An Automatic Phase Plotter for the Measurement of Microwave Fields

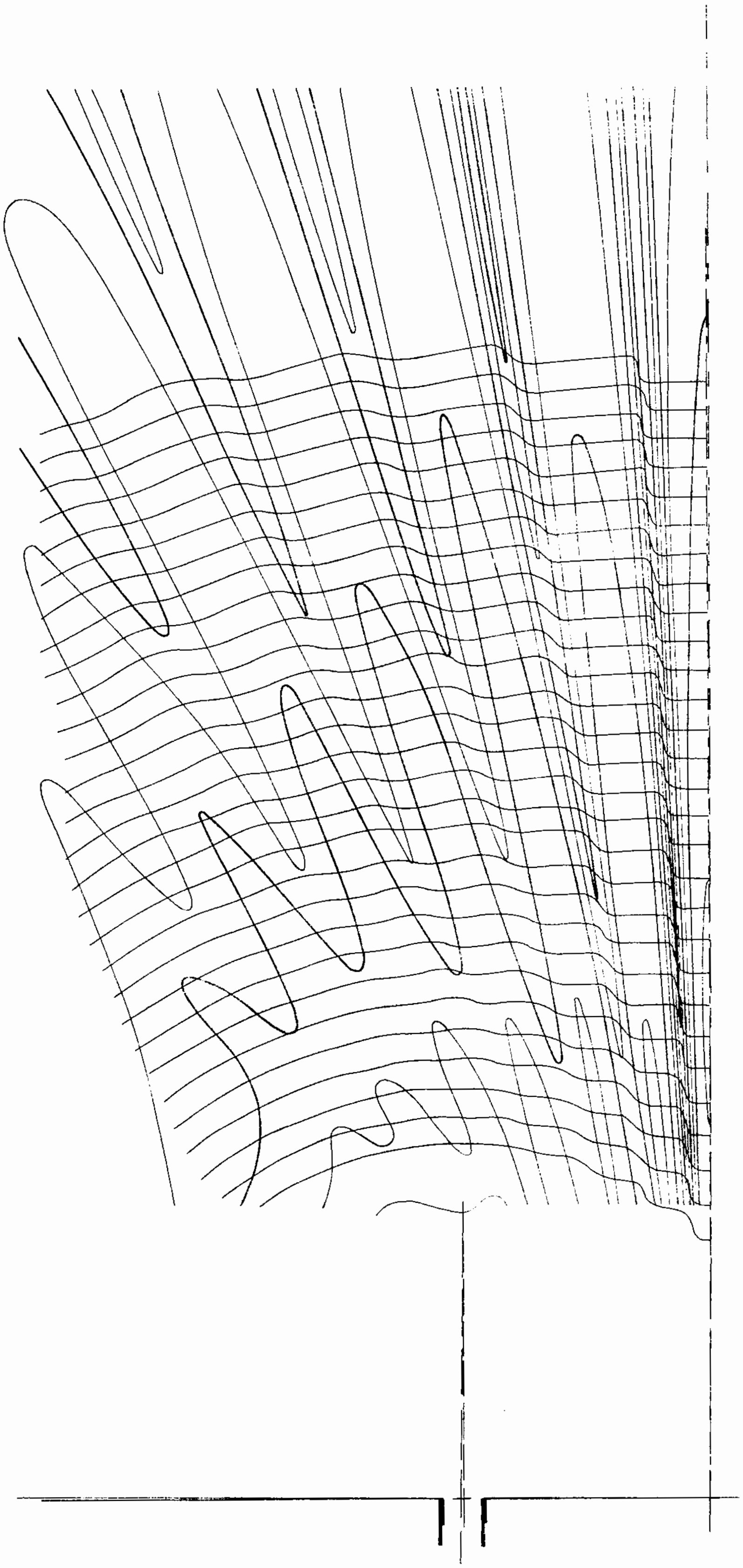
by

Tomas J. F. Pavlasek

A thesis submitted to the Faculty of Graduate Studies and Research at McGill University in partial fulfilment of the requirements of the degree of Doctor of Philosophy in Electrical Engineering

Eaton Electronics Research Laboratory
McGill University

April 1958



Frontispiece

ABSTRACT

The problem of phase measurement at microwave frequencies has been investigated and an automatic, recording system developed for use in microwave optics studies.

The phase plotter operates at 9.3 Kmc/s and measures phase and intensity of a field continuously along chosen scanning lines. The phase measurement is essentially independent of intensity variations of up to 40 db and the follow-up response during automatic operation is over 90° per second. The accuracy is $\pm 5^{\circ}$ in automatic operation and $\pm 2^{\circ}$ when operated manually.

The system's operation depends on the Homodyne technique. Automatic operation is made possible by the development of a novel modulator using ferrite microwave components. The plotter is designed to achieve system dependability and simplicity in the measurement of both phase and intensity.

The performance of the plotter is demonstrated by static calibration, by dynamic tests simulating operating conditions and by measurement of actual fields whose configuration is calculated for comparison.

ACKNOWLEDGEMENTS

The author expresses his thanks to those whose contributions have made this research possible; to Professor G.A. Woonton who proposed the problem and supervised the project and to Professor F.S. Howes who gave continued encouragement; to Dr. G. Bekefi who guided the initial stages of the work; to Professor G.W. Farnell who was a source of inspiration throughout the project and provided assistance for the theoretical background of the proof of performance of the equipment; to Mr. V. Avarlaid and his staff whose technical skill made the construction of the equipment possible; to Mrs. A.J. Patten and Mr. J. Traynor whose artistic talents contributed greatly to the graphical presentation of the thesis.

The research reported here forms part of a project on Microwave Optics supported at the Eaton Electronics Research Laboratory, McGill University by the United States Air Force, Cambridge Research Center under Contracts Nos. AF 19 (122) 81 and AF 19 (604) 2228 and by the Defence Research Board, Ottawa.

TABLE OF CONTENTS

CHAPTER I

Introduction

In recent years electromagnetic wave theory has been significantly advanced through contributions from experimental observations, particularly in relating microwave and optical phenomena. The basic measurements involved are those of the phase and intensity of fields produced by lenses or other radiators. Sets of points or scanning lines lying in plane sections of a field are obtained and then collated into phase and intensity contour maps. To facilitate this work, automatic, recording devices are required to replace manual procedures in order to increase the speed and reduce the labour and monotony of repetitive measurements. While automatic intensity measuring techniques and instruments have been widely used for some time, devices for phase measurement are not common. The research reported here has resulted in the improvement of phase measuring technique and in the development and construction of a new form of phase and intensity plotter which has flexibility, dependability and may be used with relative ease.

The problem of phase measurement is not restricted to high frequency and microwave field measurements alone. Quantities such as voltage, current and amplifier gain at single frequencies have traditionally been measured in magnitude only, while the evaluation of relative phase has been either neglected or indirectly inferred. The reason for this is that the determination of relative phase implies the measurement of time, and the higher the frequency of the quantity being measured the greater the complexity of equipment required. Even at power frequencies where voltage and current magnitude measurements are straightforward, phase measurements are inferred from power considerations or made by relatively complicated apparatus.

During the past fifteen years, the problem of measuring phase has been given increasing attention over the entire frequency spectrum of interest to the communication engineer and radio physicist. In the audio and video frequency ranges, stringent specifications of pulse transmission quality, have resulted in the development of a number of techniques for phase measurement. At radio frequencies inclusive of the microwave bands, the impetus for the development of phase measuring devices has come from two sources - the measurement of the near fields of radiating systems such as those involved in microwave optics and the measurement of wavefronts in propagation studies. The necessity of collecting large amounts of data in any given problem has given rise to the demand for measuring apparatus which is capable of rapid, automatic operation and which provides a graphical record of the results.

The plotter described here operates at a wavelength of 3.2 cm and can measure the phase and intensity of a field continuously along scanning lines covering an area about 60 cm x 120 cm. The range of phase measurement is essentially limitless but within a single scan is restricted to 3600°. The phase measurement is independent of intensity variations of as much as 40 db. In automatic operation the follow-up response of the phase measuring system is better than 90° per second. The plotter may be used either for automatic or manual operation. The accuracy in manual use is 2° and in automatic operation, 5°.

The automatic system was made possible by the development of a new modulator which permitted the use of the Homodyne method of phase measurement which previously was not dependable. The design of the new modulator was made possible by recent developments in the field of microwave ferrite components. The addition of the automatic feature to the system has been greatly aided by the growth of knowledge and techniques during the past two decades in the field of automatic control and servomechanisms.

In the course of development, the use of specially built devices was avoided as far as possible, and up-to-date microwave circuit techniques and commercially available components were used. The development has resulted in the establishment of a measuring technique as well as the construction of actual apparatus. The device, as presently constituted, should be easily reproducible by any well equipped microwave and electronics laboratory. The plotter was subjected to a number of tests and a "Proof of Performance" in order to demonstrate its effectiveness.

The thesis is concerned with a statement of the basic problems involved in the instrument's development (Chapter II) and with the solution of these problems (Chapter III and IV). In Chapter V are described details of the plotter's construction and Chapter VI reports the evaluation of the system's performance by experimental procedures. Operating instructions are added as an Appendix. It is concluded that the plotter satisfactorily meets present needs by providing a rapid and accurate means of measurement. The rate of measurement has been increased by at least two orders of magnitude in comparison with manual procedures. As suggested in the final Chapter VII, experience in operating the present device indicates possibilities of a more ambitious system. In such a system, methods of automatic data processing would be added to those of automatic measurement, thus increasing the rate of experimental investigation by another order of magnitude.

CHAPTER II

The Problem of Automatic Phase Measurement

2.1 The Problem of Measuring Phase

Relative phase measurement implies essentially the determination of short time intervals. This can be achieved either by time measurement, or by the observation of a phase dependent phenomenon. At low frequencies a time measurement method is feasible. The dividing line is at about 1 Mc/s. for up to this frequency, electronic counter procedures can be used with presently available instruments. Beyond this, at high radio and up to the microwave frequencies, recourse is taken to one of several techniques in which some particular phasing condition results in an observable phenomenon and the phase is then obtained by inference. Such techniques may be called indicative techniques since the phase is measured with the help of an indirect indication.

Since phase is a relative concept, the measurement of an unknown signal phase must be made relative to a reference signal. The measurement is normally made in terms of a calibrated phase shifter which is used to change the phase of either the unknown or reference signal until a desired indication is obtained. The phase shifter is thus the "meterstick" of the phase measurement. The indicative methods can be classed in three groups:

a. Direct comparison methods

b. Frequency translation methods

c. Modulation methods.

The first group contains methods based on the wave interference method in which an unknown signal is added directly to a reference signal and the relative phasing inferred from the resultant. The measurement is performed at the frequency of the signals. The indicative condition in this case is that, when the two signals are in 180° opposition a null resultant is obtained provided the two signal magnitudes are equal.

Methods in the second group make use of frequency translation (heterodyning) to change the frequency of both the unknown and reference signals to a lower one at which the phase measurement can be made with greater ease. The phase relationship must be preserved in the course of the translation.

The main deficiency of these two methods is that the two signals must be of essentially equal magnitude if a sharp null and therefore good accuracy is to be obtained. If the amplitudes are not equal, then one of the signals must be adjusted in amplitude to conform to that of the other.

The third group involves attempts to overcome the amplitude problem. This is achieved by modulating one of the signals in some manner such that the combined resultant has an accurately observable property which is a function of the relative phase alone, independent of the relative magnitude. The principle of operation of the phase plotter described here belongs to this general category.

2.2. The Problem of Automatic Operation

The operation involved in manual phase measurements is carried out in three steps. The condition of the measurement is first chosen, the actual measurement is made and finally the condition and measurement are recorded. In the case of a microwave field the condition is the spatial location at which a probe is placed to sample the field. Measurements are made at a number of discrete points. These are recorded and values for intermediate points obtained by interpolation. The mapping of a field even in a single plane is a lengthy, repetitious and monotonous process. It is desirable to devise means of carrying out the three steps of a measurement simultaneously, rapidly and in a continuous fashion rather than for a finite set of individual points. A device which is to be automatic must carry out three operational functions without the intermediate intervention of a human operator.

The actual measurement of phase hinges on the fact that a reference phase-shifter is adjusted until some specific property of the combined signal is obtained. This is usually a null or minimum condition and is a common feature of all three methods outlined in sec. 2-1. The mechanics of the measurement are thus those of seeking a balance. In an automatic device then, the combined signal must produce a suitable error or activating signal for adjusting the reference phase shifter to the balance condition through the agency of a servomechanism. The ultimate accuracy of the measurement depends on the reference phase shifter. However, automatic operation places additional demands on this device's calibration and range. The recording of the information obtained should be preferably in a continuous graphical form. This requires a two-co-ordinate recorder since the measurement is that of phase as a function of position. Furthermore the response speed of the recorder must be adequate to follow the rate at which the measurements are made. The positioning of the probe is essentially a problem of accurate mechanical construction and precision distance measurement.

2.3. Prior Investigations

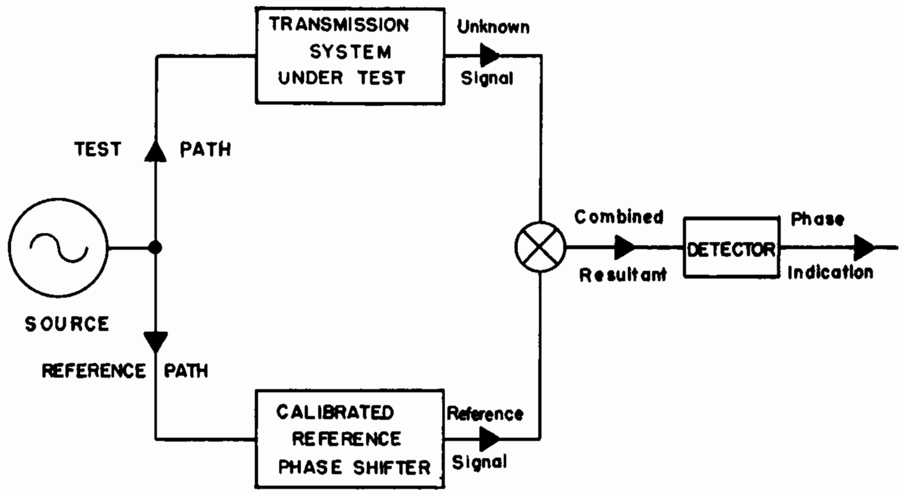
A number of microwave phase measuring devices have been reported in recent years and are outlined below. They are arranged according to the three major groups listed in sec. 2.1.

2.3-1 Direct Wave Interference Methods (Fig. 2.1a)

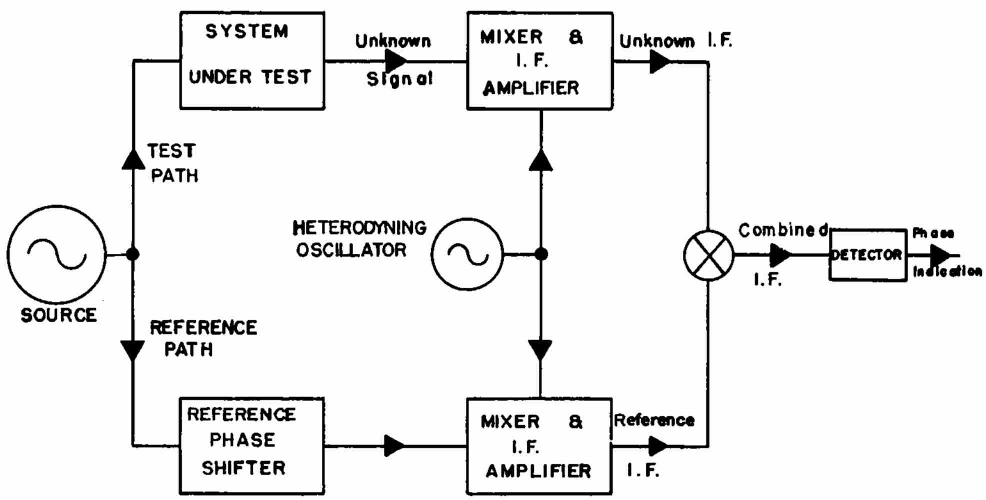
A number of writers have described apparatus based on the direct interference method and suitable for indoor laboratory use. (Ajioka[1], Beam, Astrahan, Mathis[2], Cutler, King, Kock[3], Lengyel[4], Worthington[5],). The devices described have the advantage of simplicity, but are essentially for manual operation only. They require point-by-point adjustment of intensity as well as phase in order to obtain accurate results and do not lend themselves easily to automatic operation. Hines and Boehnker[6], describe a mechanized form of the interference technique by which a record is obtained of points of equal phase along a scanning line in the field of a radiator. The arrangement is not entirely automatic since manual attenuation adjustments are necessary to make the reference signal equal to the mean intensity of the field.

2.3-2 Frequency Translation Methods (Fig. 2.1-b)

A number of workers engaged in microwave propagation studies measured phase fronts or the time of arrival of complex waves at points distant from the source and developed phase measuring apparatus suitable for the purpose. (Hamlin, Gordon, LaGrone[7]). A recent apparatus for this as described by Brooks[8], consists basically of two identical receivers with antennas placed at two parts of the received field. They employ double heterodyne detection to an I.F. frequency of 12 mc/s. The I.F. outputs of the receivers are compared in phase by a phase discriminator and the relative phase difference measured in terms of a capacitor phase shifter. Great care is taken to ensure that the phase relationship of the two I.F. outputs corresponds exactly to the original phase relationship of the two points in the measured field. This demands identical receivers, constancy of local and transmitter oscillator frequencies and requires frequent recalibration of the system.



(a) DIRECT INTERFERENCE METHOD



(b) FREQUENCY TRANSLATION METHOD

Fig. 2.1 Direct Interference and Frequency Translation Methods of Phase Measurement

An indoor range apparatus which is completely automatic was designed by Barrett and Barnes[9]. This device measures phase at an I.F. frequency of 30 mc/s by a phase detector following the heterodyning of both the unknown and reference signals. Amplitude inequality of the two signals is removed by using limiting amplifiers at the I.F. frequency. The output of the phase detector and the probe position are recorded on a plotting table giving a map of the phase fronts. The apparatus gives immediate useful information about the field but, because of the limited resolution of the recording scheme, the plots obtained are largely qualitative.

2.3-3 Modulation Techniques

(a) Phase Modulation Worthington[10] demonstrated that if one of the two signals in a phase measuring system is phase modulated sinusoidally at an audio rate, then the combined resultant will be amplitude modulated. The a.m. envelope can be detected giving an audio signal whose phase, relative to the original modulating signal, is the same as that of the two microwave signals. Phase is thus measured at the audio frequency. The difficulties in this method are the manner of producing phase modulation and the utilization of the audio signals to achieve automatic operation. The phase modulation method proposed by Worthington involved using long lengths of waveguide which result in an unwieldy system at wavelengths longer than 3 cm.

These difficulties were resolved in an automatic phase plotter described by Burrell[11]. The system first heterodynes the two microwave signals to an intermediate frequency of 60 mc/s and phase modulates one of them. The I.F. signals are then combined and the phase of the resulting audio measured by a phase detector whose output is used to adjust a servo-driven phase shifter. The phase shifter is a mutual inductance goniometer and is used in the reference signal channel at the I.F. frequency. Magnitude discrepancies of the two signals are removed by A.G.C. applied to the unknown signal i.f. amplifier. This system suffers from its complexity since it resorts both to modulation and frequency translation. In addition, the resulting phase indication signal is suitable only for a d.c. type servomechanism requiring awkward d.c. amplifiers.

A system which produces phase modulation of one of the microwave channels directly without resorting to long lengths of waveguide was demonstrated by Lavrench[12]. A motor driven rotary phase shifter (Fox[13]) was used in an experimental system as the modulator. While this apparatus was not automatic, it demonstrated the inherent simplicity which might be achieved if the phase modulator could be replaced by a mechanically static device. Producing modulation mechanically requires means of producing a reference audio signal and this is an undesirable complication. The measurement of phase could be carried out either in terms of the audio signal or by phase shifting one of the microwave signals.

(b) Single Sideband Modulation (Frequency shift) If one of the signals in a phase measuring system is single sideband, suppressed carrier modulated (frequency shifted), then the recombined unknown and reference signals yield an audio beat note equal in frequency to the side-band-carrier difference. The phase of the beat note relative to the original modulating signal preserves the phase relationship of the two microwave signals.

A phase plotter based on this system is manufactured commercially (Mariner[14]). A mechanical frequency changer is used. The phase measurement and the reference phase shifter adjustment are carried out at the audio frequency. This requires a specially built motor-alternator with an adjustable alternator field pole positioning scheme. The field pole adjustment constitutes the phase shifter in the reference audio frequency.

(c) Double Detection System This system, while not a modulation scheme, is an indirect technique which elaborates on the direct interference method. Its use in an automatic machine was described by Bacon[15]. In this method the unknown and reference signals are combined in a hybrid junction and thus both added and subtracted. The d.c. (or audio) outputs of the two detectors in the balanced arms of the hybrid are then subtracted from each other. One of the signals must be modulated if an audio output signal is wanted. This difference output experiences a null when the two input signals have a phase difference of $\pi/2$ radians and the null condition is independent of magnitude differences. The subtracted detector output is useful as a servo error signal, and A.G.C. is used to maintain the servo gain within stable limits. A major objection to this scheme is that in order to function properly, the phase detector must use identical crystals.

(d) Suppressed Carrier (Homodyne) Method A method involving modulation which results in a suppressed carrier signal was reported by Robertson[16]. In this method an audio signal is obtained from the recombined signal which is particularly suitable as an error signal to drive a servo-mechanism. The homodyne method is the basis of the phase plotter whose development is described in this thesis.

The homodyne method has been used in manually operated systems by Ornstein[17] and by Vernon[18] whose reports suggest that the technique might be suitable for automatic operation.

CHAPTER III

The Method of Phase Measurement

The method of phase measurement used in the system described here is based on the homodyne principle proposed by Robertson[16]. The homodyne technique consists of combining an unknown and reference signal as in the direct interference method with the exception that one of the signals is suppressed-carrier amplitude-modulated. The combined microwave signals yield upon detection an audio signal which has a unique relationship to the relative phase. A component of the detected signal experiences a true null independent of the relative magnitudes and is directly usable as a null indication for manual balancing, or as a servomechanism error signal.

The arrangement of the phase measuring system is shown in the block diagram of Fig.3.1. Manual operation consists of adjusting the reference phase shifter in order to obtain a null output A, of tuned amplifier ω_s. Thus if the transmission system under test undergoes a differential phase shift, a corresponding change must be produced by the reference phase shifter and the measurement is made in terms of its calibration. The development of the phase measuring system placed emphasis on designing a dependable modulator, on devising detector circuits suitable for the phase error and intensity indication, and on selecting a phase shifter which would meet the requirements of the system.

3.1. Analysis of the Homodyne Principle

The homodyne principle is based on the following considerations. A c.w. source is used to provide both the unknown and reference signals in the phase measuring system. The unknown signal is modulated by a single audio frequency. The modulation is carried out by a balanced modulator,

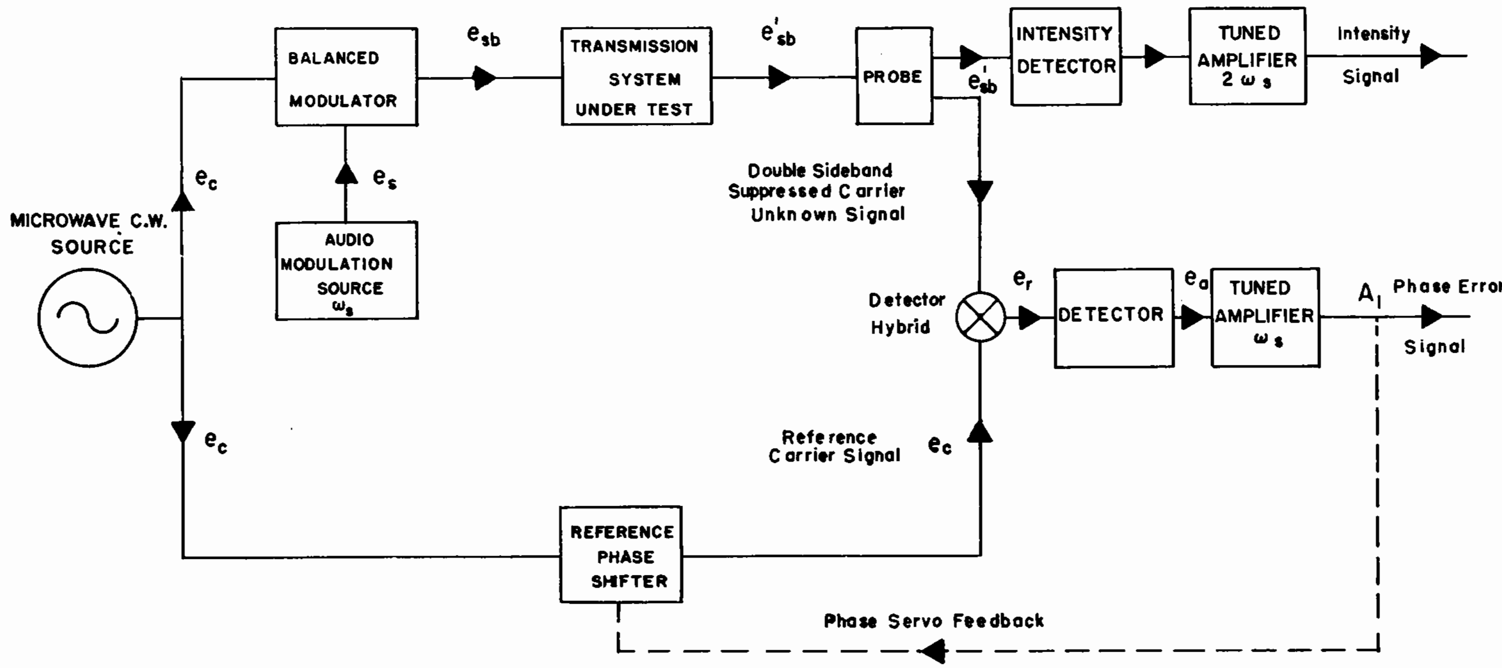


Fig. 3.1 Homodyne Method of Phase and Intensity Measurement

resulting in a double sideband signal with the carrier suppressed. When such a signal is recombined with a c.w. carrier, in this case the reference signal, and then applied to a detector, the resulting audio signal has the following properties:

(a) If the reintroduced carrier is phased so that it would be in phase or π radians out of phase with the original carrier, had this not been suppressed, then the detected audio is purely at the original modulation frequency.

(b) If the reintroduced carrier is in quadrature ($\pm\ \pi/2$ radians) with the suppressed carrier, then the detected signal is purely a second harmonic and there is an absolute null at the original modulation frequency. This null is independent of the unknown and reference signal magnitudes.

(c) Between the extremes of the above two conditions, the detected signal has a component at the fundamental modulation frequency whose amplitude varies essentially as the cosine of the carrier phase angle. Furthermore, the polarity of the fundamental component reverses from one side of a null condition to the other.

The detector output having the above properties may be amplified by a tuned amplifier to select the fundamental component. This can then be used as an audio indicating signal for manual measurements and is also suited for actuating a servomechanism. In the latter application however it is important to realise that although the null condition is independent of relative magnitudes, the amplitude of the fundamental detected signal for off-quadrature conditions is not independent. In manual operation this is not serious since the gain of the tuned amplifier can be easily adjusted in order to obtain good phase resolution. In the case of automatic operation this must be achieved by some form of automatic gain control in order to maintain the servo loop within a stable region while preserving adequate response speed.

