CONSTRUCTION OF APPARATUS FOR MICROWAVE TESTING IN THE 3 CENTIMETER REGION

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CONSTRUCTION OF APPARATUS FOR MICROWAVE TESTING IN THE 3 CENTIMETER REGION

Approved

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CONSTRUCTION OF APPARATUS FOR MICROWAVE TESTING IN THE 3 CENTIMETER REGION

INTRODUCTION

The rapidity of development of electronic equipment has of necessity been limited by a parallel development of proper apparatus for testing its performance. An idea, born on paper, and nurtured in the laboratory to an apparently successful conclusion, may easily prove its insufficiency when subjected to the rigorous standards of the testing device.

Frequency standards, power measuring devices, and the like, have long been available for the low frequencies of commercial radio. But recent applications of microwaves have presented a completely new problem. The fields of television, radar, and v.h.f. communications have required that new techniques of testing be employed. The basic principles are often the same, but the components used differ radically in their physical construction. The specialized circuits and almost infinite variety of wave shapes employed have further added to the problem. These have demanded the utilization of an elaborate set of measuring and testing equipment. It is not uncommon, particularly in equipment designed for
some special purpose, to find that the testing equipment is considerably more bulky, and even more elaborate in its electronic circuits, than is the basic equipment itself.

The recent advances in the microwave region have in turn provided a new challenge to the designer of test equipment. Certain of the older and hence more familiar components used with long wavelengths have been completely unsatisfactory in the microwave region. For instance, the radiation loss of open transmission lines becomes excessive at the higher frequencies; in the 3 centimeter region the most satisfactory method of transmitting energy is by means of hollow waveguides. When these are terminated by a proper impedance, they form a closed electrical system that minimizes radiation except at a desired point. Waveguides and their fittings are, in turn, far more critical to imperfections than the simple lines used at lower frequencies.

Again, the lumped circuit elements, familiar as the physical capacitor and inductance, have been replaced by the distributed reactances of resonant cavities. Certain definite advantages exist in the latter; resonant cavities with a Q of 10,000 or more are not uncommon. Furthermore, the almost completely enclosed nature of the electric and magnetic fields within cavities precludes extensive loss due to radiation and at the same time permits rugged construction.

On the other hand, very great differences of the
electric field at physically close points within the waveguide and cavity indicate that mechanical tolerances must be reduced to a minimum. Small errors in size or positioning lead to such mismatches between components that the efficiency of energy transfer is drastically reduced.

The designer of microwave test apparatus has these basic facts at his disposal: that transfer of energy will entail the use of waveguides and their fittings, and that in all tuning functions resonant cavities will be employed. Further, he knows that careful selection of components must be made to insure a good match between parts of the energy transfer system.

Fortunately, the basic problems of testing have not been altered essentially by the inclusion of these physically different components. Most electric transfer systems may be treated as four terminal networks, or more specifically, as two terminal pairs. One pair may be considered as coupled to the generator, the source of power, and the other to the load or recipient of power; for convenience called the receiver. The characteristics of the network may be arrived at in a variety of ways, but the essential minimum information required consists of two impedances and one transmission characteristic. The impedances measured are most commonly "input" and "output" impedances, while transmission is a measure of the attenuation and phase shift between the input and output terminals. With these properties
measured and recorded the complete characteristics of the energy transfer system may be described.

This situation holds true in waveguides as well, although the techniques may be somewhat different. The standing-wave ratio in the transmission system depends upon the terminal impedance and is conveniently used as a measure of impedance. Since impedance is a function of frequency, it is necessary to measure the latter. This is accomplished by means of wavemeters, of which many commercial types exist. Attenuation, the measured loss between input and output, may be recorded through the use of calibrated attenuators.

The designer's problem, then, is to construct apparatus which will permit measurements of impedance, attenuation, and frequency in a rapid and accurate manner. This paper will deal with a number of techniques already developed. A study of these will in turn make clear the necessary properties of testing apparatus. The apparatus will be described in considerable detail as it, rather than the testing methods, is the primary aim of this project.

II

OBJECTIVES

The primary objective of this project was to construct apparatus which would deliver required exciting and modula-
ting voltages to the 3 centimeter oscillators. A second-
ary objective was to outline processes of microwave testing
and demonstration which would be valuable aids to microwave
studies.

In practice, the testing of microwave components and
the demonstration of their properties is a natural object-
tive. In this project, however, the techniques of such test-
ing and demonstration have served only as a guide to appara-
tus design. This paper will, then, attempt to outline these
applications in order to point out the necessary properties
of the apparatus constructed.

A more detailed description of the primary objec-
tive is, first, to analyze the voltage and current waves
required for the desired tests and demonstrations, and
secondly, to incorporate in the apparatus such circuits
and voltage supplies as will furnish these in a manner con-
venient for the operator. This implies both an inherent
flexibility of control and a natural self sufficiency in
testing. To otherwise state this condition; the opera-
tor should first have available on the front panels all
the necessary controls for rapid procurement of any de-
sired voltage for modulation; he should further have in
the apparatus itself all necessary components to carry
out the testing procedures.

It follows, as a natural conclusion of the objec-
tives, that a major section of the paper is devoted to
Operating and Maintenance Instructions for the apparatus constructed. This section, Appendix I, explains the achievement of the objectives, as it describes in detail the design of the various circuits and the voltages and modulations possible.

III

COMPONENTS ESSENTIAL TO TESTING IN THE MICROWAVE FIELD

A number of elaborate systems of testing microwave units have been developed. However, in all cases certain components form the nucleus of the apparatus; to these may be added certain specialized units. Among the latter might be classified such apparatus as Panoramic Adaptors and Video Amplifiers.

The testing procedures outlined in this paper have been intended to operate with those basic components, which, as noted above, are either absolutely essential or extremely advantageous. These are listed in the following paragraphs, each with a brief description of its properties. This will suffice to show their application in testing processes; a more detailed explanation of their characteristics has been deferred to a later section.

(a). Source of Microwave Oscillations.

Two types of microwave oscillators are widely used. The first of these, the Magnetron, does not lend itself readily to laboratory work; it is expensive, works best
only at extremely high voltages, and is usually designed only for pulsed operation.

The Reflex Klystron is a convenient source of the desired frequencies. Although its efficiency is not high, it is easy to tune, and can be operated either on Continuous Wave or with pulsed operation. In addition it is an easy matter to produce and control frequency modulation of its output.

The 723A/B, reflex klystron, was selected for use in these tests. A newer and very similar tube, the 2K25, may be substituted for it. The principle of operation of such a tube is described in Section VIIIa.

(b). Crystal Detector.

The only satisfactory and readily available detector at microwave frequencies is a fixed silicon crystal, commercially identified as the 1N121, 1N221, or 1N23. The latter two are the most satisfactory in the 3 centimeter region, while the first named is commonly used for 10 centimeter equipment.

These crystals may be used either as signal mixers or as detectors. In the testing processes herein named they serve only as detectors and will hereafter be referred to merely as the Detector. The crystal is a convenient rectifier, providing a d-c output approximately proportional to the square of the amplitude of the radio frequency input.
(c): Attenuators.

A very important property of microwave components is the ability to transfer energy coupled into them with either a small loss or a specified loss. A calibrated attenuator may conveniently serve as a standard of reference for testing this important property. In addition, it is often necessary to decouple two resonant sections by a dissipative section; an attenuator may conveniently serve this purpose.

Commercial attenuators, of types described in Section VIIIId, were employed.

(d): Standing-Wave Detector.

A standing-wave detector consists, essentially, of a slotted section of waveguide into which a probe may be inserted and moved. Thus a "sampling" of the electric field at several points along the waveguide may be made. This is important information, as an analysis of the impedances of the coupled sections may be made through application of the data.

(e): Wavemeter

A calibrated wavemeter capable of indicating the oscillation frequency within narrow limits is necessary. Commercial wavemeters were used, as described in Section VIIIId.

(f): Pulse Generator.

For thorough comparison of components, it is nec-
essary to have available a pulse generator which will per-
mit a controlled pulsing of more than one oscillator, and,
further, which will provide various means of modulation of the oscillators:

By far the greatest portion of the work of design and construction has been devoted to the development of such a pulse generator. Its properties are discussed in Section VII; and its theory of operation is completely covered in the Operation and Maintenance Instructions; Appendix I.

IV

TESTING PROCESS AND EQUIPMENT

In order to present as clear a picture as possible of the problems involved; a number of test procedures will be briefly described. These are not new techniques; they are essentially a recapitulation of processes described in the literature\(^1,2\), or are processes described by the engineers who developed them. They will, as previously

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noted, serve as a guide to the type of apparatus needed and, hence, as an aid in carrying out the main objective.

The following list does not attempt to be complete; it outlines the procedures by which the principal necessary characteristics of components may be determined. It further shows the application of the basic components listed in Section III.

(a). The Measurements of Standing Waves and Impedance

As was previously noted, impedances in microwave transmission lines are a function of standing wave ratios. When a traveling wave of voltage and current on such a line meets a discontinuity (such as an imperfectly matched crystal), the resulting voltage and current distribution may be expressed as the sum of the original traveling wave and a reflected wave of voltage or current, which travels in the opposite direction. The magnitude and phase relationship of the reflected voltage, or current produced at the discontinuity, are determined by observing the standing-wave ratio in the line.

Both the current and voltage may be represented as the sum of two vector quantities which rotate in opposite directions as one moves in a given direction along the line. The total current and voltage have a maximum value when the two vector quantities are in phase and add, and a

---

minimum when the vectors are out of phase and subtract. The ratio of the maximum to the minimum values of voltage and current is called the voltage or current standing-wave ratio.

