in frequency $\Delta f = T_i^{-1}$ and with an amplitude (in radians) $a_i \sin \Omega T_i$.

A similar argument may be applied to the primary process in the return direction, the secondary process being ignored as its modulation wavelength is extremely long and the contributed error negligible.

The two cosine functions are not identical because the carrier frequencies for the forward and return path are not identical. The return path thus adds a further group of cosine functions to equation (8) which may be in or out of phase with the errors due to the forward path depending on the delays T_i and the difference between the two carrier frequencies.

The above result justifies the measurement procedure used in the Tellurometer system to eliminate errors caused by relatively weak ground reflections. This procedure consists in the measurement of the indicated phase as a function of the RF carrier frequency. This results in a quasi-periodic variation about a certain mean value which is accepted as the correct phase angle. Sufficient frequency deviation is provided to ensure that many cycles are developed when the path differences are large enough to cause a substantial error due to the large value of $\sin \Omega T_i$ in equation (8).

7.3 Effect of a single relatively strong ground reflection

In the preceding section it was shown that if the ground reflections are weak, then the phase angle read from the Tellurometer display is a function of the carrier frequency. This function was seen to be the sum of the phase angle in the absence of ground reflections and of a number of cosine functions of the carrier frequency corresponding to the individual rays reflected from the ground. It is of interest to know how far this relationship breaks down if the ground reflections are strong.

The case of a single ground reflection (i only assumes the value unity) is treated here using a graphical method based on (6) and (7). The numerators and the common denominator of M and N are plotted on the complex plane in Fig. 7 where O is the origin, Q represents unity (on the real axis)

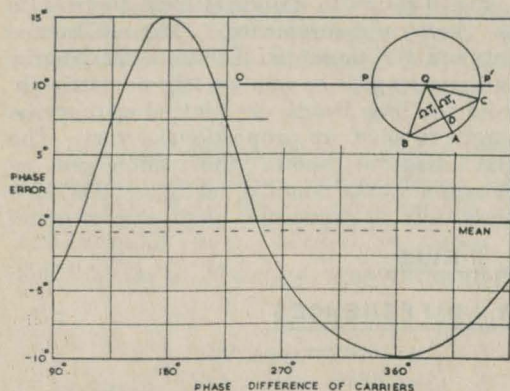


Fig 7—Diagram illustrating the asymmetry and consequent error of the mean swing due to a single very strong ground reflection

and the vectors $\vec{QA}$, $\vec{QB}$ and $\vec{QC}$ represent $a_1 \exp(-j\omega T_1)$, $a_1 \exp[-j(\omega + \Omega)T_1]$ and $a_1 \exp[-j(\omega - \Omega)T_1]$ so that the points A , B and C represent the common denominator and the numerators of M and N so that

$$M = \vec{OB}/\vec{OA} \quad N = \vec{OC}/\vec{OA} \quad \dots \quad (10)$$

The vector $\vec{OD}/\vec{OA}$ therefore represents $(M+N)/2$ and the vector $\vec{DB}/\vec{OA}$ represents $(M-N)/2$. According to equation (7) therefore the tangent of the error angle may be expressed as the ratio of the component of the vector $\vec{DB}$ perpendicular to $\vec{OA}$ to the

component of the vector $\vec{OD}$ parallel to $\vec{OA}$. As the carrier frequency varies, the points A , B and C move around on the circle without changing their relative position. It is easily seen from Fig. 7 that the error changes sign and that the largest errors β_1 , β_2 of different sign occur when A passes the real axis, i.e. coincides with P or P' where

$$\tan \beta_1 = (a_1 \sin \Omega T_1) / (1 + a_1 \cos \Omega T_1) \quad \dots (11)$$

$$-\tan \beta_2 = (a_1 \sin \Omega T_1) / (1 - a_1 \cos \Omega T_1) \quad (12)$$

Thus β_1 and β_2 are generally of opposite sign and unequal. They are approximately equal if a_1 is small and exactly equal even for large a_1 if $\Omega T_1 = v(\pi/2)$ where v is an integer. The largest asymmetry of the β , ω curve therefore occurs in the neighbourhood of $\Omega T_1 = (2v+1)(\pi/4)$ where v again is an arbitrary integer.

Fig. 7 shows β as a function of ω for $\Omega T_1 = \pi/4$. The curve was constructed using the graphical method described above and assuming a reflection coefficient $a_1 = 0.3$. The average value of β was determined by graphical integration and is indicated by the broken horizontal line. The error caused by using the mean value is 0.72 degrees or 0.2 feet if the errors on the forward and return paths add.

8. APPENDIX II

8.1 Determination of the velocity of electromagnetic waves

During April, 1957, a programme of Tellurometer measurements of the Ridgeway

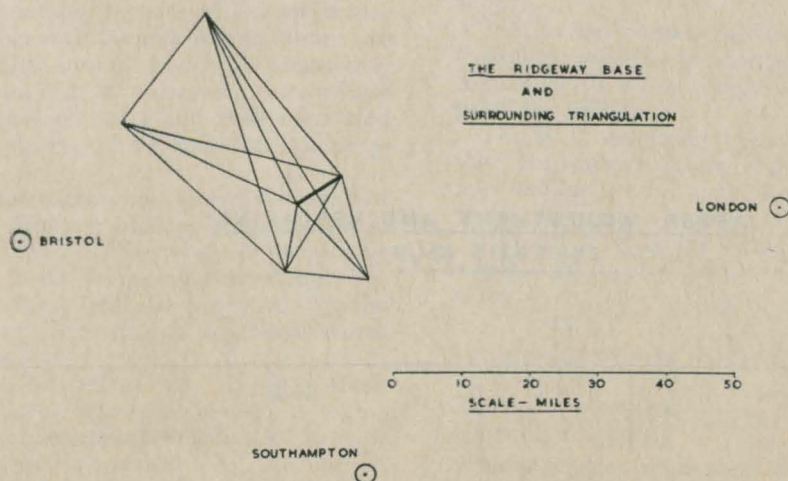


Fig. 8—Location and proportions of the Ridgeway base figure in the South of England. The double line represents the base itself

Geodetic Base in the South of England and the surrounding primary triangulation was carried out with a view to obtaining velocity measurements of high precision. This base-line, some seven miles long, is probably the most accurately taped base in the world. Fig. 8 shows the location and approximate proportions of the figure measured. The double line represents the base line itself.

Fig. 9 shows in graphical form the results of these measurements. The difference between the measured Tellurometer lengths and the lengths computed trigonometrically from the base length are plotted against the length to show up proportional errors. The first diagram shows the differences as measured at the nominal velocity of 299792.0 km/s. It is apparent that the nominal

RIDGEWAY BASE FIGURE

TRIG — TELLUROMETER DIFFERENCES

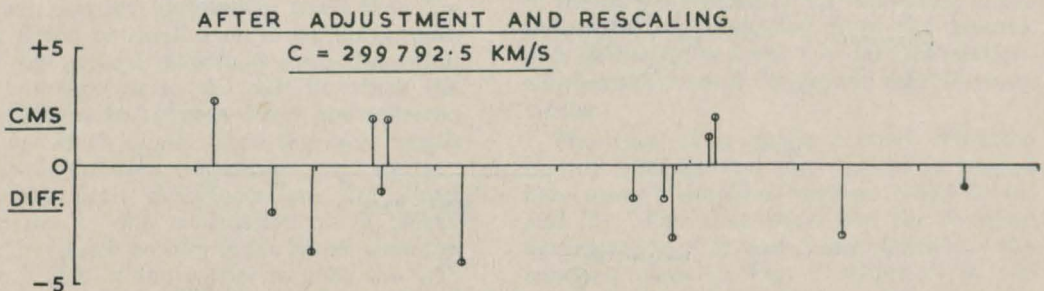
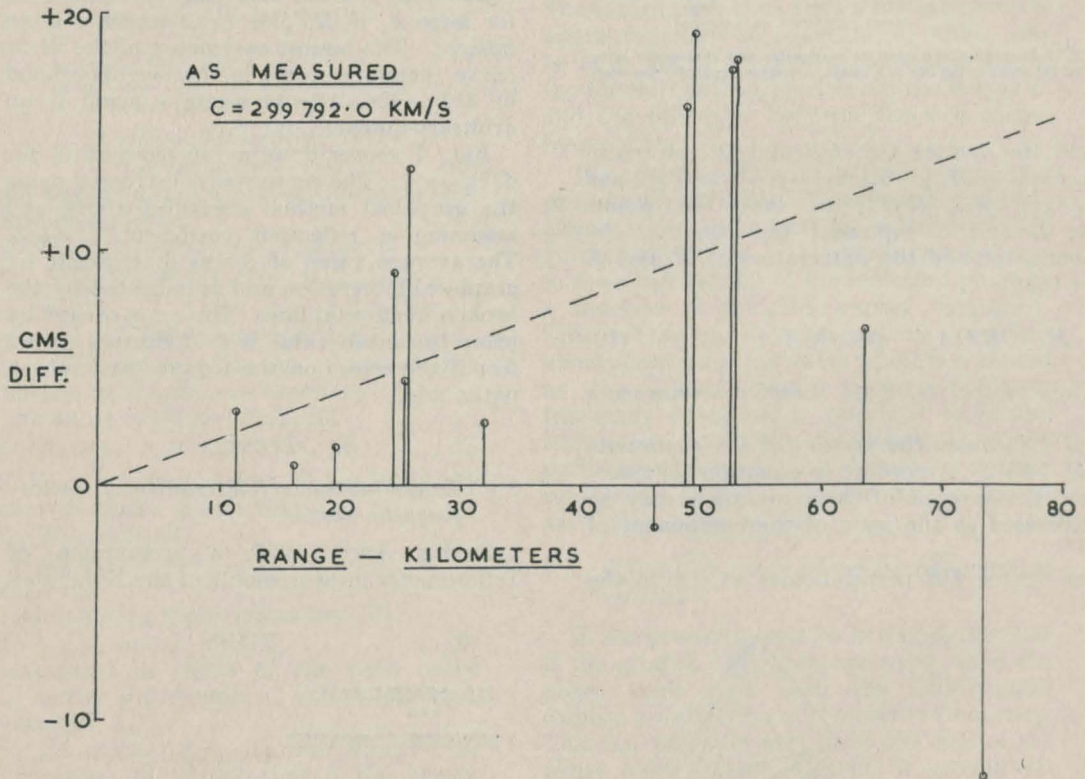


Fig. 9—The results of the measurements of the 14 lines constituting the Ridgeway figure. The dotted line indicates the rough proportionality of the errors, due to the assumed velocity being somewhat too low

velocity is somewhat low. The discrepancy on the longest line is probably due to the uncertainty of the curvature corrections applied, which increases as the cube of the range.

The second diagram shows the results after the figure has been adjusted to self-consistency by a least squares adjustment and rescaled to a velocity in vacuo of 299792.5 km/s. The mean square adjustment

was 1.7 p.p.m. and the mean square agreement after rescaling was 1.0 p.p.m.

The base accuracy is claimed to be better than $\frac{1}{2}$ p.p.m. and the accuracy of the velocity arrived at is, on the evidence of the measurements, probably of the same order. This value is in virtually precise agreement with a recent laboratory determination made by the British National Physical Laboratory and is the value presently adopted for use in Tellurometer measurement.

DISCUSSION

1. INTRODUCTORY

R. D. SMITH

Following on Mr Wadley's paper dealing with the electronic principles of the Tellurometer, these notes dealing with some of the practical aspects would perhaps be of interest.

2. BASIC EQUIPMENT

Basic equipment consists of:

(a) Master unit	...	Weight 25 lb
(b) Remote unit	...	" 25 "
(c) 2 Power supplies	...	" 10 " each
(d) 2 Tripods	...	" 10 " "
(e) Battery prime movers	...	" 28/50 lb depending on type
(f) Transit case	...	" approx. 15 lb

3. PRIME MOVERS

The heaviest single item has, up to now, been the battery prime mover. This is required to supply 6 volts at 7.5 amps and capacities between 30 and 50 amp-hours are normal. The normal lead-acid, nickel-iron and cadmium cells all come within the above mentioned weight range and have been used extensively in regard to operating temperature.

A new type battery, developed on behalf of the British Ministry of Supply, is now available, weighing 16 lb with 30 amp-hour capacity. Tests are being carried out but the choice must still be governed by the operating requirements and the temperatures likely to be experienced.

As an alternative, the U.S.A. Army Engineer Corps have developed a light-weight petrol alternator weighing 17 lb with an output capacity of 150 VA. Regulation for voltage and frequency, as referred to the

normal output of 115 V 60 cycles, is better than 5 per cent. The price factor is high for this type of unit.

4. TEST PROCEDURE

As indicated in Mr Wadley's paper, one of the prime requirements for overall accuracy in the equipment is that the modulation oscillator frequencies and drift characteristics shall be accurately known.

The 10 mgs 'A' crystal circuit, being in effect the portable yardstick, is individually calibrated against temperature over the range 10°C to 40°C. For this B.T. type crystal the nominal cross-over temperature is $28^{\circ}\text{C} \pm 2^{\circ}\text{C}$.

It is understood that, from the manufacturers' point of view, this requires maintaining the cut accuracy to within 6 minutes of arc.

The temperature in the crystal box is indicated by a thermistor operating in a bridge circuit from a regulated power supply.

Within the normal calibrated range it is, therefore, possible to interpolate the actual frequency to an accuracy better than one part per million.

The B, C and D crystals are checked over the temperature range and then matched into similar groups such that drifts due to temperature are symmetrical.

Initially a reject percentage of 30 per cent was normal, typical percentage reject figures being:

	per cent
Incorrect cross-over temperature	16
Low activity	11
Envelope breakage	2
Unstable frequency	1

More recent results show that problems of cross-over temperature and low activity

have been almost eliminated, leaving an overall rejection rate of about 5 per cent providing the specifications are adhered to.

5. MICROWAVE CARRIER SYSTEM

The variable cavity system is primarily a mechanical problem, but it has been necessary to check the frequency range before assembly, particularly in view of the restricted frequency allocation granted by the F.C.C. in the United States of America.

The dipole assembly, being a one piece moulding, created difficulties until a modified moulding technique was adopted. Careful control of assembly and moulding has enabled the variations in receiver crystal current to be held within 2 : 1 ratio. Once moulded, no adjustment is possible.

6. TEMPERATURE OF OPERATION

In the early stages of manufacture it was found that what was considered normal operation in temperate climates (10° to 40°C) was very definitely abnormal by world standards. Thus, it was necessary to provide some form of heating and lagging to the master crystals and so allow the temperature for normal operation to be extended down to 0°C.

However, this question of extending the operating temperature range down has perhaps been the most pressing problem during the past year. Whatever the temperature goal was, it has not been low enough and it is now necessary to consider operation over the full temperature range -40°C to +40°C, and safe storage down to -60°C.

This has meant many changes in approach and ideas and, of course, has increased the power drain on the battery. In South Africa this has meant going into many details of cold weather operation that are not encountered here.

The following is an extract from a report on tests carried out by the Topographical Survey Division of the Mines and Surveys Department, Canada, and indicates some of the problems involved:—

'The equipment under test was placed in a cold chamber at -60°F for approximately 24 hours before carrying out the tests.

All normal controls were completely frozen solid and immovable, with the exception of the key and rotary switches.

