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BUSHIPS Electron

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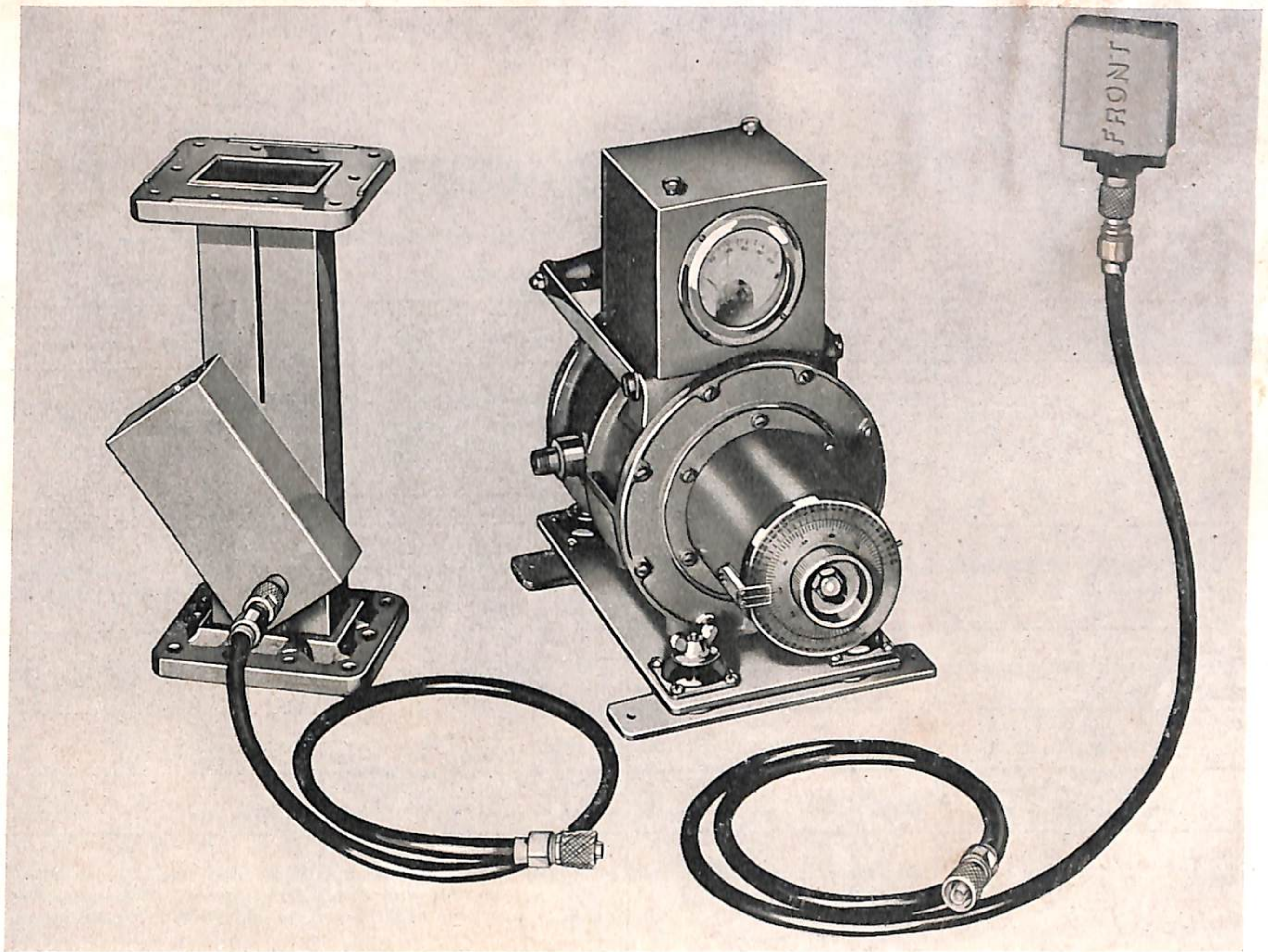


Model OBU-3 Echo Box and Directional Coupler with interconnecting cables and pick-up probe.

The Echo Box

By I. A. Bereston, *Bureau of Ships*

The echo box is the simplest test instrument for measuring radar performance and for radar trouble-shooting. Although much has already been written about its merits and use, the importance of the echo box cannot be overestimated.

IMPORTANCE

When a radar is allowed to operate day after day without being checked its performance can be expected to drop off 15 to 20 db over a period of time. Experience has shown that, without test equipment, a loss of this magnitude will probably pass unnoticed by even the most experienced technician. Table 1 shows the percentage loss of range for a radar system operating at various levels below peak performance. From this table it can be seen that a loss of 15 db means that the plane which your set was designed to "see" at 30 miles will be detected only if it comes within 13 miles of your radar. In such a case you are throwing away 58% or more of the seeing ability of your radar, and possibly as much as 100% of its tactical value.

Table I—*Effective Range of a Radar System (3000 Mc) for various reductions in relative performance.*

Relative System Performance	*Effective Range (Aircraft)*	*Effective Range (Periscope)*	*Effective Range (Cruiser)*
—1.5 db	91%	94%	98%
— 3 db	84%	88%	97%
— 5 db	76%	82%	95%
—10 db	58%	69%	90%
—15 db	**42**%	58%	**84**%
—20 db	31%	49%	78%
—25 db	24%	40%	71%
—30 db	18%	34%	62%
—35 db	14%	28%	53%
—40 db	10%	24%	45%
—45 db	8%	20%	34%
—50 db	6%	16%	21%

ECHO BOX CHARACTERISTICS

Echo Box	TS-349/UP	TS-270/UP	OBU-3, OBU-4
Frequency range.	910—980 Mc.	2700—2900 Mc.	2900—3100 Mc.
Ringtime.	5725 yards with MK 12 using 4′ RG-21/U cable.	6900 yards on SP (1 u sec pulse with 33 db directional coupler).	7500 yards on SG-1 with 27 db directional coupler.
Change in ringtime with change in input frequency.	Percentage to correct expected ringtime is marked on dial.	Percentage to correct expected ringtime is given by curve in Instruction Book.	Percentage to correct expected ringtime is given on dial for any dial setting.
Change in ringtime with change in temperature.	±5% from 20° to 120° F.	±5% from 20° to 120° F.	±5% from 20° to 120° F.
Approximate dimensions.	11″ x 7″ x 10½″.	14½″ x 8″ x 12¼″.	10¾″ x 7½″ x 11¼″.
Approximate weight.	17 lbs.	26 lbs.	18½ lbs.
Input.	Waterproof type N jack on echo box.	Input loop (brass, silver-plated probe assembly threaded from connection to type N plug).	Input loop (brass, silver-plated probe assembly, threaded for connection to type N plug).
Accessories.	Adapter UG-8/AP (type N jack to Holmdel fitting). Four foot RG-21/U cable with a type N plug on each end.	RG-8/U cable with waterproof type N plug on one end.	Pickup Dipole CABV-66 AJG. Directional Coupler 47AAN. Two lengths of RG-8 with one C-49268 (type N) plug on each end.
Construction.	Cast bronze cavity cylinder with coaxial quarterwave line. Has bronze end plate. Output loop adjustable by means of knurled sleeve.	Cast bronze cavity (silvered inner surface) with removable bronze end plates; output loop adjustable by means of knurled sleeve.	Cast bronze cavity with removable bronze end plates; output loop adjustable by means of knurled sleeve.
Calibration data.	Frequency calibration in instruction book or roughly, multiply dial reading by 10 and add 900 to get frequency in Mc. Percentage above normal ringtime stamped on meter face. Ringtime frequency variation engraved on dial.	Frequency calibration curve and correction curve for ringtime with dial setting in Instruction Book.	Frequency calibration on dial. (Curve in Instruction Book). Percentage above normal ringtime stamped on meter face. Ringtime frequency correction engraved on dial.
Notes.		Includes shock mounts.	Directional coupler supplied with OBU-4 is 47AAP. (47AAN is supplied with OBU-3.)

ECHO BOX CHARACTERISTICS

TS-275/UP	TS-311A/UP	TS-218A/AP	TS-62/AP
3400—3700 Mc.	8730—8910 Mc.	8995—9175 Mc.	9320—9430 Mc.
4,700 yards on SG-3, 4 with 27 db directional coupler (short pulse).	4,000 yards, receiver sensitivity —120 db, 50 kw peak power, repetition rate 1,000; ¼ microsec. pulse width; 23 db coupling.	4,000 yards with receiver sensitivity of —120 db, 50 kw peak power, repetition rate 1,000; pulse width ¼ microsec. coupled with 20 db coupler and 3 db patch cord.	4,000 yards with receiver sensitivity of —120 db, 50 kw peak power, repetition rate 1,000, pulse width ¼ microsec. coupled with 20 db coupler and 3 db patch cord.
Percentage to correct expected ringtime is given by curve in Instruction Book.	±4% mean ringtime.	±4% of mean ringtime.	±4% of mean ringtime.
±5% from 20° to 120° F.	±4% from 20° to 120° F.	±4% from 20° to 120° F.	±4% from 20° to 120° F.
12½″ x 7″ x 10½″.	8½″ x 10¼″ x 16½″.	11½″ x 18¼″ x 6¼″.	11½″ x 18¼″ x 6″.
23½ lbs.	12 lbs.	10 lbs.	10 lbs.
Input loop (brass, silver-plated probe assembly, threaded for connection to type N plug).	Tuned input—waterproof type N jack. Untuned input.—waterproof type N jack	Tuned—UG-11/U (to coax to waveguide to opening in cavity wall), type N jack. Untuned—UG-11/U (to coax to waveguide to crystal unit), type N jack.	Tuned—UG-11/U (to coax to waveguide to opening in cavity wall), type N jack. Untuned—UG-11/U (to coax to waveguide to crystal unit), type N jack.
RG-8/U cable with waterproof type N plug on one end.	Antenna Unit with waterproof type N jack. RG-9/U with two waterproof type N jacks.	Antenna Assembly AS-106/AP (RG-9/U with UG-23/U), Cord CG-92/U (RG-9/U with two UG-24/U's).	Antenna Assembly AS-106/AP (RG-9/U with UG-23/U), Cord CG-92/U (RG-9/U with two UG-24/U's).
Cast bronze cavity (silvered inner surface) with removable bronze end plates; output loop adjustable by means of knurled sleeve.	Incorporates crystal checker for X-band crystals.	Cavity of aluminum alloy, inside silver coated; bakelite disc with sheet of silver-plated copper foil for piston.	Cavity of aluminum alloy, inside silver coated; bakelite disc with sheet of silver-plated copper foil for piston.
Frequency calibration (in Mc) is on outer portion of outer dial (red numbers). Ringtime correction frequency curve in Instruction Book.	Frequency is marked on dial (in Mc).	Frequency calibration curve. Figure on curve on front of echo box corresponding to dial setting must be multiplied by ringtime actually observed.	Frequency calibration curve. Figure on curve on front of echo box corresponding to dial setting must be multiplied by ringtime actually observed.

The column in table I for "aircraft" is based on the theoretical inverse fourth power law which governs high-angle search. The column for "periscope" is based on experiments with an antenna about forty feet above the water. The column for "cruiser" is based experimentally on the same type of radar and the same antenna height.

As further reasoning for the use of test equipment it should be noted from Table I that the loss of range for large objects, such as cruisers, is less than that for small objects like planes. A radar 15 db down in performance will detect a cruiser at 84% of intended range as compared with only 42% of intended range for a plane. The cruiser which can be detected at 120,000 yards is detected by a radar 15 db down at 100,800 yards. If the ability of the radar to "see" a cruiser at a distance is used as the measurement of performance, the fact that the radar is 15 db down is almost certain to escape notice. (It should be noted in passing that wave propagation conditions greatly affect radar range at all levels of system performance, thereby rendering it additionally confusing to use range as a criterion of performance.)

CONSTRUCTION

The echo box is essentially a resonant cavity which is coupled to the radar transmitter output and to the radar receiver input. Coupled to the resonant cavity is a meter which indicates relative power output of the radar transmitter and also indicates when the echo box is in resonance with the transmitter frequency. The resonant frequency of the cavity is determined by the size of the cavity, which can be varied by means of a tuning mechanism and dial on the front of the box. When the resonant frequency of the cavity is adjusted to the frequency of the transmitter output, oscillations are induced in the cavity by each pulse from the radar transmitter. These oscillations in the cavity produce a pattern on the radar indicator scope as well as an indication on the relative-power meter coupled to the cavity. The pattern on the scope is translated into yards to obtain the "ringing time" of the equipment, which is the apparent duration of the oscillations set up in the echo box by each pulse.

RINGING TIME

The ringing time of an equipment is dependent upon the following factors: 1—transmitter peak power, 2—receiver sensitivity (noise level), 3—losses of either transmitter power or signal power (such as those caused by mistuned or defective TR or ATR tubes), 4—pulse length, 5—transmitter spectrum, 6—coupling losses, and 7—echo-box sensitivity.

Considering all other factors to be constant, as the peak power of the transmitter increases, the amplitude of the oscillations in the echo box will increase, therefore it will require a longer time for these oscillations to die down and consequently the ringing time will be increased. Similarly, the lower the receiver input noise level, the longer the ringing time, since the weaker signals issuing from the echo box at the trailing end of the ringing time may be seen and measured, while if the noise level is high, these faint oscillations will not appear on the scope.

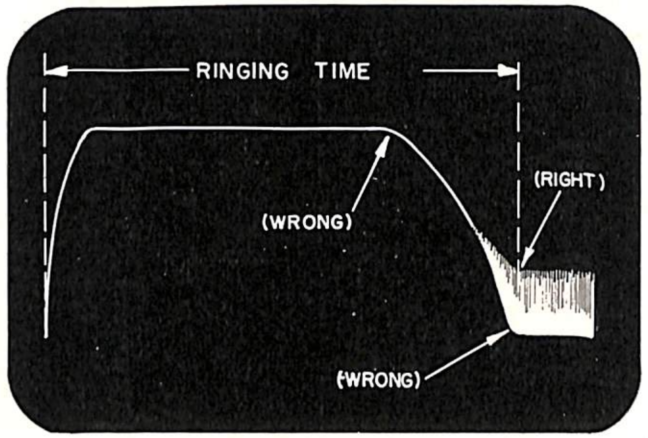
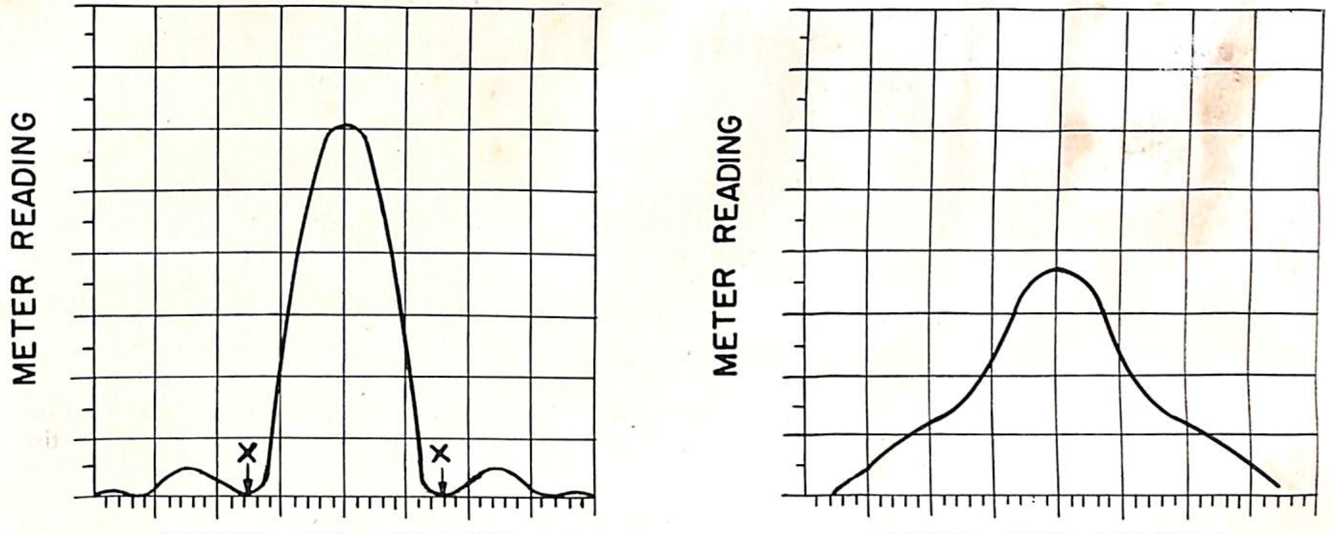


FIGURE 1—*Appearance of good ringing time displayed on an A scope, showing correct and incorrect points to which ringing time is measured. Note that the receiver gain has been adjusted so that the grass is a quarter to a third the total saturated signal height on the scope.*

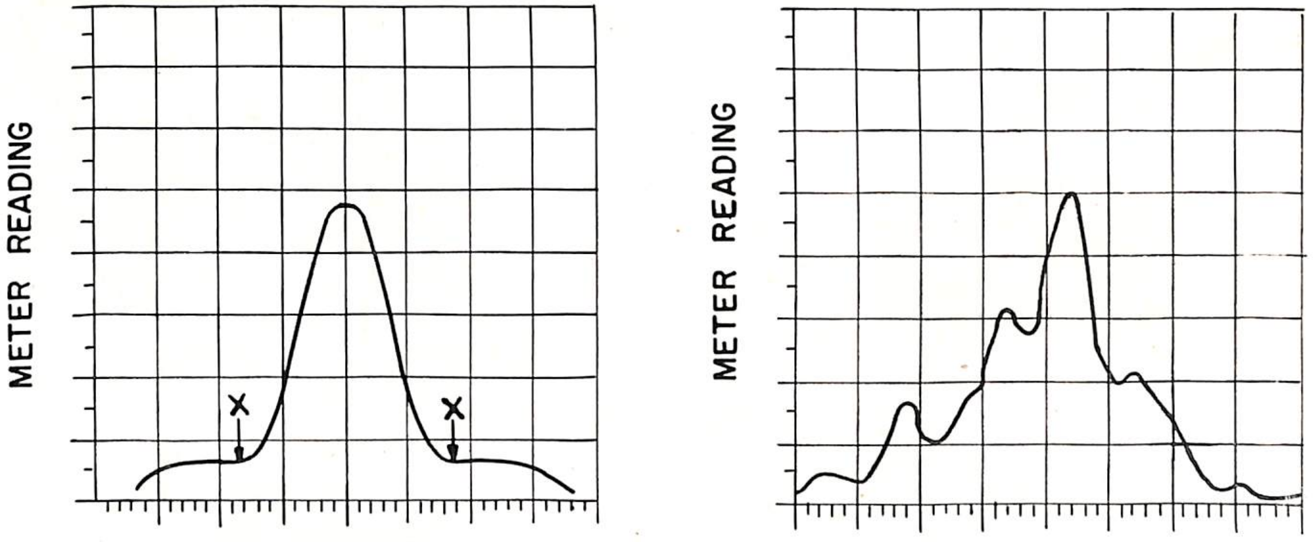
It should be pointed out here that the receiver noise level can be attributed to two principal factors, the receiver noise figure and the receiver bandwith. Of these two factors, the noise figure, which is the general figure of merit of receivers, is the quantity which one is trying to maintain when tuning a receiver. The noise figure can be defined as the noise per unit bandwith in a receiver, relative to that which would be present in a theoretically ideal receiver.

