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AN ELECTRONICALLY-LOBED TRACKING AND GUIDING RADAR

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NRL REPORT NO. R-3116

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AN ELECTRONICALLY-LOBED TRACKING AND GUIDING RADAR

by

Owen F. Foin, Jr. and Philip J. Allen

June 1947

Problem No. 36R05-01

Approved by:

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ABSTRACT

An X-band automatic tracking and guiding radar employing a new electronic-lobing technique is described. While offering attractive advantages in simplicity, stability, accuracy, and immunity to jamming, the system is adaptable to aperiodic operation, and provides wide latitude in the choice of lobing rates, including pulse-to-pulse lobing. The lobing system and the special units are briefly described. Proposals for modifications of the system are discussed.

This is an interim report on this problem; work is continuing.

AN ELECTRONICALLY-LOBED TRACKING AND GUIDING RADAR

INTRODUCTION

Two undesirable limitations are imposed on conventional radar systems which scan or lobe mechanically. First, there is the inherent periodicity of mechanical systems, and second, the practical restriction to low lobing rates. The former lends the radar system readily susceptible to synchronized jamming and consequent erroneous angle indications; the latter limits the rapidity with which data may be obtained, while both limitations invite errors from signal modulation. The subject automatic radar system, employing new electronic techniques for receiver lobe-switching, removes these limitations. Since the lobing process in this system is completely electronic, not only is pulse-to-pulse lobing made possible, but synchronization of circuits also allows lobing at a rate which is some sub-multiple of the pulse repetition frequency (PRF), and further permits aperiodic keying of the transmitter. Thus the system lends itself to applications involving the transmission of information by pulse-time or pulse-frequency modulation, while simultaneously performing as a fully automatic tracking radar.

One of the principal weaknesses of fire-control radar systems is the error introduced by modulation of the echo signal independent of the scanning or lobing process.* With low-frequency lobing and periodic keying of the transmitter, false angle error indications frequently arise from low-frequency beats developing between the lobing frequency and any low-frequency modulation component in the returning echo. This modulation may originate from such causes as fading and propeller modulation. Removing the lobing rate from this region by increasing its frequency to perhaps hundreds of cycles per second averts these low-frequency beats, while further nullifying effect may be gained by aperiodic keying of the transmitter to avoid the production of any regular beat frequencies. To attain these advantages, the system to be described departs from the conventional mechanically-lobed system to a newly developed technique of electronic lobing.

The High Speed Lobing Project at the Naval Research Laboratory was initiated in July 1943 as a problem to develop a fully automatic tracking radar of good accuracy for fire-control applications. The system was to embody a number of features not found in existing radars, but in particular it was to be capable of high-speed lobing. It was concluded that a practical mechanical lobing device could not be made to meet the switching requirements, and that efforts should be directed toward the development of an electronic switching device. Preliminary tests with early electronic gas switchtubes in January 1945 indicated that the system was promising, but that the available devices for electronic lobing were unsatisfactory due principally to incurable instability. In 1946 earlier approaches were abandoned and a new approach to the development of electronic

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* Page, R. M., NRL Report RA 3A 222A, "Accurate Angle Tracking by Radar," 28 December 1944 (Confidential)

switching devices was inaugurated as a result of a report by Kê and Smullen.† By the end of April 1946 this action had resulted in successful electronic lobing with switchtubes that were simple to use and quite stable in operation. Further development led to the Type X7047, a combination TR and gas attenuator tube for X-band switching.‡ Utilizing this tube as a wave guide switch, a new radar system, automatic in range and train, was placed in operation on 5 November 1946, and on 3 December 1946, a completely automatic high-speed-lobing radar system was successfully demonstrated.

Figure 1 is a simplified block diagram of the present sequential lobing system, while the equipment at the operating position is shown in Figure 2.