On first operating the L.T. toggle switch it was necessary to wait approximately five minutes before the switch operated and L.T. power passed to the unit.

All cables were brittle and the telephone cable broke in several places during setting up of the equipment. The main power cable was only uncoiled with difficulty.

These tests were repeated at -40°F and it was still not possible to obtain full operation. A comparison test with a unit modified by the Hydrographic Survey, and having a 20 watt heater inside, was carried out at -20°F. Satisfactory operation was possible under these conditions.

Further tests at -10°F were not possible, due to difficulty of controlling the cold chamber at this temperature.'

Tests carried out by the U.S. Army Engineer Corps have similar results.

This has meant, in some cases, somewhat protracted and acrimonious correspondence with overseas manufacturers who are unable to understand why South Africa should have these requirements.

Equipments have been modified to meet the specification and are now in Norway for trials prior to being used in the Antarctic next year. Similar modifications are proposed for equipments to be used in Greenland.

7. OPERATORS' TRAINING

The general approach on the question of suitable training for operators and operating groups has been somewhat varied.

Generally speaking, operators are surveyors or surveying assistants who have very little electronic training. The more common approach is for the operator to go through approximately four days' training at training points established in the main countries.

These courses are particularly advisable as some simple fault finding procedure can be incorporated and minor problems, such as changing fuses and tubes, can be overcome quickly.

The period of four days' training is also recommended in a report put out by the Engineering Research and Development Laboratory of the U.S.A. Army, who state:

'Average inexperienced personnel can be taught to make accurate distance measurements within the capabilities of

the instrument with approximately 16 hours of supervised instruction, and one or two days' full training and practice without assistance from an experienced operator.'

In many cases, however, equipments have been sent out to surveyors with the Instruction Manual and they have been left to fend for themselves. In a number of cases where groups are operating in remote areas, an electronic engineer or technician has been attached to the group. In most cases the best information of a technical nature has been obtained from these groups.

8. REPORTS ON FAULTS DEVELOPING DURING FIELD OPERATION

It is now possible to correlate a number of reports of groups operating throughout the world over the past year.

Most of the equipments are of early production and reports are available because they were put into use almost immediately; the figures quoted cover a total of about 20 instruments and refer to varied conditions (Alaska/Aleutians; Canada; Ethiopia; Kenya; New Zealand and United States of America).

The periods involved cover one to nine months and average four months. A total of forty-four faults are covered and the breakdown gives the following general characteristics:

	per cent
Vibrator unit and vibrator connecting cable	32
Sub-unit faults	29.5
External problems	25
Carrier	6.75
Handset	6.75

The known mileages involved during these actual survey operations referred to mounts up to a figure in excess of 25 000 miles, not counting the travelling to the start points.

All types of transport were used—commercial air transport; military helicopter; survey vessels; rail; jeep; lorry and man pack.

Conditions varied from below freezing to high temperatures and humidities. The operators in many cases had shown great ingenuity in getting the equipments operating under unexpected conditions.

9. REPRODUCIBILITY

A series of short-range tests were carried out recently with the object of determining whether, over a period of time, a slowly increasing fixed error had perhaps been introduced into the equipments. It was possible to compare instruments from very early production with mid-production and recent production pairs. The operators were varied for each run and operators under instruction were also used. Long-range tests were not undertaken but on each of the three distances measured the maximum variations between all instruments was:—

± 0.67 in ± 1.385 in ± 2.04 in

Master instrument serial numbers:
2—72—153—161.

Remote instrument serial numbers:
2—94—199—219.

10. CONCLUSION

The results quoted have been collected from as broad a field as possible. The equipments operating in Africa being closer to home have been able to give better detail but it must be recorded how much the assistance given by the various overseas agencies is appreciated.

GENERAL NOTES

1. Approximately 20 instruments covered by this report.
2. Minimum period under review 1 month.
3. Maximum period under review 9 months.
4. Average period under review 4 months.
5. Total of 44 faults reported.

APPENDIX

1. Dominion Hydrographic, Canada.
2. Directorate Overseas Surveys, Nairobi.
3. Coast and Geodetic Survey, U.S.A.
4. Hunting Aero Services Ltd., Ethiopia.
5. U.S. Army Engineer Research and Development Laboratory.
6. Lands and Survey Department, New Zealand.
7. Directorate Overseas Surveys Isiola/Malendi Traverse.
8. Fault Breakdown.

APPENDIX 1

EXTRACT FROM REPORT DATED DECEMBER 4TH 1957

DOMINION HYDROGRAPHER, CANADA

OTTAWA

Period	Faults reported	Action taken	Remarks
Survey season 1957	1. Tripods unstable	1. Wild tripods used	1. Improved tripod now available
	2. Vibrator plug connector. Loosening of shell connecting sections	2. Replaced by Jones plugs	2. Plug improvements made
Est. June/Sept.	3. Battery 12 V requested due low temperature capacity fall off	3. Larger 6 V battery used	3. 12 V battery supply can be supplied
	4. Vibrator pack damaged in helicopter crash	4. Rebuilt on board survey vessel	4. Operated satisfactorily
	5. Below zero temperature operation not possible	5. 20-watt heaters installed	5. Operation possible down to -20°F

Master Instrument Serial No. MA. 19 Remote Instrument Serial No. not reported

Power Pack Serial No. not reported

NOTE : (a) Operated from H.M.C.S. "Labrador" in Eastern Arctic waters and during a traverse along the East Nova Scotia Coast

APPENDIX 2

EXTRACT REPORT. ELECTRONIC AIDS (EAST AFRICA) LTD. NAIROBI.

DIRECTORATE OF OVERSEAS SURVEYS, NAIROBI.

DATED 21.4.9158

Period	Faults reported	Action taken	Remarks
	1. Condensor trimmer lead broken	Service by Electronic Aids (East Africa) Ltd. Nairobi	1. Leads resoldered. Support bracket fitted
	2. LT/HT switch not working		2. Switches replaced
	3. High resistance fuse		3. Replaced fuse
	4. Vibrator pack U.S.		4. New transformer required

Instrument Serial numbers not reported.

NOTE : (a) Travel details unknown.

APPENDIX 3

COAST AND GEODETIC SURVEY. (REFER TECHNICAL BULLETIN No. 2. MARCH 1958). TELLUROMETER TRAVERSE SURVEYS. (LIEUT. HAL. P. DEMUTH).

Period	Faults reported	Action taken	Remarks
June 1957 Alaska	1. Tripod requires strengthening	1. No action taken	1. Tripod improvements made
July 1957 Virginia	2. Reflection problems	2. Split readings taken	2. Unusual reflection factors
	3. Pack arrangements	3. Reported with suggested improvements	3. Light pack system now standard. Introduced July 1957
	4. Transit case should be improved	4. Reported	4. Newer, waterproof, welded case introduced Dec. 1957
	5. Low temperature operation requires additional heat	5. Warming instruments and external thick padding	5. Temperature range extension problem

Instrument Serial numbers not reported

NOTE : (a) Travel to Alaska and return. During Alaska operating unit back-packed after landing by launch from sea. During Highway Survey in Virginia normal motor transport

APPENDIX 4

HUNTING AERO-SERVICES LTD., ETHIOPIA. REPORT DATED 1ST MARCH, 1958, BY J. A. DE KOCK, CHIEF SURVEYOR, ETHIOPIAN HIGHWAYS PROJECT

Period	Faults reported	Action taken	Remarks
Oct. 1957 to Jan. 1958	1. Headphone noises	1. Repaired broken lead I.F. input	1. Locally repaired
	2. Intermittent operation	2. Faulty plug join repaired	2. " "
	3. No marker pulse	3. Adjusted discriminator plug for more pulse	3. " "
	4. Low crystal current	4. Klystron changed	4. Ex spares box
	5. " " "	5. Poor contact on crystal diode	5. Locally repaired
	6. Bad joint output socket power pack	6. Repaired	6. " "
	7. Limiting resistor burnt out	7. Replaced	7. " "
	8. Noises in headphone	8. O.C. capacitor replaced	8. At Addis Ababa

Master Instrument Serial No. MA.14.

Remote Instrument Serial N. RA.14 and 20.

Power Packs Serial Nos. CBV. 31 - 32 - 33.

NOTE : (a) No great distances travelled during period.

APPENDIX 5

U.S. ARMY ENGINEER RESEARCH DEVELOPMENT LABORATORY. 59 MASTER SET UPS. 52 REMOTE SET UPS.
TOTAL OPERATING HOURS — 152 hours.

Period	Faults reported	Action taken	Remarks
March 1957 to July 1957	1. Crystal in Remote unit damaged during commercial air shipment	1. Replaced	1. Time taken — 30 minutes
	2. Remote telephone faulty	2. Replaced insert	2. Time taken — 20 minutes
	3. Switched meter on Master sticking	3. No action	3. Not replaced or repaired
	4. Power connector short	4. Trace and repair	4. Time taken — 1 hour
	5. I.F. chassis bent and mount broken during commercial air shipment	5. Repaired	5. Time taken — 1 man hour
	6. Top reflector bent during air shipment	6. Straightened	6. Time taken — 15 minutes
	7. Door to phone compartment bent during air shipment	7. Straightened	7. Time taken — 15 minutes

- NOTES : (a) Serial numbers not specified, but very early production
 (b) During these tests units travelled 500 miles by lorry and station wagon; 5 000 miles by commercial air transport and 5 000 miles by sedan
 (c) Area—Washington and Desert Area Yuma

APPENDIX 6

REPORT FROM ELECTRONIC NAVIGATION LTD., AUCKLAND.

LANDS AND SURVEYS DEPARTMENT, NEW ZEALAND.

28.2.1958.

Period	Faults reported	Action taken	Remarks
Feb. 1958	1. Vibrator unit. Metal rectifier corrosion shorting H.T.	1. Cleaned off corrosion	All faults traced to excess moisture
	2. Flashing over at terminals and between tagboards	2. Excess moisture dried out	
	3. Defective diode	3. Diode replaced	
	Units kept in wet transit cases		No effort to dry out equipments at any time

Instrument Serial numbers at present unknown.

- NOTE : (a) These equipments were sent by sea for 120 miles and landed by small boat, taken by Army truck 60 miles over a track and then 30 miles along a beach, then $3\frac{1}{2}$ days man packed 12 miles to mountain top (5 800 ft). The area is subjected to extremely high rainfall and high humidity is normal.

APPENDIX 7

DIRECTORATE OF OVERSEAS SURVEYS. TRAVERSE ISIOLA/MALINDI. EMPIRE SURVEY REVIEW JULY 1958.

FIRST ORDER TRAVERSE WITH TELLUROMETER BY COL. G. J. HUMPHRIES.

Period	Faults reported	Action taken	Remarks
June July 1957	1. Power pack fault 2. Remote oscillator trimmer leads fractured 3. Power pack plugs and leads	1. Spare power pack available 2. Leads re-soldered in field 3. (a) Dust in fine threads of plug clamp ring causing seizing up of thread (b) Screwed braiding not sufficiently clamped by locking ring of plug. Field adjustments	1. Vibrator replacement necessary 2. Additional bracket support required and flexible leads advisable 3. (a) Cleaning of threads occasionally until possible coarse thread plug available (b) New type clamp ring more successful

DIRECTORATE OF OVERSEAS SURVEYS. (TRANSFERRED TO A NEW GROUP AT LAMU).

Period	Faults reported	Action taken	Remarks
July-end Nov. 1957	1. Fractured lead oscillator trimmer Remote 2. Whistle on headset Master unit 3. Vibrator pack noisy and intermittent 4. Recalibrate master crystal 5. Failure klystron crystal current 6. Master unit no circle 7. Noisy tests	1. Lead repaired in field 2. Returned to Cape Town for overhaul 3. November 21st. 1957 4. } 5. Replaced in field 6. Returned to Cape Town for overhaul 7. March 18th, 1958	1. Excessive vibration on solid lead. Change to flex lead and bracket 2. Broken cable headset lead. Replaced 3. New vibrators fixed (available in spares box) 4. Check recalibration 5. Loan equipments
Nov. 25th 1957 Mar. 26th 1958	8. A crystal not setting on Remote 9. Plug connections poor 10. Vibration faults on banging unit 11. L.T. switch vibrator pack O.C.	8. " 9. " 10. " 11. "	6. O.C. coupling condensor replaced 7. Chassis bonding checked and loosened bolts tightened 8. Add capacity fitted 15PF and trimmer capacity lead resoldered 9. Plug connections re-made 10. Poor earth bonding between chassis units 11. New switch fitted

Master Instrument Serial No. MA.15.

Remote Instrument Serial No. RA.15.-21.

Power packs Serial No. CBV.29-30-79.

NOTE: (a) Extensive mileage in excess 1 500 miles over all types rough road in Land Rover and 3/5-ton lorries.
Commercial air transport for repair purposes from main centres.

APPENDIX 8
FAULT BREAKDOWN

Fault	Canada Hydro- graphic	Coast & Geodetic	Overseas Surveys Nairobi	Hunting Aero- Surveys	U.S.A. Army E.R.D.L.	New Zealand Land & Surveys	Overseas Surveys Traverse Equip
Tripods	1	1					
Vibrator plug connector	1			1		1	1 + 1
Vibrator unit damage	1						
Battery capacity queried	1						
Below zero operation	1	1					
Reflection problems		1					
Carrying current		1					
Transit case improve- ment		1					
Condensor trimmer lead			1				1 + 1
High resistance fuse			1				
Vibrator pack faults			1	1 + 1	1	0	1
L.T. switch			1	0			1
I.F. input lead				1			
Discriminator adjust- ment				1			
Klystron change				1			1
Crystal diode				1			
Coupling condensor O.C.				1			1
Crystal replacement (damaged—air transit.)					1		
Telephone handset					1	0	
Meter switching					1	0	
Moisture problem						1	
Defective diode						1	
Headset cable						1	1
Vibrator replacement							1
Recalibrate A crystal							1
Bonding chassis							1 + 1
Crystal capacity added							1

I. B. WATT: All modern geodetic triangulation systems providing the framework for the survey of a country are controlled by means of base lines spaced 200 to 300 miles apart, usually at the junction of chains of triangles forming a gridiron pattern across the country. These base lines, measured with the greatest possible refinement, were 6 to 8 miles in length and were built up by means of a system of triangles to a side of geodetic length (30-40 miles) which could then be introduced into the main adjustment of the triangulation. Checks on the accuracy of the generation of distance from one expanded base to another usually produced agreement to better than $1/50\,000$ for chain distances ranging from 250 to 1 000 miles.

During the period 1930-1954 all base lines measured in South Africa and Southern Rhodesia for geodetic purposes were measured with the 'Macca' apparatus. This apparatus enabled surveyors to determine distances to a very high degree of precision ($1/8 \times 10^5$) by means of invar tapes suspended in catenary between fine measuring marks on tripods spaced approximately 100 feet apart. During measurement the tapes were supported under a tension of 20 lb. Each 100 ft bay was measured three times with each of two working tapes. Once the direct measurement had been completed a repeat measurement was made in the reverse direction using the same procedure, i.e. the base line is measured virtually 12 times.

Three additional tapes, used as field standards and calibrated before and after the base measurement at the N.P.L. Teddington to $1/10^6$, were used for a series of 3 field standardisations, one before the commencement, one after the completion of the first direct measurement and one after the completion of the return measurement.

