Wide-band rapid-following AFC system for MZPI

Hudson, A. C.; Milne, A. R.; Westby, R. L.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/21272384
Report (National Research Council of Canada. Radio and Electrical Engineering Division : ERA); no. ERA-264, 1954

[redacted]

ERA-264

NATIONAL RESEARCH COUNCIL OF CANADA

RADIO AND ELECTRICAL ENGINEERING DIVISION

WIDE-BAND RAPID-FOLLOWING AFC SYSTEM FOR MZPI

A. C. HUDSON, A. R. MILNE AND R. L. WESTBY

OTTAWA

FEBRUARY 1954

ABSTRACT

A new automatic-frequency-control system for the MZPI (AA No. 4 Mark 6) is described; the system includes both electronic control of the local-oscillator reflector and automatic motor tuning of the local-oscillator cavity. A following rate of 40 megacycles per second per second has been obtained. A search function has been included which will permit locking on the correct sideband in six seconds. The operating frequency range of the system is determined by the tunable magnetron used and is 200 megacycles per second in this application.

CONTENTS

FIGURES

FIGURES (Cont'd)

WIDE-BAND RAPID-FOLLOWING AFC SYSTEM FOR MZPI

I - INTRODUCTION

The radio-frequency components and the automatic frequency control system of an S-band radar, MZPI (AA No. 4, Mark VI), have been modified to permit operation at any frequency between 2700 and 2900 megacycles per second, as contrasted with the present fixed-frequency operation. This wide-band operation, which is essentially an anti-jamming measure, is achieved with the use of tunable magnetron Type RK-5586. The present report describes an automatic-frequency-control system which will function over the 200-megacycle band, and permit uninterrupted operation of the radar while the frequency is changing. A search function is also included in the system, so that if the radar is initially mis-tuned, the local oscillator will search and lock on the correct sideband in a maximum time of six seconds.

II - OPERATION OF THE CIRCUIT

OPERATING PRINCIPLES

Fig. 1 is a block diagram of the system. There are two alternative modes of operation which may be identified as "normal" and "search".

In the normal, or locked condition, the radar is on tune and is operating. Diode switch A is closed, and diode switch B is open. In this condition the system is ready to respond to, or is responding to, a change in magnetron frequency.

In the search condition, the radar is not tuned; diode switch A is open and diode switch B is closed. The motor is turning continuously and is driving the local oscillator, by means of a cam, over a band of approximately 220 megacycles. The 220-megacycle band is searched in about 5.5 seconds and the plunger is returned in about 0.5 second.

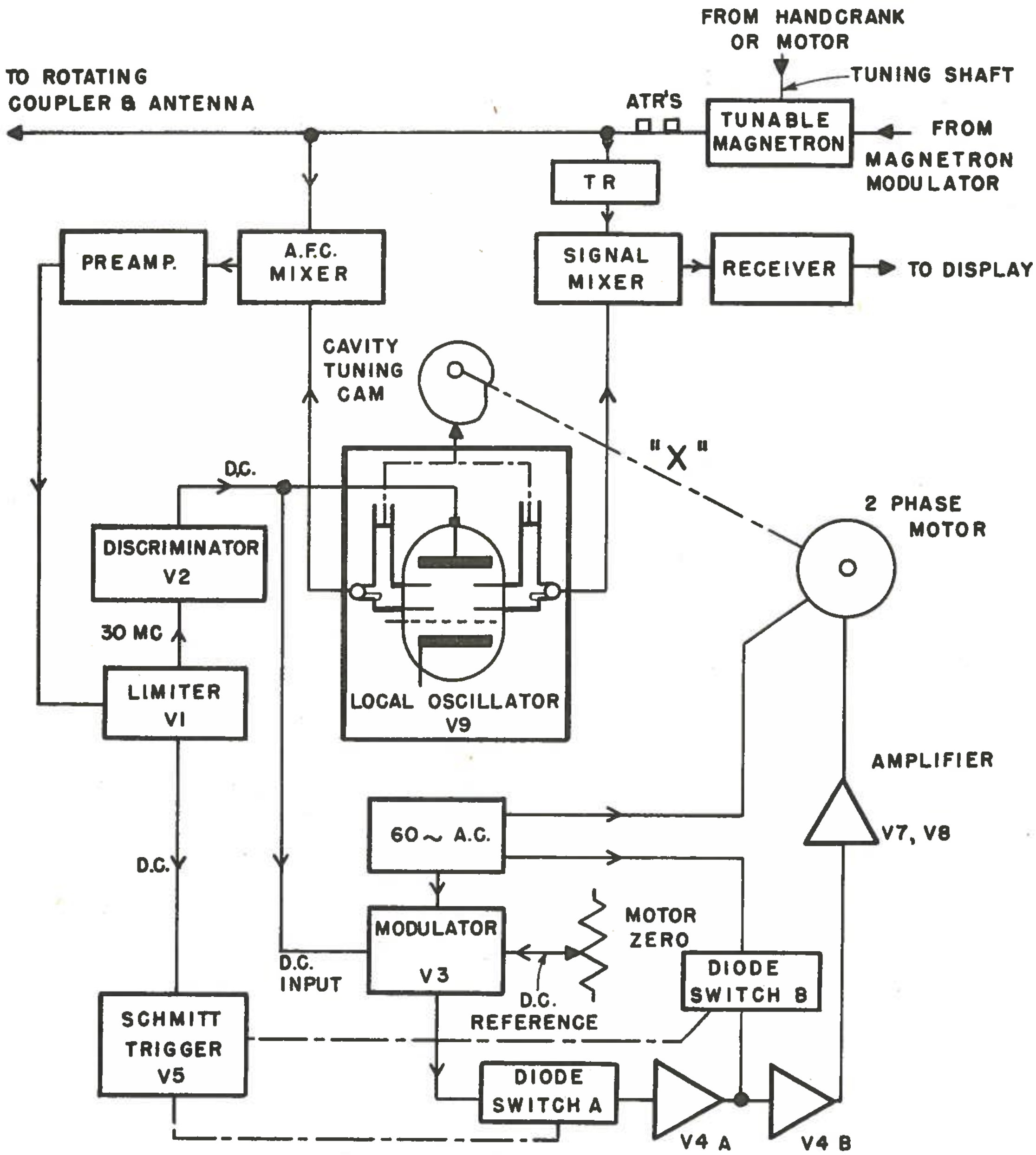


FIG. 1

SIMPLIFIED BLOCK DIAGRAM OF A.F.C. SYSTEM

SECRET

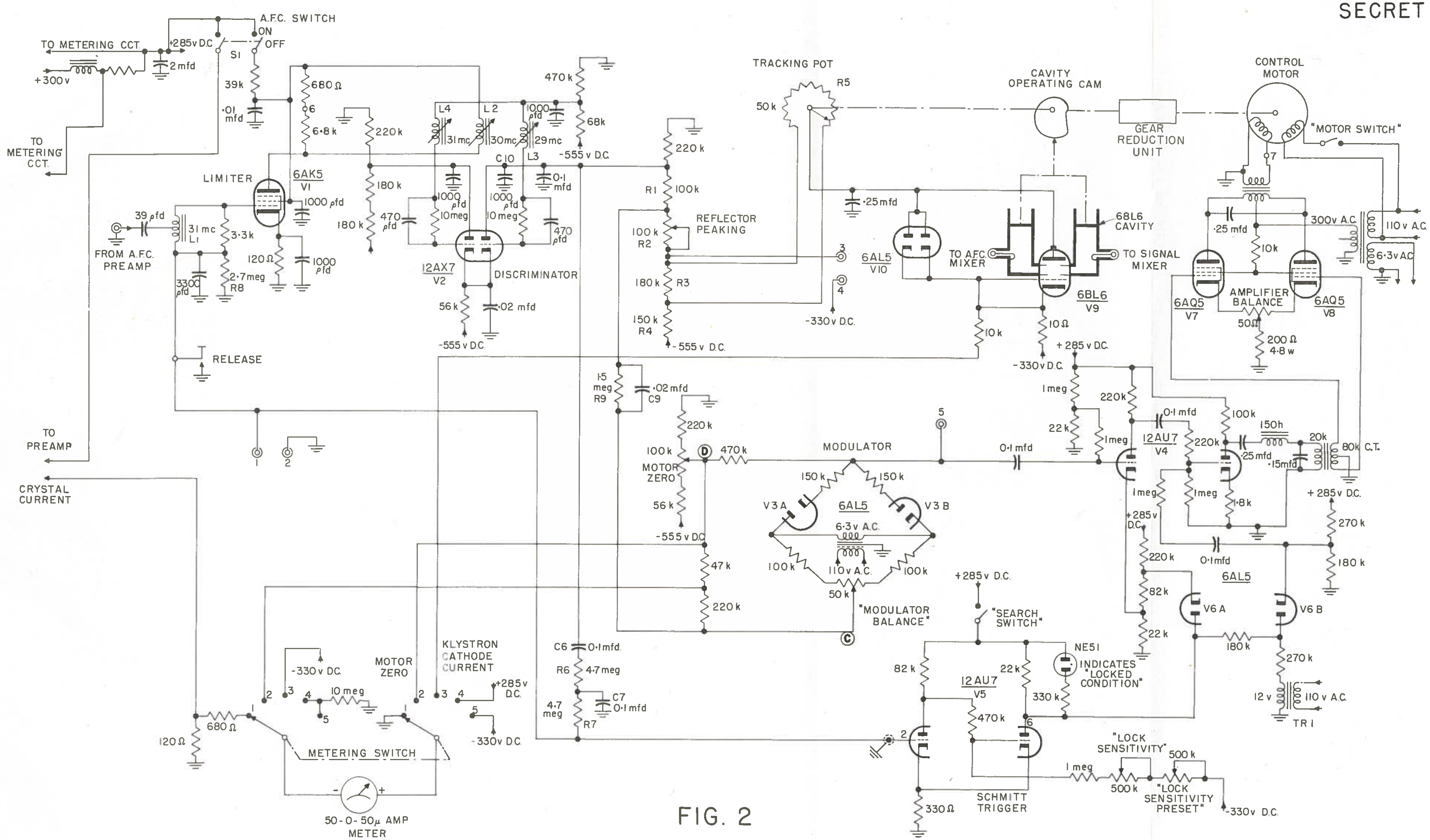


FIG. 2

SCHEMATIC OF A.F.C. CIRCUIT

In the normal condition, and with the magnetron frequency constant, the automatic-frequency-control mixer, the limiter, the discriminator, and the local oscillator may be considered to comprise a conventional automatic-frequency-control loop. It should be noted, however, that there is a d-c connection from the discriminator output to the modulator bridge, as well as to the klystron reflector (see Fig. 1).

As in normal AFC operation, the output voltage of the discriminator will have its quiescent value when the radar is tuned exactly, and it will also assume its quiescent value regardless of the radar tuning if the discriminator input signal is removed by opening switch S_1 (see Fig. 2).

The d-c reference input to the bridge (see Fig. 1) is adjusted to be equal to the quiescent d-c input from the discriminator. The bridge generates a 60-cycle output proportional in amplitude to the difference between the two d-c inputs, and with phase determined by the polarity of this difference. For the tuned condition there is no 60-cycle output from the modulator, and even though diode switch A is closed, the local-oscillator tuning motor is at rest.

If the magnetron is tuned to a new frequency, the AFC loop will reach a new equilibrium with a new reflector voltage, and the net d-c input to the modulator will no longer be zero. The amplified modulator output voltage will appear at the motor terminals, and if this voltage is large enough it will operate the local-oscillator tuning motor and hence tune the cavity. The sense of this cavity-tuning adjustment is determined so that the resulting frequency shift is in the same sense as the original electronic frequency shift caused by the reflector voltage change. Thus the discriminator need no longer apply as much electronic frequency shift. The new equilibrium voltage of the reflector is now close to its initial value and the modulator input is essentially zero. The motor will then stop until there is a further change in magnetron frequency.

In the normal operating condition described above, the function of the Schmitt trigger has been to close diode switch A, and open diode switch B. During the search operation, however, the local oscillator is not tuned, and there is no intermediate frequency input to the limiter and hence no d-c input to the Schmitt trigger. The Schmitt trigger will be in its second stable state in which diode switch A is open and diode switch B is closed. The motor will then receive a constant 60-cycle voltage which causes the local oscillator to search over the 220-megacycle band in about six seconds. When the local oscillator reaches the correct frequency (30 megacycles per second below the magnetron frequency) a voltage will appear at the limiter and the Schmitt trigger will operate, stopping the search and instituting the normal condition previously described.

The method of rejecting the incorrect sideband condition — that is, when the local-oscillator frequency is 30 megacycles per second above the magnetron frequency — will be described later.

The basic idea of the system described in this report when it is in its normal operating condition (control of both the klystron reflector and tuning motor from the discriminator output), was proposed at TRE (Page 35 of Ref. 1), although in a somewhat different form than is employed here.

In the normal condition the nominal 30-megacycle automatic-frequency-control signal is fed from the AFC preamplifier through the limiter, V_1, and to the discriminator, V_2. (see Fig. 2). The discriminator output voltage is fed to the reflector of the klystron, V_9, by means of the bleeder network, $R_1R_2R_3R_4$, and the tracking potentiometer, R_5.

During normal operation when the magnetron is not being tuned, the potential at point C, Fig. 2, is equal to the potential at the rotor of the motor-zero potentiometer. Under this condition the net d-c input to the modulator is zero, and the modulator (consisting of V_3 and its associated components) will feed no appreciable 60-cycle voltage to the amplifier, V_4- V_7- V_8, and the klystron tuning motor will be at rest. Let it be assumed that the magnetron is steady at a frequency of 2800 megacycles per second. The correct sideband has been chosen arbitrarily so that the local-oscillator frequency is below that of the magnetron. The local oscillator then will be operating at a frequency of 2770 megacycles per second. Referring to Fig. 3, it may be assumed that the system is in equilibrium at point "O". If, now, the magnetron frequency increases 0.15 of one megacycle, normal electronic automatic-frequency-control will create a corresponding increase in the local-oscillator frequency. The loop gain of the electronic automatic-frequency-control is about 8, and therefore the local-oscillator will move to its new frequency of 2770, plus approximately 0.15 megacycle — the 0.15 megacycle being in error by about 1/9th of 0.15 megacycle. The operating point has now moved to "B" in Fig. 3, as in conventional AFC systems. It may be seen that the operating point is approaching the broken line marked "-96 volts". This line represents the required deviation of the reflector voltage from its quiescent value of -95 volts needed to generate the critical 60-cycle signal level at the input of the motor amplifier, V_4, which will overcome the static friction in the motor and gear-box. As the magnetron frequency is raised further — say to 2800.2 megacycles per second — and the operating point "B" crosses the broken line, sufficient