The receiver bandwith, which does not ordinarily change, also contributes to the noise level. The wider the bandwidth the more noise is permitted to pass. A decrease in the bandwidth which, if large enough, might impair the performance of the radar, would actually increase the ringing time. When a receiver goes into oscillation due to interstage feedback, the bandwidth is greatly reduced, and under such circumstances the ringing is increased somewhat. (Oscillation can be recognized by a coarseness of the grass, by a tendency of the gain to increase abruptly at a particular gain control setting, and by a slightly less abrupt drop in the end of the ringing time than is common.) Since in radar design the bandwidth is adjusted to suit the pulse length used there is an inter-relationship between these two factors, both of which separately influence the ringing time.



(a) GOOD SPECTRUM

(c) POOR SPECTRUM



(b) FAIR SPECTRUM

(d) BAD SPECTRUM

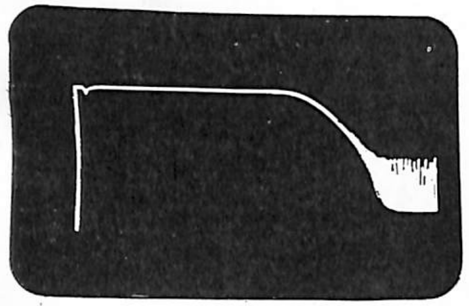
FIGURE 2—*Typical radar pulse spectra. Curves A and B illustrate desired spectrum shapes in which the pulse length is equal to twice the reciprocal of the difference in frequency of the minima (points marked X). These curves are distinguished from C and D by the presence of deep minima.*

The pulse length and transmitter spectrum both affect the ringing time. The longer the pulse the greater the ringing time since the echo box charges up to a greater extent for a longer pulse. A bad spectrum affects ringing time in that power applied in the narrow bandpass of the echo box may be reduced due to the greater frequency scattering of the transmitter energy. Radar performance, and therefore ringing time in this case, may be affected by the scattering of the transmitter energy outside the receiver bandwidth, impaired signal shape, and inoperative AFC.

Other factors such as the coupling between the box and the radar, the loss in the cable connecting the box to the directional coupler (when used), and the echo box sensitivity also affect the ringing time. If the losses in the coupling elements are low and the box sensitivity is high, the ringing time will be increased and vice versa. The preferred and most efficient method of coupling be-

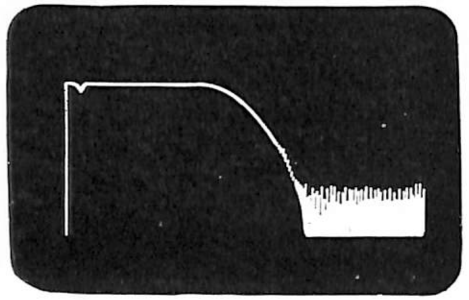
Echo Box Trouble Shooting Chart

This chart was designed to facilitate rapid trouble shooting when using various types of echo boxes. The technician is cautioned to observe scope and meter indications with great care, however, due to the fact that there may be only a very subtle difference in the symptoms for several different conditions. In some instances the scope patterns are identical, and the determining factor consists only of a slight difference in the behavior of the meter. Additional echo box tests may be found in various equipment instruction books.



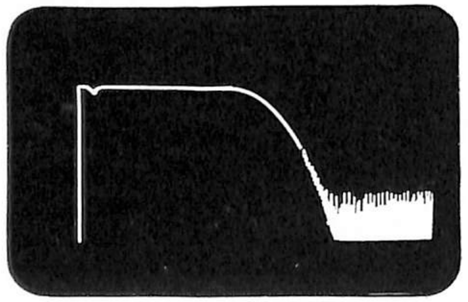

Effect: Ringtime satisfactory, test set output reading satisfactory.

Probable Cause: Radar performance satisfactory.



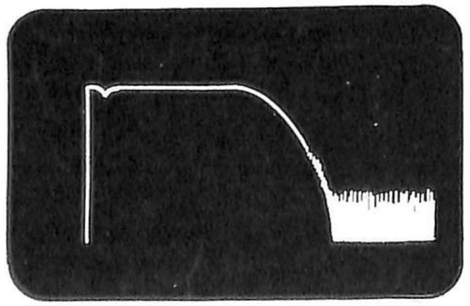

Effect: Ringtime low, test set output reading satisfactory.

Probable Cause: Receiver trouble: detuned mixer or local oscillator, bad crystal, excessive i-f noise from first pre-amp stage, adjustment of coupling loops or probes in mixer cavity. Detuned T-R box.



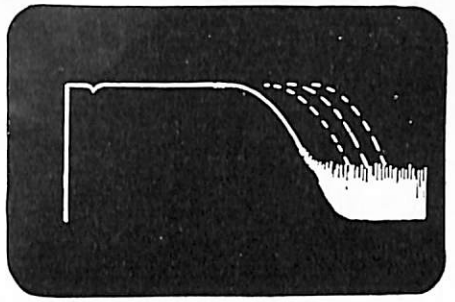

Effect: Ringtime low, test set output reading very low.

Probable Cause: Low power output. Check spectrum.



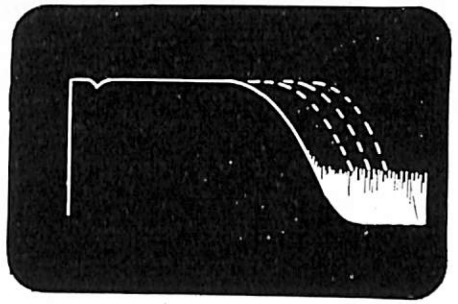

Effect: Ringtime low, test set output-reading low.

Probable Cause: Trouble probably in transmitter and receiver, and/or trouble in transmission line.



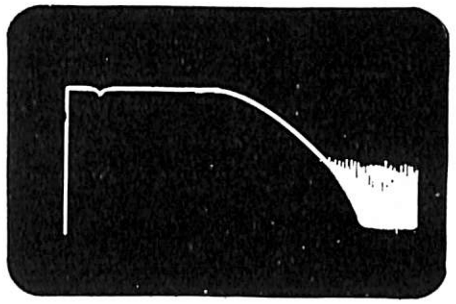

Effect: Ringtime erratic, test set output reading steady.

Probable Cause: Test set slightly detuned. Faulty pulsing, double moding transmitter, or local oscillator power supply trouble. Check spectrum.



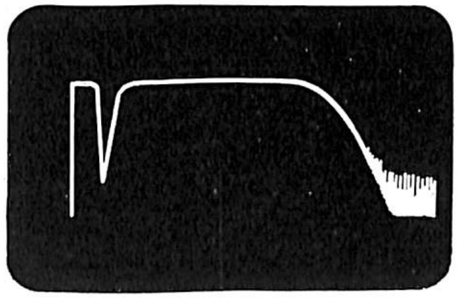

Effect: Ringtime erratic, test set output reading erratic.

Probable Cause: Faulty transmission line or poor connections—condition worse when line is rapped.



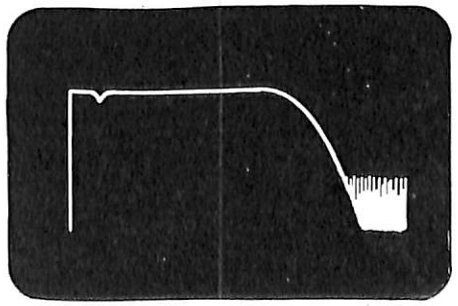
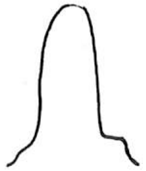

Effect: End of ringtime not steep but slopes gradually; perhaps even excessive ringing. Grass appears coarse. Test set output reading steady and satisfactory.

Probable Cause: Oscillating i-f and/or narrow-band receiver.




Effect: Pronounced dip in ringtime at end of pulse.

Probable Cause: Bad T-R tube.

Effect: Ringtime very slightly low, poor or bad spectrum.

Probable Cause: Transmitter trouble.

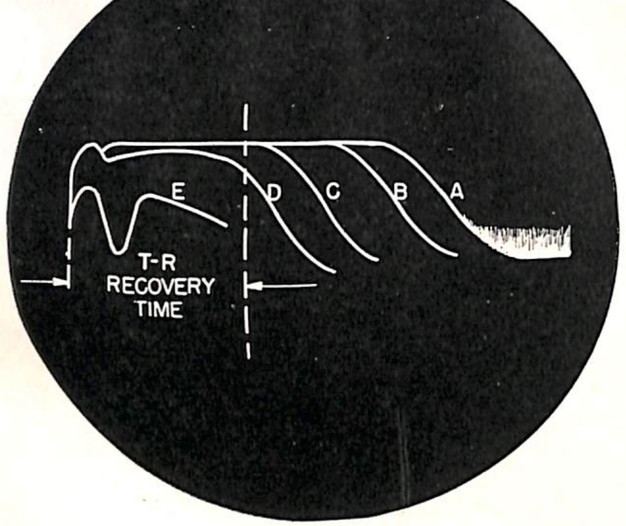


FIGURE 3—*Curves illustrating the method of measurement of TR-box recovery time.*

tween the radar and the echo box is by means of the directional coupler which enables the use of a fixed, known amount of radar power for testing purposes. Echo box sensitivity is defined as the change in ringing time which corresponds to a given change in radar performance. This is nominally a constant for any one type of echo box, but actually varies with frequency, temperature, and the individual echo box, necessitating correction of the nominal value for an accurate determination of sensitivity in a particular case. The method of calculation of sensitivity of a particular box at known frequency and temperature is given in the instruction book.

MEASURING PERFORMANCE

The instruction books for the various echo boxes (with the exception of a few earlier models) will include the necessary data for determining how long a particular echo box will ring when coupled by directional coupler, or other means, to a particular type of radar operating at peak performance. It may be noted that in such a case power losses and poor spectra are not applicable and all of the other factors determining ringing time are known. Usually the ringing time at peak performance will also be given, already computed for those radars with which the echo box is normally used.

Figure 1 illustrates the correct appearance of good ringing time on an A scope. The receiver gain is set so that the grass is from one-quarter to one-third of the total saturated signal height on the scope. The exact end of the ringing time occurs at the farthest point to the right at which the top of the grass is above the normal level. The range is measured to this particular point and noted in yards. The performance of the radar under test can be determined in terms of db below peak by a simple procedure. Consult the instruction book for the method of calculating ringing time or the published ringing time (in yards) for the peak performance of the radar under test. Subtract the ringing time as measured on your particular set from the figure obtained from the instruction book. This figure (in yards) may be divided by the sensitivity of the echo box (in yards per db) to give the number of db below peak performance of the radar being checked. However, in most cases the difference between calculated (as obtained from instruction book) and measured ringing time is used as the measure of the radar performance.

Transmitter power: The echo box meter reading is approximately proportional to the average power radiated by the radar at a particular frequency. The echo box is tuned to obtain a maximum meter reading and this reading is compared to the corresponding value as obtained on previous tests. This measurement is relative, since the degree of coupling between the radar transmitter and the box power-measuring circuit is not known and will vary with different conditions. A low meter reading, as differentiated from a normal reading, may be caused by low transmitter power, a poor spectrum, or a short pulse length.

Spectrum analysis: The spectrum of a pulse is the frequency distribution of its energy. This spectrum can be obtained by plotting the echo box meter readings with the box tuned to various frequencies. Typical spectra are shown in figure 2. The variance of curve C from curves A and B may be caused by an unstable transmitter tube, by operation of the transmitter tube with improper voltage, current or magnetic field. Another possible cause is the application of a high-voltage pulse of incorrect shape (such as sloping sides or rounded top) to the transmitter tube. Severe irregularities as in curve D may be caused by a large standing-wave ratio in the transmission line due to a faulty line connection, a bad antenna rotating joint, or obstructions in the line. Adjustment of the magnetic field or replacement of the transmitter tube may be necessary.

Pulse length: The length of the pulse is arbitrarily taken as its duration at and above the half-maximum voltage points. In the case of a good or fair spectrum, pulse length equals twice the reciprocal of the frequency difference between the two minima on the spectrum curve as indicated in figure 2. An abnormally narrow spectrum means that the transmitted pulse is too long, resulting in a long ringing time and high power reading on the echo box meter, but which leads to a false indication of exceptional radar performance.

Frequency measurement: The resonant frequency of the echo box at a particular setting is either given directly on the tuning dial or can be determined from a dial-setting frequency calibration chart supplied with the equipment. By determining the resonant frequency of the box at maximum power meter reading, the frequency of the incoming radiation can be obtained.

TR-box recovery: Reducing the receiver gain appreciably means shortening the apparent ringing time on the scope as shown in figure 3, curves A, B, and C. If the ringing time is shorter than the TR-box recovery time the echo-box pattern on the scope is distorted, as indicated in curve E. The TR recovery time is measured as shown in curve D, the slope of which differs noticeably from receiver saturation. TR-box recovery time should be less than one mile.

Receiver recovery: When the receiver recovery after a pulse is normal the grass appears approximately the same strength regardless of whether the echo box is tuned or de-tuned, assuming the receiver gain is adjusted as it would be when measuring radar performance. When the echo box is tuned the grass on the scope will appear immediately at the end of the ringing pattern as pointed out in a previous paragraph. When the receiver recovery time is longer than normal, the noise is weak and does not appear for some time after the end of the ringing pattern, or in extreme cases, not at all. Receiver non-recovery is usually an indication of a defective i-f or video stage.

TROUBLE SHOOTING

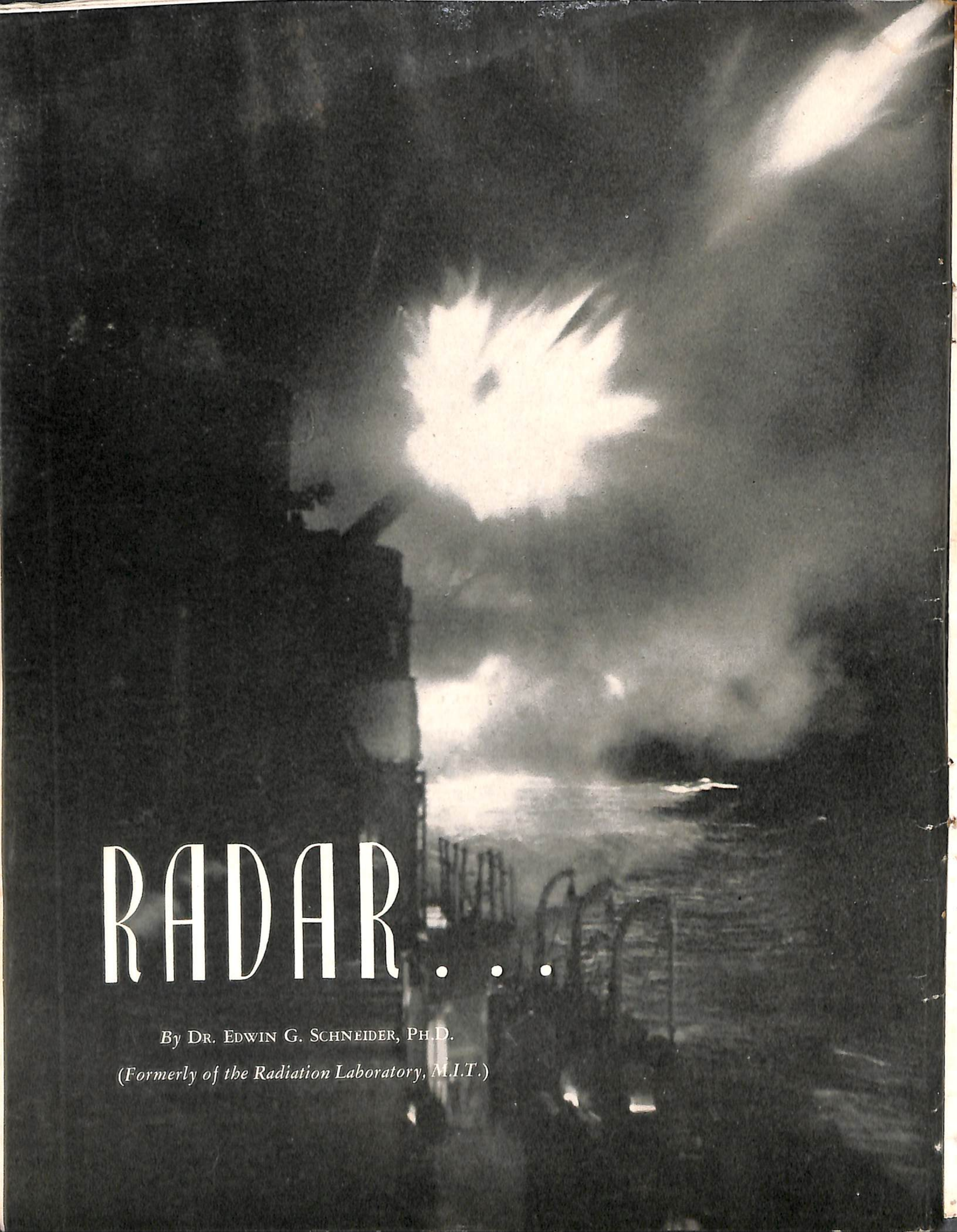
In connection with trouble shooting, radar operation may be analyzed as follows: A radio-frequency pulse is produced in the transmitter tube, which is some form of high-frequency oscillator. For good performance the pulse must have the proper frequency spectrum and must be of the desired power. This pulse must be sent to the antenna through the r-f transmission line with as little loss as possible, and then must be radiated from the antenna. If a portion of the pulse power sent out from the antenna is reflected back to the antenna as a signal, it must be conducted through the transmission line, through the T-R tube, and to the mixer, without appreciable loss. In the mixer, the r-f signal is mixed with the c-w output of a local oscillator to produce a beat frequency, or intermediate frequency, at which frequency the signal is amplified sufficiently to produce a voltage pulse that can be used for indication. Noise generated in the receiving system is amplified along with the signal. By careful design and maintenance the receiver may be made to have a good sensitivity, which means a low level of internally generated noise. The receiver must have enough gain so that noise may be seen on the indicator together with the signal, otherwise the maximum sensitivity of the receiver is not utilized, and the performance of the set is therefore lowered.