The analysis of the homodyne principle demonstrating the properties of the detected signal described above proceeds as follows:

If a modulating audio signal is defined by

$$e_s = E_s \cos \omega_s t \qquad 3.1$$

and the unmodulated r.f. signal by

$$e_c = E_c \cos \omega_c t, \text{ then} \qquad 3.2$$

an amplitude modulated signal is

$$e_m = E_c \cos \omega_c t + E_s \cos \omega_s t \cdot \cos \omega_c t \qquad 3.3$$

$$E_c \left\{ \cos \omega_c t + \frac{1}{2} m \left[\cos(\omega_c + \omega_s)t + \cos(\omega_c - \omega_s)t \right] \right\} \qquad 3.3a$$

where

e_m is the modulated signal

E_c is the carrier amplitude

E_s is the modulating signal amplitude

ω_c is the carrier frequency

ω_s is the modulating frequency

$m = \frac{E_s}{E_c}$ is the ratio of the modulating to carrier amplitudes called the "modulation index" and must be in the range $0 < m < 1$.

The significance of the symbols used here is also shown by Fig.3.1. In 3.3 the second term, $E_s \cos \omega_s t \cdot \cos \omega_c t$, gives rise to the sidebands and when a modulator is used which suppresses the carrier, then the modulated signal without a carrier is

$$e_{sb} = E_s \cos \omega_s t \cdot \cos \omega_c t = \frac{1}{2} mE_c \left[\cos(\omega_c + \omega_s)t + \cos(\omega_c - \omega_s)t \right] \qquad 3.4$$

If a phase shift θ is incurred in the original carrier, then e_{sb} becomes

$$e'_{sb} \quad \frac{m}{2} E_c \left\{ \cos \left[(\omega_c + \omega_s)t + \theta \qquad \cos \left[(\omega_c - \omega_s)t - \theta \right] \right\} \qquad 3.5$$

$$= mE_c \left\{ \cos\omega_s t(\cos\omega_c t \cdot \cos\theta - \sin\omega_c t \sin\theta)\right\} \qquad 3.5a$$

When a reference signal, $E_c \cos\omega_c t$, at the original carrier frequency is added linearly to e'_{sb}, the resultant e_r is

$$e_r = E_c \left[\cos\omega_c t + m\cos\omega_s t \cos\omega_c t \cos\theta - m\cos\omega_s t \sin\omega_c t \sin\theta)\right] \qquad 3.6$$

This is the resultant signal obtained when the unknown and reference signals are combined. The angle θ assumes the significance of the differential phase shift of the two paths. The index m assumes a more general meaning since it is no longer limited to the range $0 < m < 1$ imposed in 3.3, but can assume any positive real value. This is due to the fact that the sideband and carrier magnitudes are independently variable.

When e_r is detected to obtain an audio output e_a, corresponding to the amplitude envelope, then e_a can be obtained first by rewriting 3.6 to give

$$e_r = E_c \sqrt{1 + 2m \cos\omega_s t \cdot \cos\theta \quad m^2\cos^2\omega_s t} \times \cos\left[\omega_c t - \tan^{-1} \frac{m\cos\omega_s t \sin\theta}{1 + m\cos\omega_s t \cos\theta}\right] \qquad 3.7$$

and noting that the quantity under the radical is the amplitude envelope and describes the detected output e_a.

Thus $$e_a = E_c \left\{ 1 + 2m \cos\omega_s t \cdot \cos\theta + m^2\cos^2\omega_s t\right\}^{1/2} \qquad 3.8$$

In order to examine the harmonic content of this waveform, it is necessary to express 3.8 in a series form:

$$e_a = A_0 + A_1\cos\omega_s t + A_2\cos 2\omega_s t + A_3\cos 3\omega_s t \ldots \qquad 3.9$$

Such a series then demonstrates the dependence of e_a on the phase angle θ and on the index m. Only the fundamental component $A_1 \cos\omega_s t$ of e_a need be considered since all other components are rejected by the tuned amplifier.

A convergent series expansion may be obtained by applying the binomial theorem when $m < 0.414$. Such an expansion yields the following expression for the fundamental component of e_a.

$$A_1 \cos \omega_s t = E_c \left[\begin{array}{r} m\cos\theta \;\; - \frac{3}{8} m^3 \cos\theta + \frac{15}{64} m^5 \cos\theta - \\ + \frac{3}{8} m^3 \cos^3\theta \; - \frac{50}{64} m^5 \cos^3\theta + \\ + \frac{35}{64} m^5 \cos^5\theta - \end{array} \right] \cos \omega_s t \qquad 3.10$$

From this it is evident that for small values of m, the fundamental component magnitude A_1 varies as the cos-ine of the phase angle θ. For values of m approaching 0.414, A_1 departs somewhat from a pure cos θ variation, but the essential features are preserved, in that A_1 is still zero-valued at and reverses sign on either side of $\theta = \pm \pi/2$ and equals mE_c for $\theta = 0$ or π.

When $m > .414$, the binomial expansion is no longer valid and resort must be made to a Fourier series expansion. The magnitude A_1 of the fundamental component can then be obtained from the following:

$$A_1 = E_c \; \frac{2}{\pi} \int_0^{\pi} \left\{ 1 + 2m \cos\omega_s t \cos\theta + m^2 \cos^2 \omega_s t \right\}^{1/2} \cos\omega_s t \cdot d\cos\omega_s t \qquad 3.11$$

From this, A_1 can be determined most readily for various values of m and as a function of θ by numerical integration. The results of such a computation are plotted in Fig. 3.2 in which A_1 is plotted on a normalized scale as a function of θ for values of m ranging from 0 to 100. It should be noted that A_1 as a function of θ departs most from a pure cosine variation for $m = 1$ and tends back to a cosine variation for values of m both less than and exceeding unity. The graph of Fig. 3.2 is not complete since A_1 is continuous for all positive and negative values of θ.

The signal $A_1 \cos\omega_s t$ therefore gives a convenient indication of whether the unknown and reference signals are in quadrature with one another or not. Since the null condition is the one desired, then the presence

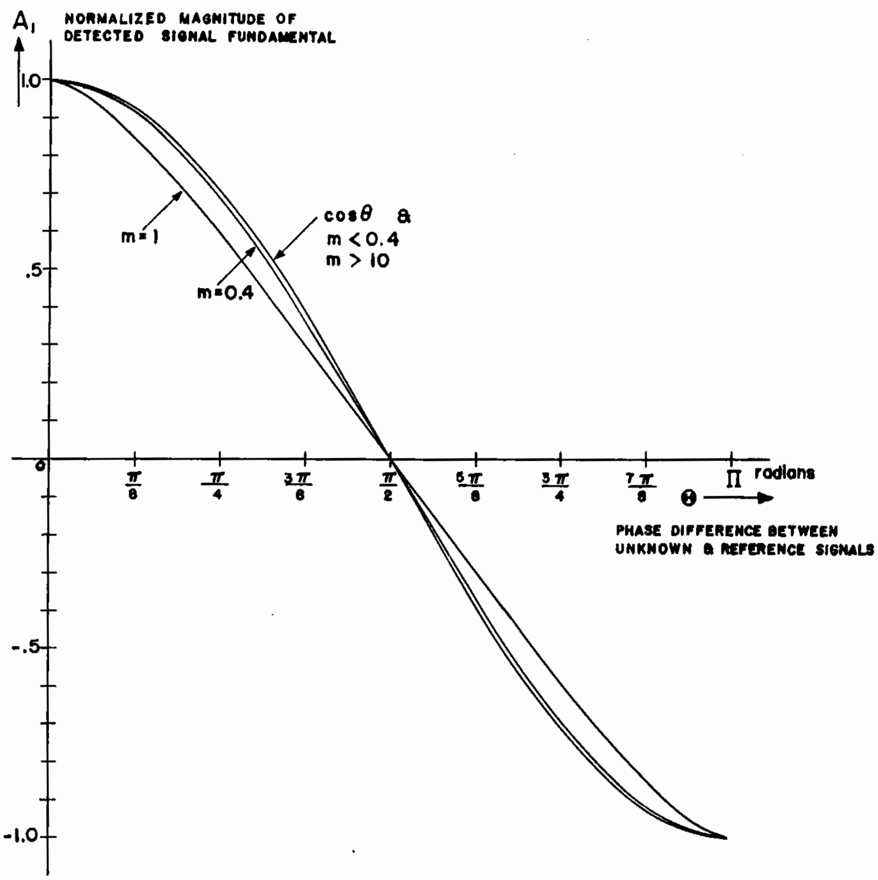


Fig. 3.2 Variation of A_1 versus θ.
(Magnitude of Detected Signal Fundamental versus Phase Difference between Unknown and Reference Signals).

of a finite $A_1 \cos \omega_s t$ signal indicates a departure from the null and that therefore an error exists. $A_1 \cos \omega_s t$, the fundamental component of the detector output, may therefore be termed the "phase error signal" and will be referred to as such in the remainder of the thesis.

3.2 The Balanced Modulator

The most important part of a homodyne system is the modulator since the usefulness of the technique depends on the degree of carrier suppression which can be achieved. Any residual carrier would be a source of error, since it would be equivalent to a false additional arbitrarily phased reference signal (Robertson[16]). It is especially important for an automatic system that the modulator balance should be invariant over long periods of operation and that its adjustment should not be a critical function of frequency. Incomplete carrier suppression results in incorrect phase indication since the nulls of the phase error signal are no longer separated by π radians as a function of θ.

3.2-1 Crystal Modulator. The modulators used by Robertson[16] and Ornstein[17] used a hybrid junction with silicon crystals in mounts attached to the balanced arms. Audio frequency and d.c. currents were applied to the crystals acting as the modulating elements. Microwave c.w. energy incident on the H-branch of the hybrid then resulted in a suppressed carrier modulated signal at the E-branch. This arrangement is a microwave analogy of the conventional bridge or ring type modulator used at lower frequencies. The degree of carrier suppression depended on how well the microwave impedances of the two crystals were matched. Balancing was achieved by adjusting the d.c. currents. However this balancing had to be carried out frequently, because of changes in the crystals. The balance was also dependent on the carrier frequency. This arrangement obviously is not suitable for an automatic system since it would not be dependable over extended periods of time.

3.2-2 Ferrite Transmission-Type Balanced Modulator. In the effort to overcome the defects of the crystal type modulator, a microwave modulator circuit was developed during this investigation, using ferrite absorbtion modulators. These modulators have become available commercially in recent years along with many of the remarkable ferrite microwave devices which are described in current literature, (Hogan[19], Rowen[20]). *

The circuit developed (Fig.3.3a) is a microwave analogy of a transmission type modulator. The modulating elements used are Gyralines (Cascade Research Corp.). As shown in Fig. 3.3a the incoming c.w. signal is split into two equal paths A and B by Hybrid No. 1. These two signals are then separately modulated by Gyralines A and B and the amplitude modulated signals e_A and e_B combined in Hybrid No. 2. The total phase delay in each branch is made exactly the same for the two branches by adjustment of limited range flap type phase shifters in each branch.

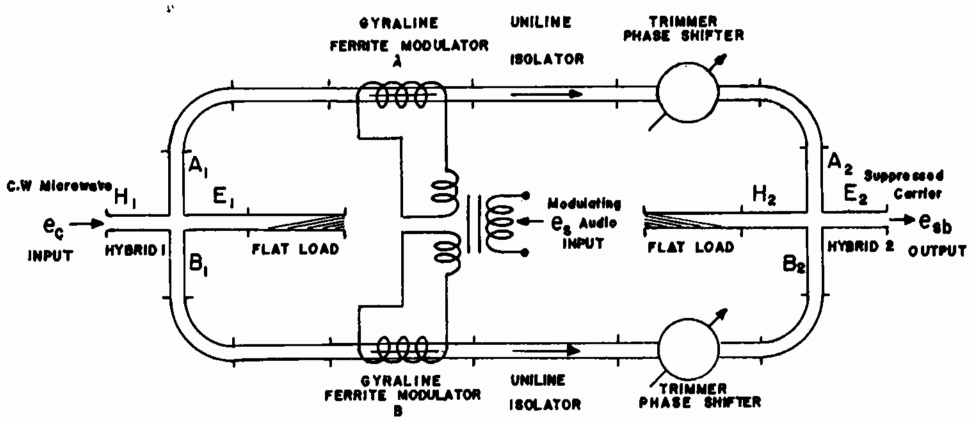
If the modulation signals applied to each branch are equal and π radians out of phase, then it can be demonstrated quite simply that the output at the H-branch of Hybrid No. 2 will be the carrier only, whereas the output from the E-branch will consist only of the sidebands. Representing the hybrids by equivalent centre tapped transformers allows the microwave circuit of Fig. 3.3a to be represented by the equivalent circuit of Fig 3.3b.

If the modulated signals e_A, e_B in A and B result from out-of-phase modulation, then

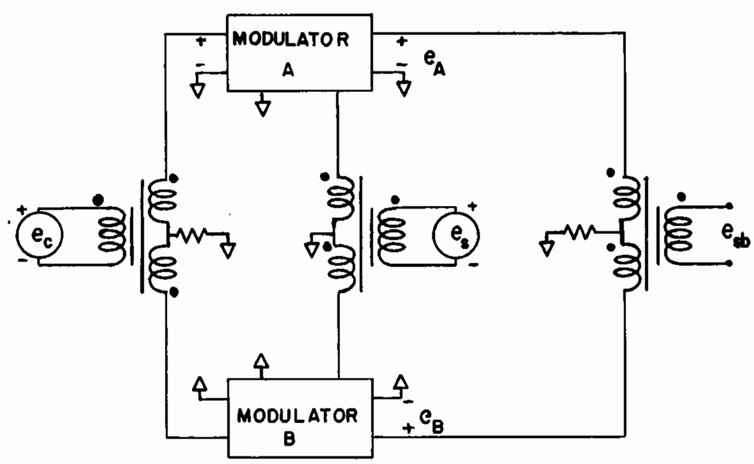
$$e_A = E_c \left[\cos\omega_c t + \frac{m}{2} \cos(\omega_c + \omega_s)t + \frac{m}{2}(\omega_c - \omega_s)t \right] \qquad 3.12a$$

---

* Further descriptions of applications of ferrites at microwave frequencies may be found in: Albers-Schoenberg[21]; Barry and Clark[22]; Chait and Sakiotis[23]; Chait, Sakiotis and Simmons[24]; Miller[25]; Suhl and Walker[26].



(a) MICROWAVE CIRCUIT



(b) LUMPED CIRCUIT ANALOGY

Fig. 3.3 Balanced Modulator, using Ferrite Gyrators, for Homodyne Method and 3.12 b

$$e_B = E_c \left[\cos\omega_c t - \frac{m}{2} \cos(\omega_c + \omega_s)t - \frac{m}{2} (\omega_c - \omega_s)t \right]$$

Since the output from branch H2 is proportional to the sum of e_A and e_B, the signal at H_2 is $e_{H2} \propto e_A + e_B = 2E_c \cos\omega_c t$ 3.13

which is purely the carrier.

The output e_{E2} from branch E2 is proportional to the difference between e_A and e_B, giving

$$e_{E2} \propto e_A - e_B = E_c m \left[\cos(\omega_c + \omega_s)t + \cos(\omega_c - \omega_s)t \right] \quad 3.14$$

which is the required suppressed carrier sideband signal.

Experimental demonstration of the effectiveness of this modulator was carried out by two tests. The first test showed the degree of carrier suppression. If the modulation is applied in phase opposition then normal operation of the modulator is obtained and the power output at E_2 can be measured. If the modulation is applied in-phase for the two modulator branches then the sidebands as well as the carrier will cancel and, ideally, a null output is obtained at E_2 if there is a complete balance. Measurement of the power at E_2 under this condition thus indicates the effectiveness of the modulator balance and the degree of carrier suppression. Such measurements indicated a carrier suppression in excess of 60 db.

The second test was an operational one consisting of placing the modulator into a closed circuit phase measuring system of the form shown in Fig. 3.1. The "Transmission System Under Test" was replaced by a phase-shift-free attenuator and a second calibrated phase shifter. The test consisted of varying the phase of the "unknown" or the "reference" path and noting whether the nulls were spaced by π radians. Departure from this spacing is indicative of incomplete carrier suppression. This test was carried out for a number of relative magnitudes of the "unknown" and "reference" signals. It was found that the sideband amplitude could be varied by more than 40 db down relative to the reference carrier without introducing an error of more than $\pm 2\frac{1}{2}^{\circ}$ in the worst case. The reference signal could only be reduced by less than 30 db before the same error was observed. This test showed that the system would function satisfactorily provided the sideband signal is used as the radiated test signal rather than the carrier. Fortunately this is the arrangement needed if intensity measurements are to be made in a convenient manner as described in sec. 3.3. The modulator was found to be remarkably stable giving reliable performance over periods of months without readjustment. Furthermore, operational experience indicates that frequency changes of 100 mc/s at 9200 mc/s do not affect the modulator balance.

The mechanical assembly of the modulator is shown in the photographs of Fig. 3.4. This assembly also includes the klystron source and means for frequency measurement. A ferrite isolator is used to ensure a constant loading on the source. The klystron shown is a Sperry type 2K39 which was subsequently replaced by a Varian V-55. The photographs also show the manner in which the separation of the unknown and reference signal paths is accomplished by a directional coupler. This is important in order to prevent back-reflections in one path from entering the other. The coupler also allows supplying the test path with the greater portion of the available power.

3.3 The Detector Circuit and Intensity Measurement

The usefulness of the phase measuring system depends also on the effectiveness of that part of the microwave circuit in which the reference and unknown signals are combined and the resultant demodulated. It is important that the combination of the two signals be achieved without allowing either signal to enter the path of the other. This would result in interference patterns in the two paths and would thus be a source of error in the measurement.

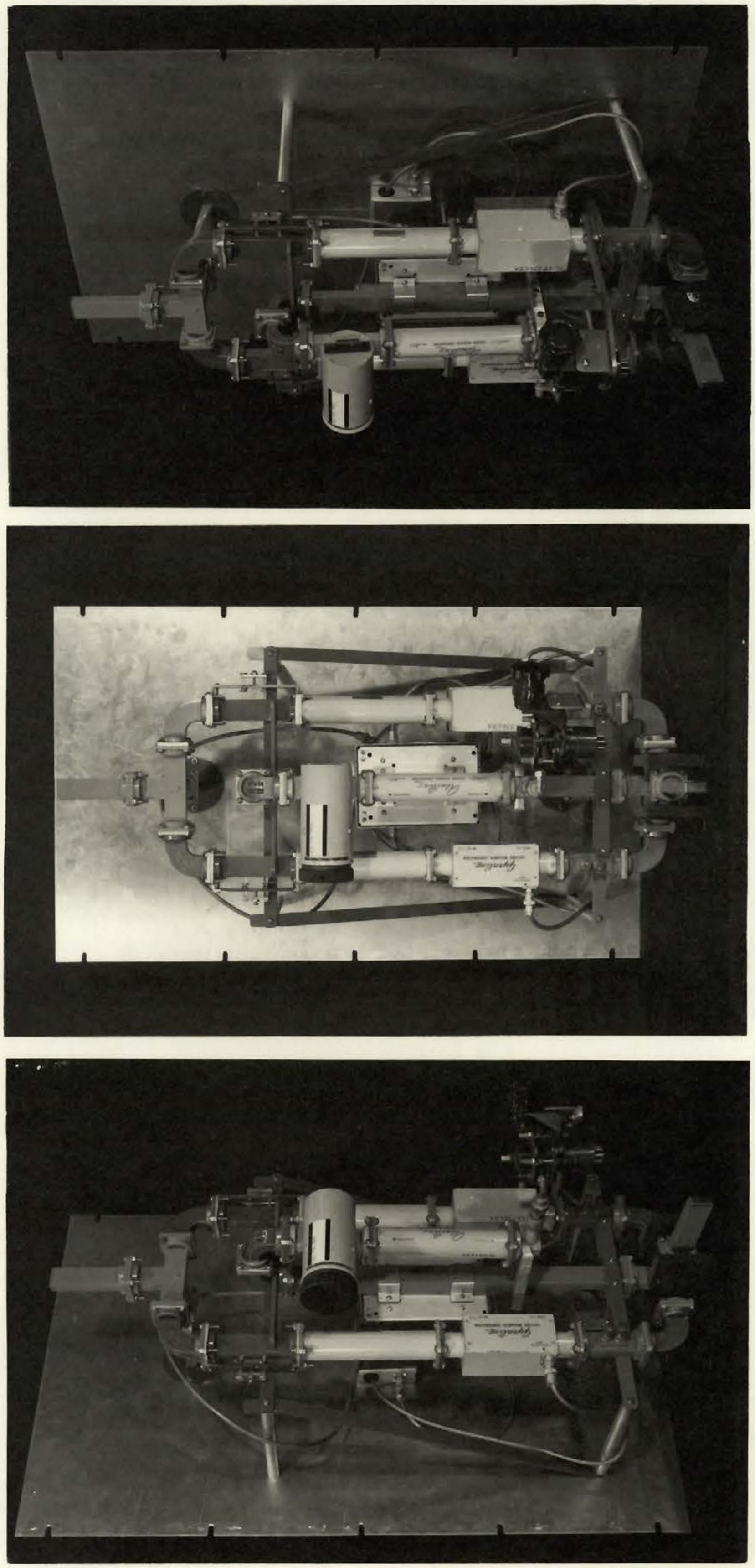


Fig. 3.4 Balanced Modulator and Klystron Source Assembly

The detector circuit is further complicated since it is necessary to measure the intensity as well as phase of the unknown signal.

The detector arrangement which was developed is shown in Fig. 3.5. The incoming unknown signal is divided by a T junction, one part being applied to a conventional single crystal detector, the audio output of which is used for the intensity measurement. The second part of the unknown signal is connected through a ferrite isolator (Cascade Research Corp. Uniline) to the E-branch of a balanced hybrid junction. The reference signal is brought to the H-branch of the hybrid junction through the calibrated phase shifter and a second isolator. The unknown and reference signals are combined in the balanced arms of the hybrid and demodulated by crystals placed in these branches. Matching of the balanced arms is ensured by a pair of isolators. The audio output of the crystals is added in an audio transformer, the output of which is the signal e_a.

The fact that two crystals are used in the phase error detector is a fortuitous result of the need for good path isolation which requires that a balanced hybrid be used. The phase error signal could be obtained equally well with a single crystal if other effective means of combining the two microwave signals were used. The path isolation achieved by this scheme, as indicated by measurement, is considerably in excess of 60 db.

The detector output e_a has the properties described in sec. 3.1. and is applied to an audio amplifier tuned to the modulation frequency ω_s, thus providing the phase error signal $A_1 \cos\omega_s t$.

The intensity signal, which is obtained by detecting the suppressed carrier double-sideband unknown signal, has a magnitude which is a function of the unknown signal intensity alone. The frequency of the intensity signal is the difference frequency between the two sidebands, namely $2\omega_s$. An audio amplifier tuned to $2\omega_s$ is accordingly used to provide the intensity

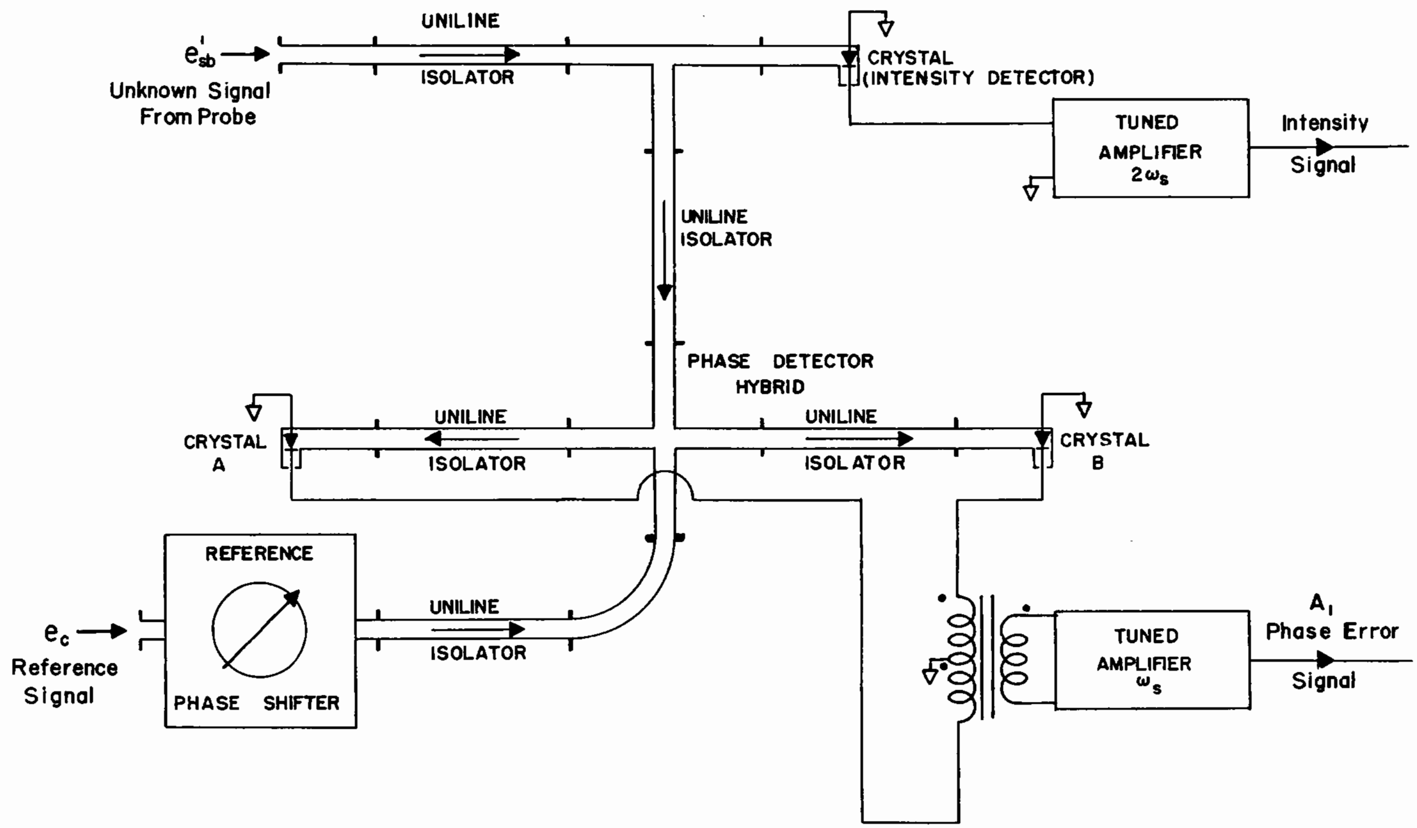


Fig. 3.5 Intensity and Balanced Phase Detector Circuit

indication. A photograph of the detector assembly is shown in Fig. 5.7.

3.4 The Calibrated Phase Shifter

While an effective balanced modulator and suitable detector are essential if the homodyne method is to be practically feasible, the accuracy of phase measurement depends ultimately on the precision of the calibrated phase shifter. The phase shifter is the reference standard of the measurement and thus determines the basic accuracy of the system. A number of different types of microwave phase shifters are known and are described in the literature. They can be classified as follows:

(a) Slotted Line Phase Shifter - The fundamental phase shifter is a flat loaded slotted waveguide (Ragan and Niemann[27]) in which use is made of the linear phase-distance relationship of a wave propagated in a reflection-free transmission system. The phase measurement can be made absolute in terms of distance and frequency. The range depends on the length of the slotted waveguide.

(b) Movable Vane Type - The phase velocity in a waveguide can be altered by inserting a vane of dielectric material inside the waveguide. (Halford[28]; Ragan and Niemann[27]). Such a phase shifter resembles vane type waveguide attenuators in construction, the lossy vane of an attenuator being replaced by a dielectric. The total phase shift through such a waveguide section is a non-linear function of the vane position and the range of variable phase shift is limited to approximately 180°.

(c) Squeeze Section Type - The propagation qualities and thus the phase shift through a rectangular waveguide can be altered by distorting the cross-section of the guide (Brady, Pearson and Peoples[29]). Such a device can be arranged by applying pressure on the vertical or horizontal walls of a wave-guide. The range of such a device is rather limited.