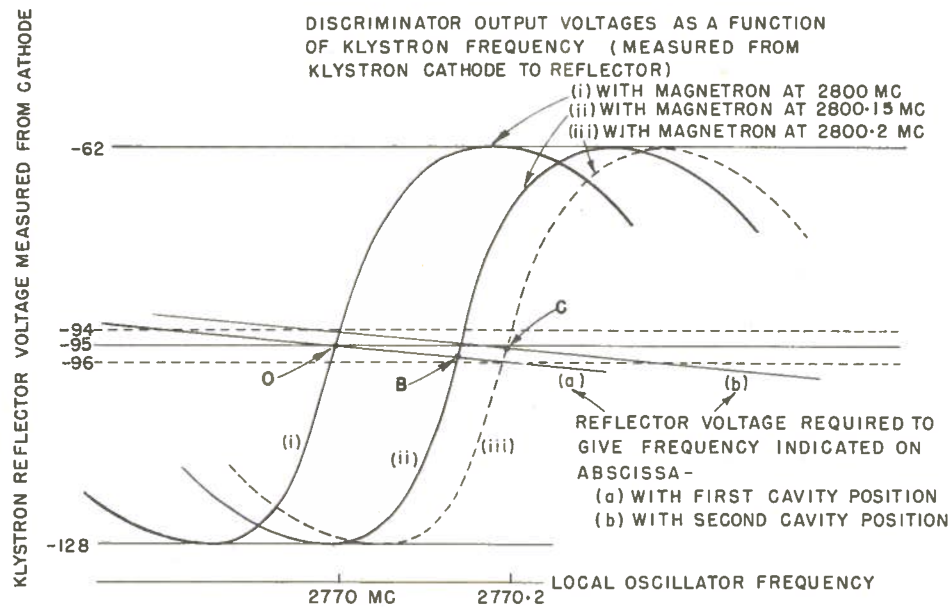


FIG. 3

BASIC AUTOMATIC FREQUENCY CONTROL OPERATION

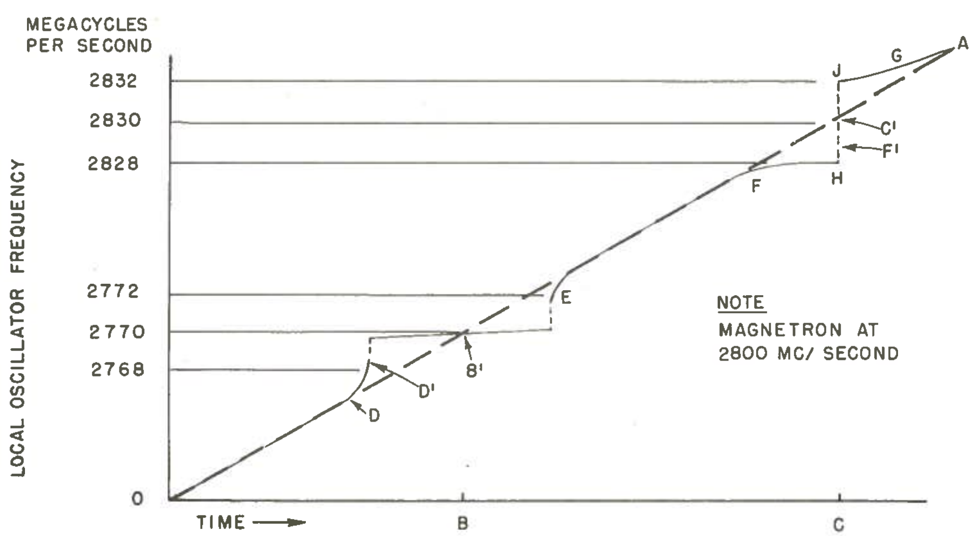


FIG. 4

DISCRIMINATOR ACTION AS CAVITY IS CONTINUOUSLY TUNED voltage is now available to cause the motor to turn. The motor will then tune the cavity in such a direction as to raise the local-oscillator frequency. The cavity now having been changed, the electronic frequency correction required of the AFC system is reduced. The reflector voltage characteristic (a) no longer applies for the new cavity position. Curve (b) will correspond to the new position of the local-oscillator cavity. The new operating point will now be "C", somewhere between the two broken lines.

V_5 comprises a Schmitt trigger (Ref. 2) circuit which has two stable states. In the normal state just described, the first half of V_5 is cut off by the negative bias on its grid. This bias is derived from the grid leak detector action in V_1, and is present only during the normal state when the radar is on tune and the nominal intermediate-frequency of 30 megacycles per second is being generated. The second half of V_5 is in a conducting state, with the result that the potential of pin 6 of V_5 is about 80 volts above ground. Both plates of diode V_6 are at a potential well below their cathode, with the result that both halves of V_6 are in effect removed from the circuit and have no influence on the operation of amplifier V_4.

In the "search" condition, which takes place when the negative bias is removed from pin 2 of V_5, the Schmitt trigger transfers to its other state in which the first half of V_5 is conducting, and the second half is cut off. Under these conditions the potential at pin 6 of V_5 rises to about 225 volts above ground. This change of state of the Schmitt trigger has two effects: firstly, through diode V_6A a large positive bias (45 volts) is placed on the cathode of amplifier tube, V_4A. This voltage cuts off amplifier V_4A with the result that the servo-amplifier will obtain no signal from the modulator, V_3. The second effect of the change of state of the Schmitt trigger is associated with diode V_6B. The plate of this diode is now sufficiently positive that a small 60-cycle voltage from the transformer, TR1, may pass through this diode and to the grid of amplifier V_4B. The effect of this constant a-c signal is to rotate the local-oscillator cam, and consequently the local oscillator will search over about 220 megacycles in a period of approximately 6 seconds.

If the radar is initially mistuned, the intermediate frequency will not be near 30 megacycles per second, and as a consequence there will be no bias on the grid of tube V_5A. The Schmitt trigger will then be in the search condition, and the local-oscillator frequency will sweep continuously from about 2660 to 2880 megacycles per second with a fast return. It will be assumed now that the local-oscillator approaches the correct frequency — that is, 30 megacycles per second below the magnetron frequency — bias will appear on the grid of tube V_5A, and the Schmitt trigger will switch from "search" to normal (locked-on) operation.

METHOD OF LOCKING ON CORRECT SIDEBAND ONLY

Reference will now be made to Fig. 4, which is a plot of local-oscillator frequency as a function of time. The broken line, OA, represents the local-oscillator frequency during search, under the assumption that the electronic AFC has been disconnected, e.g., switch S_1 (Fig. 2) "A-F-C ON/OFF" is in the "OFF" position. Assuming that the magnetron is operating at 2800 megacycles per second, point B (Fig. 4), represents the instant in time when the local-oscillator is at the correct frequency; whereas point C represents the instant in time when the wrong sideband is being received. When the electronic AFC is turned on, the local-oscillator frequency during a rotation of the operating cam is represented by the discontinuous solid curve, instead of the broken curve OA. It is important to note that at points D and E on this curve the frequency is pulled by the electronic AFC operating on the klystron reflector in a direction towards the correct frequency, while at points F and G the frequency is pulled away from the correct frequency. The fact that these two cases are fundamentally different is not a desired condition, but rather is a natural consequence of conventional discriminator circuits operating on the local-oscillator of a superheterodyne system. If this difference did not exist, then both sidebands would be equally suitable for operation, and there would be no "wrong sideband" problem.

Searching and locking on the correct sideband will now be described with reference to Fig. 4. During search the local-oscillator frequency follows the solid curve from O to D, and beyond. The dotted portions of the curve at D' and E represent a snap action where the loop gain of the electronic AFC exceeds unity and the AFC pulls in. At a point D' the Schmitt trigger will operate from "search" to "normal", and stable AFC locking will result at point B'.

The method of avoiding the wrong sideband, as described by Ratcliffe (Page 33 of Ref. 1) is interesting in that it requires no extra components. In other words, rejection of the wrong sideband is inherent in proper setup of the system just described.

The local-oscillator will search through the incorrect sideband without locking as described below. As the local-oscillator approaches the incorrect sideband it will search to a point F. If the local-oscillator frequency were to proceed slowly along this curve to point F' the Schmitt trigger would operate. However, it is to be noted that the curve HJ is essentially vertical. In other words, this portion of the curve is traversed very quickly, a snap action taking place between H and J. For this reason the Schmitt trigger will not operate and the search will continue from J onward.

As a further precaution against locking on the wrong sideband, the network C_6, C_7, R_6, R_7 has been added to the circuit (Fig. 2). Briefly the function of this network is to place on the grid of V_5A a voltage conducive to Schmitt trigger operation when the correct sideband is approached from the lower-frequency direction, and a voltage inhibiting Schmitt trigger operation when the incorrect sideband is similarly approached. It will be observed that the correct polarity of voltage to obtain this effect is present on the plate of discriminator tube V_2B. The circuit constants were determined experimentally on a completed system.

As one further aid to wrong sideband rejection, the input circuit, coil L_1, is tuned to 31 megacycles per second. This circuit is rather broadly tuned, and reference to Fig. 4 will show that at point D' where Schmitt trigger operation is desired, the intermediate frequency is above 30 megacycles per second, while at point F' where Schmitt trigger operation is not desired, the intermediate frequency is below 30 megacycles per second. It will be seen that tuning this circuit to 31 megacycles per second will discriminate in favour of operation on the correct sideband, as long as the search is carried out in a direction from low to high frequencies.

Figs. 5 and 6 represent measured discriminator output voltage as the cavity is tuned by hand (with the motor switch off). They may be compared with the corresponding parts of Fig. 4 which is in an idealized form.

It is interesting to note the very small portion of the discriminator range which is employed (see Fig. 5). In a conventional AFC system with no motor control the operating range would cover the complete region A-B.

LIMITER

Tube V_1 (see Fig. 2) comprises a conventional limiter stage with its input circuit arranged to be similar to the corresponding input circuit on the MZPI. It also functions as a cumulative grid detector, building up about 3 volts d-c across R_6 for operation of the Schmitt trigger.

CONFIDENTIAL

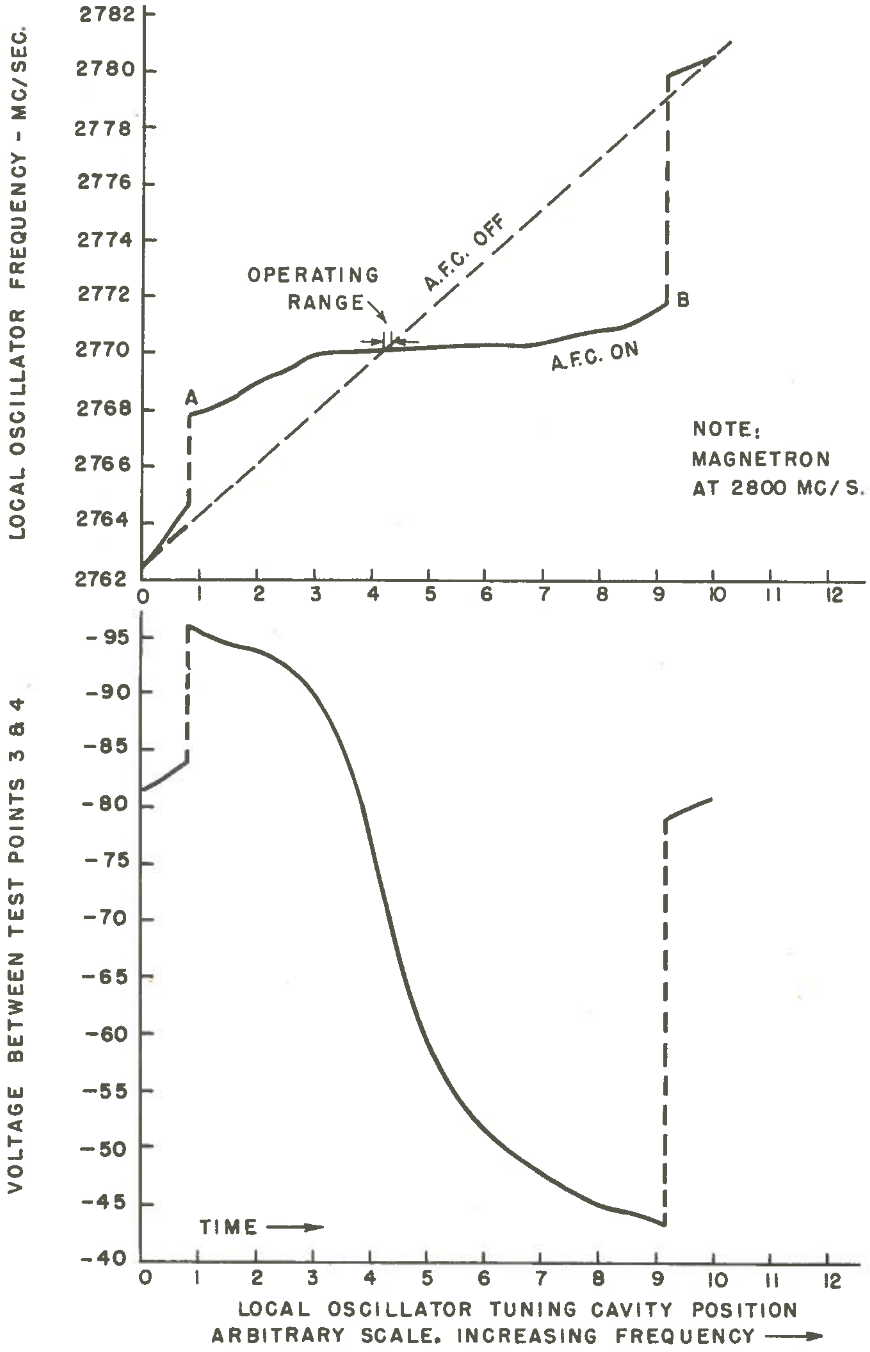


FIG. 5

ELECTRONIC A.F.C. OPERATION AS CAVITY IS DRIVEN THROUGH CORRECT SIDEBAND

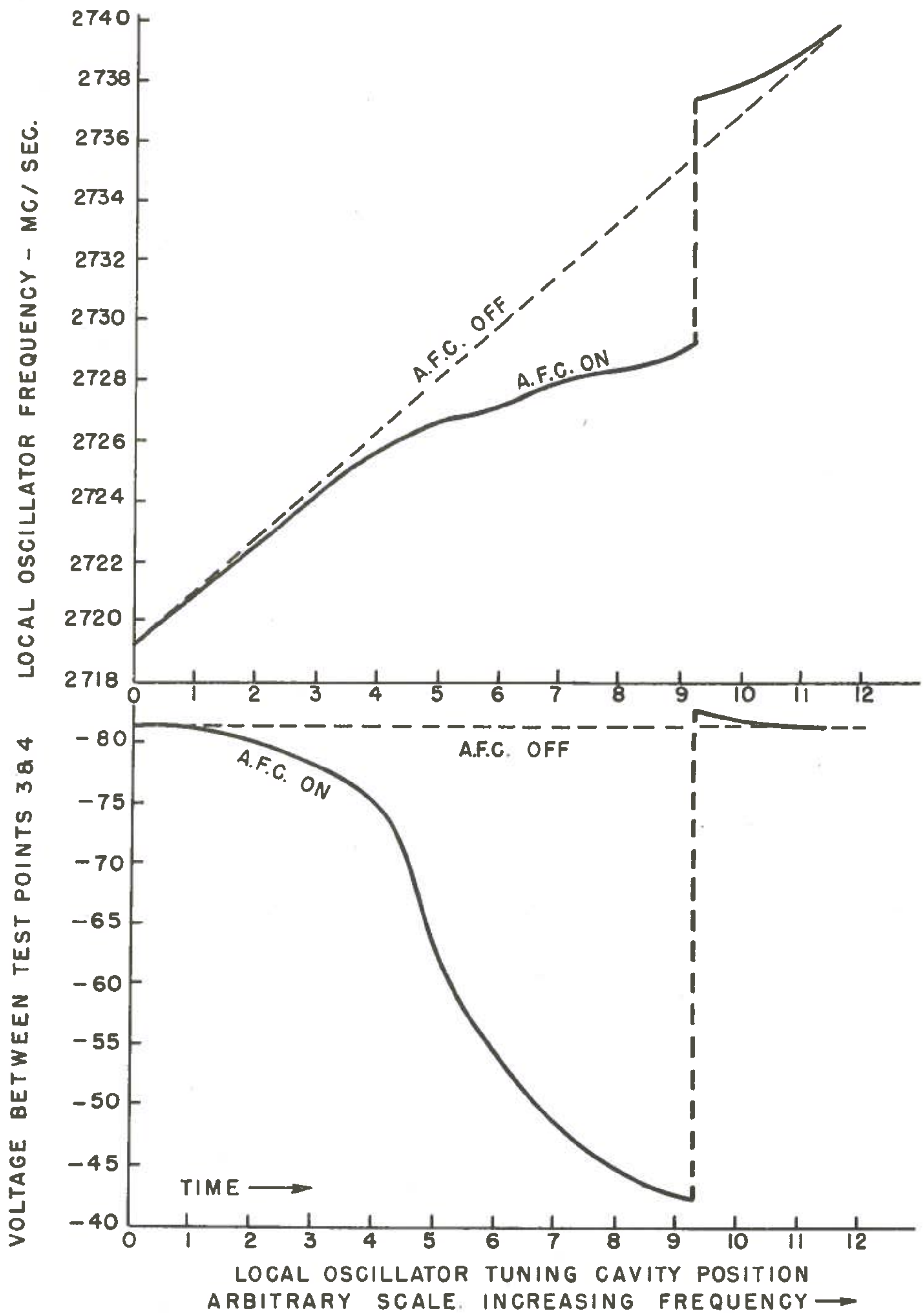


FIG. 6

REJECTION OF WRONG SIDEBAND DURING SEARCH CYCLE

DISCRIMINATOR

It will be obvious that d-c drift in the discriminator output would prevent proper operation of the system, since there is a d-c connection from the discriminator output to the modulator bridge. Because of this difficulty, a new discriminator circuit was devised (see Fig. 7). The radio-frequency coil assembly has been arranged to be similar to the assembly now in production on the MZPI. This was done for simplicity in manufacturing. It is likely that the phase discriminator type of radio-frequency coil assembly could be adjusted more easily* — this being the conventional advantage of a phase discriminator over an amplitude discriminator. The operation of this discriminator can be considered as the sum of three effects: — (1) the cumulative grid detector action, (2) the differential amplifier (also known as "cathode-coupled amplifier" or "long-tailed pair") operation associated with the large common-cathode resistor, and (3) the effect due to the fact that the cumulative grid detector action of each tube is modified by a bias derived from the other tube. The output curve of this discriminator has a peak-to-peak swing of about 130 volts, which, when referred to the klystron reflector is reduced to 65 volts. The output characteristic of this discriminator and limiter combination is shown in Fig. 8. Fig. 9 shows the test conditions under which this curve is plotted. Similar tests made with a 3,000-megacycle signal generator gave a smooth curve, and hence the variations in the data of Fig. 8 were attributed to the test apparatus. It will be noted that the frequency characteristic of the preamplifier is included in the curve.