The reflection coefficient, a vector quantity, and symbolized by \( K \), is defined as:

\[
K = \frac{E_B}{E_A}
\]

where

\[
E_A = \text{voltage of initial wave}
\]
\[
E_B = \text{voltage of reflected wave}
\]

It may further be shown that the impedance at any point in the line is simply the ratio of total voltage to total current at the point, and is given by

\[
z = z_0 \left( \frac{1 + K}{1 - K} \right)
\]

where \( z_0 \) is the characteristic impedance of the line.

The ratio of this impedance to the characteristic impedance of the line is:

\[
z = \frac{z}{z_0}
\]

This impedance, normalized to the characteristic impedance of the line, is:

\[
z = \frac{1 + K}{1 - K}
\]

If \( M \) and \( N \) are two points on a transmission line
separated by the distance \( x \), with \( M \) nearer the generator, the reflection coefficient at \( N \) in terms of that at \( M \) is given by:

\[
K_N = K_M e^{j2\pi B x}
\]  

(5)

where \( B = (2\pi/\lambda) \) = phase constant of line.

Using this relationship together with (4), the normalized impedance at any point in the line may be calculated from the reflection coefficient determined at any arbitrary reference point by measuring the value of the standing-wave ratio and the position of the minimum with respect to the chosen reference point. Actually, such calculations are usually performed with the aid of a graphical calculator such as the Smith Chart.

Measurements of standing waves are made with slotted sections, also known as standing-wave detectors. Such a device is constructed by milling an accurate slot axially through the center of one of the wider walls of the waveguide. A probe is mounted on a moveable carriage permitting calibrated motion along the slot. Great care is taken that the carriage remains at a fixed distance at all times from the axis of the waveguide, to insure that the insertion of the probe does not vary as it is moved. A variation of probe insertion of as little as \( 0.001 \) inch can cause an

error of several percent in the measured value of the standing-wave ratio. In practice, the waveguide section to be used as a slotted section is milled from a solid block to insure the required accuracy.

An equipment arrangement to demonstrate standing-wave ratio measurements is shown in Figure 1. The standing-wave detector used here in the laboratory is a rough model, hence a demonstration of the principle rather than an accurate measurement is to be expected.

In the equipment, a wavemeter, integral with the oscillator assembly, is used to record the frequency of the oscillations supplied to the system. An attenuator is used to control the amount of energy actually reaching the standing-wave detector and the following test specimen. By the incorporation of resistive pads, attenuators, or tuning-stub sections, a demonstration can be made of the improvement of standing-wave ratio.

The probe insertion must be made very small or it, in itself, will set up such reflections of voltage and current waves as to make the readings difficult of interpretation. The energy picked up by the probe is very small if the probe insertion is reduced until it does not cause reflections. An amplifier is necessary to raise the rectified output to a point where the average meter or oscilloscope will show sufficient deflection to make readings possible. The oscillator is pulsed with an audio frequency square wave, and the energy picked up by the
Figure 1. Standing-Wave Ratio Measurement
probe is rectified, amplified, and coupled to a recording device, as shown.

It is also possible to measure reflection coefficient by means of a microwave bridge. Two such devices are known, respectively, as a Magic Tee and as a Directional Coupler. Only one method of impedance measurement is to be described in this section; a description of the properties and utilization of both the Magic Tee and Directional Coupler will be found in Section VIII.

(b) Calibration of an Attenuator:

The equipment arrangement for calibration of an attenuator is shown in Figure 2. The oscillator frequency is recorded. For the first step the uncalibrated attenuator is removed. The calibrated attenuator is then set at such a point that a known deflection of the meter exists. (Full scale if possible). The uncalibrated attenuator is then coupled as shown in Figure 1, and set to its point of minimum attenuation. If there is no decrease in meter deflection, this is a point of zero loss. If a decrease in deflection of the meter is noted, there is some loss even at the minimum point. This may most accurately be determined by removing the uncalibrated attenuator and by means of the calibrated attenuator recording the loss necessary to reduce the meter deflection by the noted amount.

If waveguide clamps are available the removal and re-insertion of these components can be accomplished very
Figure 2. Equipment Arrangement for Calibration of Attenuator
rapidly.

Once the minimum loss has been ascertained, the remainder of the calibration may be completed. An arbitrary point on the meter is selected as a reference point, and for various settings of the uncalibrated attenuator the calibrated one is readjusted until the meter reading is that of the arbitrary point. The sum of the attenuation of the two attenuators is then known; this sum minus the known value of the calibrated unit establishes the attenuation of the other and may be so recorded.

If the power from the oscillator is insufficient to operate the milliammeter for the highest loss required, the oscillator may be pulsed at an audio rate (about 75 pps in this equipment) and the rectified output connected to the vertical plates of an oscilloscope through an audio amplifier. Like amplitudes of signals on the screen constitute a standard for comparison.

(c). Resonant Cavity-Frequency Measurements

The properties of resonant cavities fall into a somewhat different category as far as testing procedure is concerned. Microwave resonant cavities normally have a high $Q$, consequently the frequency range within which they are resonant is relatively narrow. It may frequently occur that the $Q$ of the cavity is considerably greater than that of the wavemeter, and in consequence the resolution of the frequency determining device is insuf-
sufficient to accurately measure the resonant frequency of
the cavity.

Figures 3 and 4 illustrate two arrangements by which
the process may be approached. Figure 3 is applicable
only if the wavemeter Q is higher than that of the cavity,
while Figure 4 is applicable in any case.

Consider the simpler arrangement of Figure 3. If
the Q of the cavity is known to be low compared to that of
the wavemeter, and further if the resonant frequency of
the cavity is within the tuning range of the oscillator,
it should not be difficult to determine the resonant fre-
quency of the cavity by tuning the oscillator until a sharp
rise in the meter readings indicates resonance and hence
excellent power transfer. The attenuator is used to re-
duce the rectified energy reaching the milliammeter, in
order to insure that the meter needle is kept on scale.
When, with a fixed attenuator setting, a maximum energy
transfer is indicated by the meter, the wavemeter is tuned
to resonance. If the wavemeter is of the absorption type,
it will absorb much of the energy at resonance. This is
indicated by a sharp "dip" or decrease in meter reading.
If this "dip" is sharp, that is, if it exists for only a
very small change in wavemeter tuning, it may be properly
assumed that the wavemeter resolution is sufficient for
accurate readings of the cavity resonant frequency. If
this "dip" is broad, existing for a considerable range of
Figure 3. Equipment Arrangement for Measurement of $Q$ of a Cavity

Figure 4. Alternate Equipment Arrangement for Measurement of $Q$ of a Cavity
wavemeter tuning, the resolution is insufficient and other techniques must be adopted.

Figure 4 shows an equipment arrangement which may be used both for measurement of frequency and of the Q of a resonant cavity. The wavemeter here illustrated is of the resonant cavity type in order that a maximum amount of energy will be transferred to its crystal detector when the wavemeter is tuned to resonance.

A "Sweep" technique is well suited to the purpose. An oscillator repeller is "swept" with a linear sawtooth voltage, hence an output which smoothly sweeps a considerable band of frequencies is produced.

Consider the visual indication on the screen. The leads of the crystal of the wavemeter have their connection reversed, so that the output of the cavity will produce a positive deflection and the wavemeter will produce a negative deflection, on the oscilloscope.

Figure 5 illustrates an oscilloscope pattern produced when the wavemeter is tuned to a considerably different frequency than the resonant frequency of the cavity.

By suitable manipulation of the mixer, the magnitude of the resonant peak of the cavity is increased and that of the wavemeter decreased. The wavemeter is tuned until the negative vertical deflection due to the wave-
Figure 5. Oscilloscope Pattern when \( f_w \) considerably different from \( f_c \). \( Q_w > Q_c \).

\[ f_w = \text{Resonant frequency of wavemeter} \]
\[ f_c = \text{Resonant frequency of cavity} \]
\[ Q_w = Q \text{ of wavemeter} \]
\[ Q_c = Q \text{ of Cavity} \]

Figure 6. Oscilloscope Pattern, Measurement of \( Q, f_w \) at half power point of Cavity output. \( Q_w > Q_c \).
meter, now considerably decreased in amplitude, occurs at a point where the vertical deflection of the cavity resonance output is one-half of its maximum. If the crystal rectifier has a square-law characteristic this will be the half-power point. This is illustrated in Figure 6.

The wavemeter is further tuned until the "dip", or negative vertical deflection of the wavemeter, occurs at the very peak of the cavity resonance curve. The wavemeter reading at this point will indicate the resonant frequency of the cavity.

If the Q of the cavity is higher than that of the wavemeter, as is often the case, the frequency of resonance of the cavity may be determined by a "calibrated screen" process. The output resonance curve of the cavity will be narrow and sharp, whereas that of the wavemeter will be rather broad. By adjusting the mean repeller voltage the cavity output curve may be centered on the screen. The wavemeter tuning is varied through a considerable range, and both its frequency and position on the screen noted for several points. In this way each division on the screen (practically constant through narrow ranges) represents a certain frequency. By interpolating between points nearest the resonance curve of the cavity, its actual frequency may be determined.

(d). Resonant Cavity-Q Measurements

The determination of the Q of a resonant cavity such as a TR Box or some other form of cavity resonator
involves measurement of the resonant frequency and the frequency difference "Delta f" between the half-power points of the resonance curve. Then:

\[ Q = \frac{f_0}{\Delta f} \]  

where \( f_0 \) is the resonant frequency.