(d) Rotary Phase Shifter - The phase shift through a cylindrical waveguide can be altered by inserting three vanes of dielectric along the axis of the guide and rotating the middle section about the guide axis (Barnett[30]; Fox[13]; Sichak and Levine[31]). The phase shift is proportional to the angle of rotation of the middle vane and can be continuously adjusted without limit.

(e) Ferrite Phase Shifter - the phase shift in a cylindrical wave-guide can be altered by inserting a rod of ferrite and subjecting it to longitudinal or transverse magnetic field (Cacheris[32]; Sakiotis[33]).

The phase shifter chosen for the phase plotter was a commercial version (Hewlett-Packard Type X885-A) of the rotary type. Its choice was dictated by the requirements of automatic operation which indicate the need for linear calibration, unlimited range and adaptability to motor driven positioning. During the development, the slotted guide and vane type phase shifters were also used but eventually discarded, since they did not meet all the requirements. A ferrite phase shifter was also used experimentally, but the particular model available was discarded because of its limited range and the problem of nonlinearity and hysteresis.

CHAPTER IV

Automatic Operation

Automatic Operation of the Phase and Intensity Plotter

The measuring system described in the previous chapter can be conveniently adapted to automatic operation. This can be achieved by using a servo motor for positioning the reference phase shifter to maintain the phase-error signal in the null condition. The phase-error signal itself is used to actuate the servo motor. As the unknown signal phase varies, the phase shifter follows the change and the phase shifter position measures the unknown signal phase shift. If the phase shifter position is made self recording, a record of the unknown signal phase shift can be obtained.

In the type of measurements to be performed by the plotter, the unknown signal phase change is a result of moving a probe in an unknown field. It is necessary therefore to measure and record also the position of the probe in the field. The phase must then be recorded as a function of the probe position which can be achieved by a suitable x-y recorder. The intensity signal can be similarly recorded as a function of the probe position.

The system adopted for this plotter is illustrated in block diagram form in Fig. 4.1. and the essential features and analysis of the automatic system are considered in this chapter.

The modulation frequency used is 400 c/s which provides a phase error signal directly usable by an induction servo motor and also provides an intensity signal suitable for a conventional, commercially made, intensity recorder. The automatic system is thus as simple as possible with components using relatively straightforward electronic circuits. Details of

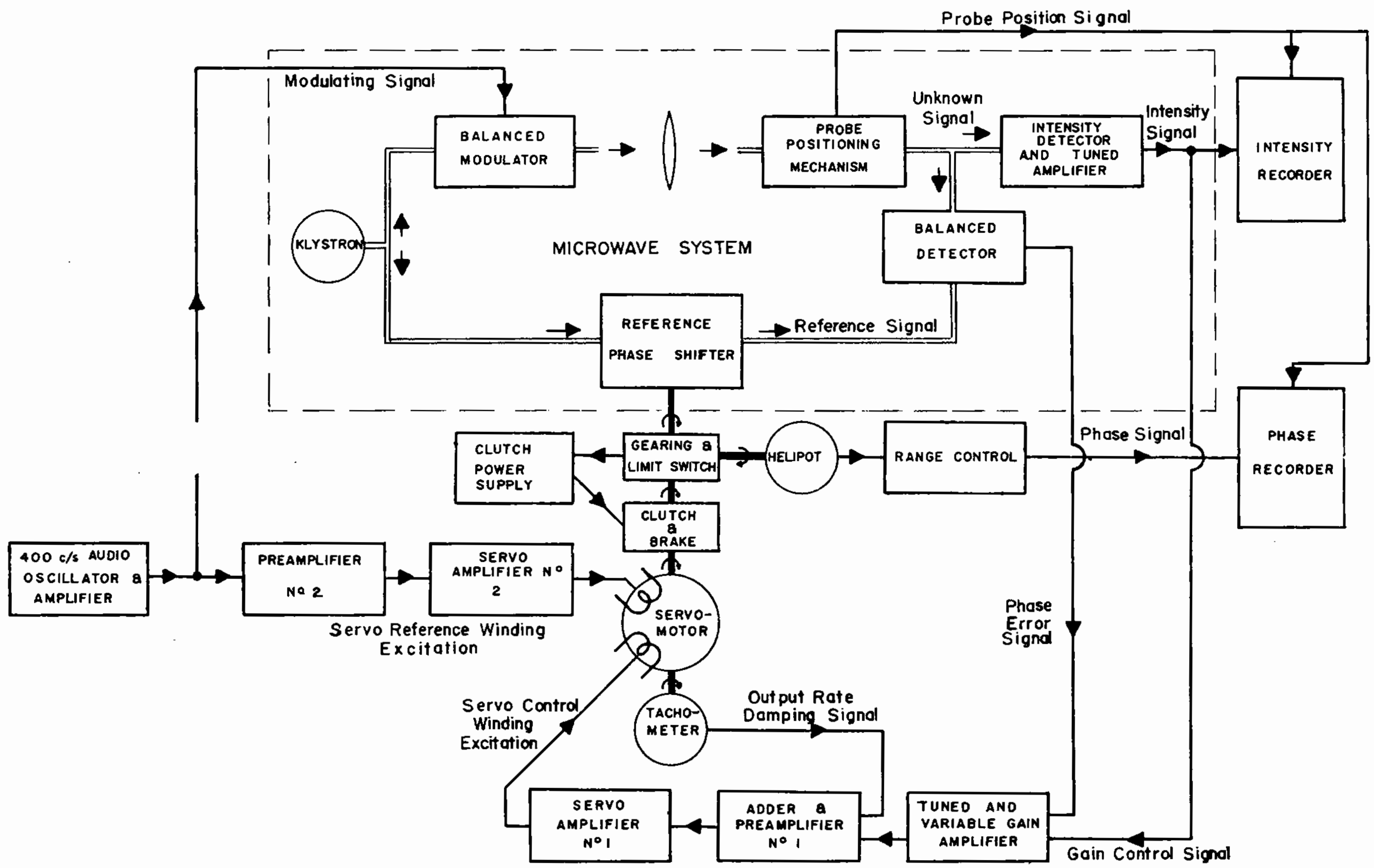


Fig. 4.1 The Automatic Phase and Intensity Plotter
Functional Diagram

the various mechanical and electrical components are described in Chapter V.

4.1 The Phase Servo

Several servo-motor schemes are possible for driving the phase shifter. Both d.c. and 60 cps motors may be used, but it is immediately evident that an ultimate system simplicity is achieved if the phase indicating signal can be used directly as the error signal. This implies using a two-phase, 400 cps induction servo-motor and modulating the microwave signal at this frequency. The phase-error signal can then be amplified by a relatively si/mple amplifier chain and applied to the servo-motor control winding. In this arrangement the servo amplifier does not require a chopper or other similar arrangement since the problem of audio to d.c. to 60 c/s conversion is avoided. Furthermore, since the phase-error signal reverses polarity in passing through a null, there is no problem in achieving a reversal of the servo motor rotation and the system is thus null seeking.

This arrangement is evident in Fig. 4.1. A 400 cps oscillator and power amplifier are used to drive the microwave balanced modulator. The servo-motor is a 400 cps, two-phase induction motor with an integrally mounted induction tachometer generator. The reference winding of the motor and the excitation winding of the tachometer are energized by a power amplifier (Servo Power Amp. No. 2), the input signal of which is obtained from the modulator oscillator through a preamplifier (No. 2, Fig. 4.1).

The control winding of the servo-motor is supplied by an identical power amplifier (Servo Power Amplifier No. 1.). The input signal to Power Amplifier No. 1 is obtained from another preamplifier (No. 1) which combines the phase error signal and the tachometer generator output. The error signal is obtained from the balanced detector via a variable-gain, tuned amplifier. The purpose of this arrangement is as follows:

a. The phase-error signal magnitude for off-quadrature conditions in the microwave system depends on the intensity of the unknown signal as described in sec. 3.1. This would result in instability of the servo-loop for high unknown signal intensities or in slow response for low intensities. To overcome this difficulty the servo-loop gain is maintained approximately at an optimum value by a variable-gain circuit incorporated in the tuned amplifier. The gain of this amplifier is controlled by the gain control signal which is a voltage derived from the intensity signal.

b. Critically damped response of the servo is obtained by using velocity damping. This is achieved by combining the phase error signal with the tachometer output voltage which is proportional to the servo-motor velocity. The function of Preamplifier No. 1 is to add these two signals in correct proportion and relative phase. This permits independent adjustment of the servo gain and damping.

c. A further function of the preamplifiers is to allow relative phasing adjustment of the reference and control winding voltages. This adjustment is required in order to achieve the quadrature conditions essential for two-phase motor operation.

4.2. The Phase Shifter and Phase Recorder

The phase shifter is a rotary one as described in sec. 3.4 and is continuously adjustable. The angular position is linearly related to the phase shift and is indicated electrically by a d.c. voltage output from a 'Helipot' multiturn potentiometer. This voltage in turn is measured and recorded along one co-ordinate of a strip chart recorder. The second co-ordinate of the chart is used to record the probe position in the measured field.

The recorder is a modified Varian Model G-10. Since the chart width is only five inches and the effective range of the phase shifter is determined by the 'Helipot' as 3600°, then the resolution of the record is very poor since the scale is 720 degrees/inch. In order to overcome this difficulty a range adjusting circuit, the Range Control, is incorporated which allows effective expansion of the scale to 72 degrees/inch. At this scale the readability of the record is to about 2 degrees, which is the accuracy of the phase shifter.

4.3. Analysis of the Automatic System

The operation of the phase plotter as an automatic device is, theoretically at least, amenable to analysis in terms of negative feedback control theory. Its actual performance may also be determined from that point of view.

The analysis is based on considering the phase of the unknown signal as the command signal and the recorder pen position as the output signal of the system. The command signal is a function of time since the unknown phase becomes time dependent as the probe scans the measured field. The phase plotter performance determination thus rests in finding the response of the recorder pen position to such input time-functions. The following sections outline the analytical procedures required for such an evaluation.

The automatic phase plotter diagram shown in Fig. 4.1 can be rearranged as a signal flow chart to bring into evidence the features of the negative feedback control system. The functional block diagram of Fig.4.2 is then obtained. In this diagram only the flow of signals and the effects on them of the individual components are considered. Thus, all the devices which are involved are represented by symbols implying their input-output relationship. The following tabulation lists the device and function represented by each box and shows the significance of each signal involved.

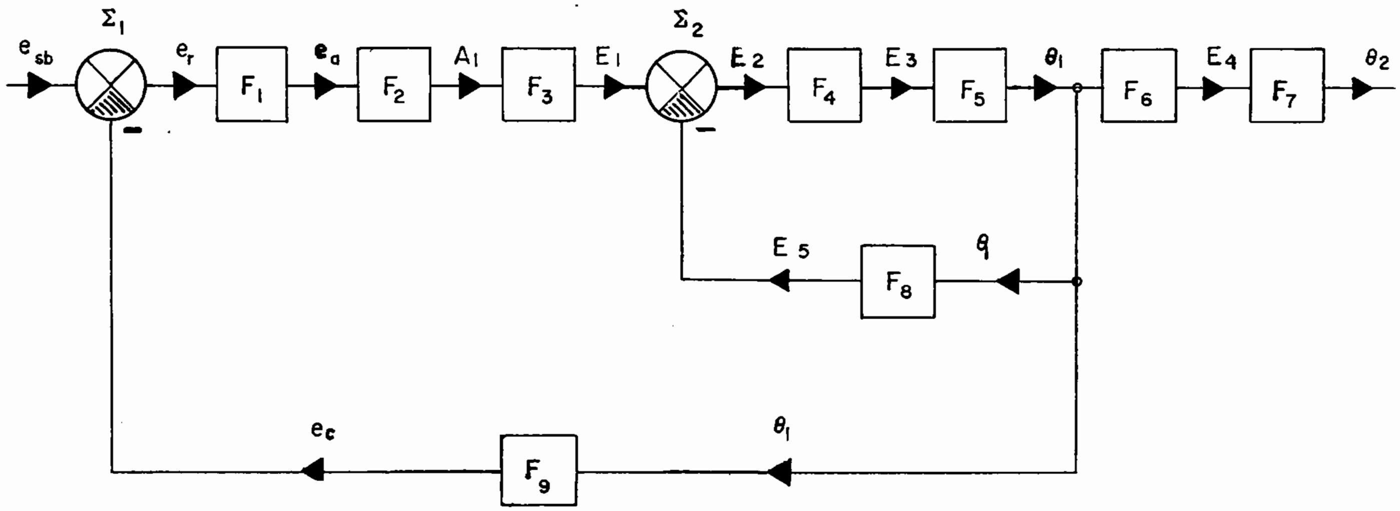


Fig. 4.2 Signal Flow Block Diagram of Phase Plotter

Elements of System

Symbol	Significance and component represented by Symbol	Input Signal	Output Signal
Σ_1	First Summing Point (Hybrid of Detector Circuit)	$e'_{sb} + e_c$	e_r
F_1	Crystal Detector Circuit	e_r	e_a
F_2	Tuned Amplifier	e_a	A_1
F_3	Variable Gain Amplifier	A_1	E_1
Σ_2	Second Summing Point - Preamplifier No.1 combining phase error and tachometer voltages	$E_1 + E_5$	E_2
F_4	Servo Power Amplifier No. 1	E_2	E_3
F_5	Servo-motor, gearing, potentiometer and phase shifter mechanism	E_3	θ_1
F_6	Potentiometer and Range Control	θ_1	E_4
F_7	Recorder Pen Servo-Drive	E_4	θ_2
F_8	Tachometer Generator	θ_1	E_5
F_9	Reference Phase Shifter - relationship of mechanical position to phase shift	θ_1	e_c

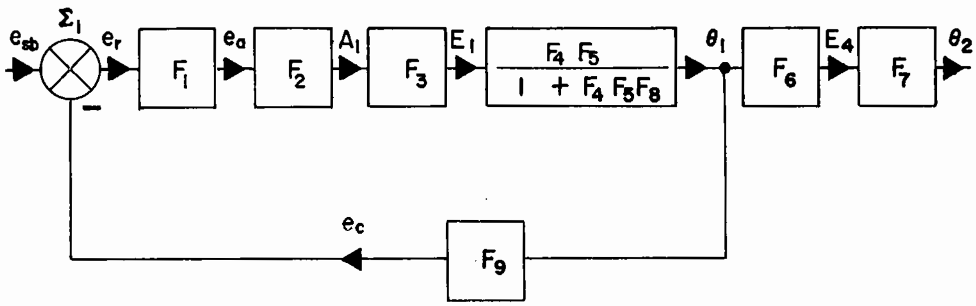
Signal Designation

Symbol	Significance
e'_{sb}	unknown signal - the input command signal
e_c	reference signal
e_r	resultant signal
e_a	detector output
A_1	phase error voltage
E_1	modified phase error voltage
E_2	servo power amplifier actuating voltage
E_3	servo motor control winding voltage
θ_1	phase shifter shaft position
E_4	potentiometer and range control d.c. output voltage
θ_2	recorder pen position (output signal)
E_5	tachometer output voltage

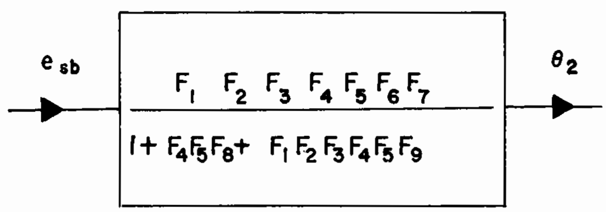
It is observed that this is a system involving two feedback loops. The major feedback loop involves the reference signal e_c, while the subsidiary feedback loop involves the stabilizing tachometer signal E_5.

If the input-output relationship of each element were representable by a linear differential equation, then each symbol could be made to represent the transfer function of an element. Reduction formulae can then be applied and the overall transfer function relating θ_2 to e'_{sb} obtained.

The elements involved in the subsidiary loop consist of components which might be represented by such linear relationships and the system would simplify to that of Fig. 4.3. The block $\dfrac{F_4\ F_5}{1 + F_4F_5F_8}$ represents the elements in the subsidiary feedback loop.



(a) REDUCED SUBSIDIARY FEEDBACK LOOP



(b) OVERALL TRANSFER FUNCTION
FOR LINEAR APPROXIMATION

Fig. 4.3 Simplified Transfer Function Diagram

Unfortunately, the final reduction is not permissible since elements F_1 and F_3 are non-linear. A complete formal analysis of the system is therefore not possible. However, piece-wise linear approximations might be made in which case the system would be reduced within each approximation to that of 4.3b. The transfer function would be

$$\frac{\theta_2}{e_{sb}} = \frac{F_1 F_2 F_3 F_4 F_5 F_6 F_7}{1 + F_4 F_5 F_8 + F_1 F_2 F_3 F_4 F_5 F_9} \quad \ldots \quad 4.1$$

Even if the linear analysis were possible, the evaluation of $\frac{\theta_2}{e_{sb}}$ would depend on evaluating the coefficients of the individual transfer functions. These can only be found by lengthy experimental procedures. The actual working out of the analysis is thus not justifiable since the overall response can be obtained experimentally also. Furthermore, the experimental overall response determination is more straightforward and simple in this system than determining the individual responses. The preceding theoretical consideration however is a helpful guide when adjusting the system during actual operation.

The procedures and results of testing and evaluating the plotter experimentally are described in Chapter VI.

CHAPTER V

Mechanical Organisation and Component Details

Details of Electrical and Mechanical Construction and the Organisation of the Phase Plotter

In this chapter are recorded details of the organisation of the plotter equipment and specific information about individual electronic and mechanical components. Although this part of the thesis properly follows in sequence with the preceding chapters, the reading of the detailed component descriptions may be conveniently deferred until Chapter VI has been read.

5.1. Mechanical Organisation

The mechanical organisation of the components of the plotter is designed to achieve flexibility of operation. The system is divided into four parts. Fig 5.1 diagramatically indicates the arrangement used for measurements on a lens. One part consists of the intensity recorder whose components are mounted on a standard relay rack and is described in sec.5.5. The other three parts comprise the major portion of the system and consist of two standard rack cabinets and the probe mechanism. The first cabinet contains a central control panel, the phase recorder, the error signal, AGC and servo amplifiers. The second cabinet contains the klystron source, power supply, the modulation source and the balanced modulator. The probe mechanism includes an optical bench, with the probe positioning mechanism, the detector and the servo driven phase shifter assembly. Appropriate cables interconnect the four major components allowing overall control from the main cabinet rack. Photographs of these three major assemblies are shown in Figures 5.2, and 5.3.

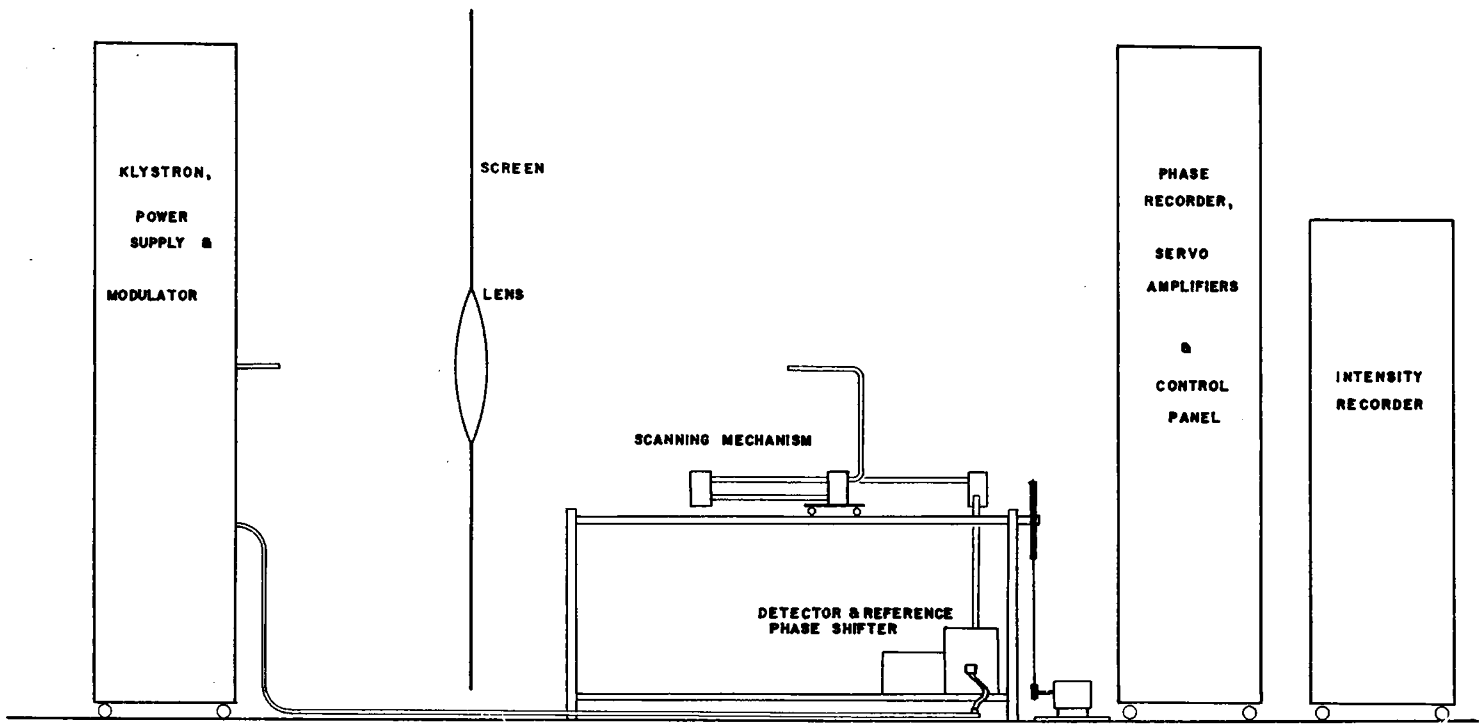
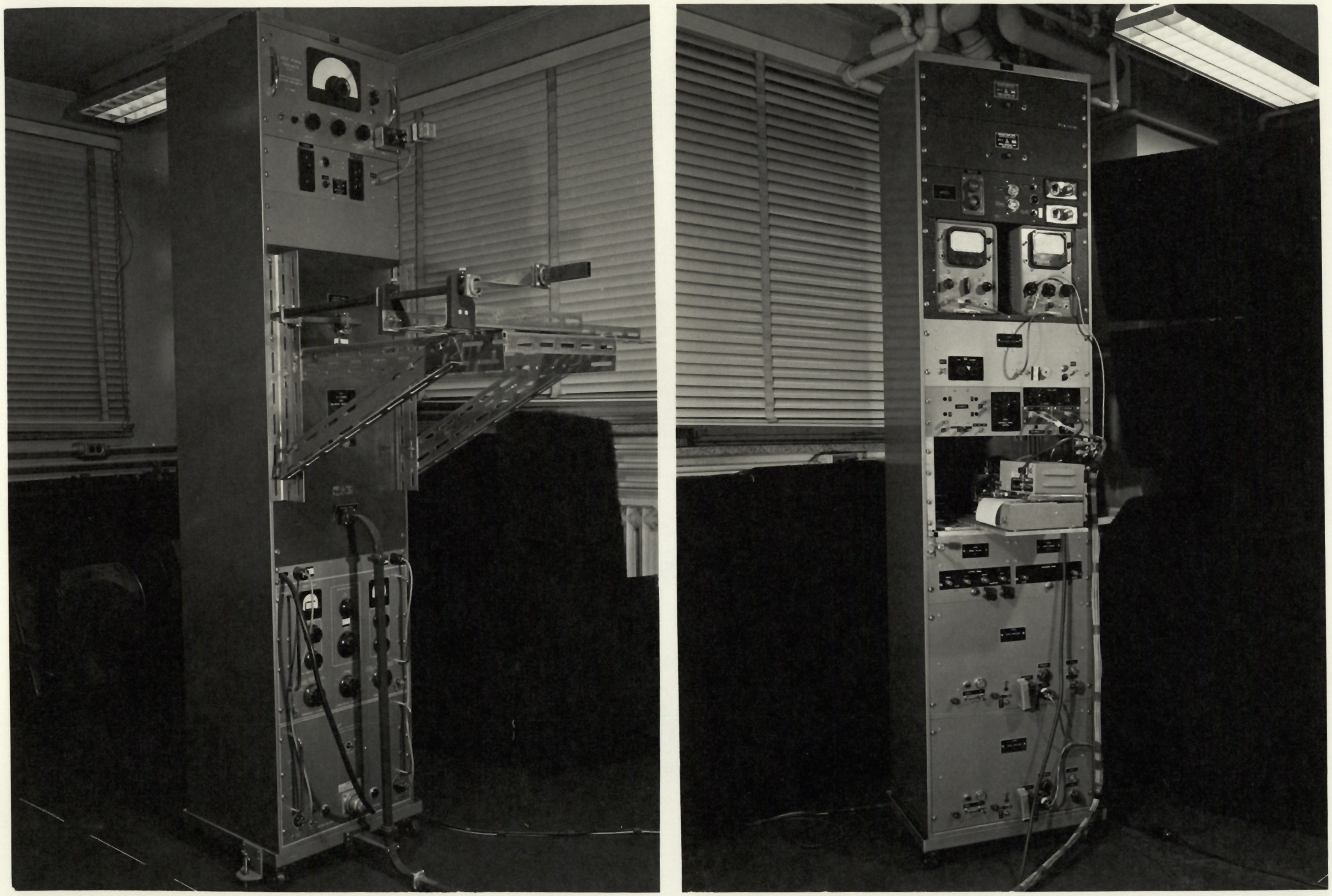


Fig. 5.1 Mechanical Arrangement of Phase and Intensity Plotter



Cabinet 2
Microwave Source

Cabinet 1
Central Control, Phase Recorder and
Servo Amplifier

Fig. 5.2

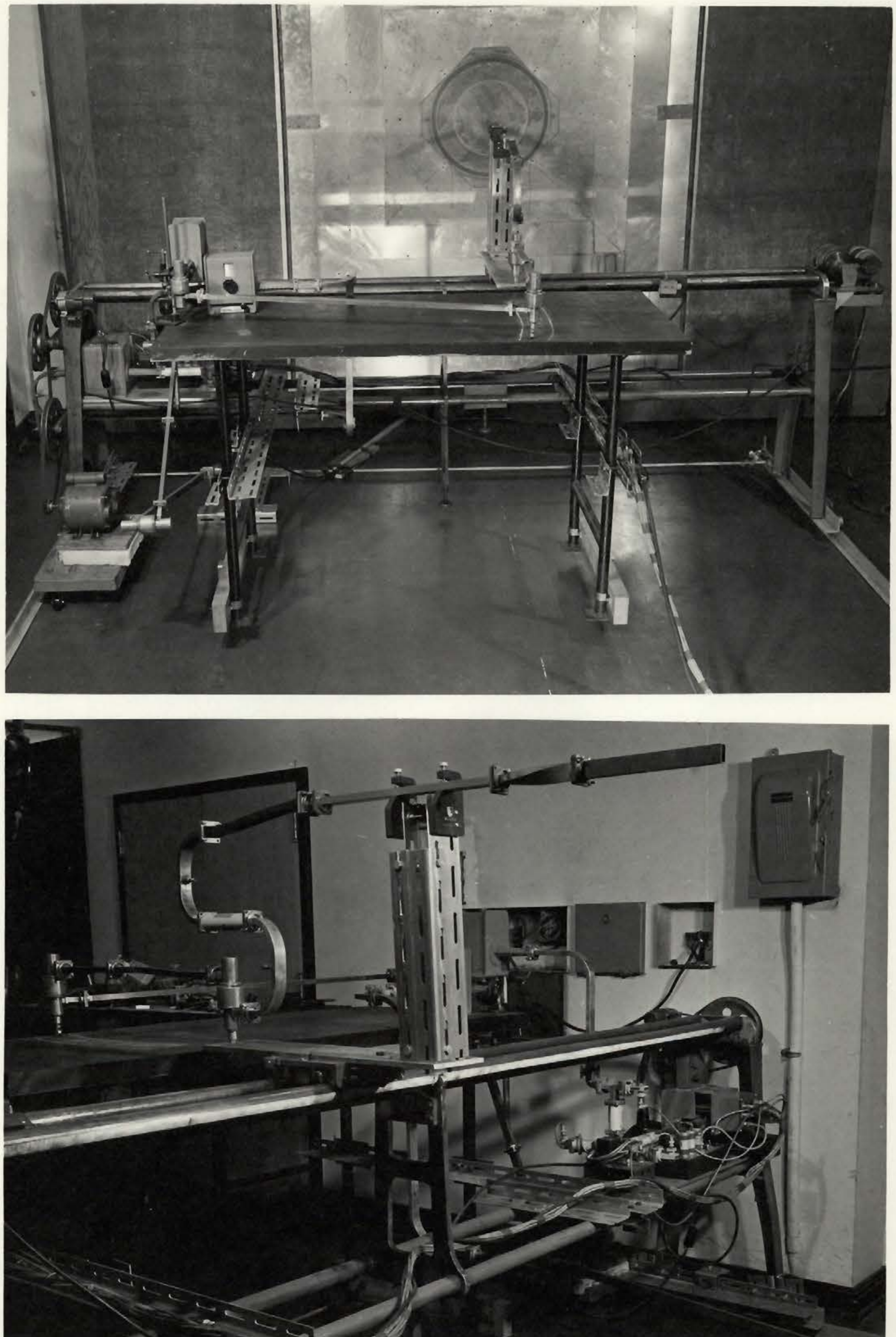


Fig. 5.3
Screen with Lens, Optical Bench Scanning Mechanism and Detector Assembly

5.2. Scanning Mechanism

The manner in which a field is scanned varies with the nature of each measurement. However, a number of general principles must be followed to minimize possible errors from this source.