The advantage of the differential amplifier connection is d-c stability. Any sources of drift which can be assumed to appear in phase on each grid of the discriminator tube will not appear in the output. In practice, it has been found that when once adjusted, no day-to-day adjustment of the "motor zero" control is necessary. A differential amplifier has been used in the British Cockcroft discriminator (see Fig. 23 of Ref. 1). If it is desired to make the complete voltage swing of the discriminator available on the reflector of the klystron, various circuit arrangements are possible. However, they all have disadvantages and there is adequate swing in the present circuit so that tapping down by means of the bleeder network shown in Fig. 2 is satisfactory. The reflector operating voltage is adjusted by control R_2.

* A phase discriminator version of the circuit is described in Appendix II.

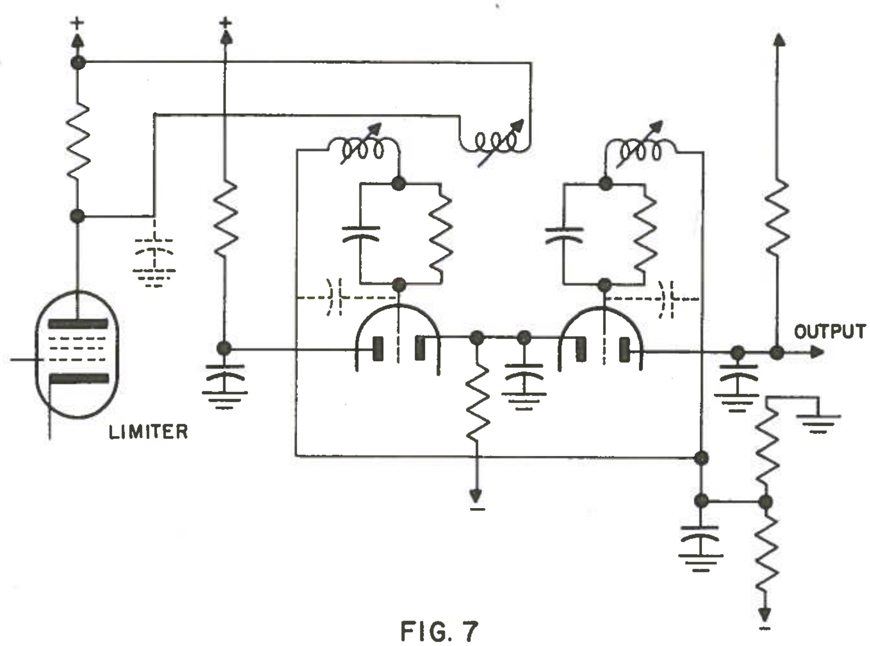


FIG. 7

BASIC DISCRIMINATOR CIRCUIT

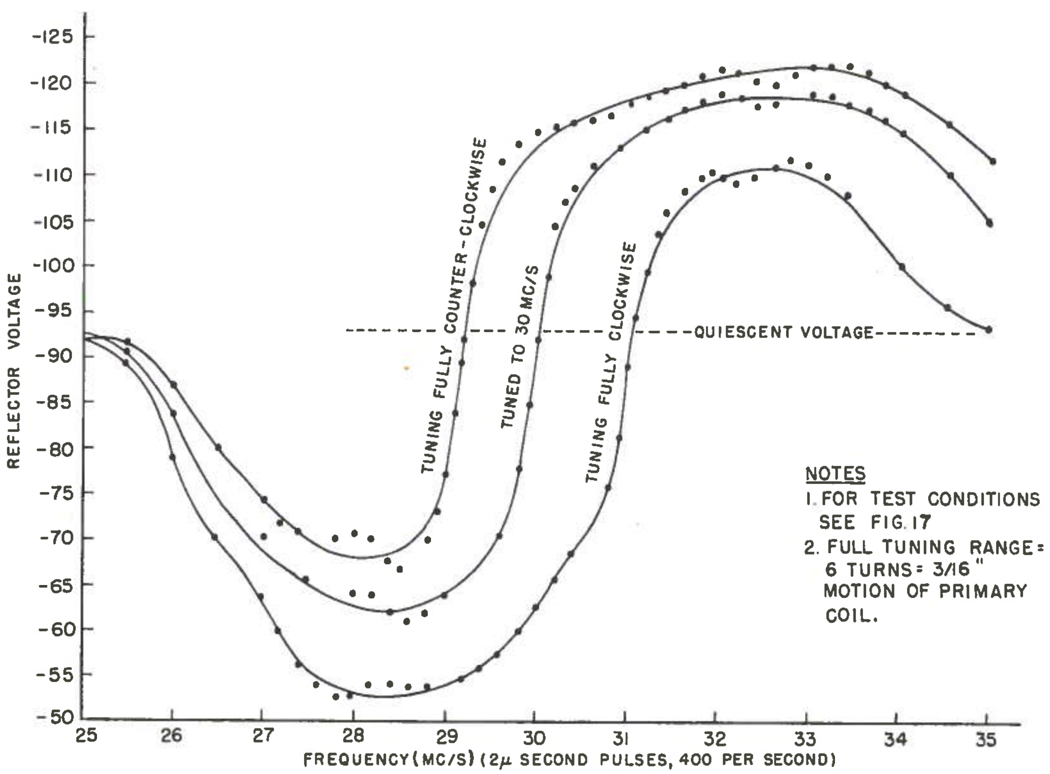


FIG. 8

DISCRIMINATOR CHARACTERISTICS

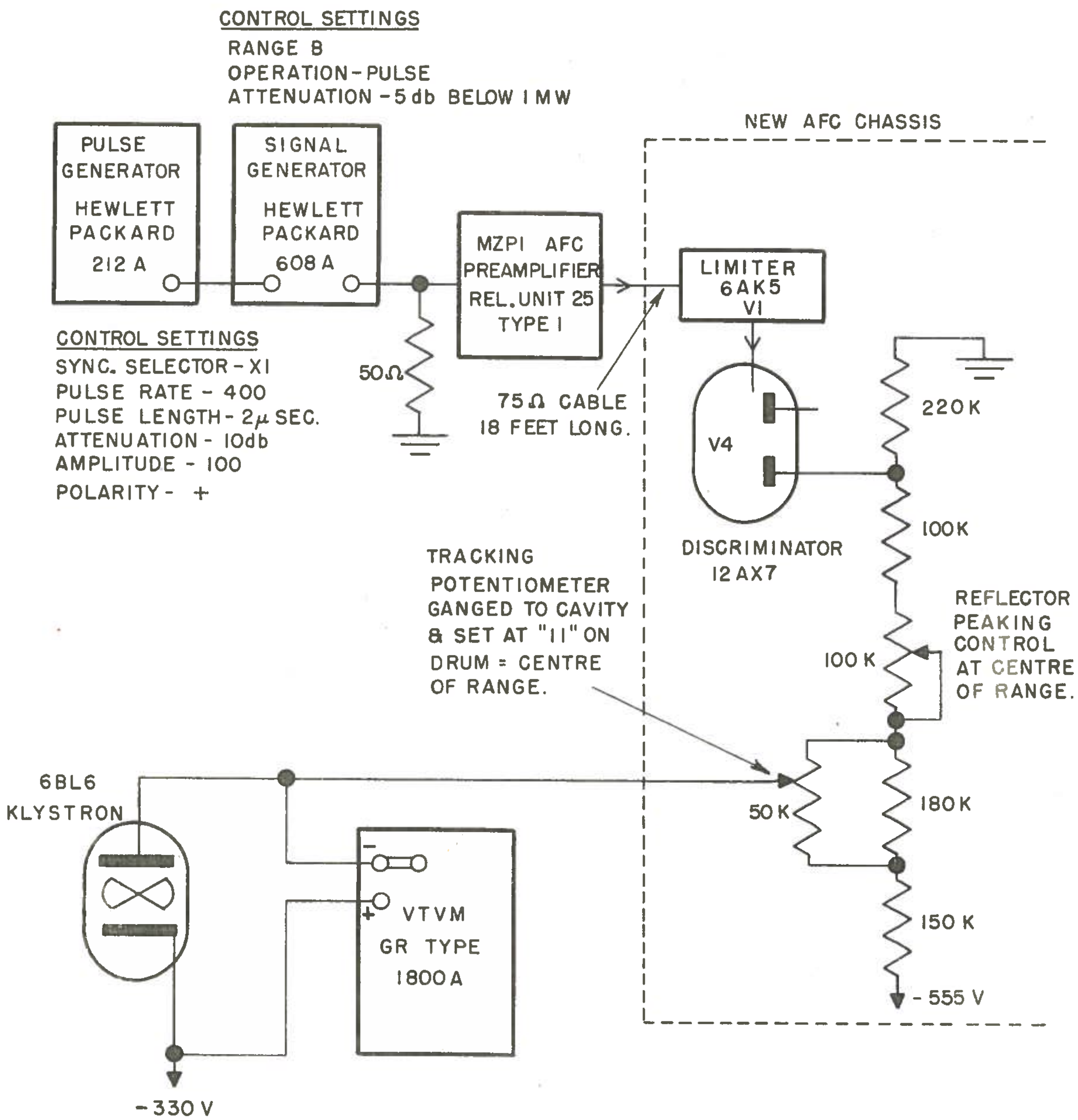


FIG. 9

ARRANGEMENT OF TEST INSTRUMENTS

TRACKING

In the discussion of the circuit so far, for simplicity it has been assumed that the reflector voltage necessary to maintain klystron oscillation at its full value — in other words, at the peak of the mode — does not change with cavity tuning. Unfortunately, however, it is a property of klystrons that the optimum reflector voltage becomes more negative as the operating frequency is increased. This is compensated for automatically by means of the tracking potentiometer, R_5, which is driven mechanically from the shaft which drives the klystron cavity-operating cam. This potentiometer may be seen in the photographs, Figs. 10 and 11.

Operation of the circuit can be explained without special consideration of the tracking problem, if it is assumed that the combination of the klystron and a correctly adjusted tracking potentiometer results in a fictitious klystron which, when referred to some such point in the circuit as Test Point 3, for example, does not require any change in reflector voltage along with cavity tuning in order to maintain oscillation at maximum output. More complex systems for tracking, such as three-point tracking, could be employed, but the simple circuit shown has been found satisfactory.

Fig. 12 is a simplified schematic of the discriminator output circuit, including the tracking potentiometer.

Fig. 13 shows klystron reflector voltage as a function of position of the tracking potentiometer. Data are shown for four typical klystrons operating in the $2\frac{3}{4}$ mode, as well as the limits of voltage obtainable with the reflector adjustment R_2.

It is not necessary, or even desirable that the klystron reflector voltage be at the peak of the mode. Reference to Fig. 14 will show that two-thirds or more of full klystron power will be obtained over a range of at least 20 volts. The best operating point is well to the left of the peak and it is usually found that the fully counter-clockwise position of the reflector control is satisfactory.

The range of the control has been made small to reduce the possibility of incorrect adjustment.

Operating to the left of the peak is desirable, because of the asymmetry of the klystron characteristics, and also because of the serious hysteresis.