The apparatus of Figure 4 lends itself directly to \( Q \) measurements, and the process used for frequency determination may be used with but little variation. If the \( Q \) of the wavemeter is high compared to that of the cavity; apply the process described on page 17, paragraph 5. This will immediately lead to the desired conclusion: The frequency at a half-power point is determined; it is best then to determine the frequency at the other half-power point because of possible non-symmetry of the curve. The resonant frequency is determined, and the \( Q \) calculated by formula (6).

If the \( Q \) of the cavity is high compared to that of the wavemeter, a calibrated screen process must be used. Refer to Figure 7. The frequencies corresponding to two well separated points, \( L_1 \) and \( L_2 \), are found by means of the wavemeter curve. The gain of the horizontal amplifier of the oscilloscope is set at a rather high level in order to "spread" the patterns on the screen. The curve of cavity output can be reduced nearly to zero while the frequency points are determined. The cavity curve is then increased in amplitude and that of the
Figure 7. Oscilloscope Pattern based upon Calibrated Screen

Figure 8. Oscilloscope Pattern to Illustrate Tuning Range of Repeller Voltage.
wavemeter decreased to zero. If the cavity output curve was initially centered, a presentation such as that of Figure 7 should be seen. The distance $L$ between the half power points is measured. Then:

$$f = \left( \frac{\Delta L}{L_2 - L_1} \right) (f_2 - f_1)$$

(7)

The $Q$ may then be computed by means of formula (6).

V

CLASSROOM DEMONSTRATION APPLICATIONS

In an educational institution there is no more valuable aid than equipment which, in the classroom, can quickly demonstrate the basic principles which are being discussed. The apparatus constructed is compact and portable, and needs only 115 volt, 60 cycle power for complete operation. The microwave components have been placed upon a portable assembly, and further made flexible by clamp couplings which will permit of rapid changes in desired connections.

Figure 9 shows a composite grouping of several microwave units by which a number of the properties of the associated parts may be demonstrated. A number of the applications are herewith described:

(a). Frequency Deviation of the Oscillator with Change of Repeller Voltage.

One oscillator tube is used, with its repeller...
swept by a sawtooth voltage. An absorption type wave-meter is used. The output is fed through the crystal detector to the oscilloscope vertical amplifier. A "peak" of output is seen on the screen; by tuning the wavemeter a "dip", or decrease in vertical deflection at the frequency of resonance of the wavemeter, is added. A presentation similar to that of Figure 8 will be seen. The "dip" is moved by tuning the wavemeter until it is centered separately at three points, as illustrated, these being the right half-power point, the maximum point, and the left half-power point. The frequency is recorded for each of these points. The difference between the frequencies at half-power points is the frequency deviation desired to be known, while that of maximum deflection is the center frequency to which the cavity of the oscillator is tuned.

(b). Calibration of an Attenuator.

By using one oscillator, one calibrated attenuator, and one uncalibrated attenuator, the demonstration of calibration can quickly be performed by the method already described in Section IVb.

(c). Standing-Wave Ratio Measurements.

Three oscillators, a standing-wave detector, and a crystal detector, are coupled into the waveguide. Resistive pads or tuning-stub sections are used to improve the match between microwave components,
The three oscillators are tuned each to a different frequency. These frequencies may quickly be measured by use of the wavemeter and milliammeter.

One oscillator is now operated "pulsed", the others being turned off. Resistive pads, if used, are removed from the line and a test specimen coupled between "E" and "F". The carriage of the standing-wave detector is slowly moved, and the standing-wave ratio is determined by noting the height of the "pulse" on the oscilloscope. The resistive pads or tuning-stub sections are now placed in the assembly and varied until the standing-wave ratio is reduced to whatever minimum is possible with the components available. The tests can quickly be repeated by turning off the oscillator in use and turning on the others. Checks of operation and "matching" can be thus made at three different frequencies in a short interval of time.

VI

FURTHER APPLICATIONS

The reflex klystron lends itself readily to modulation, particularly by means of variation of repeller voltage. Figure 10a shows that the righthand edge of the output curve is quite steep. If the amplitude of the "sweep" voltage applied to the repeller is in the neighborhood of 35-40 volts, as is usually the case with this equipment, then each small division on the horizontal scale of the
oscilloscope screen may easily be made to represent approximately one volt change in repeller voltage. On the steep trailing edge of the output curve a change of repeller voltage of 1-2 volts will represent a correspondingly large change in amplitude of oscillator output. At the same time, the steepness indicates that in this area there is a small frequency change, \( \delta f \), corresponding to a large amplitude change, \( \delta a \). In this portion of the curve used for amplitude modulation we may assume that there is an almost linear relationship between repeller voltage and frequency.

This is an admirable condition for a satisfactory application of amplitude modulation. The mean repeller voltage is set at the midpoint of this steepest part of the curve, and the repeller modulated with an audio signal of amplitude something less than one volt. An output modulated through a considerable range in amplitude, but containing little frequency modulation, can be obtained.

The sweep voltage applied to the repeller in this equipment is a "falling" voltage, hence the repeller is most negative for the latter portion of the sweep. Hence, to mechanically place the oscillator's mean repeller voltage at the midpoint of the steep side, it is only necessary to proceed as follows: With the aid of the milliammeter, tune the oscillator to maximum output, then with the repeller voltage control make the repeller more negative by tuning the control counterclockwise until the meter reading drops
to about half scale. The desired point will have been reached.
The repeller must now be modulated with an audio voltage as
described above.

A quick demonstration of the capabilities of this method of modulation may be made by radiating the r.f. energy
by means of a horn into the air of the room in which the
demonstration is held. Energy picked up at another station
by another like horn is coupled to a crystal detector. The
rectified energy must be amplified in an audio amplifier,
to which may be attached headphones or loudspeaker.

Frequency modulation may be as easily accomplished,
Again referring to Figure 10a, it is seen that the very top
of the output curve is relatively flat for a very small
change in repeller voltage. Hence if the mean repeller vol-
tage is initially set at the point of maximum output, a small
amplitude modulation of the repeller voltage will result
in a large frequency modulation of the output with a cor-
respondingly small amplitude change.

Detection of the signals requires the use of some sort
of Discriminator. A convenient one might be an absorption
type wavemeter of the type normally used in this equipment.
The curve of energy transfer has the appearance shown in
Figure 10b. The trailing edge is very steep, which means
that a small change in frequency, $\delta f$, leads to a large change
in amplitude, $\delta A$. If the mean frequency of the oscillator
can be adjusted so that it falls at the middle of this steep
Figure 10a. Curve of output voltage of Oscillator, illustrating Amplitude Modulation Area

Figure 10b. Response Curve of Absorption WAVemeter
edge; a small change in oscillator frequency is converted into a large change in amplitude of output. By this method, then, frequency modulation of the oscillator can be converted into amplitude modulation at the receiving station. This can be amplified as before, and reproduced by headphones or a loudspeaker.

VII

APPARATUS NECESSARY FOR CONTROL OF THE OSCILLATOR

It has been stated that the principal objective of the project was to construct apparatus capable of furnishing all necessary exciting and modulating voltages required by the oscillator. A few of the tests and applications have been described; from these, and from known characteristics, we may now summarize the units and circuits which were constructed in order to provide all of the required inputs:

(a). A power supply, capable of producing necessary filament supplies and in addition such thoroughly regulated positive and negative d-c voltages as are necessary both for operation of conventional receiving type tubes and for the operating potentials of microwave oscillators.

(b). A three-phase square wave generator capable of pulsing by "square waves" the repellers of as many as three microwave oscillators, the pulsing to occur in a successive but never overlapping manner.
(c). A sweep generator of variable frequency for "sweeping" the repellers of the oscillators.

(d). A synchronizing system to insure synchronization of the oscilloscope sweep and the repeller modulation.

(e). An audio amplifier, with gain control, whose output may be coupled to the repellers of the oscillators.

These units and circuits have been constructed and are described in detail in Appendix I. Complete schematics of the entire equipment may be found in Figures 25 and 26.

VIII

PROPERTIES OF SOME MICROWAVE COMPONENTS

The properties of several of the microwave components were mentioned in Section III, in order that their functions in the testing processes might be understood. Inasmuch as a rather thorough understanding of their properties is a prerequisite to their proper use, a more detailed description of vital components follows.

(a). The Oscillator.

The oscillator tube used is the 723A/B or its newer counterpart, the 2K25. This tube is designed to oscillate between 8500 and 9600 megacycles per second.

Figure 11 shows a schematic diagram of a Reflex Klystron, while Figure 12 shows a profile view of the 723A/B.

The reflex Klystron is so named because the same set
Figure 11. Schematic Diagram of a Reflex Klystron

Figure 12. Outline of 723A/B
of grids is used both for bunching and extracting energy from the electron stream. A negative repeller is used to deflect the electrons that have passed through the grid so as to force them to re-enter the cavity.

The basic control of frequency is through a change in the size of the internal cavity. In the 723A/B this is accomplished by manual "flexing" of the bows on the side of the tube.

Tuning over a narrow range may be produced by changing the repeller voltage. In practice the two tuning controls, the bows and the repeller voltage, are varied simultaneously so as to insure a peak output for each change of size of the cavity.

For security reasons, it was formerly the practice to issue information on this tube on a basis of wavelengths in terms of letters rather than numbers. Typical curves on this basis are shown for the 723A/B in Figures 13 and 14.