The probe used is a flange-less open guide which has been shown to be a satisfactory probe for measurements of this type (Bekefi[34]). In the measurement of intensity alone, the probe scanning a field may be moved with relative ease since the detector crystal is mounted at the probe and connected to the intensity recorder by a microphone cable. Phase measurements however require delivering the measured and reference signals to the detector assembly. Since the detector and reference phase shifter assemblies are of appreciable size, it is not convenient to move them with the probe. The connections must be made with waveguides and the unknown signal connection requires a mechanical linkage with rotary joints in order to allow motion of the scanning probe. These connections must not produce any variation in phase during scanning. Precision phase-shift-free rotary joints are necessary. The linkage must be designed to minimize the degree of rotation of the joints to reduce such phase errors as may be present. Flexible coaxial connections cannot be used instead of a waveguide linkage because the flexing of coaxial cables produces intolerably large phase shifts. This has been reported by Burrell[11] and has been demonstrated during the plotter development by the simple test of inserting a coaxial line in the measuring system and flexing the line. A coaxial line connection may be used for convenience in part of the reference signal path provided that it is not moved during measurement.

A simple scanning arrangement is shown in Fig. 5.4. This was used by Farnell[35] for a single scan measurement along a lens axis. It will be noted that the probe is mounted on an optical bench and positioned by a lead screw. Usually an area scan is required, in which case the optical bench is

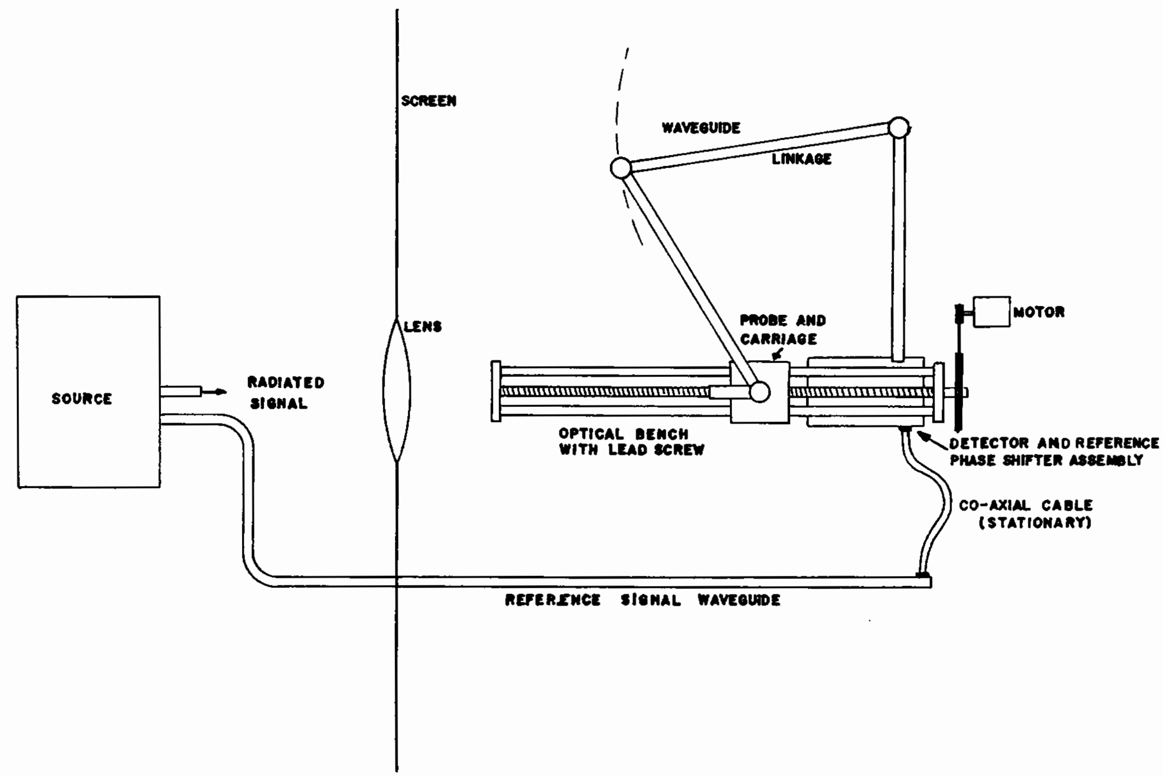


Fig. 5.4 Plan View of Scanning Mechanism for Measurements along Lens Axis

mounted parallel to the screen. The bench is on rails, allowing it to be moved away from the screen. An additional guide linkage is used in the reference signal path. The probe can then be positioned to any point in an area of about 120 x 60 cms. This arrangement is shown in Fig. 5.3.

The measurement and the remote indication of the probe position during scanning is another vital part of the mechanical arrangement. Because of the relatively short wavelengths used (3.2 cm) the probe must be positioned and moved with considerable precision. This is achieved by using the optical bench with a motor driven lead screw. The angular position of the lead screw and thus the probe position along the optical bench is reported by two synchro generators. One provides the position signal for the phase recorder and the second serves the intensity recorder.

The phase recorder (Varian Type G.10) is normally equipped with a constant speed chart drive. This has been replaced by a synchro-motor drive which positions the chart in accordance with the probe position as shown in Fig. 5.5. Because of the nature of the chart feed, the motion can be in one direction only and the arrangement does not provide a true X-Y recorder. This is quite adequate however since the scans are always made in one direction only in order to avoid back-lash errors in the scanning mechanism. The intensity recorder is a true X-Y recorder and the chart positioning is servo driven.

The accuracy of recording the probe position depends on the mechanical precision of the optical bench and lead screw, on the synchro-generators as well as on the accuracy of the recorders and the chart paper.

The distance of the optical bench from the screen is adjusted manually between scans and the distance measured by scales permanently mounted on the rails.

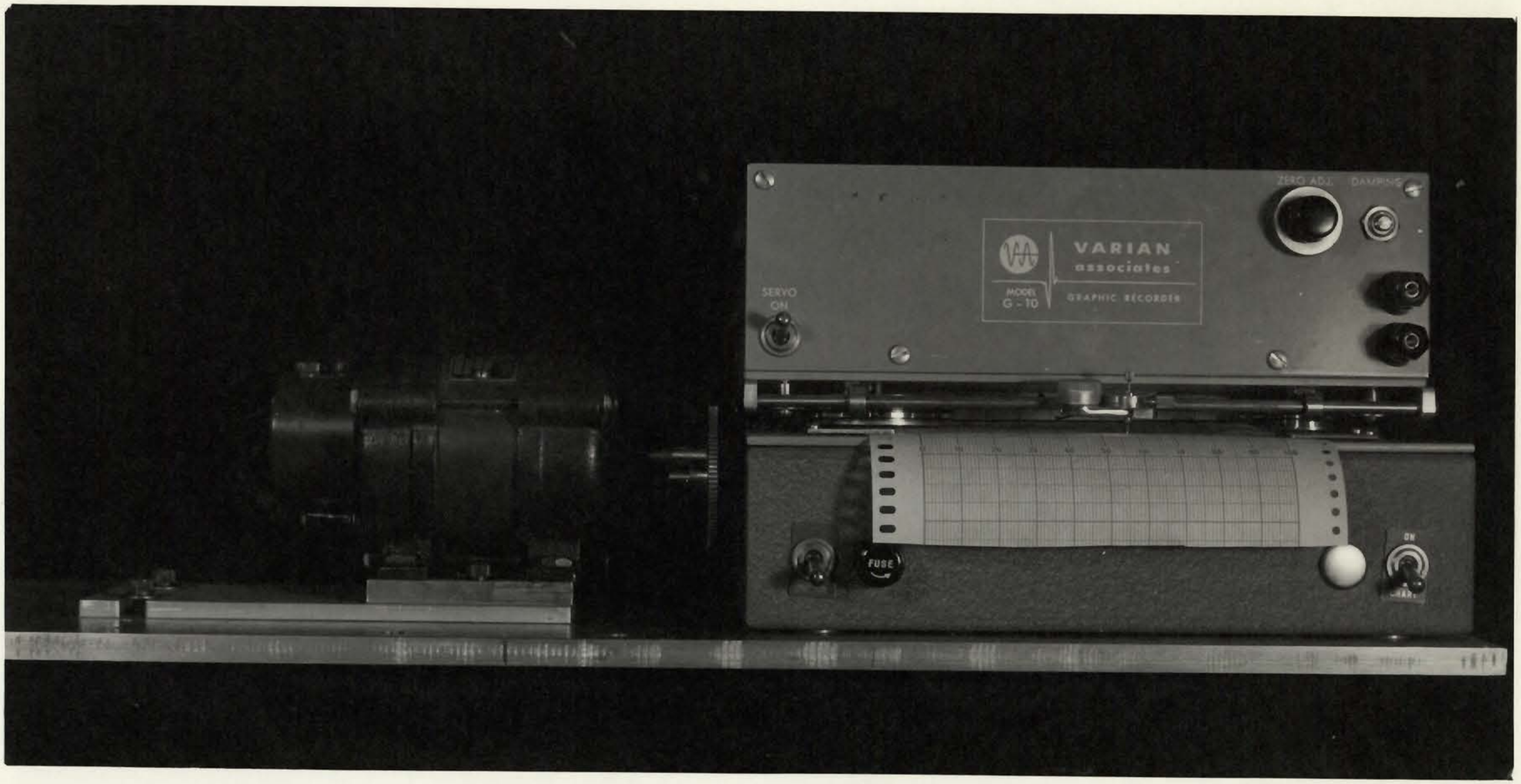


Fig. 5.5 Phase Recorder with Synchro-Motor Chart Drive

5.3. <u>Detector and Servo-Driven Phase Shifter Assembly</u>

The detector and phase shifter assemblies are described functionally in Chapters III and IV, and diagramatically shown in Fig. 3.3. The mechanical assembly is shown in Fig. 5.6. The servo driven reference phase shifter assembly consists of the following components:

(a) A Hewlett-Packard Type 885-A Rotary Phase shifter whose stated accuracy is 2^{o}.

(b) A Diehl Type S.S. FPE 49-51-1 Servo Motor and Tachometer.

(c) A Helipot, Type A ten-turn 20 KΩ linear potentiometer.

(d) A Starling Precision Instrument Type T.506 magnetic brake-clutch.

(e) Limit switches with manual cut-out and appropriate gearing.

These components form an integral mechanical assembly mounted with the detector circuit on a common base. The arrangement and functional relationship of the components is evident from the photographs in Fig. 5.7.

The limit switches and magnetic brake-clutch are required as protection for the ten-turn potentiometer whose rotational range thus determines the range of the entire phase measuring system. The gear ratios are chosen such that one revolution of the potentiometer represents a phase shift of 360^{o}, giving a total range of 3600^{o}.

5.4. <u>Intensity Recorder</u>

The instrument used for producing the intensity records is a commercial device, the Type 373, Airborne Instruments Ltd., Antenna Pattern Recorder. It is a strip chart recorder in which both the paper position and the pen motion are servo driven. The paper drive responds to the scanning probe position and may be driven in either direction. The pen deflection is proportional to the relative intensity in decibels. This is achieved by a logarithmic potentiometer used in the error detector circuit of the pen servo-drive.

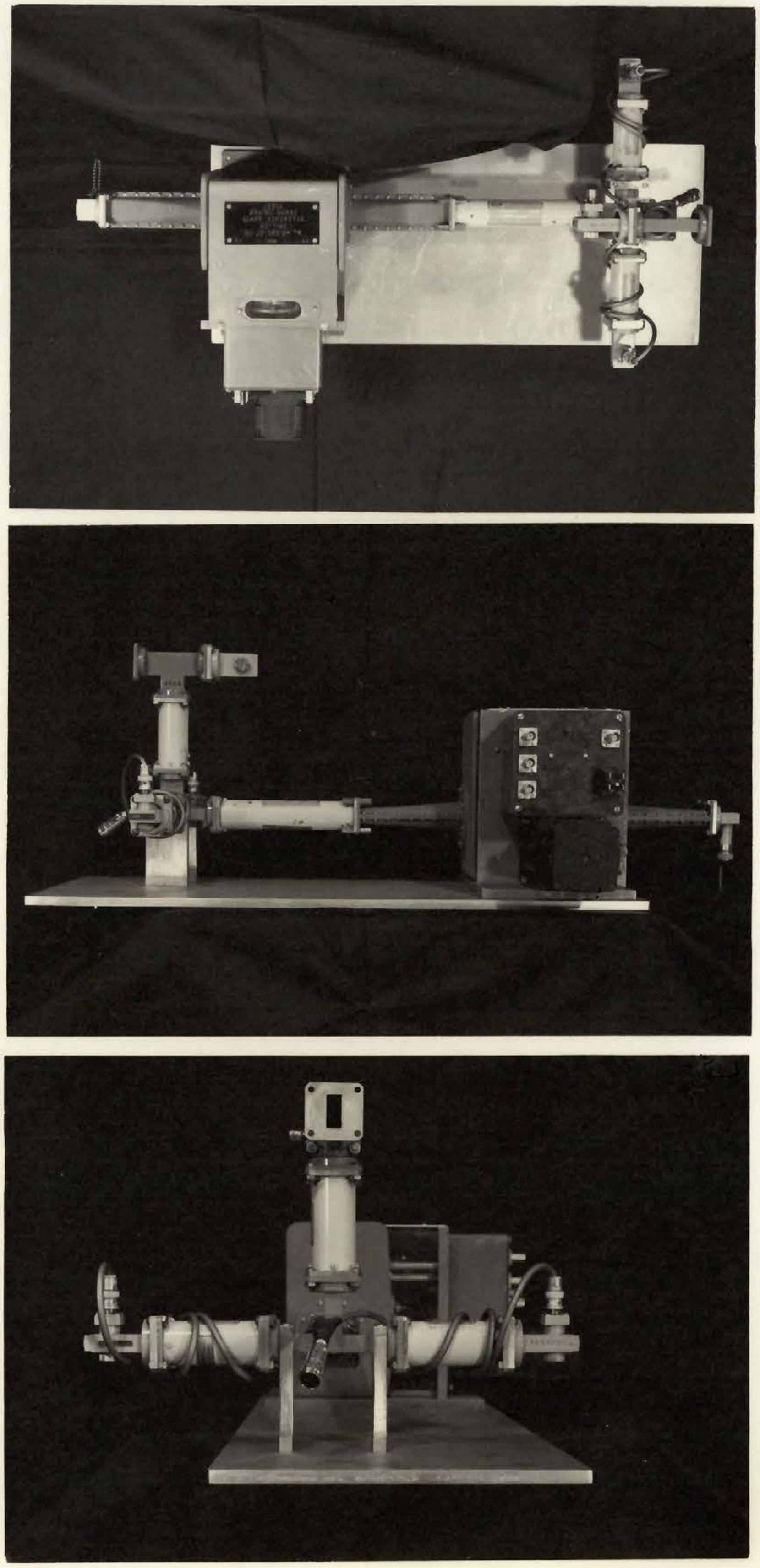


Fig. 5.6 Detector and Servo-Driven
Phase-Shifter Assembly

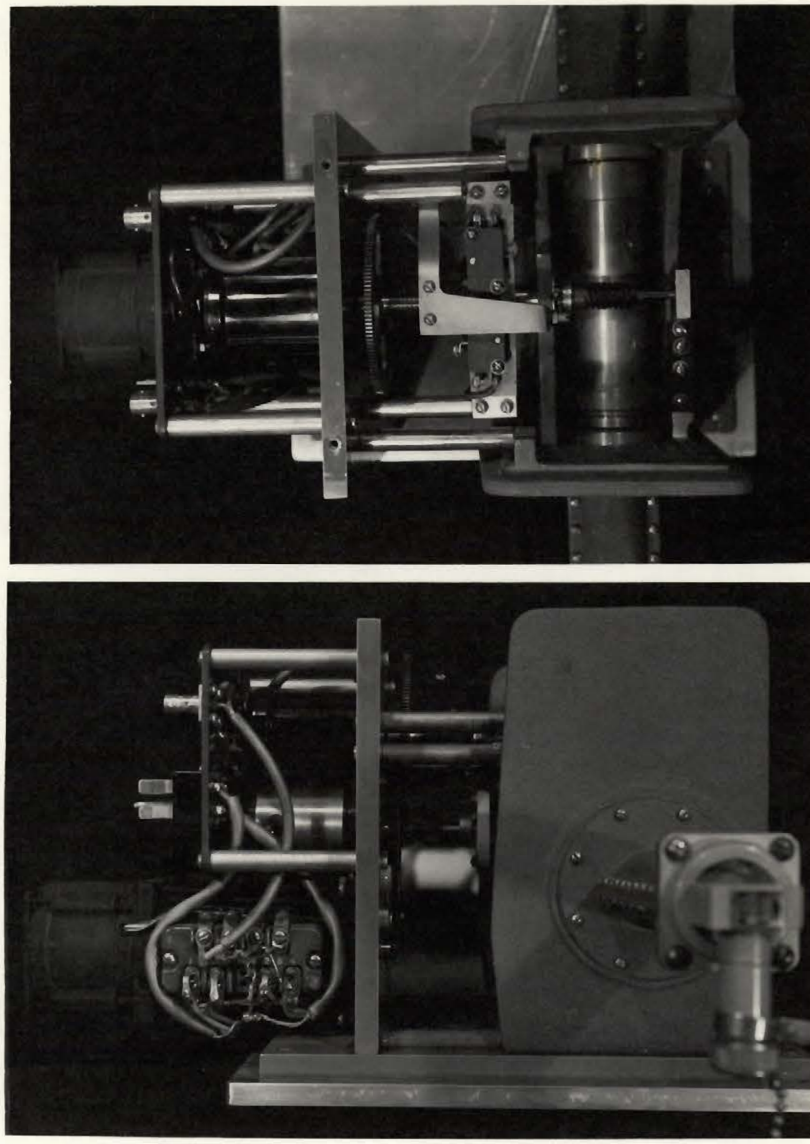


Fig. 5.7 Detail of Servo-Driven Phase-Shifter Assembly

The use of this recorder follows well established techniques, (Borts, Carruthers, Woonton[36], Hamer and Foot[37]). The only departure from conventional procedure is in the nature of the intensity signal which is derived from the unknown signal as described in sec. 3.3.

5.5. <u>Details of Electrical Components</u>

5.5-1 <u>Audio Oscillator and Modulation Power Amplifier</u> Fig. 5.8.

The modulation source consists of a conventional Wien Bridge Oscillator and a Power Amplifier capable of delivering 20 watts. The source impedance is adjustable to a number of convenient values.

5.5-2 <u>Variable Gain Amplifier</u> Fig. 5.9.

The variable gain amplifier consists essentially of a modified logarithmic amplifier (Carruthers[38]). In the original form the input signal to the amplifier produces an a.g.c. voltage which controls the gain so as to produce a logarithmic amplitude relationship between the output and input. In the modified form used, the a.g.c. voltage is derived separately from the intensity signal. A limiter is used in the a.g.c. circuit in order to prevent complete cut-off in the case of extremely high intensity peaks.

5.5-3 <u>The Tuned Amplifiers</u>

The tuned amplifier used for selecting the phase-error signal is a Hewlett-Packard Type 415-B Standing Wave Indicator tuned to 400 c/s. It is modified to provide the selected audio output for subsequent use in the phase servo amplifier. The visual meter indication is preserved and is used for adjustment of the plotter prior to automatic operation or when the system is being used in manual measurements. An identical amplifier with the same modification, but tuned to 800 c/s is used to provide the intensity signal required by the variable gain amplifier.

A separate tunable amplifier, adjusted to 800 c/s is integral to the Airborne Instruments Intensity Recorder.

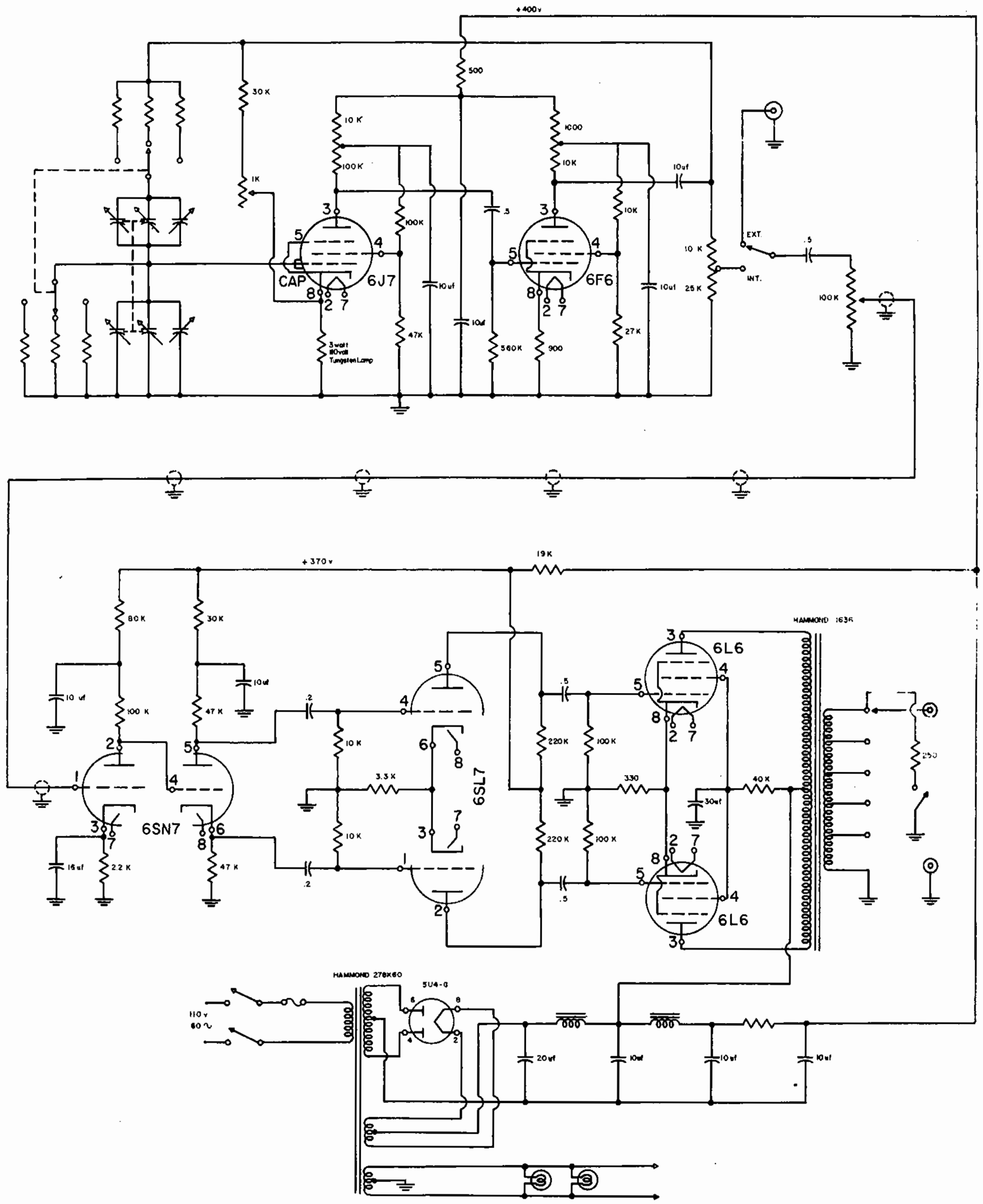


Fig. 5.8 Circuit Diagram of Modulation Source Oscillator and Power Amplifier

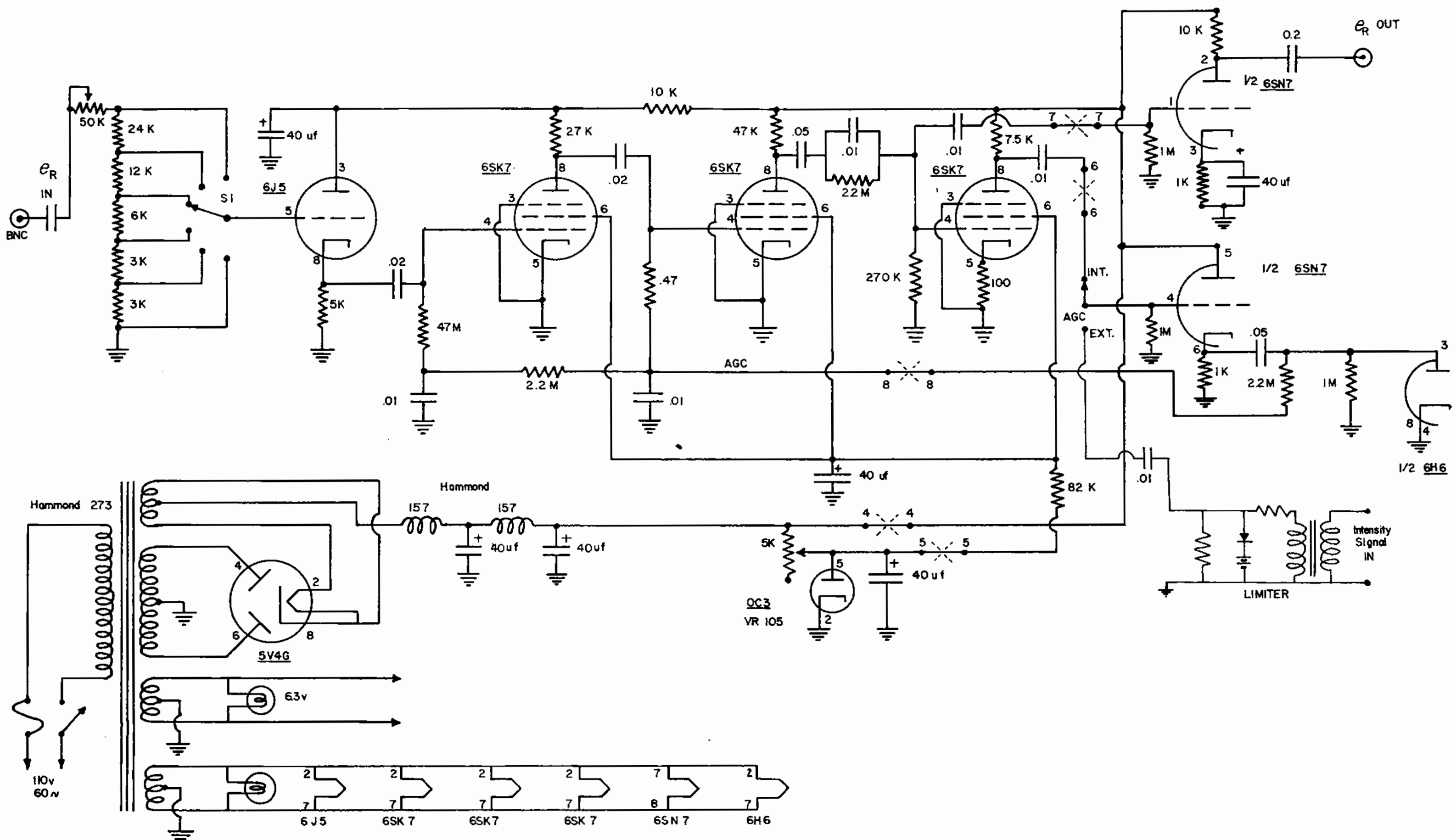


Fig 5.9 Circuit Diagram of Variable Gain Amplifier

5.5-4 The Servo Preamplifiers Fig. 5.10.