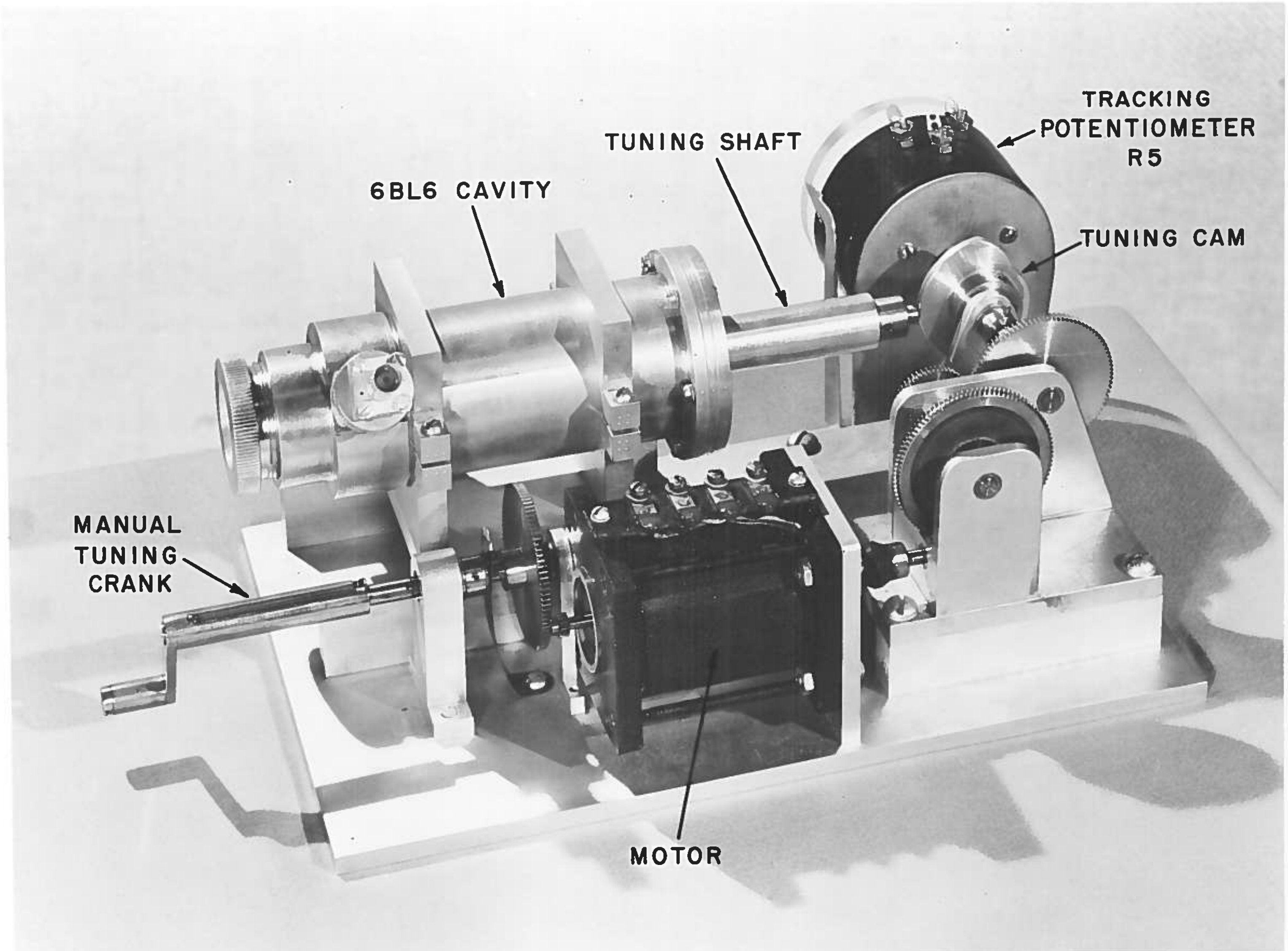


FIG. 10

KLYSTRON CAVITY AND DRIVE

CONFIDENTIAL

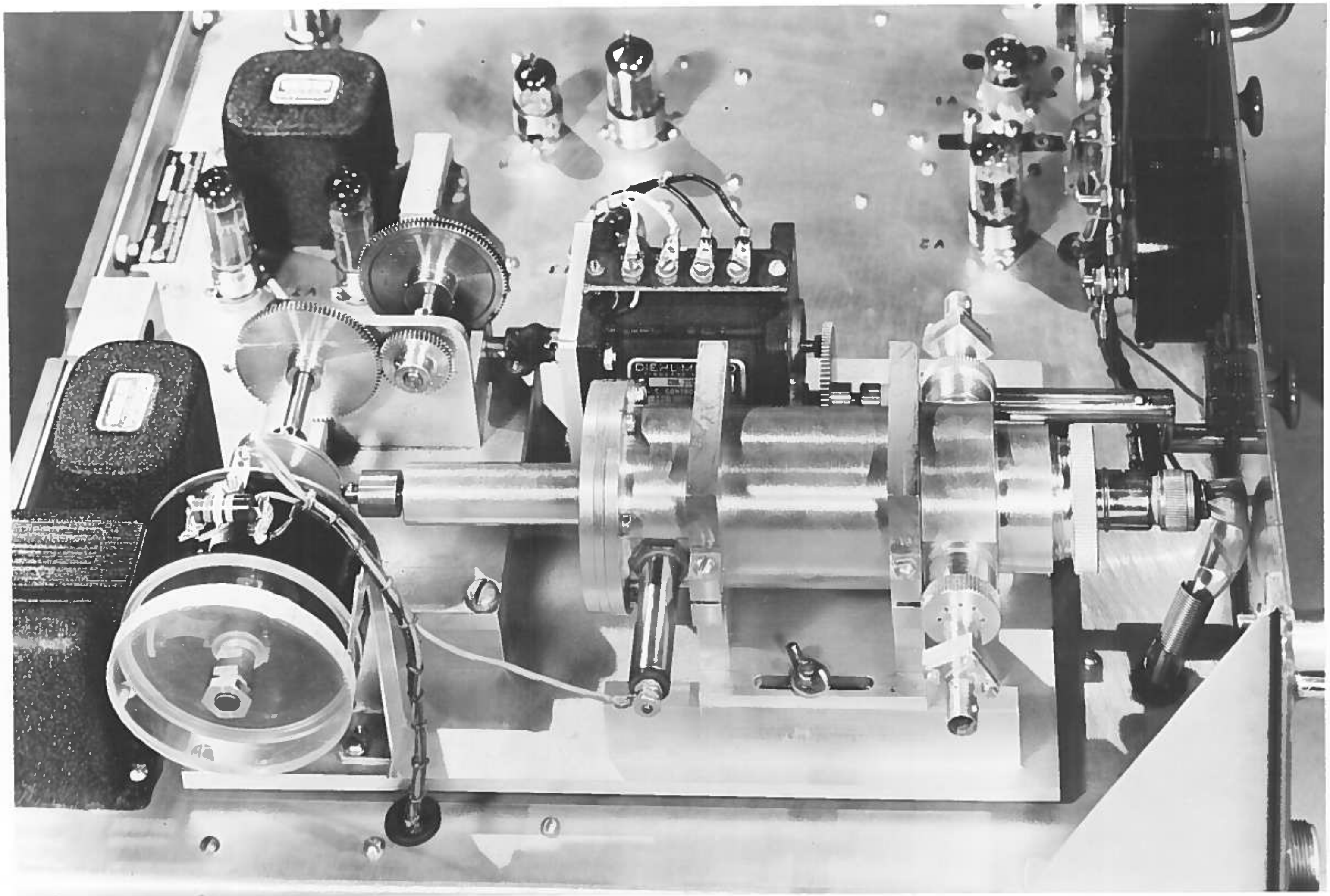


FIG. 11

KLYSTRON CAVITY MOUNTED IN A.F.C. CHASSIS

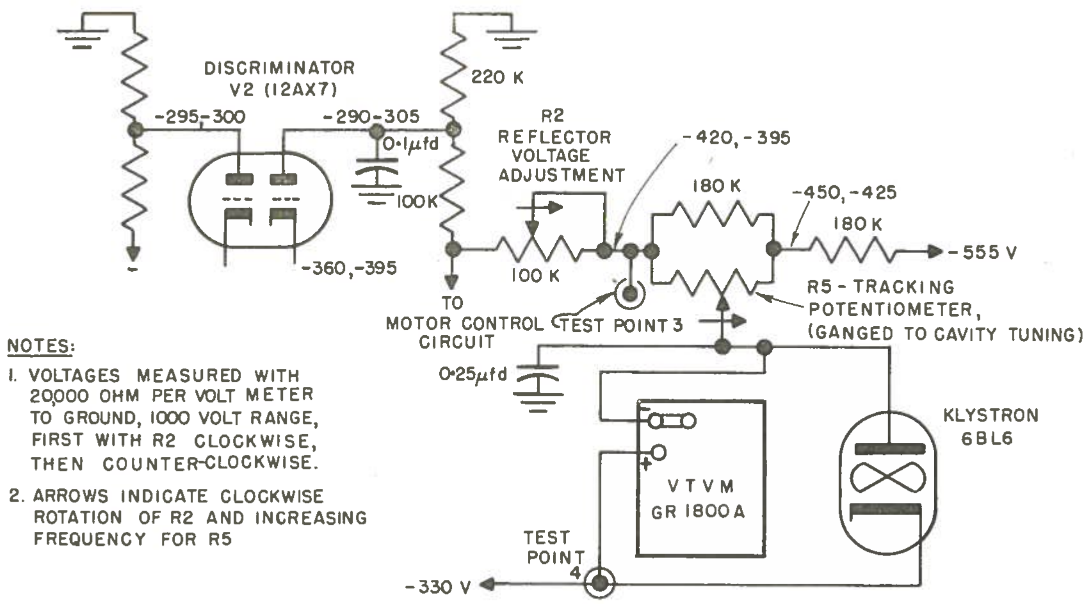


FIG. 12

SCHEMATIC OF DISCRIMINATOR VOLTAGE DIVIDER

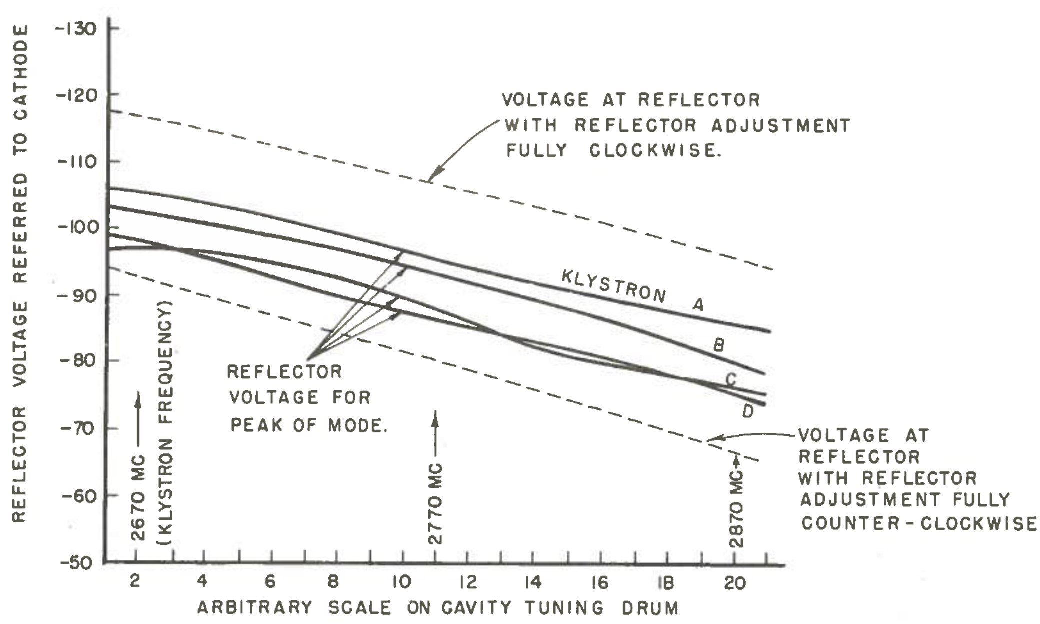


FIG. 13

VOLTAGE REQUIRED FOR REFLECTOR TRACKING

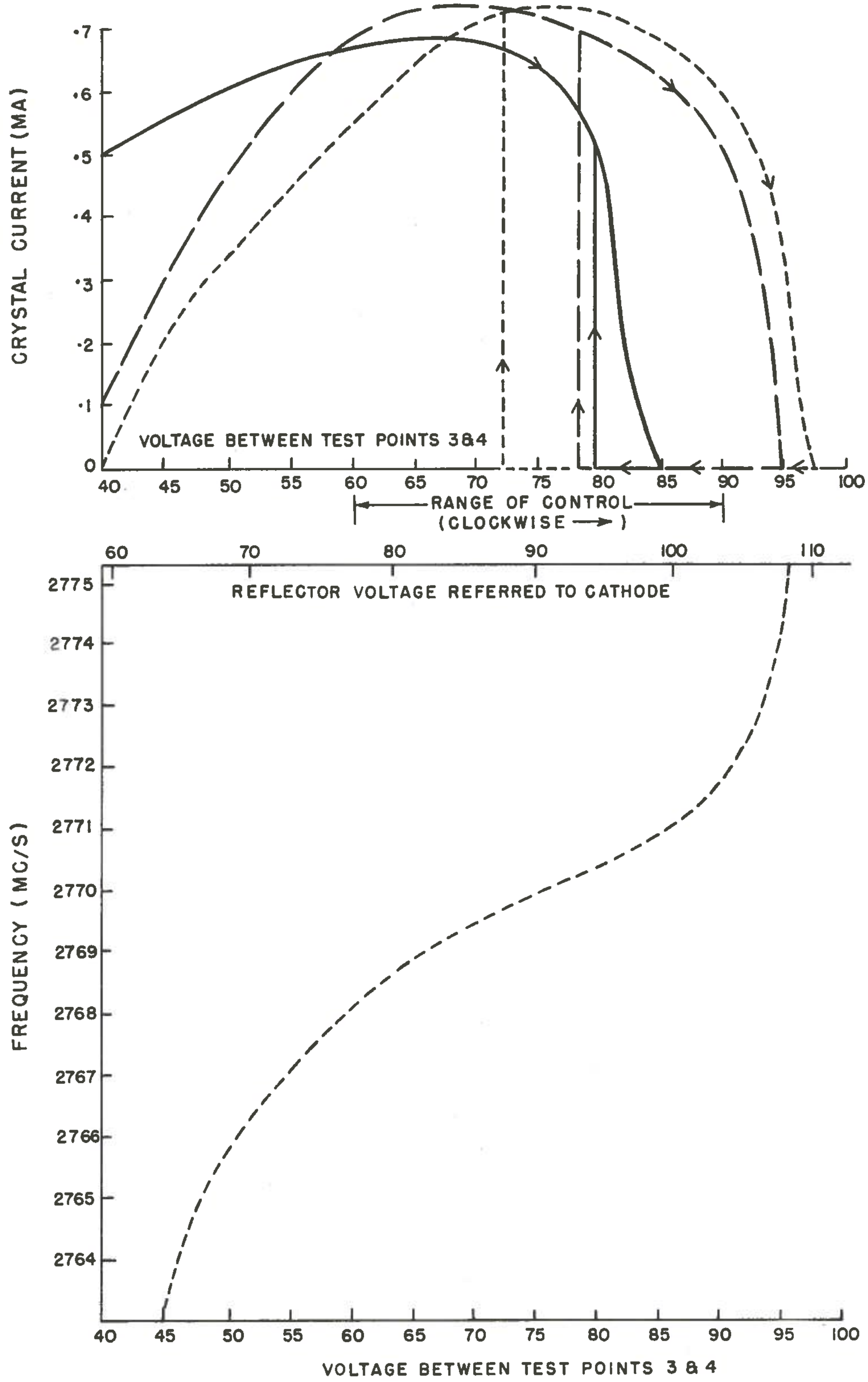


FIG. 14

6BL6 CHARACTERISTICS

SCHMITT TRIGGER

The basic Schmitt trigger circuit is described in Reference (2). A schematic diagram of the Schmitt trigger and associated control circuits is shown in Fig. 15. The voltages existing in this circuit under its two conditions are indicated in Table I.

The operating characteristic of the Schmitt trigger is shown in Fig. 16. The circuit consists of a pair of triodes having two stable states, depending on the input voltage. Referring to Fig. 16, as the negative input voltage increases from zero, with the sensitivity control at the middle of its range, the Schmitt trigger will switch from its "search" to "normal" state when the voltage has reached -2.1 volts. If now the input voltage is reduced, the circuit will revert to its initial state at a voltage of -1.8 volts. A similar diagram to Fig. 16 could be drawn for a mechanical relay, in which case the abscissa (reversed) could be spring tension and the ordinate could be coil current.

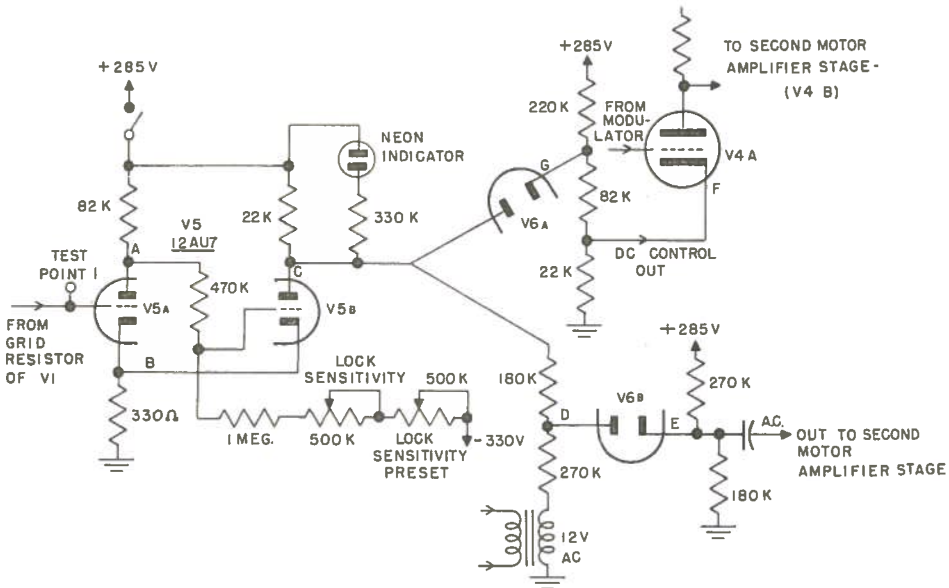
The common cathode resistor couples V_5B to V_5A rather than vice versa, because of the larger current drawn by V_5B when it is conducting.

LOCAL-OSCILLATOR TUNING-MOTOR CIRCUIT

In the block diagram, Fig. 1, the d-c modulator input may be seen to be the difference between two potentials marked "D-C Reference" and "D-C Input". In Fig. 2, these two points may be identified as D and C, respectively. Let it be assumed that the potential of point C under quiescent conditions is -355 volts referred to ground. If the motor zero control is now adjusted for zero meter reading, then there will be no net input to the modulator. (The exact setting up procedure is described in Section III).

The function of the modulator is to develop a 60-cycle output with amplitude and phase dependent on the amplitude and polarity of the d-c voltage applied across the input terminals C,D. The modulator used is similar to that described on Page 382 of Ref. 3. The a-c reference input signal is fed in through a 6.3-volt shielded transformer*, the shield being required to prevent a voltage of the wrong phase being capacitively coupled to the modulator bridge from the transformer primary. V_4A and V_4B are conventional amplifier stages, with the exception that V_4A has provision for being cut off by means of the voltage applied through diode V_6A, while V_4B has provision for feeding

* Transformer #32890, Hammond Manufacturing Co. Ltd., Guelph, Ont., Canada.



