Techniques and Facilities for Microwave Radar Testing*

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Methods and devices are described for testing microwave radars in the radio frequency range from about 500 mc to 25,000 mc, and at associated video frequencies. In general, the same instruments and techniques are applicable also in testing microwave communication systems.

Introduction

THAT radars are marvels of ingenuity has long since become common knowledge. This ingenuity is reflected, however, in complexity of circuits. A rough index of this is found in the number of vacuum tubes, which for a single radar may range from 50 to 250. Notwithstanding the most careful design, it is easy for the radar performance to become impaired under operating conditions.

Not only is radar complex, but its performance criteria are less tangible than those of conventional communication systems. Ordinary radio is to some extent self-testing in that reception of intelligible speech or signals frequently constitutes a sufficient check of satisfactory performance. With radar, the greater the range coverage and the more accurate the data, the more valuable the information is likely to be. However, the working range may fall to a fraction of the possible maximum or some other degradation or malfunctioning may occur, with nothing in the operation of the radar to tell that this has happened. Since lack of maximum performance may have serious military results, measurement of performance assumes the utmost importance in radar work.

The new techniques and new frequency ranges employed for radar necessitated the wartime development of a wide variety of new types of test equipment. A large part of this development work was concentrated at Bell Laboratories and at the N.D.R.C.'s Radiation Laboratory at M.I.T., working in close coordination with one another and with the technical services of the Army and Navy. In the manufacture of radar test equipment, Western Electric took a major part. This article discusses the techniques of radar testing and describes the types of test gear developed by Bell Laboratories and manufactured by Western Electric. These cover the radio frequency range from about 500 megacycles to 25,000 megacycles, together with associated video frequencies.

Because of its importance during the war, emphasis has been placed on

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the testing of microwave radars. However, similar methods and instruments have also been employed in the testing of microwave communication systems and such applications can be expected to increase. In this situation the developers and users of microwave communication systems are fortunate in that almost all of the techniques and devices developed for radar testing are equally applicable to communication systems. This is even true of the video units, which are useful in connection with pulse modulated telephone systems and AM or FM television systems.

So many persons, both within and outside Bell Laboratories, have contributed to the developments described that the authors have reluctantly reached the conclusion that the assignment of individual credit should not be attempted.

Requirements

Operation of Typical Radar

Subsequent discussion may be simplified by first reviewing briefly the operation of a somewhat typical radar, as shown in Fig. 1. Under the control of d.c. or so-called video pulses from the modulator, short pulses of radio frequency energy are delivered by the magnetron transmitter to a highly directive antenna, ordinarily arranged to scan a section of space. Energy reflected from an object or "target" in the path of the beam is intercepted by the same antenna. The received pulses or echoes are converted to an intermediate frequency by heterodyning against a local oscillator, the frequency of which may be automatically controlled.

To enable the same antenna to serve for both transmitting and receiving, a TR tube or transmit-receive switch is usually provided. This consists of a partially evacuated resonant cavity containing a spark gap which breaks down during the transmitted pulse, thus preventing the transmitted power from injuring the sensitive receiver. An RT tube, consisting of a similar resonant cavity and spark gap, may be provided to prevent absorption of the received signal by the transmitter. After amplification and detection of the received signal, the resultant video pulses are applied to an indicator which may present information in any of several different ways. Customarily the direction of the target (determined by antenna orientation) and its range (determined by reflection interval, 10.7 microseconds per mile) are shown. The system may be used merely for searching, or for fire control, bomb direction, or other functions, with additional equipment as required.

Types of Tests and Test Sets

Figure 2 shows an early assemblage of radar test equipment for the 10 cm range, initially produced in 1942, which has seen wide usage.

The more important types of tests required in radar work, either at radar operating locations or at centralized service points, are: (1) Over-all Performance (Range Capability), (2) Transmitter Power, (3) Receiver Sensitivity, (4) Transmitter Frequency, (5) Transmitter Spectrum, (6) Standing Wave Ratio, (7) R. F. Envelope, (8) Receiver Recovery, (9) AFC Tracking, (10) I.F. Alignment, (11) Video Wave Shapes, (12) Range Calibration and (13) Computer Calibration.

The principal types of test sets required for carrying out the above are: (1) Signal Generators, (2) Echo Boxes, (3) Frequency and Power Meters (separate or combined), (4) Standing Wave Meters, (5) R.F. Loads, (6)

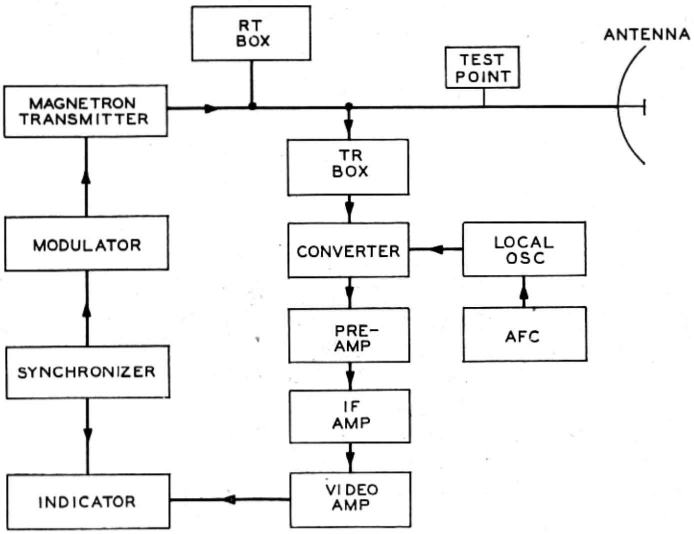

Fig. 1—Diagram of typical radar.

Oscilloscopes, (7) Video Dividers and Loads, (8) Range Calibrators, (9) Computer Test Sets and (10) Spectrum Analyzers. Various auxiliary testing instruments are also employed, including vacuum tube testers, I.F. signal generators, audio oscillators, flux meters, etc. Before discussing the above tests and devices individually, some of the requirements for radar test equipment, especially those resulting from military usage, will be summarized.

Generality of Application

Radars perform a great variety of functions, including search and surveillance, gun laying and fire control, bomb direction, and navigation. They are used in the air, on shipboard, and on the ground, in attack and in defense, in combat zones and in rear areas. To realize the advantages of different parts of the frequency spectrum, avoid interference, and keep ahead of enemy countermeasures, it has been necessary for radar to exploit many different frequency bands and sub-bands. These diversities have

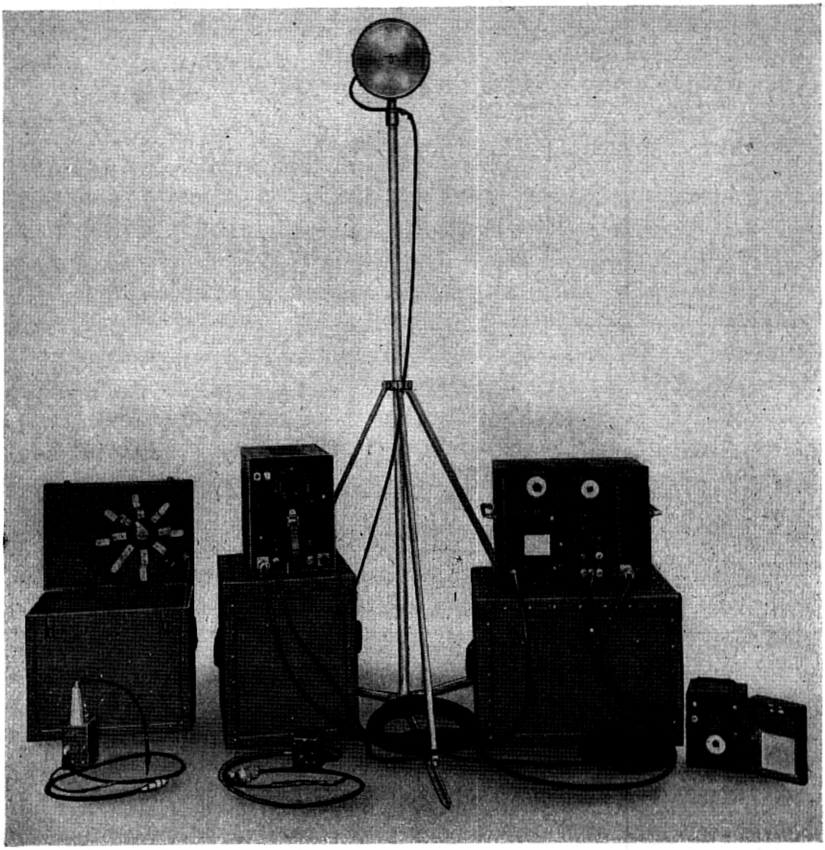

Fig. 2—Early radar test set for 3000 mc range—includes signal generator, oscilloscope, power meter, test antenna and auxiliary units.

bred a multiplicity of types of radar, with a corresponding variety of testing problems and requirements.

Maintenance and testing of radars must be performed at many different locations. In the Army these locations, known as echelons, include (a) the operating unit, (b) central service points, either fixed or mobile, for a number of operating units, and (c) large depots either in the military theatres or in the United States. Navy maintenance and testing are carried out on board the fighting ships or auxiliaries, and at advance and overhaul bases.

In developing test equipment, an offhand approach might have been to provide specialized equipment for testing each radar under specific conditions. Since this would have made the total burden of development, manufacture and field maintenance well nigh intolerable, a coordinated plan was followed whereby (with minor exceptions) each test set was made capable of widespread application in testing as many radars under as varied conditions as possible.

Broadbanding

Generality of application required the designing of test equipment for broad frequency bands, bands as a rule much wider than those of the radars themselves. It was necessary, therefore, not only to develop new microwave testing techniques, but to advance the art still further to render the testing components as far as possible insensitive to frequency.

Precision

A radar itself is an instrument of considerable precision. The test equipment used for checking the radar performance in the field has to have still higher accuracy. It is noteworthy that the measuring accuracy realized throughout the microwave range is comparable with that obtainable at lower frequencies where many years of background exist.

Packaging—Size and Weight

Light weight and compactness are of paramount importance where a test set has to be carried any distance by the maintenance man, where it is used in cramped quarters in a plane, truck or submarine, or where it has to be taken up ship ladders or through small hatchways. To permit portable use under such conditions, the design objective was established of a weight not exceeding about 30 lbs. (exclusive of transit case), combined with a ruggedness adequate for all conditions of use. Through rigorous attention to both mechanical and electrical design, this objective has been realized (in many cases with considerable margin) except for a few sets intended primarily for bench use. Figure 3 illustrates the use of lightweight test equipment in maintaining airborne radars.

Environmental Influences

Military usage requires that the test equipment be capable of efficient operation at any ambient temperature between a minimum of the order of $-40°$ to $-55°$ C and a maximum of the order of $+65°$ to $+70°$ C, as well as at any relative humidity up to 95%. In addition the set must withstand continued exposure to driving rain, dust storms and all other conditions encountered in tropical, desert or arctic climates. Often the test set in its transit case must be capable of submergence under water without ill effects. Fungus-proofing with a fungicidal lacquer is a standard requirement.

Simplicity, Reliability, Accessibility

Not only must the functioning of the test set be reliable, stable and trouble-free, but the set must make minimum demands for special skill or technique on the part of the maintenance man. Access for maintenance purposes, while important in radar test sets, is not as controlling as in the radars themselves and sometimes has to be sacrificed in part for compactness.

Fig. 3—Portable units used in checking airborne radars at Boca Raton, Fla.

Ruggedness

For general application, the test equipment must be capable of withstanding airplane vibration, the shock of heavy guns, depth charges and near misses, and the combinations of shock and vibration connoted by the requirement of "transportation over all types of terrain in any Army vehicle." Test and experience have made it possible to translate these general requirements into two specific requirements, namely the ability to withstand (1) vibration at frequencies from 10 to 33 cycles per second with $\frac{1}{16}''$ excursion for 30 minutes in each of three axes and (2) the shock produced by a 400 lb. hammer falling through distances of 1, 2 and 3 ft. in each of three axes, and striking an anvil to which the set is attached. These requirements have been met without using shock and vibration mounts, which are undesirable in test sets because they increase size and weight.

Range Capability

The range capability of a radar, like that of any radio system, depends upon three things; the transmitted power, the loss in the medium, and the minimum perceptible received signal. Two of these can be combined by taking the ratio of the radiated signal to the minimum perceptible received signal. This ratio, ordinarily expressed as a level difference in db, is variously termed the "system performance," "over-all performance" or merely the "level difference." It may be determined by separate measurement of transmitter power and receiver sensitivity, or by a single overall measurement. With the powers and sensitivities commonly employed in radar, the level difference is of the order of 150 to 180 db.

The actual range that can be spanned for a given performance ratio varies considerably. For a given transmitted power, the echo power received by a radar theoretically varies inversely as the fourth power of the range. The reason for this is simple. In free space the power intercepted by a target which is small in comparison with the area of the radar beam in its vicinity will vary according to the inverse square of the distance from the radar. Similarly, that fraction of the energy reflected from the target which is intercepted by the receiving antenna will vary as the inverse square law. Since the received power involves the product of these two factors, the relation becomes:

$$P_r = K\frac{P_t}{R^4}, \quad \text{or}, \quad R = \left(K\frac{P_t}{P_r}\right)^{\frac{1}{4}} \tag{1}$$

where P_t and P_r represent, respectively, the transmitted and received power, R the range and K a constant determined by antenna design, character of target, etc.