A measurement of this nature took, on an average, $2\frac{1}{2}$ weeks to complete with a field party of eight Europeans and 30 to 40 African assistants.

It should be noted that the $2\frac{1}{2}$ weeks mentioned above were occupied in the actual measurement; in the case of the Wankie base, S. Rhodesia, $2\frac{1}{2}$ months were spent in clearing the line and bringing it into a suitable state for measurement.

With the Tellurometer, assuming for the moment that the time used in the reconnaissance for selecting the points and the

construction of the monuments marking the ends of the line or the apex points of the triangles would be similar to that used for selecting points for a tape measurement, a longer line of the expansion figure could be measured to the same degree of accuracy in 20 minutes and would require the services of only two surveyors and possibly two assistants.

It will be appreciated that in the case of ground measurements, due to the very great expense involved, base lines were spaced at their maximum possible distance apart, commensurable with the degree of relative accuracy required in the various parts of the triangulation. The Tellurometer will enable the geodetic surveyor to provide more frequent scale control in his work at far less cost than previously.

Use of the Tellurometer in the field

Last December I had the opportunity of measuring a few lines with the Tellurometer and so became familiar with the method of operation. There are a few remarks that I would like to make as a result of my somewhat limited experience with the instrument. Firstly, the points on the trial exercise were selected so that they could be driven up to by car. Only one of them required the transportation of the equipment up a hill for more than 200 yd horizontally and 100 ft vertically. Subsequently, however, I have transported the instrument and accessories up climbs of 1 500 feet over rough country and have found only the 6 V accumulator awkward to carry.

The instrument is easy to set up, requires no careful levelling and is quickly orientated on the strength of signal basis. Once communication has been established between the master and the remote station and the crystal synchronisation has been checked, the actual measurement of the line takes only 10 minutes to complete.

In learning to operate the Tellurometer one of the greatest drawbacks from my point of view was my complete lack of familiarity with electronic equipment of any description. All angle measurements made by a land surveyor rely on the bisection of a distant target by the cross-hair in the field of view of a telescope by means of the rotation of a tangent or slow motion screw. As optical micrometers are in general use in most modern theodolites the method of

obtaining the angle reading once the distant mark has been bisected is very similar in principle. The Tellurometer, with its initial synchronisation of the crystals by means of the CRT image and the audible 1 000 cycle tone requires a fair amount of practice before an operator can turn a setting screw the requisite amount without repeatedly overshooting the critical setting.

For any survey involving lines whose lengths are greater than 10 miles and where an accuracy of $1/10^5$ is required a trilateration using the Tellurometer would save considerable time in the field as compared with a theodolite triangulation. The amount of preliminary reduction (i.e. the conversion of the observed double transit time into a plane distance on a reference projection) of the observations and the calculation of the results would be shorter than for a corresponding triangulation survey.

New methods of calculation and adjustment required

Since the time of Snellius triangulation has been used universally for first order control surveys. Field equipment and techniques have reached the utmost refinement commensurable with the limitations imposed by weather conditions in the field and the frailty of the human senses. Most of the textbooks dealing with advanced survey techniques and methods of adjustment devote most of their discussion to the fixation of horizontal control by triangulation, taking it for granted that it is the best and most generally used method for providing control points over large areas of the earth's surface.

With the post-war development of Bergstrand's Geoidimeter and the subsequent perfection of the Tellurometer system of measurement by Mr Wadley, trilateration has now become an established method of surveying. Calculation and adjustment procedures will now have to develop along new lines. For a given figure connecting a series of points to be surveyed relative to one another, trilateration produces far fewer redundancies (i.e. measurements over and above those absolutely necessary to define all points relative to one another) when compared with the observation of all the angles. This will require better adjustment techniques based on modern statistical theory for work of first order quality and the development of graphical methods for the

elimination of observational inconsistencies when the Tellurometer is used for ordinary everyday survey operations.

Applications of the Tellurometer

Most of the published literature (in the English language) deals with the adjustment of face networks of trilateration only. In the Union and S. Rhodesia where the basic geodetic framework has been virtually completed the Tellurometer can be used to 'fix' positions of primary stations relative to the geodetic over distances of 15 to 25 miles to the same order of accuracy as that obtained from triangulation using first order theodolites.

In his article in the Empire Survey Review, Mr Wadley has mentioned the use of the Tellurometer for providing scale triangles at frequent intervals in geodetic triangulation chains.

The Tellurometer has been used in Canada in conjunction with the theodolite and helicopter for surveying points 20 miles apart by the method of traversing.

In the United States Tellurometer traverses have been used to provide control for road location surveys in areas where triangulation would have proved more difficult and consequently more costly.

Where control is required for air survey mapping on topographical scales, the Tellurometer in conjunction with the theodolite will enable the surveyor to fix control points in both position and elevation with a great economy in time.

Conclusion

In conclusion it should be mentioned that a great deal of thought has been put into the complete revision of training programme for surveyors throughout the world as a result of the introduction of advanced electronic and optical equipment into their sphere of operations. In this connection I would like to quote from an article by T. J. Blachut of the National Research Council, Ottawa, Canada, who makes the following comments on the academic training of survey engineers:

'Another subject basic to university studies in surveying is physics. Surveying methods during the last few years have advanced to such an extent that a very thorough training in physics is imperative. Photogrammetry, various applications of

radar in field operations, modern electronics and optical distance measuring devices, new devices in laboratory equipment and an extensive use of electronic computers seem to shift the centre of gravity from conventional theodolites and measuring tapes to the field of complicated physical equipment and methods. In order to keep pace with this general development, the modern surveyor must be properly equipped with a knowledge of physical science. Besides a general course in physics, there must be an additional course in instrumental optics and electronics.'

PROFESSOR STANLEY JACKSON read the following communication he had received from Brigadier Michael O. Collens of the Department of Federal Surveys, Salisbury, Southern Rhodesia.

In reply to your MS. letter of the 6th May, I find myself in some difficulty, as it is early days as far as the Tellurometer is concerned. Inevitably, therefore, any comments one might make are based on thoughts as to what one might do, rather than a description of what has been done. To my mind it has two uses which will, I think, probably tend to encourage its further development along two separate lines.

The first requirement is a geodetic one and here again its uses are twofold, firstly, the measurement of lengths in a primary triangulation to eliminate base measurement and to provide scale control. Overseas Surveys are measuring the four sides of a quadrilateral at Broken Hill for which it is impossible to get the diagonal rays. We in the Federation are not very happy about this particular instance of scale control and would prefer to see a fully braced polygon where all sides and angles are measured. Such a controlling figure should provide a better scale control than a base measured on the ground with invar wires and should save considerable time and manpower. The other use in geodetic work is the facility for undertaking a traverse instead of triangulation in flat or difficult country. It has already been used in this way in East Africa with substantial savings in time and we plan to use it on the copperbelt this year to run a primary traverse round a piece of heavily wooded rolling country where visibility is

difficult without resorting to steel towers as observing stations.

The geodetic requirements will produce a constant demanding pressure for accurate length measurements over long distances. For this the present type of master and slave instruments are suitable and so any tendency would be towards increasing their performance rather than any fundamental change in their shape.

The second use that I foresee is the question of topographic control for mapping from air photographs. Triangulation is a relatively slow process in such cases, as you may have to provide more control than you really need to use. There is no doubt that some instrument which would measure lengths over relatively short distances would be of great value.

It would, however, have to operate with a master station carried by a surveyor and an 'all round' remote station to which the Master could be directed from any point at any time. A couple of such remote stations would give you the necessary additional check to a point fixed by a single distance and bearing. Such instruments could, of course, also be used for rapid traversing. Such topographic control necessitates using the instrument over a range of 1 to 10 miles. We have used our Tellurometer with success on a traverse control for separate hydrographic surveys. Such a use has been not entirely similar to the one I describe above. It was really a breakdown of primary triangulation, the lengths being of the order of 10 miles or so. This was convenient in this particular instance but I would not like to regard it as a very normal surveying requirement.

My own view is that measurement of length by waves rather than by tape or bars, etc. has opened a new era in land measurement which is only just beginning and whose use will grow as more instruments are perfected.

F. J. HEWITT (Associate Member): It is an unusual privilege to be 'in on the ground floor' when an invention of the nature described tonight is made. I should like to give you a brief summary of the early events, because this is, as it were, an invention 'made to order' and not just a sudden inspiration which suggested a new line of thought.

The use of radio for surveying is no new idea. The precision bombing systems developed during the war were put to immediate peace time use for long range survey applications but they lacked the resolution required for the intermediate ranges.

Thus even in 1946, at the first Telecommunications Advisory Committee, radio distance measurement for survey was on the agenda. We were confident that some solution was possible but the incentive to commence work at the expense of other projects was lacking. It was not till nearly eight years later that Col. H. A. Baumann, then Director of Trigonometrical Survey, persuaded the Council for Scientific and Industrial Research that the revolutionary possibilities of such a device justified a full-scale investigation. At the time it was expected that Col. Baumann would be able to persuade his Department to support the work financially. In the event, this support was not forthcoming and the Council undertook the work at its own expense.

On 14th June, 1955, the first real field results were obtained, the distance between two trig. beacons Waterval and Doornrantje being determined by radio as $98\,908.05 \pm 0.05$ English feet. This caused something of a problem as the various survey authorities had some difficulty in agreeing as to what the value as determined by normal trigonometrical methods actually was. Finally, 10 days later we received a ruling from the Trigonometrical Survey office in Cape Town which indicated that Mr Wadley's figure differed from theirs by 9 inches but added that it was doubtful whether their figure was accurate to better than 6 inches anyway.

This research programme is an excellent example of how, in my mind, applied research should function.

First of all the problem was posed by an authority in his own particular field, who knew exactly what he wanted. Now as we know from bitter experience, the extraction of a realistic 'operational requirement' from a potential user is often very difficult. The user either asks for the moon, or worse still, he tries to anticipate half the scientists work and frames the operational requirement accordingly. In this he is almost inevitably

wrong with the result that the work gets off on the wrong foot.

In the case of the Tellurometer, Col. Baumann framed the operational requirement very well. He asked for direct distance measurement with portable equipment over ranges from 3 to 30 miles with an accuracy of one part in 100 000. He based this on realistic considerations of what the surveyor could really use, without making the requirement prohibitively exacting. I think we must give him full credit for his assessment of the problem. In the light of our present knowledge there is no need to change it.

Mr Wadley's paper tonight and the remarks of other contributors give some idea of the success he has achieved. I would like to recall an early overseas reaction to the invention. When the Canadians heard of Mr Wadley's preliminary results two senior officials, the Director of Surveys and Mapping and the Director of the Division of Applied Physics of the National Research Council of Canada, flew out almost immediately to Johannesburg. One morning in the field convinced them. Their requirement called for only 1 in 10 000 and even this figure had not been obtained elsewhere despite the expenditure of large sums of money. They placed an order for, if I remember correctly, six sets though arrangements for production were still not clarified. These sets were, I am glad to say, delivered in due course and I understand have given good service under very arduous conditions.

Regarding production, it was thought appropriate that this wholly South African development should be followed by South African production. The Council applied for patents in a large number of countries and production was entrusted to a new firm, Tellurometer (Pty.) Ltd., of Cape Town. The instrument you see here tonight was a very early production model that has seen a lot of field use. Hundreds are now in use throughout the world. The speed with which this instrument was put into production in South Africa is most creditable and a fitting follow-up to the speed with which Mr Wadley solved the very severe technical problems.

5 (4)
SOUTH AFRICAN COUNCIL FOR SCIENTIFIC AND
INDUSTRIAL RESEARCH

National Telecommunications Research Laboratory



Thesis

THE TELLUROMETER SYSTEM OF DISTANCE MEASUREMENT

BY

T. L. WADLEY

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THE TELLUROMETER SYSTEM OF DISTANCE MEASUREMENT

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National Telecommunications Research Laboratory, South African
Council for Scientific and Industrial Research.

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1. INTRODUCTION

The principle of using the transit time of electromagnetic waves for measuring distance for survey purposes is becoming fairly familiar to surveyors. This principle is extensively used for general navigational purposes and navigational equipment, usually in some modified form, has often been used to give measurements of useful accuracy for some survey purposes, particularly over distances of the order of a few hundred miles. Over shorter distances the instrumental accuracy available with such equipment, and propagation difficulties, limit the uses to which it can be adapted.

Instruments have been developed making use of visible light for measuring relatively short distances and are capable of giving accuracies

suitable for geodetic purposes. Although visible light possesses some advantages for this purpose, it also suffers disadvantages particularly over the medium distances most useful in geodetic work, say 20 to 30 miles. It is difficult to compete against the daylight and measurements at night may not be convenient. Good visibility is required, relatively precise alignment of the optical components must be maintained and the colour of the light suitably controlled to avoid dispersion effects.

The Tellurometer system of distance measurement which is described in this paper has been designed primarily to meet the requirement for an instrument of geodetic accuracy over useful geodetic distances. It operates on radio microwaves of 10 cm. wavelength. The use of such waves enables adequate sensitivity to be obtained easily, there are no dispersion effects and visibility is of no account, although in general line of sight conditions are required. Observations can be satisfactorily made through haze, mist and smoke, and perhaps even light rain but heavy rain might interfere with accuracy. Natural sources of interference on these wavelengths are negligible and interference from other services should be rare as some beaming is always employed at these frequencies and this part of the radio spectrum is relatively uncongested. Alignment of the radio beams need be only very approximate and operation from a simple scaffolding or tower of minimum stability is possible where necessary. Considerable angular instability up to a few degrees can be tolerated and longitudinal stability need only be comparable with the accuracy with which it is desired to measure.

The instrument measures slope distance. This may be reduced to the horizontal with adequate accuracy by means of barometric height differences, except perhaps in the case of rather short lines of extreme slope. Reductions to sea level require rather higher accuracy than can be obtained directly from barometric readings, depending of course upon the nature of the work and, in general, it is necessary to have absolute height data available for some control point at least.

An objection to the use of radio waves for these purposes, namely, that of the relatively wide beams introducing errors due to stray reflections, is largely overcome by the use of microwaves which are effectively scattered by most ground surfaces, and such residual effects as are present are eliminated by the measurement technique.

A further objection, that the velocity of radio waves in air is more influenced by humidity than light waves, is found to be of less consequence than might be thought, and meteorological limitations are probably mainly due to temperature uncertainties, which affect both light and radio waves to much the same extent.

The instrumental technique which has been developed gives the required degree of accuracy, with the minimum of complexity. The instruments are light, small and fully portable. On account of this they may be used for many purposes in addition to the primary purpose of geodetic survey, whether the full accuracy of the instrument is needed or not, or where the acceptable errors at very much shorter distances are within the instrumental accuracy.

It is the purpose of this paper to describe the instrument in its operational aspects with the minimum of electronic detail, and to report the results of



Fig. 1. An experimental model of the Master Tellurometer measuring a line between beacons in Pretoria and Johannesburg.