SCHMITT TRIGGER AND CONTROL CIRCUITS

	LOCKED CONDITION	SEARCH CONDITION
NEON INDICATOR	ON	OFF
VOLTAGE TO GROUND *		
A	150	50
B	3·5	0·8
C	80	225
D	45	122
E	110	122
F	22	45
G	92	225

* BOTH SENSITIVITY CONTROLS IN CENTRE OF RANGE

TABLE I
SCHMITT TRIGGER VOLTAGES

FIG. 15

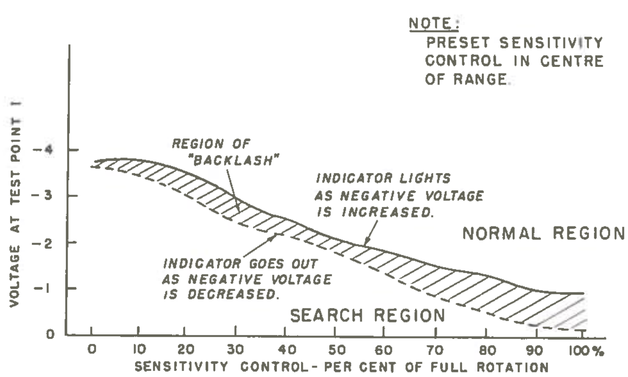


FIG. 16
SCHMITT TRIGGER SENSITIVITY

RESTRICTED

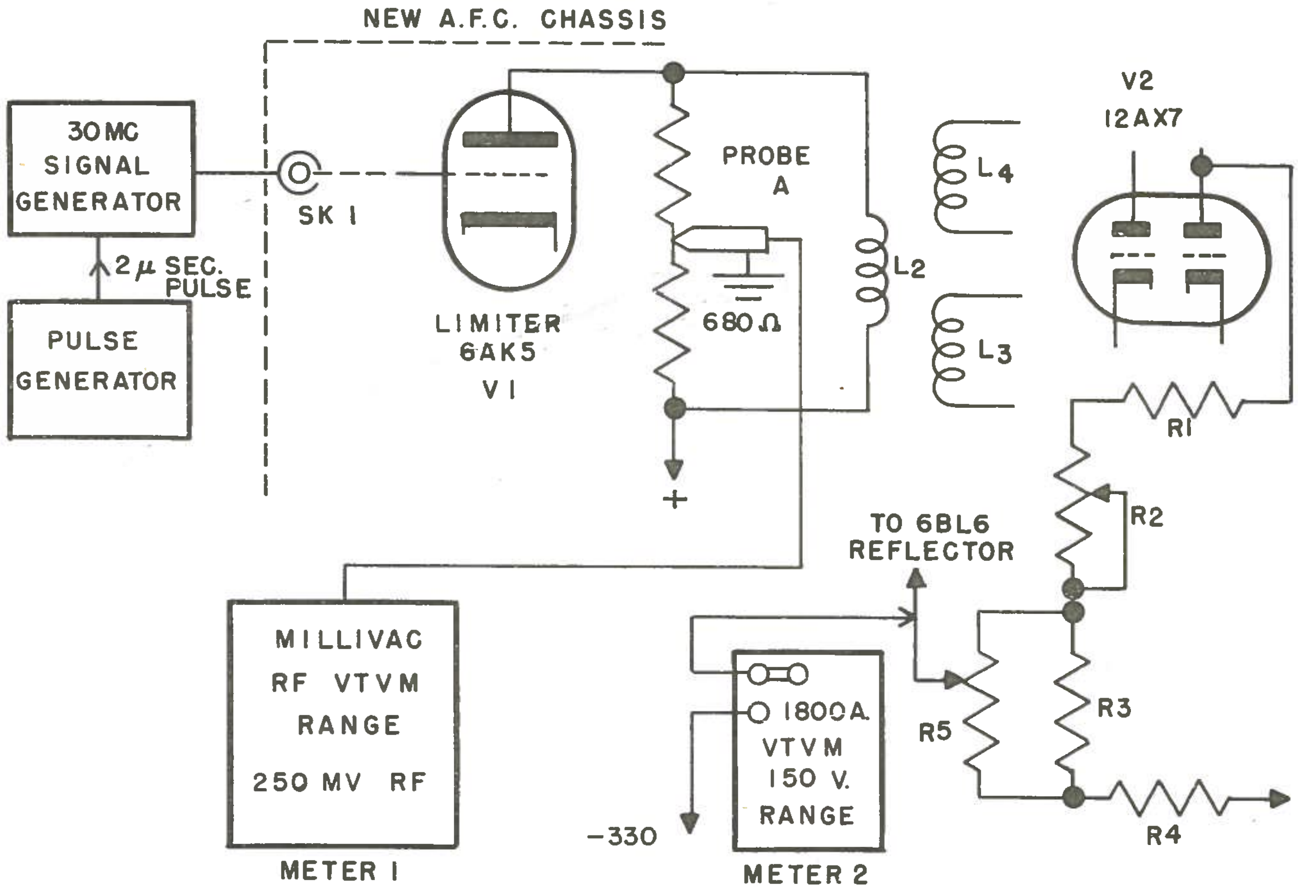


FIG. 17

APPARATUS FOR ALIGNMENT OF DISCRIMINATOR in a second a-c input through the diode V_6B. In the output circuit of the triode V_4B, the first condenser is a coupling condenser, while the choke and second condenser comprise a phase-shift network which is adjusted to give the required 90-degree phase shift of voltage on the control winding of the servo-motor compared to the voltage on its reference winding. The particular phase-shift network chosen was one which would discriminate against the undesirable 400-cycle pulse recurrence frequency present at this point. The amplifier stages, V_7 and V_8, are driven with a-c on the plates in order to reduce d-c power requirements while the grids are driven in push-pull. This circuit is described on Page 440 of Ref. 3. The motor is a Diehl low-inertia, servo-mechanism motor of the drag-cup type. The local-oscillator tuning cam is a linear cam with a 48-degree return, driven by the Diehl motor through a gear reduction ratio of 200:1. Components R_9 and C_9 comprise a conventional d-c lead network to reduce hunting. (see Page 332 of Ref. 4).

III - DISCUSSION OF CONTROLS

SEARCH "ON/OFF" SWITCH

If the Schmitt trigger tube and its associated components were omitted entirely, it would be necessary to tune the local-oscillator initially by hand, after which the oscillator would follow in a satisfactory manner. Under normal conditions of operation the "search" switch will be left on. However, the "search on/off" switch has been located in the +300-volt line for the Schmitt trigger and diodes, rather than in other possible locations, for a definite reason. This reason is that in the event of any trouble in the search circuit, turning off the "search" switch will cut off both halves of diode V_6, and the AFC system will operate normally.

AMPLIFIER BALANCE CONTROL

This adjustment should be necessary only when tubes V_7 or V_8 are replaced. To effect this adjustment, V_4 is removed and the voltage appearing at Terminal 2 (Test Point 7) of the motor winding is examined with an oscillograph. A distorted 60-cycle wave will be seen. This waveform will decrease, go through zero, and emerge in opposite phase as the amplifier balance control is turned. The control is then adjusted for the zero condition.

MODULATOR BALANCE CONTROL

This adjustment should not be necessary in the field. With the AFC switch "off", and the search switch "off", and with the meter-range switch in Position 2 "Motor Zero", the "Motor Zero" control, or alternatively the "Reflector" control, are adjusted until the meter on the front panel reads zero (mid-scale). With V_4 replaced in its socket and adequately warmed up, the modulator balance control is adjusted until an oscillograph connected to Pin 2 of the motor winding will indicate the zero condition for the 60-cycle fundamental voltage.

AFC TUNING CONTROL

This adjustment should not be necessary in the field, except when replacing a receiver chassis or receiver preamplifier. Using either the echo-box or a fixed echo, and examining the radar type-A display, the tuning control is adjusted when the AFC is properly locked on for maximum ringing time or echo height respectively. The tuning adjustment which is used at present in the AFC coil assembly of the A.A. No. 4, Mark VI consists of a set of three brass slugs which are driven simultaneously into the three coils by means of a cam arrangement. It is expected * that this arrangement will also be used for the new system, in order to minimize changes necessary in production. This standard assembly was not available during development, however, and an interim tuning means was used in which the center coil is moved by a screw driver adjustment closer to one or the other secondary coil.

REFLECTOR ADJUSTMENT

This adjustment should not be necessary in the field except when a type-6BL6 klystron is replaced. As may be seen from the photograph (Fig. 11), the local-oscillator driving cam is connected to a drum which is arbitrarily numbered from 0 to 24. The approximate magnetron frequency may be determined from the following formula:

$$\text{Magnetron frequency} \doteq 2920 - \left(\frac{\text{drum dial reading}}{0.9}\right).$$

Or alternatively, the drum dial reading for a given magnetron frequency is approximately 0.9 x (2920 - magnetron frequency).

---

* Recent tests have shown that the phase discriminator (see Appendix II) will simplify the tuning procedure considerably.

To adjust the reflector control, the local-oscillator drum is set at approximately "11" which represents the middle of its range. The reflector control is operated until AFC crystal current is a maximum, and then turned about 15° counter-clockwise. It is not serious if the maximum is obtained at one end or the other of this control, as the range on the control has been deliberately kept low in order that the adjustment itself be not critical.

MOTOR ZERO CONTROL

The motor zero control must always be adjusted after any change in the position of the reflector control. The three switches ("motor", "search", and "AFC") should all be turned off, and the meter range switch turned to its second position, "motor zero". The control is then adjusted until the meter reads "zero".

LOCAL-OSCILLATOR CAVITY POSITION

This adjustment should not be necessary in the field. Two wing-nuts support the local-oscillator cavity assembly, and when loosened allow a longitudinal displacement of the cavity in order to center its frequency range.

LOCK SENSITIVITY PRE-SET CONTROL

To set this control the "lock sensitivity" control is set at the middle of its range, and a source of variable negative voltage is connected to Test Point 1. The "lock sensitivity pre-set" control is adjusted so that increase of this external voltage to -2 volts will just fire the "locked" neon bulb. Further adjustments of this control should not be necessary until V_5 is replaced.

LOCK SENSITIVITY CONTROL

This control determines the level at which the Schmitt trigger will switch to the locked condition. It should be set at about the center of its range, and should not require adjustment by the operator. If it is set too high, there may be some magnetron frequencies at which locking on the wrong sideband, or on the back of the cam, will occur. If it is set too low, there may be some frequencies at which the radar will not lock.

RELEASE BUTTON

The release button may be pressed to clear any undesired locking or to test the search function. After pressing the release button and holding it for about one second, the local oscillator will search and lock on the correct sideband.

TUNING SLUGS IN AFC COILS

Adjustment of the AFC coils for the discriminator is described in Appendix I.

METERING

Five metering positions are available, as follows:

1) AFC Crystal Current — 1 milliampere full-scale.

2) Motor Zero — 100 volts full-scale referred to the reflector.

3) Local-Oscillator Cathode Current — 50 milliamperes full-scale (normal operating current about 25 milliamperes).

4) +300 Volts — This is normally about 280 volts owing to the drop in the filter choke and the metering resistor.

5) -330 Volts

A peculiarity of the crystal-current metering circuit is that with the AFC switch off, there is no plate voltage on the first tube of the AFC preamplifier. Random emission current from the cathode of this tube then flows through the crystal current measuring circuit.

IV - R.F. COMPONENTS

DUPLEXER

In a rapid-tuning receiving system it is necessary to avoid the use of any narrow-band radio-frequency components that cannot be conveniently ganged with the tuning mechanism. In order to eliminate the necessity of tuning a T/R cell, a new duplexer which uses a low-Q type-1B58 T/R cell has been used. This duplexer which can be seen in Fig. 18, replaces the existing duplexer which uses a type REL # 64 high-Q T/R cell. Since the cold impedance of the magnetron varies with frequency, two anti-T/R cells, types 1B44, and 1B56, are used to isolate the magnetron from the signal mixer when the radar is in the receiving condition. The method of design of the duplexer is described more fully in Ref. 5. The T-junction and T/R mount are as described in Ref. 5 while the anti-T/R mounts and waveguide-to-coaxial transition are based on a Canadian Arsenals design.

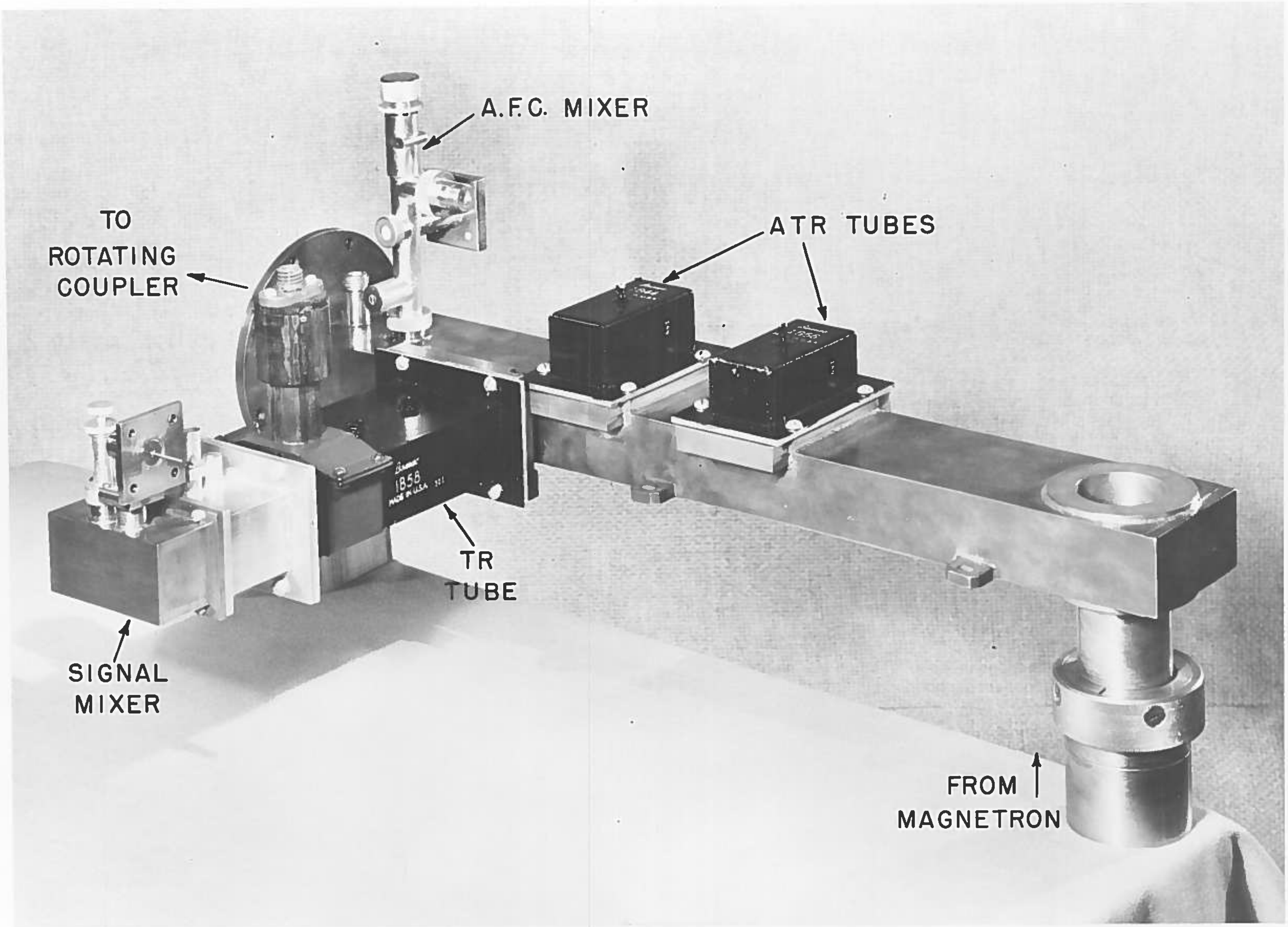


FIG. 18

DUPLEXER AND MIXERS

AFC MIXER

The AFC mixer which was designed by Canadian Arsenals Limited, is shown to the left of the T/R cell in Fig. 18 and is of coaxial line construction, having a flange for mounting the AFC intermediate-frequency amplifier directly on the mixer. A sample of the radio-frequency signal transmitted by the magnetron is picked up by a short electric field probe in the waveguide and is mixed with the signal from the local oscillator in a type-1N21B crystal. When the difference frequency generated is within the bandwidth of the AFC intermediate-frequency amplifier the amplified signal is used to control the frequency of the local oscillator klystron by methods previously described. The magnitude of the local-oscillator drive is adjustable at the mixer by varying the distance of a probe from the crystal. A resistor disc terminates the local-oscillator cable at the mixer.