Under operating conditions considerable departure from the above relationship may be experienced, due to such factors as (1) the curvature of the earth, (2) interference between the direct beam and single or multiple reflections, and (3) attenuation due to atmospheric absorption. Except under conditions of severe attenuation such as may occur at the very short wavelengths, the received power commonly varies somewhere between the inverse fourth power and the inverse 16th power of distance. To state it another way, the change in effective range is somewhere between the fourth and the sixteenth root of the change in system performance. The former condi-

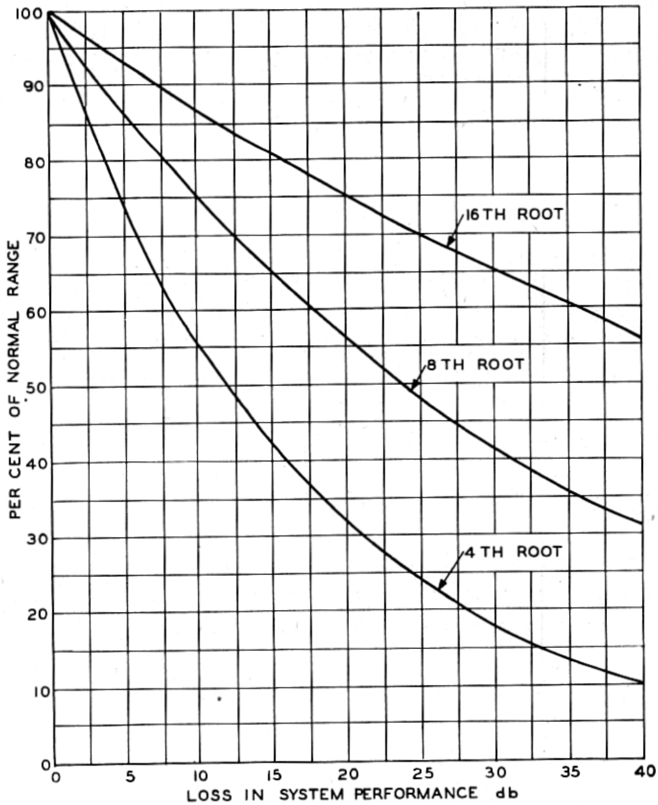

Fig. 4—Effect of reduction in system performance on radar range.

tion might hold for high angle plane-to-ship search in clear weather, the latter for ship-to-ship search in fog. The loss of range resulting from a given degradation of system performance is shown for 4th, 8th and 16th root laws by the curves of Fig. 4. Whatever the propagation law, reduction in performance always means loss of range.

Field surveys have shown that when test equipment is not available or not used, radars in the field are likely to give no more than $\frac{1}{2}$ to $\frac{1}{4}$ of the maximum range of which they are capable. Hence it is necessary to know with good accuracy the over-all performance. Known, or so-called standard, targets have often been used in the field for checking performance. Because of wide variations in transmission due to many factors, results obtained from such targets are frequently misleading.

Signal Generators

Signal generators for radar work deliver one or more different types of test signals, which may serve a variety of functions. More important among these functions are tuning or alignment of the radar components (TR and RT boxes, converter, beat oscillator, AFC, etc.), measurement of receiver sensitivity, checking TR and receiver recovery, measurement of loss, detection of frequency pulling, check of AFC following, measurement of IF bandwidth, check of automatic range tracking, measurement of standing wave ratio and check of video "gating" circuits. Many signal generators include means for measuring the power and frequency of the test signal, and also of an incoming signal.

Types of Signals

The test signals delivered by a signal generator may be CW, pulsed, or frequency-modulated. Occasionally square wave or sine wave modulation is provided.

Pulsed signal generators deliver a succession of single RF pulses or pulse trains, either of these generally synchronous with the pulses of the radar under test. Multivibrator or trigger techniques[1] are used to generate the pulses for modulating the microwave generator. The trigger pulse for synchronizing the pulsing circuits is commonly produced by rectifying RF pulses from the radar transmitter, thus avoiding a separate video connection to the radar. To avoid possible difficulties in video response, the RF test pulses should be of comparable width to those of the radar under test. For observing the test signals, either the radar indicator or an auxiliary oscilloscope may be used. With the single pulse method, provision is usually made for varying the delay of the test pulse with respect to the radar pulse. The width of the test pulse may also be adjustable or variable.

If the frequency of the signal generator is swept over a sufficiently wide frequency band, the IF output of the radar traces the curve of IF selectivity, thus producing a kind of pulse. With a suitable rate of frequency sweep, this pulse becomes comparable in width to the transmitter pulse, and when synchronized with the radar it can be used for test purposes. Since the pulse is produced in the radar, comparison of the shapes of receiver input and output pulses is not possible. The nominal duration of the pulse in the IF output is

$$T = B/\gamma \qquad (2)$$

where B is the width of IF band in cycles per second (for this purpose conveniently measured between 6 db points) and γ is the speed of frequency sweep in cycles per second per second. For best results this nominal width should be similar to the width of transmitter pulse for which the IF and video circuits are designed. This means that the scanning speed should be in the neighborhood of $B^2/2$.

A CW input of the same frequency as the transmitter produces in the output of the IF detector merely a direct current to which the video amplifier and radar indicator do not respond. However, CW test signals may be utilized by observing on a d.c. meter (built into the radar or separate) the change produced in detector current or converter current.

Receiver Sensitivity

Just as in radio, the sensitivity of a radar receiver is defined as the minimum received signal that is perceptible in the presence of set noise.* At microwave frequencies atmospheric disturbances are usually negligible, so that unless accidental or deliberate interfering signals are present, the operating sensitivity is the same as the intrinsic sensitivity of the receiver.

Receiver sensitivity is commonly stated as the minimum perceptible signal power in db referred to a milliwatt, (abbreviated as dbm). In practice, the receiver sensitivity depends upon the noise figure of the converter, the conversion loss, and the noise figure of the IF amplifier. If an RF amplifier is used, as is the practice at lower microwave frequencies, its noise figure is likely to be controlling. By noise figure in each case is meant the noise power in comparison with the thermal noise. The thermal noise in watts delivered to a load is kTB, where k is Boltzmann's constant, T is absolute temperature in degrees K, and B is the frequency bandwidth. Thus for a 4 mc band at 25° C the thermal noise is -108 dbm. With good design the over-all receiver noise is of the order of 10 to 15 db higher than thermal noise. The minimum detectable signal is usually not equal to the receiver noise but depends on the type of indicator, particularly on whether the presence of an echo is indicated by spot deflection or spot modulation.

With a CW signal generator, receiver sensitivity is measured by determining the minimum input power necessary to produce a perceptible change in meter reading. This affords a satisfactory relative measure of receiver performance, but since the radar indicator usually permits better visual discrimination against noise, the minimum input as read with the meter ordinarily differs from the minimum pulse input for barely discernible indicator response.

* The term noise is commonly used even though the disturbances are observed on a cathode-ray screen.

RF Oscillators

Beat oscillator tubes for radars deliver (with sufficient decoupling or isolation to prevent undue frequency pulling) a power of the order of milliwatts. This power being adequate for most test purposes, such tubes are well adapted for use as signal generators.

Throughout the greater part of the microwave range, reflex velocity-modulated tubes,[2] both the type with built-in cavity (Pierce-Shepherd) tuned mechanically or thermally, and that with external cavity (McNally) tuned by plugs, vanes or adjustment of dimensions, have been used. The former is more convenient for general use but the latter usually permits wider frequency coverage. Oscillation occurs when the repeller voltage is adjusted so that the round trip transit time corresponds to an odd number of quarter wavelengths. Ordinarily there are several different ranges of repeller voltage, corresponding to different numbers of quarter waves, each of which supports oscillation over a range of frequencies, called a mode of oscillation. Pulsing or frequency modulation is accomplished by applying a pulse or sawtooth wave to the repeller.

At the longer microwaves, a triode with closely spaced electrodes, or so-called "lighthouse" tube[3], has been employed in a tuned-plate tuned-grid oscillator of the positive grid type. Two coaxial lines, conveniently placed one inside the other, provide the tuning, with the feedback through interelectrode capacitances supplemented by loop coupling. The inner cavity (between plate and grid) controls the frequency of oscillation, while the outer cavity (between grid and cathode) provides a suitably high grid impedance. Mechanical arrangements are provided for tracking the tuning of the two cavities over a wide frequency range.

Some Design Principles

Standard signal generators which have been employed in the past for measuring the sensitivity of radio receivers usually deliver a known voltage across a low impedance. This voltage is applied in series with a dummy antenna to the receiver under test. In the microwave range this technique is inconvenient, and signal generators are designed to deliver test power on a matched impedance basis. Receiver sensitivity is stated in terms of power (dbm) instead of volts.

The components of a signal generator or other test unit are commonly arranged along a microwave transmission line. The wave guide type of line possesses certain advantages over a coaxial line in affording a lower loss, facilitating attenuator design as discussed in a subsequent section, etc. Hence the wave guide type of line is used in test equipment for those wavelengths where its size is not excessive, i.e. from about 4,000 mc upwards, and coaxial line for lower frequencies.

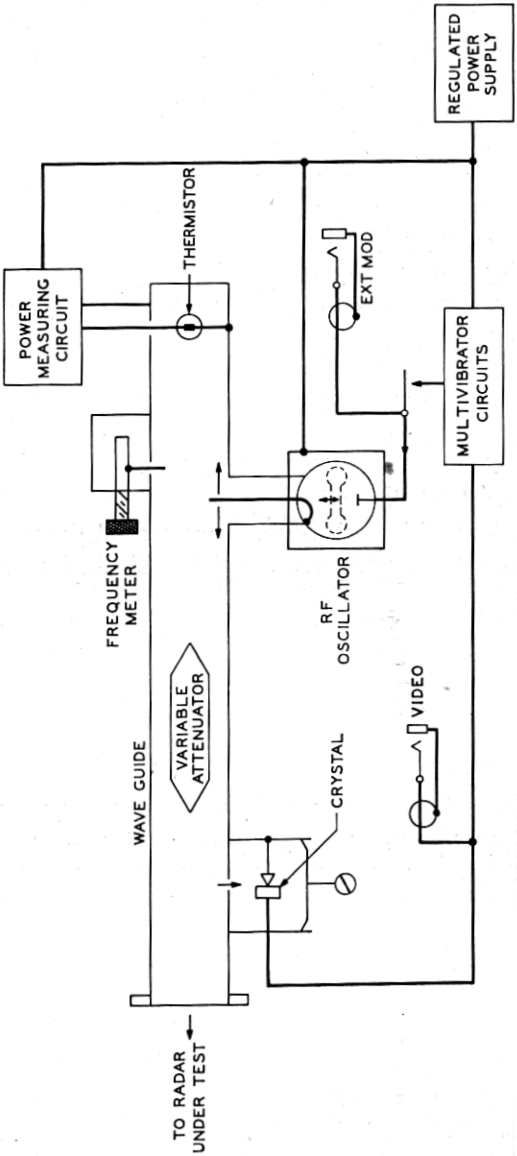

Fig. 5—Block diagram of TS-35A/AP signal generator.

A major problem in the design of microwave signal generators is the provision of shielding adequate to reduce leakage signals due to unwanted couplings or stray fields well below the minimum signal required for receiver testing. This minimum level may be as low as −70 or −80 dbm, depending on the coupling loss in the test connection.

A Pulsed and FM Signal Generator

To illustrate the functioning of a signal generator, there is shown in Fig. 5 a block schematic of a design (Army-Navy type TS-35A/AP) which covers a 12% frequency band in the vicinity of 9000 mc. An RF connection to the radar is established with a wave guide flange coupling. The frequency and power of the radar transmitter are measured by means of a coaxial-type frequency meter and thermistor power measuring circuit as described in subsequent sections. The attenuator and pad are adjusted to reduce the incoming average power to about 1 milliwatt, which gives a suitable deflection on the indicating meter. The thermistor is mounted across the wave guide.

An RF pulse train is employed in many tests. To produce this the RF oscillator output is modulated by a multi-vibrator which pulses continuously except when being synchronized. Synchronizing pulses are derived by crystal rectification of the RF pulses from the radar transmitter. The result is an initial RF pulse of 7 microseconds followed by an off period of about 10 microseconds followed by a train of RF pulses each 2 microseconds wide and recurring every 8 microseconds until resynchronization occurs at the next radar pulse.

Using the pulse train, the radar system components can be tuned for maximum sensitivity by maximizing the signal on the indicator. To check receiver sensitivity the CW power is first adjusted so that a power of 1 milliwatt is delivered to the pad and attenuator. Then with the set in the pulsed condition the amplitude of the test signal is adjusted by means of the attenuator and pad until the signal on the radar indicator is barely discernible. It is necessary for this test that the frequency of the test signal be equal to the magnetron frequency. The frequency meter is provided as part of the signal generator for this purpose.

The receiver recovery, i.e. the time required by the receiver to recover after disablement by the transmitter pulse, determines the minimum range at which a radar can be used. With this test set the receiver recovery characteristic is indicated by the amplitude of the test pulses in the interval immediately following the transmitter pulse.