Performance is influenced by the transmitter, because it determines the power and frequency characteristics of the pulse. It is influenced by the condition and tuning of the transmission line adjustments, which must be properly tuned or attenuation through them may be great. It is also influenced by the tuning and the condition of the T-R tube. In the preamplifier mixer and receiver, performance is influenced by the frequency and power of the local oscillator input to the mixer, by the effectiveness of the r-f to i-f converter, and by the noise generated in the first r-f tube or crystal and first i-f tube. Beyond the first i-f stage performance is not greatly altered by the characteristics of the receiver, gain is not important, except that it must be sufficient to allow noise to be seen on the indicator. Other components of the radar system (modulator, synchronizer, etc.) must be functioning properly, of course, but they have little part in determining overall performance.

The relative influence upon performance of the components mentioned above must be understood in testing a radar set. Ruinous losses are most likely to occur in the components that deal with the received signal from the time it is picked up by the antenna until it passes the first i-f stage. Small troubles, bad connections, and lack of adjustment, unimportant though they may seem, may cause the complete loss of a signal as weak as that picked up from a small target. The receiving part of the radar is by far the most likely place for losses to occur that affect performance. Noise generated in the preamplifier and mixer cannot be reduced below some certain minimum. If a signal has dissipated too much of its energy before reaching the receiver, no amount of amplification will enable it to be seen above this noise on the indicator, since the noise is amplified with the signal. In the receiving system there are many opportunities for half the signal power or more to be lost, and pyramiding of these losses may make the performance extremely poor.

The transmitting system is not as likely to be the cause of impaired performance. If more than half the output power is lost, the trouble will usually be indicated by improper transmitter current, a spectrum of low amplitude, standing waves in the r-f line, or arcing in the line.

The echo box has proved to maintenance personnel its value as an aid in trouble shooting. For additional information on preferred echo boxes for particular radars, see p. 25 of the March 1946 ELECTRON.



RADAR . . .

By Dr. Edwin G. Schneider, Ph.D.

(Formerly of the Radiation Laboratory, M.I.T.)

Now that it is possible to discuss radar more or less openly, there has appeared in the literature a veritable flood of material on the subject. Most of this is "old stuff" to the experienced technician, and holds very little in the way of value or interest for him. Now, out of this material, Electron *presents what is believed to be one of the finest, most comprehensive, stories on radar. It is felt that the reading of this excellent story should be compulsory, and that all persons associated with electronics or radar will benefit by studying it carefully. It is reprinted here, by permission, from the August, 1946, issue of the* Proceedings *of the Institute of Radio Engineers. Due to the length of the article, it will be printed in four parts in consecutive issues of* Electron.

■ Since a fairly large percentage of the effort of physicists and electrical engineers in this country and in England was expended on radar development during the war, techniques in electronics have advanced at possibly ten times the normal peacetime rate. The purpose of this paper is to give a brief survey of the wartime developments in electronics and to show how these were used in a few radar sets. Because the applications of radar to civilian activities will probably be of minor importance when compared with the sum total of other electronic applications, this survey makes no attempt to give a complete description of any particular radar set.

BASIC PRINCIPLES OF RADAR: ELECTRONIC TECHNIQUES OF RADAR

Basically, radar determines the existence of an object by observation of reflected radio energy. In the case of tail-warning radar and one type of air-search equipment mounted on submarines, the prime use is to give warning of the presence of aircraft in the neighborhood, the exact location being a secondary consideration. However, most radar sets are designed to give reasonably accurate information on the position of the objects which are reflecting energy. Bearing or azimuth is normally determined by rotating a directional antenna to the position of maximum echo, a process similar to locating an object by use of a searchlight beam. Similarly, one method of measuring angle of elevation is to tilt the antenna to center the beam on the target. In contrast with the optical case, in which range must be measured by difficult triangulation methods, radar simply measures the time for a short pulse of radio energy to travel to the target and return. Although a great deal of work has gone into development of timing circuits, range measurement is operationally an extremely simple process compared with optical measurements. Furthermore, the range accuracy with properly designed equipment is such that secondary bench marks may be located for topographical surveys by measuring the range to primary points. An interesting example of the discovery of a map error by radar occurred in northern Italy. During the operations, a blind-bombing system called shoran was very successfully used for bombing pinpoint targets such as bridges. This system consists of an airborne radar which triggers two coded radio beacons at known points on the ground. The signals from the two beacons, which merely serve to give signals which cannot be mistaken for other objects, are displayed on a cathode-ray tube in the aircraft. By suitable timing circuits the range to each of these beacons is measured with an accuracy of a few yards, and the position of the plane is located by triangulation, using the beacons as reference points. With one beacon set up in Corsica and the other in Italy, the positions being accurately located from maps, a bombing mission was run. Strike photographs showed a miss of almost a thousand yards. Since this was about 50 to 100 times the error expected, a recheck of the calculation of target position was made but no error was discovered. The suggestion was then made that the position of Corsica as shown on the map might be wrong. The problem was therefore worked backward to correct the position of Corsica. A correction of very nearly 1,000 yards in the map position of Corsica was used on the next bombing run with strike results indistinguishable from optical bombing. That this result was not fortuitous was borne out by several months of successful bombing using the corrected position for Corsica.

Since the pulse energy travels the distance to the target twice, once on the way out and again on the return trip, the time required to receive an echo from an object a mile away is that necessary for a radio wave to travel two miles. With radio waves traveling at a speed of 186,000 miles a second, 10.7 microseconds elapse between the time the pulse is sent out and the time it is received from a target one mile away. It is apparent, therefore, that time measurements must be made in terms of millionths of a second. Furthermore, the transmitted pulse may be a large fraction of a mile or even several miles in length. For this reason the range must be measured by determining the time interval between the start of the transmitted pulse and the beginning of the received pulse. Methods for measuring range and displaying target positions will be discussed in detail later.

MAXIMUM RANGE OF A RADAR SET

Before discussing details of actual equipments, let us examine some of the factors which determine whether or not a measurable reflection of energy can be obtained from an object. To be detectable, the received power P_r must obviously be greater than the minimum power sensitivity of the receiver. The problem of determining the maximum range of the set is, therefore, one of calculating the range at which the received power is just measurable. The relationship between the major factors which affect the received power may be derived as follows.

The power per unit area at the "target" will be proportional to the instantaneous peak power transmitted by the radar P_T, and will be proportional to the gain G of the transmitting antenna, where the gain in a given direction represents the increase in power resulting from focusing of the radio energy by the antenna as compared with that which would have been present if the energy had been radiated equally in all directions. For example, placing a dipole at the focus of a searchlight type of reflector may result in an increase of a factor of 1,000 in the amount of power sent in one direction. The reflector has, therefore, resulted in a gain of 1,000 in the direction of the focused beam as compared with the dipole, while in other directions the amount of power has been correspondingly greatly reduced. Unless otherwise specified, the gain is understood to mean the ratio of power increase in the strongest part of the beam. A so-called "isotropic radiator," one which radiates equally in all directions, is usually considered as the source for measuring gain. On this basis a dipole in its strongest directions of radiation has a gain of 3/2; hence, the antenna in the above example has a gain $G = 1500$. Using the above facts, we may write for a target a distance R from an isotropic radiator.

$$\text{power per unit area} = P_T/4\pi R^2 \qquad (1)$$

and for an actual antenna with a gain G,

$$\text{power per unit area} = P_T G/4\pi R^2. \qquad (2)$$

This energy is intercepted by the target and scattered in many directions, a portion being reflected to the receiving antenna which may or may not be the same as the transmitting antenna. Since most targets are of a very complicated form, it is customary to use an effective scattering cross section for the target which is defined as the cross section of a perfectly reflecting sphere which would give the same strength of reflection in the direction of the radar as does the actual object. (The scattering by such a sphere can be shown to be isotropic.) If this cross section is denoted by S, the total power received by the equivalent sphere is

$$\frac{P_T G S}{4\pi R^2}.$$

This power will be reradiated equally in all directions, and the amount intercepted by the receiving antenna and thence transmitted to the receiver will be

$$P_r = \frac{P_T G S}{4\pi R^2}\,\frac{A}{4\pi R^2} \qquad (3)$$

where A is the area of the receiving antenna.

A rather complex calculation shows that the gain of an antenna is given by

$$G = K\,\frac{A_T}{\lambda^2} \qquad (4)$$

where A_T is the area of the antenna, λ is the wavelength, and K is a constant which varies with the type and efficiency of the antenna but is, in general, between 3 and 10 in magnitude.

Since most radars use the same antenna for transmitting and receiving, we may take the antenna areas in (3) and (4) as being equal for simplicity of discussion. Substituting (4) in (3) and rearranging we obtain

$$R = \sqrt[4]{\frac{P_T S K A^2}{16\pi^2 P_r \lambda^2}} = \sqrt[4]{\frac{C P_T S A^2}{P_r \lambda^2}} \qquad (5)$$

where

$$C = K/16\pi^2.$$

If P_r is considered to be the minimum energy detectable by the receiver, (5) shows that the maximum range at which an object can be detected is proportional to the fourth root of the power, the square root of the antenna area, and the square root of the frequency since frequency bears a reciprocal relationship to the wavelength. We see, therefore, that changing the power output or the receiver sensitivity does not alter the maximum range as rapidly as a change in antenna area or wavelength. Before making a sample substitution in (5), let us see what values may be considered reasonable for the above factors.

If a more accurate value for K is not known from experimentally measured gains on antennas of the type to be used, a value of 5 will serve as a fairly representative number for range calculations.

The effective cross-section area of the target is usually not under the control of the radar set designer. For detection of aircraft, for example, the set must be built with due regard to the effective reflection from standard planes. In a few cases, such as the use of radar to locate a rubber life raft carrying a metal reflector, the size of the reflecting surface can be varied within reasonable limits to obtain the desired performance. For objects such as aircraft or ships, the effective cross section S will obviously vary with the size, being larger for the larger craft. On the other hand, because of the complicated shape of such objects the reflection will vary considerably with the orientation. This is especially true where there are flat surfaces which may give an intense directional reflection for a very specific orientation. The flash of the sun from the windshield of an approaching car when it is in just the right position is a common example of such a highly directional reflection. This variation in reflection results in a radar signal which varies considerably in strength as a plane is deflected slightly from its course by rough air or by small changes in steering by the pilot. In the case of a ship, the rolling caused by the waves may easily be seen in the changing signal strength. The net result is that the maximum range of a set is not a definite quantity. It not only varies with the size of the object, but will vary from one trial to another with the same object. For example, a plane flying away from a radar set will show a continuous but fluctuating signal when near the set. As it gets farther away the signal will at times drop below the minimum detectable value, causing the tracking to become intermittent. As the distance increases still more, the intervals during which the signal is lost become longer because only the peaks are seen. Eventually even the strongest peaks are too weak to see. The range at which the last signal is seen will, therefore, depend on just how the plane happened to be bounced around by rough air. For radar-set design, it is customary to consider the range of a set for a particular target as that distance for which the signal is visible half of the time. It has also been customary to use the effective cross section of a medium-sized plane such as an A-20 or B-25 for computing ranges on planes. Fighters will then give ranges about 25 per cent less, small planes such as "Cubs" will be about 35 per cent less, while large bombers and transports may be followed 20 to 30 per cent farther, depending on the size. Experimentally, it has been determined that a value of $S = 2\pi^2$ will give a reasonable prediction of the range on a medium bomber when used in (5) for frequencies between 100 and 9000 megacycles. This value is only approximate, and the π^2 is used not for theoretical reasons but in order to simplify the numerical calculation.

In general, the value of S for a given object is very small when the dimensions are small compared with the wavelength. As the wavelength is decreased, S rises rapidly as half-wave resonance is approached, and then falls very gradually with further decrease in wavelength. The exact shape of the curve is dependent on the shape of the object, the maximum at resonance being much more pronounced for a properly oriented wire than for a wide object.

The maximum transmitter power available will vary with the frequency chosen for the set. For example, at extremely short wavelengths, say in the neighborhood of 1 centimeter, the antenna dipoles and transmission lines may impose the eventual limit to the power which can be handled, whereas at 1 meter the transmitter tube may always remain the limiting factor. At present, in all frequency regions used for radar, the power output of existing transmitters is the limiting factor. For wavelengths longer than about 7 centimeters, present techniques will permit a peak pulse-power output greater than 1,000,000 watts, provided the spacing between pulses is great enough to keep the average power within the ratings of the tubes. In the neighborhood of 3 centimeters, peak powers of about 250 kilowatts are available, while near 1 centimeter only about 50-kilowatt output may be realized with present tubes. Where weight and size of the transmitter are not considerations and it is desired to obtain as great a range as possible, a radar system should be designed to use the maximum power available with existing techniques at the chosen frequency. Frequently weight and size are important and may set the limit on the practical power for the application. For example, in an aircraft it may not be feasible to carry a sufficiently large transmitter unit nor to supply the power to operate a set with an output of 1 megawatt. In such cases, consideration of the proper allotment of weight between the transmitter and antenna must be made to obtain the optimum-range performance.

In computing the maximum range to be expected from a radar, P_r is the minimum power which the receiver can detect. For the frequency range commonly used in radar, receivers can detect signals as small as 1 to 0.1 micromicrowatt. Since the cost in weight, size, and complexity of a good receiver is at most only slightly greater than that of a poor one, the receiver is always designed to have the greatest possible sensitivity.

Antenna sizes are usually determined by considerations of mechanical design, space, or weight. It is at present considered impractical to build antennas much over 30 feet wide for transportable field equipment, although larger sizes might be quite practical for permanent fixed installations. For ship or airborne sets and for many ground purposes even this size of antenna is impractical. Furthermore, in many applications the maximum possible range is unnecessary; hence, a small antenna is adequate. The aspects of antenna design will be more fully covered in later sections on antennas and radar systems.

The factors controlling the choice of frequency are wave-propagation effects and antenna beamwidth. These will be discussed in detail in later chapters. Let us now use (5) to compute the range of a large microwave set which might have the following values:

$$A = 200 \text{ square feet}$$
$$\lambda = 4 \text{ inches} = 1/3 \text{ foot}$$
$$P_T = 750 \text{ kilowatts} = 750{,}000 \text{ watts}$$
$$P_r = 5 \times 10^{-13} \text{ watt}$$
$$R = \sqrt[4]{\frac{5}{16\pi^2} \frac{7.5 \times 10^5 \times 2\pi^2}{5 \times 10^{-13}} \times \frac{(200)^2}{(1/3)^2}}$$
$$= 760{,}000 \text{ feet} = 144 \text{ miles}$$

or roughly 150 miles on a medium bomber.

WAVE PROPAGATION AND ATMOSPHERIC EFFECTS: HORIZON LIMITATION

FIGURE 1—*Maximum pick-up range on target.*

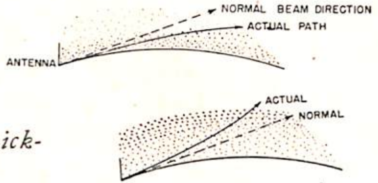


FIGURE 2—*Anomalous propagation effects.*

Because the effective scattering cross section of an object decreases very rapidly for wavelengths greater than the maximum dimension of the object, wavelengths longer than a few meters are not practical for detection of aircraft and small ships. This fact is unfortunate, because at high frequencies very little energy reaches the region below the horizon. Hence, the maximum range of detection of ships and of very low-flying aircraft is usually determined by the horizon rather than by the performance of the radar. A very easily remembered formula which takes into account a small penetration of the radio energy below the optical horizon can be used to calculate the horizon ranges. The formula is

$$R = \sqrt{2H} \qquad (6)$$

where the range R is in land miles and the height H is in feet. As may be seen from Figure 1, the range to the target from the antenna is the sum of the target horizon range R_T and the antenna horizon range R_A. Hence the maximum pickup range (if the set performance is not the limiting factor) will be

$$R = R_T + R_A = \sqrt{2H_T} + \sqrt{2H_A} \qquad (7)$$

where H_T is the target height and H_A is the antenna height. As an example, a plane at 50-feet elevation will first be seen by a radar at 200 feet when it approaches to

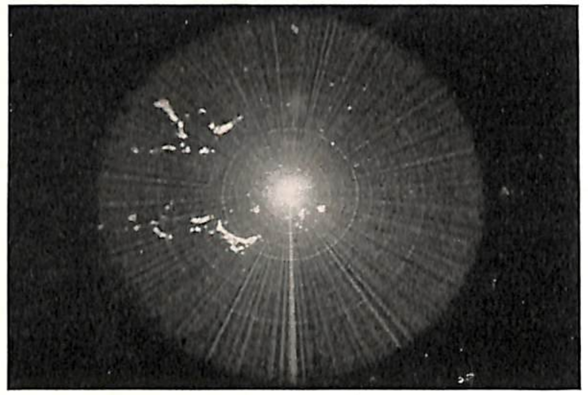
$$R = \sqrt{2 \times 50} + \sqrt{2 \times 200} = \sqrt{100} + \sqrt{400} = 30 \text{ miles.}$$

Note that R is slant range to the target rather than ground range, because the radio waves travel in straight lines rather than following the surface of the earth.

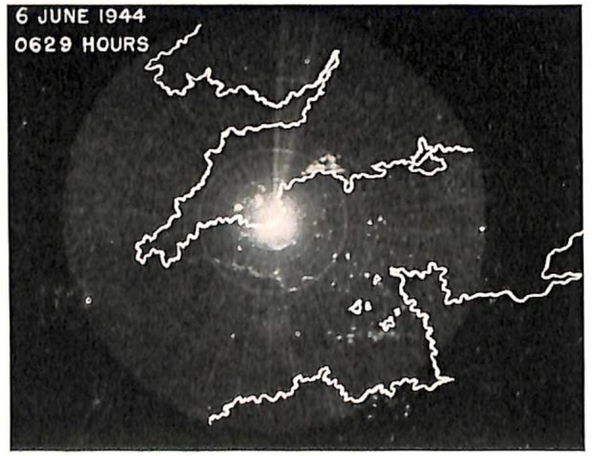
For large vessels which have an appreciable superstructure, the maximum pickup range will be determined by the antenna height and the height of the superstructure of the target. On the other hand, very small boats will not be seen appreciably beyond the distance from the antenna to the horizon.