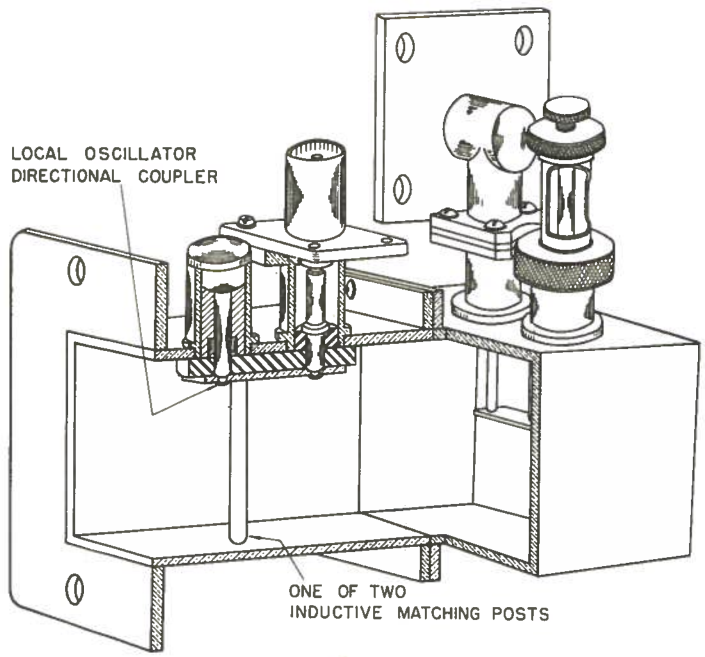
SIGNAL MIXER

The MZPI signal mixer has been replaced by a broad-band waveguide type mixer which fits directly onto the flange of the type-1B58 T/R cell. This mixer constitutes a redesign for a lower frequency range of an existing "loop-type" mixer previously constructed for operation at frequencies between 3100 and 3500 megacycles per second [6]. The mixer is suitable for use between frequencies of 2700 and 2900 megacycles per second using type-1N21B or 1N21C crystals.

The construction of the mixer crystal mount is shown in Figs. 19 and 20. The broad-band characteristics of the mixer are a property of the loop circumference and the crystal mounting structure, which together act like a folded dipole over a ground plane with the crystal as a series load [6]. The back-plate on the waveguide is positioned to tune out the susceptance of the crystal mount. The intermediate-frequency signal is brought out by an extension of the loop which passes through a broad-band radio-frequency choke. A flange is provided for the mounting of the intermediate-frequency preamplifier directly onto the mixer assembly in order to minimize the input capacity to the preamplifier. This capacity is 9 μμF, which includes an allowance of 1 μμF for a typical crystal.

---

6 Harold L. Wheeler, Consulting Radio Physicist, Great Neck, U.S.A. "S-Band Converter" — four reports (NRC Radio and E.E. Document Office, No. 26248.)



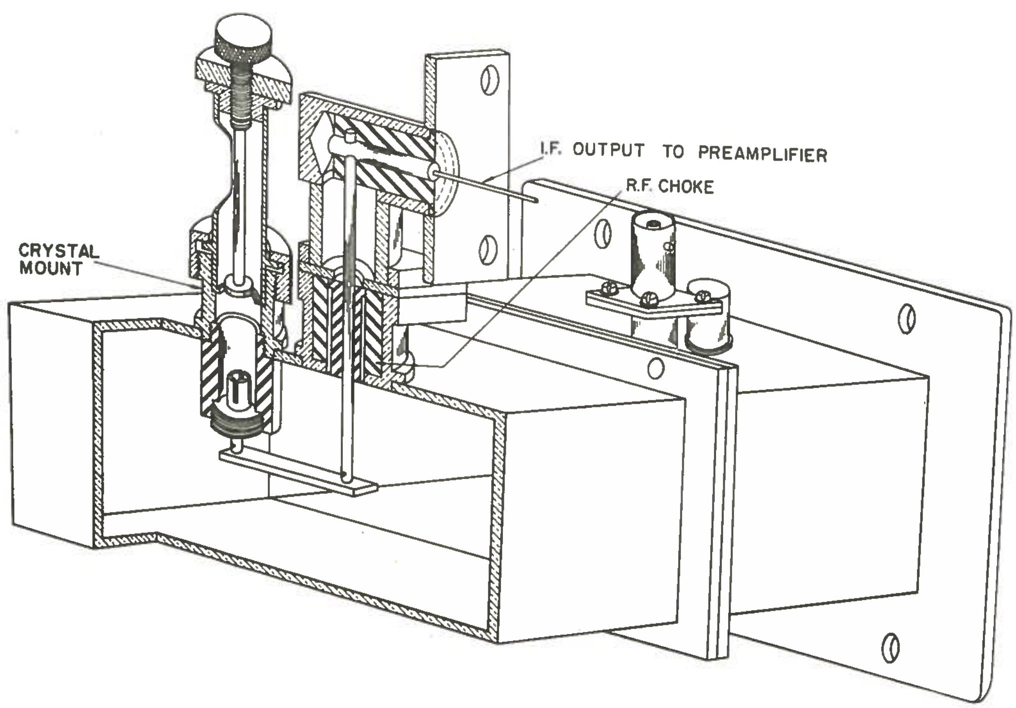


FIG. 19
SIGNAL MIXER

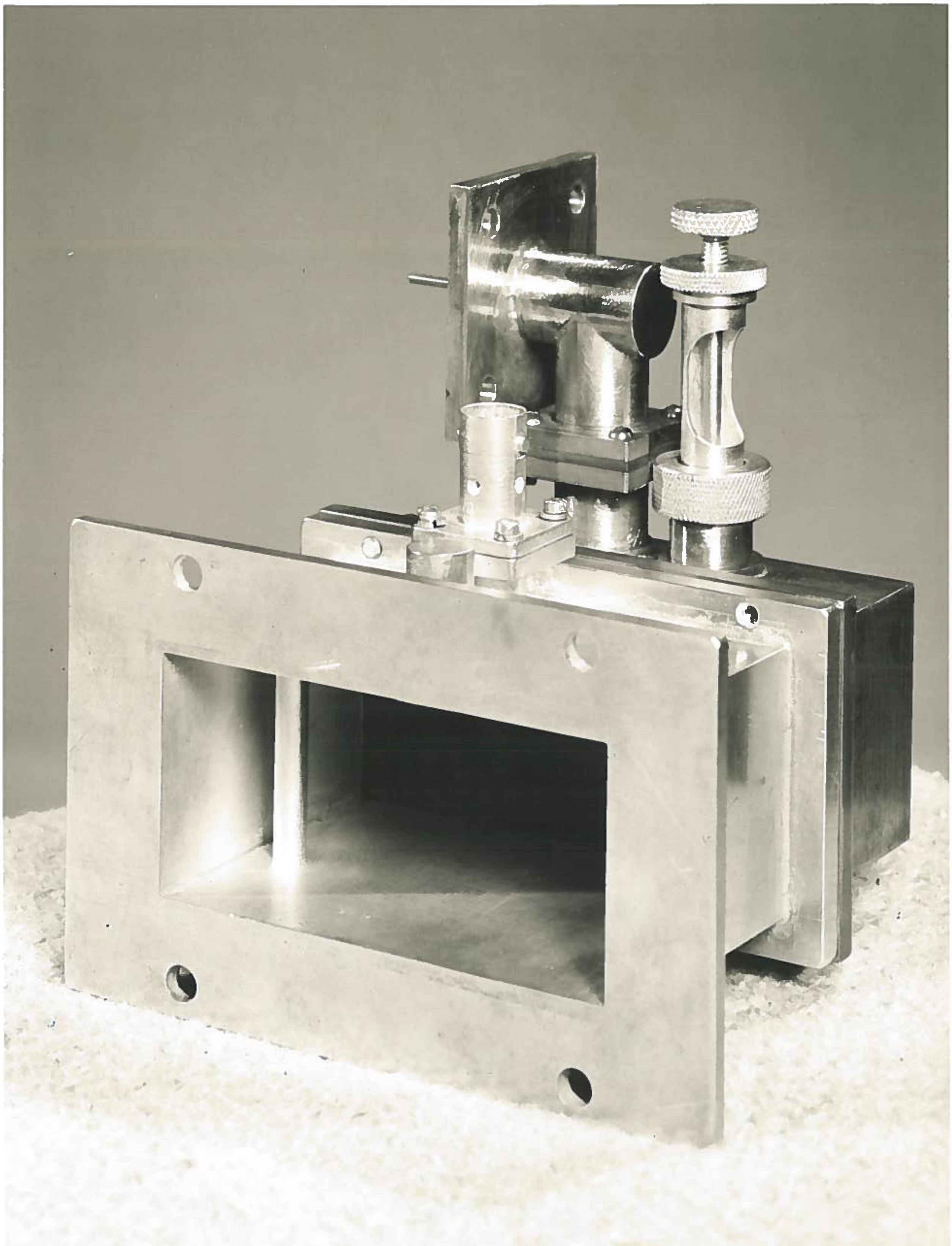


FIG.20
SIGNAL MIXER

RESTRICTED

The injection of the local-oscillator signal is accomplished by the use of the directional coupler shown in Fig. 19. A directional coupler reduces the local-oscillator power travelling toward the antenna to the level of that reflected from the crystal mounting, and also reduces the change of local-oscillator drive with changing antenna impedance presented at the mixer input. The action of this injector [6] is similar to that of a wave-type antenna, where the combination of magnetic and electric field coupling is adjusted to aid propagation in one direction and cancel in the other direction. The major part of the local-oscillator signal is dissipated in a matched powdered-iron termination so that the loading of the local oscillator will not vary with frequency. For two particular injector units constructed, the voltage standing-wave ratio of each, including a type-BNC Cable Connector, was less than 1.60 over the design bandwidth. In order to minimize the insertion loss of the local-oscillator injector, the coupling to the waveguide carrying the wanted signal must be low; conversely, the coupling should be high to reduce the loading of the local-oscillator. In the final design a compromise decoupling factor of 12.8 db was used, so that approximately 10 milliwatts of local-oscillator power at the injector will give a crystal current of 0.5 milliampere. This decoupling factor gives a signal insertion loss of 0.26 decibel. The directivity varies between 18 and 19 decibels for frequencies between 2700 and 2900 megacycles per second.

The directional coupler introduces a capacitive susceptance into the waveguide, which is cancelled by the inductive susceptance of a pair of inductive matching posts [7]. The presence of these posts in the vicinity of the directional coupler has no adverse effect on its measured properties. One of these posts may be seen in Figs. 19 and 20.

Fig. 21 shows the variation of the input admittance with frequency for thirty-two type-1N21B crystals. These measurements were made using the crystal mount without the local-oscillator directional coupler unit.

LOCAL-OSCILLATOR

A type-6BL6 reflex-klystron, with an external coaxial cavity is used as a local-oscillator, and is situated on the new automatic-frequency-control chassis, No. 54, in the receiver rack. Two separate loops are provided to couple the radio-frequency power from the cavity to the signal and AFC mixers. The insertions of both coupling loops are separately adjustable so that the local-oscillator signal level to each mixer can be changed at the cavity.

The constructional details of the cavity are shown in Fig. 22.