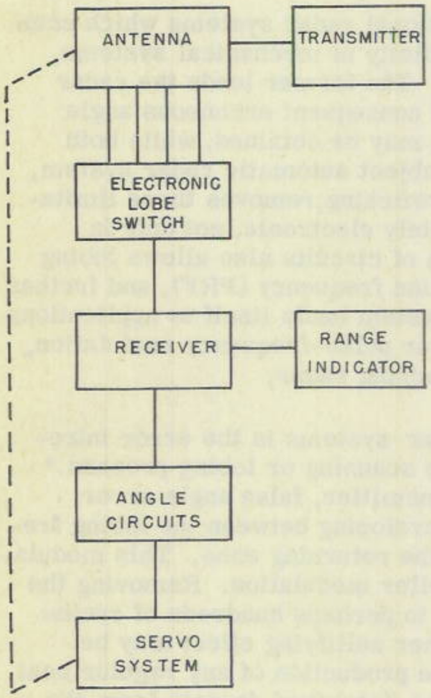

Fig. 1 - Simplified Block Diagram of Sequential Lobing System

Fig. 2 - Radar Console and Equipment at Operating Position

It is this operating system, now undergoing tracking tests at the Naval Research Laboratory, which is to be described, while planned modifications of the system will be discussed under "Proposals".

All lobing is done by shifting the effective receiving antenna pattern, while the transmitter beam retains a fixed position along the axis of the antenna. By means of four

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† Kê, T. S. and L. D. Smullen, MIT Radiation Laboratory Report No. 841, " A Low Power X-Band R-F Gas Switch," October 1945 (Restricted)

‡ Hastings, A. E., NRL Report R-3074, "An X-Band Electronic Attenuator, Switch and TR Tube," March 1947 (Confidential)

Type X7047 attenuator tubes, the input of the receiver is electronically switched from one wave-guide feed to another to sample energy in the different lobes. Lobing rates of 250 to 1000 cps are currently being used, while work is under way to extend the range down to 30 cps for test purposes. Angle-error information is obtained by comparing, at highest video level, the energies received from the target in the two lobes of each plane. A difference in signal amplitudes causes a d-c error voltage to be developed in the angle circuits which is then used to control the antenna servo mechanism for automatic tracking.

THE ANTENNA AND LOBING SYSTEM

The antenna consists of a four-foot paraboloid reflector, and a multiple-polyrod wave-guide feed located at the 45-inch focal position. The transmitter, a portion of the receiver, and the wave-guide switching system are located behind the reflector, and the whole assembly is suspended in the yoke of a modified navy searchlight mount. Figures 3 and 4 show the antenna mount which is being used in present tests.