ANOMALOUS PROPAGATION

Since the atmosphere is not uniform in either density or moisture content, it is possible for local conditions to exist under which the radio beam is appreciably bent by inhomogeneities. Conditions under which the beam does not follow the normal straight-line path are called conditions of "anomalous propagation." Bending of the beam is most apt to occur on days when there is little wind and in places where the air temperature is different from the surface temperature. Anomalous propagation is most prevalent over water, where a pronounced temperature gradient may be established by heat interchange between the water and the air immediately above it. Over-water conditions are also favorable for formation of a moisture gradient by evaporation from the water surface. Since the velocity of the radio wave is slightly less in dense or moist air than in less dense or dry air, the beam will be bent in the direction of the optically dense layer. Figure 2(a) shows one condition which will cause downward bending, while Figure 2(b) shows a condition which will cause upward bending. Under the conditions indicated in Figure 2(a), surface targets may be seen far beyond the horizon. Perhaps the most extreme case of this type of anomalous propagation has occurred over the Indian Ocean where the coast of Arabia has been seen by a station on the west coast of India, a distance of 1200 miles. Less spectacular examples of this type of anomalous propagation are quite frequent. Figure 3(a) shows the outline of the Cherbourg Peninsula as seen from Start Point, in England, on the evening of 7 June, 1944. In addition to the echoes from the land, some of the invasion shipping and air activity can be seen. The concentric circles are centered at the radar station and are separated by ten-mile intervals. Figure 3(b) shows the appearance of the same indicator a few hours earlier when the atmosphere was behaving normally. From this station during the spring and summer, part of the French coast was visible several evenings a week. As a rule, near land the conditions for anomalous propagation are more favorable in some directions than others. For example, at this site the Cherbourg Peninsula was much more frequently observed than the Brest Peninsula, although the distances and heights of the land masses were not appreciably different.



(*a*) *Note echoes corresponding to map position of Cherbourg*



(*b*) *The map outline traced on the photograph does not appear on radar*

FIGURE 3—*Radar photographs of Cherbourg Peninsula*

Anomalous propagation of the type shown in Figure 2(a) favors long-range detection of ships and low-flying aircraft, while that shown in figure 2(b) prevents seeing objects on the surface until they are very close to the radar. Although the condition of figure 2(b) is less common than that in figure 2(a), it has been observed a number of times. For example, a station on the coast of Rhode Island normally saw Block Island as an extremely strong signal at a distance of 19 miles, but on several days no trace of this signal could be observed for several hours at a time. During these same periods, echoes from hills beyond Providence were of normal strength indicating both that the set was operating normally and that the unusual atmospheric conditions existed only over the water. On these days visibility was good near the surface of the water but graded into a dense fog at a few hundred feet, giving visible evidence of a moisture gradient.

Since many complex conditions may exist, such as the partial trapping of the energy in a layer which is well above the surface of the earth, this discussion by no means covers the subject of atmospheric conditions leading to anomalous propagation. These propagation effects are dependent on frequency and are usually more pronounced at high frequency but, in the case of trapping layers, may show rather large changes in behavior near critical frequencies which are related to the thickness of the layer. In order to get trapping or to show a pronounced bending, it is necessary for the antenna to be at about the same height as the layer in which the gradient exists. For example, a radar set on Saipan was sited at 1500 feet above sea level, where an almost continuous condition favorable to trapping of energy exists. This resulted in unusually long range pickup of aircraft at altitudes of 1000 to 2000 feet. However, on the days when this condition moved up to 2500 feet, no effect could be observed on the pickup range of aircraft at any altitude.

So far, nothing has been said about the magnitude of these bending effects. The amount of bending of the radio beam is rarely more than one or two degrees because change in the index of refraction of the atmosphere with moisture content and density is actually very small. Furthermore, only the energy traveling within the layer and within one or two degrees of the direction of the layer is appreciably affected by the refractive gradients.

GROUND REFLECTION

A quite different phenomenon of nature still further limits our ability to place the radio energy exactly where we desire it. Land and water are good reflecting surfaces for radio waves, particularly at grazing incidence. Consequently, if a part of the wave from the transmitter strikes the earth's surface, it will be reflected into the beam above the surface. If this reflected wave is in phase with the direct wave, it will reinforce, and if out of phase, it will cancel. Furthermore, if the reflected wave is equal to the directly transmitted wave in amplitude, there will be places where the cancellation is complete and others where the amplitude is doubled. If the earth is assumed to be flat, the directions of maximum reinforcement and cancellation can be computed easily. Many readers will recognize this as the well-known optical problem of the Lloyd's mirror. Calculation of the exact distribution of the wave, especially for a curved earth, is beyond the scope of this paper.

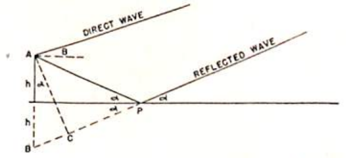


FIGURE 4—*Reflection of radar beam*

The direct wave from the antenna, figure 4, makes an angle β with the reflecting plane, while the reflected wave which reaches the same point in space starts downward striking the earth at an angle α. Since the angle of reflection is equal to the angle of incidence, the reflected wave will leave the earth at an angle α and will appear to have come from the mirror image *B* of the antenna at *A*. If the line *AC* is drawn perpendicular to *BP*, the distance *BC* will very nearly equal the difference in path between the direct and reflected waves from the antenna to the point of intersection of these two lines in space. The more nearly the direct and reflected waves parallel each other, the more accurate is this approximation. The approximate path difference is then

$$BC = 2h \sin \alpha. \tag{8}$$

The condition for reinforcement is that the direct and reflected waves be in step. This condition will obviously be met when *BC* is a whole number of wavelengths if there is no phase shift upon reflection. (This condition of no phase shift holds for vertical polarization only.) Mathematically

$$BC = n\lambda \tag{9}$$

where n is an integer. Hence,

$$\sin \alpha = n\lambda/2h. \tag{10}$$

Equation (10) may be written as

$$\alpha = n\lambda/2h = \text{direction of maximum reinforcement} \tag{11}$$

if α is small and only the first few maxima above the horizon are considered. It must be remembered that this equation was derived with the use of several approximations and does not apply for large values of n nor for conditions where the antenna is only a few wavelengths high.

For horizontal polarization there is a 180-degree phase shift on reflection so that (10) and (11) become the conditions for cancellation.

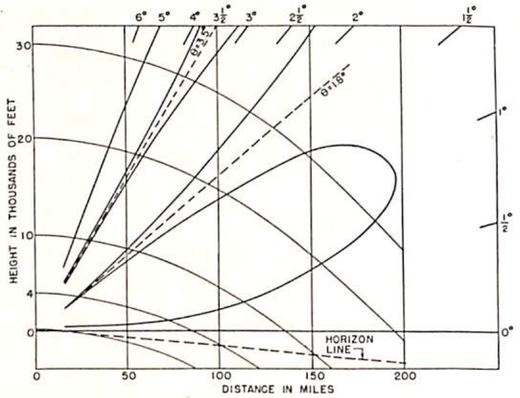
Cancellation for vertical polarization and reinforcement for horizontal polarization will occur at angles halfway between those determined by (11).

The result of reflection from the earth's surface is a series of lobes in the vertical plane of the antenna pattern. The spacing between these lobes decreases linearly with antenna height and increases linearly with wavelength.

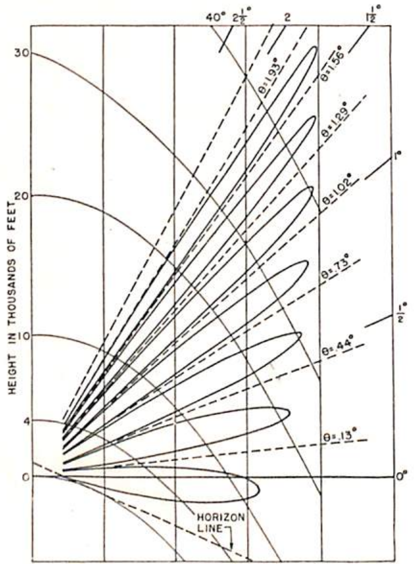
Figure 5 shows the lobe pattern for two different antenna heights for the SCR-270 Army radar which operates at 106 megacycles. The energy striking the ground is essentially equal to the direct radiation, with the result that virtually complete cancellation takes place in the "nulls." In the directions of the lobe maxima the range is twice what it would have been without ground reflection, because the amplitude of the wave has been doubled by reinforcement. The power at the target is thereby increased by a factor of 4, and another factor of 4 in power occurs by reinforcement of the received radiation.

Although the range has been doubled in certain directions by ground reflection, this has been accomplished at the expense of causing blind regions. If the curves of figure 5 are interpreted as the lines along which the signal from a given-sized aircraft is just measurable, it is apparent that between the lobes the plane will not be seen, while well within the lobes the signal will be strong. The fading of the signal from an approaching plane on account of this lobe pattern can be very troublesome operationally. For example, at 30,000 feet, under the conditions of figure 5(a), between 115 and 145 miles the whereabouts of a plane cannot be determined. This presents a very serious difficulty when the set is being used to intercept hostile aircraft or to avoid possible collision between friendly planes.

A further disadvantage of designing a set which depends on ground reflection arises from the fact that reinforcement in the desired directions can be obtained only over relatively flat ground. Sets such as the SCR-270 were not successful in the mountainous country of Burma because in many places there was no surface flat enough to give reflection. Moreover, in other places the surface was far from horizontal, with the result that the vertical pattern was unpredictable and differed radically with the compass direction. On the other hand, these sets were extremely successful on the Pacific islands where they were used for air search over water. At wavelengths of 20 centimeters or less, tree tops and bushes absorb so much of the energy that very little reflection can be expected. However, at these short wavelengths a flat surface, such as an air field or a water surface, acts as an excellent mirror.



(*a*) *Antenna height = 125 feet*

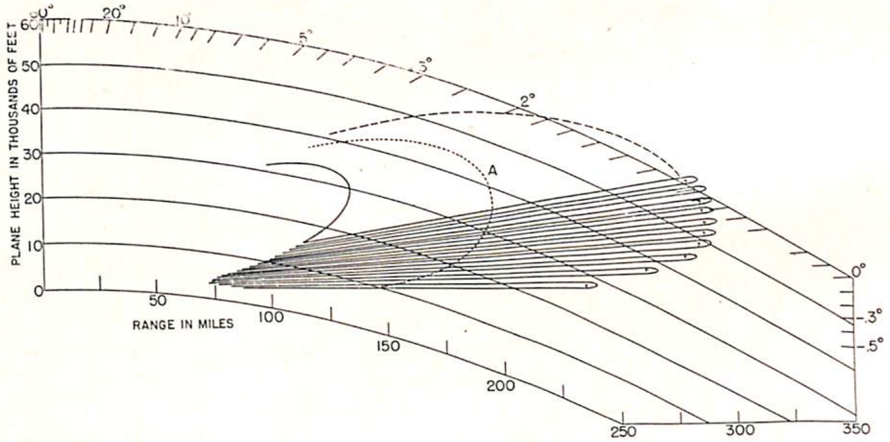


(*b*) *Antenna height = 1000 feet*

FIGURE 5—*Vertical-coverage diagram for 106 megacycles*

Figure 6 shows the coverage diagram of a large set operating at a wavelength of about 10 centimeters. Figure 6(a) shows the calculated coverage over water when the center of the beam is pointed 1 degree above the horizon. The nulls do not go to zero because the power striking the water is considerably less than the direct wave. The dotted curve labeled *A* shows the coverage of this set with the same antenna angle, but when no ground or water reflection occurs. Figure 6(b) shows the calculated coverage with the antenna pointed so that the center line of the antenna beam lies along the water. It might be argued that these lobes are so close together that the nulls would not be troublesome. Tracking results taken with somewhat reduced performance but under conditions corresponding to figure 6(b) are shown in figure 7. The main difference attributable to the reduced performance is that the whole pattern is proportionately reduced in slant range so that the aircraft flights do not have to be as long to pass out of the coverage of the set. The intermittent tracking is due to the lobe structure, but with lobes this closely spaced, variations in aircraft altitude and unsteadiness in the atmosphere make it impossible to repeat observations on the exact positions of the nulls. When the lobes are as large as those in figure 5, flight tests show consistent results on the null positions.

(*a*) *Antenna pointed 1 degree above horizon. Curve A is for no ground reflection and is adjusted to match the SCR-270 performance.*



(*b*) *Antenna pointed at horizon*

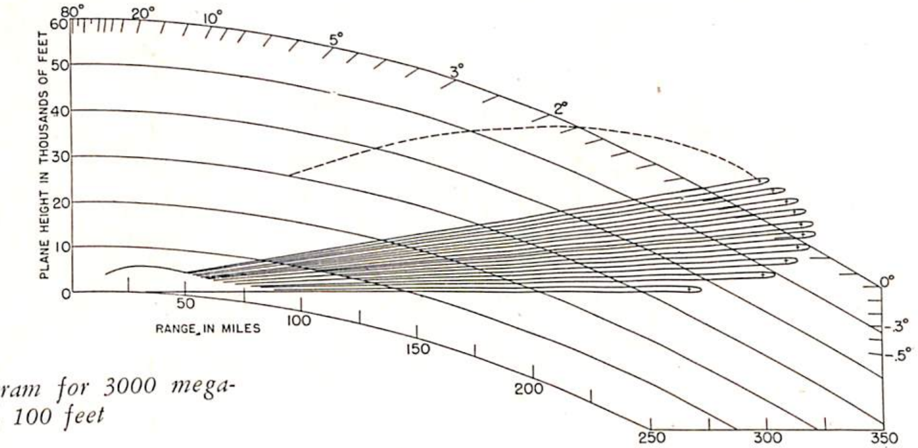


FIGURE 6—*Vertical coverage diagram for 3000 megacycles. Antenna height, 100 feet*

The only advantage in designing a set to use ground reflection is to avoid building a tall reflector or radiating surface. The same range without the nulls can always be obtained by making the vertical aperture of the antenna four times as great and tilting the center of the beam to prevent a large amount of the radiation from striking the ground.

ATMOSPHERIC ABSORPTION

Absorption of energy by the atmosphere may limit the use of certain frequencies for radar. For wavelengths greater than 2 centimeters, the absorption of moist air is not likely to impose a serious limitation. At shorter wavelengths there are strong absorption bands caused by water vapor and oxygen, with some narrow transparent regions between these bands. Because of this absorption it will probably never be practical to use wavelengths below 2 centimeters for long-range operation.

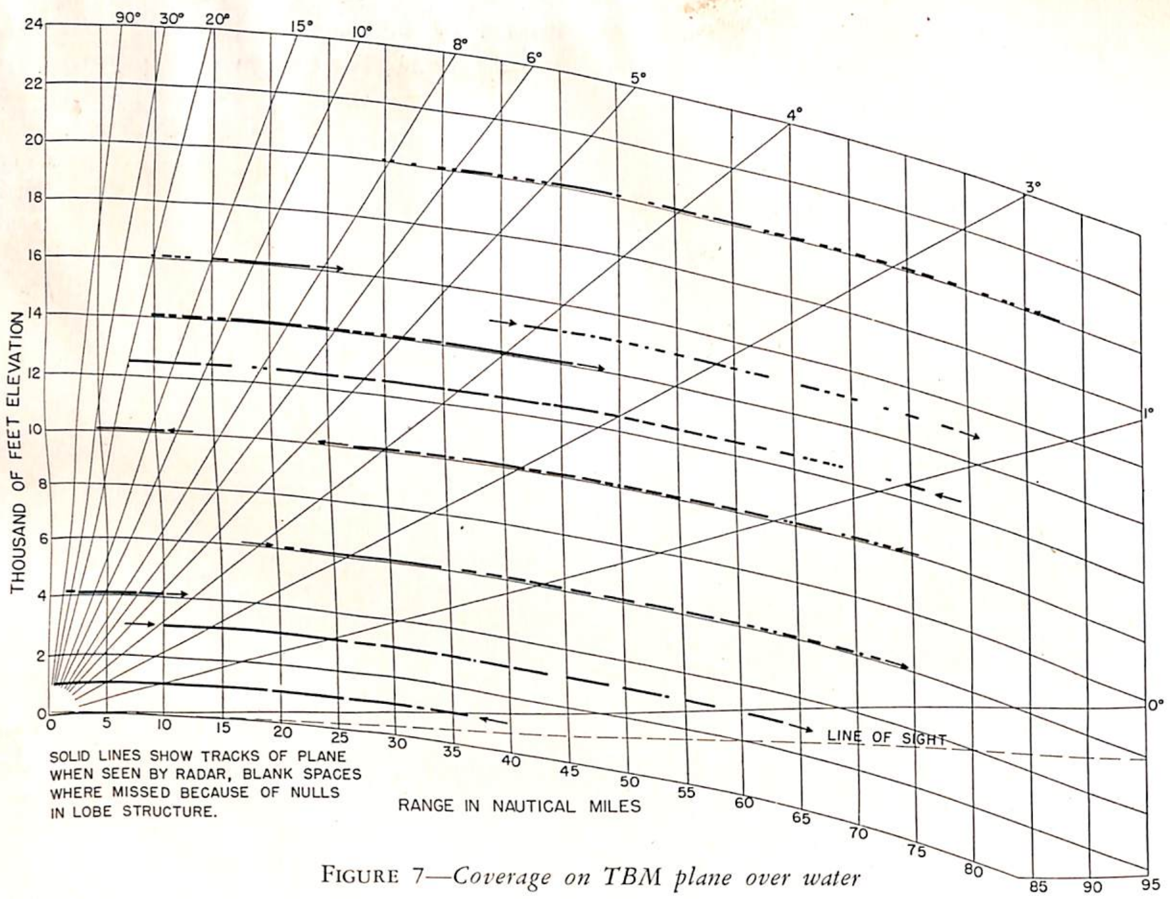


FIGURE 7—*Coverage on TBM plane over water*

At 3 centimeters the absorption and scattering of radiation by the water droplets may cause a serious decrease in signal strength of a target beyond a heavy tropical shower 10 miles across.