RESTRICTED

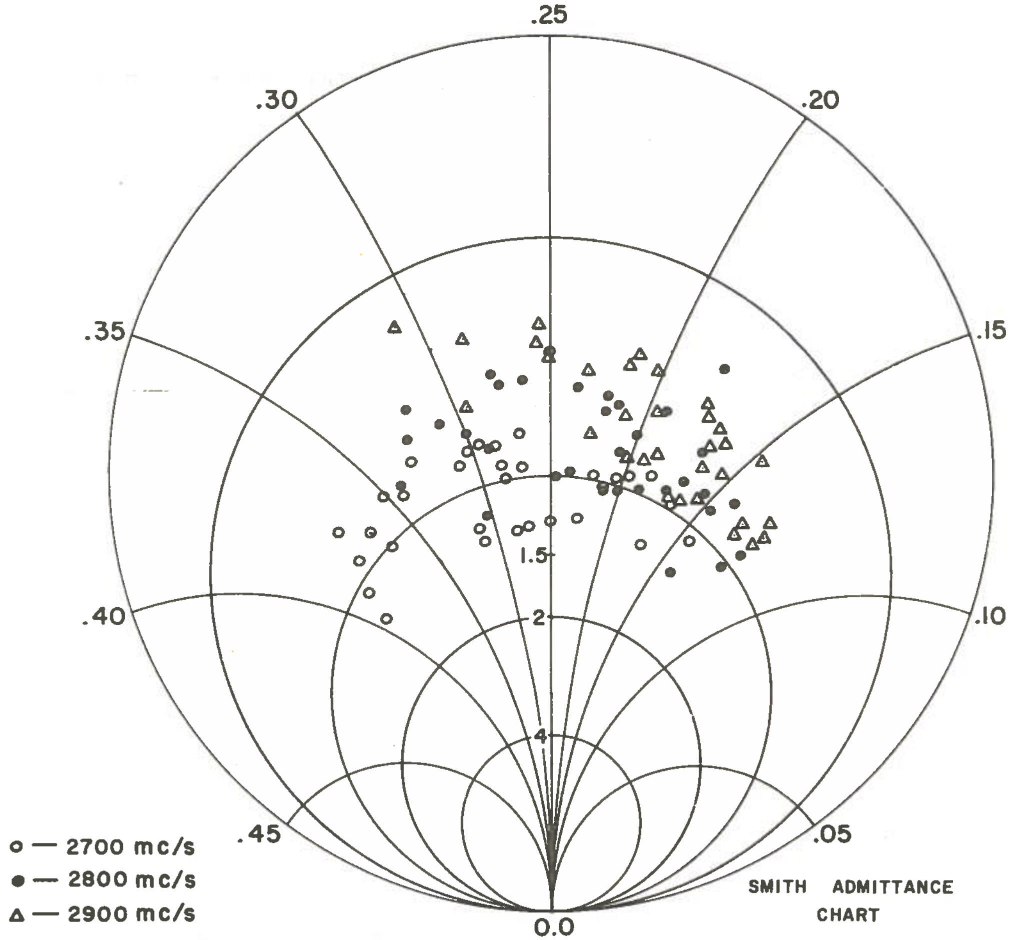


FIG. 21

LOOP-TYPE MIXER INPUT ADMITTANCES

FOR 32 TYPE-IN21B CRYSTALS

CONFIDENTIAL

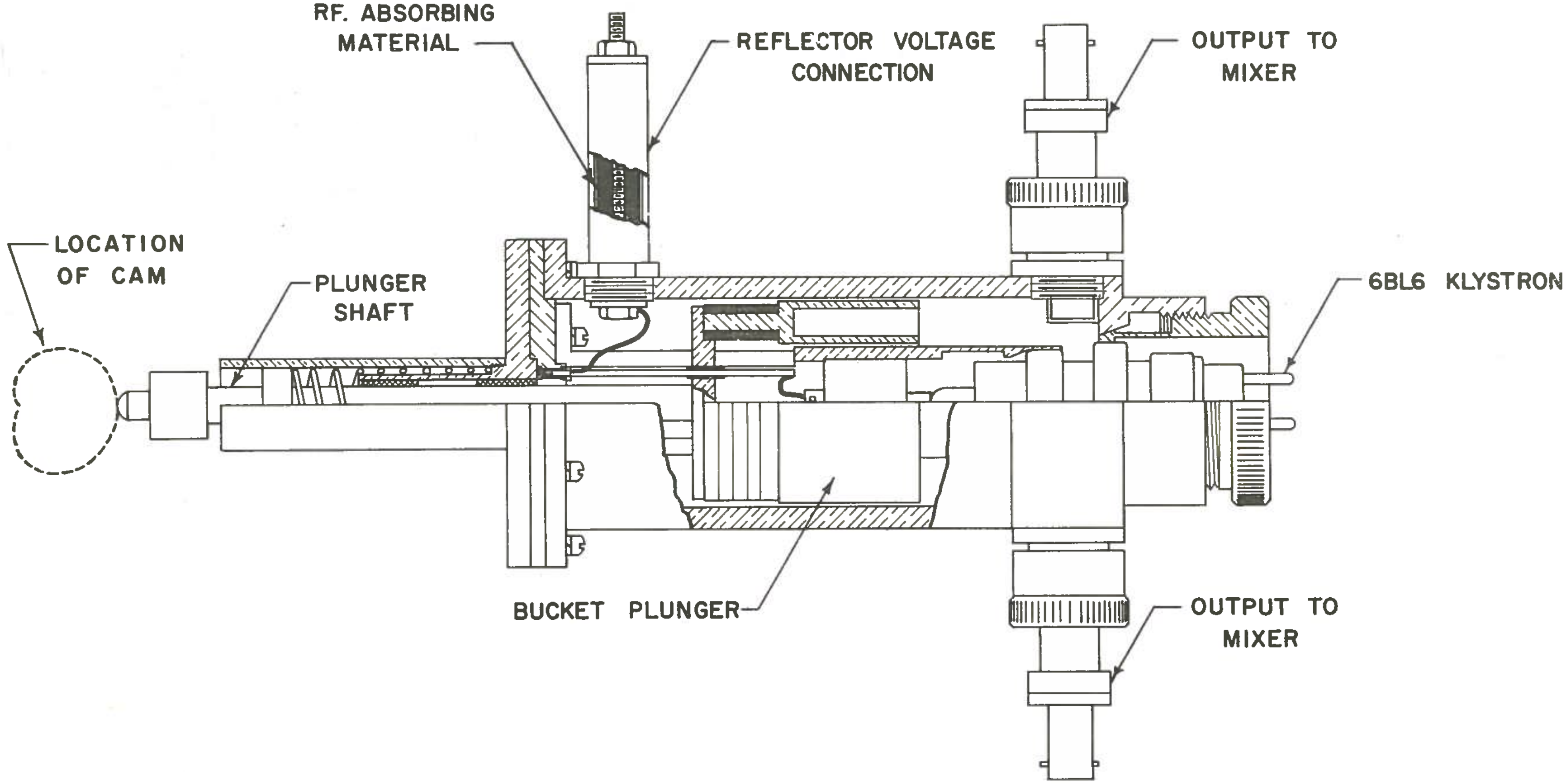


FIG. 22

6BL6 REFLEX KLYSTRON AND COAXIAL CAVITY

The cavity tuner is a non-contacting type of bucket-plunger (Ref.8, p.927) supported by a spider extending through the center conductor of the cavity. A shaft, to which the spider is attached, slides in two Oilite bearings and is actuated by a cam, as shown in the photograph, Fig. 10. This photograph also shows the reflector-voltage tracking potentiometer, which, together with the cam, is rotated by the tuning motor through a gear reduction ratio of 200:1.

The type-6BL6 klystron generates approximately 100 milliwatts of power at frequencies in the vicinity of 2800 megacycles per second when operating in the two and three-quarter reflector mode. The cavity has been designed so that, for a three-quarter wavelength T_{EM} cavity mode, there will be no interfering cavity modes possible over a 220 megacycle per second tuning range. The local oscillator is required to supply approximately 30 milliwatts of radio-frequency power to each output coupling loop when 15 feet of RG-58/U cable are used to connect each mixer to the local oscillator.

The relation between the plunger motion and wavelength is closely linear when a linear potentiometer is used for tracking the reflector voltage. The cam used to move the spring-loaded plunger shaft has a linear rise, so that the angular position of the cam-shaft is directly proportional to the wavelength of the local-oscillator output.

V - DISCUSSION OF FURTHER DEVELOPMENT

UNDESIRABLE RESPONSE AT IMAGE FREQUENCY

With the substitution of a broad-band T/R (type-1B58) tube for the previous tunable tube (type-REL-64), there is no longer any rejection of the image frequency in the radio-frequency system. This has three undesirable results:

1) degradation of noise factor, (see Reference 5)

2) susceptability to jamming at the image frequency,

3) interference or crystal damage from adjacent radars.

Three possibilities could be considered, as follows:

a) accept the disadvantages in the interest of simplicity;

b) return to a narrow-band T/R tube, and gang its external resonant cavity to the local-oscillator cavity;

c) gang a pre-selector cavity to the local-oscillator cavity.

It is felt that proposal (a) is preferable, but if pre-selector technique is considered to be necessary, then proposal (b) is simpler than (c). The use of a broad-band T/R tube followed by a narrow-band tunable pre-selector, as proposed in (c), places six resonant circuits in the waveguide, the first five being designed to broaden the band, and the sixth being required to reduce it, while proposal (b) requires only one resonant circuit. It would be expected then that the latter method should result in a more economical design.

The effect of image response on the noise factor of a radar such as the MZPI is negligible because the antenna is looking at a "cold sky".

In the case of narrow-band jamming, the use of a pre-selector merely forces the jammer to use the radar operating frequency rather than the image, and this does not appear to be a very worthwhile restriction. In the case of broad-band jamming, the maximum improvement with a pre-selector would be 3 decibels, and thus a low-Q device (i.e., proposal (b)) should suffice. It is believed, however, that the complexity of either of the ganging systems (b) or (c) is not warranted.

NOTE ON STARTING-UP OR TURNING-OFF THE RADAR

If the radar is completely turned on, but the main Variac is not turned up, then the klystron will search continuously, making one complete cycle every six seconds. If this should continue for a matter of hours it would cause undue wear on the motor and gearing. It can be prevented by turning the motor switch off during periods when the radar is on but when the main Variac is not turned up. In a production model it might be advisable to install a small bell, operated mechanically from the cam-shaft, which would ring every six seconds under these conditions, and thus ensure that the operator will turn off the motor switch.

SQUINT CORRECTION

The squint of the latest MZPI antenna is 5.05 degrees at mid-band, with a total excursion of 5.7 degrees as the magnetron is tuned. A servomechanism to correct the display for this squint is presently under construction.

The obvious source of information for the squint correction servomechanism is the magnetron tuning shaft. Use of this, however, would require special alignment each time a magnetron is replaced. It is considered very important to make magnetron replacement a simple operation, and for this reason it is planned to drive the squint correction servomechanism from the same shaft which carries the local-oscillator tuning cam.

MISCELLANEOUS

It would be possible by means of suitable reversing switches to permit choice of either sideband for the local oscillator.

It is also possible to eliminate the motor zero control. In addition to the d-c output from the discriminator, there exists at each plate a saw-tooth waveform at the pulse repetition frequency which changes from positive to negative going as the frequency goes through 30 megacycles per second. This waveform is particularly reliable in the case of the phase discriminator discussed in Appendix II. Various circuit arrangements are possible which convert this to a 60-cycle motor control voltage, and, in fact, in certain applications it would be convenient to drive the motor through an amplifier from this voltage. In this way no d-c connection is required from the discriminator to the motor-control circuit and the motor-zero control can be eliminated.

LIMITATIONS OF THE MAGNETRON

For freedom from jamming it is generally desirable to maximize the following speed. As will be described below, it is expected that the present speed of 40 mc/sec/sec can be increased by at least an order of magnitude. It is important, however, to assess the limitations imposed by the magnetron, and also it is important to ensure that there is operational justification for an increase in speed, which will compensate for the added strain on the magnetron.

In general, an increase in the tuning rate of the system will increase the danger of magnetron failure, and this will be so even if the magnetron design is modified, for example, by the substitution of a stainless steel diaphragm.

It is true that the results of certain diaphragm life tests performed by the manufacturer on two magnetrons appear to conflict with the above statement. These tests give a mechanical life of about 500 complete 30-second cycles, increasing to 2500 for 8-second cycles. However, the three following factors must be considered: (1) The trend would probably reverse for still faster cycles. (2) The irregular tuning to be expected in an operating system is not directly similar to life test conditions. (3) During conditions of a raid, with severe jamming, it is likely that a faster system will be subjected to more tuning cycles in a given period. One of the prime aims should be to reduce the likelihood of magnetron failure during a raid. This suggests that it would be much safer for the end of magnetron life to come for electrical, rather than mechanical reasons.

A further source of mechanical failure in the magnetron is the built-in Geneva mechanism. The complete tuning range of the magnetron is achieved by 115 turns of a worm which cause 4 turns of a worm gear which drives the diaphragm through a threaded cam. Destruction of the diaphragm by the cam is prevented by a non-definite Geneva mechanism *, which, when correctly adjusted, limits the worm gear to 4 particular revolutions. The worm can not be used for tuning rates above about 40 mc/sec/sec.

It is practicable to modify the magnetrons so that one turn of the worm gear covers the full tuning range. With this modification a simple and solid stop can replace the Geneva mechanism.

A modified magnetron ** is shown in Fig. 23.

The photograph shows that a sleeve having a four-start thread has been fitted over the original sleeve which had a single start thread. The travel of the worm gear is limited to one turn by means of a pin (not shown) on the worm gear which engages the fixed stop.

A reliable and definite stop on the magnetron travel becomes increasingly important as faster tuning rates are contemplated. Such a stop will permit the use of a slipping drive for tuning the magnetron, which should prove more reliable than limit switches to prevent overtravel. Limit switches are also to be avoided because they increase the time and skill required to replace a magnetron.

An interesting alternative to the slipping clutch is the self-reversing motor (G.E. Cat. No. 5 SMY 50 H 56 40 IN/OZ 75 R.P.M.). This motor has the peculiar property of rotating in one direction if it cannot rotate in the other. It has suitable torque and speed for connection to the worm gear, through, for example, a sprocket drive. Unfortunately the motor is too critical to manufacture and has been withdrawn (see Reference 9).

---

* This magnetron attachment is not a true Geneva mechanism because the rotation of the intermittent-motion wheel is constrained only by friction. An accidental displacement of this wheel by vibration, or other causes, would in most cases probably result in destruction of the diaphragm.

** The design and construction of this modification is due to Mr. H.C. Aubrey of this Division.

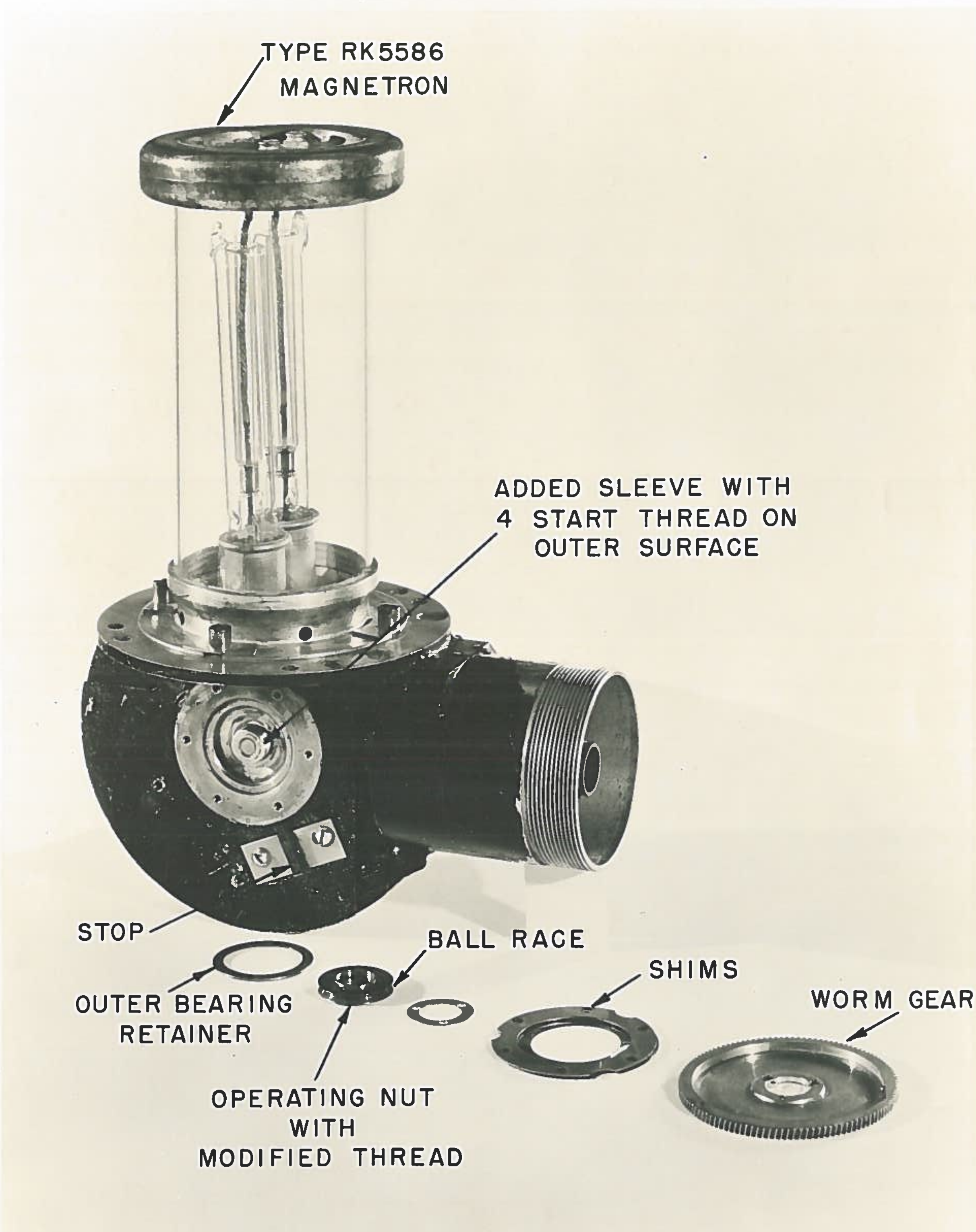


FIG. 23

MODIFICATION OF MAGNETRON TUNER

Some final remarks about the magnetron follow:

(1) Hand tuning of the magnetron by means of a shaft through the magnet should be considered.

(2) Magnetron sparking due presumably to diaphragm vibration becomes more severe with rapid tuning rates. (see Reference 10).

SERVOMECHANISM

The direct methods which are available to increase the speed of response are listed below, approximately in order of importance.

1) Reduction of cavity plunger inertia and spring load, with concomitant reduction in motor gear ratio.

2) Addition of tachometer feedback to the servomechanism, with appropriate increase of loop gain.

3) Increased power in the motor amplifier, for example, by using direct current for the output stage supply.

4) Use of a two-sided cam to eliminate the spring in the local-oscillator cavity.

All these methods are under consideration.

GANGED DIFFERENTIAL SYSTEM

The general problem of keeping the local oscillator on tune would be solved directly by ganging the local-oscillator cavity to the magnetron tuning mechanism, while relying on a conventional AFC for final adjustment. While this system would certainly be workable in the laboratory, it is felt that certain obvious disadvantages would arise in the field.

A system presently under construction will include all the components described in this report, with the addition of a differential at "X", Fig. 1. The magnetron tuning shaft will be coupled to the extra input of this differential in such a way as to tune the local-oscillator cavity along with the magnetron. It is seen that the search and automatic lock functions are retained, while the AFC system is now required only to correct for errors in the ganging.

The following advantages are expected:

1) Increase in speed by a factor of about 10, or conversely, a relaxation of the servomechanism requirement.

2) The ability to key off the radar and change frequency quickly, then restore operation without retuning.

3) Essentially, self-setting up when a magnetron is changed.

4) Reduced dependence of satisfactory AFC on spark-free magnetron operation.

AZIMUTH BLANKING

A further proposal* permits automatic interruption of the radar transmitter except for a desired small sector or sectors. An entirely random frequency change could be made during the OFF period without interfering with the AFC tracking. This proposal is to add d-c fed potentiometers to the magnetron tuning drive and the local-oscillator cam shaft. The voltage difference between the rotors of the potentiometers could be fed to the existing servomechanism input modulator to track the local-oscillator when the radar transmitter is off.