The variation of frequency with change of repeller voltage is listed below:

<table>
<thead>
<tr>
<th>Mean Repeller-Cathode Voltage for Oscillation in a Given Mode.</th>
<th>Limits of Mean Electronic Tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Repeller-Cathode Volts for Oscillation in the Given Mode.</td>
</tr>
<tr>
<td>-32 (Mode 0)</td>
<td>$7.0$</td>
</tr>
<tr>
<td>-50 (Mode 1)</td>
<td>$9.0$</td>
</tr>
<tr>
<td>-100 (Mode 2)</td>
<td>$12.0$</td>
</tr>
<tr>
<td>-150 (Mode 3)</td>
<td>$15.0$</td>
</tr>
<tr>
<td>-250 (Mode 4)</td>
<td>$20.0$</td>
</tr>
</tbody>
</table>

where $E_r$ is the difference between the repeller voltages
Figure 13. Operating Range of the 723A/B

Figure 14. Output Power of the 723A/B
at each of the half power points.

The information given in the above table and that in Figure 13 has been copied from the Technical Information pamphlet received with the tube. It will be noted that certain discrepancies exist between the table and Figure 13. Both agree basically, however, insofar as the mean repeller voltages of the two modes shown in the figure are concerned. The characteristics of individual tubes may be easily checked in the laboratory by means of the apparatus constructed.

(b). Wavemeters.

For routine laboratory measurements of frequency, sufficient precision is obtained by the use of resonant sections as frequency measuring devices. In general, these fall into two classifications; the transmission type wavemeter and the absorption type wavemeter.

Transmission type wavemeters are so named because the transmission loss is very high at frequencies other than the resonant frequency of the cavity, but can be made low at the resonant frequency. A cross sectional diagram of such a wavemeter is shown in Figure 15a. Microwave energy is fed in through the upper loop and taken out through the lower loop to a detecting system, normally a crystal detector. The crystal output is fed to a milliammeter which indicates when the wavemeter is tuned to resonance.

The resonant frequency is adjusted by moving the plunger with a micrometer adjustment. The micrometer may be
Figure 15a. Transmission Type Wavemeter (Top)

Figure 15b. Reaction Type Wavemeter (Bottom)
calibrated either in wavelength or frequency.

The absorption, or reaction, type wavemeter, operates upon a different principle. Its cavity is coupled to the waveguide through an iris, and normally presents an extremely low impedance in series with the guide. However, when tuned to resonance, it presents a high impedance in series with the waveguide; a sharp reduction in energy transfer down the guide results. This is visually noted by a reduction in deflection, or "dip", in the meter used to record the actual energy transfer through the waveguide.

A cross-sectional diagram of such a type is shown in Figure 15b.

The two cross-sectional diagrams shown are representative of several possible arrangements. The coupling of energy to the cavity of the wavemeter is not restricted to the method shown in each case. Energy may be coupled from the main guide to either a transmission or absorption cavity by means of a loop, probe, or coupling iris.

(c). Directional Couplers.

One of the more difficult problems of microwave techniques is that of extracting energy from a transmission line without producing spurious effects. That is, the coupling device either adversely affects the main transmission line by the introduction of "reflections" or the readings made of the extracted energy may not be independent of standing-waves in the main line.
A coupling device which is independent of the standing waves in the main transmission line has been designed and is known as a "Directional Coupler", since the amount of power extracted from (or put into) the main line is proportional only to the power of the wave which travels in a preferred direction.

Figure 16 shows a cross-sectional diagram of a directional coupler. To understand its action, consider the main wave: The path length to the detector is the same and energy from the main wave reaches the detector in phase. Energy from the main wave, however, proceeding in the direction of the termination, finds a path length difference of two quarter wavelengths. Hence waves toward the termination are 180 degrees out of phase and so cancel.

Reflected waves in the main guide, however, find an entirely reversed situation. These reflected waves that attempt to reach the detector arrive 180 degrees out of phase and so cancel. Those proceeding to the termination arrive in phase, but the termination is made of a "lossy" material that completely absorbs the wave. As a result of these actions, only energy from the main wave is recorded by the detector circuit.

The ratio of the power in the main wave to that fed to the detector is defined as the coupling of the device. This coupling is a function of the size, number, and position of the coupling holes, and of the frequency. A coup-
ling loss of the order of 25db's is commonly used.

Certain attractive properties of directional couplers make them valuable as microwave testing devices. The type shown in Figure 16, for example, provides a natural method of measuring the power in a line, particularly if the standing-wave ratio is small. The coupling loss of the directional coupler is normally known, hence a power reading at the detector gives immediate information as to the power in the main guide.

As another example, assume that the termination of Figure 16 is replaced by another detector. Since the reflected energy coupled from the main guide reaches this end in phase, a detector may be used to indicate the power in the reflected wave. Thus another form of standing-wave device is at one's disposal.

(d). Attenuators.

The control of attenuation at microwave frequencies requires great care in the construction of the component parts. In particular this is true of a variable attenuator of sufficient accuracy and control to permit of accurate calibration.

Many types of attenuators have been designed, but most of them fall into one of two classifications:

(1). The wave guide beyond cutoff.

(2). The resistive insert.

The first of these is shown in Figure 17. Attenu-
ation is based upon the fact that for diameters smaller than the critical diameter, the fields are attenuated exponentially at a rate which depends upon the diameter of the tube and the mode of oscillation. These values are known analytically. In fact, for the TE$_{1,1}$ Mode which is utilized in the attenuator of Figure 17, the rate of attenuation, in decibels-per-diameter separation of the loops, is given by:

$$\text{Rate of Attenuation} = 32.0 \sqrt{1 - \left(\frac{1.71}{\lambda}\right)^2} \text{ DB/Dia} \quad (8)$$

The abbreviation DB/Dia refers to decibels per diameter change in separation of the loops. The diameter in question is the internal diameter of the metallic guide as illustrated in Figure 17. Such a dimension serves as a convenient reference in an attenuator of this type.

Since the rate of attenuation can be calculated to a high degree of accuracy, this type of attenuator provides an excellent standard. One great difficulty, however, in practice, lies in the presence of other modes in the attenuator and resulting inaccuracies. For large linear displacement, all modes except the TE$_{1,1}$ Mode are negligible, but this large displacement corresponds to a large insertion loss, a feature which can hardly be eliminated if a high degree of accuracy is required.

Resistive insert types (also known as dissipative types) utilize material which, when inserted into the
Figure 16. Directional Coupler

Outer conductor of incoming coaxial
Inner conductor of incoming coaxial
Metallic Guide

Magnetic Field decreases exponentially in this direction

To Detector

Termination

Figure 17. Wave Guide beyond cutoff Attenuator
electric field within a wave guide, acts to absorb a fraction of the radio-frequency energy present. A practical method of producing such resistive material is to coat a dielectric, such as glass, with a very thin coating of resistive metal, such as nichrome. The unit resistance can be controlled by varying the thickness of the metallic deposit. A desired condition is to have the attenuation insensitive to frequency changes; this is largely accomplished if the metallic deposit is made less than the depth of penetration.

If a metallized plate is placed in the waveguide with the metallized surface very close to the narrow sides of the guide, the attenuation provided is extremely small. As the plate is moved into the guide to the region of stronger electric fields, higher losses occur.

All of the resistive types must be calibrated against some basic standard of suitable accuracy.

(e). The Magic Tee.

It was previously stated that another device for making measurements of standing-wave ratios is the Magic Tee. This unit, a microwave counterpart of the Wheatstone bridge, consists of two tees soldered together, one lying in the plane of the electric vector and one in the plane of the magnetic vector. These will hereafter be referred to as the E and H arms.

A simple sketch of the magic tee is shown in Figure
18. The basic property of the tee is that of dividing the power fed into the H arm between the two test arms. If these are terminated in reflectionless loads the power will be divided equally between these two arms, with no power delivered to the E arm.

Now, if one of the two arms has a reflectionless load, as above, but the other has attached to it a test specimen which is improperly matched, some of the power is fed to the E arm. This latter power is proportional to the square of the magnitude of the reflection coefficient of the test specimen.

Utilization of these properties can be effected as follows: It is known that a perfectly matched test specimen will have no reflection and that the power fed to the E arm will be zero. A metal plate replacing the test specimen will result in one hundred percent reflection and the power delivered to the E arm will result in a certain deflection of the meter used in the detector circuit. This deflection can be calibrated as one hundred percent, or in other units as desired. Since the power delivered is proportional to the square of the magnitude of the reflection coefficient, the meter can be calibrated throughout.

There remain two essential difficulties in the employment of the magic tee. The first of these, and unfortunately a serious difficulty, is that the power delivered to the detector is, in contrast to the directional coupler,
sensitive to the "phasing" of the waves reaching it. Hence one is not assured of the complete accuracy of the readings.

A second difficulty lies in the fact that the power delivered to the E arm is a function of the mismatch of the two H arms. Hopefully, many of the test specimens will have a low reflection coefficient. In that case, the power delivered to the E arm will be very small and considerable amplification must be used before suitable readings can be taken.

Inasmuch as investigation of the impedance characteristics of a specimen are usually made at more than one frequency, it is a tedious task to carry out such an investigation with only one oscillator. By the use of three oscillators, each tuned to a different frequency and each pulsed in such a manner that no two are in oscillation at the same time, it is possible to carry out studies that encompass a considerable band of frequencies in a short time. A suitable arrangement which does not require a number of specialized units is shown in Figure 19.