Obviously, this loss in performance is a serious handicap in certain long-range applications such as warning of approaching hostile aircraft. At 10 centimeters, 50 miles of heavy rain between the radar and the target causes no serious decrease in performance, while at longer wavelengths the loss is not readily measurable.

A part of the loss in a heavy shower is due to absorption of energy and a part is due to scattering by the droplets. The scattering not only weakens the beam beyond the shower but also returns energy to the receiver, with the result that an echo is observed. At 1200 megacycles, only the very heaviest tropical showers give an appreciable echo. At 3000 megacycles, a moderate rain will give a return, while at 9000 megacycles, very light rain can be seen. However, even at frequencies as high as 9000 megacycles, fog particles which make up the ordinary cumulus clouds cannot be seen; drops large enough to be considered rain rather than a heavy fog are necessary to give an echo.

Since the rain echo is the sum of the reflections from a large number of drops spread over a volume of space, the relative echo strength compared with some object such as an aircraft will depend on the beamwidth and pulse length of the radar as well as the frequency. If the rain storm is wider than the beam, changing the beamwidth with all other factors constant will not affect the strength of the returned signal, because a fixed fraction of the energy will be reflected. A plane, on the other hand, is usually much smaller than the beam; therefore, any concentration of the energy into a narrower pencil will result in a greater amount being intercepted by the plane and also in an increased signal. Again, if the storm is longer than the wave train in one pulse, energy will be received simultaneously from drops along the length of this wave train, while the aircraft will be returning energy from only a short length of the wave. Hence, decreasing the pulse length will increase the plane signal relative to the storm. Investigations in Florida by the Army Air Forces indicate that at 3000 megacycles a 1-degree beamwidth and a 1-microsecond pulse length will give plane signals larger than storm signals where it is safe to fly. In the tropical thunderstorms prevalent in that part of the world, turbulent centers of much greater echo strength are present. In none of the cases investigated were the pilots willing to risk entering the regions of very strong storm echoes. Thus the possibility exists of guiding planes through gaps in bad weather where the presence of dangerous local storms would make it unsafe to fly unaided. At 9000 megacycles, most rain storms give echoes stronger than small planes, while at 1200 megacycles, only the most intense regions in a storm are visible. Figure 8 shows the appearance of thunder storms on a 10-centimeter radar set. The set was located on the west coast of Florida.

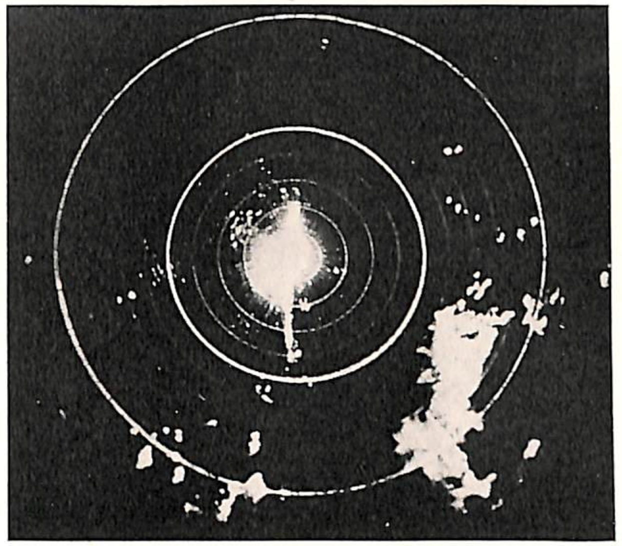


FIGURE 8—*Echoes from dense clouds on 10-centimeter radar*

THE BASIC RADAR SET

So far, this discussion has involved the general behavior of the radiation in space. Let us now see what is needed to build a radar set. Figure 9 shows the basic components which must be used in all sets.

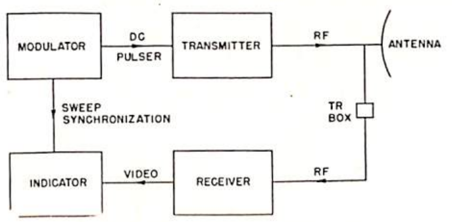


FIGURE 9—*Block diagram of basic radar set*

The modulator, otherwise known as a keyer or pulser, is a pulse generator. Its output consists of a series of short square-topped voltage pulses separated by time intervals much greater than the pulse duration. These pulses drive the transmitter, which in turn generates short wave trains of high-frequency radiation. These are piped to the transmitting antenna through coaxial cable or wave guide in most sets. Since reception takes place in the time intervals between the transmitted pulses, it is more economical to use the same antenna for transmitting and receiving, although this is not necessary. Where a common antenna is used, the receiver must be isolated by a very fast-acting switch to prevent damage by the outgoing power. Since mechanical switches are not fast enough, a gas discharge device is normally used. The term "TR box" (transmit-receive box) has become the generally accepted designation for this switch. During reception the radio-frequency energy is channeled to the receiver, where it is amplified and converted into video signals. These are then displayed on an indicator which is usually some form of cathode-ray tube. In a few cases, the display is in the form of a meter or an audio tone. Since range is measured by timing the pulse to the target and back, the indicator must have timing circuits which are synchronized with the out-going pulse. Hence, a sweep synchronizing voltage is needed. If the set also determines azimuth position of the target by the directional properties of the antenna, some means must be used to indicate the antenna position.

Although all radars have these basic components (with the exception that the TR box may be replaced by a separate receiving antenna), there is considerable variation in the construction and refinements. Specialized components are frequently added to accomplish some particular purpose. In general, once the frequency of a new set is chosen, the antenna together with its mount, the indication, and the special-purpose components require the most development.

MODULATOR DESIGN

The major problems consist of controlling the pulse-repetition frequency (PRF), and of generating a high-voltage pulse suitable for driving the transmitter. Since the voltage applied to the transmitter may be as high as 50 kilovolts with peak power of 5 megawatts there are also problems of insulation and suitable control, and safety circuits must be provided. Although there has been considerable improvement in high-voltage cable and connector design and in control-relay construction during the war, these techniques are essentially those used in standard radio transmitters and need no special discussion.

SINE-WAVE CONTROL OF PULSE RATE

In most of the earlier radar systems, and in systems where extremely accurate range measurements must be made, a sine-wave oscillator is used to control the pulse-repetition frequency. The oscillator frequency will then be the same as the pulse-repetition frequency or some multiple of it. If the exact spacing between the pulses is not critical, a simple tuned-circuit oscillator or the alternating-current power line may be used to obtain the sine wave. Where the spacing between pulses must be held very constant, a crystal-controlled oscillator is used.

A number of methods can then be used to convert this sine wave into a series of pulses suitable for driving the transmitter.

a. Overamplification and "differentiation": By the use of several stages of amplification in which the tubes are driven beyond cutoff, the sine wave can be converted into a series of almost square waves, as shown in figure 10(b). If this square wave is fed into a small capacitor-and-resistor combination, as shown in figure 10(e), the output will appear as in figure 10(c). During the time the voltage applied to the left-hand side of the capacitor is rising, the voltage applied to the grid of the following amplifier will rise because of the action of the capacitor. Because of this rise in voltage, current will also flow through the resistor and partially discharge the capacitor, thereby preventing the voltage from rising to the full value of the input. As soon as the applied voltage becomes constant, the current through the resistor starts discharging the capacitor. Since the capacitor will discharge to about one-third of its original voltage in a time $R \times C$ seconds ($R =$ resistance in ohms and $C =$ the capacitance in farads), the width of the pulses in figure 10(c) can be adjusted accordingly. Since these pulses are saw-tooth in shape, further amplification and clipping by driving tubes beyond cutoff is necessary to obtain square-topped pulses as shown in figure 10(d). Proper adjustment of the amplifier-bias points will determine the section of the saw tooth which is finally used. This method of obtaining square pulses is apt to be expensive in tubes and power, because of the total amplification involved. Furthermore, unless the amplification is extremely great, the sides of the pulses will not be steep.

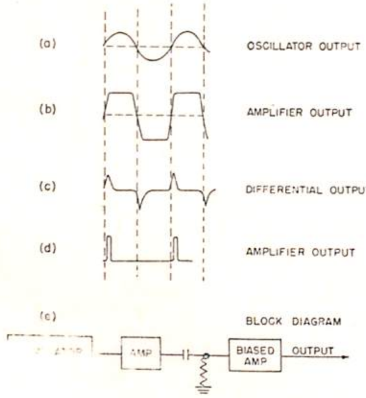


FIGURE 10—*Square-wave generation from sine wave*

b. Triggering a square-wave generator: Rather than using the brute-force method outlined above, the sine wave with a moderate amount of amplification can be made to trip a square-wave generator such as a "multivibrator." One type of multivibrator is shown in figure 11(a). Other types will be discussed in the section on indicators.

Before the input is turned on, tube 1 is running at zero bias and tube 2 is biased beyond cutoff. When a wave form such as that in figure 11(b) is applied to the grid of T_1, the grid is driven negative to cutoff. This voltage change is then amplified by the two tubes and is fed back onto the grid of T_1 by the capacitor C_1. T_1 is thereby held beyond cutoff until the charge on C_1 leaks off through R_1. When T_1 again becomes conducting, the multivibrator rapidly returns to its original condition. The wave forms in figure 11(b) show the voltage changes on the various electrodes.

The values of R_2 and C_2 are not critical. If they are so small that the grid of T_2 drops back to cutoff before T_1 begins to draw current, the width of the square pulse will be determined by this circuit rather than by the grid circuit of T_1 as discussed above. On the other hand, if R_2 and C_2 are very large, the excess negative overshoot (see figure 11(d)) caused by the drop in voltage of plate 1 may not have time to leak back to approximately the bias point. When this happens, the next cycle turns T_1 off, but the impulse on the grid of T_2 may not be great enough to cause T_2 to draw current. Under this condition, the multivibrator fails to catch and nothing happens in the output. Although large values of R_2 and C_2 may be chosen purposely to make the multivibrator go only alternate times or even less frequently, for the purpose under discussion the value is chosen to insure recovery within one cycle. It is advantageous to have the grid circuit of T_2 recover only shortly before the next cycle because this prevents triggering by stray pickup before the desired time.

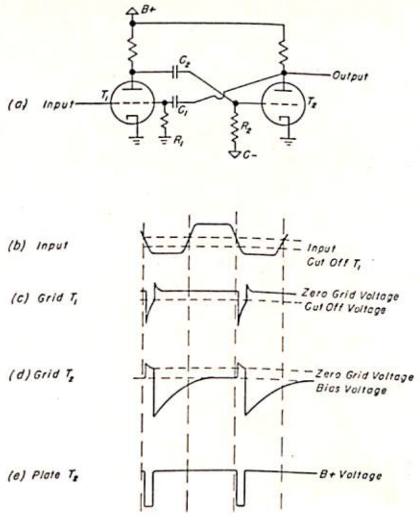


FIGURE 11—*Multivibrator and wave forms*

By replacing C_2 with a resistor of the proper value to give the correct negative bias on the grid of T_2, it is possible to avoid the problems introduced by the recovery time of T_2. This form of multivibrator is particularly advantageous where the trigger spacing is not uniform.

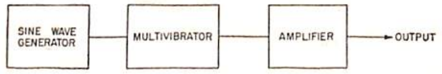


FIGURE 12—*Block diagram of modulator employing multivibrator*

Figure 12 shows the block diagram of a modulator using a multivibrator for producing pulses.

GENERATION OF A TRIGGER TO OPERATE SWITCHING DEVICES

In a later section, networks will be described which give a square wave when discharged. To operate these, some form of electronic switch such as a thyratron or spark gap is used. These switches are activated by a sharp voltage impulse which may be obtained from a sine wave by either of the methods described above or by use of a blocking oscillator which is tripped by a sine wave.

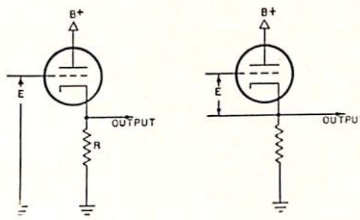


FIGURE 13—(*a*) *Cathode follower.* (*b*) *Bootstrap amplifier*

Where very accurate pulse spacing is not required, it is not necessary to use a sine wave as the starting point for pulse generation. A saw-tooth generator similar to those used in cathode-ray oscilloscopes has been employed to set the pulse-repetition frequency using techniques similar to those described above. Another method is to start with a multivibrator similar to that shown in figure 11(a) in which the grid of T_2 is returned to ground rather than to a negative bias. Such a multivibrator will operate without an input trigger and will have a pulse-repetition frequency which is determined by the slowest grid-recovery time. A third method is to use a rotary spark-gap.

MODULATOR TYPES

Radar modulators fall into two general categories: (a) those in which the pulse is formed at low level and is amplified for application to the transmitter; and (b) those in which the pulse is generated at high level by means of a special network which is discharged into a transmitter through a switching device.

HARD-TUBE MODULATORS

Modulators which operate by amplifying a small pulse require the use of high-power vacuum tubes together with the necessary direct-current power supply to operate them. For experimental purposes they have the advantage that the amplification is easily controlled by adjustment of the voltages, but for field use they have the disadvantage of being heavy and complex. Although the amplification could be obtained by several stages of conventional amplification, this would be extremely expensive in power because some of the tubes would be carrying full current for the long intervals between the transmitted pulses. In order to keep the average current as small as possible it is desirable to operate all tubes near cutoff and have them turned on only during the transmitting period. This requires that all tubes operate on positive input pulse. In the conventional amplifier, a positive grid input causes a negative plate output which is coupled to the next tube. If the load resistor is placed in the cathode circuit, this phase inversion can be avoided. Figure 13 shows two circuits in which the load resistor is placed in the cathode circuit.

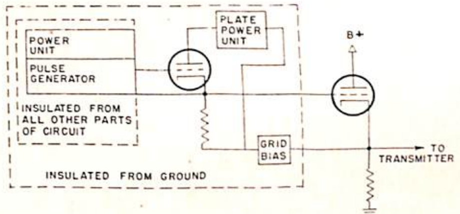


FIGURE 14—*Hard-tube modulator*

When the voltage E is applied to the grid of the "cathode follower" (see figure 13(a)), the voltage between the grid and cathode will be $E - I_pR$ where I_p is the plate current. A study of the output voltage using the curves for any triode will show that the output voltage may be nearly equal to the input voltage but can never be appreciably greater. Hence, no practical voltage amplification occurs. On the other hand, the voltage E may be supplied from a low-current source and still control a large current through the resistance R. The cathode follower is, therefore, useful in obtaining current amplification. Expressed in another way, the cathode follower is a useful device for matching a high-impedance circuit to a low-impedance load.

In the case of the "bootstrap amplifier," the input voltage is the actual voltage between the cathode and grid and is not altered by the voltage drop across the cathode resistor. This means that the output voltage will be I_pR, and will be determined from the tube characteristics in the same way as the plate output of a conventional amplifier with the cathode at ground and the load connected between the plate and $B+$. The one disadvantage of the bootstrap amplifier is that the whole circuit supplying the input voltage is at a voltage I_pR above the ground. This means that the chassis must be insulated for this voltage and that the filament and plate transformers must be insulated to withstand this voltage. Furthermore, at high frequencies the capacitance between this unit and ground may be equivalent to an appreciable by-pass capacitor across *R*.

Figure 14 shows the essential parts of a modulator making use of two stages of bootstrap amplification.

Each of the units enclosed within the dotted lines, including filaments, must be direct-current insulated from ground either by the use of batteries or with transformers built to stand the voltage labeled B+ between primary and secondary. If the pulse from the pulse generator is positive, all output pulses will be positive. The tubes will carry appreciable current only during the time of transmission and the current during the dead interval will be determined by the bias voltages.

A modulator of this type giving an output pulse voltage of 30 kilovolts and a 1-megawatt direct-current output pulse of 1-microsecond duration is used in the SCR-584. The direct-current power supply to furnish the voltage for the output stage weighs about 1800 pounds and fills a cabinet about 24 × 30 × 60 inches. The modulator unit is about the same size and weighs approximately 1500 pounds.

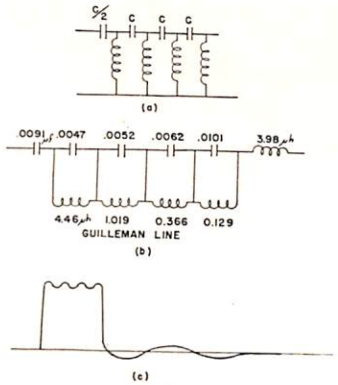


FIGURE 15—*Pulse-forming network (a) Artificial line (b) Pulse network (c) Pulse output*

PULSE-NETWORK MODULATORS

Much lighter-weight modulators can be built by using a "pulse-forming network" which is discharged directly into the transmitter by means of a suitable switch. The disadvantage of this type of modulator over the type described above is that the pulse width is not readily altered. The pulse-forming network is based on the principle that a charged transmission line will maintain a constant current through a short-circuiting resistor which is suddenly placed across the line until the whole length of line is discharged, and then the current will suddenly drop to zero. If the line is terminated at the far end by a resistor equal to the impedance of the line, no further current will flow. The time for this discharge to take place is equal to the time required for an electrical impulse to travel the length of the transmission line. If the far end of the line is not properly terminated, this initial pulse will be followed by a number of oscillations which rapidly die out. Instead of an actual transmisison line, an artificial line made up of chokes and capacitors may be used. Figure 15(a) shows one method for making such an artificial line, where all chokes *L* have the same inductance, and all capacitors *C* are of the same capacitance. This combination of inductances and capacitances will behave more and more like an actual transmission line as the number of elements is increased. At least ten elements are necessary to obtain a reasonably good approximation to a transmission line. Only a few circuit elements are necessary to give the desired wave form, if the values of *L* and *C* are properly chosen to have critical values not all equal. A very complex calculation is required to work back from a given wave shape to the values of the capacitors and chokes necessary to obtain this desired wave shape. This calculation has been carried out for a number of cases, and networks which give a square voltage and current pulse when discharged through the proper impedance are now commercially built. Figure 15(b) shows a circuit used to obtain a pulse 1-microsecond wide at the base. The output pulse is as shown in figure 15(c).