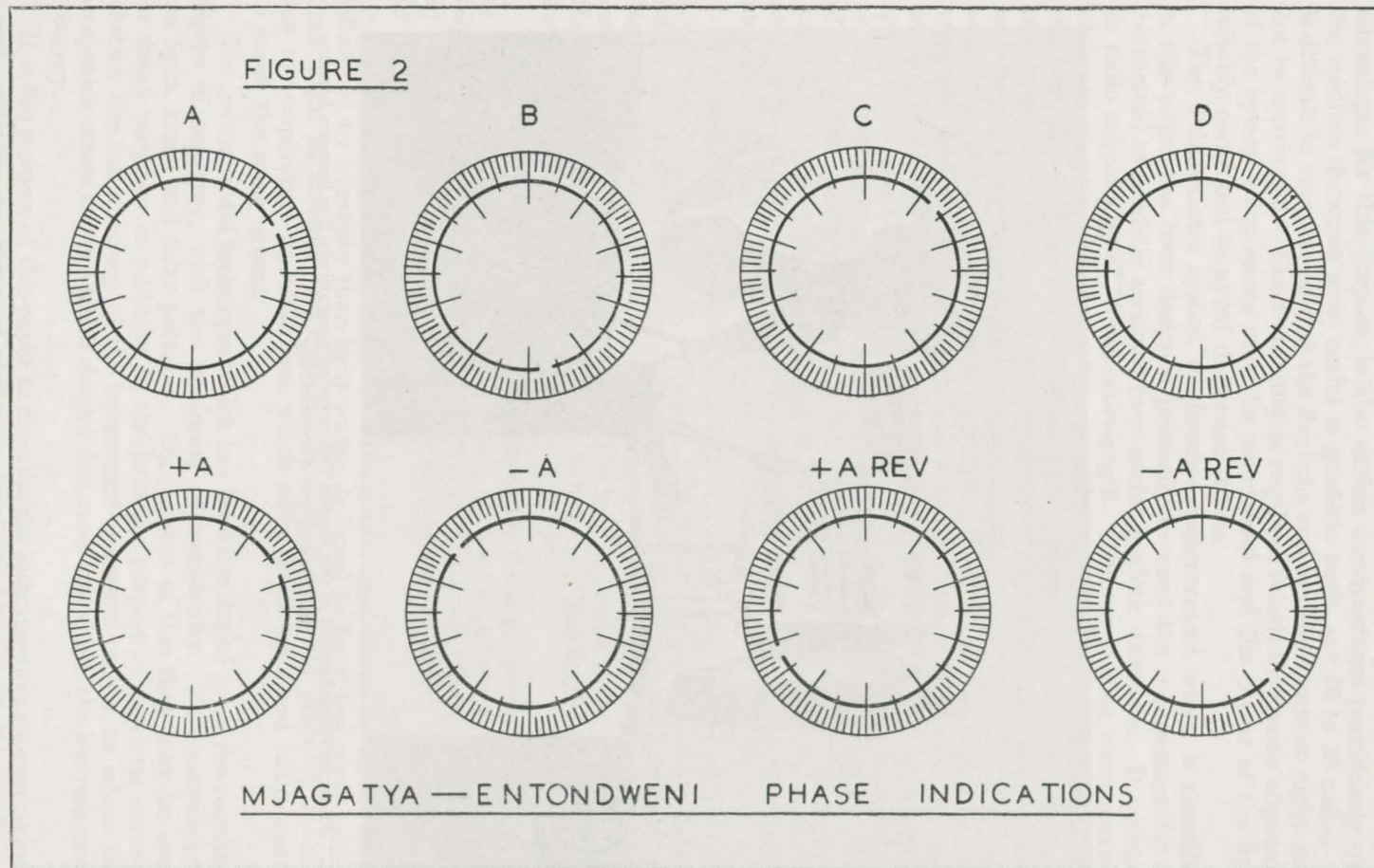


Fig. 2. Diagrams of the actual phase indications on the line Mjagatya to Entondweni, showing the coarse readings and a single set of fine A readings. The scale is taken as 00 at the top and read in a clockwise sense. For example, the A indication reads $16\frac{1}{4}$.

fairly extensive tests of its accuracy which have been made to date. Triangulated and trilateral measurements of the same trigonometric figures are compared.

2. DESCRIPTION OF THE INSTRUMENT

2.1. Physical Description. The measurements are made between two instruments referred to as the Master and Remote stations respectively. The observations are made at the Master station, whilst the Remote station is manned by an operator whose function is to perform the various switching operations on instruction from the Master observer. A duplex telephone is provided as an integral part of the system using the same channel and circuits as are used for the measurements.

Both instruments are of similar external physical appearance and are mounted on a tripod or upon a trigonometrical beacon so that their electrical centre corresponds with the centre of the tripod or beacon.

The aerial system in each case is a parabolic mirror of 18 in. aperture, at the focus of which the transmitting and receiving dipoles are situated. The measurement takes place to the focus via the mirror surface and the instrument is therefore mounted with its centre in the directrix plane of the parabola. This is also approximately the centre of gravity of the instrument. The instrument and aerial system form an integral unit which in the experimental equipment weighed about 16 lb. A power supply unit also weighing approximately 16 lb. with internal lightweight accumulator is required and is placed on the ground under the instrument. Alternatively a standard accumulator may be connected externally. The power consumption is about 8 amp at 6 volts.

An aneroid barometer and whirling hygrometer for determining the meteorological conditions complete the equipment required at each station. This equipment, suitably packed and strapped, has been carried by one man on climbs of up to 1,000 ft.

2.2. Description of Measurement Technique. A continuous radio wave of 10 cm. wavelength (3,000 Mc/sec) is radiated from the Master aerial system. This is modulated by what may be referred to as the pattern frequency, which is 10 Mc/sec and other frequencies of similar order as explained later. This modulated wave is received at the Remote station aerial and in effect re-radiated from the transmitting system of the latter station. The precise electrical method by which this is accomplished cannot be described in a paper of this nature. The re-radiated wave is, however, a similar wave of more complex modulation which effectively re-transmits the pattern frequency modulation.

For the purpose of this discussion, however, it should be stated that this re-radiation is in effect more or less instantaneous, no time delay in the Remote circuits contributing sensibly to the path length, the measurement thus taking place to the focus of the parabola.

The return wave as received back at the Master station is compared with the transmitted wave, the instrument indicating the phase shift between the outgoing and incoming modulation. Here again the comparison refers to the waves at the focus of the mirror.

The phase is indicated on an oscilloscope in the form of a circular sweep or trace in which a small break marks the phase against a circular scale. A decimal scale with 10 major and 100 minor divisions is used, the leading edge of the break in a clockwise sense being read usually to the nearest minor division or at short ranges to perhaps $\frac{1}{2}$ or even $\frac{1}{4}$ divisions.

With a pattern frequency of 10 Mc/sec a complete rotation of the phase indication represents a change of $\frac{1}{10}$ of a microsecond or 100 millimicroseconds in the transit time over the double path. Each minor scale division thus represents one millimicrosecond and is equivalent to just under 6 in., a complete rotation of phase being equal to approximately 50 ft.

The 10 Mc/sec pattern or A pattern phase as it is usually referred to, thus indicates the final two figures in the transit time in millimicroseconds, the preceding figures or whole number of A pattern rotations being unknown. These are resolved by providing three further patterns. The pattern frequencies are:—

A pattern...	...	...	...	10.000 Mc/sec
B pattern...	...	...	...	9.990 Mc/sec
C pattern...	...	...	...	9.900 Mc/sec
D pattern...	...	...	...	9.000 Mc/sec

The difference between the A pattern reading and the B, C and D readings respectively give phase readings relative to the difference frequency of the modulations and thus coarse patterns, as follows, are derived from which the preceding figures are determined:—

A minus B.	10 Kc/sec pattern ...	50,000 ft.
A minus C.	100 Kc/sec pattern ...	5,000 ft.
A minus D.	1000 Kc/sec pattern ...	500 ft.
A itself.	10 Mc/sec pattern ...	50 ft.

For lines of length longer than 50,000 ft. the first figure must be provided from a rough knowledge of the length of the line. A further pattern frequency could resolve this but is regarded as unnecessary.

Other arrangements of frequencies are of course possible, the above series being chosen first because they are close together, the modulating circuits being identical, and secondly, because the differences are all with respect to the A frequency, which by necessity has to be accurately set. All the frequencies are provided from quartz crystals, the A crystal being accurately set by reference to some standard, preferably the 10 Mc/sec standard signals radiated by the Bureau of Standards in Washington. The other crystals may be set to a lower order of accuracy. A temperature against frequency calibration of the A crystal is used for the most accurate work.

It will be noted that the coarse patterns being difference readings are free of zero errors due to say a maladjusted scale, minor phase defects, systematic reading errors, etc. The A reading itself, which is the most important in determining the time, is, however, subject to these defects. To overcome this and make all readings differences, a so-called negative A reading is provided. This may be treated for all computing purposes as arising

from a pattern frequency of minus 10 Mc/sec. That is to say, the reading when subtracted from the $+A$ reading gives a 20 Mc/sec pattern free of all internal instrumental error, personal error, etc. The $-A$ reading rotates backwards relative to the clockwise increase of the positive patterns as the instruments are moved further apart. The display is still in the same sense and is read in the same manner, the reversal being in the fundamental physical process, not the indicating circuits. The same 10 Mc/sec crystal is retained at the Master station, the operation being controlled by the Remote operator only.

In addition to the above, a simple reversal of phase provides reverse indications on both the $+A$ and $-A$ readings and, by averaging, any centring error in the display is eliminated. This function is also under the control of the Remote operator only, the Master observer retaining the 10 Mc/sec pattern as before.

These four "fine" A readings, as they are referred to, are somewhat analogous to theodolite readings, the $+A$ and $-A$ readings being equivalent to the two readings on the distant stations, the circle setting being unimportant, as a difference is taken. The reverse $+A$ and $-A$ readings are then similar to "circle left" and "circle right" readings, *i.e.* plus or minus 50 divisions on the scale.

Further readings equivalent to different circle setting could be taken but this is found to be unnecessary, as sufficient scale accuracy is achieved by simply eliminating centring and zero errors.

A more important source of error arises from propagation effects, due to stray reflections from objects in the microwave beam, and of course from the ground itself, as the beam being relatively wide, *i.e.* about 10° , cannot be elevated free of the ground.

These errors are in the majority of cases almost negligible, as most ground surfaces diffuse the ground reflection sufficiently to leave only the direct ray. However, occasionally ground surfaces are encountered which reflect quite effectively and, in general, water surfaces will give pronounced surface effects. If, however, the indirect ray path is not very different in length from the direct, little or no ground error will arise regardless of the reflecting properties of the surface. On paths of the order of 20 miles length, little error is involved if the ground clearance of the ray path is less than about 200 ft.

These ground reflection effects cause the readings to deviate from the true reading by an amount which is a function of the excess length of the indirect ray, the strength of the ground reflection and, most important, the relative phase of the microwave carrier over the two paths. The error will in either sense be dependent on the relative phase of the carriers and will assume all values around the true value as the carrier phase is changed. This effect has been analysed in some detail and, although no attempt will be made here to present this analysis, the theoretical treatment and practical tests confirm this swing about the true reading.

The errors involved in most ground conditions are unobservable or so small as to be absorbed in incidental errors. However, as a matter of routine, all measurements are made on a series of carrier frequencies spaced perhaps 10 Mc/sec apart, the difference in the ray paths causing the indirect carrier to assume all values of phase relative to the direct ray. If the ray paths are very different a number of cycles of swing will be developed and, if the

ground is highly reflective, the swing will reach a maximum which cannot exceed about 4 ft. in the worst case. As the ray paths become more equal, only a fraction of a cycle may be developed but in this condition the amplitude of the swing will be small even if the ground is highly reflective; perhaps a small fraction of a foot and inseparable from incidental errors.

In practice a series of perhaps ten or twelve readings are taken on successive carrier frequencies. The Remote operator controls the progressive steps of carrier shift, the Master observer follows and reads all fine A readings on each step. The other patterns are not read again as the coarse pattern differences remain sufficiently constant regardless of the carrier frequency. This procedure is roughly analogous to taking a series of circle readings on a theodolite, and the number of readings taken will be determined by the nature of the work. The readings are relatively coarse and cannot be compared in this respect with theodolite readings. The necessity for repetitive reading does not arise out of the need to increase the reading accuracy, although some slight advantage is gained in this respect. For certain mapping and photogrammetric work a simple set of readings on a single carrier frequency might be sufficient in most cases. For the most exacting geodetic work any number of sets of readings may be taken. At this stage a full description of the operational procedure might be given to illustrate the above discussion.

2.3. Description of Operational Procedure. The operational procedure outlined below refers to typical conditions of geodetic work. About 15 minutes are spent in making the measurements, with perhaps 30 minutes spent at the station in all including unpacking and packing the instruments.

Both operators align their beams to within 5 or 10 degrees of the true line. After switching on, checking and peaking of the microwave crystal current ensures that the transmitter is radiating and, in conjunction with the presence of thermal noise in the earphone and on the oscilloscope, ensures that the receiver is functioning. The Remote operator remains on a fixed carrier frequency and it is the function of the Master observer to find him, although usually the instruments will be in tune if they have been working together previously. The instruments can be brought "into tune" from either end and are automatically correct both ways, but the Master observer must retain the tuning function or confusion will result.

Upon establishing voice communication which is duplex, *i.e.* both ways simultaneously, instructions are given to align beams accurately by observing the signal strengths as indicated on meters at each end.

If the instruments have been in previous use together the measurement may then be commenced. However, if working together for the first time, or if maladjusted, the Master observer will instruct the Remote operator to synchronize his crystals and set modulation levels. The latter are passive adjustments and generally are not concerned with the accuracy of the measuring patterns which are a function of the Master crystals only. The latter are not touched in the field but their temperature is observed so that their frequency may be suitably corrected if necessary. The Master observer switches to all four patterns in turn, whilst the Remote operator makes the necessary adjustments. At the same time the Master observer checks his display circle for shape, centring, focus and brightness.

The observer may at the same time read the pattern phases to obtain the coarse readings or, after all adjustment is completed, instruct the Remote operator to switch in turn to the four patterns, this switching being necessary at both ends to obtain each reading. Should the stations be switched to the incorrect pattern, this is obvious both on the oscilloscope and in the earphone. Either operator may break into the measurement and speak at any time by operating his speak/measure switch. In practice, the whole measurement proceeds with little exchange of instructions between experienced operators as it is obvious at all times what is required. Usually little more than a grunt is necessary by way of instructions and the running conversation is usually confined to irrelevant matters.

On completion of the coarse readings, the Master observer will instruct the Remote operator to observe the meteorological conditions, that is humidity, temperature and barometric pressure, at the same time observing these conditions at the Master station. These readings are recorded together at the Master station and give the mean meteorological conditions at the start of the fine readings.

The observer then notes his crystal temperature and calls for all fine A readings in turn, these being under the control of the Remote operator only. These are given in a prescribed sequence without further instruction, the switching being done on receipt of a break in the measuring wave to indicate to the Remote operator that the next reading is required.

For the next set of readings the observer will then instruct the Remote operator to shift frequency. The observer follows the frequency shift and completes the fine tuning. The shifts of frequency should be of approximately equal intervals but the observer may instruct otherwise to suit conditions. The observer then calls for all fine A readings again and so on until sufficient readings to suit conditions have been obtained. This process may take five minutes or so. At the end the observer will again call for the meteorological conditions and after re-measuring crystal temperature and repeating his own meteorological measurements, the measurement is complete. The instruments are then returned to their initial frequency.