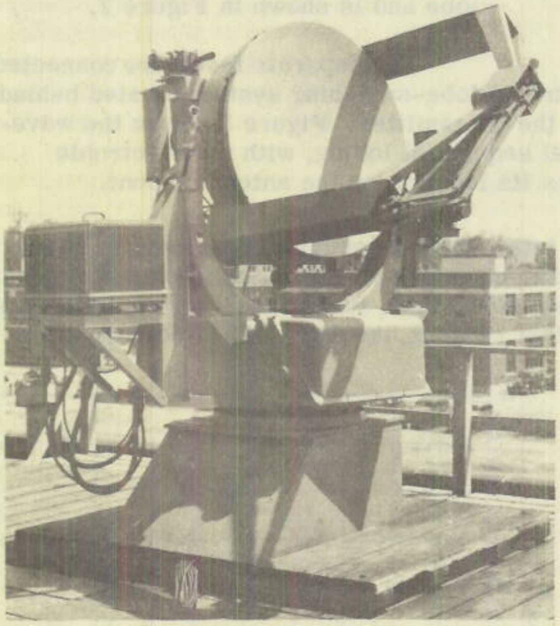

Fig. 3 - Antenna Mount, Front View

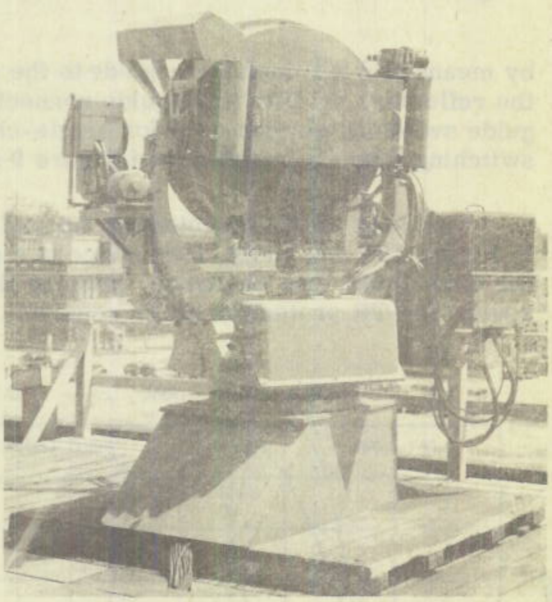

Fig. 4 - Antenna Mount, Rear View

The five-guide polyrod feed assembly, which is supported at the focal point of the reflector, comprises a central transmitting feed located on the axis of the reflector at the focal point, and four similar receiving feeds arranged about the transmitting feed. A displacement of one of the feeds from the axis of the reflector results in a displacement of the secondary pattern from the axis of the antenna. This characteristic is utilized to form the four off-axis receiving lobes.

The five feeds are grouped and oriented as shown in Figure 5, this arrangement bringing the centers of the feeds as close as physically possible to the axis of the reflector. This condition is important, since for a chosen lobe displacement, a greater feed separation would require a longer focal distance, which would further complicate

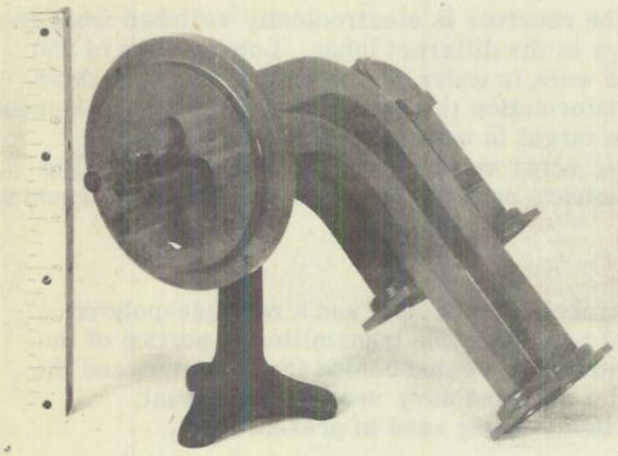

Fig. 5 - Five-Lobe Polyrod Antenna Feed

the feed and its support. The feed assembly is mounted, as shown, at a 45-degree angle (resulting in 45-degree polarization) so that the axes of the two pairs of receiving feeds will lie in vertical and horizontal planes.

The secondary pattern of this antenna in one plane is illustrated by the theoretical pattern of Figure 6. This shows the relationship between right and left receiving lobes and the transmitting lobe. The resultant two-way pattern is the product of each receiving lobe with the transmitter lobe and is shown in Figure 7.

The separate feeds are connected by means of $\frac{1}{2}$ x 1-inch wave-guide to the electronic lobe-switching system located behind the reflector. A fifth wave guide connects to the transmitter. Figure 8 shows the wave-guide switching section used for single-channel sequential lobing, with the electronic switching tubes in position, and Figure 9 shows its location on the antenna mount.

The Type X7047 combination TR and gas interaction-attenuator tube used is shown in Figure 10. Basically, this device is a gas-filled tunable cavity which is placed across the wave guide. One electrode, entering the side of the tube, functions as a keep-alive ion source for TR protection of the receiver. In this respect, the Type X7047 performs the