Preamplifier No. 1 has two inputs and one output, allowing the combination of the phase-error and the output rate damping signals. Each input signal is separately adjustable in phase and magnitude and the two are then linearly added.

Preamplifier No. 2 is identical to No. 1 with the exception of having one input only.

The phase adjustments in the amplifiers allow proper quadrature phasing of the servo motor control and reference signals. The magnitude adjustments permit optimum servo gain and damping conditions.

5.5-5 Servo Power Amplifiers Fig. 5.11.

The two servo power amplifiers are identical. They are conventional Class-B push-pull power amplifiers, with a power output of approximately 40 watts at 110 volts. The final stage is broadly tuned at 400 c/s.

5.5-6 Recorder Range Control Fig. 5.12.

The Recorder Range Control serves to expand the effective scale of the Phase Recorder. It is essentially a precision voltage divider with an adjustable series d.c. bias voltage. The range control allows adjusting the recorder scale to any one of the following scale factors for any position of the phase shifter:

Range	Full Scale Range Degrees	Degrees/inch	Degrees/small division
10	3600	720	36
5	1800	360	18
2	720	144	7.2
1	360	72	3.6

Range 1 allows a readability of the record to about 2° since

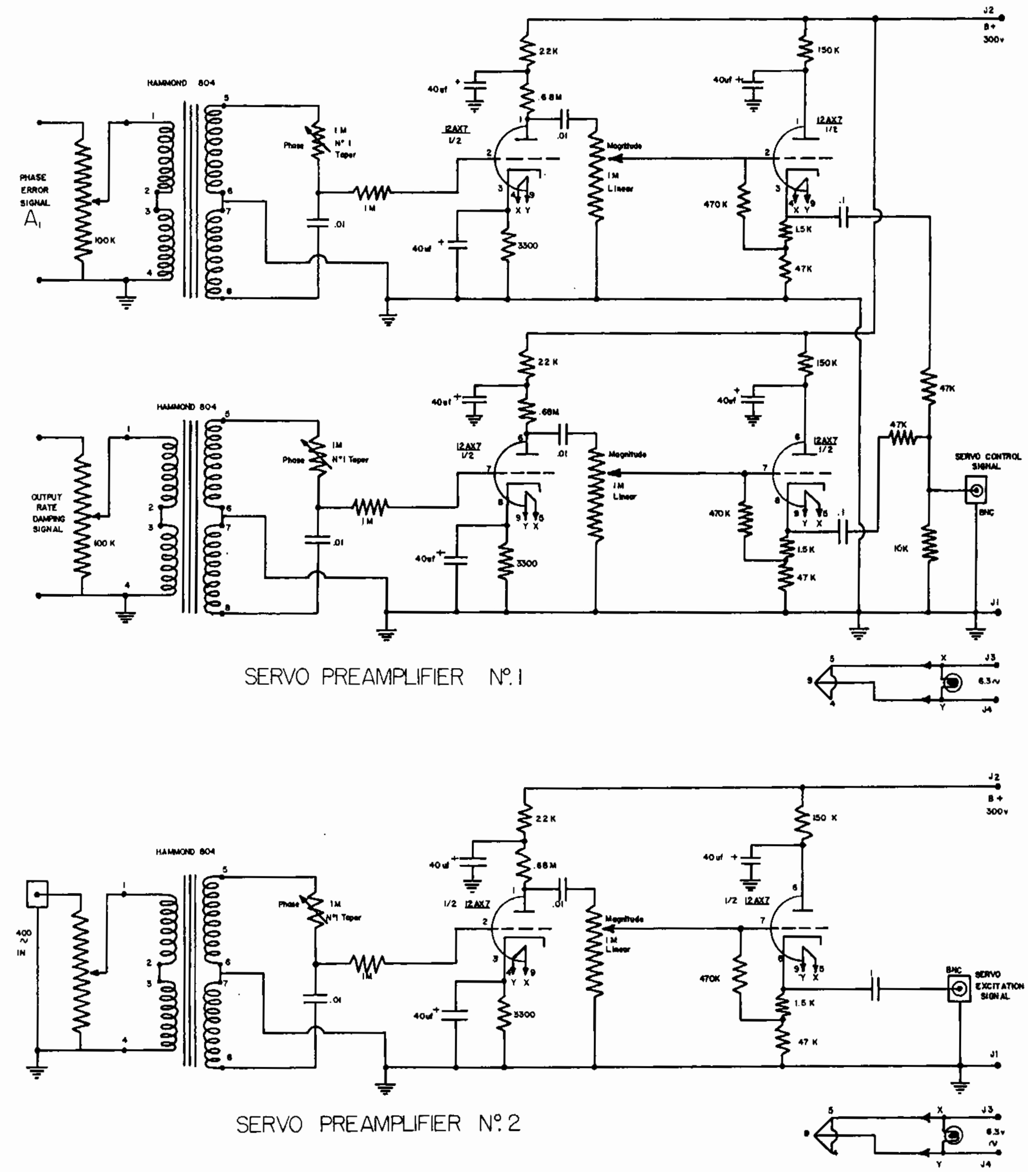


Fig. 5.10 Circuit Diagrams of Servo Preamplifiers

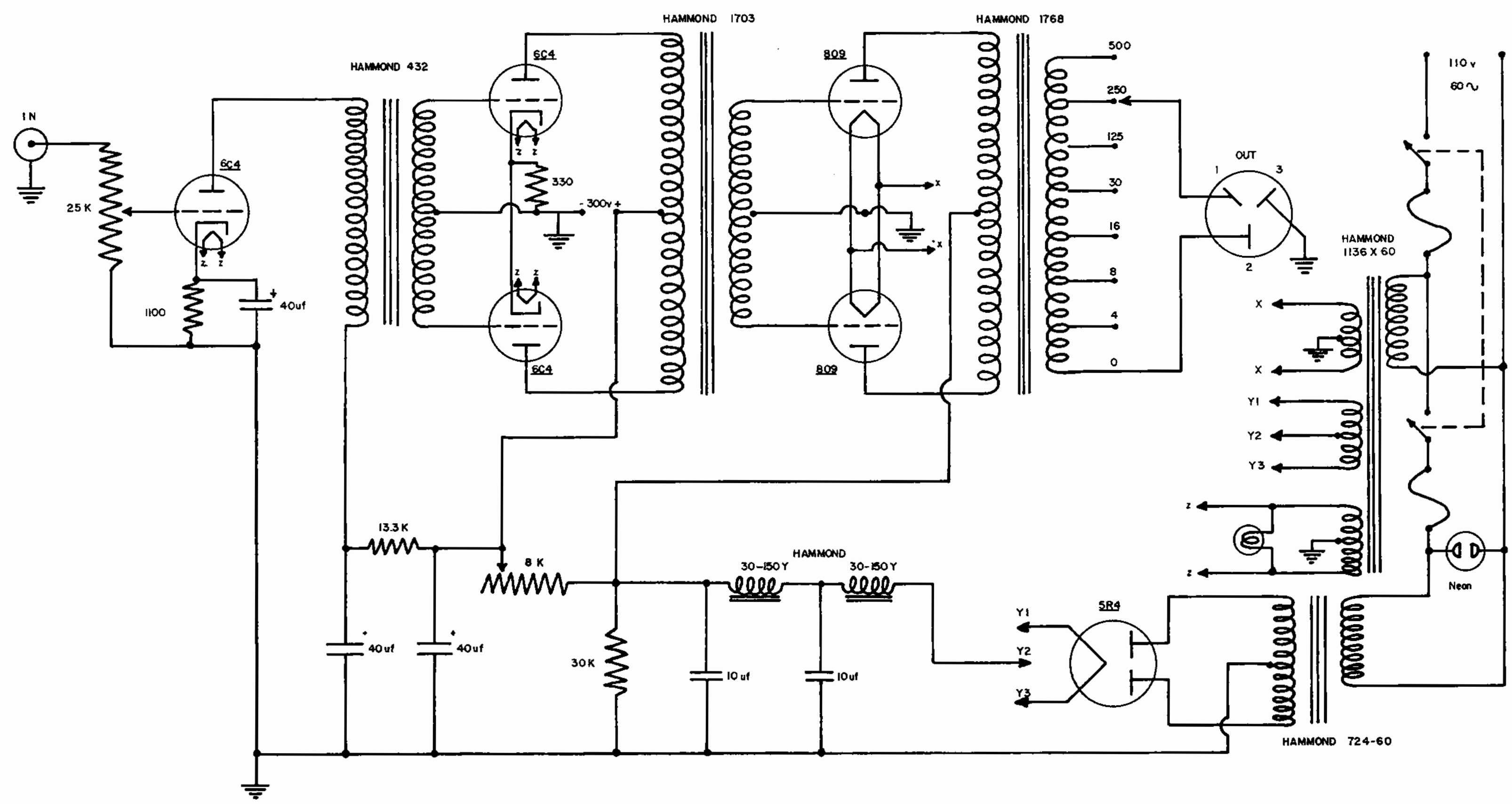


Fig. 5.11 Circuit Diagram of Servo Power Amplifier

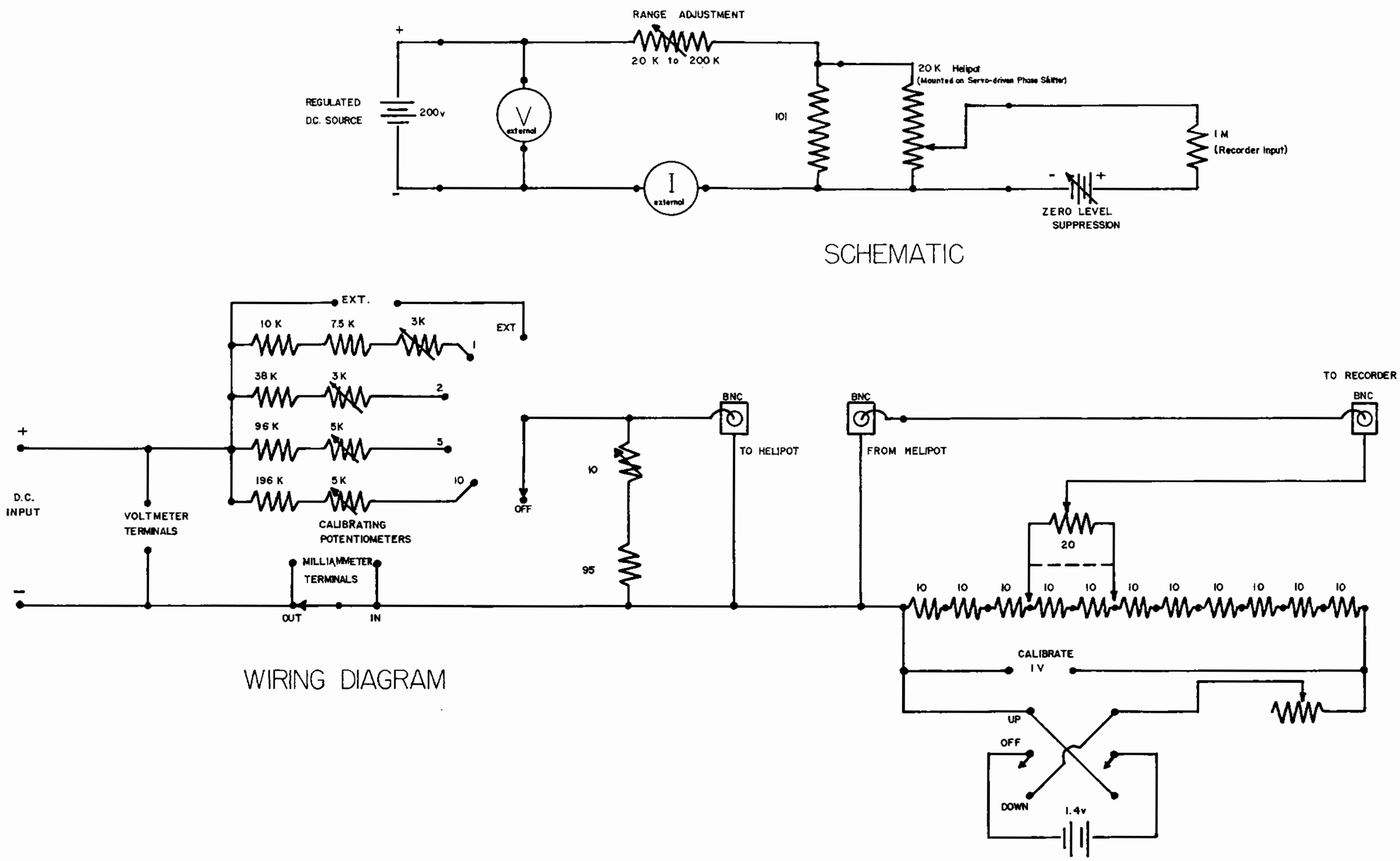


Fig. 5.12 Circuit Diagram of Recorder Range Control

the recorded line is fine enough to allow interpolation between the small divisions of the chart. The recorder resolution is thus of the same order as the accuracy of the phase shifter. Provision is also made for use of external precision resistors to adjust the scale factor to any other desirable value.

CHAPTER VI

Experimental Evaluation of the Phase Plotter

The Experimental Evaluation of the Phase Plotter

The performance of the phase plotter was determined both by procedures synthesizing artificial test signals and by subjecting the system to operational conditions.

The test procedures are essential to demonstrate various important aspects of the system. The significant ones which were tested were the accuracy of the system and the response speed of the plotter at various signal intensity levels.

In the experimental evaluation of the system, however, greater stress was placed on the operational "Proof of Performance" of the phase plotter since ultimately only the behaviour in actual use can prove its full effectiveness. The operational demonstration of the system consisted first of establishing suitable known, calculated fields and measuring them with the plotter to compare measured and calculated results. Secondly the operational demonstration showed how the equipment can be used to make extensive measurements in order to map a complicated field.

6.1. Test Procedures

The test procedures described here demonstrate the two most significant qualities of the phase plotter. These are the accuracy of its calibration and its ability to record rapidly varying phase under extreme variations of intensity.

6.1-1 Calibration Test

A calibration test of the system can be made by producing a known phase change in the unknown or the reference signal path. The recorded phase indication is then compared with the known phase change. Fig. 6.1. shows such a sample calibration record made prior to a sequence of actual operational measurements. This calibration was made for the 720° range setting of the recorder. It shows that the recorded reading is correct in each case within the tolerance of half a small division on the recorder chart. Each division at this range represents 7.2° and the deviation from the correct value is therefore 3.6° or less. The displacement or position co-ordinate in this record is proportional to time and is used merely as a convenient means to separate the several readings.

The known phase change is produced by a manually adjusted phase shifter of a type identical to that used as the reference phase-shifter. The test is therefore an evaluation of the overall calibration of the system but is not an indication of the absolute accuracy of the reference phase shifter. It is a static test in the sense that the intensity of the unknown signal is kept constant and that no attempt is made to consider the speed of response while the phase is being adjusted.

This calibration test forms a conclusive demonstration of the accuracy of the system under static and slowly changing conditions.

6.1-2 Dynamic Test

The dynamic behaviour of a system can be indicated by determining the steady state response to sinusoidal excitation over a range of frequencies or by observing its transient response to a step function or square wave input. These are the tests normally applied to servomechanisms and automatic devices (Brown and Campbell[39]).

In the case of the phase plotter the "input" is a change in the unknown signal phase. The square wave test is the more appropriate to demonstrate the response-speed of the system. It can be carried out easily, though crudely, by manual adjustment of the additional phase shifter used in

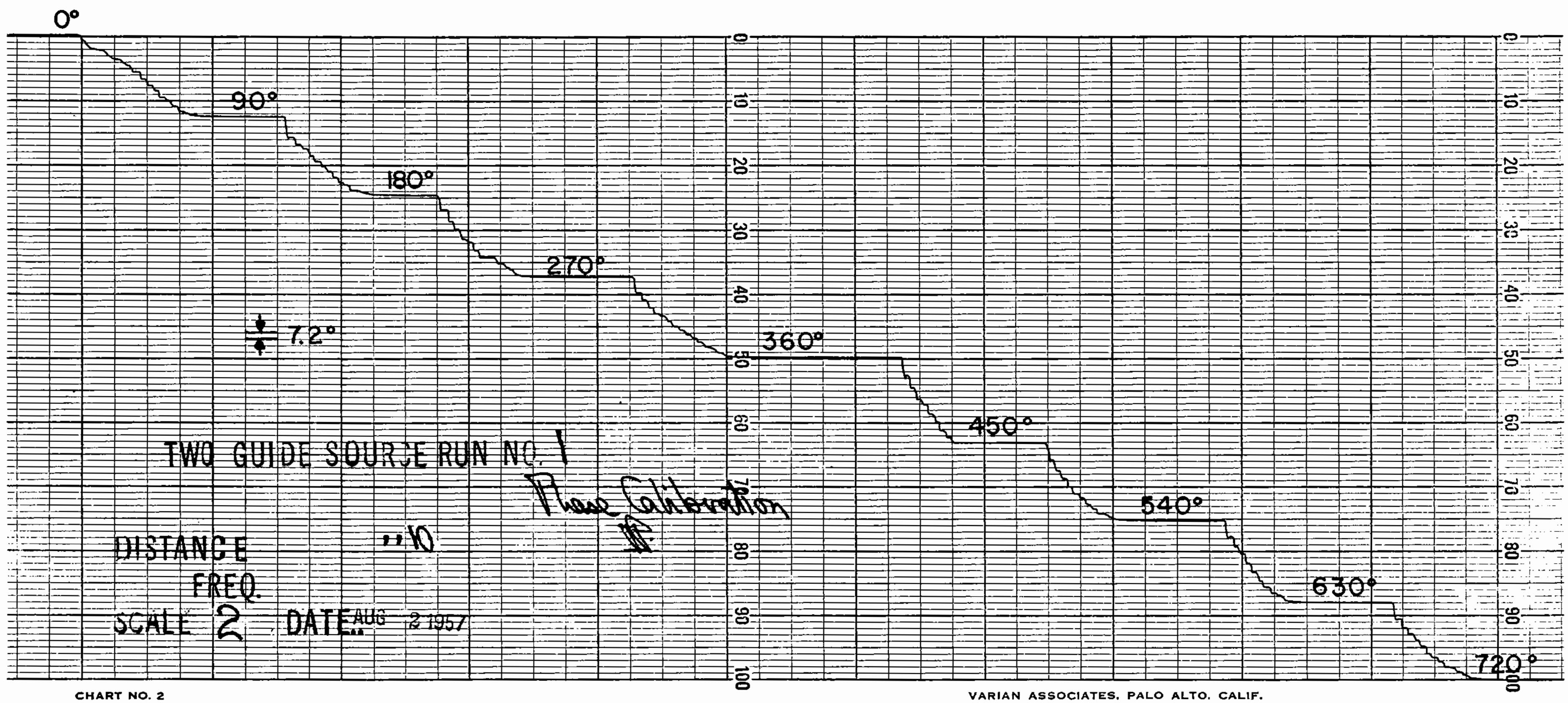


Fig. 6.1. Static Calibration Test of Phase Plotter

the previous calibration test. The phase shifter range must first be mechanically limited to some chosen value and the setting then varied rapidly by hand between the mechanical limits in a square wave fashion. This simulates a square wave of phase input albeit in an imperfect manner since the manual adjustment can only be made at a finite speed. Furthermore, the amount of phase change or the "amplitude" of the square wave thus produced is not constant, again because of the shortcomings of hand operation. The period of the square wave is at the convenience of the operator and is not necessarily constant.

Despite the shortcomings of a manually simulated square wave input the dynamic performance of the phase plotter was satisfactorily demonstrated by such tests. The essential point to be proven is that the phase plotter is equally responsive to sudden changes of as much as 180° even though the unknown signal intensity may vary over a range of 40 db. These conditions approximately simulate the situation which exists in the vicinity of nulls or minima in the focal region of a microwave lens system as described by Farnell[40]. A series of tests was carried out at different intensity levels, intensity being adjusted by means of an attenuator inserted in the unknown signal path. Results of these tests are shown in figures 6.2, 6.3, 6.4, 6.5, and 6.6, which are the actual recorder charts produced by the plotter in response to the manually generated square wave of phase input. The first chart shows the response when the full intensity of the unknown signal was used and the remaining four show the response as the intensity was progressively decreased in - 10 db steps down to - 40 db. It is obvious from these records that the response is equally good over this entire intensity range. The phase change to which the plotter was subjected by the test was approximately 180° peak to peak.

In an attempt to isolate the component of the phase plotter

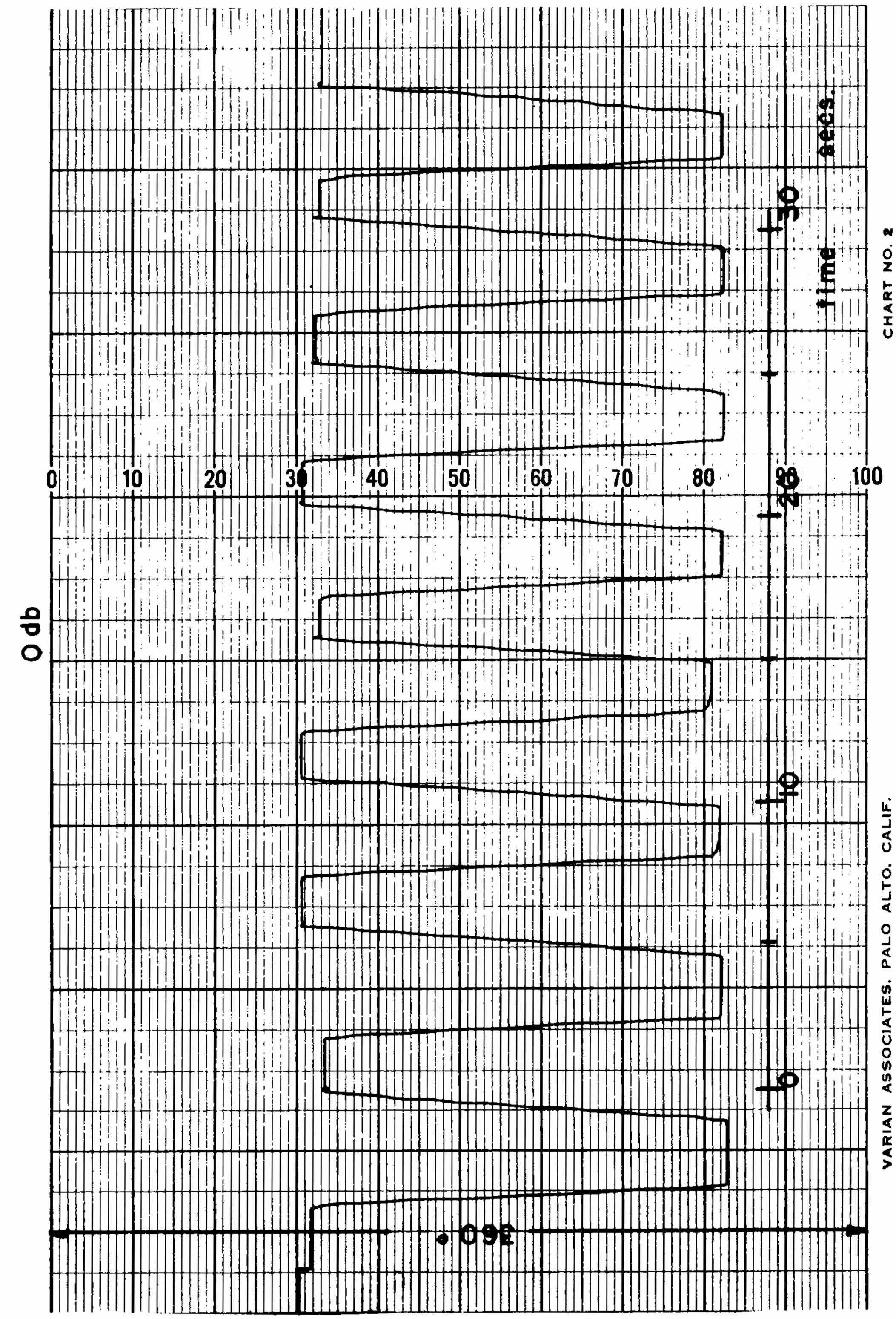


Fig. 6.2. Response of Phase Plotter to Manually Generated Square-Wave of Phase Input

Relative Intensity 0 db

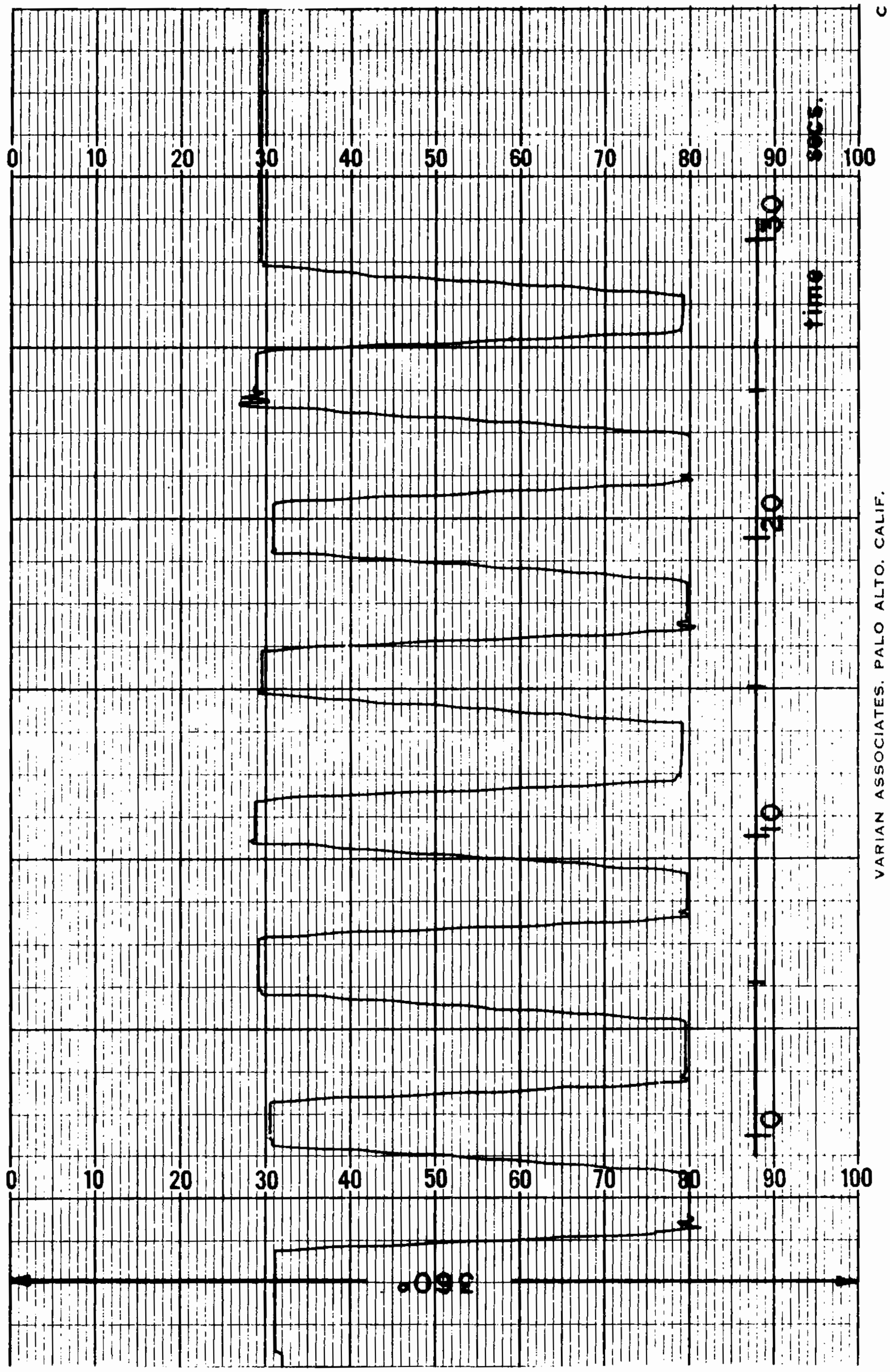


Fig. 6.3. Response of Phase Plotter to Manually Generated Square-Wave of Phase Input