The set is also adapted to serve as an FM signal generator. A sawtooth wave applied to the repeller gives a succession of frequency sweeps, each

Fig. 6—1942 model signal generator compared with one produced in 1945.

about 20 mc wide, and lasting about 6 microseconds. With this frequency modulated signal the width of receiver response may be observed on a Class A oscilloscope (i.e. one showing signal amplitude vs. time). However, with non-adjustable IF strips such measurement is seldom required. Failure of the radar AFC to follow frequency changes due to antenna scanning or other causes is indicated by a change in the indicator presentation. Pulling of the magnetron frequency due to changes in load impedance can be detected by turning off the AFC.

Signal Generator Designs

Designs of signal generators developed for the military arms during the war are interesting as landmarks of progress. The signal generator of the IE30 test set, deliveries of which began in May 1942, delivered pulsed RF signals in the 10 cm range, using sine wave synchronization. Following only three months later was the signal generator of the Army IE57A and Navy LZ test sets (Fig. 6), which covered a then very broad frequency band of 20% in the vicinity of 10 cm, and was designed to be triggered by the incoming RF pulse from the radar instead of by a separate synchronizing connection. This set and a redesigned version of it have seen wide usage in testing Army, Navy and Marine Corps radars.

Delivery of a test set for the 3 cm range, designated TS-35/AP, started in the fall of 1943. This set furnished both a train of pulses and a train of FM signals, both of which features have proved valuable. It covered a 9% frequency band with no tuning adjustment except for the oscillator. An improved design known as TS-35A (see Fig. 6) covered a 12% band.

Progress in reducing the size and weight of the test units is indicated by the fact that the IE30 signal generator weighed 121 lbs., IE57 74 lbs., whereas TS-35 and TS-35A weigh approximately 30 lbs.

FREQUENCY MEASUREMENT

Usually a radar need not operate at a precise frequency. Accurate measurements are required in the field, however, to keep the operating frequency within limits, to set the local oscillator, to check the measuring frequency, etc. In the laboratory, accurate frequency measurement is fundamental.

Frequency measurement in the microwave range is ordinarily accomplished by (1) a resonant coaxial line or (2) a resonant cavity, generally cylindrical. These types are illustrated in Fig. 7. Sometimes a combination of the two, referred to as a hybrid or transition type resonator, is employed. The measurement is actually one of wavelength, with the scale calibrated in frequency or a conversion chart provided. Some specific designs of frequency meters are shown in Fig. 8.

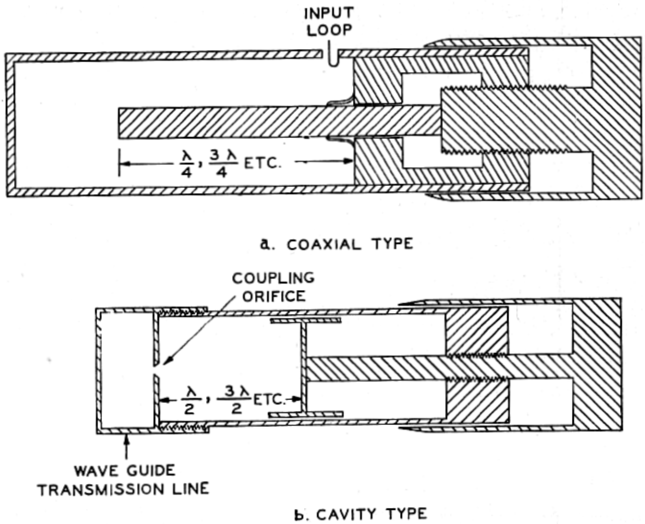

Fig. 7—Types of frequency meters.

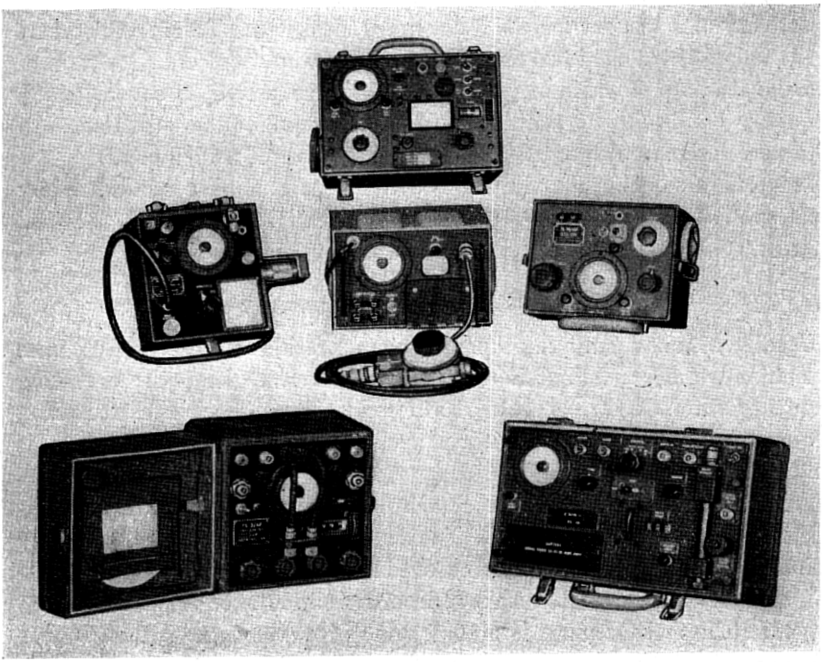

Fig. 8—A group of frequency and power meters designed for various bands in the frequency range 500 to 25,000 mc.

Coaxial Wavemeters

A coaxial wavemeter is formed of a section of coaxial transmission line of small enough diameter so that only the coaxial mode (in wave guide notation $TM_{0,0,n}$) can exist. Usually the line is short-circuited at one end and open at the other, in which case resonance occurs at the odd quarter wavelengths $\lambda/4$, $3\lambda/4$ etc.). The open circuit is obtained merely by terminating the inner coaxial conductor, the continuing outer conductor acting as a wave guide below cutoff. Sometimes the line is short-circuited at both ends, giving resonance at the even quarter-wavelengths ($\lambda/2$, λ, etc.).

Cylindrical Cavity Wavemeters

A cylindrical cavity wavemeter is merely a section of cylindrical wave guide transmission line[4] whose length is varied. In order to avoid confusion with other modes, it is preferable to use the dominant mode (described in wave guide notation, $TE_{1,1,n}$*) i.e. the mode with the lowest cutoff frequency. The cutoff wavelength (λ_c) of this mode is $1.706D$, where D is the diameter in meters. For a higher Q it may be necessary to use the circular electric mode $TE_{0,1,n}$. The cutoff wavelength for this mode is .82D. No useful purpose is served by using modes with l and m subscripts above unity. *TM* modes are often used for fixed frequency cavities, but for variable cavities *TE* modes are preferable since these have zero current at the inner wall of the cylinder and thus obviate moving contact difficulty. If any mode higher than the dominant one is used, suppression of unwanted modes may be required.

The accuracy of a wavemeter is dependent on its resolving power. This in turn depends upon Q, which is an index of the decrement of the resonant circuit, and is equal to $f/\Delta f$, where Δf is the distance between 3 *db* points on the resonance curve.

In a coaxial wavemeter, maximum Q for a given inner diameter is obtained with a diameter ratio of about 3.6[5] The basic Q of a coaxial wavemeter, assuming copper of standard conductivity, is roughly[6]

$$Q_0 = 0.042D\sqrt{f} \qquad (3)$$

This expression neglects end effects and hence gives somewhat too high a value of Q.

The basic Q's for $TE_{1,1,n}$ and $TE_{0,1,n}$ cylindrical cavity resonators employing copper of standard conductivity are, respectively,

* *TE* and *TM* represent, respectively, transverse electric and transverse magnetic. The subscripts l, m, n denote, respectively, the number of wavelengths around any concentric circle in the cross section, the number of wavelengths across a diameter, and the number of half wavelengths along the length of the cylinder.

$$Q_0 = 0.0937 \times 10^{10} \frac{A^3}{\sqrt{f}} \frac{1}{1 + B^2\left(0.826 \frac{B}{n} + 0.295\right)} \tag{4}$$

$$Q_0 = 0.2762 \times 10^{10} \frac{A^3}{\sqrt{f}} \frac{1}{1 + B^2\left(2.439 \frac{B}{n}\right)} \tag{5}$$

with $A = \frac{\lambda_c}{\lambda}$, $B^2 = A^2 - 1$, and f is in cycles per second.

The value of Q which determines accuracy is not the basic Q, but the loaded or working Q, herein designated Q_L.

The resolving power of a wavemeter used for measuring a single frequency can be made considerably better than f/Q_L. With a sensitive meter it is readily possible to detect differences less than 1 db, which corresponds to a frequency interval of $f/2Q_L$.

The required accuracy in a wavemeter is generally absolute rather than a percentage. Hence increasingly large values of Q_L are required at the higher frequencies. Thus for a resolution of 1 mc, assuming 1 db discrimination, the values of Q_L required for different frequencies are:

Frequency	Q_L	Frequency	Q_L
1,000 mc	500	10,000 mc	5,000
3,000 mc	1,500	25,000 mc	12,500

An unnecessarily high value of Q_L has the disadvantage of making it more difficult to find the desired frequency.

Linearity

The displacement of the coaxial plunger of a coaxial type wavemeter for resonance is substantially a direct linear function of free space wavelength and if an ordinary centimeter micrometer drive is used it is possible to read wavelength differentials directly. Over bandwidths less than 20 per cent, displacement vs. frequency is also quite linear which is of considerable advantage for some uses.

For the cavity type wavemeter the displacement is a variable function of free space wavelength and becomes very non-linear as the cutoff frequency of the guide or cavity is approached. This is evident from the relation between wavelength in the guide, λ_g, wavelength in free space, λ, and cutoff wavelength, λ_c:

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \frac{\lambda^2}{\lambda_c^2}}} \tag{6}$$

A cam or mechanical linkage may be employed to obtain a linear scale.

Frequency Coverage

Increasing the length of a wavemeter is desirable because this gives a larger mechanical displacement for a given frequency interval. The permissible increase is limited, however, by ambiguity with the next lower mode in going toward the upper end of the frequency scale and with the next higher mode in going toward the lower end. This means that, if ambiguity is to be avoided, the ratio of top to bottom frequency cannot exceed $(n + 2)/n$ for a coaxial line of n quarterwaves. For a cylindrical cavity resonator the ratio for the $0,1,n$ mode must be less than $n + 1)/n$, the exact limit depending on proximity to cutoff.

Guideposts

The following guideposts are suggested for choosing the type of wavemeter in the microwave range. Where limitations of size and Q permit, the coaxial quarter-wave type should be used because of its greater linearity. If this type is inapplicable, the cavity type with $TE_{1,1,n}$ should be used unless its Q is inadequate, in which case $TE_{0,1,n}$ should be employed.

Couplings

A loop, orifice or probe may be used for coupling to a wavemeter. Coupling to a coaxial wavemeter is generally effected by a loop placed near a short-circuited end so as to be in the maximum magnetic field. For coupling to a cylindrical cavity wavemeter, an orifice in or near the base of the cavity is usually employed. The coupling to the wavemeter is kept small enough to avoid serious reduction of loaded Q.

Types of Detectors

Various types of detectors may be associated with a wavemeter, the most commonly used being (1) a crystal rectifier and microammeter, or (2) a thermistor bolometer. When a crystal rectifier is employed with a cavity or coaxial wavemeter a circuit similar to that shown in Fig. 9 is used. Important items in such a circuit are the "RF by-pass" condenser, and the "video" condenser. The latter, by providing a low-impedance path to the video signals, improves rectification efficiency when the input signal is pulsed. The quarter-wave stub shown in the figure is used when the input or coupling circuit does not provide DC and video paths. When the signal is pulsed at a low duty cycle, high peak currents through the crystal are obtained even though the average current through the meter is small, and it is possible to impair or burn out the crystal unless extreme care is taken. The use of a thermistor, which is self-protecting for large overloads, avoids this danger. Another expedient is to limit the crystal current to a small value and employ a video amplifier and oscilloscope.

Methods of Use

A wavemeter may be used as either a transmission or a reaction instrument. In the former case (Fig. 10a) it is inserted directly in the transmission path, so that substantially no through transmission occurs except at resonance. In the latter case (Fig. 10b) the wavemeter is coupled to the transmission path or a branch circuit. When the meter is tuned off resonance it presents such a high impedance to the main path that its effect is negligible. At resonance, however, it offers a lower impedance which reflects energy in the main line so that less power reaches the detector and

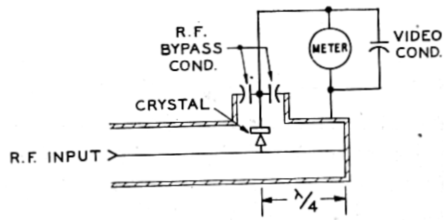

Fig. 9—Crystal detector for pulsed RF signals.