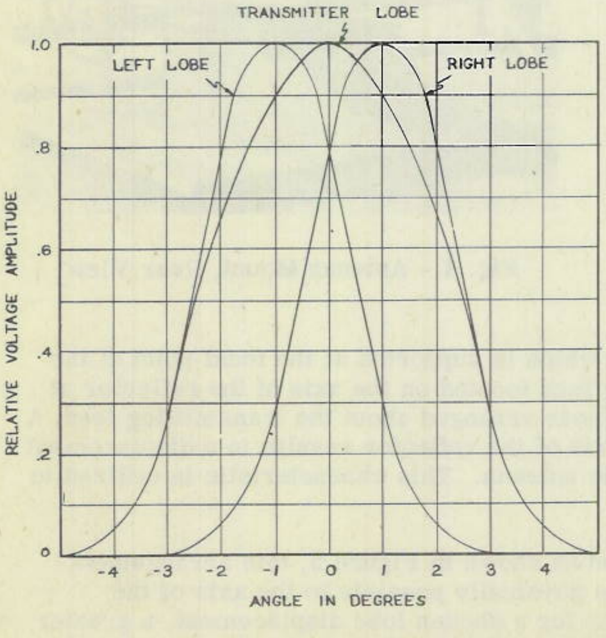

Fig. 6 - Theoretical One-Way Antenna Pattern

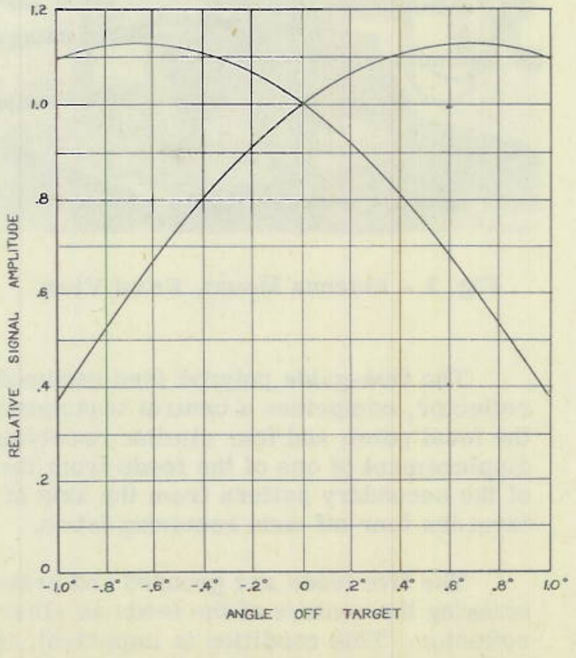

Fig. 7 - Resultant Two-Way Antenna Pattern

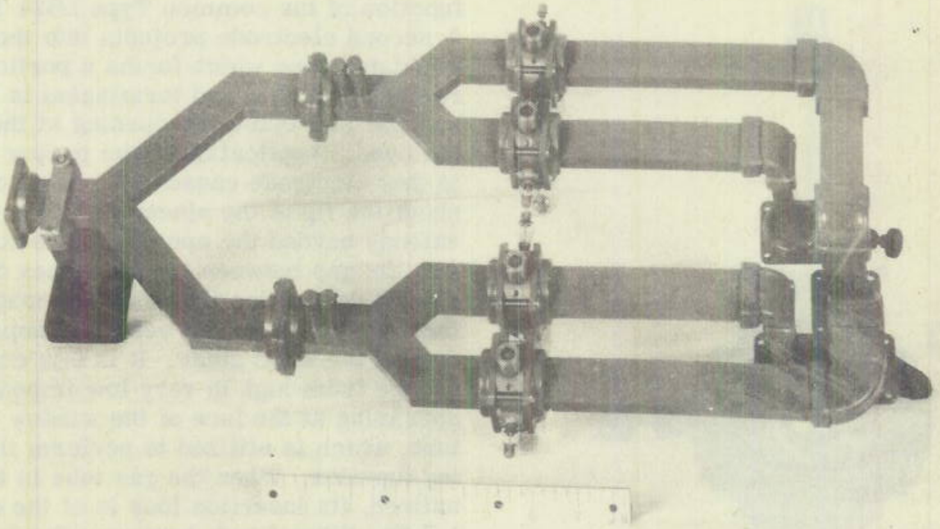

Fig. 8 - Wave-Guide Electronic Switching Section

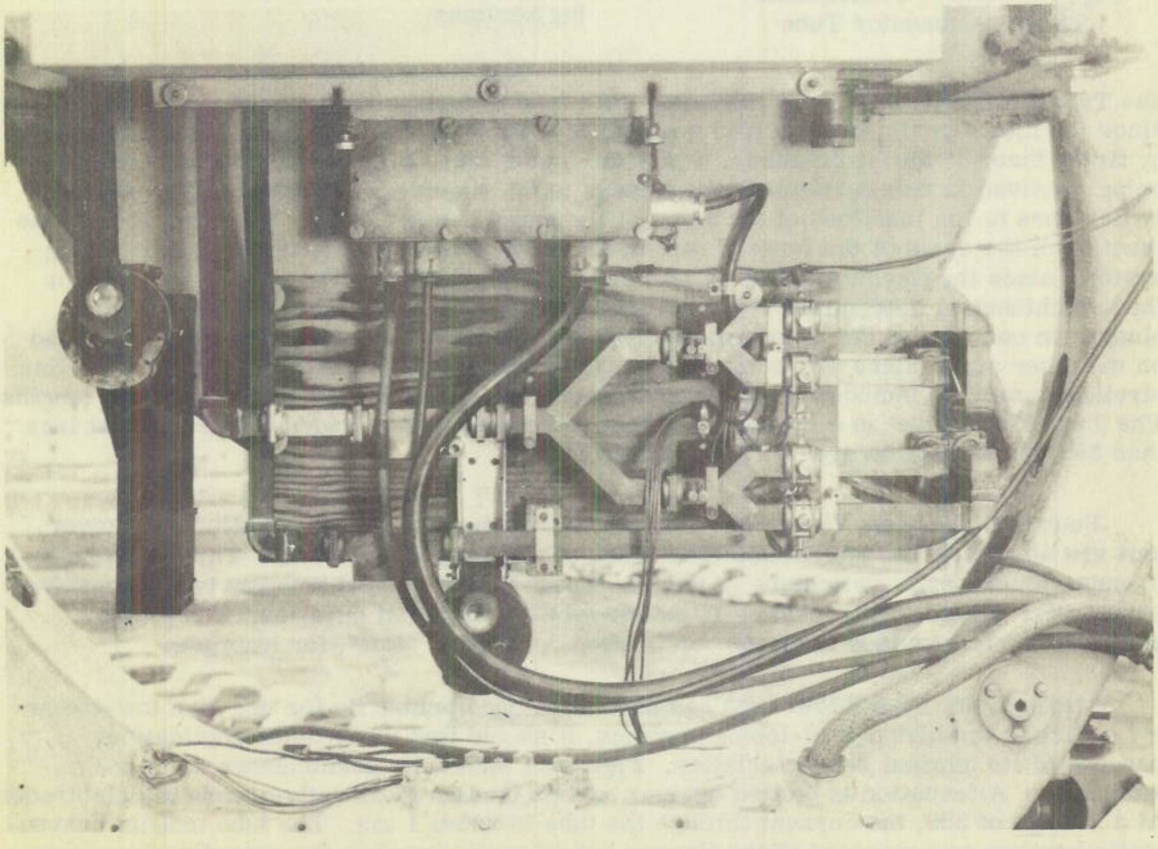

Fig. 9 - Wave-Guide Switching Section Mounted in Position

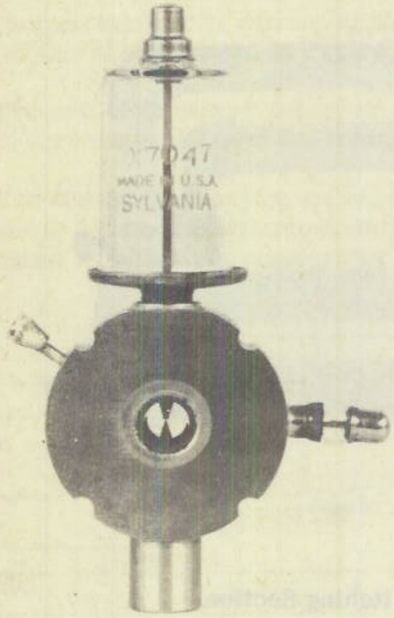

Fig. 10 - X7047 Combination TR and Attenuator Tube

function of the common Type 1B24 TR tube. A second electrode projects into the hollow truncated cone which forms a portion of the reentrant cavity, and terminates in a cathodic surface just below the opening at the tip of the cone. Application of the proper voltage to this electrode causes ionization of the gas about the tip of the electrode. This plasma extends beyond the opening in the cone and into the gap between the two cones of the cavity, destroying the resonant properties of the tube and placing a very low impedance across the wave guide. It is this controllable change from high to very low impedance, appearing at the face of the window of the tube, which is utilized to perform the switching function. When the gas tube is tuned and unfired, its insertion loss is of the order of 1.5 db. When fired, however, the device can offer attenuations of the order of 35 db. In the application being described, the tube acts both as an attenuator device and as a wave-guide "shorting" device in the Y switching sections.