It will be noted that the Pulse Generator must be capable of generating a three-phase square wave. It is to this end, as well as for other reasons already described, that such a square-wave generator was designed.
Figure 18. The Magic Tee
Figure 19. Equipment for Utilization of the Magic Tee
IX

CONCLUSION

This paper has outlined a few of the techniques involved in microwave testing. From these procedures there has evolved a listing of components and equipment capable of properly executing these tests. This list has been further subdivided into those items which are commercially available and those which are either not commercially available or more logically should be constructed in the laboratory.

The equipment constructed, as described in the Operating and Maintenance Instructions, has been designed to incorporate several properties. A variety of modulation methods, a synchronizing system, and an amplitude control have been provided to insure flexibility. The tests and demonstrations described can thus be rapidly executed. Further it is believed that the apparatus will form the nucleus of a precision microwave testing bench by which a wide variety of accurate calibrations may be made. Invaluable information as to the capabilities of microwave components can thus be gained in the laboratory with a minimum of delay.

In final recapitulation, the testing techniques described have led to a logical selection of circuits and units which must be constructed in order properly to con-
trol the oscillator and recording units. Appendix I de-
scribes the circuits and at the same time provides the
operator with all necessary information for their effici-
ent use.
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APPENDIX I

OPERATING AND MAINTENANCE INSTRUCTIONS

SECTION I

COMPONENTS AND THEIR USES

(a). Purpose of the Equipment

The Signal and Test Generator is designed for the purpose of generating pulses of special shapes and controlled repetition rates. These activate 3-Centimeter Oscillators (one, two, or three) the outputs of which may be observed, compared, and studied.

These various possible outputs are described in detail in later sections.

(b). Main Components.

The complete equipment consists of seven units, numbered and identified as shown in the following table:

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Component Numbers</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1-99, Inclusive</td>
<td>Pulsing Circuits</td>
</tr>
<tr>
<td>1</td>
<td>101-199, Inclusive</td>
<td>Sweep &amp; Aux: Ckts.</td>
</tr>
<tr>
<td>2</td>
<td>201-299; *</td>
<td>Power Supply</td>
</tr>
<tr>
<td>3</td>
<td>301-399; *</td>
<td>Remote Control</td>
</tr>
<tr>
<td>4</td>
<td>401-499; *</td>
<td>Oscillator No. 1</td>
</tr>
<tr>
<td>5</td>
<td>501-599; *</td>
<td>Oscillator No. 2</td>
</tr>
<tr>
<td>6</td>
<td>601-699; *</td>
<td>Oscillator No. 3</td>
</tr>
</tbody>
</table>

(c). Unit 0. Pulsing Circuits.

This unit contains the Master Multivibrator which
establishes the repetition rate and the basic pulse widths. It is followed by a three-phase square-wave generator and three oscillator control tubes. By various switching arrangements the three oscillators may be either pulsed in succession, or operated on Continuous Wave. Oscillator No. 1 may in addition have its Repeller voltage varied by an audio-frequency voltage or by a sawtooth wave form.

(d). Unit 1. Sweep and Auxiliary Circuits.

A "linear sweep" circuit comprises the essential section of this unit. When synchronized internally from the Master Multivibrator, a delay circuit permits variation in time of the initiation of the "sweep" of from about 500 to 6000 microseconds. This will permit a controlled lateral movement on the oscilloscope of the output of the oscillator under observation.

The unit also contains an Amplifier whose output may be connected to the Repeller of Oscillator No. 1.

Units 0 and 1 are packaged in the same case, although each is on a separate chassis.

(e). Unit 2. Power Supply.

This unit contains a regulated power supply, with the following characteristics:

Power Input: 115 v., 60 cycle, 1.4 amps.

Outputs: (1). 6.3 v., 60 cycle, filament supply, 5 amps.
(2). 6.3 v., 60 cycle, filament supply, 5 amps.
300 v d-c, regulated, with output capable of control to 300 volts for a load change from 30 ma to 130 ma. Normal expected current drain 60 to 120 ma, maximum allowable 130 ma.

Ripple voltage not over 20 mv at 80 ma.

-300 v, d-c, regulated, with variation in allowable output from 0 to 80 ma. Normal expected current drain 12 ma.

(f). Unit 3. Remote Control Unit.

The remote control unit serves both as a junction box and as a tuning control for the oscillators. Three potentiometers serve, respectively, as repeller voltage controls for Oscillators 1, 2, and 3. In addition, switches are provided by which the plate voltage to the oscillators may be interrupted.

A milliammeter is provided in the unit as a tuning indicator. Through a selector switch, it may be connected to any one of as many as three crystals which are used as detectors in the oscillator assemblies.

(g). Units 4, 5, 6. Oscillator Assemblies.

Each of these units, fundamentally the same, consists of a reflex klystron oscillator, plus such other microwave components as may be needed for particular tests. The 723A/B tube is used. This is mounted and coupled to sections of waveguides. By means of these, connections may be made to resonant cavities, attenuators, waveguide fittings, etc., as necessary.

A normal component of each oscillator assembly is a crystal-monitor, by which the rectified radio-frequency
energy may be monitored by the milliammeter or by an oscilloscope.

SECTION II

ELECTRICAL CHARACTERISTICS

(a) Master Multivibrator.

V 1, a 6SN7GT, serves as the two sections of a conventional plate coupled multivibrator. Both grids are returned to ground, as are the cathodes, hence the multivibrator is free running. C 1 and C 2 are equal; each of 0.01 microfarads; the grid-to-ground resistance of triode 1 is approximately twice the corresponding resistance of triode 2. As a result the plate voltage pulse of triode 2 is nominally one-half the length of that pulse of triode 1. The time constants are such that the repetition rate centers at about 75 cps.

R3-R4, ganged potentiometers, change the time constants of the grid circuits equally, and hence control the frequency with a corresponding small change in the ratio of the widths of the two plate pulses. As will be seen later, a desirable condition is for the plate pulse of triode 2 to be exactly one-half as long as the plate pulse of triode 1.

In order to achieve this condition, R5 is placed in the grid circuit of triode 2. By varying R5 the width of the plate pulse of triode 2 may be varied without too great effect upon the pulse repetition rate. This plate pulse
is used to control the three-phase square-wave generator.

Figure 20 shows a simplified schematic of this circuit.

(b). Three-Phase Square-Wave Generator.

Tubes V3, V4, and V5 together form a square-wave generator whose outputs are nominally equal in duration and occur in 1-3-2 sequence.

Figure 21 is a simplified schematic of this portion of the unit. To understand the operation, consider the condition when V1 (Master Multivibrator) is removed from its socket. V2 then receives no grid driving voltage, the grid rests at ground potential, and the tube conducts heavily; Its plate potential drops to about 30 volts above ground.

The control grid of V3 is coupled on a voltage divider between -300 volts and the plate of V2, and will rest at about -130 volts. Thus V3 is cut off and will remain so indefinitely as long as V2 is in a conducting state.

A similar voltage divider couples the suppressor grid of V4 between the plate of V3 and -500 volts. With V3 cut off, the suppressor of V4 is adjusted to ground potential by means of V4 Bias (R16). The control grid of V4 is returned to B plus and hence V4 conducts heavily.

A third similar voltage divider (R80-21-22-23) couples the suppressor of V5 to the plate of V4. When V4 is conducting, the suppressor grid of V5 rests at about -130 volts, cutting off flow of current to its plate.
Figure 20. Master Multivibrator
Fig. 21. Square Wave Generator
Based upon the preceding analysis, it is evident that the V3-V4-V5 combination acts in a sense as a "one shot multivibrator", with V4 conducting, and with V3 and V5 cut off (i.e., no plate current flowing).

Now consider the action when V1 is re-inserted in its socket. Assume for purpose of analysis that the Master MV has a repetition rate of 83 $1/3$ ops. This odd number is chosen for illustration because the period becomes $10^6 \cdot \frac{1}{83 \frac{1}{3}} = 12,000$ microseconds. It was shown under the topic of Master Multivibrator that the output of the latter consists of the conventional "square" negative and positive waves, with the further stipulation that the width of the negative pulse should be one-half the width of the positive pulse. By two stage amplifier action, the same pulse widths occur at the plate of V3. We will henceforth consider V3 as the controlling tube for the remainder of the circuit. The fourth waveform in Figure 21a illustrates the wave shapes at the plate of this tube.

When V3 conducts, its drop in plate voltage is transferred to both V4 and V5. (To V4 by voltage divider action to the suppressor grid, and by capacitive coupling to V5). This action then cuts off the plate current of V4 and holds V5 at cutoff.

When V3 goes out of conduction, its normal action would be to reverse the process and turn both V4 and V5 on. This would occur, were not the plate of V5 coupled to the
Figure 214. Waveforms of the Three Phase Square Wave Gen.
control grid of V4. V5 actually goes into conduction, but its resultant plate drop drives the control grid of V4 below cutoff. Hence for the second sequence of events it is seen that only V5 conducts.

Continuing the discussion; multivibrator action now occurs between V4 and V5. In 4000 microseconds the control grid of V4 rises to cutoff. As V4 begins to draw current the drop in plate voltage is coupled to the suppressor of V5. This results in a rise in the plate voltage of V5 driving V4 control grid up. Rapid cumulative action quickly cuts V5 off and turns V4 on. As shown previously, no further action would take place, but at the end of another 4000 microseconds the Master MV reinitiates the entire cycle of events.

The plates of V3, V4, and V5 are individually coupled to the control grids of V6, V7, and V8 respectively. These latter tubes control the repeller voltages of the oscillators.

(c). Repeller Control Tubes, V6, V7, and V8.