Relative Intensity <u>-10 db</u>

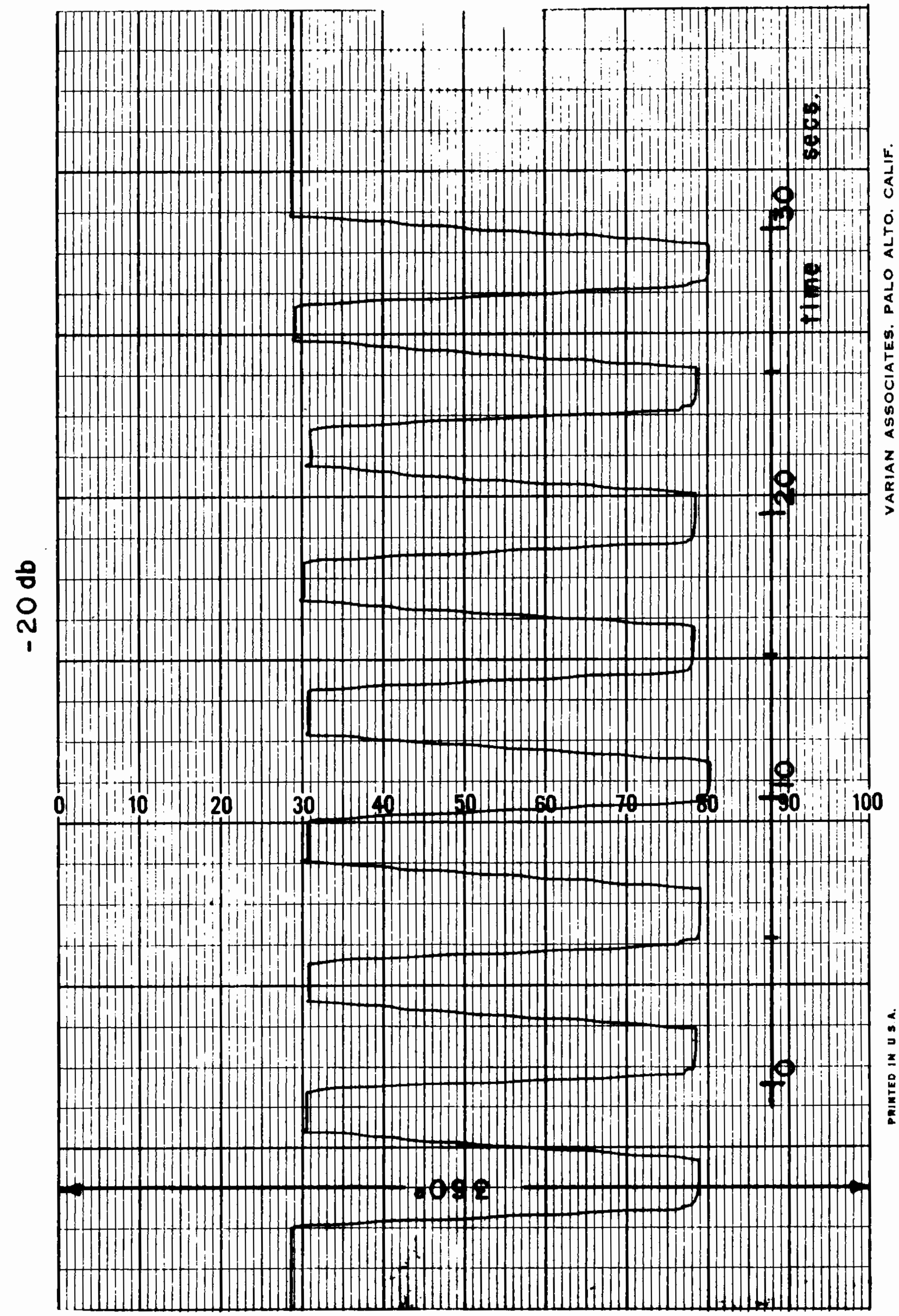


Fig. 6.4. Response of Phase Plotter to Manually Generated Square-Wave of Phase Input

Relative Intensity -20 db

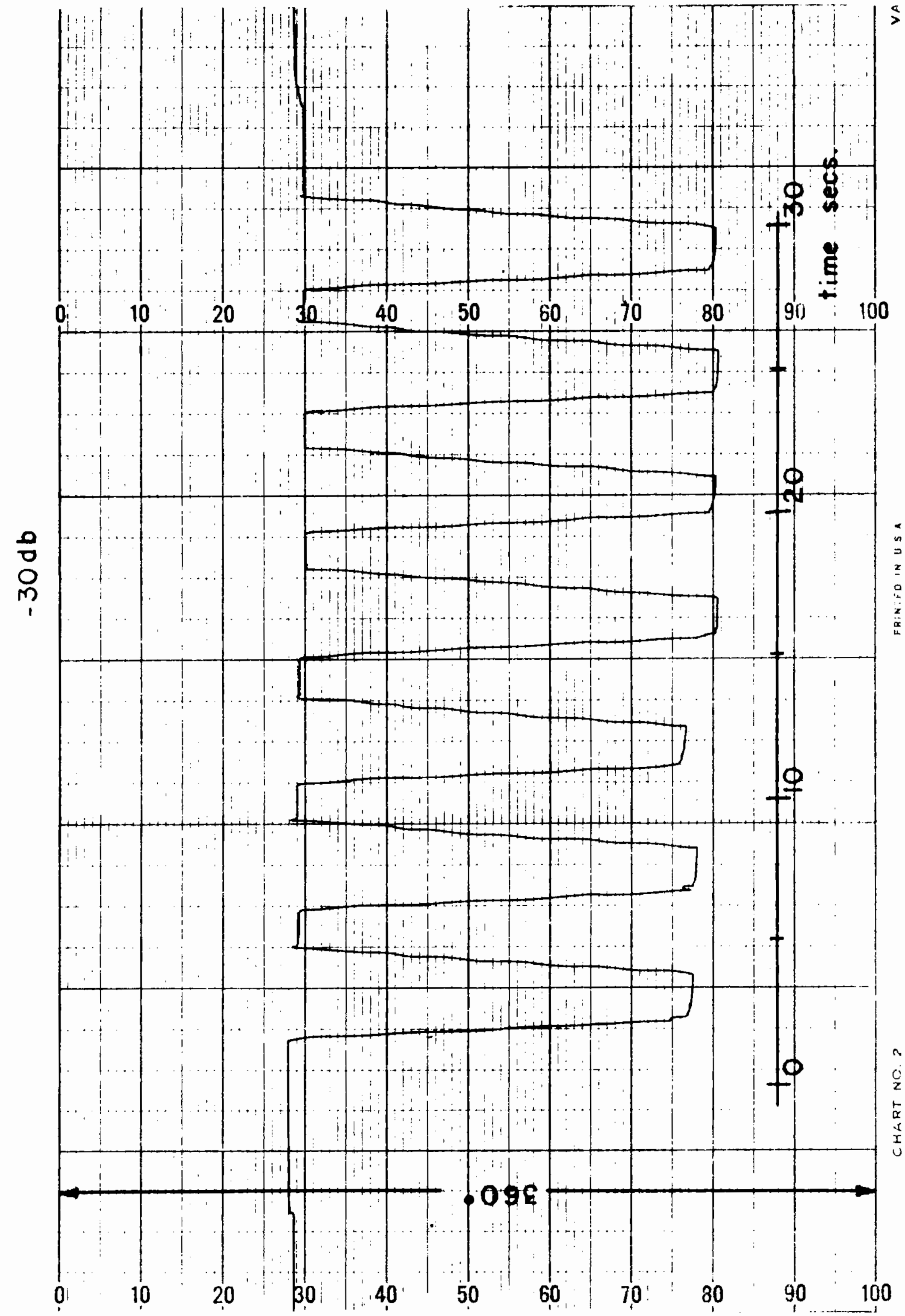


Fig. 4.5. Response of Phase Plotter to Manually Generated Square-Wave of Phase Input

Relative Intensity <u>-30 db</u>

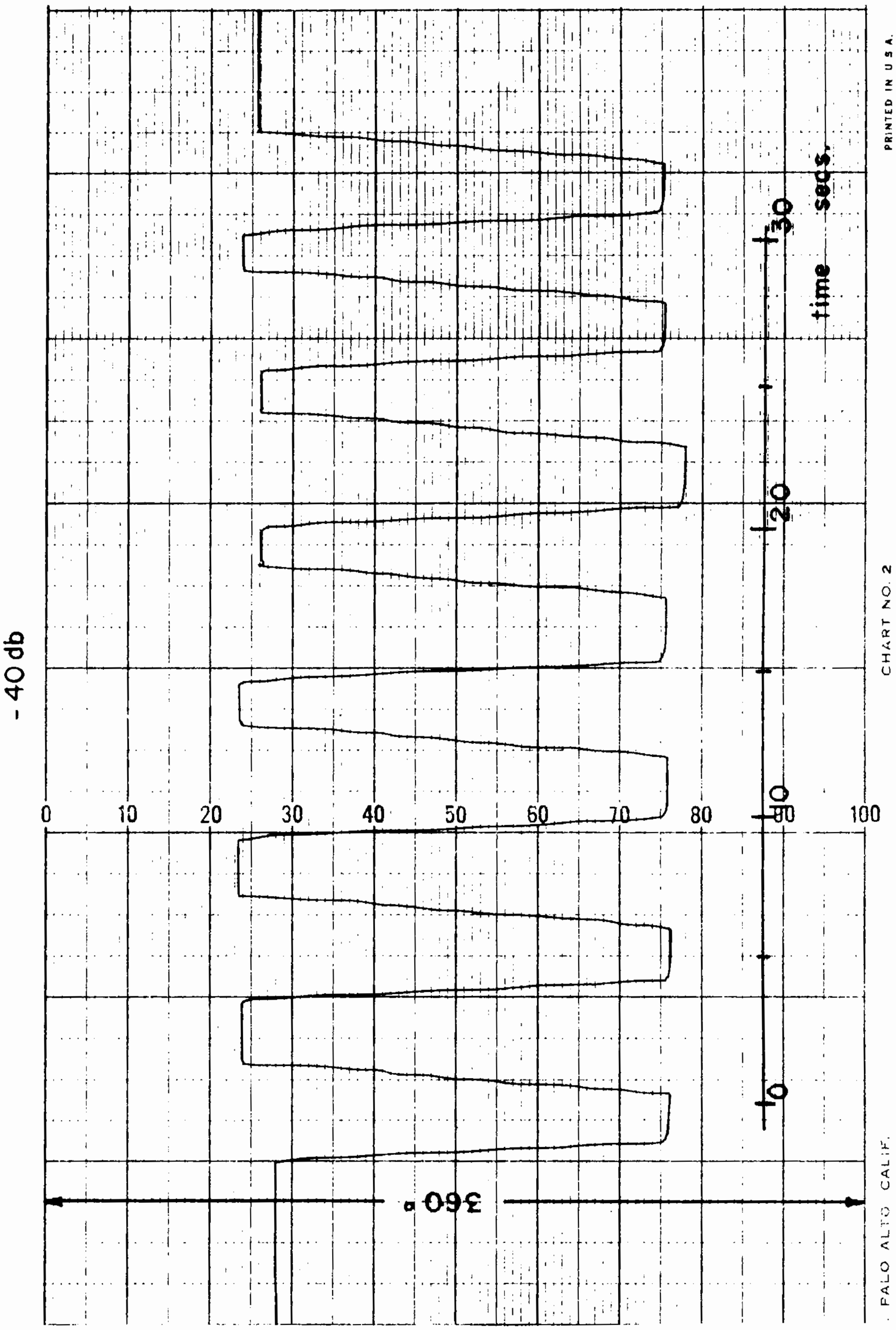


Fig. .6. Response of Phase Plotter to Manually Generated Square-Wave of Phase Input

Relative Intensity <u>-40 db</u>

system which is the limiting factor in the overall system response, an electrical square wave input, was applied to the Varian chart recorder. The test signal was chosen to have a period and magnitude corresponding to those existing in the above dynamic test. The recorder chart obtained is shown in Fig. 6.7. It is strikingly similar to the records obtained in the tests of the overall system. It can be concluded that in the present system the component limiting the system response is the chart recorder and that the phase-servo is as good as, or better than, the chart recorder. It is apparent from these tests that the response rate is 90^{o}/second.

6.2. Operational Proof of Performance

Although the two tests described in the previous sections adequately indicate the phase plotter performance, the most satisfactory demonstration of the system can only be obtained operationally. In order to carry out such a demonstration it was necessary to choose fields which could be calculated with relative ease, established experimentally with reasonable confidence and would have properties suitable for a full demonstration of the phase plotter's abilities.

The operational demonstration was carried out in three distinct stages:

a. The calculation and measurement of a limited region of a simple field. The field chosen was that of an open rectangular wave guide placed in a plane screen.

b. The calculation and measurement of a limited region of a field resulting from two rectangular wave guides placed a fixed distance apart in a plane screen and excited in phase with equal amplitude signals.

c. The measurement of a substantial area of the two-guide array field and the drawing of phase and intensity contour maps from the recorded results.

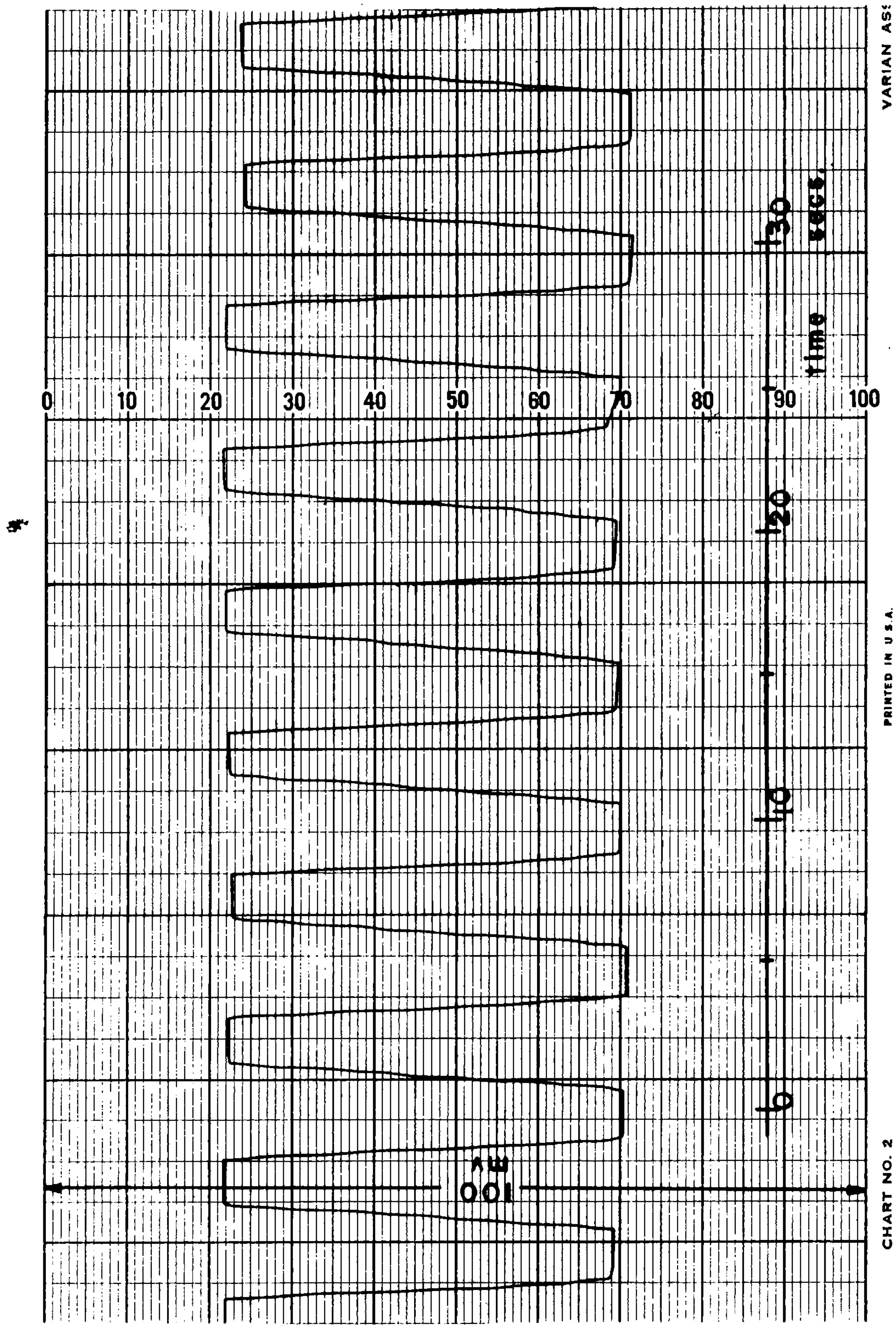


Fig. 6.7. Response of Recorder Alone to Electrical Square-Wave Input
Period approx. 5 sec.

6.2-1 The Field Due to a Rectangular Wave-guide

The problem of radiation from a rectangular wave guide is described by a number of authors such as Barrow and Green[41], Chu[42], Shelkunoff[43], Horton[44] and Silver[45]. In the form to be considered here it is the problem of calculating the field due to the radiation from an aperture in a plane screen. The physical configuration assumed is shown in Fig. 6.8. The co-ordinate axes are chosen to have their origin at the centre of the

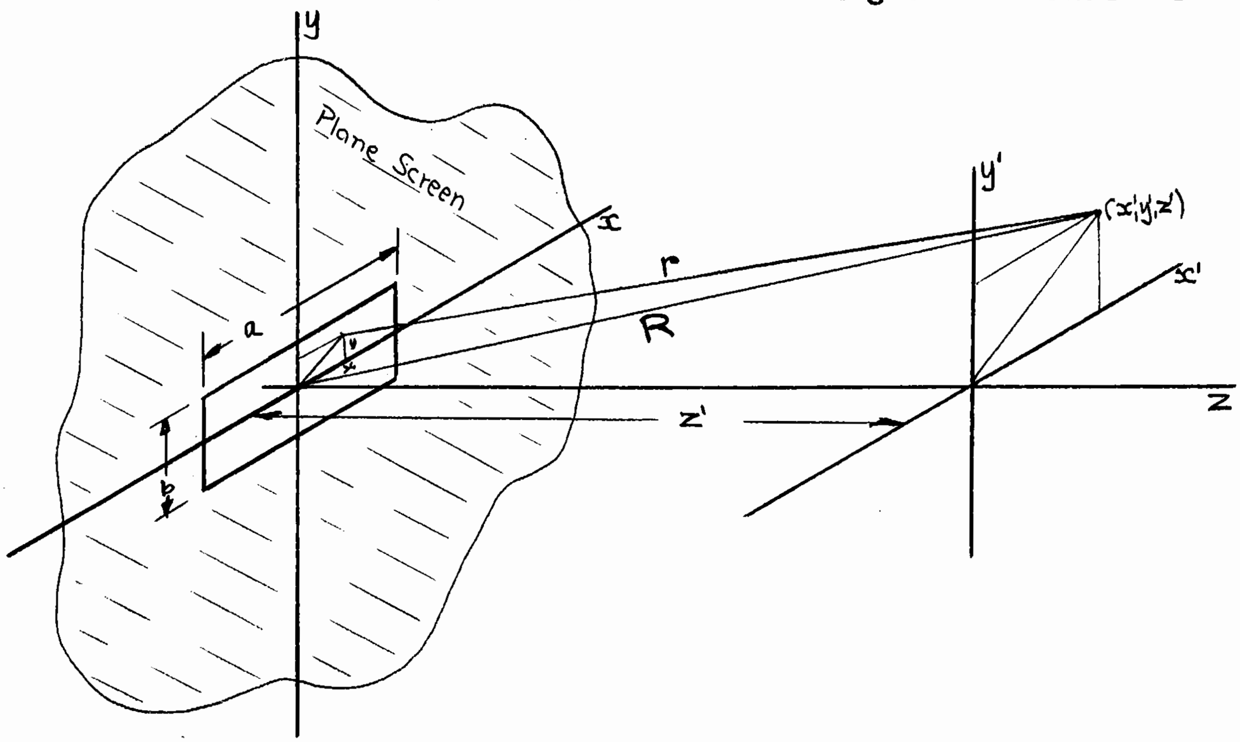


Fig. 6. 8 Geometry of Radiating Rectangular Guide

guide mouth and the z-axis corresponds to the guide axis. The co-ordinates of the point at which the field is to be evaluated are x',y',z'. The x-axis is parallel to the H-vector and y-axis to the E-vector.

It is assumed that although the problem is an electromagnetic one, nevertheless scalar diffraction theory is applicable and that the scalar Kirchhoff theory solution can be used.

If it is assumed that the field in the aperture is the same as if the guide were continued indefinitely (Shelkunoff[46]), then it can be represented by

$$\mathcal{E}\,(x,y) = P \cos \frac{\pi x}{a} \qquad 6.1$$

Where a is the wide dimension of the guide and P is an arbitrary amplitude.

Furthermore the field point is assumed to be in the Fraunhofer region and therefore the distance from a contributing point (x,y,0) in the aperture to the field point (x' y' z') may be expressed as

$$r \cong R \quad - \frac{xx'}{R} \quad - \frac{yy'}{R} \qquad 6.2$$

The field at (x',y',z') assuming distance z' constant, is then

$$\mathcal{E}\,(x'\ y') = \frac{P}{4\pi} \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} \frac{\cos \frac{\pi x}{a}}{r} \; e^{-jkr}\, dxdy \qquad 6.3$$

Now $\frac{1}{r} \cong \frac{1}{R}$, since $R \gg a/2$ and $R \gg b/2$

With this approximation and substituting 6.2 for r, then 6.3 may be integrated to yield

$$E\,(x'\,,\,y') = \frac{Pab}{4} \cdot \frac{e^{-jkR}}{R} \cdot \frac{\cos \frac{kax'}{2R}}{\frac{\pi^2}{4} - \left(\frac{kax'}{2R}\right)^2} \cdot \frac{\sin \frac{kby'}{2R}}{\frac{kby'}{2R}} \qquad 6.4$$

The time dependence e^{-jwt} is implied throughout. The four terms on the right hand side of 6.4 show that E(x' y') has the properties of an inhomogeneous spherical wave. The first term is a constant, the second represents a pure spherical wave and the third and fourth are amplitude modifying terms dependent on the co-ordinates x' and y'.

The amplitude and phase of this field were computed along the x' axis which corresponds in the physical case to a scanning line perpendicular to the guide axis and contained in the H-Plane. The computation involved the numerical evaluation of the second and third terms of 6.4 at a chosen distance z' and for a number of values of x'. The distance z' was chosen to correspond to 15 λ at the frequency of operation (9,323 mc/s). The range of values of x' was from 0 to x' = 12 λ, the intervals of x' being chosen to give equal phase increments along the scanning line. The first and fourth terms of 6.4 were disregarded since the first is a constant and the fourth reduces to unity for y' = 0.

The calculated phase and the relative amplitude in a decibel scale are shown plotted in Fig. 6.9. superimposed on the recorded phase and intensity as measured experimentally by the plotter. These graphs show that the measured values agree very closely with the calculations, especially in the case of the phase. The agreement is particularly good within five wavelengths of the center line. The departure beyond this is attributable to the approximations interent in the theoretical calculation. The variation of phase and intensity, however, is very gradual and the capabilities of the plotter are not fully tested, except to show that a single scan of a field can be made at a rate of about 25 cm/min.

6.2-2 <u>The Field Due to two Rectangular Waveguides</u>

A convenient field which has regions of rapidly varying phase and intensity can be obtained by using an array of two rectangular waveguides separated by a fixed distance. Such an arrangement is physically convenient and an approximate calculation can be made with ease. Fig. 6.10 shows the physical arrangement and dimensions.

The calculation was based on the following assumptions:

a. That the field due to each guide taken separately would be the same as that computed for a single guide in sec. 9.2-1.

b. That the combined field can be computed by assuming the separate fields to be scalar, or that they have identical polarization at all points and

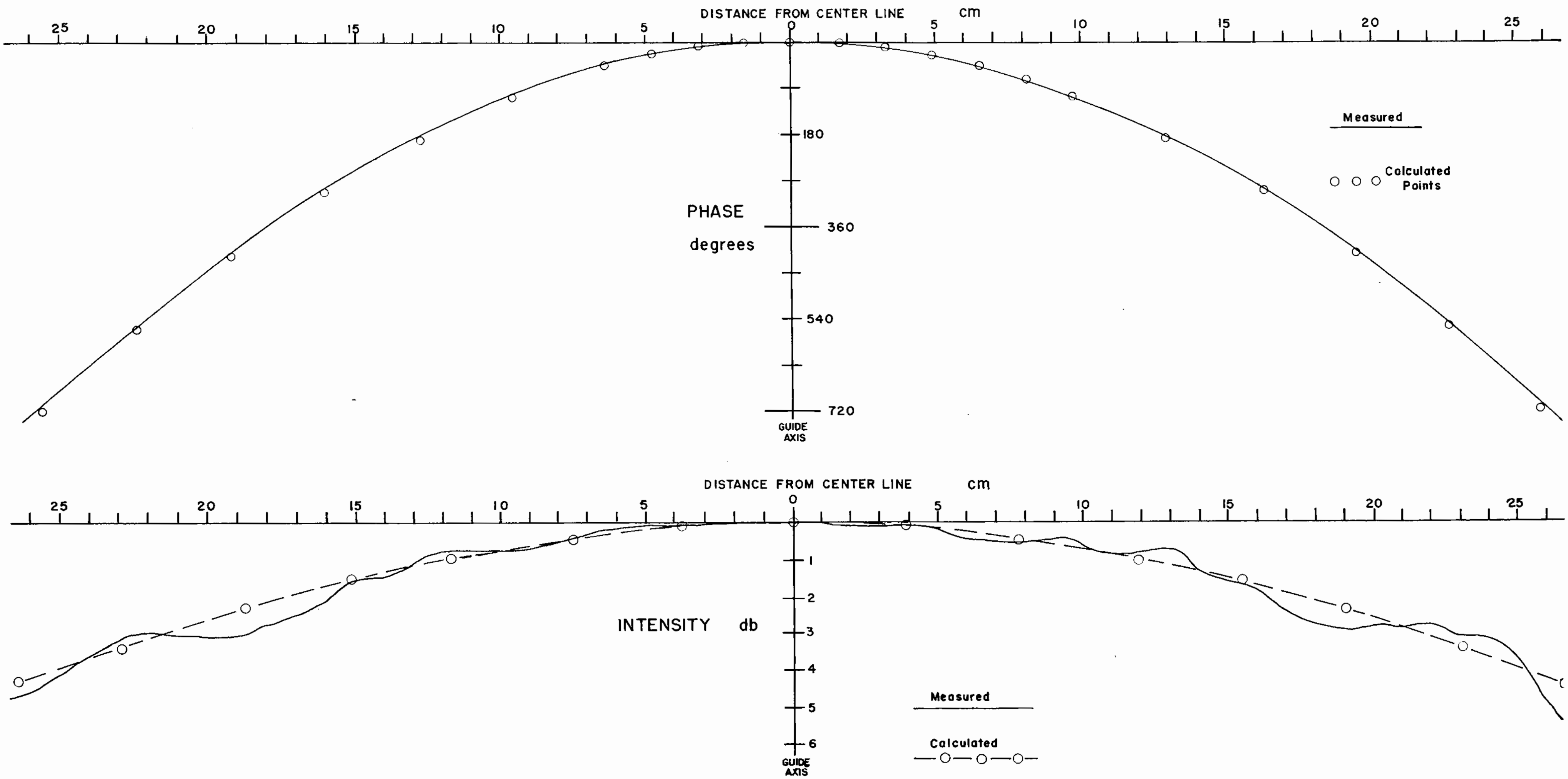


Fig. 6.9 Measured and Calculated Phase and Intensity of the Field of a Single Rectangular Waveguide along a Transverse Scan Perpendicular to the Guide Axis and Contained in the H-Plane. Distance from Guide 15 λ, Frequency 9,323 mc/s. The Center Line is along the Guide Axis

that the combined field can be obtained by the addition of the real and imaginary components of the separate fields.

c. That the two guides are excited in phase and with equal amplitude.