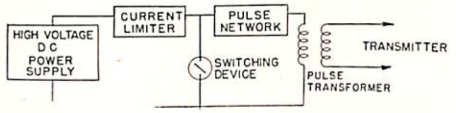


FIGURE 16—*Modulator using pulse-forming network*

A network of this type can drive a transmitter directly, provided the transmitter impedance is correct; or, the impedance may be matched by use of a pulse transformer which has been developed to pass the high-frequency components in the pulse without serious amplitude or phase distortion. Although these transformers are iron-cored, they pass video pulses of less than 1 microsecond in width. Figure 16 shows the basic circuit for a modulator of the pulse-network type.

The pulse-forming network is charged by the high-voltage power supply in the interval between transmitted pulses. At the proper time the switching device closes and allows this charge to be dissipated in the transmitter. The current limiter is placed in the circuit to prevent overload of the power supply while the switch is in the closed position. The current obviously must be kept within the rating of the power supply but must be great enough to permit charging of the pulse line during the time the transmitter is off. As mentioned above, the output may go to a pulse transformer between the modulator and transmitter. When the impedance of the modulator is less than that of the transmitter the pulse transformer used for impedance matching will also step up the pulse voltage, thereby permitting a low-voltage modulator to drive a tube at high voltage. For example, if 30 kilovolts are needed at the transmitter and the pulse transformer gives a voltage step-up of 3 to 1, only 10 kilovolts need be handled in the modulator, thus simplifying insulation problems. Since the transmitter may be some distance from the modulator, it is customary to make the modulator impedance 50 ohms. The modulator will then be matched to a 50-ohm cable, a type which is readily available and is suitable for handling high-voltage pulses.

The switching device in figure 16 may take a number of different forms. Gas tubes such as thyratrons or ignitrons may be used. These must be tripped by a trigger, which may be obtained by the methods discussed in the first part of this chapter but need not necessarily be a square wave, provided the leading edge is steep. One interesting development in thyratrons for this purpose is a hydrogen-filled tube which will operate a modulator with a peak power output of over 1 megawatt. This tube is only slightly larger than a glass 6L6. Higher powers can be handled by using these tubes in parallel. The firing time with a suitably fast trigger is reliable enough that two tubes may be fired simultaneously to within 1/50th of a microsecond, provided the time delays in the transmission of the pulse to the grids are equalized.

Another switching device which has been successfully used is a triggered spark gap. The pulse-repetition frequency is set at the desired value by applying a voltage impulse to the gap. Since this voltage is merely used to initiate the spark, the main power and voltage coming from the pulse-forming network, a simple low-powered trigger unit can be used.

Probably the simplest type of switching device which can be used is the rotary spark gap in which the pulse-repetition frequency is determined by the rotor speed and the number of points in the gap. This type of switch has the one serious disadvantage that it cannot be used in applications where the spacing between pulses must be held constant. The time interval between pulses may vary as much as 100 microseconds because of motor-speed variations and irregularity in the distance that successive sparks jump as the gap closes. For many applications this is no handicap.

Modulators built around the basic circuit shown in figure 16 will weigh about one quarter to one eighth as much as the type described first and will occupy less than half the space for the same power output.

One other trick which can be used to simplify modulators where the pulse-repetition frequency can be tied to the frequency of the modulator power supply is to allow the switching device to act as the rectifier. If the direct-current power supply in figure 16 is replaced by an alternating-current source, the pulse network will alternately be charged positively and negatively. If a positive charge on the network is the desired condition at the time of closing the switch, the modulator will operate if the switching device is made to close at the peak of the charging cycle. This can be done by generating a trigger from the alternating-current which is then applied to a thyratron or fixed spark gap. A phase shift may be required to adjust the timing trigger for optimum performance, but this presents no great difficulty. An alternate method is to operate a rotary gap with a synchronous motor, again adjusting the phase properly.

Since the pulse-forming network acts as a capacitance in the circuit and the current limiter may be an inductance, the values may be chosen to obtain resonance at the alternating-current frequency. This results in a voltage higher than the output of the transformer, thereby decreasing the size of the transformer needed. Resonant charging by the same method will also take place with a direct-current source of power as shown in figure 16 if the circuit is resonant at the pulse-repetition frequency.

An early experimental modulator furnishes a good example of a rotary-gap type using alternating-current charging. The circuit is essentially that shown in figure 16. Since the set operates on 60-cycle power and a pulse-repetition frequency of about 400 pulses per second is desired, a motor generator is used to obtain 400-cycle single-phase power from the main 60-cycle power. This power is applied to the pulse network through a step-up transformer without being rectified. The current limiter does not appear as a separate choke because of the special design of the transformer to obtain resonance with the pulse network. The switching device is a rotary gap mounted on the same shaft as the motor generator, the phasing being adjusted by moving the fixed spark-gap points. This modulator, including control box, weighs only 600 pounds and has a power output of 3 megawatts. The over-all dimensions are approximately 20 × 30 × 40 inches.

TRANSMITTERS

The wartime trend in radar has been steadily toward higher frequencies, but the eventual limit imposed by the absorption of air is rapidly being approached. It is interesting to note the wavelengths of about 1 centimeter, at which Hertz carried out his studies of electromagnetic radiation, are again becoming the subject of investigation.

The early work on radar was carried out in the frequency region between 30 and 100 megacycles, largely because the techniques were more advanced than at the higher frequencies. As techniques improved, the higher frequencies offered the advantages of higher antenna gains with smaller antennas and also provided better resolution because the energy can be focused into a sharper beam with a moderate-sized antenna.

It now appears that the best frequencies for long-range search are between 600 and 6000 megacycles, and those for most airborne applications lie between 3000 and 60,000 megacycles, the air being too opaque for satisfactory operation at higher frequencies.

CONVENTIONAL-TUBE TRANSMITTERS

Up to 1000 megacycles, transmitter techniques are largely extensions of the use of the conventional circuits using triodes, tetrodes, etc. Two factors which limit the use of conventional types of tubes and circuits at high frequency are (1) the time of flight of the electrons between the cathode and plate; and (2) stray inductance and capacitance of lead wires and tube elements. If the frequency is so high that the plate or grid alternating voltage reverses during the time of flight of the electrons from the cathode to these electrodes, the tube will fail to oscillate, or at best will put out only small power. Within limits, the time of flight may be reduced by decreasing the electrode spacing and by increasing the direct-current potentials; but manufacturing difficulties, low power dissipation of small electrodes, and voltage breakdown make these solutions of the problem less practical as the frequency is increased.

CAVITY RESONATORS

The problems of stray capacitance due to lead wires, of internal capacitance in coils, and of internal inductance in capacitors may be easily eliminated by using metallic cavities as electrical resonators. Although great improvements in tuned-cavity techniques have been worked out during the war, the fundamentals were well known prior to 1940. Basically, a hollow metallic cavity will act as a tuned circuit if electrical energy is coupled into the interior of the cavity by some means such as a dipole, probe, or loop. The resonant frequency of such a cavity will be determined by its size, its shape, and the method of coupling. Figure 17 shows a cross section through a cavity, the connections being made through coaxial cable.

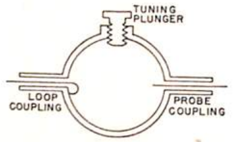


FIGURE 17—*Resonant cavity*

On the left, the power is coupled by means of a loop, while on the right, a probe type of coupling is shown. Tuning may be accomplished by screwing a plunger in or out. The choice of coupling method and the position of the coupling devices will depend on the orientation of electric field to be established. In most cavities it is possible to set up several different "modes" or ways in which the cavity will oscillate. A common mechanical example of this behavior is a metal rod which may vibrate with bending or with a twisting motion or may have a compression wave traveling in it. Each of these general types of vibration may also have harmonics. Since the electric fields will be quite different for the different modes, the position and type of input coupling used will frequently decide which mode is excited. Most or all of the energy will go into those modes of oscillation which have electric and magnetic fields most nearly like those of the coupling device at the position of the input. For example, if a mode of the cavity requires a voltage zero at the input and the input sets up a high voltage at this point, that mode will not be set into oscillation. If the frequency of the input power is not determined by the cavity itself, only the modes for which the natural frequency of vibration is very close to that of the input will be excited. For most applications, the shape and size of the cavity are chosen to give the cavity a single mode in the desired operating frequency region. The inputs and outputs are then chosen and are placed to couple with this mode.

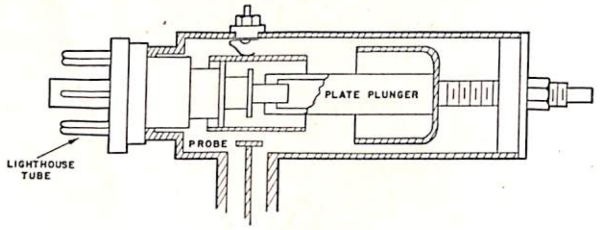
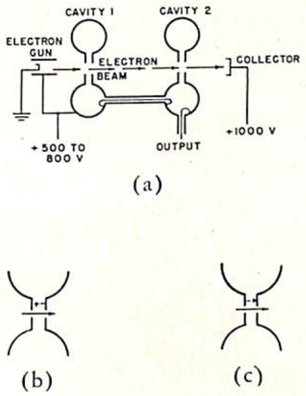


FIGURE 18—*Lighthouse tube in re-entrant cavity*

The loop type of coupling is desirable where a direct-current return path is needed, while a probe or dipole is useful where direct-current insulation between the cavity and feed line is required. The coupling efficiency of a loop will increase with size and may also be varied by changing the orientation of the loop, provided the rotation does not cause excitation of a new mode. The coupling efficiency of a probe will depend on its penetration into the cavity. In both of these cases, altering the coupling may change the tuning of the cavity.

LIGHTHOUSE TUBE

The "lighthouse tube" offers the best example of the successful stretching of triode oscillator techniques into the region above 1000 megacycles. As may be seen from figure 18, the name is derived from the appearance of the tube. The cathode, grid, and plate are parallel planes with extremely small spacing between them and are held in place by copper disks which extend through the glass envelope of the tube. Because of the small spacing between tube elements it has not been possible to build tubes with an average power output of more than a few watts, but it has been possible to obtain a peak-pulse output of over 1 kilowatt. The tube is "wired" to its circuit by placing metal cylinders against the disks, as shown in figure 18. These cylinders must be direct-current insulated from each other to permit the application of direct-current voltage as in normal triode applications. The cavities formed by the spaces between these cylinders are the tuned circuits, and feedback from plate to grid is accomplished by using a coupling loop or a small hole between the cavities. This oscillator has both tuned grid and tuned plate circuits, and the tuning is accomplished by sliding the tube in the cylinders to change their lengths. Conventional methods may be used for modulating the radio-frequency output of these tubes.



(a)

(b) (c)

FIGURE 19—*Klystron*

THE KLYSTRON

A quite different type of high-frequency oscillator for low-power applications is the klystron. Although klystrons were discussed in the literature before the war, a brief discussion will help in understanding the more recent developments. The present designs use cavity-type circuits; but at frequencies below 1000 megacycles, where cavities become too large to be convenient, it should be possible to use coils and capacitors for the tuned circuits. As shown in figure 19, a steady stream of electrons is focused into a beam by an electron gun similar to that used in a cathode-ray tube. Since the electron velocity is already appreciable by the time these electrons strike the working part of the tube, the distance traveled in one cycle will be much greater than in a triode where the electrons start with low velocity within the working region; hence, the difficulties due to time of flight become troublesome only at much higher frequencies than in a triode with the same spacing.

The stream of electrons from the gun in figure 19 is directed through two toroidal cavities and finally reaches a collector. The cavities, which are normally of similar construction, are designed to oscillate in a mode which causes an alternating electric field to exist between the entrance and exit holes for the electron beam, as indicated in figure 19(b) and (c). Now, assuming cavity 1 to have been set in oscillation by some means such as the turning-on of the tube (this assumption of already existent oscillations is necessary to visualize the behavior of any oscillator), let us see what happens to the electrons passing through it. Electrons passing through the cavity while the far side is positive, as in figure 19(b), will be speeded up, while those passing through a half-cycle later will find the far side negative, as in figure 19(c), and will be slowed down. Thus, for alternate half cycles the electrons are speeded up and slowed down. After the electron stream has gone beyond cavity 1 the faster electrons will begin to overtake the slower ones, thereby causing a bunching in much the same way a group of fast cars which has been held up by a traffic light overtakes a group of slower cars held up by the previous turning of the light. This traffic concentration obviously occurs some distance beyond the light. The region at which the electron traffic jam occurs is fairly sharp; and because the amount of speeding-up or slowing-down of the electrons varies with the phase of the oscillation, it can be shown that the electrons which passed through the cavity between the extreme voltage conditions will all tend to pile up at about the same place along the electron beam.

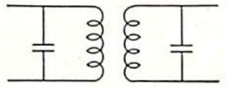


FIGURE 20—*Double-tuned circuit.*

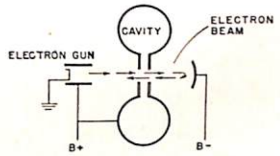


FIGURE 21—*Reflex klystron*

If cavity 2 is placed where this electron bunching occurs, this group of electrons will set up oscillations as it passes through the cavity by inducing charges on the walls. When the two cavities are tuned to identical frequencies the oscillations in cavity 2 will maintain a constant phase relationship with those in cavity 1, the phase having been established by the time the first group of electrons entered cavity 2. If we now return our attentions to cavity 1, we see that a steady stream of electrons is still entering and the oscillations in cavity 1 are continuing. Therefore, 1 cycle after the first group of electrons has passed, conditions are duplicated and are proper for forming a second bunch which will arrive at cavity 2 at the proper time to feed more energy to it. By drawing a few sketches of the bunched electrons crossing the cavity and remembering that the wall nearest the electron group will have positive charges induced on it, the reader may verify this statement and may also satisfy himself that the maximum power will be extracted from the electrons if their time within the cavity is a half cycle. It may also be seen that the field will be in a direction to slow down the electrons. The energy going into the electric oscillations has been obtained, therefore, by robbing the electrons of some of their kinetic energy.

The tube described so far will operate only so long as the accidental oscillations in cavity 1 continue. In order to insure that these oscillations continue, a small amount of energy from cavity 2 is fed back into cavity 1 by means of a short length of coaxial transmission line coupled by loops in the two cavities. The length of this line must obviously be chosen to maintain the proper phase relationship between the two cavities. Another effect of this coupling system is to tie the two circuits together so that they act as a double-tuned circuit similar to that shown in figure 20. As long as the two coupled cavities are each tuned for approximately the same frequency they will oscillate as a unit with a single-frequency output; and over small ranges the tuning of one cavity will then shift the resonant frequency of the system as a whole.

The collector beyond the second cavity in figure 19(a) is used to dispose of the electrons after they have served their purpose.

When the frequency of operation of the klystron is chosen, the design of the cavities and the separation between them can be fixed. In order to provide a reasonable tuning range the cavities may be made adjustable in size by making the walls of airtight metal bellows. After the two cavities have been adjusted to resonate at approximately the same frequency, the voltage used to accelerate the electrons from the gun is adjusted for maximum power output. Frequently, several resettings of the controls are required to obtain optimum performance and to make the tube oscillate over a reasonable range of frequencies.

Much of the difficulty in adjusting this type of klystron arises from the fact that there are two cavities which must be matched. A great simplification in operation can be made by eliminating one cavity. The "reflex klystron" uses the same cavity for bunching the electrons and for extracting power by reflecting the bunched electrons back through the cavity, as shown in figure 21.

In this device the electrons, on their way through the cavity from the gun, are speeded up or slowed down as in the two-cavity klystron. This process on the average requires no power, because half of the time electrons absorb power by being speeded up and the other half of the time give power to the cavity by being slowed down. After the electrons have passed through the cavity they are reflected by a negative voltage on the reflector, so that they return through the exit hole into the cavity. The reflector must be properly shaped to keep the electrons focused into a beam. The point at which these electrons turn around will depend on the voltage applied to the reflector; hence, the distance traversed outside of the cavity may be adjusted by changing this voltage. During the time these electrons are outside of the cavity the faster ones are catching up on the slower ones, as was previously discussed. Now, if the dimensions and voltages are properly adjusted, the electron bunches will start back through the cavity in the proper phase to increase the oscillations. When this condition occurs, the cavity will oscillate and power can be extracted. Since only one cavity is involved, oscillation will occur at the resonant frequency of the cavity when the voltage on the reflector is properly set. Hence, the frequency is primarily set by the cavity and the power output can be adjusted by the reflector voltage. If the exit hole of the cavity is large, a change in the reflector voltage will also cause a shift in frequency and may be used for tuning over a small range. Likewise, altering the cavity size will cause a change in power output. Reflex tubes are available in two types; one with a built-in cavity and the other with copper-disk seals similar to those in a lighthouse tube, to which an external cavity may be attached.

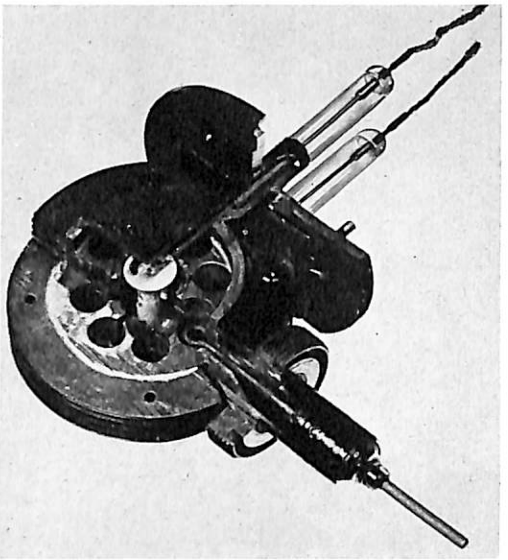


FIGURE 22—*Cutaway view of magnetron*

All klystron transmitters can be amplitude modulated by varying the current from the electron gun. Although the average power output is limited to a few watts, pulse peak power of a few kilowatts may be obtained from the larger tubes. It is interesting to note that the reflex klystrons which may be tuned by varying the voltage of the reflector are readily frequency modulated by applying the signal to the reflector.

MAGNETRONS

For high-power radar sets at frequencies above 1000 megacycles, the most successful tube is the magnetron. For the same frequencies at which a few kilowatts of pulse power may be obtained from a triode or klystron, a magnetron will give 2 or 3 megawatts. For example, at 3000 megacycles, tubes capable of giving over 1000 kilowatts have been in large-scale production for some time and tubes giving 2500 kilowatts are now being produced. The former will operate with an average power input of about 1200 watts and the latter at about twice this level. Since these tubes will not operate well as continuous-wave oscillators and cannot be modulated readily except by a square pulse of less than 5 microseconds duration, their use is largely limited to radar, pulse-communication systems, and other applications using pulse techniques. A somewhat different design of magnetron is built for continuous-wave use. The maximum output is about 10 kilowatts at 3000 megacycles, but here again modulation is difficult.