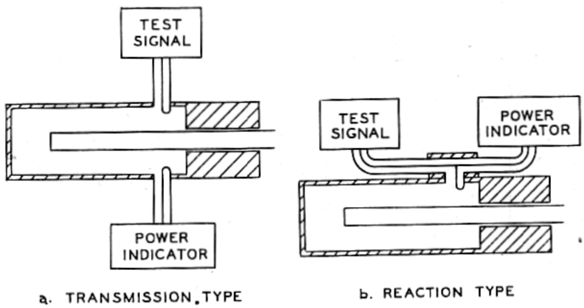

Fig. 10—Types of frequency meter circuits.

a dip in the reading occurs. For most applications the reaction arrangement is preferable since the power transmitted when the wavemeter is off tune may serve various purposes. For analysis of frequency spectrum the transmission method is necessary. This method requires two couplings to the wavemeter, which lowers the Q as compared with the reaction type.

Drive and Scale

A direct drive with a precision lead screw of the micrometer type is frequently used. Accuracy of reading is insured by spring loading to minimize backlash and by specifying close tolerances for threads and for concentricity of plunger and cavity. The scale on a wavemeter must be fine enough to permit utilization of the resolving power. The conventional micrometer type of scale sometimes makes accurate reading difficult in a small compact meter. Scale mechanisms which have been used include counter types, clock face or expanded drum types with gearing between vernier and coarse scales, and a single direct reading scale with divisions arranged in a spiral for compactness.

Effect of Temperature and Humidity

To minimize the effects of temperature on the accuracy of readings, invar has been employed for elements whose dimensions affect the wavelength. For accurate work, the scale reading must be corrected for temperature. A rough approximation is that the scale reading varies in accordance with the coefficient of expansion of the metal.

Water vapor included in the air dielectric of a wavemeter has an appreciable effect on the dielectric constant and hence on the resonant frequency.[7] Thus, for example, in going at sea level from 25° C, and 60% humidity to 50° C, and 90% humidity, the scale reading should be reduced by .03%. Correction can be made by means of a chart, a convenient form of which has been prepared by Radiation Laboratory.

Calibration

Frequency meters are calibrated against sub-standards which in turn are calibrated against a multiplier from lower frequencies for which a high order of accuracy can be obtained. Such multipliers have been made available at Radiation Laboratory and the National Bureau of Standards. The accuracy obtained at interpolation frequencies is of course less than at exact multiples of the base frequency. In the microwave range the accuracy is believed to be of the order of one part in 100,000.

Power Measurement

There are two needs for power measurement in radar maintenance, namely (1) in evaluating transmitter performance and (2) in standardizing test signals. Power output is, of course, only one factor in transmitter performance, others being (a) frequency and (b) spectral distribution or shape of RF envelope. Ability to measure absolute power is desirable to permit interchangeable use of test sets in the field.

Measurement of Pulse Power

The transmitter power as used in Formula (1) is the average power during the pulse. The relationship of pulse to (long) average power is

$$\frac{P_t \text{ av.}}{P_t \text{ pulse}} = Tf_r \tag{7}$$

T is the pulse duration in seconds and f_r is the pulse recurrence frequency (P. R. F.) in cycles per second. The product Tf_r is the duty cycle. (Sometimes the reciprocal of this number is referred to as the duty cycle. The magnitude is usually such that no ambiguity arises.)

During the early days of radar it was the practice to measure pulse power. The test equipment was coupled to the radar by a path of known loss. The RF envelope was derived by means of a crystal rectifier and applied to an oscilloscope. With the aid of an RF attenuator the level applied to the crystal rectifier and oscilloscope was held constant. Calibration was obtained by using a signal generator whose output was standardized, prior to pulsing, with an averaging type of power meter. The procedure was rather involved, with several sources of possible error. Since it is much simpler to measure (long) average power, field measurement of pulse power was soon abandoned. Though the pulse power can be computed from average power if the pulse width, pulse shape and repetition rate are known, it soon became the practice to specify field performance requirements in terms of average power.

Thermistor Power Meters

A number of devices have been used for measuring average power in the microwave range. Those suitable for handling the small amounts of power normally involved in field tests include (1) thermistors, (2) platinum wires and (3) thermocouples. In each case the RF power to be measured is absorbed in the measuring element. The measurement consists in observing the resistance change in the thermistor or platinum wire, or the thermoelectric voltage from the thermocouple. By analogy with devices used for measuring minute quantities of radiant heat, either a thermistor or a platinum wire instrument is sometimes referred to as a bolometer. The platinum wire device has also been termed a barretter.

A thermistor for microwave power measurement is a tiny bead (about 5 mils in diameter) composed of a mixture of oxides of manganese, cobalt, nickel and copper, constituting a resistor with a very high negative temperature coefficient.[8]

The thermistor has a number of advantages for microwave work, namely: (1) resistance is highly sensitive to change of heating power, which obviates any need for amplification or a super-sensitive meter, and makes it possible to use a rugged d.c. meter; (2) reactance is low compared with RF resistance, which makes it possible to incorporate the thermistor in a power absorbing termination which matches the impedance of a microwave transmission line over a wide band; (3) resistance change is the same function of electrical heating power at any frequency, which permits direct comparison of the unknown microwave power with easily measurable d.c. power; (4) sensitivity to damage and burn-out is inherently low, and added protection results from impedance mismatch during overload. Because of these characteristics thermistors have been far more widely used than other detectors for microwave power measurement. Broad-band thermistor mounts have been designed to match both wave guide and coaxial transmission lines, the latter not only in the microwave range but also down to low frequencies. Some of the test sets specifically intended for power measurement or for combined power and frequency measurement are shown in Fig. 8.

The change in the thermistor resistance due to RF heating current is determined by placing the thermistor in one arm of a d.c. bridge. By noting the d.c. power necessary to balance the bridge with and without RF power in the thermistor, the magnitude of the RF power may be determined. For most purposes, however, a direct reading power meter is preferable. This can be obtained over a moderate range of power levels by employing an unbalanced bridge. The bridge is balanced for d.c. only and the measurement consists in noting the meter deflection when RF power is added.

The resistance of a thermistor is a highly sensitive function not only of electrical heating power but also of ambient temperature. For convenient field measurement, the effect of ambient temperature must be cancelled out in the indicator circuit so that the indication depends only on RF power.

Water Loads

A method which has been used in the laboratory and factory for measuring high-level microwave power consists in terminating the RF transmission line in a water load arranged as a continuous flow calorimeter. This method can be made quite accurate but is cumbersome. More recent practice is to terminate the RF line in a solid load of a type described later in this article, and to couple a thermistor power meter to the line by means of a directional coupler (described below) of known loss. Very close correlations have been obtained between the two methods over the entire microwave band.

Echo Boxes

A device unique to radar testing is a high Q resonant cavity, known as an "echo box" or "ring box." The cavity is coupled to the radar transmission line or antenna as indicated in Fig. 11. During the transmitted pulse, microwave energy is stored in the cavity. In the period immediately thereafter, energy is returned to the radar over the same path, producing a signal on the radar indicator. The energy in the cavity builds up exponentially to an amplitude dependent on the radar power. At the end of the pulse the returned energy decays exponentially, disappearing into the noise at a point determined by receiver sensitivity. The time interval between the end of the transmitted pulse and the point where the signal on the radar indicator disappears into the background noise, called the "ring time," therefore measures the over-all performance of the radar.

An echo box is a particularly useful instrument for radar testing because it measures over-all performance directly, because it permits a rapid tune-up, and because it utilizes the radar transmitter as its only source of power and therefore can be made extremely portable. Figure 12 shows typical ring-time patterns on different types of indicators. In actual practice the ring-time is read in miles on the radar range scale and hence is measured from

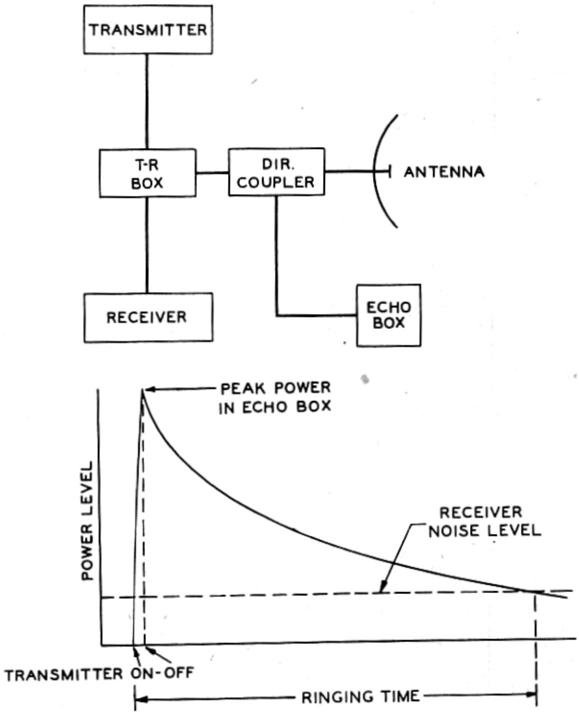

Fig. 11—Radar test with echo box.

the beginning of the transmitted pulse rather than the end. The difference is unimportant, however, since standard and limiting values of ringtime are established for operating conditions. It will be noted that the echo box does not return a true echo to the radar, so that the name "echo box" is not entirely appropriate.

Types and Uses

Echo boxes are of two general types, tuned and untuned. A tuned echo box is designed to resonate in a single mode adjustable over the operating frequency range. An untuned echo box is a fixed cavity of a size sufficient to support a very large number of modes within the working range. Tuned echo boxes are more versatile and more widely used than untuned boxes.

The most common type of tuned echo box is designed for hand tuning. While other shapes are possible, the most convenient one is a right cylinder whose length is adjusted by a movable piston. The $TE_{0,1,n}$ mode gives

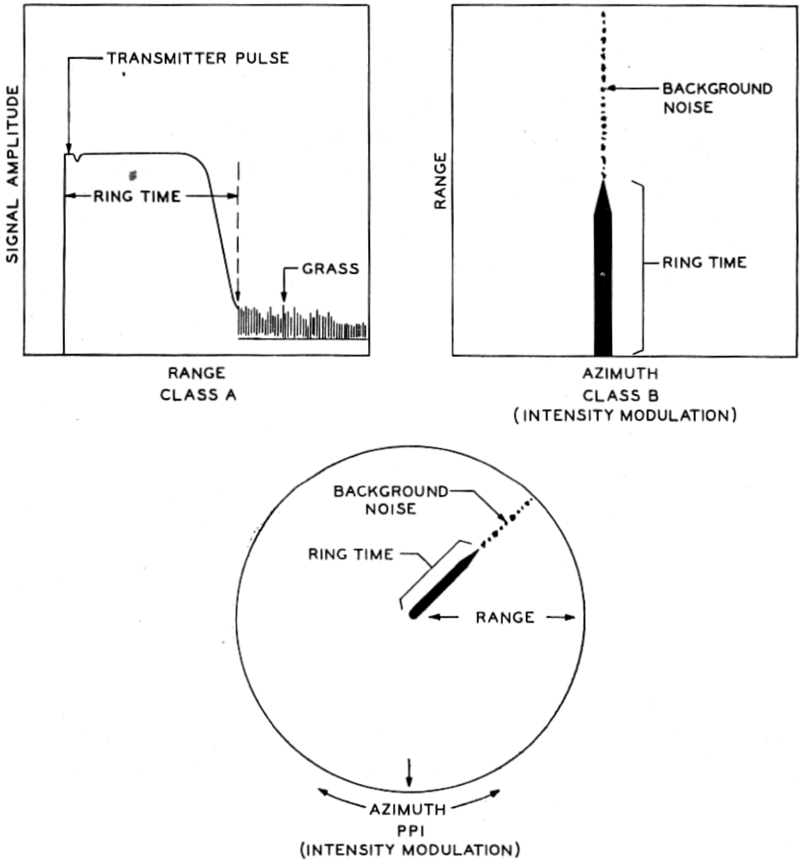

Fig. 12—Typical ringtime patterns on radar indicators.

maximum Q for a given volume and minimizes the number of unwanted modes present within the desired band. The value of n is determined by the desired value of Q (see formula 5). Unwanted modes can be partially avoided by choice of design parameters. However, for high values of Q, and especially for broad frequency bands, the suppression of unwanted modes involves design problems of the highest order.

As indicated in Fig. 13, a tuned echo box cavity is usually provided with two couplings. One of these is to the radar pick-up; the other to an attenuating device, crystal rectifier, and meter, which serve for tuning the cavity and for other purposes. With such an instrument, not only can the radar be tuned up and its over-all performance determined, but many other tests can be made, to wit: (1) the setting of the plunger at resonance indicates the transmitter frequency or wavelength; (2) calibration of the crystal affords a rough measure of output power; (3) since the Q required for adequate ringtime is so high that the cavity selects only a narrow segment of the transmitter spectrum, a spectrum analysis can be made by plotting frequency versus crystal current reading; (4) slow recovery of TR box and receiver after the transmitted pulse can be detected by noting the behavior of the ringtime pattern at short ranges as the echo box is detuned; (5)

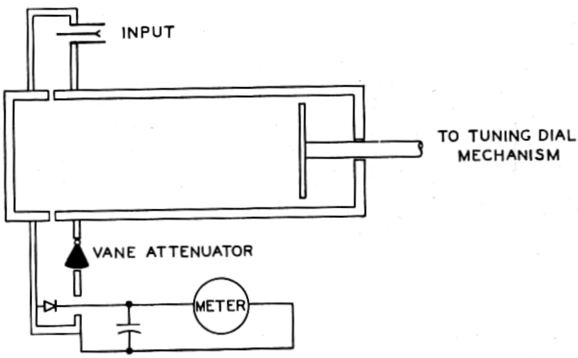

Fig. 13—Functional schematic of tuned echo box.

inability of the receiver to recover promptly after a strong signal (the result of imperfect d.c. reinsertion in the video amplifier or of overloading of the I.F. amplifier) is indicated by a blank following the end of the ring; (6) improper pulsing (e.g. double moding or misfiring) can be determined with a class A oscilloscope; (7) the frequency and power of the local oscillator can be measured. In tuned echo boxes, requirements for extreme fineness of tuning control and precise resettability have given rise to interesting problems in the design of the mechanical drive and indicating mechanism.