The real and imaginary components of a single guide pattern were calculated from the results of the preceding section. The real and imaginary components from each guide were graphically plotted, the patterns being spacially displaced by a distance corresponding to s, the spacing

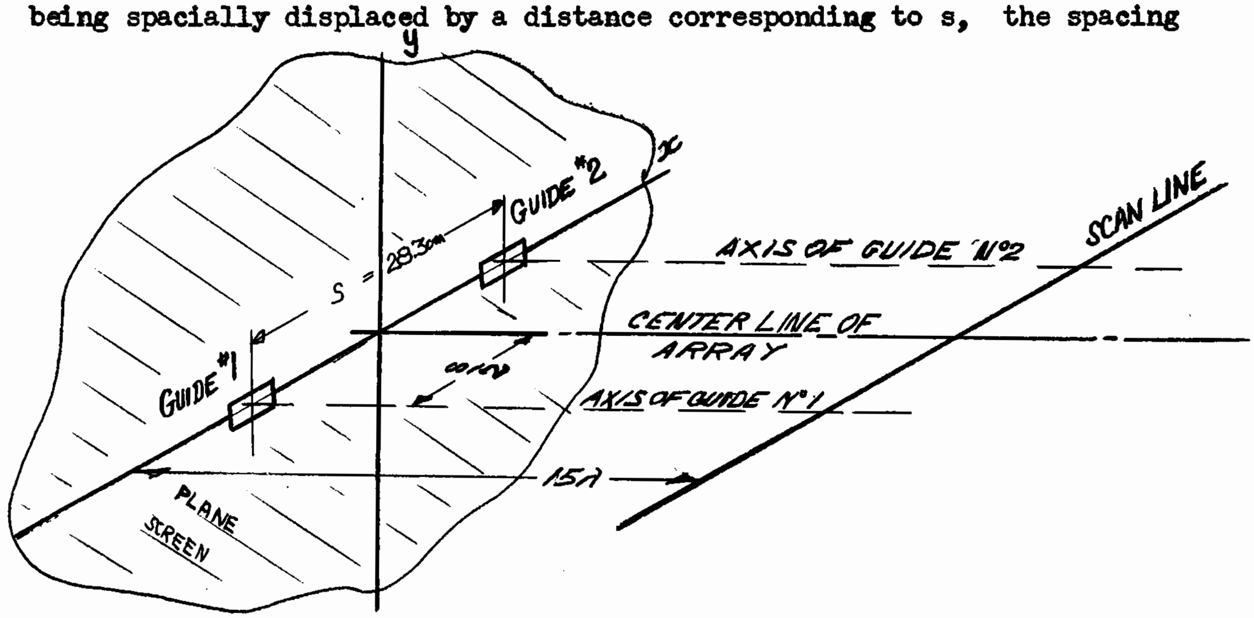


Fig. 6. 10 Physical Arrangement of Two-Guide Array

between the two guides. This is shown in Fig. 6.11 a and b. The real and imaginary components were then graphically added, giving the real and imaginary components of the combined field shown in Fig. 6.11c. The resultant real and imaginary components yield the amplitude and phase of the combined field.

This graphical procedure is more expeditious than a numerical process, since significant regions are immediately evident whereas they might be lost in a numerical computation involving a finite set of chosen points.

The plots of the calculated phase and intensity are shown in Fig. 6.12 superimposed on the experimental results obtained by the plotter. The agreement is particularly good in the region between the axes of the two

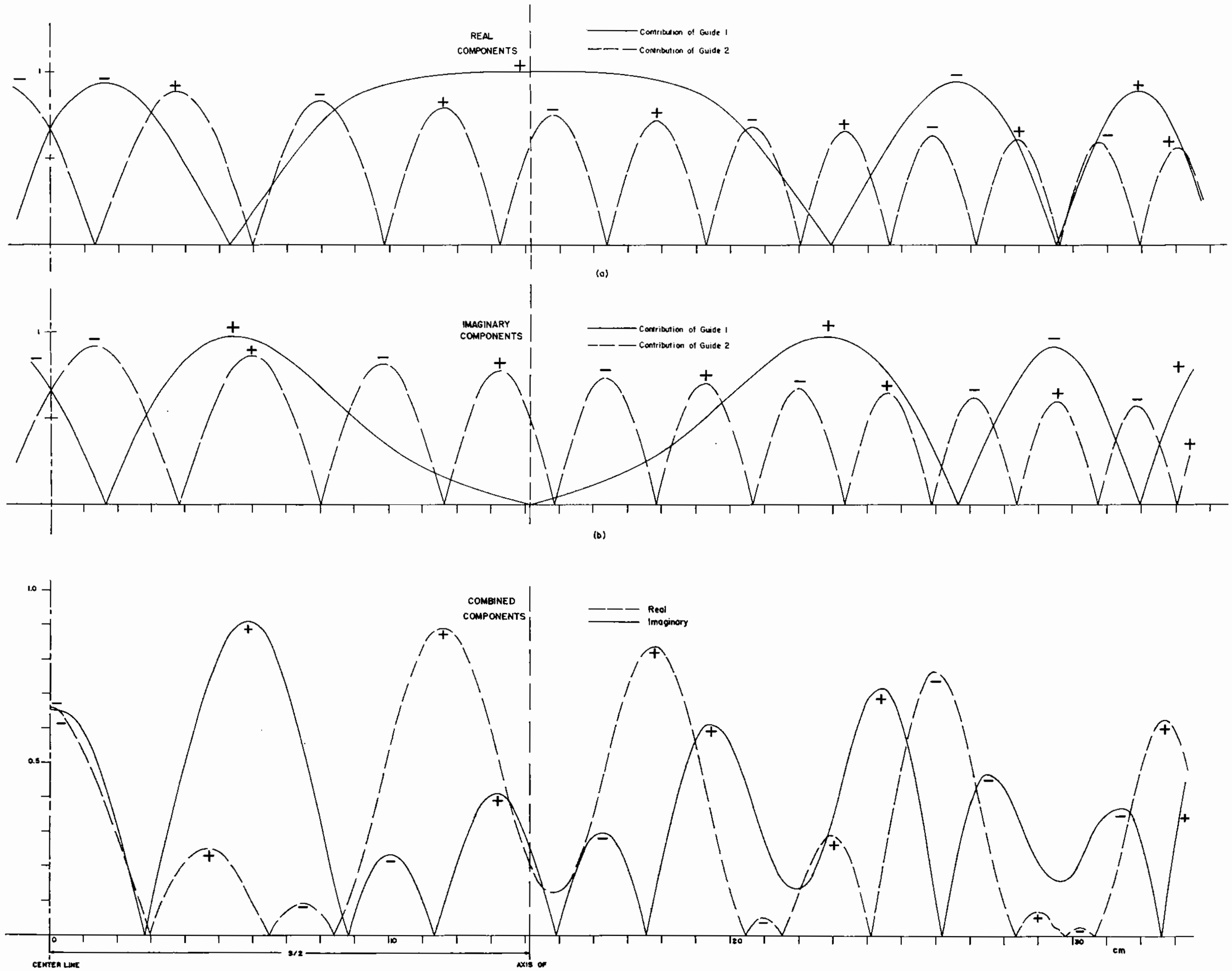


Fig. 6.11 Graphical Computation of the Field Radiated by a Two-Guide Array with Equal In-phase Excitation and Spacing S

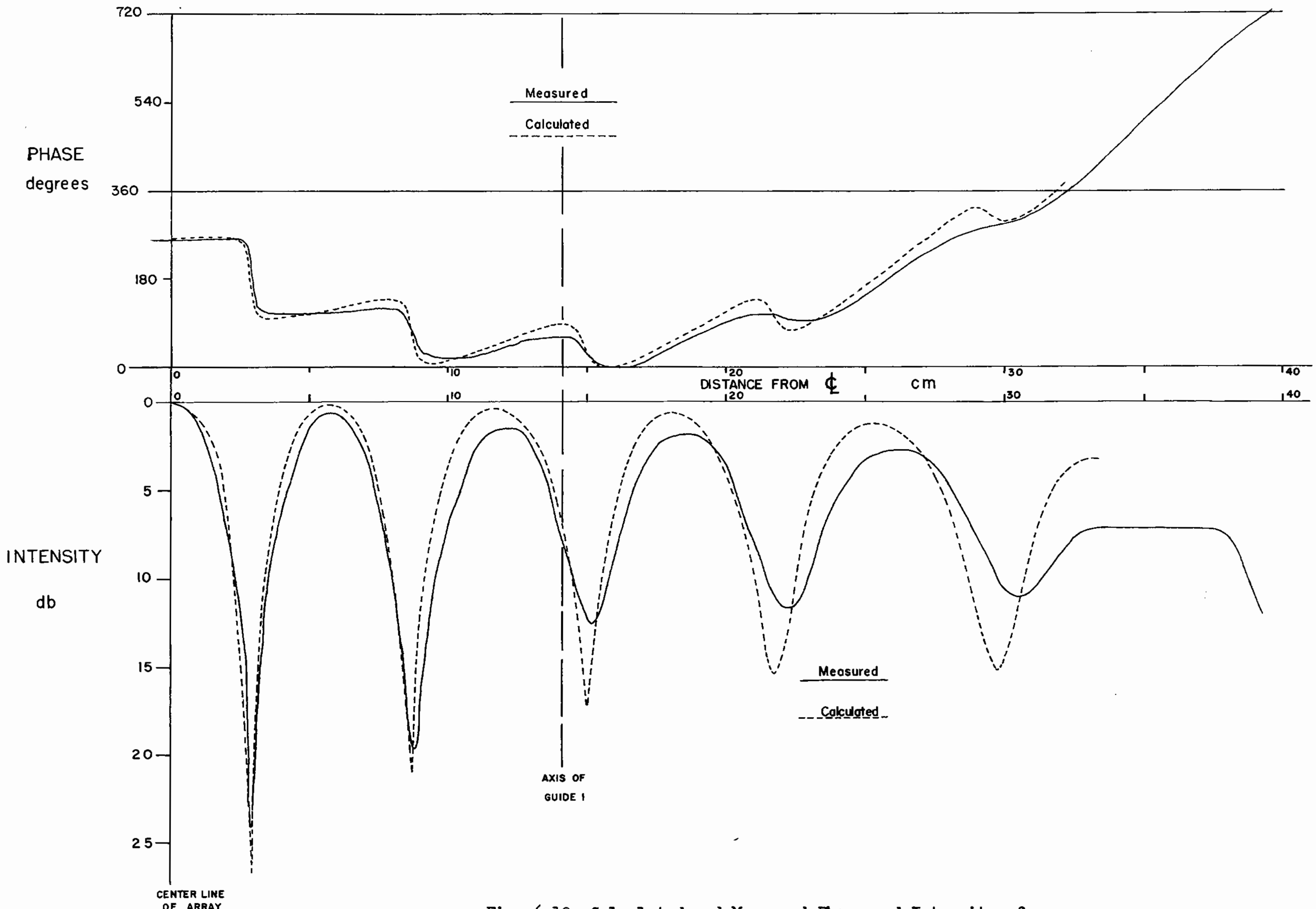


Fig. 6.12 Calculated and Measured Phase and Intensity of a Two-Guide Array along a Scan 15 λ from Center of Array

guides. Within this region the separate fields due to both guides are fairly accurately known as pointed out in the previous section. These graphs are a demonstration of the plotter's ability to measure rapidly varying phase in region of large intensity variations. The departure of the calculations from the measurements can be attributed at least in part to

(a) The assumptions made in the simplified calculations, and

(b) The departure of the experimental conditions from the assumed conditions.

In order to investigate the second possibility, a measurement of the field was made along a scan only 1 1/3 wavelengths from the array. Reproductions of the actual records obtained are shown in Fig 6.13 a and b. These records show that the two sources differ in phase by approximately 18 degrees whereas the calculations assume them to be exactly in phase. In addition, these records are a striking proof of the plotter's performance since the measurement of the phase in the region between the two guides was made at intensities which were so small as to be immeasurable by the intensity recorder, as shown in Fig.13 b.

A sample of an actual phase record is included in Fig.13 c and of an intensity record in Fig.13 d. These records were made during a set of measurements and were produced by repeating a scan several times to provide a number of identical copies.

6.2-3 Complete Area Plots

The ultimate purpose of the plotter is to produce information for mapping the phase and intensity of a field throughout a chosen cross-sectional area or several such areas in order to obtain a graphical representation of the field.

When a field is measured throughout a plane area, the intensity and phase may each be represented by a three dimensional surface. In such a

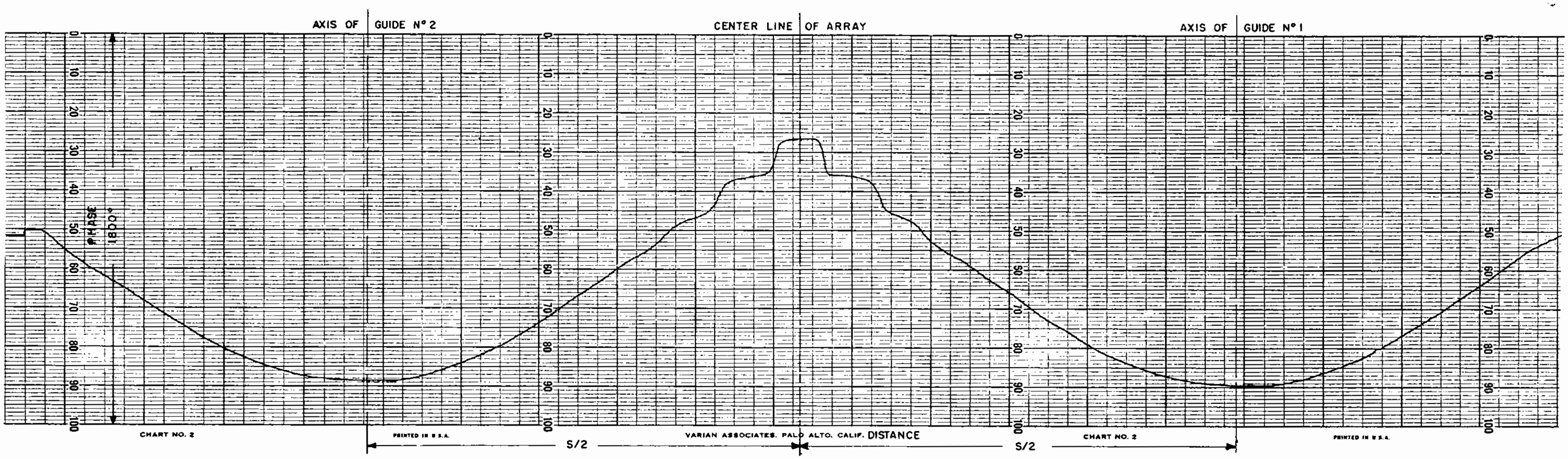


Fig. 6.13 a Record of Phase Measurement of a Two-Guide Array along a Scan at a Distance of 1.3 λ .

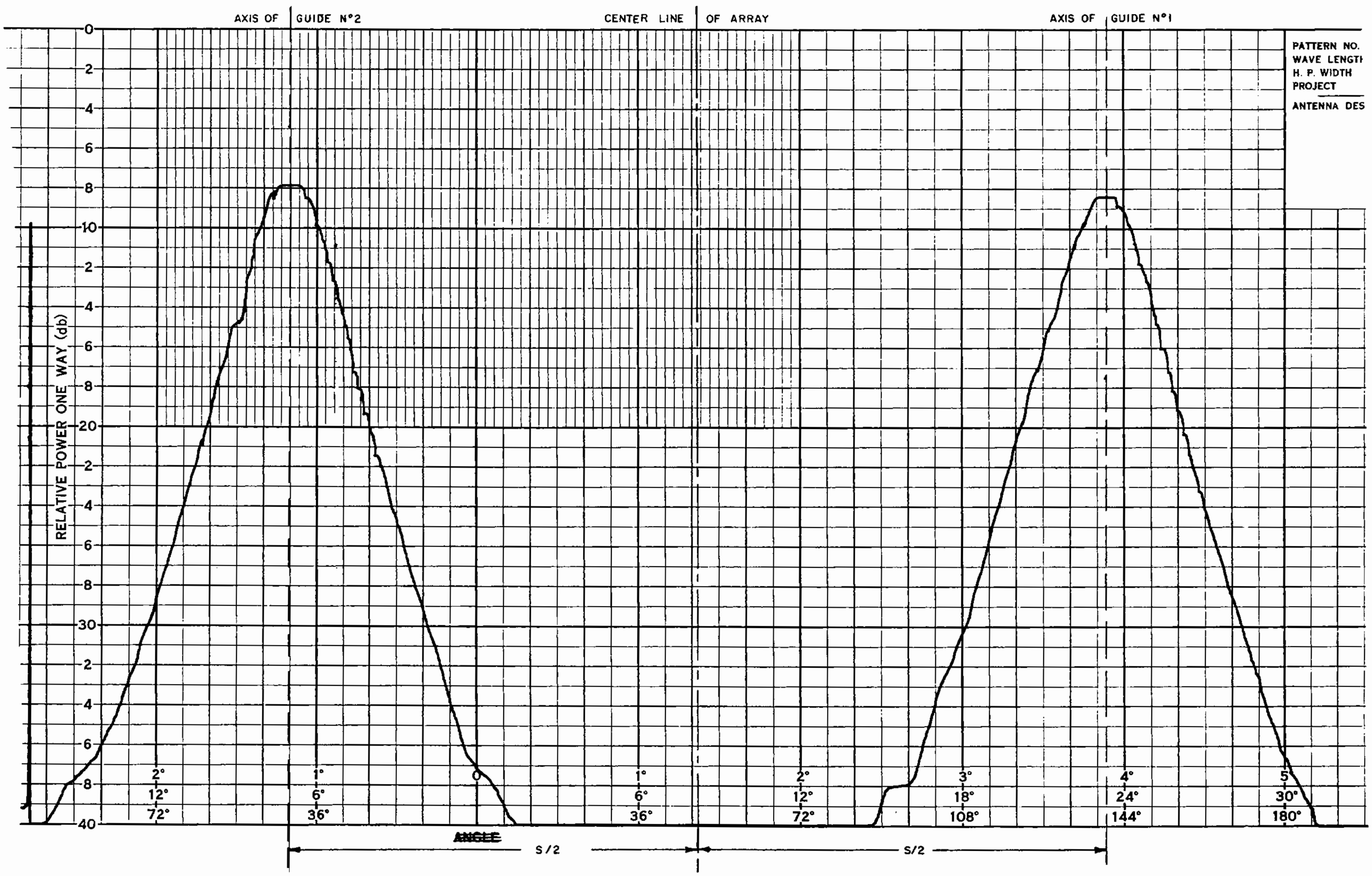


Fig. 6.13 b Record of Intensity Measurement of a Two-Guide Array along a Scan at a Distance of 1.3 λ

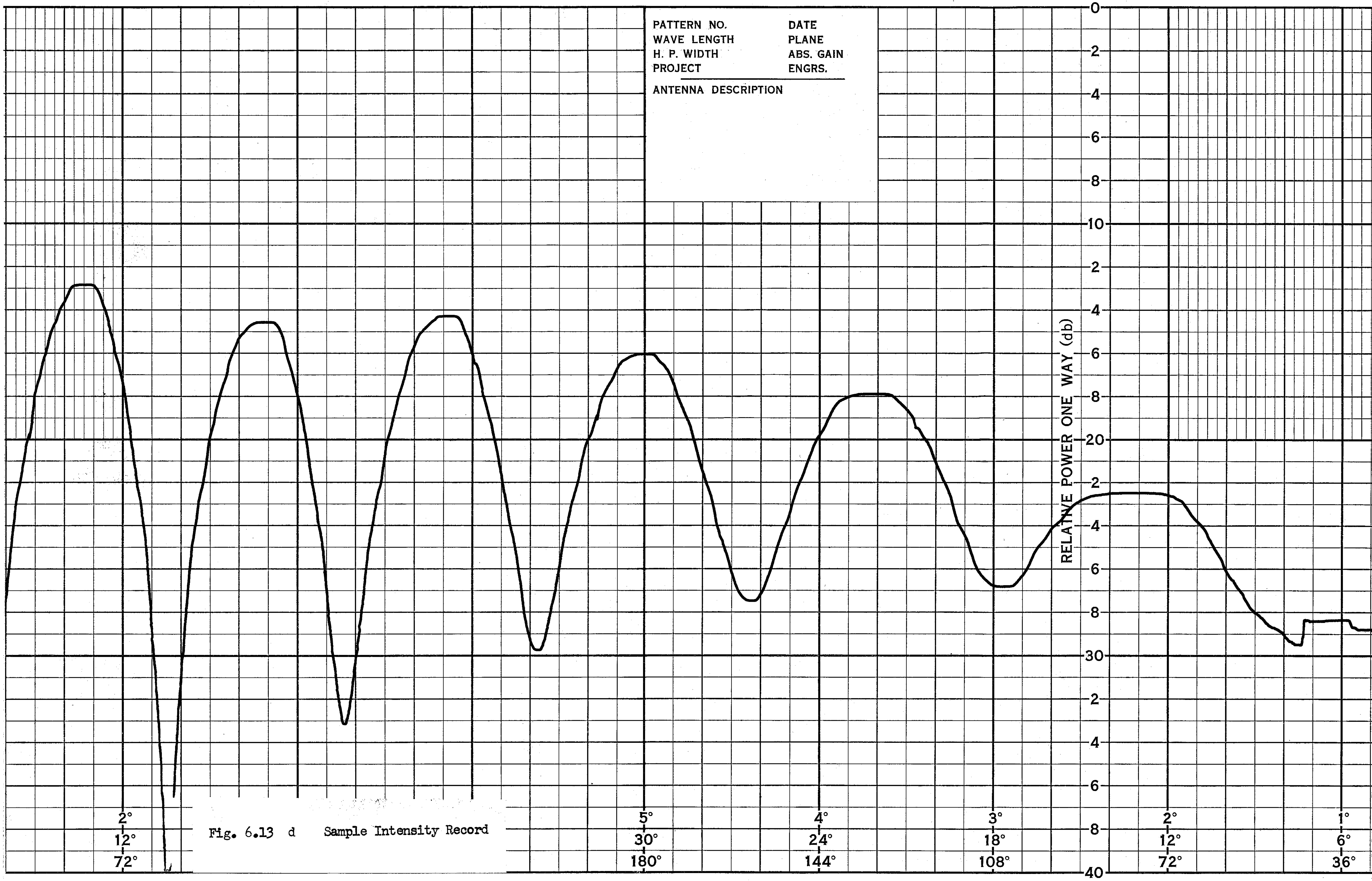


Fig. 6.13 d Sample Intensity Record

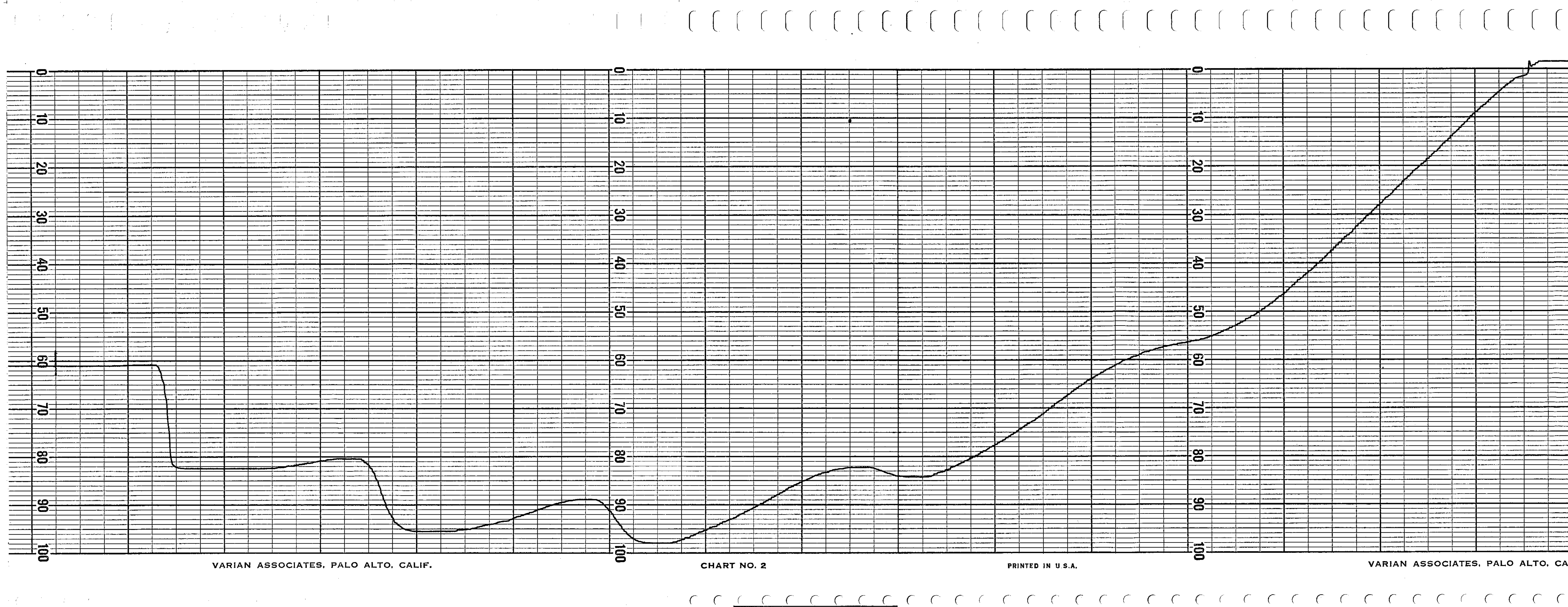


Fig. 6.13 c Sample Phase Record

Phase Scale 1" = 144^0
Distance Scale 1 : 1

surface, as indicated in Fig. 6.14 for a phase surface, the x',z' co-ordinates

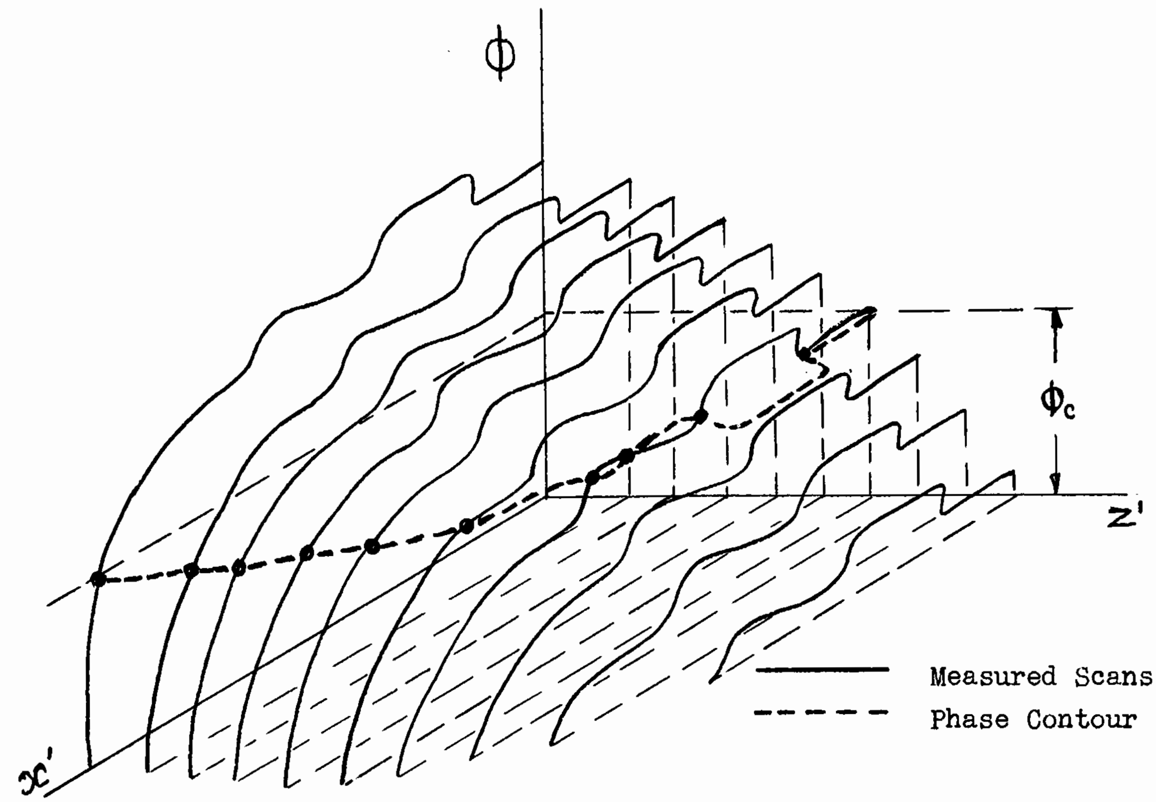


Fig. 6. 14 Phase Surface

specify the position of a point in the chosen plane area and the vertical or elevation co-ordinate represents the phase. The recorded scans produced by the plotter are in effect vertical sections of this surface, by planes parallel to the x-Ø plane. If a larger number of such scans is made then the entire surface can be determined. However, this is not the most useful way of showing the surface and a constant phase contour map is more informative. This corresponds to sectioning the phase surface by planes parallel to the z-x plane and projecting the outline of these sections on that plane. This is achieved by replotting the measured scans by the hodograph technique. In order to demonstrate the results which can be obtained, the field of the two-guide array was measured by 30 scans lying in the H-Plane and containing the center-line of the array. The scans covered an area approximately twelve wavelengths square, centered at a distance of fifteen wavelengths from the array center along the center-line.