As a check of the measurements, particularly the coarse readings, to ensure no gross mistake and to ensure that the measurement "breaks out" satisfactorily, the approximate transit time should be calculated in the field. At long range, and in very hot or cold weather, the crystal frequencies may require correcting before the measurement will "break out" but usually corrections are only applied to the A crystal frequency in the most exacting work.

3. REDUCTION OF FIELD READING AND CORRECTIONS APPLIED

3.1. *Detailed Example of a complete measurement.* The following is a detailed example of a set of field readings and their reduction, in a typical case. They refer to the line between Entondweni and Mjagatya beacons which is the main extension of the Mtubatuba base in Zululand, Natal. This is a comparatively modern base near to the 30th meridian. The complete measurement of a figure containing this line is referred to later.

Fig. 2 is a diagram of the "scope" indications on this line, showing the sets of coarse readings and a single set of fine A readings. The approximate line length is 25 miles—the first figure in the transit time is therefore 2, that is, there are two unresolved rotations of the 50,000 ft. pattern.

Coarse Readings

+A 16 Scale Zero Error *E* assumed 00
 B 46
 C 12
 D 77

20 to 30 miles ...	+A 16	+A 16	+A 16	+A 16
First figure ...	B 46	C 12	D 77	E 00
2	diff. 70	diff. 04	diff. 39	diff. 16

Approximate Transit
Time

2 7 0 4 1 6

millimicroseconds

Fine Readings

Start—Crystal Temperature 32°C.

Meteorological conditions:

		<i>Dry</i>	<i>Wet</i>	<i>Corrected</i>
		<i>Temperature</i>	<i>Temperature</i>	<i>Barometer</i>
Master ...		71½	67½	29.61
Remote ...		72	64	28.92

+A 16½

Reverse 67½

—A 85½

Reverse 35½

diff. 31

32

Mean

Halved

31.5

15.8

17½	68	<i>Mean</i>	<i>Halved</i>	18	69	<i>Mean</i>	<i>Halved</i>
85½	36½			85½	36½		
32	31½	31.8	15.9	32½	32½	32.5	16.3
18	68½			16	66½		
86	36½			87	38		
32	32	32.0	16.0	31	28½	29.8	14.9
16½	67			17	66½		
87	36½			85½	35½		
29½	30½	30.0	15.0	31½	31½	31.5	15.8
16½	67½			16	66		
85	36			85½	36		
31½	31½	31.5	15.8	30½	30	30.2	15.1
16½	67			17	67		
86	36			85½	36		
30½	31	30.8	15.4	31½	31	31.2	15.6

Mean of all 15.6

Finish—Crystal Temperature 33°C.

Meteorological conditions:

		Dry Temperature	Wet Temperature	Corrected Barometer
Master	...	71	67	29.58
Remote	...	73	65	28.93
Measured Transit Time	...		270415.6	m μ s
Mean Crystal Temperature	...		32.5°C.	
A Crystal Frequency	...		9.999,989	Mc/s
Time corrected for:				
Frequency	...	...	270415.90	m μ s
Zero correction	...	...	-0.40	m μ s (see 3.4 below)
Correct Transit Time	...	...	270415.50	m μ s
Mean Dry Temperature	...		72°F.	
Mean Vapour Pressure	...		.562"	
Mean Barometer	...		29.26"	
Mean Refractive Index	...		1.00034182	(see 3.3 below)
Transit Time corrected to Vacuum or				
Distance in vacuum millimicroseconds			270323.10	v.m μ s.
Distance at assumed velocity of				
299792.0 Km/s	...	...	40520.351	International metres.
Distance in feet (Sears 1928 Relationship)			132,941.01	British feet.
Trigonometric Slope Distance	...	...	132,941.01	British feet.

Note that the agreement here is large coincidence as the velocity is thought to be too low by some 3 parts per million (see below).

3.2. *Ground Effects.* Fig. 3 (A) shows the " swing " of the fine readings against carrier frequency in the case of the detailed measurement above. The curve is typical of most land lines. No obvious structure is apparent and random reading errors probably account for most of the structure.

Fig. 3 (B) by contrast is an example of a land line showing a considerable swing due to a large ground clearance coupled with an abnormally high surface reflection due to some peculiarity of the ground, *i.e.* flatness and lack of vegetation. Note the number of " cycles " developed indicating a large difference in path lengths. The mean of the curve nevertheless gives a good value for the distance which has been checked by deriving the distance from an extensive figure with many redundancies.

Fig. 3 (C) is an example of an over water line with a relatively large ground clearance. Here the difference in path length is not as great as in (B) and a number of " cycles " were not developed. The large amplitude of the swing is largely due to the strong surface reflection. It is apparent that insufficient carrier frequency range was available to resolve this line really satisfactorily and more recently designed equipment has an extended range available to meet such a requirement. In addition to this the poor scatter of the points is due to the indirect ray changing length during individual observations, as the swell of the sea causes the reflecting surface to rise and fall, each point being itself a mean of a smaller irregular swing. The mean of these points nevertheless gives good agreement with the rest of the figure measured.

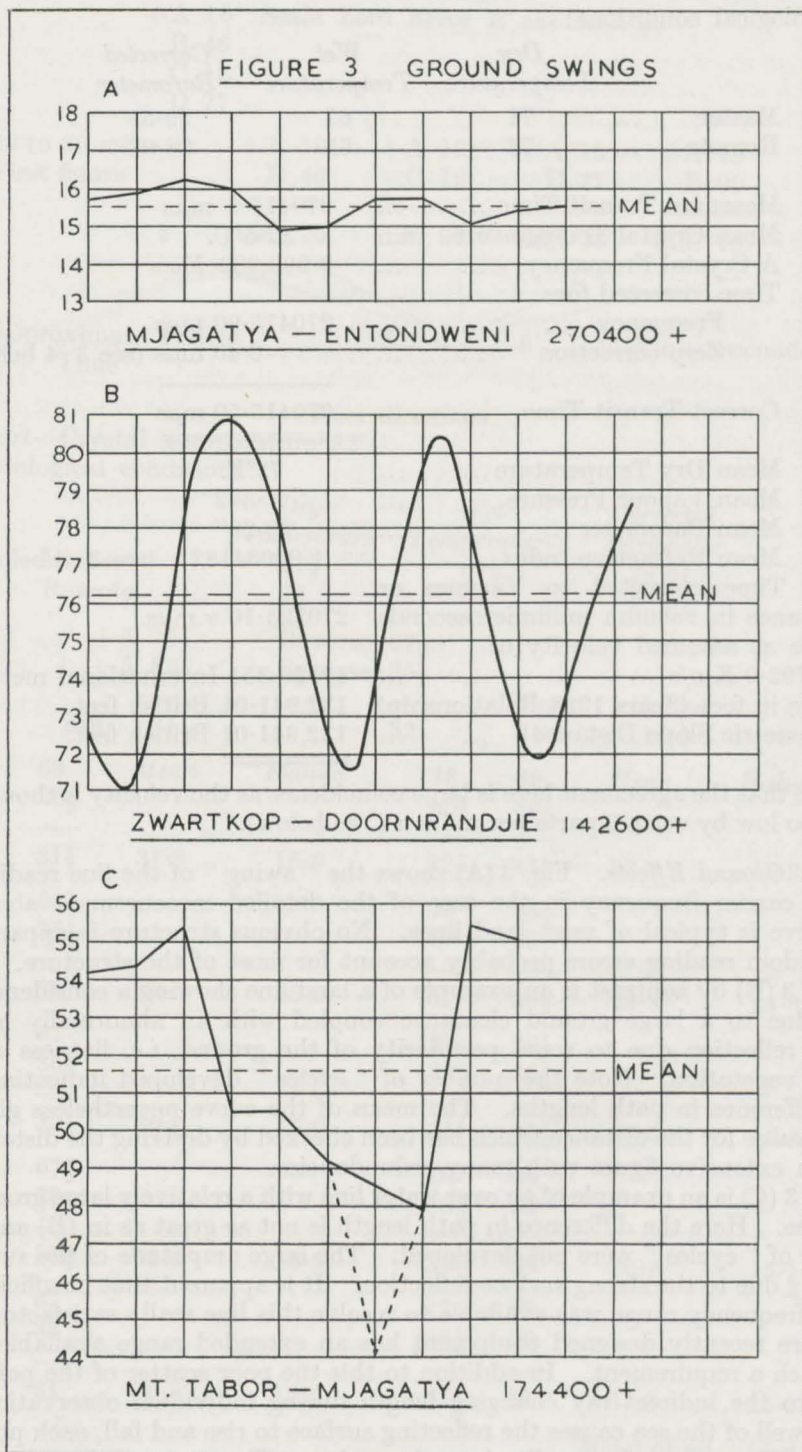


Fig. 3. The swing of the distance readings expressed in millimicroseconds plotted against carrier frequency to an arbitrary scale, in the case of: (a) a normal land line; (b) an abnormal land line; (c) an over-sea line with a high surface clearance to the ray path.

The lower point on the curve corresponded with a "deep fade" and should perhaps be ignored. The complete figure referred to is given in detail below.

A more suitable siting on such a line to give a smaller surface clearance to the ray path would give more satisfactory readings with less swing.

3.3. Refractive Index. The final calculations in this paper were based on the refractive index formula given by Smith and Weintraub¹ as follows:

Where n = refractive index

$$N = (n-1)10^6 = \frac{77.6}{T} \left(p + 4.81 \times 10^3 \frac{e}{T} \right).$$

Where p = Total atmospheric pressure mb .

e = Partial pressure of water vapour mb .

T = Temperature in $^{\circ}K$.

for which an accuracy of $\cdot 5\%$ in N is claimed over a range of

-50 to $+40^{\circ}C$.

200 to 1100 mb . Total pressure.

$0-30$ mb . Vapour pressure.

Up to $30,000$ Mc/sec .

The older Radio Meteorological formula originating in the Smithsonian Physical Tables of 1933 were used in the earlier work and some of the systematic error obtained was attributed to this formula. Although these measurements do not constitute a complete check on the formulae, the more recent formula has been used at high and low altitude and high and low humidities with results consistent with the other data.

The above formula is consistent with most modern references on the subject and there is little reason to doubt its accuracy within the limits stated.

This formula converts to the following form for practical use in this type of work.

With pressure in inches and temperature in $^{\circ}F$:

$$N = \frac{4730.0}{459.5 + ^{\circ}F} \left(p'' \times \frac{8658e''}{459.5 + ^{\circ}F} \right).$$

Aneroid barometers used in these measurements have been calibrated against a number of mercury standards at various altitudes.

3.4. Zero Corrections. As stated above the instruments are virtually free of zero error. In so far as effects within the equipment are concerned this is strictly true. However, minor effects at the dipoles themselves, the precise details of the focusing and in the original instrument a small mechanical error in mounting, give rise to a small zero error relative to the mounting screw. On a single measurement this error would probably be

absorbed into the other errors but the statistical results of a number of measurements will show it up. The instrument was therefore subjected to a series of tests at ranges of about 400 ft. which gave a zero correction of $-.20$ ft. or $-.40$ m μ s. the mean square scatter of the complete set of readings being about $.05$ ft. A distance of 400 ft. is about the minimum range at which measurements can be made without possible overload effects interfering with the accuracy. Greater ranges than this were found difficult to tape to the required accuracy with our limited skill in these matters. The above figure was checked by an independent method in the laboratory and the doubts as to overload effects largely removed. The zero correction was thus $-.10$ ft. at each instrument and the experience to date indicates that an error of this order and sense is likely on any individual pair of instruments, unless allowed for in the mounting arrangements.

4. FIELD TESTS

4.1. *Nature of the Field Tests.* The instrument has been subjected to a series of three full-scale tests, the results of which are presented here in greater or less detail in chronological order corresponding to certain stages of development and knowledge of the sources of error. In each case a complete trigonometric figure with redundancies has been measured and subjected to analysis. The lines as measured have been corrected for slope due to the relative height of the stations, reduced to sea level, and corrections applied to bring them into an appropriate plane projection. It has been assumed that the ray path is optically straight and curvature corrections have been applied accordingly. In radio practice it is assumed that at ground level such waves travel in straight lines relative to an apparent earth's radius $\frac{4}{3}$ times the actual radius, due to the normal vertical gradient of refractive index. If this value of radius is used in the curvature formula, the dip of the ray into a region of higher refractive index and its curvature is completely allowed for in normal atmospheric conditions. The corrections are quite small below 30 miles but increase rapidly at greater ranges.

The lines have then been adjusted on a least squares basis to produce a self-consistent figure and the mean square adjustment used as a measure of the probable error of the measurements in those cases where sufficient conditions exist. The lengths have been compared with the trigonometric distances, the differences being plotted against the distance. The mean slope of the points indicate proportional errors due to an incorrect refractive index coefficient, an incorrect nominal velocity *in vacuo*, incorrect conversion factors between units, or finally, possible error in the trigonometric scale. The mean square scatter of the points from the mean slope gives an indication either of the accuracy of the adjusted measurements, the accuracy of the triangulation over and above the scale differences, or some combination of both. It is possible to form some estimate as to which set of measurements is contributing the bulk of the differences by an examination of the respective linear and angular adjustments.

4.2. *The Kroonstad Base Extension Measurements.* These measurements constituted the initial tests on the instrument before it was fully developed. The measurements were all made on a fixed carrier frequency and the extent of ground effects was unknown. These were probably quite small as the

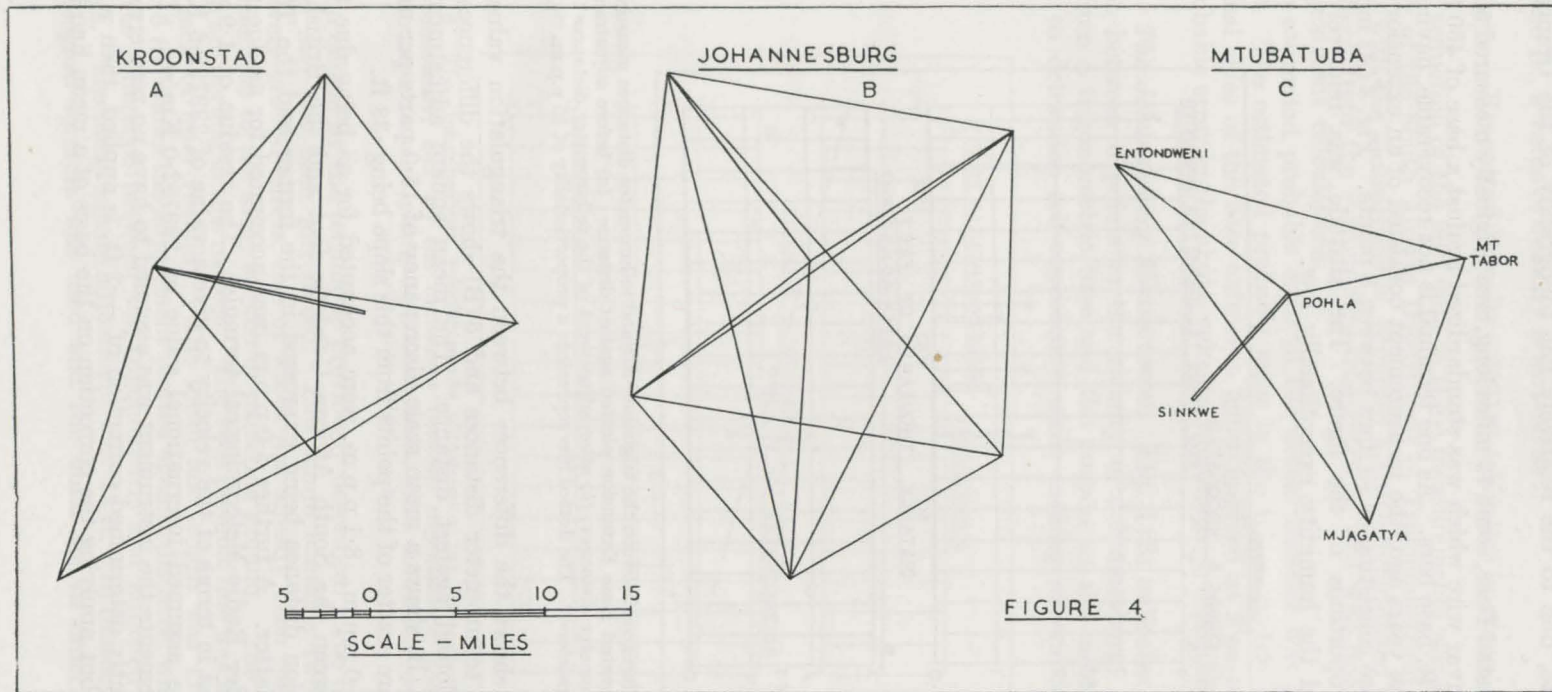


Fig. 4. Diagram showing the rough proportions of the trigonometric figures measured. The double lines indicate taped base lines which were not, however, measured.

results indicate, due to the relatively flat topography of the Orange Free State.