Although the magnetron was invented by Hull in 1921, it was not put to much practical use until early in the war when the British first investigated it as a pulsed transmitter. The "cavity magnetron" as used during the war is a split-anode type with resonant circuits built into the tube. Most of the British and American tubes have had eight or more anode segments with a resonant cavity between each segment. The Japanese used four-segment tubes in their 10-centimeter radar. Figure 22 shows the internal construction of an 8-cavity magnetron. The anode is the solid metal block into which the resonators are cut as slots and holes. The natural frequency is determined largely by the width and radial depth of these slots and to some extent by the axial length and the position of the ends of the tube. The space which is left between each end or lid of the tube and the block in which the slots are cut serves to act as a coupling cavity between the separate oscillators, and also provides space for the cathode and heater leads. The cathode lies along the axis at the center of the block and is usually an oxide-coated nickel tube enclosing a heater winding. The radio-frequency power is extracted by a coupling loop in one of the cavities and is brought out through a short coaxial line. The tube is normally operated with the anode at ground potential since this simplifies the problem of connecting the output to the remainder of the system.

For operation, the magnetron is placed between the poles of a magnet so that the field is parallel to the axis of the cathode. An electron leaving the cathode thus finds itself in a radial electric field produced by the cathode-anode potential and also in an axial magnetic field. The electric field tries to accelerate the electron toward the anode, while the magnetic field acts to make the electron circle back to the cathode. When the magnetic field and anode voltages are adjusted to make the tube oscillate these two counteracting effects are balanced, so that most of the electrons come close to the anode but do not quite strike it. Because of the complicated geometry and the effects of space charge on the electron paths, it has not been possible to work out a complete analysis of the operation of the magnetron.

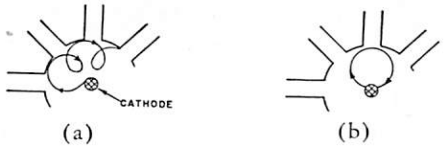


FIGURE 23—*Electron paths in magnetron*

It is certain, however, that the presence of the oscillating fields across the openings of the resonators causes the electron cloud to become bunched in the region close to the anode. It is also certain that this electron cloud rotates around the cathode at the correct rate for these electron groups to feed power into the circuit as they pass the resonator openings. The probable mechanism for the electron bunching is as follows: the magnetic field causes the electrons which miss the anode to return to the vicinity of the cathode. Since the sharpness of curvature of the path of an electron moving in a magnetic field is greater for slow than for fast electrons those electrons which have been slowed down by giving power to the oscillators will be bent around sharply and will miss the cathode, as shown in figure 23(a). Those which have neither gained nor lost energy should just touch the cathode, while those which have increased speed by gaining energy should strike the cathode, as in figure 23(b), and be captured. (That the latter action occurs is proved by the large amount of secondary electron emission from the cathode and by heating which may be sufficient to permit turning-off of the filament power in some tubes after oscillations start.) The net result of these changes in electron velocity is to remove those which passed a slot during one half cycle of oscillation of the resonator, while those which passed the slot a half cycle later remain to go through another loop, as shown in figure 23(a). This remaining group of electrons will feed energy into the next oscillator if it passes during the proper phase in the radio-frequency cycle. Since the first passage of the electrons gave no net energy to the resonator, it is obvious that the voltage and magnetic field must be adjusted to obtain this timing of the electrons if the tube is to oscillate.

Because the factors controlling efficiency, power output, and stability of magnetrons are only partially understood, successful designs at one frequency are often transferred to a different frequency by scaling. If all dimensions are scaled in proportion to the wave-length, the tube will have similar characteristics. The operating voltage and average power output will remain constant, but the magnetic field will vary inversely with the wave-length.

Some idea of the operating conditions may be obtained from Table I.

TABLE I

Wave-length in Centi-meters	Power Peak Pulse Output in Kilowatts	 Average Input in Watts	Per Cent Effi-ciency	Anode Voltage in Kilovolts	Gauss Magnetic Field
23	1000	2000	50	28	1800
10	1000	1200	50	28	2800
3	250	700	40	21	5000
1	50	100	22	14	7600

These values are near maximum output for particular tube types but may vary with the design of the tube and must be taken merely as an indication of what may be expected for the different frequency regions.

Most of the magnetrons now in use are "fixed tuned," i.e., the frequency is determined by the construction at the factory and is not controllable in the set. These tubes are tested and labeled to show the frequency region of operation, but individual tubes of a particular marking may differ by several megacycles. A definite preassigned frequency for each station cannot be made, therefore, without laborious tube selection. Recently, tunable tube designs have been worked out, one method being a movable diaphragm which changes the size of the space between the resonator block and the lid. Thermal expansion of the resonant cavities makes exact frequency control difficult, even with tunable tubes.

Another factor which makes operation on an exact frequency difficult is the frequency "pulling" which occurs when standing waves exist in the transmitting system. A change in phase and amplitude of a wave reflected back into the magnetron may cause a shift in frequency of the output. Under certain conditions this frequency change may alter the reflected-wave phase in the proper direction to change the frequency still further. When this happens there may be a frequency region in which the magnetron will not operate unless the reflected wave is changed by altering some other part of the radio-frequency system. The pulling may cause considerable trouble in systems where the reflected wave changes with antenna position. For example, in aircraft radar installations where the antenna must be housed in a streamlined plastic dome, the reflection from the plastic may vary with the direction of the antenna. When this happens the frequency of the transmitter varies with antenna orientation, making it difficult to keep the receiver tuned. The best cure is to reshape the antenna housing.

The frequency pulling can, however, be used as a method of frequency modulating a magnetron. If a resonant cavity is placed in the transmission line near the magnetron, the frequency of the transmitter may be varied by tuning this cavity. Voice modulation, for example, may be applied by making one side of the cavity a thin diaphragm which vibrates under the impact of sound waves, thereby changing the cavity dimensions and hence its resonant frequency. When a magnetron is tuned by this means, care must be taken to see that the standing waves do not cause voltage breakdown in the transmission line.

(Continued next month)

• • •

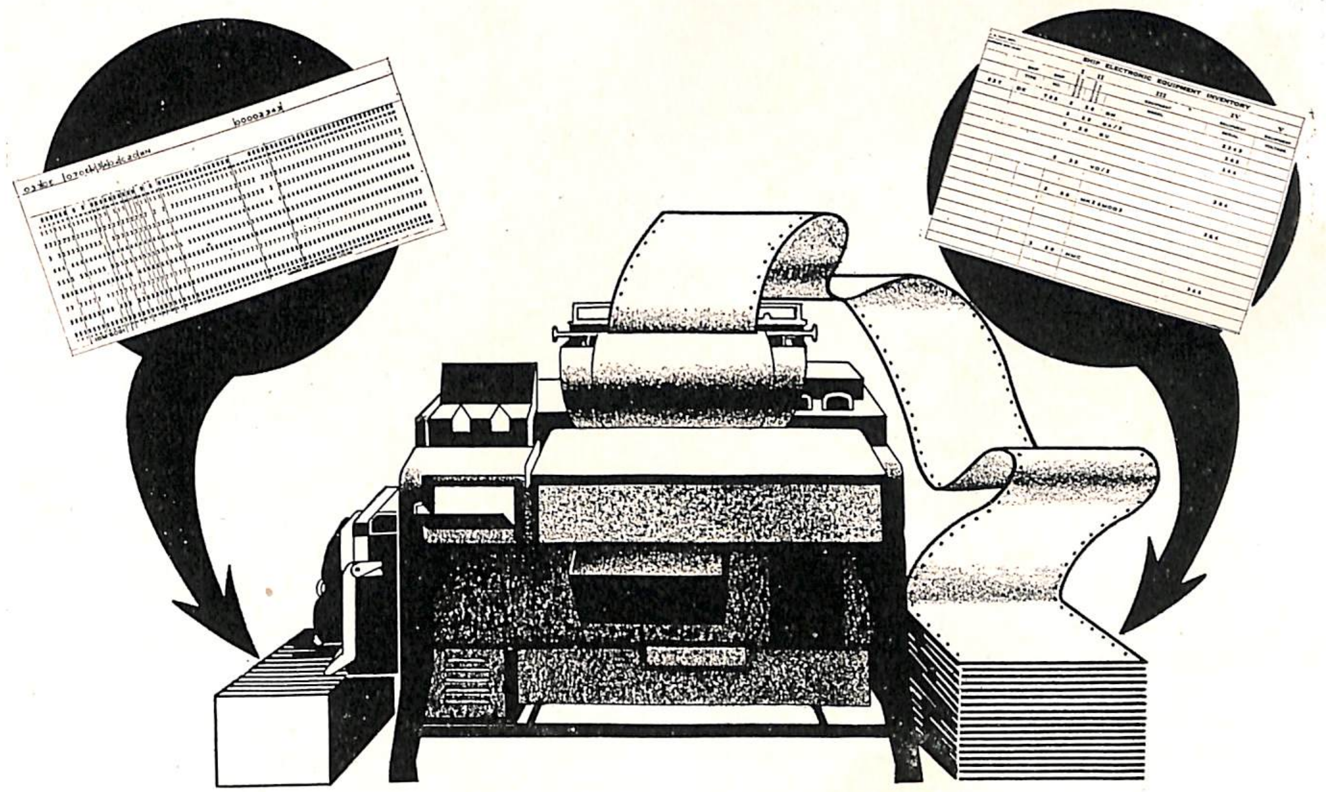
VJ RADAR REPEATER DAMAGE

The Bureau of Ships recently received reports of eight Model VJ Radar repeater installations on one vessel. Six of these reports indicated that the ranging mechanism (helipot and synchro) in the indicator had been misaligned or damaged when the range transmitting synchro was removed to gain access to the indicator's terminal boards during installation.

The proper method of gaining access to the terminal boards in the indicator is to disconnect and remove the video amplifier chassis. This unit is held in place by thumb screws. The ranging mechanism should not be removed except when the unit serial number is below #400, and the indicator is installed in CIC and connected to the target designation system. When installed in this manner it will be necessary to re-zero the range transmitting synchro electrically at 10,000 yards.

The first 400 equipments were supplied with range transmitting synchros electrically zeroed at 0 yards. Beginning with serial #401, the range transmitting synchros will be electrically zeroed at 10,000 yards when shipped from the factory.

Your Ship's Electronic Inventory Report in the making



Operator punches a card for each equipment listed on ship's inventory—the card is then placed in the machine which prints the complete inventory in report form—each card is coded and punched and contains the Ship type, Ship number, Equipment type, Equipment model, Equipment serial, Equipment Navy type number, Equipment location aboard ship, and the Equipment voltage. The finished product is a complete up-to-date inventory report—copies of the inventory are mailed to the ship service force, type commander home yard and the installation and procurement sections in the bureau.

■ Every ship in the fleet will receive a printed list of the electronic equipments which the Bureau believes to be aboard that ship. This list was compiled after expending considerable effort in studying all available information including ship's inspection and installation records. By the time you read this, you probably will have received a copy of your Ship Electronics Inventory, together with a full set of instructions on the new business-machine accounting system.

These new Electronic Inventory Reports serve as a system with which BuShips, C. N. O., Service Force and other activities can keep their eyes on 200,000 pieces of equipment as effectively as they might 200 pieces. The fleet has a vital interest in a system which so affects every piece of electronic equipment installed today or to be installed in the future. Such interest by the fleet is essential to the success of the system, as a guarantee that the US Navy will, electronically, always be the best equipped navy in the world. To adopt a system that will provide accurate information, be readily available, and which will ultimately simplify and reduce the number of reports required from ships, the Chief of Naval Operations has vested the entire responsibility for such reports with the Bureau of Ships. The bureau appreciates the cooperation given by C. N. O. and Service-Force personnel in the establishment of this system and the elimination of duplicate ship reports to their respective organizations. It is not an easy task to set up this new system. It was necessary to check all available data on ship installations, and to establish the nomenclature and codes used to determine equipment locations.

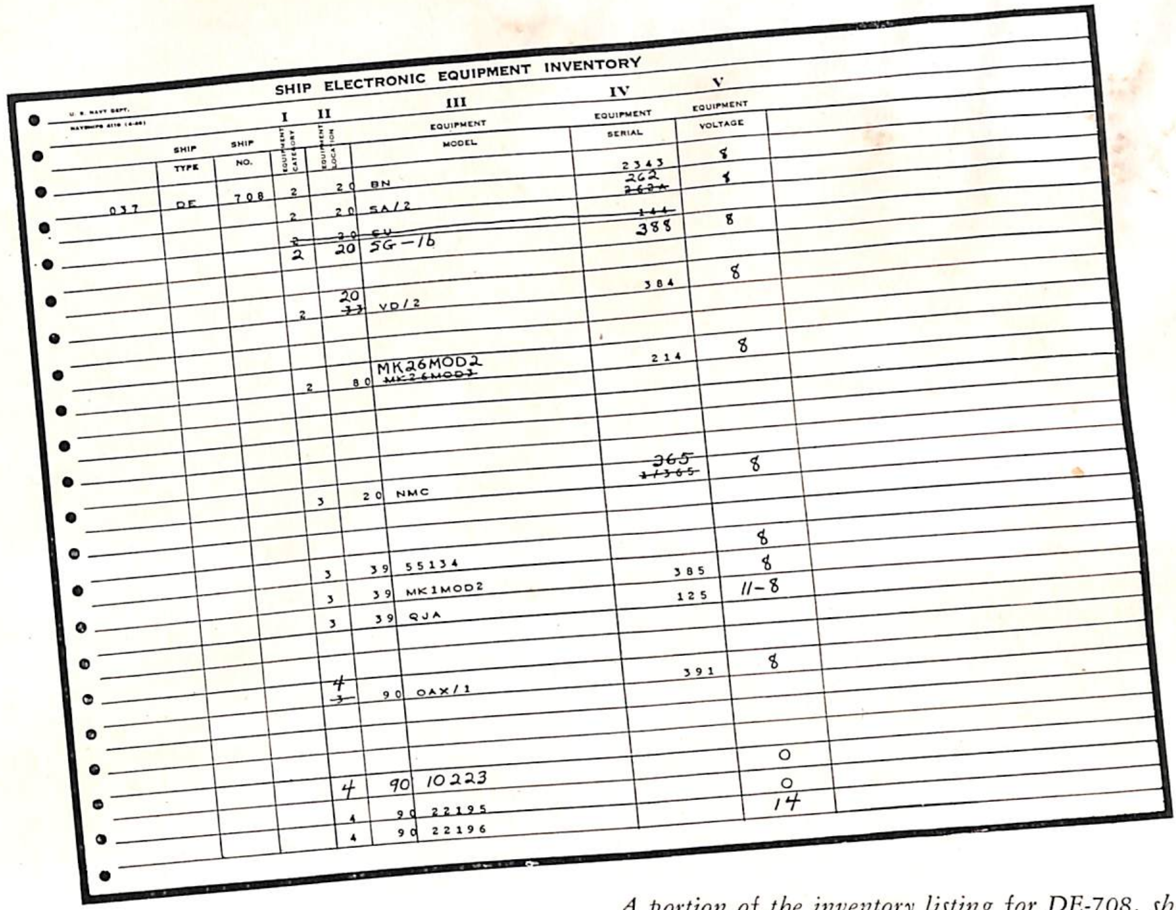
This machine automatically takes information contained in the punched cards and converts it into a complete inventory of all electronic equipments on board each ship.

It was also necessary to endeavor to anticipate all pitfalls, difficulties, future ship and equipment improvements, etc.

The June issue of ELECTRON told how the electronic equipment inventory simultaneously reduces the number of inventories a ship must submit, and yet enables the bureau to serve the fleet more efficiently than ever before. It is planned this month to give a more detailed view of the inner mechanics of this new system. Ships can see exactly how the inventories they mail to the bureau today will be used to equip the fleet of tomorrow, and to maintain the fleet of today.

The bureau must serve the fleet in two distinct ways. It must design, procure, and distribute equipments so that they will be available where needed. The bureau must also determine what equipments are needed on each class of ship, give proper priority by ship type to installations of new and expensive equipments, draw up necessary installation plans, and determine adequate weight and moment compensation for equipments. For convenience we will speak of these two functions of the bureau in general terms as procurement and installation. The installation section of the bureau must complete information regarding what should be and what is installed on each ship in the navy, listed ship by ship. The procurement section of the bureau must have the same information in an entirely different form. They are not concerned with what equipments are in a particular ship, but want to know only how many models XYZ equipments there are in the fleet and how many are in certain classes of vessels, or how many are in active, reserve, or inactive ships.

The problem of obtaining this second type of information is quite complex and exceedingly cumbersome. The peacetime navy will consist of approximately 4000 vessels active, inactive and reserve. If one wants to know the total quantity installed of each of 1000 models of equipments, he must go through 4000 separate inventories, counting each equipment 1000 times. This is equivalent to scanning approximately 16,000,000 pages, assuming that an average ship inventory will cover four pages. The problem is further complicated by the fact that a straight addition is inadequate. It is necessary first to go through each inventory and checking whether installed equipments are adequate substitutes for the equipments considered to be the newest. This is necessary because equipments which are considered adequate substitutes on smaller or inactive ships may be considered inadequate for larger or active ships. Obviously, tabulating information of this sort in the bureau by hand is inefficient and likely to require so much time that it will possibly suffer in accuracy and value.