In another type of echo box, hand tuning is supplemented by motor-driven tuning or so-called "wobbling" over a frequency range wide enough to embrace expected variations in transmitter frequency. Operation is controlled by a single push-button which energizes the motor and actuates the cavity coupling. Such an instrument may be permanently installed in a plane and used to check the radar during flight.

For an untuned or multi-resonant echo box, rectangular shape is convenient. The box should be large enough to make it highly probable that over the operating band one or more modes will be present within any frequency interval of width equal to the main concentration of the transmitter spectrum. For a given rectangular volume a cube gives the largest number of modes. The total number of modes up to a frequency of wave length λ is

$$N_M = 8.38\ V/\lambda_0^3 \tag{8}$$

where V is the volume. However, because of the cubical shape many different modes tend to coincide in wavelength, a condition referred to as

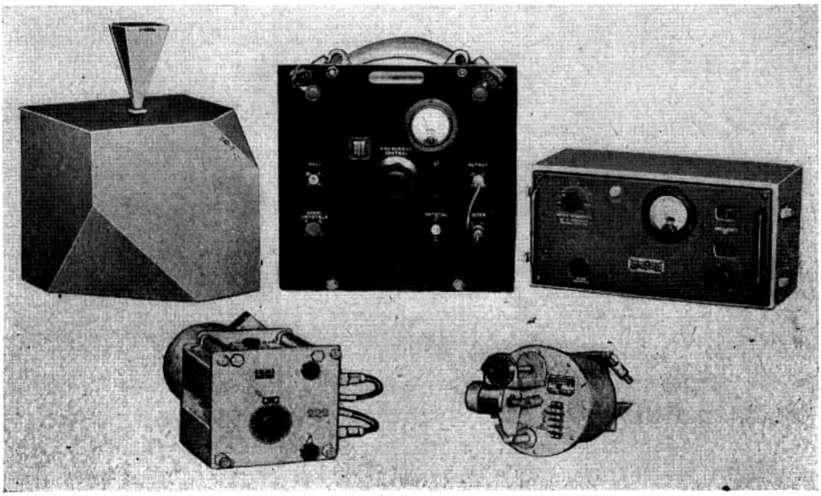

Fig. 14—A group of echo boxes of various types.

degeneracy. To spread out the modes, the box is made slightly off cube and one or more corners sliced off. At the longer microwaves the size of box is determined by the number of modes, and the size becomes quite awkward. For the shorter microwaves the size is determined by the required value of Q. Hence the use of untuned echo boxes has been limited to the frequency range from about 9000 mc upwards with sizes of the order of 12 to 24 inches on a side. Even with an extraordinarily high probability of finding modes within the radar band, substantial differences in response are found for relatively small changes in frequency. Accordingly untuned echo boxes are more useful for rough tune-up than for precise measurement.

A number of specific designs of echo boxes for different microwave bands are shown in Fig. 14.

Q and Ring Time

For satisfactory measurement the ringtime must extend beyond nearby echoes which would obscure the test signal. For most radars a ringtime of 20 to 30 microseconds (about 2 to 3 miles) has been found satisfactory although considerably higher values have sometimes been provided. Even apart from echoes, a long ringtime is desirable since this gives a lower decay rate and a more sensitive measurement.

Computation will show that an extremely high value of Q is necessary to obtain the desired ringtime. For maximum ringtime the cavity coupling should be such as to make the working Q (Q_L) about 90 per cent of the non-loaded Q. Values of working Q which have been provided in different frequency ranges are approximately as follows:

Frequency	Q_L	Frequency	Q_L
1,000 mc	70,000*	10,000 mc	100,000
3,000	40,000	24,000	200,000

* In this case a higher Q was needed for a long range ground search system.

The difference in performance corresponding to a given change in ringtime can be determined from the decay rate which is

$$d = 27.3\, f/Q_L \;\; db/\text{microsecond} \tag{9}$$

For a given frequency the ringtime is directly proportional, and the decay rate inversely proportional, to Q. For a given ringtime, the required Q is directly proportional to frequency.

Accurate measurement of extremely high Q's is essential in echo box work. A decrement method, in which a pulsed RF oscillator and oscilloscope are used to determine the loss corresponding to a known time interval, has proved most satisfactory.

Spectrum Analysis

The frequency components of a non-repetitive rectangular d-c. pulse may be determined by well known methods using Fourier integral analysis. The envelope of amplitudes is of the form $(\sin x)/x$ where $x = \pi f T$. This envelope is shown by the right-hand side of the curve of Fig. 15a, f_0 being assumed to represent zero frequency. The first zero occurs at the frequency $f = 1/T$.

Similarly the envelope of the spectrum of a rectangular a-c. pulse is given by the complete curve of Fig. 15a, f_0 in this case being the carrier frequency. For a non-repetitive pulse all frequencies are present in amplitude as shown by the envelope. When a stable carrier frequency is pulsed at uniform intervals and in precise phase relation, only harmonics of the repetition frequency are present under the envelope. In radar practice conditions are, as a rule, not sufficiently stable for this to occur.

Because of its bandwidth, an echo box cannot reproduce the ideal spectrum envelope of Fig. 15a. Instead the curve for a good spectrum may resemble that of Fig. 15b, while spectrum irregularities detrimental to radar performance may be revealed by curves such as those of Fig. 15c and 15d. Broadening of the spectrum is undesirable because less energy falls within the receiver band. Energy removed from the main concentration may result from double moding or from the occurrence of a different frequency during the rise or fall of the pulse. Frequency modulation due to a sloping

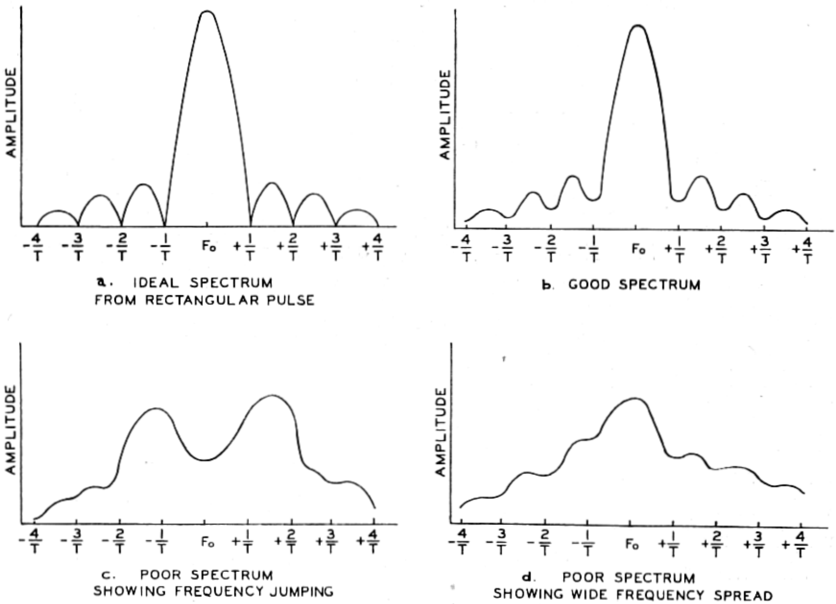

Fig. 15—Radar spectrum analysis with echo box.

or spiked input pulse produces a non-symmetrical spectrum, not infrequently characterized by a high side lobe. Frequency jump in the middle of the pulse, due to line reflection, may produce two distinct maxima.

Another device widely used for this purpose is the "Spectrum Analyzer" as developed by Radiation Laboratory, which provides an oscilloscope presentation of spectrum component amplitudes versus frequency.

Standing Wave Measurements

Theory

The expression for the distribution of current or voltage along a misterminated line of appreciable electrical length yields two terms which may be considered as representing two waves transmitted in opposite directions, one (the incident wave) from the generator toward the load, the other (the reflected wave) from the load toward the generator. The summation is a standing wave pattern. The standing wave ratio (SWR) is defined as the ratio of the wave amplitude at a maximum point (anti-node) to that at a minimum point (node). If the standing wave ratio is stated as a numeric, it is necessary to specify whether it applies to voltage (VSWR) or power (PSWR). Possibility of ambiguity is avoided by stating the ratio in db.

The ratio of the reflected current to the incident current is the *reflection coefficient*, here designated as ρ. The value of the reflection coefficient is given both in magnitude and phase by

$$\rho = \frac{Z_0 - Z}{Z_0 + Z} \tag{10}$$

where Z_0 is the characteristic impedance of the line and Z is the load impedance. The reflection coefficient is related to the standing wave ratio as follows:

$$VSWR = \sigma = \frac{1 + \rho}{1 - \rho}, \quad \text{or,} \quad \rho = \frac{\sigma - 1}{\sigma + 1} \tag{11}$$

Plots of the relationships are shown in Fig. 16.

The reduction of radiated power due to reflection losses in a radar transmission line, while important, is usually less serious than other effects of impedance irregularities. Since the load impedance reacts on the oscillator circuit, the frequency and output of most transmitter tubes are quite sensitive to load impedance. If the line is electrically long, so that its impedance varies rapidly with frequency, marked instability of oscillator frequency may occur, a condition referred to as "long line effect."

Since radar transmission lines contain many potential sources of impedance discontinuity, including not only the antenna but a variety of couplings, bends, wobble joints, rotating joints, switches, etc., measurements of standing wave ratio are frequently required. The need for such measurements depends in part on whether the line is "preplumbed" or is provided with field adjustments.

Devices

Standing waves may be detected and measured by several different types of devices, including (1) a slotted line, (2) a squeeze section, (3) a directional coupler and (4) a hybrid T. All of these furnish information on the magnitude of the standing wave ratio. In some cases phase information may be obtained also, which permits determination of impedance,[9] but this knowledge, while useful in the laboratory, is seldom required in field work.

A block diagram of an arrangement employing a slotted line for measuring standing waves is shown in Fig. 17. The oscillator source is commonly followed by a pad or attenuator to prevent frequency pulling. The slotted section may be either a coaxial or a wave guide line employing a mode which is not disturbed by the presence of the slot (e.g. normal coaxial mode; $TE_{1,0}$ in rectangular wave guide; $TM_{0,1}$ in round wave guide). A traveling pick-up probe or loop projects through the slot and couples energy from the line into a detector which delivers d-c. or audio-frequency to the indicator. The

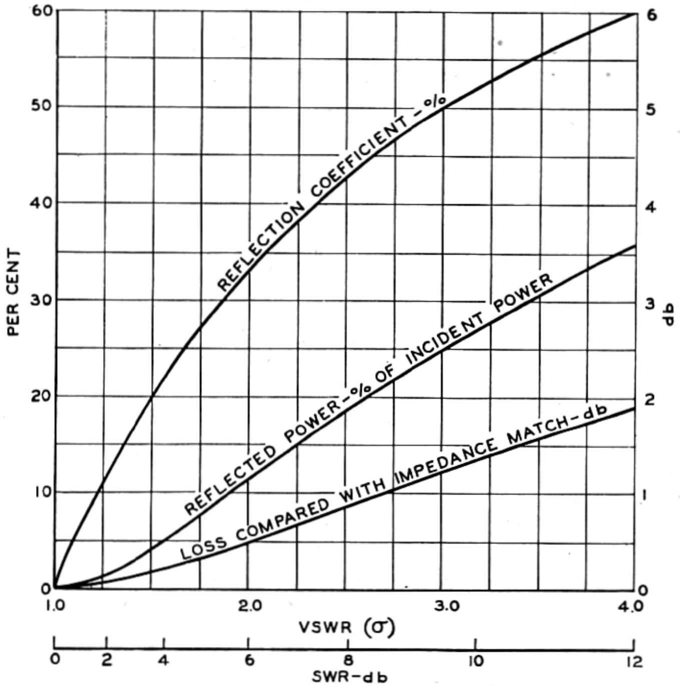

Fig. 16—Relations in mismatched transmission lines.

probe is moved longitudinally to find points of maximum and minimum field strength. To avoid distortion of the field within the line, the probe should be small and should project only a short distance inside the slot. For accurate results extreme care must be exercised in design and construction to avoid variation in depth of immersion as the probe is moved. Several slotted lines employed for standing wave measurements are shown in Fig. 18.

A squeeze section consists of a section of rectangular guide with slots milled in the center of both broad faces so that the width of the guide can be varied by external deforming means. This changes the wave length in

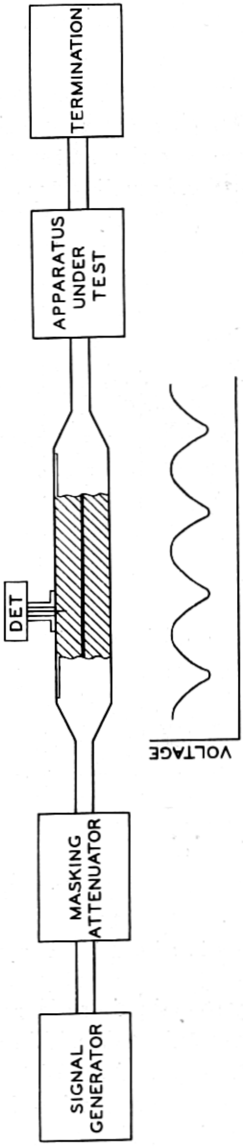

Fig. 17—Standing wave measurement.