The constant phase contour map is shown in Fig. 6.15 and the map of constant intensity contours is shown in Fig. 6.16. Only half of the total map is shown on the assumption that the field is symmetrical about the array center line.

Several features of interest can be noted about these maps:

(i) The phase map shows that the phase fronts are essentially circular (spherical wave) and are centered on the center of the guide (on the other half of the map they would be centered on the second guide).

(ii) The ripples caused by the interfering second guide progress uniformly over the phase fronts as the distance from the source increases. This progression lies almost exactly along radials centered on the center of the array.

(iii) The intensity map is suggestive of the lobes of the intensity pattern which would be obtained in the far field of the array. The pattern of the intensity map is also centered on the array center.

(iv) The regions of intensity minima evidently correspond to the regions of rapid phase change (phase ripples) in the phase map. This is shown in the combined map appearing in the frontispiece.

The complete set of scans required to produce these maps was produced in one working day in about nine hours. It is estimated that if manual measurements were feasible, the time required would be approximately six weeks.

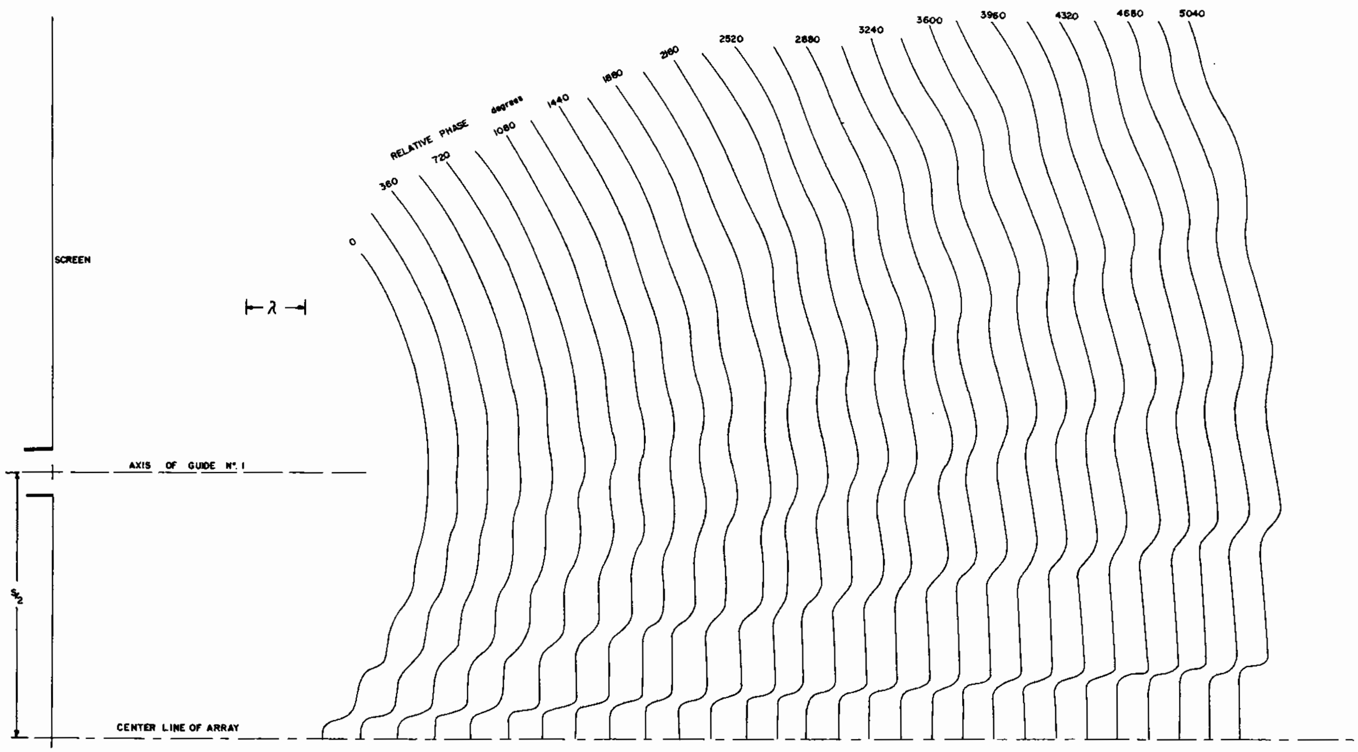


Fig. 6.15 Map of Constant Phase Contours of the Field of a Two-Guide Array (Only one half of complete map is shown)

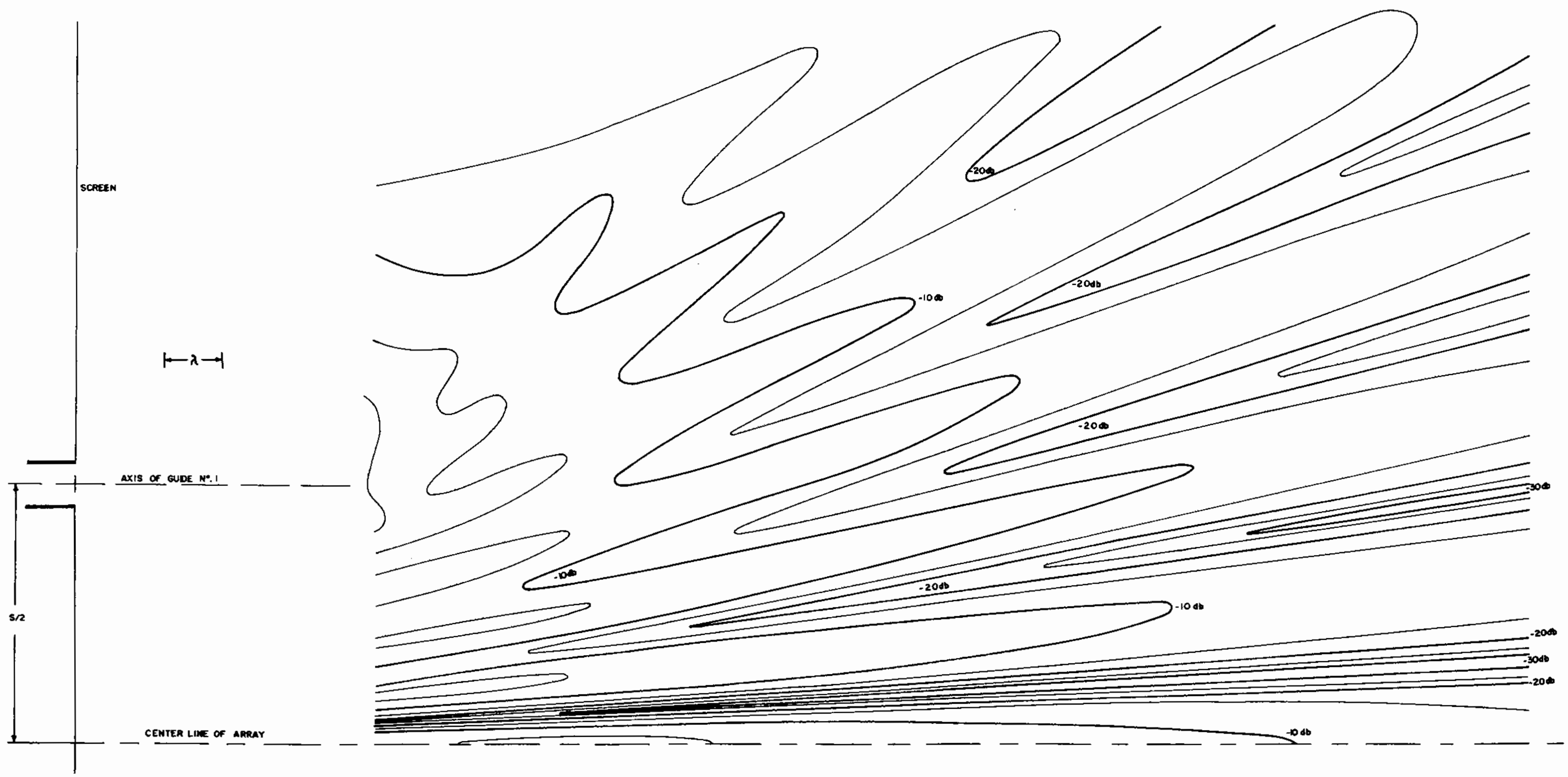


Fig. 6.16 Map of Constant Intensity Contours of the Field of a Two-Guide Array (Only one half of complete map is shown)

The final proof of the system lies in its use for actual experimental investigations. The plotter has been used in such work by Farnell[35] for the study of phase distribution in the focal region of a microwave lens. This included measurements and calculations along the axis of a lens as well as complete area scans. The experimentally produced field maps agree closely with those predicted by theoretical calculations. The effectiveness of the phase plotter is thus conclusively demonstrated.

CHAPTER VII

Conclusions

The purpose of this investigation has been to study the methods of, and to devise an automatic device for, measuring and recording phase of microwave fields. Such an apparatus has been successfully constructed based on the Homodyne principle. The application of this principle was made possible by the development of a novel modulator circuit utilizing ferrite components.

Tests and operational use have demonstrated the accuracy, reliability and usefulness of the system. The significant features of the device are: a. the elimination of the magnitude problem and, b. the increase in the rate of accurate measurement as compared with manual procedures. The magnitude problem has been eliminated to the extent that variations in intensity over a range of 40 db of the measured signal can be tolerated. The increase in measuring rate is by two orders of magnitude since a scan requiring a day manually, is produced in approximately five minutes. The rate advantage is particularly useful for area scans.

Conclusions and recommendations arising from the project can be divided into two parts. The first part contains observations serving as guides to the limited objective of possible improvements to the present system. The second suggests the possibility of more ambitious apparatus combining the functions of the present type of device with a data processing system to facilitate interpretation of the recorded data. These suggestions are written with the awareness that an effective, useful system has been built, proven and used but that as is the case in any machine, "if it works, it is obsolete". The primary intention is therefore to point the way for future developments in this type of measurement.

7.1. Limited Improvements

a. The development of the plotter emphasized measurement of phase, while reliance was placed on commercially built equipment for measuring and recording intensity. It is apparent from operational experience that a more sensitive intensity recorder is needed to match the phase plotter's ability to measure low level signals. The availability of a reference signal suggests that a form of synchronous detection might be developed to achieve this purpose.

b. If an improvement in the measuring rate is found to be desirable, the present chart recorder will have to be replaced by one having considerably higher response speed. Since the present form of recording also limits the range of measurement, a different recording method might prove useful. The present method is in analogue form and the possibilities of a digital one should be investigated.

c. The servo driven phase-shifter will require improvement or a different phase shifter will need to be developed if any significant increase in response speed is to be obtained. A ferrite phase-shifter with a transverse rotating field offers another worthwhile problem for research.

d. The scanning mechanism presently used is motor driven along one co-ordinate only. A complete mechanical redesign is indicated in order to obtain true x-y scanning and provisions should be made for three dimensional scanning.

7.2. Advanced Systems

The implementation of the above changes depends on the demands of future measurements. It is evident however, that any further increase in the rate at which measurements can be made will not be a major contribution to the whole problem of experimental procedure. Measured results can already be produced much faster than they can be processed and analysed. It is apparent that there is need for a system which would replace the present manual graphical processing of recorded data as in the case of plotting contour maps from transverse scan records. The present plotter produces in one day data requiring many days of analysis and replotting.

a. If the final form in which the data is wanted is known à priori, then the plotter could conceivably be altered to suit. An example of this is the need for contour maps. It is possible to rearrange the scanning mechanism so that the probe would follow either constant phase or constant intensity contours. In this case, however, two complete sets of measurements would be required in any one problem. This type of solution to the data handling problem would furthermore provide only a more specialized device having a restricted application.

b. A more general and flexible scheme is suggested. The data obtained by a field measuring system consists of five quantities. These quantities are the intensity, the phase and the three space co-ordinates locating the point of measurement. The proposed device would record these quantities in digital form for every measured point. The number and spacing of points could be arbitrarily chosen and varied at will. The records could be in one of the known forms such as magnetic tape or punched cards. The recorded data would then be introduced into a digital computer to carry out the processes of re-arrangement, interpolation and curve smoothing which are currently performed manually.

The essential problems to be resolved in order to achieve such a system would be:

i. A further increase in the rate of measurement

ii. Design of three-dimensional scanning and position measurement

iii. Digital recording

iv. Choice of final form in which recorded data is required (i.e. contour maps, three dimensional surfaces, etc.)

v. Programming of computer to perform data processing.

In conclusion it is noted that the principal function of the plotter which has been built, or of other more sophisticated systems which may yet be devised, is to provide graphical representation of certain physical aspects of electromagnetic fields. Inasmuch as such a visualization is an aid in furthering the understanding of these fields, then the work done in this research has been a useful contribution.

Bibliography

1. Ajioka, J.S. — "A Microwave Phase Contour Plotter" Proc. Inst. Radio Engrs. N.Y. 43 (1955), 1088.

2. Astrahanan, M.M., Beam, R.E., Mathis, H.F. — "Open-Ended Waveguide Radiators" Proc. Nat. Electronics Conf. 4 (1948), 472-486.

3. Cutler, C.C., King, A.P., Kock, W.E. — "Microwave Antenna Measurements" Proc. Inst. Radio Engrs. N.Y. 35 (1947), 1462-1471.

4. Lengyel, B.A. — "A Michelson Type Interferometer for Microwave Measurements" Proc. Inst. Radio Engrs. N.Y. 37 (1949), 1242.

5. Worthington, H.R. — "R-f Phase Measurements Technique of Microwave Measurements" M.I.T. Rad. Lab. Series 11, 915, McGraw Hill N.Y. (1947)

6. Boehnker, C.H., Hines, J.N. — "Measurement of the Phase of Radiation from Antennas" Proc. Nat. Electronics Conf. 4 (1948), 487-495.

7. Gordon, W.E., Hamlin, E.W., LaGrone, A.H. — "X-Band Phase Front Measurements in Arizona During April 1946". Electrical Engineering Research Laboratory Report No. 6 University of Texas. (1947).

8. Brooks, F.E. — "A Receiver for Measuring Angle-of-Arrival in a Complex Wave". Proc. Inst. Radio Engrs. N.Y. 39 (1951), 407.

9. Barnes, M.H., Barrett, R.M. — "Automatic Antenna Wave-Front Plotter" Electronics. 25 (1952), 120-125.

10. Worthington, H.R. — "Measurement of Phase in Microwave Antenna Fields by Phase Modulation Method" Radiation Laboratory Report 966, (1946). Technique of Microwave Measurements, M.I.T. Rad. Lab. Series" 11 919. McGraw Hill N.Y. (1947).

11. Burrell, C.M. — "An Automatic Phase Recorder" Proceedings of a Conference on Centimetric Aerials for Marine Navigational Radar. Ministry of Transport, London, U.K. (1950), 127.

12. Lavrench, W. "Measurement of Phase at Microwave Frequencies". Paper Presented to N.R.C. Science Association Meeting, Ottawa, (1955).

13. Fox, A.G. "An Adjustable Wave-Guide Phase Changer" Proc. Inst. Radio Engrs. N.Y. 35 (1947), 1489.

14. Mariner, P.F. "An Aerial Phase Plotter". Instruction and Maintenance Manual, Elliot Bros. Ltd., London, U.K. (1953).

15. Bacon, J. "An X-Band Phase Plotter". Proc. Nat. Electronics Conf. 10 (1954), 256.

16. Robertson, S.D. "A Method of Measuring Phase at Microwave Frequencies". Bell Syst. Tech. J. 28 (1949), 99 - 103.

17. Ornstein, W. "Phase Measurement in Microwave Fields" M.Sc. Thesis, McGill University, (1949).

18. Vernon, F.L. Jr. "Applications of the Microwave Homodyne" I.R.E. PGAP AP-4 (1952), 110-116.

19. Hogan, C.L. "The Ferromagnetic Faraday Effect at Microwave Frequencies and its Application - The Microwave Gyrator". Bell Syst. Tech. J. 31 (1952), 1.

20. Rowen, J.H. "Ferrites in Microwave Applications". Bell Syst. Tech. J. 32 (1953), 1333-1367.

21. Albers-Schoenberg, E. "Ferrites for Microwave Circuits and Digital Computers". J. App. Phys. 25 (1954), 152-4.

22. Barry, J.W., Clarke, W.W.H. "Microwave Modulator Uses Ferrite Gyrator" Electronics 28 (1955), 139.

23. Chait, H.N., Sakiotis, N.G. "Ferrites at Microwaves", Proc. Inst. Radio Engrs. N.Y. 41 (1953), 87.

24. Chait, H.N., Sakiotis, N.G., Simmons, C.G. "Microwave Antenna Ferrite Applications" Electronics 25 (1952), 156.

25. Miller T. "Magnetically Controlled Waveguide Attenuations" J. App. Phys. 20 (1949), 878.

26. Suhl, H., Walker, L.R. "Faraday Rotation of Guided Wave" Phys. Rev. 86 (1952), 122.

27. Niemann, G.L., Ragan, F.L. "Microwave Transmission Circuits" M.I.T. Rad. Lab. Series 9 478, 513-514. McGraw Hill N.Y. (1947).

28. Halford, G.J. — "A Wide-Band Waveguide Phase Shifter". J. Inst. Elect. Engrs. 100 III (1954), 117.

29. Brady, J.J., Pearson, M.D., Peoples, S. — "Squeeze Section Phase-Shifter for Microwave Measurements". Rev. Sci. Instr. 23 (1952), 601.

30. Barnett, E.F. — "A New Precision Waveguide Phase Shifter" Hewlett-Packard Journal 6 No. 5 (1955).

31. Levine, D.J., Sichak, W. — "Microwave High Speed Continuous Phase Shifter". Proc. Inst. Radio Engrs. N.Y. 43 (1956), 1661.

32. Cacheris, J. — "Microwave Single-Sideband Modulator Using Ferrites". Proc. Inst. Radio Engrs. N.Y. 42 (1954), 1242.

33. Sakiotis, N.G. — "Ferrites at Microwaves". Proc. Inst. Radio Engrs. N.Y. 41 (1953), 87.

34. Bekefi, G. — "Studies in Microwave Optics" Chapter IV. Final Report to the Air Force Cambridge Research Center on Contract AF 19(122)-81 AFCRC-TR-56-179 ASTIA Doc. No. AD.110152.

35. Farnell, G.W. — Phase Distribution in the Focal Region of a Microwave Lens System. Ph.D. Thesis McGill University, (1957).

36. Borts, R.B., Carruthers, J.H. Woonton, G.A. — "Indoor Measurements of Microwave Antenna Radiation Patterns by Means of Metal Lens". J. App. Phys. 21 (1950), 428-430.

37. Hamer, E.G., Foot, J.B.L. — "An Automatic Recorder of Aerial Radiation Diagrams". J. Brit. Instn. Radio Engrs. 14 (1954), 33-42.

38. Carruthers, J.H. — "A 60 db Nonlinear Amplifier" Canad. J. Res. A. 28 (1950), 287-292.

39. Brown, G.S., and Campbell, D.P. — "Principles of Servomechanisms" (Chapter 10), Wiley (1948), New York.

40. Farnell, G.W. — "Calculated Intensity and Phase Distribution in the Image Space of A Microwave Lens". Canad. J. Phys. 35 (1957), 777.

41. Barrow & Green. — "Rectangular Hollow Pipe Radiators" Proc. Inst. Radio Engrs. N.Y. 26 (1938), 1498.

42. Chu, L.J. "Calculation of the Radiation Properties of Hollow Pipes and Horns". J. App. Phys. 11 (1940), 603.

43. Shelkunoff, S.A. "Kirchhoff's Formula, Its Vector Analogue and Other Field Equivalence Theorems" Symposium on Theory of Electromagnetic Waves. Interscience Publishers, N.Y. (1951).

44. Horton, C.W. "Theory of Radiation Patterns of Electromagnetic Horns". Proc. Inst. Radio Engrs. N.Y. (1949), 744.

45. Silver, S. "Microwave Antenna Theory and Design", M.I.T. Rad. Lab. Series" 12, 341. McGraw-Hill N.Y. (1949).

46. Shelkunoff, S.A. "Electromagnetic Waves". Van Nostrand, New York, (1945), 359.

APPENDIX

Operating Instructions

Operating procedures for the various component parts of the phase plotter are generally self-evident and follow normal practice for electronic instruments. Some parts of the system, however, require special attention during initial adjustment and calibration in order to obtain satisfactory operation. These adjustments are not needed frequently but should be made at about half-yearly intervals. The components concerned are a. the balanced modulator, b. the variable gain amplifier a.g.c., c. the servo preamplifier phasing and d. the recorder range control and recorder calibration.

a. The Balanced Modulator As described in Secs. 3.1 and 3.2, the reliability of the phase measuring system depends on the degree to which the carrier component is suppressed in the output of the balanced modulator. Two adjustments are available in the modulator to achieve adequate carrier suppression. The first ensures that the signals in the two branches are delayed equally in phase. As shown in Fig. 3.3-a a trimmer phase shifter is provided in each arm of the modulator which may be adjusted to obtain this condition. The second adjustment ensures that the degree of modulation is equal in each branch of the modulator. This is important to the proper suppression of the carrier since the ferrite modulators are of the absorbtion type and modulation is thus achieved at the expense of the carrier level. In order to obtain complete carrier cancellation at E_2 of the A_2 hybrid (Fig. 3.3-a), the carrier components in the two branches must be of equal amplitude as well as in phase. This therefore implies equal percentage modulation in each branch. Adjustment of the modulating signal e_s at each modulator can be made by a simple potentiometer control. The tests which need to be carried out to determine the degree of carrier suppression are outlined in Sec. 3.2-2.

b. Variable Gain Amplifier A.G.C. The function of the variable gain amplifier as described in Secs. 3.1, 4.1 and 5.5-2, is to maintain the phase servo loop gain at an optimum value. Adjustment of the basic gain is made during operation to suit the mean intensity level of the measured signal. However, a feature is incorporated in the a.g.c. system to prevent complete cut-off of the variable gain amplifier (and thus of the servo-amplifier) in the presence of extremely high intensity signals. This consists of a diode limiter (viz Fig. 5.9) which prevents the a.g.c. signal from reaching excessive values. The limiter bias is provided by a pen-light type dry cell which requires periodic replacement. The semiconductor diode in the limiter also requires periodic testing to assure proper functioning.

c. Servo Preamplifier Phasing Correct operation of the phase servomotor requires that the reference winding excitation and the control winding excitation be in phase quadrature (viz Fig. 4.1). In addition, the rate damping and error signals must be combined in phase opposition for stable operation. The purpose of the servo preamplifiers described in Sec. 5.5-4 and Fig. 5.10 is to provide the necessary controls to achieve these conditions. The quadrature phasing of the control and reference signals is carried out by measuring the relative phase of the output of the two power amplifiers while the servomotor is running at full speed. Monitoring terminals are provided for this purpose at the output of the two power amplifiers. The phase measurement can be made with an oscilloscope or more conveniently with an Acton Laboratories Type 320 A/B Audio Phase Meter. The error and damping signal phasing can be measured similarly at monitoring jack plugs provided on the panel of Preamplifier No.1., while the phasing adjustment is carried out with the appropriate controls. The degree of damping may also be altered by adjusting the error and damping signal amplitudes independently.

d. <u>Range Control and Phase Recorder Calibration</u> The range control provides scale expansion and zero suppression for the phase recorder. This is achieved by a voltage divider circuit of which the Helipot used for reporting the microwave phase shifter position, forms an integral part. (viz Fig. 5.12) The zero level suppression is provided by means of a d.c. biasing source. The range control will operate satisfactorily if it is supplied from a regulated d.c. source with 200 volts. This voltage may be measured at terminals provided on the range control panel and adjusted to the required value. The d.c. bias for zero suppression is derived from dry-cells. A calibrating adjustment is provided to enable a step-wise zero shift corresponding to full-scale deflection on the recorder. This adjustment requires establishing a one volt potential at the input to the zero suppression circuit and voltmeter terminals are provided for this calibration. The phase recorder proper requires occasional calibration adjustment since its operation as a potentiometer type recorder depends on a reference cell. This calibration is achieved most readily by replacing the microwave phase shifter Helipot by an equivalent one which can be set independently of the phase measuring system. The recorder calibration can then be adjusted to give the correct pen deflection corresponding to the Helipot and range control setting.