The Kroonstad Base, some 12 miles long, was originally measured 50 years ago with an invar wire which was standardized against a base of 460 ft. laid down with 10 ft. base bars. As one terminal is not recoverable, having been destroyed some years ago, the measurement consisted of an extension figure around the base consisting of 10 lines between 5 points. Fig. 4 (A) indicates the rough proportions of the figure. The altitude was relatively high (5,000 ft.) and the humidity exceptionally low.

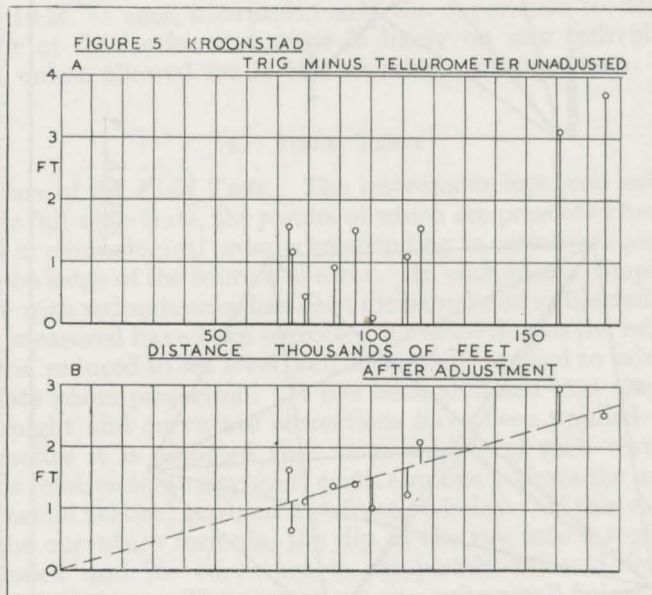


Fig. 5. Differences between the trigonometric and tellurometer distances measured on the Kroonstad Base Extension plotted against distance : (a) before adjustment of the tellurometer distances; (b) after adjustment of the tellurometer distances for self-consistency. The dotted line represents a proportionality of 15 p.p.m.

Fig. 5 (A) shows the differences between the triangulation values and the measured tellurometer distances and 5 (B) shows the differences after adjustment plotted against distance. The mean square adjustment was .60 ft. Fig. 5 (B) shows a mean scale discrepancy of 15.0 parts per million, the mean square scatter of the points from this slope being .38 ft.

Of this 15.0 p.p.m., 8.1 p.p.m. were accounted for as being due to the difference between the South African Geodetic foot and the British foot, the triangulation distance being expressed in the former and the Tellurometer in the latter. A further 5.0 p.p.m. was accounted for as due to the use of the older Radio-Meteorological formula. The residue of 1.9 p.p.m. was interpreted in terms of the velocity to give a value of 299792.6 Km/sec as against the assumed international value of 299792.0 Km/sec. In the above measurements the instrument was assumed to have no zero error. If the more recently determined correction of $-.2$ ft. is applied, then without re-computing but applying the correction on the basis of a mean line length

of 107,000 ft., a value of velocity is arrived at:

Kroonstad Velocity: 299793.1 Km/sec *in vacuo*.

The reduction of the field data in these measurements was subject to the scrutiny of the South African Department of Trigonometrical Survey, who assisted with the measurements, provided a specially adjusted trigonometric figure freed from the surrounding triangulation, and who finally confirmed the adjustment calculations.

The estimated probable error in the actual baseline was given as 1 in 868,000. The estimated probable error in the trigonometric length of the individual sides of the base extension figure is given as 2 parts per million. The probable error in the above velocity is perhaps $\pm .5$ Km/sec.

4.3. *The Johannesburg Measurement.* Fig. 4 (B) indicates the figure of 14 lines between 6 points in the vicinity of Johannesburg. This is well away from a trigonometric base and the purpose of the measurement was mainly to determine self-consistency while making allowance for ground

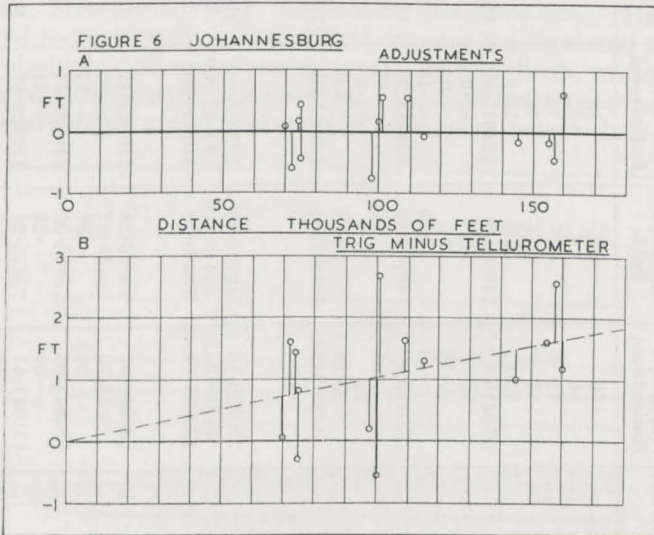


Fig. 6. The Johannesburg measurements shown as: (a) the adjustments for self-consistency, and (b) the differences between trigonometric and adjusted tellurometer distances plotted against distances. The dotted line represents a proportionality of 10.1 p.p.m.

reflection effects by the technique previously described. The use of reverse readings had not been introduced. This figure contains two lines which show severe ground effects, one of which has already been referred to and both being due to the same stretch of reflecting ground. The remainder of the lines are normal in this respect. The 15th possible line was immeasurable due to lack of inter-visibility. The mean line length was 110,000 ft.

Fig. 6 (A) shows the adjustment plotted against distance, while Fig. 6 (B) shows the difference between the trigonometric and adjusted tellurometer distances. The mean square adjustment was .43 ft. In this case the revised meteorological formula was used and the units are in order. The mean

TABLE I
TELLUROMETER MEASUREMENTS OF THE MTUBATUBA BASE EXTENSION

April 1956.

Beacons	Mjagatya Entondweni	Mjagatya Pohla	Mt. Tabor Entondweni	Mt. Tabor Pohla	Pohla Entondweni	Mt. Tabor Mjagatya	
A Reading	16	64	16	90	30	53	
B Reading	46	13	92	76	99	80	
C Reading	12	65	75	57	07	10	
D Reading	77	86	14	70	87	08	
Mean Fine A's	15.6	61.6	15.8	89.2	29.5	51.65	
Time $m\mu s$	270415.6	149761.6	224015.8	113189.2	132429.5	174451.65	
Mean Crystal Temperature	32.5	30.5	30.0	28.75	32.5	30.0	
Frequency Correction	+ .30	0	- .04	- .10	+ .10	- .03	
Zero Correction	- .40	- .40	- .40	- .40	- .40	- .40	
Corrected Time	270415.50	149761.20	224015.36	113188.70	132429.20	174451.22	
Mean Vapour Pressure	.562	.535	.675	.649	.457	.640	
Mean Temperature	72	71	74.5	75	78	75	
Mean Barometer	29.26	29.78	29.23	29.75	29.39	29.68	
Refractive Index	1.0003418	1.0003434	1.0003559	1.0003563	1.0003234	1.0003544	
<i>Tellurometer Distance</i> ($c = 299792.0$ Km/sec)							
$v.m\mu s$	270323.10	149709.80	223935.66	113148.38	132386.39	174389.42	
International Metres	40520.351	22440.900	33567.060	16960.490	19844.190	26140.277	
British Feet	132941.01	73625.13	110128.34	55644.75	65105.72	85762.21	
<i>Trigonometric Slope Distance</i>							
British Feet	132941.01	73625.28	110129.12	55644.67	65105.87	85762.80	<i>Root Mean Square</i> .40
Total Corrections to Plane Projection	+18.76	+13.87	+15.80	+11.89	+1.82	+19.09	
Least Squares Adjustments	+ .08	- .08	+ .07	- .06	- .13	+ .03	
Adjusted Tellurometer	132941.09	73625.05	110128.41	55644.69	65105.59	85762.24	
Trig. minus Adjusted Tell.	- .08	+ .23	+ .71	- .02	+ .28	+ .56	
Rescaled Unadjusted Tell.	132941.41	73625.35	110128.67	55644.92	65105.92	85762.47	.40
Trig. minus Rescaled Unadjusted Tellurometer	- .40	- .07	+ .45	- .25	- .05	+ .33	

Rescaling to $c = 299792.9$ Km/sec.

slope shown in Fig. 6 (B) is 10.1 p.p.m. of which some 3 or 4 p.p.m. may be accounted for if the Kroonstad velocity is substituted for the nominal velocity of 299,792.0 Km/sec, which was used in the calculations. The balance of some 6 to 7 p.p.m. are interpreted as the deviation of the overall trigonometric scale due to the distance from the bases concerned. The mean square scatter about this mean slope is .85 ft. In view of the value of mean square tellurometer adjustment and the relatively large number of conditions, the figure of .85 ft. is regarded as being largely due to real trigonometric errors. This may well be so as the beacons were selected at random and are not primary stations. No special triangulation adjustment was made. A number of seamlines were straddled and it appears that the measurement constitutes a severe test of the triangulation under the least favourable conditions.

The main purpose of this set of measurements, however, was to confirm the improvement in self-consistency obtainable in spite of unfavourable ground conditions. The residual errors as indicated by the mean square adjustment are thought to be approaching the limit set by meteorological uncertainties on lines of these lengths.

4.4. *The Mtubatuba Base Extension Measurements.* This base has been referred to previously. The altitude is near sea level and the humidity was relatively high. The equipment was in its final form, reverse A reading being included to remove centring errors. Units of length and meteorological and other corrections are consistent with the most recent data available.

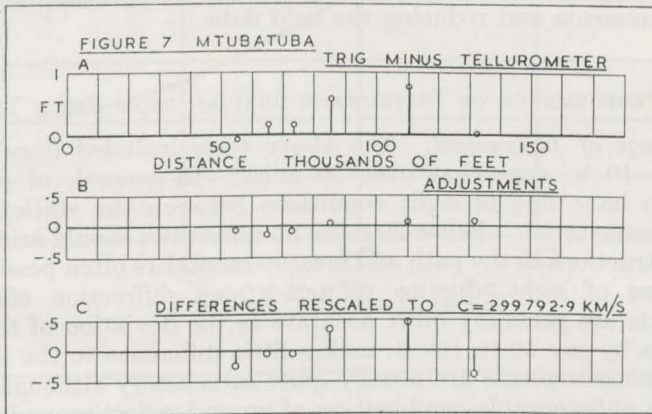


Fig. 7. The Mtubatuba Base Extension measurements shown as: (a) the unadjusted differences; (b) the adjustments for self-consistency, and (c) the unadjusted differences re-scaled to a velocity of 299,792.9 Km/sec for optimum fit with the trigonometric data.

A figure of 10 lines between 5 points was planned. Unfortunately, one base terminal has become immersed in a forest and three of the lines, including the base itself, were not measurable. Six of the remaining lines form a redundant figure as shown in Fig. 4 (C). The detailed results of the measurement of these lines are given in Table 1. This figure includes the two lines previously referred to, the base extension and the overseas line.

Fig. 7 (A) shows the trigonometric-unadjusted tellurometer differences plotted for a nominal velocity of 299,792.0 Km/sec. Fig. 7 (B) shows the

adjustments for self-consistency. These are quite small but, due to there being only a single redundancy, little significance can be attached to this. The mean square adjustment was .08 ft. Fig. 7 (C) shows the result of re-scaling the unadjusted tellurometer distances to 299,792.9 Km/sec to give the optimum fit with the triangulation data. The velocity derived from these measurements is therefore

Mtubatuba Velocity: 299,792.9 Km/sec.

This is in good agreement with the Kroonstad velocity. The mean square scatter of the points after re-scaling is .30 ft. and is much the same whether the tellurometer figure is adjusted or not. As the figure has insufficient redundant lines, the latter must be taken as the real indication of the accuracy of these measurements. It includes, of course, the trigonometric errors but is within the claimed limit of accuracy of the instrument.

As to the accuracy of this base the same remarks as in the case of the Kroonstad base would apply, although this is a much more recent base (1936). On the other hand, it is understood that some discrepancies in the standardization against tapes and the South African bar standards arose. The trigonometric figures are based on the bar standard and, in so far as the measurement proves anything, it confirms that the latter was probably more correct relative to the Kroonstad base and the other local bases which are standardized against the same bars.

Representatives of the Department of Trigonometrical Survey and the Survey Department of the Witwatersrand University assisted in making these measurements and reducing the field data.

5. PERFORMANCE OF INSTRUMENT DERIVED FROM FIELD TESTS

5.1. Range of Instrument. The above tests included lines ranging in length from 10 to somewhat over 30 miles. In general, of course, it is necessary to have line of sight conditions between the stations although visibility is immaterial. Below 20 miles no difficulties should arise even with isolated obstructions in the path and measurements are often possible without complete line of sight, due to refraction and diffraction effects. Such measurements are generally quite accurate as the deviation of the ray path in the centre by say 50 to 100 ft. makes little difference to the length. Up to 30 miles measurements are usually quite satisfactory although in isolated instances an unfavourable combination of ground reflection and direct path may give rise to weak signals at certain carrier frequencies or sometimes, in the case of a very shallow line, at all frequencies. Beyond 30 miles and up to 40 and possibly 50 miles, measurement will be possible in favourable conditions of topography.