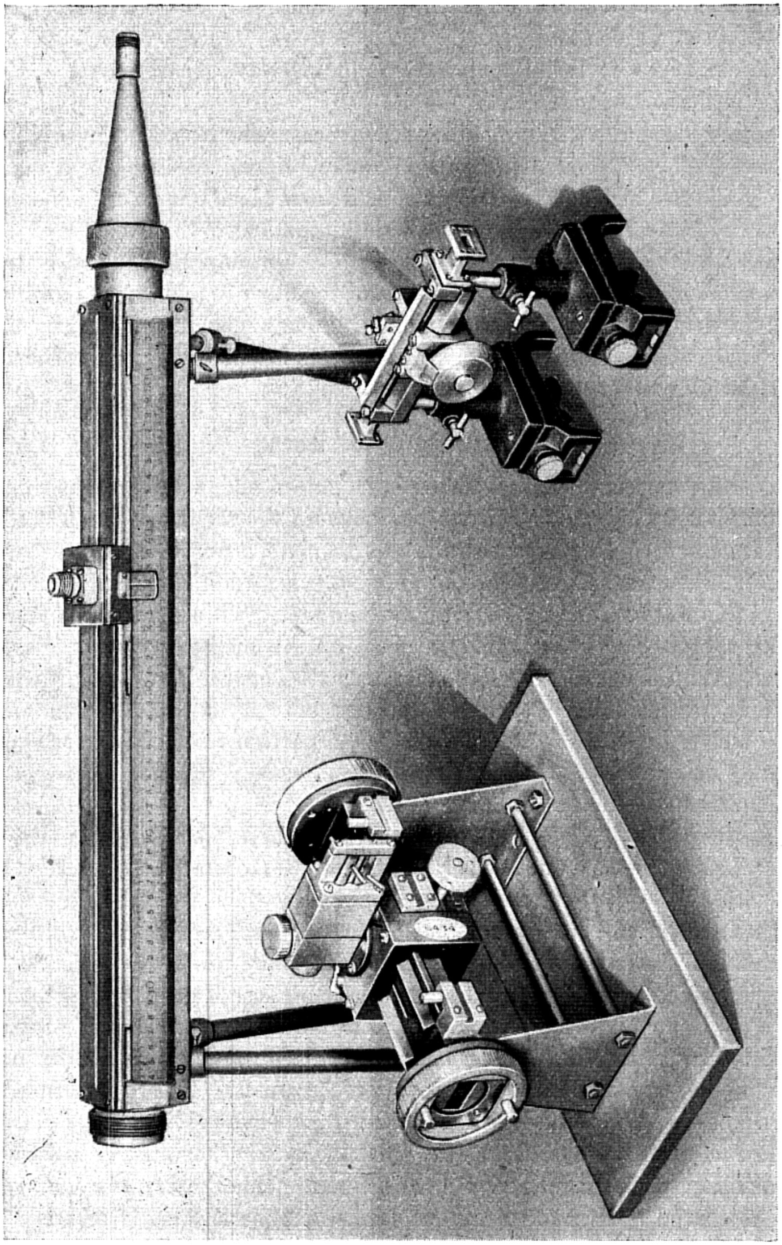

Fig. 18—Standing wave detectors used on coaxial and wave guide transmission lines.

the guide, so that maximum and minimum values may be determined by a fixed probe and indicator.

The use of a directional coupler for standing wave measurement is discussed in the following section.

Another useful device for standing wave measurement is the "hybrid T" or "magic T". This is a sort of microwave bridge, consisting of a main wave guide to which an E plane branch and an H plane branch are joined in the same physical plane. With matched terminations of the two ends of the main guide, the two branches are conjugate. Terminating one end of the main guide in the unknown impedance and the other in a matched termination, the degree of impedance mismatch of the unknown is indicated by the magnitude of the reflected wave which appears in one branch when energy is fed into the other.

Directional Couplers

Accurate measurement of transmitter power and receiver sensitivity requires a coupling path of known loss between the radar and the test set. The first method employed for this was to place a portable test antenna (see Fig. 2) in the field of the radar antenna. Depending on the frequency range, this test antenna took the form of a dipole,[10] with or without a small reflector, or an electromagnetic horn.[11] With this method it was necessary to calibrate the loss of the space coupling path between the two antennas. Since it proved difficult to locate the test antenna at exactly the same point and to be sure that the main antenna pattern remained the same, a separate calibration of the coupling loss was usually required whenever a measurement was made.

An alternative method was to place a single probe in the radar transmission line. This introduced another sort of difficulty. Accuracy of measurement was vitiated by the presence of standing waves which rendered the probe pick-up a function of frequency and of location with respect to the irregularities. A highly satisfactory answer to the entire problem was found in a device which is called a directional coupler because it couples only to the wave propagated in one direction. In its simplest form a directional coupler consists of two couplings to the main transmission line, which add for one direction of transmission and cancel for the other. Thus, for example, Fig. 10a shows a form of directional coupler for wave guide which is placed in the radar transmission line at the point indicated schematically in Fig. 1. An auxiliary wave guide is coupled to the main guide through two identical orifices spaced $\lambda_g/4$ between centers (or more generally $n\lambda_g/4$ where n is an odd integer). Assuming the incident and reflected waves in the main guide to be directed as shown, and the auxiliary guide to be terminated on one end, a test circuit connected to the other end will be coupled to the incident wave, while theoretically the two couplings to the reflected wave will differ by $\lambda/2$ and therefore cancel one another.

With such a device measurements may be made of the characteristics of the incident wave independently of reflections. If the coupling to the main line is not too close there is no appreciable effect on the incident wave, and continuous monitoring can be had. Conversely, test signals applied through the directional coupler will travel in the main guide in the proper direction for testing the radar receiver.

If the locations of the termination and the test connection point in Fig. 19a are reversed, the couplings to the main transmission line are also reversed. Such an arrangement therefore permits measurement of the reflected power which in turn makes it possible to adjust for minimum reflected power and hence for minimum SWR. Comparison of the reflected power with the direct power determines the SWR. For convenience in measurement, two directional couplers pointed in opposite directions are frequently used, the combination being referred to as a bi-directional coupler (Fig. 19b). One advantage of this arrangement is that the ability to measure the reflected power from the antenna and that part of transmission line beyond the coupler provides means for detecting trouble in that part of the system. Directional couplers may be applied to any type of transmission line. Figure 19c shows a simple form of directional coupler for a coaxial line.

One characteristic of importance in a directional coupler is the coupling loss. A small value of coupling loss affords increased sensitivity of measurement, while a sizable value is desirable to minimize reaction on the main transmission line as well as for other reasons. A loss of around 20 db has usually been found a good compromise. It is now the practice to incorporate a directional coupler in every radar to obtain a test connection point.

Due to unavoidable imperfections, a directional coupler never gives complete cancellation for the undesired direction of transmission. The departure from ideality is indicated by the directivity (also referred to as front-to-back ratio) which is defined as the scalar ratio of the two powers measured at the test connection point when the same amount of power is applied to the main guide, first in one direction and then in the other. For measurements of the direct wave and of receiver characteristics, a moderate directivity, of the order of 15 db or better, is sufficient. In measuring reflected power, however, the directivity determines the amount of direct power which appears at the point of measurement and therefore controls accuracy. The chart of Fig. 20 will facilitate determination of the maximum

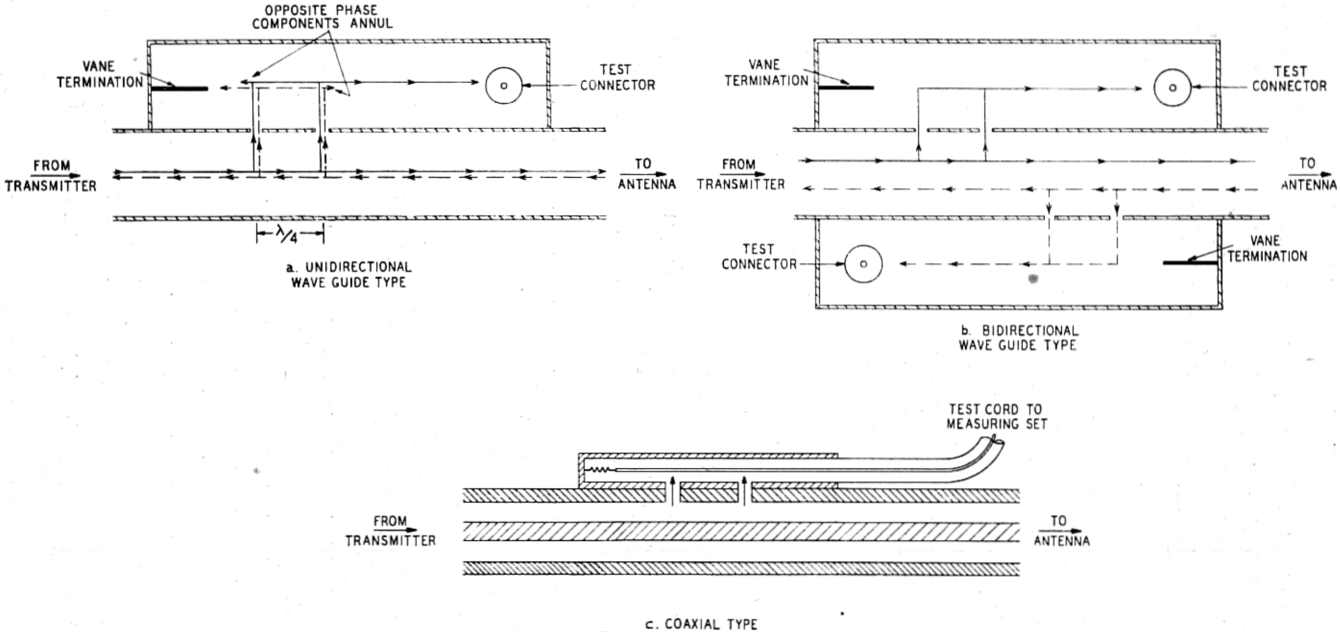

Fig. 19—Directional coupler arrangements.

error that may occur in measuring different values of SWR with various assumed directivities.

With a simple two-hole coupler, the directivity deteriorates rapidly as the frequency departs from that corresponding to quarter-wave spacing.

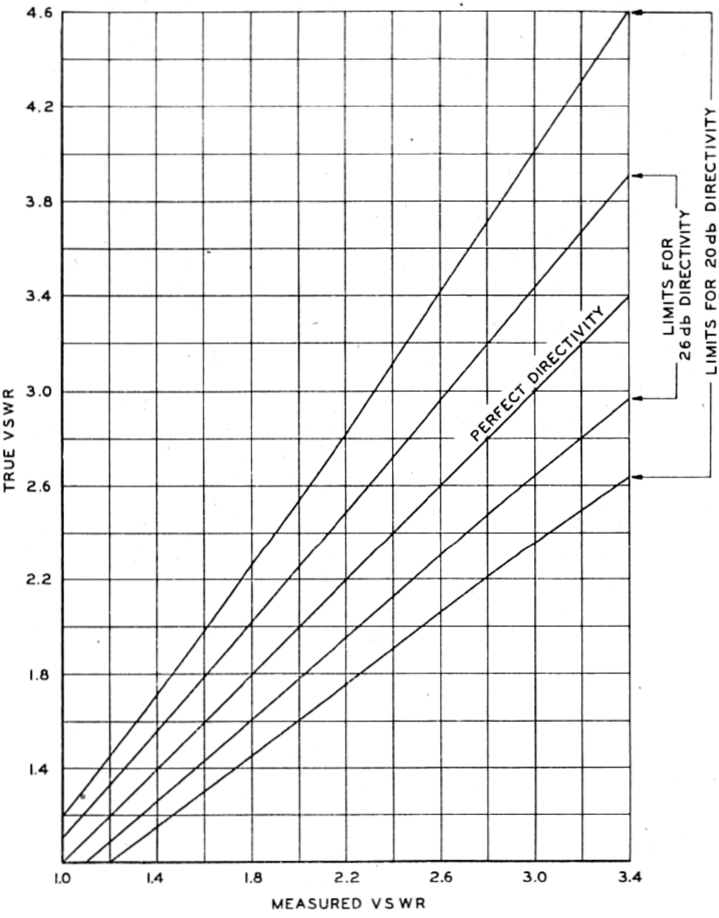

Fig. 20—Error in standing wave measurements caused by directivity of directional coupler.