SHIP ELECTRONIC EQUIPMENT INVENTORY

U. S. NAVY DEPT.
NAVSHIPS 4110 (4-46)

	SHIP TYPE	SHIP NO.	I EQUIPMENT CATEGORY	II EQUIPMENT LOCATION	III EQUIPMENT MODEL	IV EQUIPMENT SERIAL	V EQUIPMENT VOLTAGE
037	DE	708	2	20	BN	2343	8
			2	20	SA/2	262 ~~262A~~	8
			~~2~~ 2	~~20~~ 20	~~SU~~ SG-1b	~~144~~ 388	8
			2	20 ~~33~~	VD/2	384	8
			2	80	MK26MOD2 ~~MK26MOD1~~	214	8
			3	20	NMC	365 ~~11365~~	8
							8
			3	39	55134	385	8
			3	39	MK1MOD2	125	11-8
			3	39	QJA		
			4 ~~3~~	90	OAX/1	391	8
							0
			4	90	10223		0
			4	90	22195		14
			4	90	22196		

A portion of the inventory listing for DE-708, showing the manner in which the ship should enter corrections. Note the line through the SU radar and the new entry beneath it. This indicates that the ship no longer has an SU radar but now has an SG-1B radar, serial #388, operating on 115-volts single phase, and located in C.I.C. The remainder of the markings show a change in location, a correction to a model number, and the addition of a new piece of test equipment. The numbers used under "location", "voltage" are part of a code which is fully explained in the instructions for this new system, which have been sent to all ships.

In the new system, a punch is used to make identifying holes in a separate punch card for each equipment on board every ship. These cards are then placed in a tabulating machine which automatically prints the information previously punched in the cards. The result is an inventory of the equipment which the bureau believes to be aboard that particular ship.

THE FLEET CAN HELP

Full cooperation is expected from the fleet in correcting and completing the data on these listings. They were collected under the stress of wartime from numerous and diversified inspection systems, and it is known that they will often be found inaccurate or incomplete. But they are the best the bureau has, and the bureau must have accurate and complete knowledge of existing installations in order to properly serve the fleet.

When the corrected listings have been returned to the bureau the punch cards will be corrected to agree with the ship's corrections. The bureau will keep an accurate file of all existing installations, kept up to date through the annual inventories received from ships and the departure inspection inventories received from naval shipyards after each overhaul. Whenever any electronic equipments are installed or removed from a ship the bureau should be notified at once. Upon receipt of this information a new listing will be prepared and copies sent to the ship and other cognizant activities. The correct listing will enable the bureau to procure replacement equipment, set up an allowance for necessary spare parts and make all necessary preparations in sufficient time to insure that proper repairs and alterations are accomplished during scheduled overhauls.

WHAT THE MACHINES WILL DO

The punch-card business-machine system will be capable of supplying, almost instantaneously, information which formerly required months to obtain. A few of the many tricks which the business machines can do with punch-cards will be explained. The machine can:
1—print an inventory of what is on board a given ship,
2—print an allowance list of what should be on board

that ship, 3—compare these two lists mechanically and print a list of what equipments still must be installed to bring the ship up to allowance, 4—print another list of what obsolete equipments are aboard and should be removed, and 5—take those punch cards used to print the list of equipments required for all of the ships in the Navy, reshuffle them, and print a list of requirements by equipment rather than by ship; i.e., listing all ships requiring a model XYZ equipment and giving total quantities required for all active ships, for certain classes, or for the entire fleet.

The ship electronics inventory report is, as the name implies, an inventory of installed electronic equipments listed according to ships. A separate page (or group of pages) is printed for each ship in the navy. Each listing consists of a tabulation of the equipments presently installed in a vessel and should, in general, be identical in content with the latest inventory of the ship's electronic equipment received from the ship or from its last overhauling activity.

A complete, corrected copy of this report will be mailed to the ship to which it pertains. The ship will thereby know what equipments the bureau believes to be on board and where they are located. The ship will then be capable of checking the bureau's records and insuring that they are correct. This feature of the system will prevent misunderstandings arising in correspondence regarding future alterations, and will serve as insurance that no important installations are overlooked during overhaul. Moreover, it will aid the ship in making its annual inventory report (Ship's characteristic card) by supplying an "on board" list which can be readily checked for accuracy.

ACTION IS NEEDED NOW

To insure the electronic effectiveness of the fleet, the individual ship's cooperation in the establishment and maintenance of its current inventory is necessary. This can be accomplished in two ways. The business machine tabulations are now being mailed to ships for verification and correction. Ships should ascertain that these listings are corrected by competent personnel, that they are complete in every respect, and that the instructions accompanying the inventory are followed carefully. The business machines are entirely mechanical and can total equipments only if they are always referred to by the same standard nomenclature. The fleet can again cooperate by preparing accurate annual inventories for submission with the ship's characteristic card next January, and by cooperating fully with naval shipyard inspectors when they make post-overhaul inspections preparatory to submitting departure inventories to the bureau. Finally, whenever a change of installation occurs it should be reported immediately, following the inventory form, listing equipment added and equipment removed.

ARE YOU AVAILABLE?

Unfortunately, there has been some confusion in the past in the Naval service about the exact meaning of the different terms associated with the availability of Naval vessels. In order to insure the proper use of the terms "availability", "restricted availability", "technical availability", "regular overhaul", "voyage repairs" and "emergency availability", as used in connection with work on Naval vessels, these expressions have been defined recently by CNO Letter, serial 3941-P-414, dated June 1946.

Availability: The uninterrupted period of time assigned by competent authority to a vessel at a naval shipyard or other repair facility for the accomplishment of work.

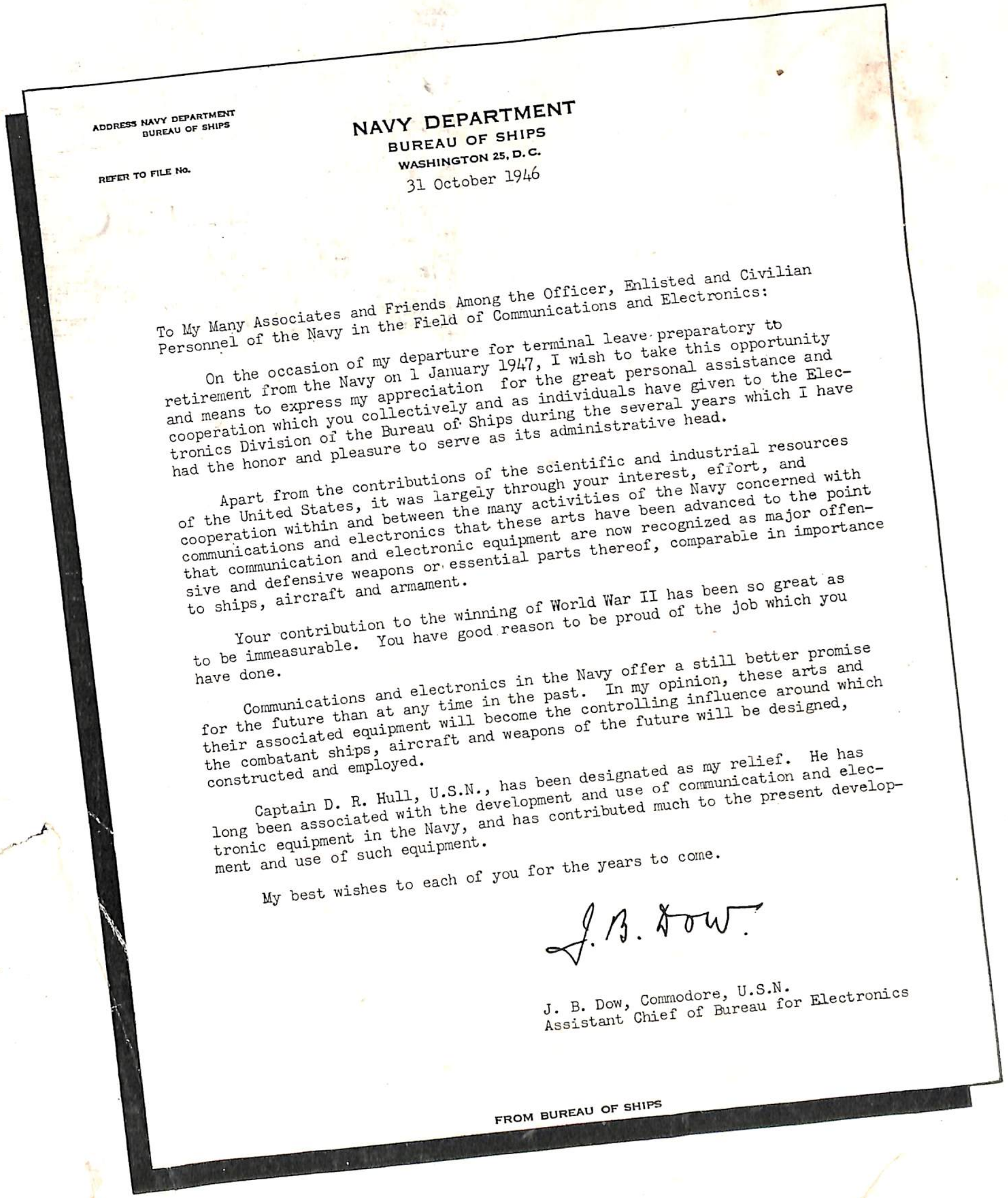
Restricted availability: The availability assigned for the accomplishment of work.

Technical availability: Assigned for the purpose of employing the manufacturing or shop facilities of a naval shipyard or repair facility for the accomplishment of specific work when the ship is not physically present.

Regular overhaul: Periodic overhauls scheduled by competent authority for the accomplishment of repairs and alterations that have been properly approved and authorized. Regular overhauls are normally scheduled well in advance, in accordance with an established cycle and for predetermined periods of time at naval shipyards or other shore-based repair facilities.

Voyage repairs: Covers emergency work necessary to enable a vessel to continue on its mission and which can be accomplished without requiring a change in the vessel's operating schedule or the general steaming notice in effect. Voyage repairs may be undertaken by repair activities without formal assignment of availability provided funds are available to accomplish this work.

Emergency availability: This expression is not authorized and its use is to be discontinued.



ADDRESS NAVY DEPARTMENT
BUREAU OF SHIPS

REFER TO FILE No.

NAVY DEPARTMENT
BUREAU OF SHIPS
WASHINGTON 25, D. C.

31 October 1946

To My Many Associates and Friends Among the Officer, Enlisted and Civilian Personnel of the Navy in the Field of Communications and Electronics:

On the occasion of my departure for terminal leave preparatory to retirement from the Navy on 1 January 1947, I wish to take this opportunity and means to express my appreciation for the great personal assistance and cooperation which you collectively and as individuals have given to the Electronics Division of the Bureau of Ships during the several years which I have had the honor and pleasure to serve as its administrative head.

Apart from the contributions of the scientific and industrial resources of the United States, it was largely through your interest, effort, and cooperation within and between the many activities of the Navy concerned with communications and electronics that these arts have been advanced to the point that communication and electronic equipment are now recognized as major offensive and defensive weapons or essential parts thereof, comparable in importance to ships, aircraft and armament.

Your contribution to the winning of World War II has been so great as to be immeasurable. You have good reason to be proud of the job which you have done.

Communications and electronics in the Navy offer a still better promise for the future than at any time in the past. In my opinion, these arts and their associated equipment will become the controlling influence around which the combatant ships, aircraft and weapons of the future will be designed, constructed and employed.

Captain D. R. Hull, U.S.N., has been designated as my relief. He has long been associated with the development and use of communication and electronic equipment in the Navy, and has contributed much to the present development and use of such equipment.

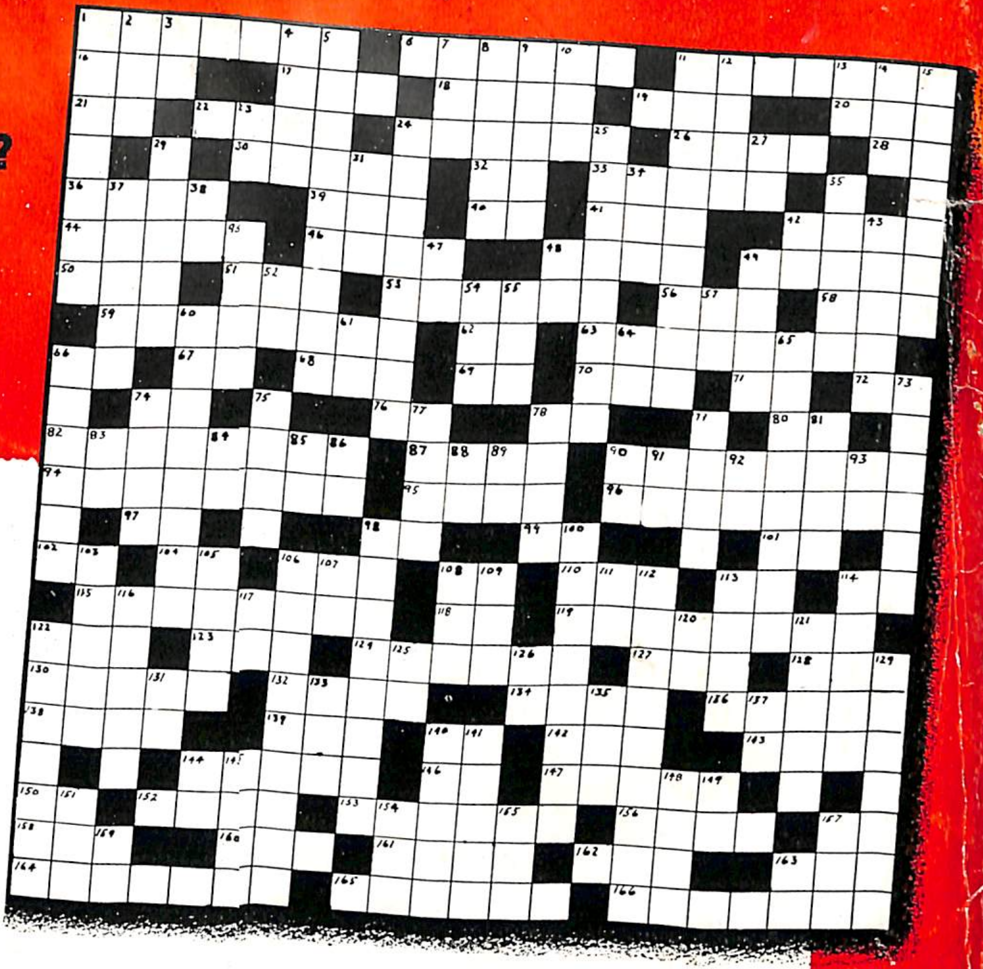
My best wishes to each of you for the years to come.

J. B. Dow.

J. B. Dow, Commodore, U.S.N.
Assistant Chief of Bureau for Electronics

FROM BUREAU OF SHIPS

HOW'S YOUR ELECTRONIC IQ?



HORIZONTAL

1 Electronic emitter
6 Electronic gate
11 Type of vacuum tube
16 Employ
17 Teletype monitor
18 We need more of these
19 Gal's name
20 Wire measure
21 Lead (chemical symbol)
22 Powdered rock
24 Proportions allotted
26 God of love
28 Myself
30 Rested
32 Bone
33 Antenna passage
36 Horses' chow
39 Neither
40 Same guy as 28 (horizontal)
41 Lamb's papa
42 Lacking firmness
44 Merge
46 Kind of duck
48 Bristle
49 Sculler
50 The sun
51 Corn comes in these
53 Bomb-sight
56 Pedal digit
58 Siamese racial stock
59 Procrastinating
62 Gold (chemical symbol)
63 Facility of speech
66 Voice recorder (Navy model)
67 End of radio message
68 Radio link
69 Aircraft homing beacon
70 Muscle spasm
71 Atop
72 Obsolete shipboard transmitter
76 Printer's measure
78 Magnetic curve
80 Comparative ending
82 Rough fix
87 A mechanical engineering society
90 Leads carrying no voltage
94 Loud voiced persons
95 Transfer a liquid
96 Defamed
97 Master of arts
98 New England state (abbr.)
99 Mutual conductance
101 Impersonal pronoun
102 Bone
104 Transmission line
106 Ocean
108 Latest type of broadcasting
110 Literary collection
113 Obsolete aircraft transmitter
114 Carrier-based search radar
115 Supplicant
118 Tall corn state (abbr.)
119 Sweet scented
122 Metric unit of area
123 Electrically charged atom
124 South American rodent
127 Type of directive antenna
128 Exist
130 Smoke (south of the border)
132 Irishman
134 Italian volcano
136 Pertaining to a node
138 Obsolete motor cars
139 Lighted
140 Heavy cruiser
142 Attila was one of these
143 Fully developed
144 What you call a chick in Paris
146 Either
147 Aquatic mammal
150 Light cruiser
152 Units of length
153 Unexclusive
156 Capable
157 Ancient vacuum tube transmitter
158 Air (combining form)
160 Decay
161 What you made to 144 (horizontal)
162 Past
163 Nip cent
164 Uncharged particle
165 These are handy in auto or radio stations
166 One who goes in

VERTICAL

1 Containing copper
2 Airborne search radar
3 Tellurium (chemical symbol)
4 Child's toy
5 Cam
7 Humor
8 Colloquialism
9 Taut
10 Feline
11 Air-operated
12 Merit
13 What one ham calls another
14 Feeble
15 Electricity (combining form)
23 Like
24 Choke
25 Power
27 All right
29 Steps over a fence
31 American poet
34 Rodent
35 Wails
37 Positive pole
38 Foggiest city in California
42 Thus
43 Banquet
45 Interval of time
47 Behold
48 Rectifier (chemical symbol)
49 City in Nevada
52 Champagne
54 Beam
55 Owing
57 Obsolete transmitter test equipment
60 Make of thin layers
61 Painted on wings of all commercial aircraft
64 Chinese weight
65 Cleaning solvent
66 Magician's command
73 Knowledge
74 Article
75 Jail
77 Back of neck
78 Mass of ice
79 Void
81 Rave
83 A submarine radar
84 Chalk marks on an empty acetylene cylinder
85 A switching tube
86 Unit of quantity of electricity (electrostatic system)
88 Small craft search radar
89 Amplification factor
90 Sonic depth finder
91 Aircraft emergency power supply
92 Type of palm tree
93 French article
98 Powerfully attractive
100 Long race
103 Pouring gate in mold
105 Den
106 One card of a suit
107 Half 'em
108 Suitable
109 UHF transceiver
111 Northeast
112 Benefit
113 Narrow valley
114 Narrow piece
116 Citrus fruit
117 Accomplish
120 Receiver test set
121 Opposite of zenith
122 Native of Dark Continent
125 Modulating equipment (RCM)
126 That is (abbr.)
129 Fastidious
131 Like
133 Atmosphere
135 Hard shelled fruit
137 Either
140 Punctuation mark
141 Protection
144 Cerium (chemical symbol)
145 Brave warrior
148 Black
149 Obsolete receiving equipment
151 Opposite of weather
154 Radar test equipment
155 Native metal
157 Number
159 Aircraft receiving equipment
163 Search radar