The minimum range may be taken as 500 ft., below which overload effects may interfere with accuracy, although there is no real lower limit to the range.

5.2. Accuracy of Instrument. Based on the above series of tests and extended measurements on single lines, the accuracy of the instrument is stated to be 2 in. + 3 p.p.m. This is shown graphically in Fig. 8, where the two sources of error are added on a vector basis.

The constant error is the instrumental error and is estimated at 2 in. for an average observer. In certain tests this figure has been improved upon as in the case of the zero determination referred to. Quite unskilled observers are not likely to exceed this figure by much, as has been determined by experimenting with different observers.

The 3 p.p.m. arises mainly from the meteorological limitations. It has been found that, in spite of the relatively high vapour pressure correction for radio waves, the limitation due to humidity is not very severe except perhaps in the highest humidities, as the vapour pressure tends to be reasonably constant over wide areas and the measurements at each end

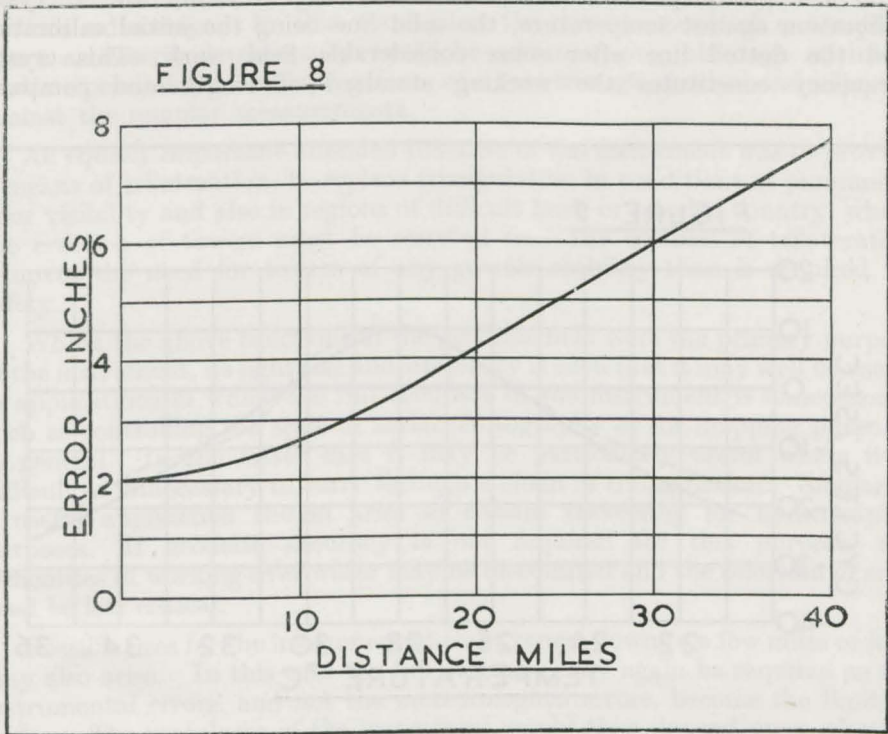


Fig. 8. The estimated probable error of a single tellurometer measurement plotted against the distance measured.

of the line are fairly representative. Note that this remark refers to vapour pressure and not relative humidity, the latter being immaterial. The temperature on the other hand shows quite large short and long term variations. For example, successive measurements of the air temperature show sudden jumps of a few degrees—sometimes up to as much as 5°F . It is thought that the main source of meteorological error arises from temperature readings which are not truly representative of the path. The temperature corrections are much the same for any type of electro-magnetic radiation and temperature uncertainties are thus the limiting factor in all this type of work.

It seems reasonable, and there is some experimental evidence to support the possibility, that as lines become longer the meteorological measurements become less and less representative. For instance, in very long range work over a few hundred miles, it is hardly possible that the meteorological variation along the path could ever be suitably determined to the order of accuracy under discussion. For any given instrument then an optimum range must exist, which is a function of the instrumental accuracy. In the case of the tellurometer this range is thought to be of the order of 25 miles. In some weather conditions it may, however, be somewhat lower—perhaps 15 miles or even less.

5.3. *Stability of the Working Standard.* Fig. 9 shows the A crystal calibration against temperature, the solid line being the initial calibration and the dotted line after some considerable field work. This crystal frequency constitutes the working standard of length and compares

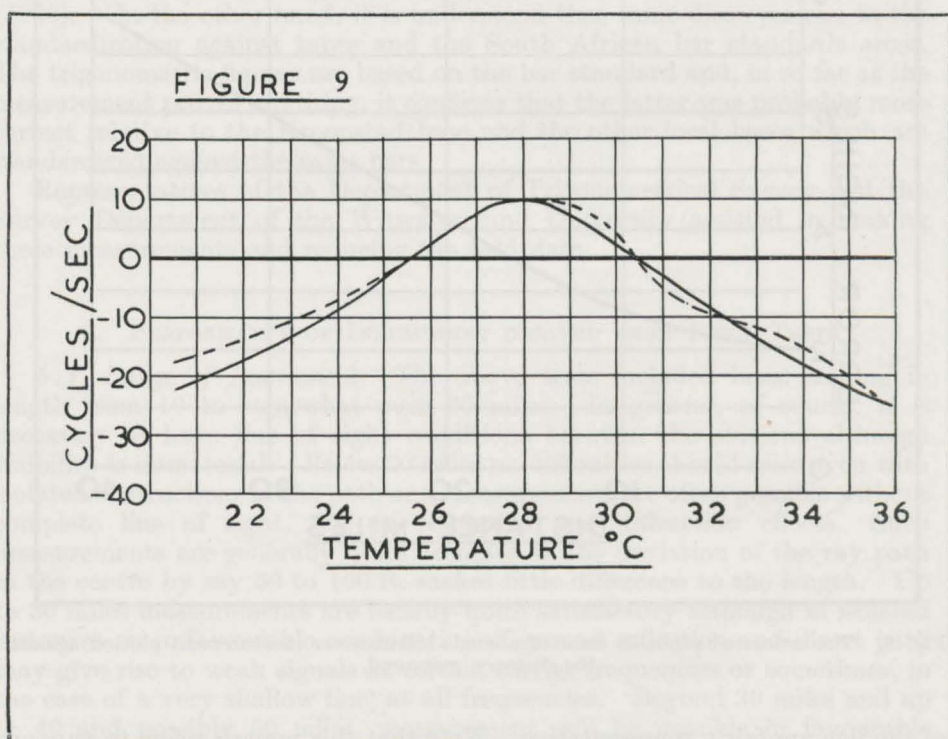


Fig. 9. The stability of the working standard of length, showing the deviation of the A crystal frequency from its nominal value of 10,000,000 cycles/second plotted against the temperature. The solid and dotted lines respectively are the calibration before and after some weeks of field work.

favourably as regards stability with an invar tape. It will be seen that over a range from 23° to 32°C. the crystal is within ± 1 p.p.m. of its nominal frequency. This is typical of such a crystal which has been specially specified for these conditions. Outside this range the coefficient increases to about

1 p.p.m. per °C., but if the crystal is brought into this range where necessary by artificial means the question of errors due to the accuracy of the working standard should not arise. It would, of course, be possible to oven this crystal but this is regarded as unnecessary and may involve loss of time whilst waiting for the oven to settle down. A crystal suitably cut for full ovening would be quite unsuitable for use at ordinary ambient temperatures.

5.4. *Possible useful applications of the Instrument.* The primary purpose for which this instrument was developed was as a means to replace existing methods of taping a geodetic base. In this rôle it is not necessary to restrict the length of the base to the shorter lines more commonly the practice with taped bases and, furthermore, bases may be laid down more frequently with obvious advantage. In this connection the measurement of a complete figure as described previously would be advantageous, although an intermediate possibility is the laying down of a base triangle checked and adjusted against the angular measurements.

An equally important intended function of the instrument was to provide a means of trilateration, to replace triangulation in conditions of permanent poor visibility and also in regions of difficult bush or wooded country, where the erection of towers must be resorted to. The method of trilateration removes the need for towers of any greater stability than is required for safety.

Whilst the above functions in the geodetic field were the primary purpose of the instrument, its lightness and simplicity is such that it may well be useful in applications in which the full accuracy of the instrument is unnecessary, such as controlling the scale of aerial photography or for mapping purposes in general. In the latter case it may be particularly useful where it is difficult or unnecessary to carry through a chain of triangulation. Similarly, a useful application should arise in coastal traversing for hydrographic purposes. If geodetic accuracy is not required for this purpose, the difficulties of working over water may be discounted and the selection of sites need be less critical.

Possible uses for the instrument at short range, down to a few miles or less, may also arise. In this case the full accuracy may again be required as the instrumental errors, and not the meteorological errors, become the limiting factor. The usefulness of the instrument would then depend upon whether the procedure of setting up the instrument and taking sufficient readings to obtain the desired accuracy was justified relative to other methods. At ranges less than 1,000 ft. it is not likely that sufficient accuracy or convenience, as compared to taping, could be achieved. Above this distance, the accuracy should soon become comparable with simple taping and a gain may result, particularly in cases where triangulation is difficult or impossible and distance measurement must be resorted to.

6. THE VELOCITY OF LIGHT

The velocity of light, or, more strictly, of electro-magnetic waves in vacuo, was until fairly recent years given as 299,775 Km/sec. This figure came under suspicion mainly as a result of radio measurements, which tended

to show a much higher value. In 1954 the General Assembly of the International Scientific Radio Union accepted a value of $299,792.0 \pm 2$ Km/sec as a result of numerous modern measurements including both radio and light.

This figure has been used as a nominal value in this work and, of course, in practical work of this nature it is essential to retain a single value to avoid confusion. These measurements tend to indicate, however, that a somewhat higher value is more correct, although within the tolerance given above. It is difficult to give a precise tolerance to the value arrived at as numerous factors must be considered, such as the possible existence of systematic errors in the methods of taping a base, and the practical limits of the accuracy with which standards can be laid down and inter-compared quite apart from any possible systematic errors in the tellurometer measurements themselves.

It is possible that in time an agreed international value for survey purpose will be arrived at but, as a practical means of preserving measurements in a least ambiguous form, we have made a practice of recording all measurements in terms of what we have described as vacuum millimicroseconds or the double transit time corrected to vacuum. This, in a sense, constitutes a unit of length in its own right, dependent only on the properties of space and the definition of the unit of time. Time is sufficiently well defined and universally available by means of radio signals and frequencies to meet any likely accuracy the surveyor will demand in this respect.

Some confusion has arisen in this work as a result of using British feet as our unit and it would have been more satisfactory to confine our practical unit to international metres. The only excuse for doing this is that the original approach was an engineering one and the uncertainties in the inter-comparison of units were not appreciated.

7. CONCLUSION

The tellurometer system of microwave distance measurement has been described and the results of tests reported, from which the application and usefulness of the instrument can be inferred. This instrument is light and simple and its accuracy sufficient to meet a wide range of applications. The range obtainable is adequate for most purposes, being limited in general only by line of sight requirements. The accuracy obtainable with microwaves is shown to be comparable with that obtainable by any type of electromagnetic wave.

Measured values of the velocity of electro-magnetic waves are given.

8. ACKNOWLEDGMENTS

The initial interest in this work was stimulated by Col. H. A. Baumann, former Director of Trigonometrical Survey in South Africa, and Dr. F. J. Hewitt, Director of the National Telecommunications Research Laboratory of the South African Council for Scientific and Industrial Research.

The author also wishes to acknowledge the assistance of Mr. J. A. Fejer of the above Laboratory, in subjecting the theory of the instruments to rigorous mathematical tests and his assistance with computation and inter-

pretation; Mr. C. H. Meredith for his assistance in constructing the instruments and Mr. R. W. G. Owen-Jones, his "Slave" operator, who has tended to become part of the instrument.

The assistance of Prof. G. B. Lauf, of the University of the Witwatersrand, and of the staff of the Trigonometrical Survey in providing the necessary background of survey information, assisting with the measurements and confirming the computations, is also acknowledged.

Finally, the author wishes to thank the South African Council for Scientific and Industrial Research for permission to publish this paper.

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APPENDIX

THE RIDGEWAY BASE FIGURE MEASUREMENTS

During April 1957 a programme of tellurometer measurements of the Ridgeway base and surrounding primary triangulation was carried out with a view to gaining further data on the accuracy of the instrument and to obtain velocity measurements of higher precision than previously. The Ridgeway base has been taped on two separate occasions, using modern methods with an agreement of $\frac{1}{2}$ part per million between measurements, and it is therefore probably the most suitable line available for making accurate velocity determination with a tellurometer.

NATURE OF THE MEASUREMENTS

The baseline itself, some seven miles long, was measured four times in each direction under varying meteorological conditions. A figure of six points including the baseline was measured, 14 of the 15 possible lines being measured once only. The points were primary stations with one exception (Point 5, Toney Wood) where a 103 ft. tower was erected near a primary station and tied into it, for the purpose of gaining inter-visibility which had been lost due to tree growth. This also gave an opportunity of observing the performance of the instrument on a high tower and, in spite of high winds, performance was in all respects normal.

The measured figure was subjected to analysis as previously described.

Crystal frequency calibrations were checked at intervals and errors in this respect were believed to be not greater than 0.2 p.p.m. Calibration checks on the aneroid barometers used indicate that errors not greater than an equivalent amount are likely to have arisen.

The Ordnance Survey of the United Kingdom assisted with these measurements, provided the trigonometric data and confirmed the calculations and adjustments.

RESULTS OF THE MEASUREMENTS

The mean of the base measurements gave a velocity (corrected to vacuum) of 299,792.80 Km./sec.

The mean velocity derived from the complete figure was 299,792.54 Km/sec. The least squares adjustment of the tellurometer figure was made with each line weighted according to its length. The mean square adjustment was 1.7 parts per million and re-scaling the velocity to 299,792.6 Km/sec. gave

a mean square agreement with the trigonometric lengths of 1.0 parts per million. Details of the measurements are given in Table II. The apparent accuracy of these measurements is about twice the accuracy previously claimed. Topographical conditions were more or less ideal for accurate measurement and weather conditions, although rather windy and cold, were reasonably stable.

DISCUSSION OF RESULTS

There is every reason to believe that these measurements should give a reliable working value of velocity for tellurometer use, and their relation to recent laboratory measurements is therefore important.

The British N.P.L. have recently completed a determination of radio velocity by means of a millimetre wave-interferometer. The result, which awaits a re-measurement of the length standards before publication, is not expected to differ from 299 792.5 Km/sec. by more than one or two parts in 10 million and is expected to have an accuracy of about 0.1 Km/sec. This work, however, is based on a refractive index formula differing slightly in the water vapour coefficient from the formula used in the tellurometer calculations due to Smith and Weintraub. The National Physical Laboratory formula due to Essen and Froome^{2, 3, 4} for which a higher degree of experimental precision is claimed gives in the practical form for tellurometer use the following:

$$N = (n-1) 10^6 = \frac{4730}{459.5 + ^\circ\text{F.}} \left(p'' + \frac{8540e''}{459.5 + ^\circ\text{F.}} \right).$$

If this slightly different formula is applied for the mean conditions of vapour pressure measured at Ridgeway of .302'' and .257'' respectively then the velocities become

Ridgeway Base Velocity	...	299,792.60 Km/sec.
Ridgeway Figure Velocity	...	299,792.37 Km/sec.
Mean Ridgeway Velocity	...	299,792.49 Km/sec.