By providing additional couplings suitably spaced, the residuals from different sets of couplings can also be cancelled against one another and the directivity versus frequency characteristic can be materially broadened. With multiple hole couplings a minimum directivity of 26 to 30 db over a frequency band of 10 to 20% is readily practicable in quantity production,

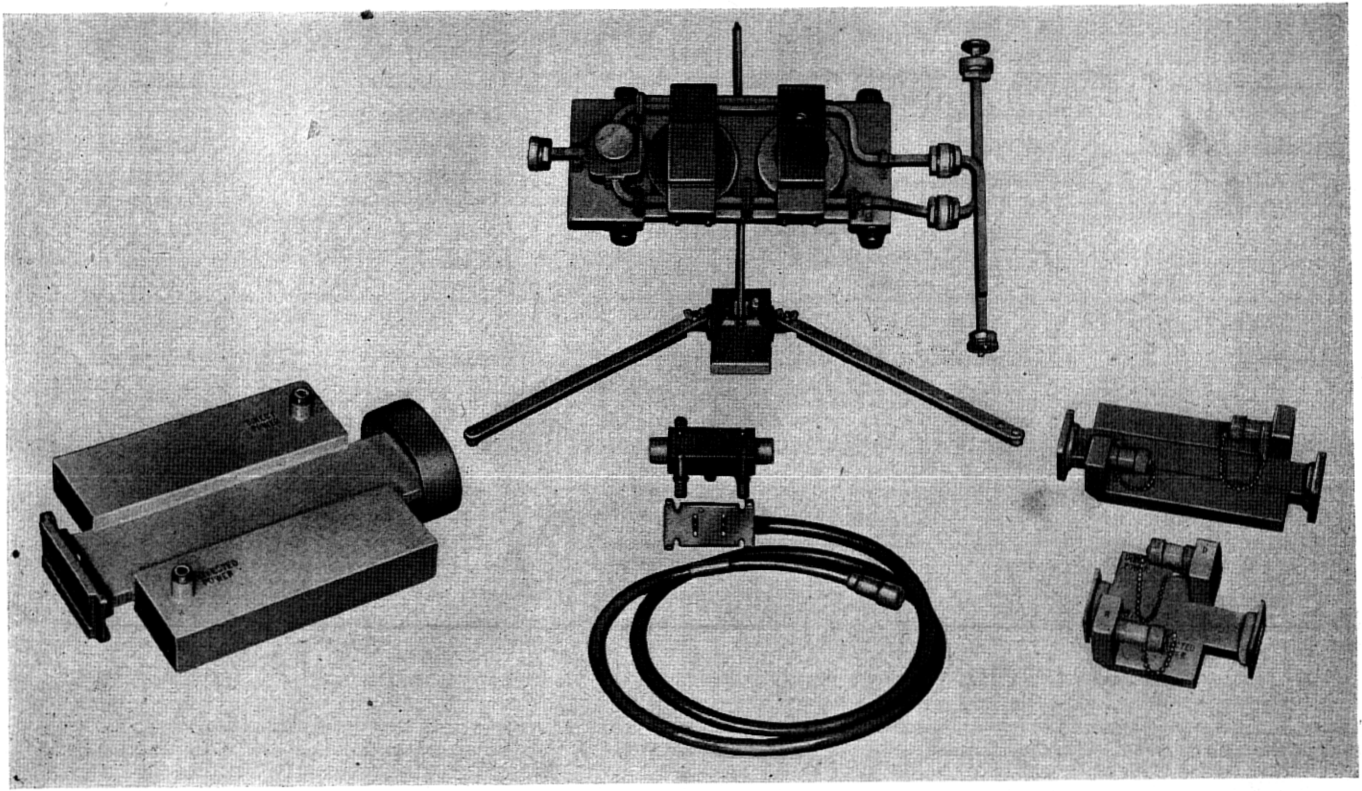

Fig. 21—A group of microwave directional couplers together with a directional coupler test set.

and much better values are obtained in the laboratory. Some of the numerous designs of directional couplers developed for association with operating radars are shown in Fig. 21.

Because they are more convenient than slotted lines and can be made more accurate, directional couplers have been extensively used for SWR measurement in the laboratory. A number of special arrangements have been devised to improve both accuracy and convenience. A directional coupler arrangement which has been provided for field measurement of SWR in the vicinity of 25,000 mc is also illustrated in Fig. 21. In this the direct power is brought to equality with the reflected power by an attenuator whose dial is calibrated directly in SWR. A wave guide switch facilitates the power comparison.

Auxiliaries and Components

RF Loads

An RF load (or dummy antenna) which will absorb the radar power in an impedance which matches the transmission line is very useful in radar work. Such a device permits testing the radar in operating condition without actual radiation which might give information to the enemy or interfere with other radars. It also makes it possible to test the radar in locations where reflections from the ground or nearby objects would otherwise hamper or prevent a test. RF loads for microwave work usually consist of a section of transmission line (either coaxial or wave guide, depending on wavelength) containing a high-loss dielectric. The impedance of such a load is necessarily low and must be matched to the radar line by tapering the dielectric over a distance of several wave lengths.[10] Moreover, if the line is to handle high power, tapering over a considerable length is necessary to distribute the heat.

A coaxial load is preferably tapered from outer conductor to inner conductor, since this both reduces the voltage gradient and facilitates heat dissipation. A dielectric consisting of a mixture of bakelite, silica and graphite, molded in place, has been found satisfactory. For wave guides a ceramic containing carbon may be preformed, with taper in one or two dimensions, and cemented in place.

Figure 22 shows a number of RF loads developed for different frequency bands. One of these, TS-235/UP, provides an excellent impedance match over the frequency range from 500 mc to above 3,000 mc. When equipped with a blower designed for uniform transverse ventilation, it will handle a peak power of the order of 750 kw with a duty cycle of about .001.

Microwave Attenuators and Pads

RF attenuators and pads are cornerstones of microwave testing. Attenuators are used to adjust unknown signals to levels suitable for measure-

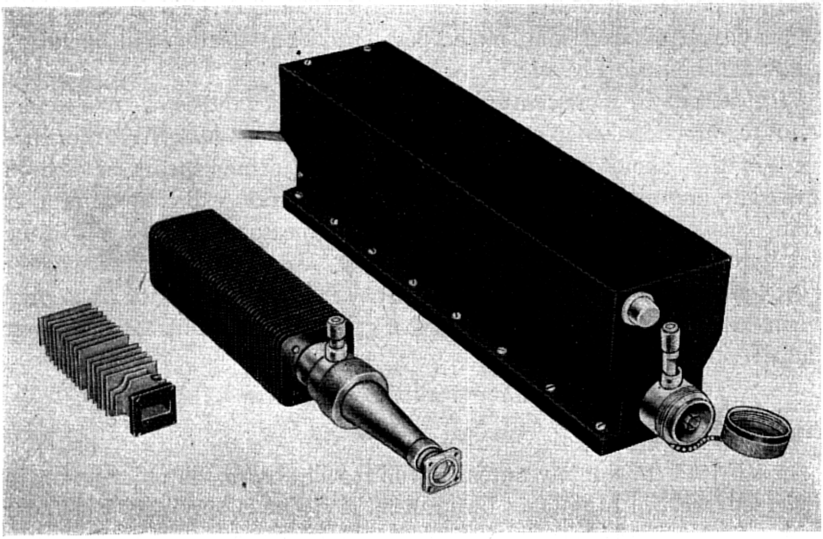

Fig. 22—RF loads for different bands in the microwave frequency range.

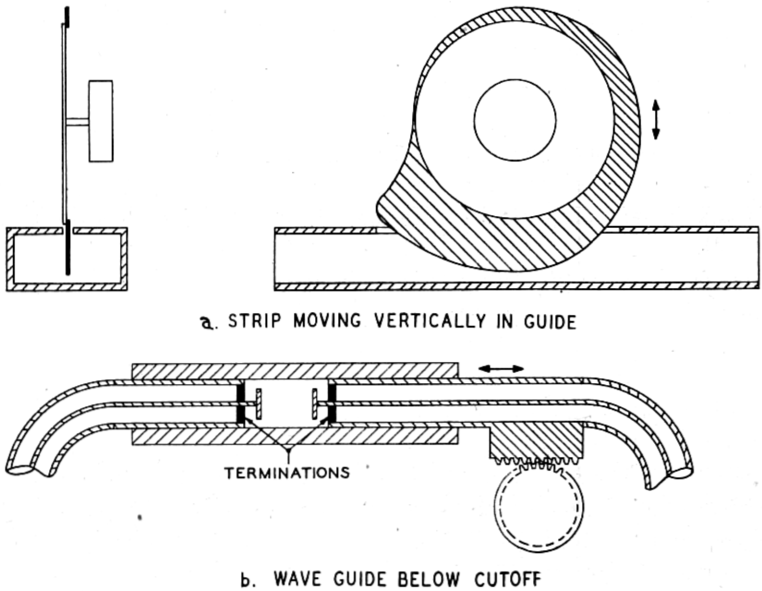

Fig. 23—Microwave attenuators.

ment and to obtain the minute test signals required for measuring receiver characteristics. Pads serve to change levels and to prevent interaction between testing components. Microwave attenuators and pads are of two general types (a) those which employ dissipative elements to absorb power and (b) non-dissipative devices which introduce propagation or coupling loss.

For the shorter microwaves the most convenient form of attenuator is of the dissipative type, employing a strip or vane of dielectric coated with a resistance material, as for example, carbon-coated bakelite. This is placed in rectangular wave guide with its plane paralleling the side of the guide. The attenuation is varied by varying the depth to which the vane is inserted in the guide (Fig. 23a) or by changing its position in the guide. A valuable feature of such attenuators is that the minimum loss can be made substantially zero. For good impedance match the strip must be tapered. By using two strips the over-all length of the attenuator can be reduced. Extremely satisfactory attenuators of this type covering a frequency range of 8 to 12%, with loss variable from 0 to 35 or 40 db, have been obtained in the frequency range 4,000 to 24,000 mc.

For the longer microwaves, where wave guides are inconveniently large, attenuators of the wave guide-below-cutoff type are very useful. These consist of a section of round wave guide whose diameter is small compared with wavelength and whose length is adjusted by telescoping (see Fig. 23b). The $TM_{0,1}$ mode has been found very satisfactory, and $TE_{1,1}$ has also been used. Connection is made to the attenuator by a coaxial circuit at each end, with disk excitation for the $TM_{0,1}$ mode and loop coupling for $TE_{1,1}$. The attenuation formulas are:[12]

$$TM_{0,1}. \qquad A = \frac{41.8}{D}\sqrt{1 - \left(\frac{1.31D}{\lambda}\right)^2}\ db/\text{meter} \tag{12}$$

$$TE_{1,1}. \qquad A = \frac{32.0}{D}\sqrt{1 - \left(\frac{1.71D}{\lambda}\right)^2}\ db/\text{meter} \tag{13}$$

where D = diameter of wave guide in meters. Because of the effect of other modes when the coupling is close, a minimum loss of 20 to 30 db is required before the attenuation becomes linear with displacement. The attenuation differentials are substantially independent of frequency. Attenuators of this type present a large impedance mismatch at either end, the effect of which may be alleviated by padding or by a termination.

Types of pads employed in microwave work include the following:

(1) Flexible coaxial cable, usually with high resistance inner conductor.
(2) Coaxial π with carbon coated rod and discs.
(3) Coaxial with carbon coated rod as inner conductor.
(4) Resistance strip in wave guide.
(5) Directional coupler.

In calibrating microwave attenuators and pads, comparison with an accurately calibrated IF attenuator, using a heterodyne test set, has been found to give excellent results.

RF Cables and Connectors

Flexible RF cables for connecting test equipment to equipment under test are an important adjunct of field testing. At frequencies of 10,000 mc and below, flexible coaxial cables of about .4″ over-all diameter with solid or stranded inner conductor, solid low-loss dielectric (polyethylene) and braided outer conductor have been used satisfactorily, although in the upper part of this range special measures have been necessary to prevent attenuation change due to flexure and aging. Over most of this range coaxial jack and plug connections have been found satisfactory but wave guide connectors are preferable at the upper end. In the range above 10,000 mc, coaxial

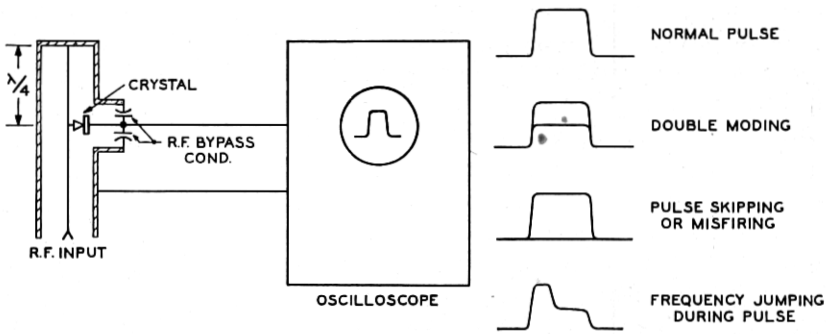

Fig. 24—Radar pulse envelopes.

cables of requisite stability have not yet been obtained and rubber covered wave guide with soldered articulated joints is the best form of flexible cable now available.

Oscilloscopes

Oscilloscopes are used extensively in radar maintenance (a) for examination of video waves and (b) for viewing RF envelopes. Satisfactory radar performance depends on a variety of video wave shapes which may include trapezoidal or triangular pulses, sawtooth waves, square waves or combinations of these. Observation of these wave shapes, supplemented if necessary by measurements of amplitude and duration, helps in diagnosing many troubles.