V6, V7, and V8 are conventional amplifiers but here serve a special purpose. Referring to Figure 28, it is seen that the plate of V6 is directly coupled to the Repeller Voltage potentiometer in the Remote Control unit. Direct coupling was used in order to avoid variations in voltage due to capacitor charge and discharge.

The plate and screen grid of V6 are both connected
Fig. 22. Repeller Control Tube Circuit
to ground through large resistors, while the cathode is connected to a negative voltage point. The plate voltage, then, is always negative with respect to ground and as such may be used as the source of repeller voltage for an oscillator.

The circuits of V6, V7, and V8 are all basically identical, hence only that of V8 will be described in detail.

Referring to Figure 22, Point A (Cathode) is by voltage divider action resting at -200 volts. Point B by voltage divider action rests initially at -225 volts. This is the condition when SI is set either at CW, Sawtooth, or Audio. The control and suppressor grids are both returned to -300 volts, cutting the tube off. Point C would then be at -210 volts and the plate at about -120 volts. The voltage at the remote control unit has then a range of from -120 to -210 volts.

When SI is placed in "Pulsed" position, the tubes will conduct at all times except when its grid is driven far below cutoff by a square wave from V3. When V6 is conducting its plate drops to about -180 volts. The voltage swing at the plate is transferred to the Remote Control Unit and in a reduced amplitude to the repeller of the oscillator.

(d). Delay Multivibrator and Clippers, V101 and V102.

The negative (150 volt amplitude) 4000-microsecond square wave at the screen grid of V3 is coupled to the con-
trol grid of triode 1 of V101.

Referring to Figure 23, it is seen that the coupling capacitor and the plate resistance of V102A serve as a sharply differentiating circuit for the negative leading edge of the pulse. In the same way, the capacitor and the series resistance of the grid-to-cathode resistance plus cathode resistor of V101 serve as a differentiating circuit for the positive trailing edge. Hence the waveform is as shown at the control grid of triode 1.

The two triodes of V101 comprise a "one shot" multivibrator, cathode coupled. With no input pulse to the tube, triode 2 will conduct, since its grid is returned to B plus through variable resistors. The voltage at both cathodes will then be close to thirty volts positive, sufficient to keep triode 1 cut off, its grid being at ground potential.

The negative leading edge of the input pulse does not affect the multivibrator. In addition, it is clipped sharply by the diode of V102A. The positive trailing edge, however, drives the grid of triode 1 sufficiently positive to cause this triode to conduct. Its drop in plate voltage drives the grid of triode 2 below cutoff. The cathode of triode 1 will drop until limited by the current through that section of the tube. The large plate resistor limits this current to a small amount and consequently the cathode voltage rests only a few volts above ground while triode 1 is
Fig. 23. Delay Circuit
conducting;

The rise in plate voltage of triode 2 is sharply clipped by $V_{102B}$. The multivibrator will flip back to its original state when the grid of triode 2 rises to cutoff. This time of rise is controlled by $R_{104-109}$, which in turn is controlled by the switching action of $S_{101}$. Hence a variable width of plate pulse of triode 2 from about 500 to 6000 microseconds is obtained.

The trailing edge of this plate pulse is coupled through a condensor to the "Sync" input of the following Sweep circuit. Thus a variable delay of from 500 to 6000 microseconds (after $V_3$ turns off) is obtainable.

(e). Sweep Circuit.

A Sweep circuit of a type publicized by Puckle was used. Tubes $V_{104}$ and $V_{105}$ comprise the Sweep Generator. Refer to Figure 24. $V_{105}$ serves as a "Sync" amplifier for synchronization of the sweep with any desired input. A switch ($S_{102}$ of Fig. 25) permits the input of a "sync" pulse from either Internal, External, or a 60 cycle source.

To understand the operation, first assume that there is no synchronizing pulse delivered to $V_{103}$. $V_{104}$ and $V_{105}$ are then "free running". $C_{106}$ initially charges to some positive voltage. As the cathode potential rises, the conduction through $V_{104}$ decreases, and its plate begins to rise.

---

Fig. 24 SWEEP CIRCUIT
This rise is coupled to the control grid of V105. The resulting drop in plate voltage of V105 drives the control grid of V104 below cut-off. C106 now begins to discharge through the parallel combination of resistors in the cathode circuit. This exponential drop comprises the sweep voltage. After the cathode voltage has dropped a certain amount, V104 again begins to conduct. A reversal of the previously described action between V104 and V105 takes place, and V104 is driven into heavy conduction, with V105 driven to cutoff.

The amount by which the cathode of V104 drops before a "flip-flop" action begins is a function of the control grid voltage of V104. This is determined by the allowed conduction through V105. R124, in the cathode circuit of V105, is variable, and will control the quiescent plate voltage of V105. Hence a variation in R124 establishes the quiescent control grid voltage of V104. This in turn controls the amplitude of exponential drop at the cathode of this tube before reinitiation of the cycle. Inasmuch as the first portion of the exponential drop is very linear, R124 controls the linearity of the "Sweep".

In order to have a rapid "retrace", it is necessary that C106 charge rapidly. C105, 16 microfarads, serves as a source of current during the conduction of V104. The effective plate resistor is only 500 ohms, and the internal resistance of the tube is low when its grid is positive. Therefore C106 has a short time constant of charge; its vol-
tage rises rapidly to the predetermined point at which V104 begins to cut off.

The synchronizing pulse must be "negative". This negative pulse is inverted and amplified at the plate of V103. The sharp rise is coupled directly to the screen grid of V104 and by capacitive coupling to the control grid of the latter. These both act to sharply bring V104 into active conduction, initiating the retrace, followed by the sweep.

The "Sweep" voltage is a "dropping" rather than a "rising" voltage, and with a conventional oscilloscope it may be found that the "sweep" is from right to left, rather than left to right. If this is undesirable an inverter must be added externally.

(f). Audio Amplifier.

The Audio amplifier shown in Figure 25 is a conventional, resistance coupled audio amplifier. Its gain is about 5000, so that an input directly from a microphone is amplified to produce a peak output amplitude of about 40 volts. This output is then coupled to the repeller of the oscillator, resulting in sufficient amplitude at the repeller to produce frequency modulation over a wide band of frequencies.

(g). Power Supply.

The Power Supply was designed primarily to furnish proper voltages to the microwave oscillators. It is neces-
sary that both the plate supply and the repeller voltage of the reflex klystron maintain a constant amplitude if frequency modulation of the oscillator is not to result. This requires that the average amplitude be constant, and in addition that the ripple voltage be reduced to a minimum.

The fixed level of average amplitude is obtainable with what is now a rather standard type of circuit, consisting of series resistor tubes controlled by an amplifier. Satisfactory ripple control for the average power equipment is obtained by coupling a portion of the ripple in the output back through the amplifier as negative feedback. Additional ripple control may be effected by a coupling from the output of the filter section directly to the amplifier tube, in a method publicized in recent articles.7

Refer to the schematic of Unit 2, Figure 25, the Power Supply. The positive voltage is supplied from V201. With no external load upon the supply, a peak voltage of about 500 volts is obtained at the plates of the series tubes, V105-107. If the internal resistance of the tubes is high the only current passing through the tubes, that to the bleeders, produces sufficient voltage drop to lower the output terminal voltage to 300 volts. As the external load is

increased, the internal resistance of the tubes must be decreased in order to maintain the constant output voltage.

This power supply was designed for an external load of from 60 to 120 milliamperes. A constant output voltage of 300 volts is obtained through the use of an amplifier tube, W108, whose plate potential controls in turn the grid potentials of the series resistor tubes, W105-107. An assumed rise in output potential raises the potential of the grid of the amplifier, W108. This produces an amplified and inverted action at the grids of the series tubes. Since the grids become more negative in potential, the internal resistances of the series tubes increase and the voltage drops across them also increase, tending to lower the output voltage to nearly the original level.

By a like analysis, it is seen that these tubes tend to maintain a fixed output voltage regardless of the change in output load or supply voltage. A high degree of stability is gained through this method.

"Ripple" voltage is reduced considerably by the negative feedback obtained through C206. An instantaneous rise in output voltage due to ripple is coupled through C206 to the grid of W108. The resulting action is the same as previously described in the preceding paragraphs.

In order to reduce the ripple to an absolute minimum, R210 and C205 are added. These couple the ripple at the plates of the series tubes to the screen grid of the
amplifier. This grid serves as a low-gain control grid, so the ripple is amplified in reversed phase at the cathodes of the series tubes. When a high resistance is used in series with $C_{205}$, little of this ripple is inverted and the original ripple appears at the cathodes of the series tubes. As $R_{210}$ is decreased, the ripple at the cathodes is seen to decrease, and finally to reach zero and reverse phase. By the use of an oscilloscope, this change may be observed and the point selected wherein the ripple reaches zero amplitude.

The negative supply is controlled directly by the use of Voltage-Regulator tubes. The filter input is a 40 microfarad condenser, while the first series resistor has a value of 2000 ohms. The impedance of the condenser to 120-cycle ripple is very low compared to 2000 ohms; the ripple is reduced at this point by a ratio of about 60 to 1. A further reduction occurs in the following section, composed of a 30-microfarad condenser and a 1000-ohm resistor. Finally, the voltage-regulator tubes tend to hold the voltage at 300 volts, while in addition absorbing much of the remaining ripple.

(h). Remote Control Unit.

There are three groups of elements of interest in this unit. The first of these are three potentiometers, each coupled across the one megohm resistor in the plate circuit of a Repeller Control tube. (See Figure 22).
The variable tap on each of these potentiometers is directly connected to the repeller of its associated oscillator. Hence for CW operation these may be used directly for setting the Repeller voltage and as such are tuning controls.