VI - TRIALS AT FORT BLISS

Two chassis, essentially as described in this report, were built and taken to Fort Bliss, Texas, in April, 1953, where an A.A. No. 4 Mark VI with the broad-band magnetron already installed was available. Testing facilities were provided by Board IV, U.S. Army Field Forces. Satisfactory performance was observed, with the exception of one klystron failure. This was in turn caused by failure of mica condenser C_{10}, which allowed the klystron reflector to become positive with respect to its cathode. The protective diode, now shown in the circuit as Tube V_{10}, was not then used. It has now been appreciated that the klystron should have a protective diode to prevent its reflector voltage from going positive, and that a high-impedance reflector circuit by itself does not provide adequate protection.

The system was operated fairly continuously at Fort Bliss during the second half of 1953, and no other difficulties were reported. With the particular manual gearing available to tune the magnetron,

---

* suggested by Mr. W.C. Brown.

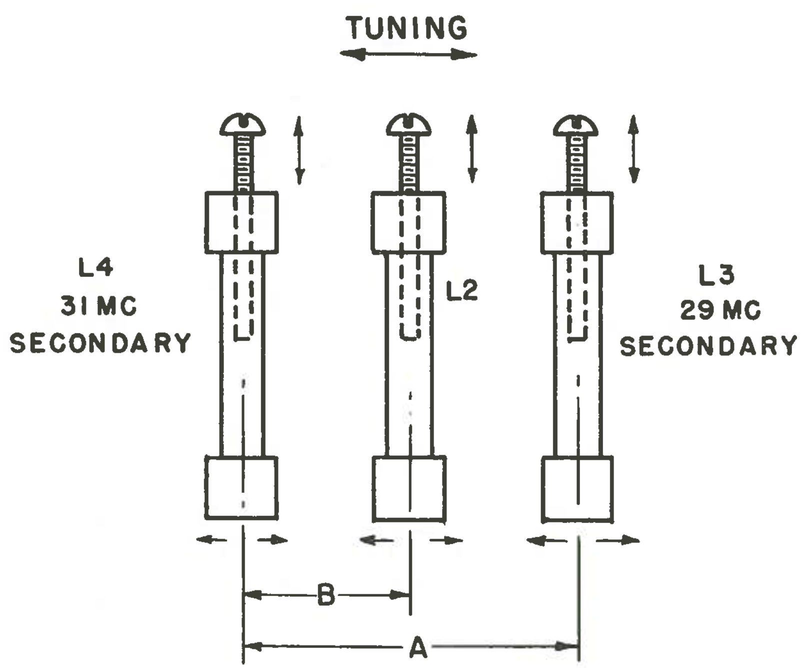


FIG. 24

INTERIM DISCRIMINATOR
COIL ASSEMBLY

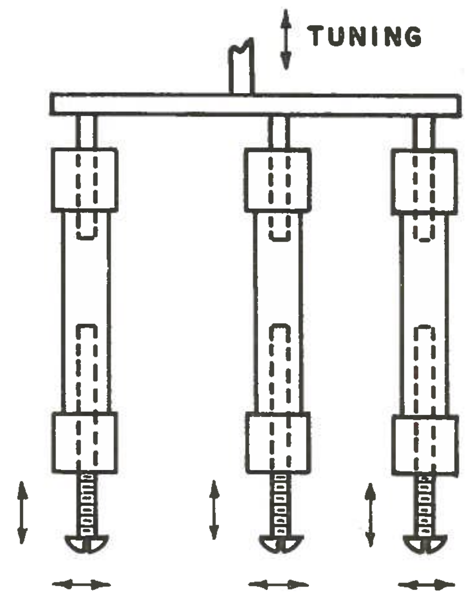


FIG. 25

PROPOSED DISCRIMINATOR
COIL ASSEMBLY

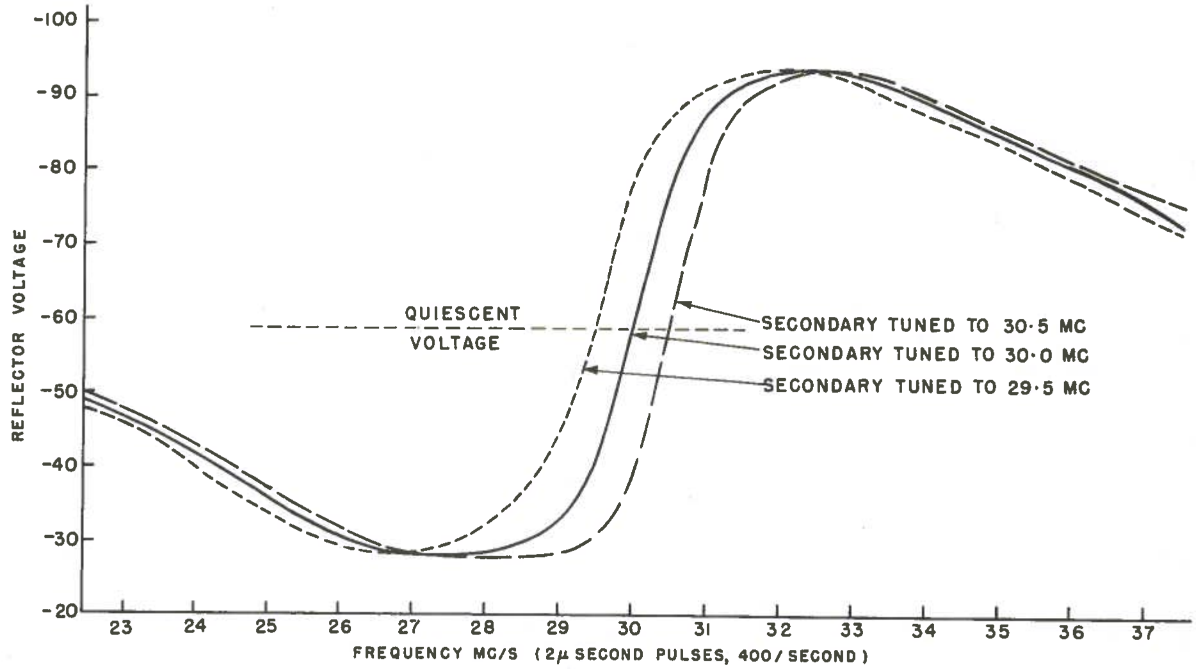


FIG. 26

DISCRIMINATOR CHARACTERISTIC USING PHASE DISCRIMINATOR R.F. CIRCUITS

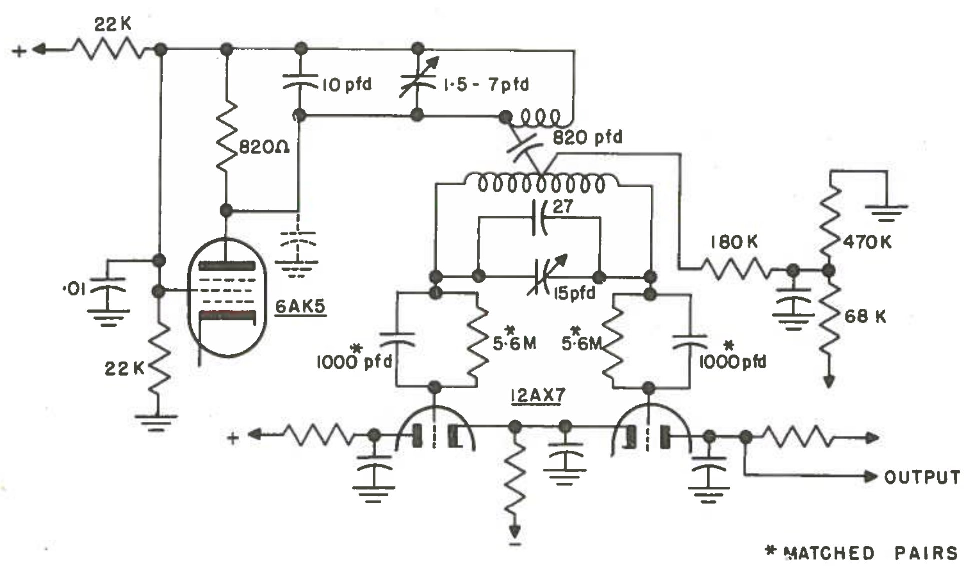


FIG. 27

LIMITER AND PHASE DISCRIMINATOR

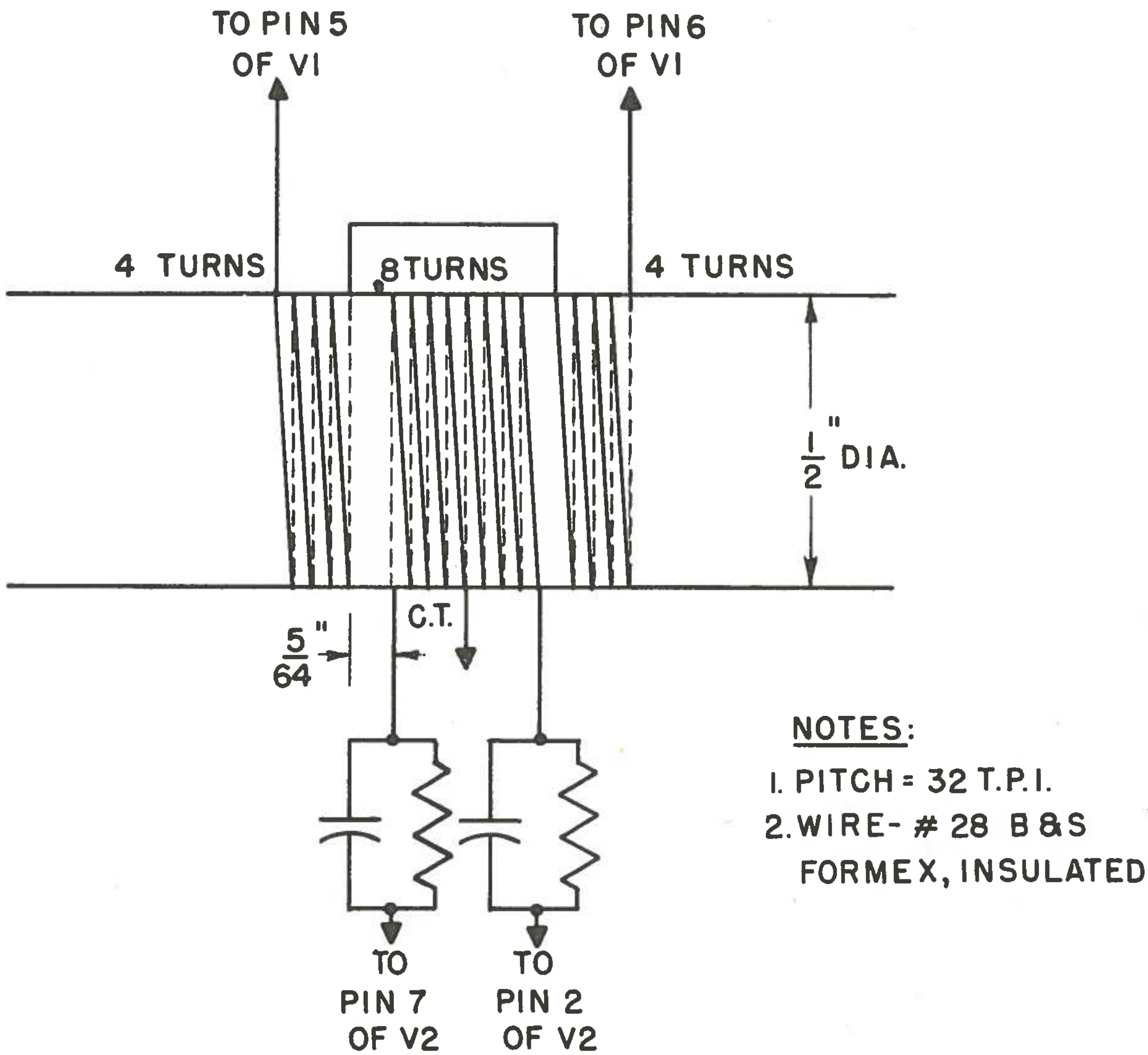


FIG. 28

COIL FOR PHASE DISCRIMINATOR

it was possible to tune it over its complete frequency range in 17 seconds. At this speed no difficulty was observed with the AFC system. Later tests have shown that 5 seconds is the minimum time for following a 200-megacycle change.

Several types of air-borne jamming equipment such as the AN/APT-16 were tried against the radar. Preliminary reports have stated that electronic jamming was completely ineffective. It was possible to change radar frequency immediately when jamming was observed; it would then require from 30 seconds to 5 minutes for the jammer to locate and transmit on the new frequency.

* * * * * * *

ACKNOWLEDGMENT

The list of persons and groups whose cooperation has made possible the completion of this project includes the Directorate of Armament Development, the Instrument and Radar Division of Canadian Arsenals Limited, Mr. J. Akeroyd of this Division, and many others.

* * * * * * *

REFERENCES

(1) S. Ratcliffe, "Design of AFC for Centimetre Primary Radar", T.R.E. Report T2138 (NRC, R. and E.E. Doc. Control No. 22802), Restricted.

(2) O.S. Puckle, "Time Bases" (John Wiley and Sons, Inc., 2nd Edition), p. 81.

(3) Greenwood, Holdam, and MacRae, "Electronic Instruments", M.I.T. Radiation Laboratory Series, Vol. 21 (McGraw-Hill Book Co.).

(4) M.I.T. Radiation Laboratory Staff, "Principles of Radar" (McGraw-Hill Book Co., 2nd Edition).

(5) A.R. Milne, "A Wide-Band Duplexer for S-band Operation", N.R.C. of Canada, Radio and E.E. Division Report, ERA-256.

(6) H.A. Wheeler, Consulting Radio-Physicist, Great Neck, N.Y., U.S.A., "S-Band Crystal Converter" (4 reports), N.R.C. of Canada, Radio and E.E. Document Control No. 26248.

(7) H. Gruenberg, "Symmetrically Placed Inductive Posts in Rectangular Waveguide", Can. J. Phys. 30: 211-217 (1952).

(8) H.J. Reich (editor), "Very High Frequency Techniques", Vol. II (McGraw-Hill Book Co.).

(9) Letter to N.R.C. from L.M. Danckert, Canadian General Electric Co. (December 7, 1953; NRC File 45-9-3).

(10) H. Le Caine, "Notes on a Visit to Raytheon's Magnetron Department, September, 1953". (Informal notes.)

APPENDIX I

INITIAL ADJUSTMENT OF AMPLITUDE DISCRIMINATOR CIRCUIT

Figs. 24 and 25 show the two alternative coil arrangements, while Fig. 17 indicates the apparatus used for setting up the discriminator. The steps are as follows:

1. Adjust dimension A to 1.25" and B to 0.67".
2. Set the signal generator to 33 dbm and a frequency of 31 mc/s.
3. Adjust coil L_1, Fig. 2, for a maximum reading on Meter 1.
4. Set signal generator to 33 dbm at 30 mc/s.
5. Adjust L_2 for a maximum reading on Meter 1 (typical value 100 millivolts).
6. Short-circuit coil L_4.
7. Set signal generator to 16 dbm at 29 mc/s.
8. Switch signal on and off, and adjust L_3 for maximum deflection of Meter 2.
9. Remove short circuit on L_4 and short-circuit coil L_3.
10. Tune signal generator to 31 mc/s.
11. Adjust coil L_4 for minimum reading on Meter 2.

APPENDIX II

PHASE DISCRIMINATOR

The new discriminator circuit has been tested using the phase instead of amplitude discriminator technique. Performance has been found satisfactory, and the characteristic is much more uniform during tuning (see Fig. 26, compared with Fig. 8). At the same time the tuning adjustment is simpler, being a trimmer condenser across the secondary. The characteristic of Fig. 25 was measured under the same conditions used for Fig. 8. The phase discriminator circuit is shown in Fig. 27, while the coil details are given in Fig. 28. The coil arrangement is a compromise between the need to equalize capacitive coupling and the merits of simplicity.

The phase discriminator coil should be much easier to manufacture than the coils described in the body of the report. The adjustment of the circuit is quite straightforward. The secondary trimmer is adjusted for cross-over at 30 megacycles per second and the primary for equal peak amplitude with the signal-generator level reduced well below the level at which limiting occurs.