Examination of the envelope of the RF pulse is a convenient but less informative alternative to spectrum analysis. The envelope should be a clean, single trace of good shape. Figure 24 shows traces sometimes experienced. Double moding, i.e., oscillating at different frequencies on different pulses, is shown by a double trace. Frequency jumping during a pulse is shown by a break in the envelope. Misfiring gives a base line under the envelope. Other abnormalities in the RF envelope may result from incorrect video wave shape. Observation of the RF envelope requires a rectifier, usually a crystal, together with a suitable video amplifier. Since limitation of the scope to video functions permits general application to radars of all frequencies, the rectifier is generally provided externally.

The oscilloscopes available before the war did not meet the requirements of radar. Fast sweeps were necessary to permit viewing of pulses ranging from several microseconds to a fraction of a microsecond. Amplifiers were required for such pulses with low phase and amplitude distortion over a broad frequency band. Existing methods of synchronizing and phasing sweeps were also inadequate. The progress of the oscilloscope art during the war is illustrated in the successive designs of field test oscilloscopes shown in Fig. 25.

The BC910A oscilloscope, gotten out as a "stop gap" not long after the attack on Pearl Harbor, incorporates fast sweeps and broad-band amplification. Following close upon this was the BC1087A (Navy code CW60AAY) which replaced sine wave synchronization by a start-stop sweep triggered by the incoming pulses. This feature made it possible to superpose the erratic pulses produced by spark wheel and similar pulsers and at the same time avoided external synchronizing connections. A valuable feature conjoined with the start-stop sweep was a delay network in the main transmission path which gave the sweep time to start before the pulse reached the cathode-ray tube. This oscilloscope in original and modified form has seen wide service in all theaters. However, its weight of more than 60 pounds was a handicap for many uses.

Further advances in oscilloscope circuitry and in weight limitation resulted in TS-34/AP, weighing only 25 pounds. This combined the short pulse features of the previous design with those of the conventional oscilloscope for viewing slower waves. A schematic diagram is shown in Fig. 26. A redesign, coded as TS-34A/AP, incorporated variable start-stop sweeps and improved mechanical design. These two oscilloscopes, TS-34 and TS-34A, were produced to a total of some 12,000 and universally used by all branches of the service for both radar and radio testing. Toward the end of the war the trend toward shorter pulses, coupled with the need for precise measurement of wave amplitude and duration, led to a new design, TS-239/UP, which embodied wide advances over TS-34A in performance and versatility but with an increase in weight.

In association with different oscilloscopes, other video devices have been

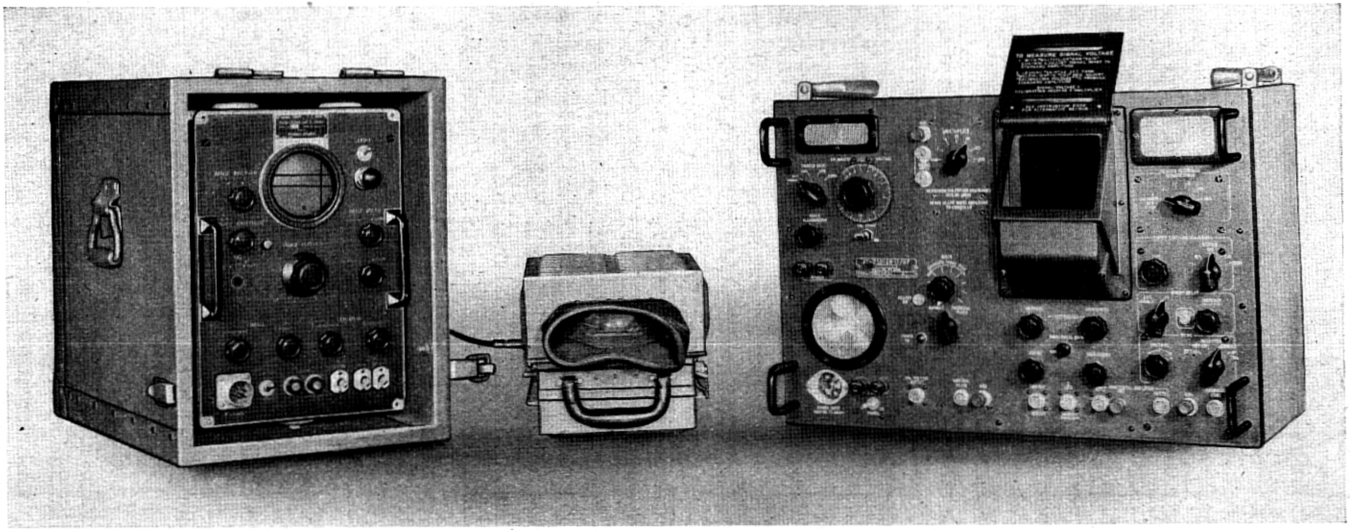

Fig. 25—Test oscilloscopes for viewing wave forms in radars. Left to right: BC-910-A (1942), TS-34A/AP (1944) and TS-239/Up (1945).

employed. The amplitude of pulse applied to the magnetron is thousands of volts. To derive a voltage suitable for application to the oscilloscope, a voltage divider of the condenser type is used (TS-89/AP). Suitable video terminations, dividers, and loads, sometimes of high voltage and power capacity, are required to obtain proper test conditions and provide convenient test points (TS-98/AP, TS-390/TPM-4, TS-90/AP, TS-234/UP). Originally a high-impedance connection to the oscilloscope was effected by a single-stage amplifier unit (BC1167A), but a simple divider type of probe was later found more satisfactory for this purpose.

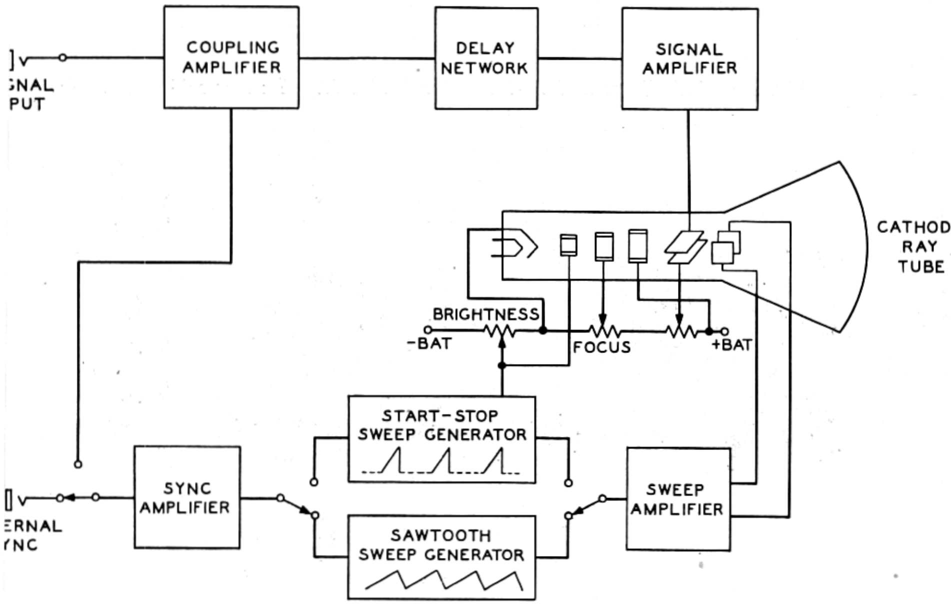

Fig. 26—Block diagram of TS-34/AP and TS-34A/AP oscilloscopes.

Range Calibration

Types of timing circuits used for radar range determination include (a) multi-vibrators, (b) coil and condenser oscillators (generally without but sometimes with temperature control) and occasionally (c) quartz crystal oscillators. The first two depend for their accuracy on condensers, resistances, coils and other elements which are subject to error due to aging, temperature, humidity, mechanical damage and the like. Nor is the quartz crystal oscillator wholly immune to error. Consequently, portable range calibrators are required for field maintenance.

TS-102A/AP (Fig. 27) and its predecessors TS-102 and TS-19 are precision calibrators which have been extensively used for checking a large

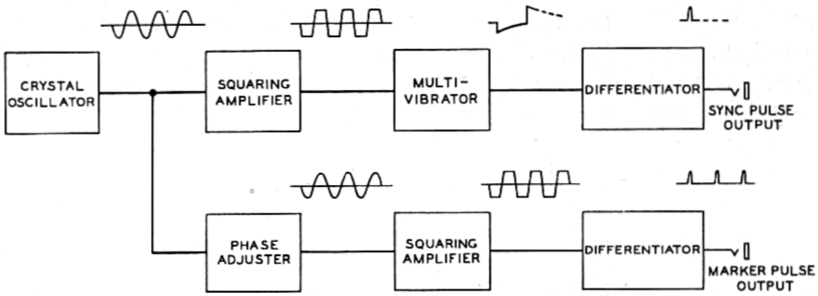

Fig. 27—Block diagram of TS-102/AP and TS-102A/AP range calibrators.

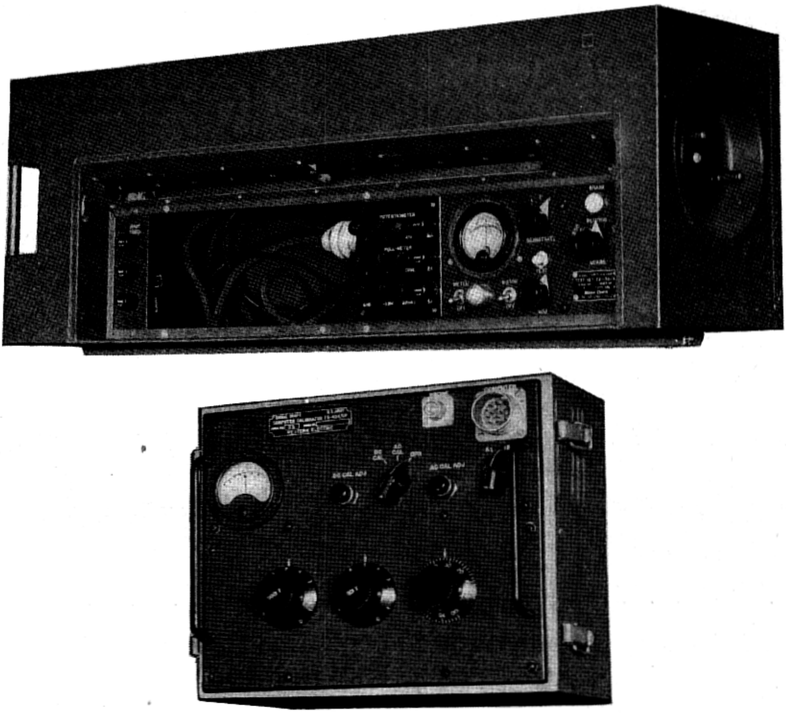

Fig. 28—Two test sets for checking the computers used in bombsight and fire control radars.

number of different airborne bombing and gunlaying radars and shipborne fire control and search radars. These sets deliver accurately spaced marker pulses, derived from a quartz crystal oscillator, for checking the radar range pulses. A trigger pulse derived from a multi-vibrator synchronized with the quartz oscillator is also provided for actuating the radar timing circuits. With certain radars the calibration procedure requires an oscilloscope as well. Extreme stability of marker pulses, better than $\pm.02$ microsecond, is obtained. A stop watch is included in these sets for checking rate of change in range.

Less precision is required in range calibration of search radars. For this purpose the TS-5/AP calibrator provides marker pulses of $\frac{1}{4}$, 1, 5 or 10 nautical or statute miles, derived from a coil and condenser oscillator with closely controlled temperature coefficients. This calibrator is designed to be triggered by the radar or some other external source.

Computer Test Sets, Etc.

A number of radars are equipped with computers which receive the data on location of target and its direction and rate of change, together with essential related information on such factors as wind velocity, ground speed, altitude, etc., and deliver the solution of the ballistic problem in the form of a voltage which releases bombs, points the guns or serves other purposes. Means for checking the accuracy of these computing devices are generally required. The type of test set needed depends upon the computer design, which has taken different forms according to the nature of the problem and the state of the art.

Two types of computer test set are shown in Fig. 28. TS-158/AP, designed for use with certain airborne bombing radars, furnishes to the computer a signal representing a target approaching at known speed and checks the accuracy of bomb release. TS-434/UP, designed for several airborne and ground radars, is an accurate instrument for determining the voltage ratios at various points in a computer and thus checking its performance.

Conclusion

More than 200 different designs of test sets were developed during the war by Bell Laboratories to meet the exacting requirements of radar field maintenance. These differed radically from previous art. Outstanding features were portability, precision and generality of application. The large number of designs is due partly to the varied functions of radar and to the varied conditions of use. Largely, however, it results from the fact that the frequency band that can be handled in any one set is limited, whereas many frequency ranges and subranges had to be covered in all.

Altogether more than 75,000 radar test sets were manufactured by Western Electric Company and these were used in all theatres of war by the

United Nations forces. The production rate at the end of the war exceeded 5,000 test sets a month. In numerous cases, moreover, small preproduction quantities of test equipment were built on a "crash" basis for special missions and for training purposes. The test equipment produced for the field had to be more precise than the radars, and the equipment used in the factory and laboratory to test the field test equipment had to be still more precise.

Trends of development at war's end were toward (a) further broad-banding, simplification and precising, and (b) coverage of new frequency ranges.

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