CONCLUSIONS

The agreement obtained between the National Physical Laboratory work and these tellurometer measurements is very satisfactory and forms a basis on which a firm recommendation can be made for the purpose of geodetic and other tellurometer work. It is suggested that the accepted velocity for this work should be:

Working Velocity 299,792.5 Km/sec. in conjunction with the rounded off practical working formula for refractive index given above.

[Note that the working velocity if the Smith and Weintraub formula is used would be .2 Km/sec. higher. The preference for the National Physical Laboratory refractive index formula, apart from the higher claimed accuracy, is based on the fact that the determination of both this formula and the National Physical Laboratory velocity have been made under the same controlled conditions by one authority, and that the velocity measurements have been made relative to the same length standards as the Ridgeway base.]

TABLE II
RIDGEWAY BASE FIGURE
Comparative results from Tellurometer trials

Line		Tellurometer Spheroidal lengths ($C = 299792.0$ Km/sec.) Metres			Adjusted Tellurometer lengths re-scaled to $C = 299792.6$ Km/sec.	Adjusted Triangulation Spheroidal lengths	Difference Trig. minus Tellurometer ($C = 299792.6$ Km/sec.)	Fractional Difference 1 in.
From	To	Unadjusted	Adj. corrn.	Adjusted				
1	2	11260.159	-0.020	11260.139	11260.162	11260.189	+0.027	417,000
	3	25803.453	+0.064	25803.517	25803.569	25803.588	+0.019	1,358,000
	4	25633.696	+0.004	25633.700	25633.751	25633.740	-0.011	2,330,000
	*5	52644.087	+0.059	52644.146	52644.251	52644.263	+0.012	4,387,000
	6	48846.230	+0.076	48846.306	48846.404	48846.390	-0.014	3,489,000
2	3	24430.772	+0.020	24430.792	24430.841	24430.861	+0.020	1,221,000
	4	16200.124	-0.005	16200.119	16200.151	16200.132	-0.019	853,000
	*5	46381.539	-0.097	46381.442	46381.535	46381.522	-0.013	3,568,000
	6	49655.759	+0.123	49655.882	49655.981	49655.951	-0.030	1,655,000
3	4	19645.235	+0.012	19645.247	19645.286	19645.250	-0.036	546,000
	*6	73394.964	-0.261	73394.703	73394.850	73394.841	-0.009	8,155,000
4	*5	52837.882	+0.054	52837.936	52838.042	52838.062	+0.020	2,642,000
	*6	63402.368	-0.032	63402.336	63402.463	63402.434	-0.029	2,186,000
5	*6	32072.318	+0.003	32072.321	32072.385	32072.344	-0.041	782,000

* Ray not observed in triangulation and therefore not an integral part of the triangulation figural adjustment.

- | | |
|-----------------------|-----------------|
| 1. White Horse Hill. | 4. Martinsell. |
| 2. Liddington Castle. | 5. Toney Wood. |
| 3. Inkpen. | 6. Cleeve Hill. |

THE CAITHNESS BASE MEASUREMENT

Tellurometer measurements were made of the Caithness base early in May 1957. Unfortunately, the baseline of some 15 miles length was found to suffer from excessive ground reflection effects and, although measurements of the expected accuracy under such conditions were made, the accuracy was inadequate for precise velocity determinations. The absence of vegetation at the time of year on the relatively smooth ground, coupled with a fairly large ground clearance, accounts for these strong ground effects.

The base, however, consists of two sections defined by a central beacon each some seven miles long. Measurements of these two sections separately gave reliable readings with little ground swing due to the lower ray clearances. Three measurements were made on each section and the mean of the distances based on the Ridgeway figure velocity computed.

On this basis the Eastern section shows exact agreement with the taped measurement, the Western section, however, measuring some 7 cm. long relative to the taped measurement. It is understood that the self-consistency of the taped measurements leaves the accuracy of this base open to some doubt within the limits of precision needed for a velocity determination, and in the absence of a complete figure measurement to check the tellurometer measurements no reliable figure for velocity was obtained.

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THE USE OF SENSITIVE PRESSURE DEVICES IN SURVEYING

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(Continued from No. 105, page 127)

APPENDIX 4(B)

THE ASKANIA MICROBAROMETER AND MICROBAROGRAPH

MICROBAROMETER

The pressure-sensitive element of the Microbarometer (Fig. 1, *Plate XIII*) is a Bourdon tube (6) in the form of an evacuated helical spring tube. The upper end of this Bourdon tube is fastened to the torsion head (3) whereas the lower part is firmly connected with the suspension (7) of a torsion bar. This torsion bar is a steel wire (5) which is fastened by means of clamps (1) to the torsion head (3) and to the bottom to the housing and held under tension by a pressure spring. The steel wire is firmly clamped to the suspension (7) so that only the ends between clamps (1+4) are effective as a torsion bar. The suspension (7) is equipped with a mirror (8) and a copper disc (10) on its lower end.

R.G.S. DISCUSSION ON "THE TELLUROMETER SYSTEM OF DISTANCE MEASUREMENT"

[*Note*.—In our issues for July and October, 1957, vol. xiv, Nos. 105 and 106, we published a paper by Dr. T. L. Wadley on "The Tellurometer System of Distance Measurement". This paper was discussed at a meeting held on Wednesday, 24th April, 1957, in the Lecture Hall of the Royal Geographical Society, advance copies of it (less the Appendix which was not then available) being provided for this purpose. The following is a condensed account of the discussion which Dr. Wadley has prepared for this *Review* and is published here by kind permission of the R.G.S. This account only deals with the technical questions raised with the author of the paper and does not include preceding addresses by the Chairman, Major-General R. Ll. Brown, Colonel H. A. Baumann, Brigadier M. Hotine and Colonel G. J. Humphries. (EDITOR, *E.S.R.*)]

In reply to a question the pronunciation of "Tellurometer" was given with the accent on the third syllable.

Major-General J. C. T. WILLIS (Ordnance Survey) asked what errors might be expected if the assumption, that the mean of the temperature and humidity measurements is valid, proved within foreseeable circumstances faulty.

The author (in reply) stated that meteorological uncertainties accounted probably for 90 per cent of errors in the system and a statistical study of measurements indicated that these would not exceed three parts per million, except perhaps when the meteorological conditions causing greater errors were more or less apparent. The apparent lower accuracy of the 45 mile line measured at Ridgeway was probably partly due to meteorological uncertainty and this assumption was probably breaking down. If one measured lines over a 100 miles long it was obvious that this would happen and for this reason precise work should not be attempted at ranges greater than say 35 miles.

Brigadier A. H. DOWSON (Ordnance Survey) asked for some information as to robustness of the equipment, its probable reliability and ease with which defects might be rectified in the field.

The author (in reply) stated that the instruments which he used at Ridgeway had been treated as ordinary luggage in transit and that there was no need to treat them as delicate instruments. The quartz crystals were as robust as electronic valves, which today were fairly reliable. The Ridgeway measurements were made without any failure except a small defect on arrival, and re-calibrations during the measurements indicated no sensible crystal changes. It should be possible for those using the instruments continually, even if not expert electronic engineers, to form some idea of the average run of faults and put them right in the field, and a fault-finding procedure had been drawn up for this purpose. Obscure electrical faults would need the attention of a skilled electronic mechanic but it was perhaps more important that he should be familiar with this particular equipment rather than very skilful in a general way.

Mr. R. F. HANSFORD (Decca) asked whether the existing value for the velocity of radio waves corrected to ground level gave accurate measurements or whether it had been found necessary to correct this value.

The author (in reply) stated that the accuracy of the measurements made was dependent upon the accuracy of the refractive index formula used and

the velocity (corrected to vacuum) arrived at would be in error if the refractive index formula were in error. The older Radio Meteorological formula gave a considerable error in velocity relative to the existing value, but closer agreement was obtained by the use of the more recent formulae. (It is possible that the ground level corrections referred to by Mr. Hansford were not the refractive index corrections discussed above but corrections for a ground attached wave, which are not applicable to propagation of centimetric waves even near the surface of the ground—Author.)

Mr. FROOME (National Physical Laboratory) stated that the N.P.L. had done a good deal of work on the refractive index of air, and that there was considerable reason to suppose that the Smith and Weintraub refractive index formula was slightly in error in respect of the water vapour corrections and, at the pressures quoted, would probably give errors of about one part per million in the velocity.

Mr. Froome stated that on page 107 of the paper, in the example given, the difference in the refractive index at Master and Remote was 18 parts per million on account of the water vapour pressure differences. Under these circumstances he questioned the procedure of taking readings at the ends of line only to obtain the accuracy claimed.

The author (in reply) said that he doubted whether the difference was as great as stated but agreed that, if so, an accuracy of three parts per million in the line measurement could not be justified. (Mr. Froome's statement was correct. The example given is a rather extreme case with one terminal at the seaside, the other 25 miles inland.)

Mr. Froome stated that a number of recent determinations of the velocity of microwaves made at the N.P.L. and by others gave values ranging between 299,792.0 Km/s. and 299,793.0 Km/s. which was in good agreement with the author's measurements. The figure of 299,792.0 Km/s. was regarded as definitely too low.

The author (in reply) agreed with this view and stated that the value of 299,792.8 Km/s. measured on the Ridgeway Base might come into line with the Geodimeter light value of 299,792.4 Km/s. measured on the same base if the water vapour corrections referred to by Mr. Froome were applied, and that he would follow this up.

Dr. ESSEN (National Physical Laboratory) stated that it was well known that the atmosphere was extremely patchy and that one patch of air a few yards from another could differ by 20 parts per million in refractive index. He suggested that readings should be taken at three points at least and averaged over the whole measurement time.

The author (in reply) stated that more intensive meteorological measurements might help a little but that he believed that no practical method could reduce the errors substantially. The current procedure was regarded as the practical limit to which these measurements should be taken for ordinary survey operations.

Mr. THOMPSON (University College) inquired, in connection with the method of dealing with reflections by measuring on a series of carrier frequencies, by what means the instrument distinguished the direct or true ray from the reflected.

The author (in reply) stated that the assumption was made that the direct ray was stronger than any combination of indirect rays. If this were so, and it was a fair assumption, the method measured the direct ray. If the indirect ray were stronger it would measure the indirect path. He stated that the technique had been confirmed practically by subjecting badly reflecting lines to analysis in an extensive redundant figure and also theoretically by his colleague, Dr. J. A. Fejer, by an analysis of the physical processes. The latter were somewhat complicated by the complex spectrum involved and the fact that the carrier frequencies in each direction were different. The accuracy of the technique was a function of the frequency deviation used, namely 200 Mc/s., and it could be shown that this deviation would give certain maximum errors in given conditions.

A SPEAKER asked what crystal calibration and index error procedure were recommended in the course of field work.

The author (in reply) stated the index error or zero error could be determined once and for all, unless the instrument were damaged or some major mechanical change to the aerial system were made. It was also believed that the error was constant from one instrument to the next, depending upon the degree of precision under discussion. The A crystal frequency during the Ridgeway measurements had been recalibrated a number of times as a precaution but no sensible variations had been noted. In doing very accurate geodetic or scientific work one would recalibrate at every conceivable opportunity but, for ordinary field survey work, recalibration once every three to six months should be adequate. The order of frequency calibration changes were a few parts in 10 million and, if an accuracy of one part per million were acceptable, the need for calibration should be rare.

Commander FRYER (Admiralty) inquired whether, if used for fixing or off-shore sounding, the instrument could be read coarsely and quickly with movement and whether it could run 10 hours per day without overheating.

The author (in reply) stated that there was no question of overheating. It was doubtful whether coarse readings could be satisfactorily taken in rapid motion with the existing instrument as difference readings were involved, but lower pattern frequencies could be used, say 1 Mc/s. instead of 10 Mc/s., giving a pattern 10 times as coarse as the geodetic pattern. This was the lower limit of modulation that could be applied as the method broke down at lower frequencies.

Dr. BARREL (National Physical Laboratory) inquired whether the return of the wave from the Remote Station involved a delay; whether this was taken into account and whether it was very constant.

The author (in reply) stated that, apart from a small delay, equivalent to about 1 inch at each instrument due to the dipoles themselves, which was calibrated out as explained in the paper, the internal delay in the amplifier circuits was very small as the comparison frequency of 1 Kc/s. was low compared to the band pass of the amplifiers; this small delay was balanced as it occurred at both Master and Remote stations and that, due to the procedure of positive and negative patterns, any internal delay deliberate or otherwise was of no account. For the same reasons sensitivity to temperature and ageing effects were non-existent.

Mr. MORGAN (Marconi) wanted to know the transmitter power, the receiver noise factor, the final detected bandwidth, the signal to noise ratio of the circle at 45 miles, and the minimum workable signal.

The author (in reply) stated that the transmitted power was 100 milliwatts. The receiver noise factor was probably inferior by perhaps 6 or 10 db to a modern radar receiver of similar frequency, due to the nature of the transmitter to receiver coupling. The final post detection band pass on the circle was about 10 Kc/s., the bandpass on the pulse being the full I.F. bandpass of some 500 Kc/s. At 45 miles the circle signal to noise ratio was perhaps 5 or 10 to 1, the signal to noise ratio of the pulse being about 1 to 1 which was about the minimum workable signal.

Mr. LIGHTFOOT (Marconi) inquired whether, due to the similarity of the instruments at the Master and Remote stations, a dual purpose instrument at each end operating as either would serve any useful purpose.

The author (in reply) stated that this possibility had been considered. Retaining the existing crystals, pattern frequencies based on 9.999 Mc/s. would be obtained which would be inconvenient and a remote could obviously not work with a remote. Otherwise a total of 18 crystals in all would be required to retain the present system of patterns with complete flexibility, and the overall complexity in this case was considered undesirable. In principle, however, this possibility of dual functions was sound.

THE MUNICH COURSES IN DISTANCE MEASUREMENT

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[*Note.*—At the beginning of this article the author disputes the accuracy of certain statements regarding the Munich Courses in Distance Measurement which were contained in a review that was published in our issue for January, 1957. In letters published in our issues for April and July, 1957, Dr. M. Kneissl, the principal organizer of the courses, and Mr. J. A. Weightman have shown that these statements were not correct and the author of the review has since declared that he accepts unreservedly Dr. Kneissl's assurances in the matter, the statements in question having been made because of a misunderstanding. Hence, from the point of view of correcting these statements, it is not necessary to publish the following article. However, it not only contains a short personal account of the course held in 1955, but it also gives some useful references to recent work and literature on optical distance measurement, and for that reason we have decided to publish it in full.—EDITOR, *E.S.R.*]

THE January 1957 issue of the *E.S.R.*, xiv, 103, 44, reviews a book, "Internationale Streckenmesskurse in München", which was published for the Course in Distance Measurement held in Munich in October 1955, and which presented some material from the previous course, held in 1953, with the addition of some of the material for the 1955 course. The review states or implies that:

1. The course was not truly international. ("The lecturers were all Germans.")

2. It was not a genuine meeting for the exchange of views and experiences between geodesists or surveyors. ("The aim is . . . to advertise the qualities of German instruments.")