When the oscillator is activated by Sawtooth or Audio voltages, the potentiometer in question may be used to set the average value of repeller voltage. When the oscillator is "pulsed" by square waves, the potentiometer also acts as a tuning device.

The second group of elements consists of three switches by which the plate voltage of the oscillators may be interrupted. They are thus convenient controls for switching the oscillators off and on.

The third group consists of a milliammeter and a three-position switch for connecting it to the crystal monitor of any of three oscillators. An indication of the rectified d-c from the crystal is thus shown on the milliammeter in the Remote Control Unit. This is of particular value in tuning the oscillator.

{1}. The Oscillators.

The 723A/B Vacuum Tube is designed as an oscillator to function in the 3 centimeter region. It is of the conventional reflex klystron type, having three vital elements. These are: the Gun, or Cathode, the emitter of electrons; the Resonator, consisting of the cavity in which oscilla-
tions occur and the shell, these together being the final catcher for electrons; the Repeller, operated at a voltage negative with respect to both cathode and resonator, and serving to reverse the direction of motion of the electrons. Further information on the reflex klystron in general and the 723A/B in particular are given in the main body of the paper, Section VIII.

Operating Conditions and Characteristics are:

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Absolute Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater Voltage</td>
<td>6.3 volts</td>
<td>6.5 volts</td>
</tr>
<tr>
<td>Potential Difference</td>
<td>0.0 volts</td>
<td>45 volts</td>
</tr>
<tr>
<td>between heater and cathode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resonator Voltage</td>
<td>300 volts</td>
<td>330 volts</td>
</tr>
<tr>
<td>Cathode Current</td>
<td>22 ma</td>
<td>35 ma</td>
</tr>
<tr>
<td>Repeller voltage range range</td>
<td>-20 to -300 volts</td>
<td>-350 volts</td>
</tr>
<tr>
<td>Ambient Temp.</td>
<td></td>
<td>110° C</td>
</tr>
<tr>
<td>Nominal Heater current</td>
<td>0.44 amps</td>
<td></td>
</tr>
</tbody>
</table>

Two methods of tuning, each interdependent, are provided. The first is mechanical adjustment, by which the size of the cavity may be varied. The second is electrical, by variation of the negative voltage applied to the repeller:

Oscillating conditions may be obtained in a given tube at a number of different repeller voltages. These various points of oscillations are called "modes". As high as five modes of oscillation may be found, although the first of these is low in amplitude and is often overlooked and the last is often outside the electrical tuning range. For the midrange of frequencies at which the tube
is capable of operating the mode of oscillation of greatest amplitude is normally found with the repeller voltage somewhere in the range of -120 to -160 volts.

The tube is mounted with its output lead directly coupled into a section of waveguide. Variation of the depth of insertion into the waveguide will change the amount of energy transferred to the waveguide. In the mounting used in this equipment full insertion is normally used, and the amount of energy transfer down and the waveguide is controlled by attenuators.

SECTION III

OPERATION

(a). Equipment Assembly.

The basic equipment, in addition to the oscillator mounts, consists of three main packages: The Power Supply, the Signal and Test Generator (hereafter to be referred to simply as the Signal Generator) and the Remote Control Unit. Three cables are provided for their interconnection; one for input 115 volt, 60-cycle power, one from the Power Supply to the Signal Generator, and one from the latter to the Remote Control unit.

Each oscillator mount has a cable connecting it to the Remote Control Unit. There are three multi-connection jacks on the right side of the Remote Control Unit, the one at the extreme rear being the connection to Osc. #5, while
the one of these nearest the front is the connection to Ose. #1. In addition, a coaxial cable is furnished to connect the crystal monitor of each mount to the desired recording point.

In order to place the equipment in operation, assemble the equipment by connecting the cables between the three main units. Connect as many oscillator mounts as desired by securing the multiwire cables to the proper outlet of the Remote Control Unit.

(b). Power Supply Operation.

The entire system requires a current of about 1.4 amperes from a 115 volt, 60 cycle, source. The power cable has a conventional plug which may be inserted in the usual wall socket. A front panel, "On-Off" switch, is the only control, as closing of this switch energizes all internal circuits. The fact that the circuits are energized is indicated by a small amber Indicator light at the bottom of the front panel. When this lamp lights, all power circuits are activated and there is then provided to the other units 500 volts positive, 300 volts negative, and 6.3 volts filament supply.

(c). Controls and Their Uses (Unit 0).

<table>
<thead>
<tr>
<th>Name and Number</th>
<th>Location</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Freq&quot;, R3-4</td>
<td>Reached through top panel.</td>
<td>Sets basic prf of the Master MV.</td>
</tr>
<tr>
<td>&quot;Pulse Width&quot;</td>
<td>&quot;</td>
<td>Controls ratio of duration of &quot;On&quot; and &quot;Off&quot; pulses of Master MV.</td>
</tr>
<tr>
<td>R5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name and Number</td>
<td>Location</td>
<td>Application (cont.)</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>&quot;V3 Bias&quot;, R13</td>
<td>Reached thru</td>
<td>Controls Bias on V3, Grid 1.</td>
</tr>
<tr>
<td></td>
<td>top panel</td>
<td></td>
</tr>
<tr>
<td>&quot;V4 Bias&quot;, R18</td>
<td></td>
<td>Controls Bias on V4, Grid 3.</td>
</tr>
<tr>
<td>&quot;V5 Bias&quot;, R23</td>
<td></td>
<td>Controls Bias on V5, Grid 3.</td>
</tr>
<tr>
<td>S 1</td>
<td>Front Panel</td>
<td>Allows Osc. 1 to be operated &quot;CW&quot;, &quot;Pulsed&quot;, &quot;Sawtooth&quot;, or &quot;Audio&quot;.</td>
</tr>
<tr>
<td>S 2</td>
<td></td>
<td>Allows Osc. 2 to be operated &quot;CW&quot; or &quot;Pulsed&quot;.</td>
</tr>
<tr>
<td>S 3</td>
<td></td>
<td>Allows Osc. 3 to be operated &quot;CW&quot; or &quot;Pulsed&quot;.</td>
</tr>
</tbody>
</table>

(d). Controls and Their Uses. (Unit 1).  
(All front panel except as otherwise noted.)

<table>
<thead>
<tr>
<th>Name and Number</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Coarse Delay&quot; S101</td>
<td>Permits variable delay, by steps, in the initiation of the &quot;Sweep&quot;.</td>
</tr>
<tr>
<td>&quot;Fine Delay&quot; R105</td>
<td>Permits continuous variable delay in the initiation of the &quot;Sweep&quot;.</td>
</tr>
<tr>
<td>&quot;Sync&quot; S102</td>
<td>Permits selection of &quot;Sync&quot; input.</td>
</tr>
<tr>
<td>&quot;Sync Ampl.&quot; R111</td>
<td>Controls amplitude of synchronizing pulse.</td>
</tr>
<tr>
<td>&quot;Freq-Coarse&quot; S103</td>
<td>Sets basic &quot;Sweep&quot; rate, by steps.</td>
</tr>
<tr>
<td>&quot;Freq-Fine&quot; R117</td>
<td>Permits continuous variation of &quot;Sweep&quot; rate.</td>
</tr>
<tr>
<td>&quot;Linearity&quot; R124</td>
<td>Permits control of linearity of &quot;Sweep&quot;. (Located on Unit 1 chassis, left center).</td>
</tr>
<tr>
<td>&quot;Audio Ampl.&quot; R125A-B</td>
<td>Controls Amplitude of Audio input.</td>
</tr>
</tbody>
</table>
(e). Controls and Their Uses (Unit 2).

(Application unless otherwise noted.)

<table>
<thead>
<tr>
<th>Name and Number</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;On-Off&quot; S201</td>
<td>Interrupts input of 115 volt, 60 cycle power to unit.</td>
</tr>
<tr>
<td>&quot;Voltage Adjust&quot; R214</td>
<td>Controls bias on V208, hence controls output voltage.</td>
</tr>
<tr>
<td>&quot;Ripple Adjust&quot; R210</td>
<td>Controls ripple voltage in the output. (on upper chassis).</td>
</tr>
</tbody>
</table>

(f). Controls and Their Uses (Unit 3).

(Application)

<table>
<thead>
<tr>
<th>Name and Number</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Repeller Volts&quot;</td>
<td>Controls Repeller Voltage of Oscillators.</td>
</tr>
<tr>
<td>R301-302-303</td>
<td></td>
</tr>
<tr>
<td>&quot;Plate Volts&quot;</td>
<td>Interrupts plate voltage to Oscillators.</td>
</tr>
<tr>
<td>S301-302-303</td>
<td></td>
</tr>
<tr>
<td>S304</td>
<td>Permits selection of input to meter.</td>
</tr>
</tbody>
</table>

(g). Operation of Oscillators.

The Oscillators must be tuned to a desired frequency and to a suitable maximum output before tests are conducted. Two methods to achieve this are immediately applicable:

(1). Throw the controlling switch of the oscillator concerned to "CW". The microwave assembly should include the oscillator, a wavemeter, an attenuator, and a crystal monitor. Connect the coaxial cable from the crystal monitor to one of the monitor input jacks on the Remote Control Unit, placing S104 in such a position as to connect this
Jack to the meter.

Set the attenuator to give several db. attenuation, and make certain that the oscillator probe is fully inserted into the waveguide. Throw the "Plate Volts" switch on the Remote Control Unit to "On" for the oscillator concerned. Now slowly flex the bellows of the oscillator by the control provided, and for each small variation rotate the "Repeller Volts" potentiometer through its entire range. The oscillator should provide r.f. energy at some position of these controls, as will be indicated by a deflection of the meter. If no deflection is noted, slowly reduce the attenuation in small steps.

When a meter deflection is noted, "Peak" this to maximum by means of the "Repeller Volts" potentiometer. Reduce the attenuation until at "peak" the meter shows about two-thirds full scale deflection, if possible.

Slowly rotate the wavemeter knurled knob until the deflection of the meter suddenly drops to a minimum. For an absorption meter this indicates resonance at the frequency of the oscillator. Read the graduated scale and record the frequency either on a basis of wavemeter graduations or by a calibration chart, if provided. Retune the oscillator as necessary to reach a desired frequency.

(2). A second method utilizes an oscilloscope. Proceed as before, with the two exceptions that the oscillator is placed in "Pulsed" operation, and the crystal output is
fed to the vertical amplifier plates of the oscilloscope. A square-wave output will be seen on the screen. Tune for a maximum in the same manner that the meter was used. Tune the wavemeter; its "dip" will now be indicated by a decrease in the amplitude of the square wave as seen on the oscilloscope.

SECTION IV

MAINTENANCE


Before adjusting the Power Supply, interconnect the main unit, and also connect one or two Oscillator Assemblies.

Open the top of the Power Supply to expose TS201. The positive 300-volt supply is on the "front" half of the strip, third pin from the left. Place a voltmeter between this point and ground. On the Remote Control Unit throw all plate voltage switches to the "Off" position.

Rotate the "Voltage Adjust" potentiometer on the front panel of the Power Supply to obtain an output voltage of 300 volts. Rotate the control fully counterclockwise and then fully clockwise. A voltage variation of at least 60 volts either side of 300 should be obtainable. Reset to 300 volts.

At the Remote Control turn to "ON", in succession, the Plate Voltage switches. These close the plate voltage
circuits to the oscillators. As each switch is closed an additional current of 16-20 mA is required from the power supply. As each switch is closed check the output voltage of the power supply. No change should be observed.

Check the negative supply-voltage, which is reached at the pin immediately to the left of the one just used. A voltage of -300 should be noted.

To adjust the ripple output in the positive supply, connect the vertical amplifier plates of an oscilloscope between the positive 300-volt lead and ground. A shielded lead should be used in order to minimize 60 cycle "pick-up". Calibrate the instrument for a deflection of from 50 to 100 millivolts per inch, as is applicable with the individual scope in use.

Open the top panel of the Power Supply to expose the "Ripple Adjust" potentiometer, which is located on the top chassis. Rotate this, observing the ripple on the screen. The ripple should decrease; go to zero, and reverse phase. Reduce it to zero and leave the potentiometer at that setting.

(b). Master Multivibrator.

After adjusting the power supply, open the top panel of the Signal Generator case to make available the screwdriver controls. Insert a test probe from the oscilloscope to Tst. 1, which will permit one to observe the plate wave
form of V3.

Connect an Audio Oscillator across the Horizontal Amplifier inputs of the scope and use this oscillator to drive the sweep. Adjust the oscillator rate until a fixed single pattern is observed. Note the pulse repetition frequency. The Signal Generator is normally adjusted for prf of approximately 75 cps.

For most operations, it is desirable that the plate wave of V3 should have the characteristic that its "On" time [i.e., plate voltage minimum] is one third of the period. In such case the "down" portion of the plate wave will be one-half as long as the "up" portion. If these are not in this proportion, adjust the "Pulse Width" to make it so, adjusting as necessary the "Freq" control to hold the prf close to 75 cps. (a variation of plus or minus 10 cps is acceptable).

The pulse seen at Tst. 1. should be very square both at the top and bottom. If the pulse is not square it may normally be improved by use of "V3 Bias" potentiometer.

Now check the pulses of V4 and V5 as seen at Tst.2 and Tst. 3. These should be clean and square at the top and bottom. If these are not square, improve them with use of "V4 Bias" and "V5 Bias". Fuzziness on the edge may normally be eliminated with some changes in "Pulse Width" and "Freq".

Although the basic prf is not critical within a con-
siderable range, it is well to keep it several cycles away from 60 cps because of danger of interaction due to line voltage pickup.

When checking the pulse shape and width, one must use the Internal Sweep of the scope. By simply switching the horizontal amplifier switch to "Off", with the Audio Oscillator still connected to the Horizontal Input, a quick check of prf may be made.

(c). Square-Wave Generator and Oscillator Control Tubes.

Most of the information explaining how to properly adjust the Square-Wave Generator has been given in Section IV(b). After the three outputs have been checked, one may proceed to the checks of the Oscillator Control Tubes, V6, V7, and V8.

The outputs of these tubes may most easily be seen at the output plugs of the Remote Control Unit. Place S1, S2, and S3 in "Pulsed" position. Now place a probe from the oscilloscope on the "Rep" pin of P302, P303, and P304, in succession. A square wave similar to that seen at Tst 1, 2, and 3, with the exception that each will have been inverted, should be seen. The amplitude should be considerably less than that at Tst 1, and should be capable of variation by the "Repeller Volts" potentiometers. If the expected output pulse is not seen, it will be necessary to open the Signal Generator, remove the upper chassis, and test directly at Pin 8 of V6, etc.
CAUTION: C9 AND C10, 60-MICROFARAD CAPACITORS, ARE CHARGED TO A HIGH NEGATIVE VOLTAGE. PERSONNEL PROTECTION IS OBTAINED BY MEANS OF A SHIELDING CAN, BUT THE OUTPUT TERMINALS ARE EXPOSED ON THE UNDER SIDE OF THE CHASSIS TO R38 AND R42, 1 MEGOHM RESISTORS. IT TAKES ABOUT FIVE MINUTES FOR THESE CAPACITORS TO COMPLETELY DISCHARGE AFTER THE POWER IS TURNED OFF. IN CASE UNIT C IS REMOVED FROM THE CASE, THE OUTPUT LEADS FROM THESE CAPACITORS (BRIGHT RED LEADS) SHOULD BE SHORTED TO GROUND.

After the "Pulsed" position has been checked and found properly operating, a check should be made of Oscillator #1 as it has two other additional modulations. Place S1 in the "Sawtooth" position, and test with the probe as before at the Remote Control Unit. A linear sawtooth wave, which can be varied by the "Repeller Volts" potentiometer, should be seen. If this wave is not visible, check the output at the "Sweep" terminal on the upper right corner of the front panel of Unit 1. If the "sweep" is visible here but not at the Remote Unit, some error has developed in interconnections.

After the "Sawtooth" modulation has been checked, check the "Audio" position of S1, with the probe at same point in Remote Control Unit. Inject an audio frequency signal into the Audio Input jack of Unit 1, turn the Audio Ampl. control fully clockwise and observe the output on the oscilloscope. An audio signal, variable from zero to several volts in magnitude, should be visible. If this is not visible,
difficulty probably exists in the Audio Amplifier of Unit 1.

(d). Delay Multivibrator, V101.

This circuit may best be checked by removing Units 0 and 1 from the case. (Note - Remember CAUTION on capacitors). Test the waveforms at the pin as indicated.

Using the output of Test 1 as a reference, since its time duration, based on the prf, is known, check the width of the plate pulse of triode 2 of V101. This may be observed at pin 2. By means of S101 (Coarse Delay) and R105 (Fine Delay) this plate pulse should be variable from about 500 to 6000 microseconds.

(e). Sweep Generator.

Leave units 0 and 1 removed from the case. Connect the "Sweep" output of Unit 1 to the vertical amplifier inputs of the scope. Turn S102 (Sync) to INT; turn R111 (Sync. Ampl.) fully counterclockwise, reducing the Sync Amplitude to zero.

V104 and V105 should now "free run". By means of S103 (Coarse Freq) and R117 (Fine Freq) vary the frequency and observe the output. A sawtooth with a rapid exponential rise and a slow exponential drop should be observed.

R124 (Linearity) determines the plate voltage of V105 and hence the grid voltage of V104. This potentiometer is located on the chassis of Unit 1, left middle. Rotate this, observing the sawtooth output, having first obtained
a sweep speed of 60-90 cps. An improvement in linearity may be observed, but the resistance in this circuit is critical and too great rotation will throw the circuit out of operation. Adjust the potentiometer for good linearity but compromising as necessary to obtain consistent sweep voltages at all points. (Note: The sweep generator does not operate at the higher numbered positions on the switch).

With the basic perf of the sweep generator in the region of 60-90 cps, slowly increase the Sync Amplitude. The sweep should "lock in" with Hill (Sync. Ampl.) increased to not more than mid-position. A slight change in the Fine Frequency control may be needed to bring the basic rates close enough together for proper synchronizing.

(f): Audio Amplifier.

This may be checked in the conventional manner by connecting a known audio voltage (about 7-10 mv) to the input and checking the output with meter and scope.
SECTION V

SCHEMATICS

Figure 2A: Units 0 and 1.
Figure 2B: Units 2, 3, and 4.
# APPENDIX II

## PHOTOGRAPHS

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<tr>
<td>III. Power Supply</td>
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<td>IV. Signal and Test Generator</td>
<td>95</td>
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<tr>
<td>V. Remote Control Unit</td>
<td>96</td>
</tr>
</tbody>
</table>
I. Equipment Assembly, Standing Wave Measurement
II. Oscillator Assembly:
III. Power Supply
IV. Signal and Test Generator
V. Remote Control Unit