The combination of wave-guide Y's and the Type X7047 tubes permits switching each feed in turn to the input of the receiver. Since the lobe signals are received sequentially, three of the wave guides are blocked off by firing three of the switchtubes, while the fourth tube, unfired, allows the r-f energy being received in that particular lobe to pass to the receiver. The distances from the switchtubes to the junctions of the arms of the small Y's, and from the switchtubes to the junction of the arms of the large Y, are critical for proper functioning of the switching system, since the fired tubes act as shorts across the guides. The proper location for the switchtubes is determined experimentally for each Y using a standard wave-guide plunger in one arm of the Y and positioning this to obtain a flat line with a matched load on the other arm. Since this component is somewhat frequency sensitive, dielectric line stretchers may be included in the arms of each Y for adjustment at different wave lengths. The Type X7047 tube is a frequency-selective device, with a loaded Q of somewhat less than 350, but is tunable over a 12 percent band.

Four out-of-phase, 75 percent duty-cycle, rectangular pulses supplied by a keyer unit are applied to the interaction electrodes of the Type X7047 tubes. Thus, with pulse-to-pulse lobing, each switchtube in turn is "open" for the period between two successive transmitter pulses, and reception is on one lobe only for that duration. The lobing sequence for four pulses might be "up", "down", "right", "left", for example.

Although the Type X7047 tube has been developed primarily for use as a low-power r-f switch in the high-speed-lobing systems, it should find many other applications because of its unusual characteristics. Figure 11 shows its performance as an r-f attenuator. Attenuation is plotted against voltage measured directly across the electrodes. At a voltage of 350, the current through the tube is under 1 ma. The tube mounts conveniently between two standard choke flanges and is easily tuned to the operating frequency by screwdriver adjustment of a differential tuning screw. Since the attenuation of the tube can be controlled electronically, it is readily adaptable to such applications as automatic gain control, low-power r-f modulation, or, as in this application, to r-f switching by using suitable electronic control circuits.

THE TRANSMITTER

The X-band transmitter, housed with the receiver behind the antenna reflector, uses a Type 2J49 magnetron. Since it is of conventional design and has no special features, it will not be described further. The r-f power from the magnetron is piped through $\frac{1}{2}$ x 1-inch wave guide to the center feed in front of the reflector.

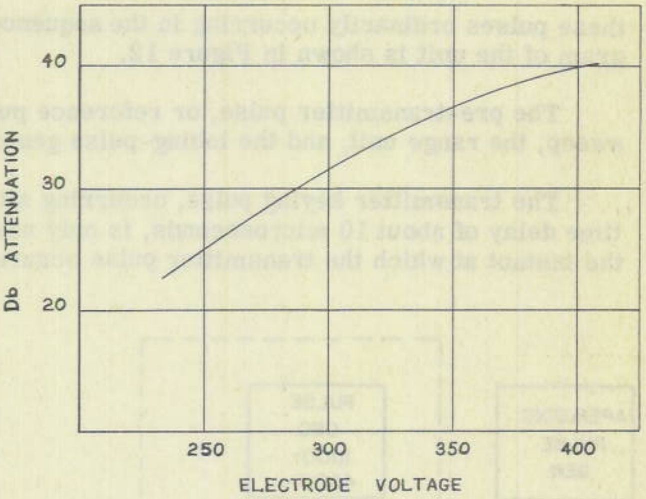

Fig. 11 - Typical X7047 Attenuation Curve

THE MODULATOR

The modulator unit, which may be seen in Figure 3 attached to the side of the antenna mount, receives a low-level keying pulse from the timing generator which is located "below deck". This keying pulse is amplified within the modulator unit and triggers a Type 4C35 thyratron to discharge a pulse-forming line. The modulator, designed to allow aperiodic operation, employs d-c resonance charging of the .25-microsecond pulse-forming line from a 4000-volt supply through a blocking diode, and will operate at PRF's up to 4000 cps. The modulator pulse is applied to the magnetron through a step-up transformer at the transmitter. A pulse cable connects this transformer to the modulator.

Also housed in the modulator unit is a high-voltage supply to furnish direct current to keep-alive electrodes of the four Type X7047 switchtubes. Current-limiting resistors are located near the tubes.

THE RECEIVER

No detailed description of the receiver will be given since it is of conventional design having an 8-mc bandwidth. Ungated video is furnished to the indicator, while gated video is provided for automatic range, elevation, and train circuits, and for developing selected signal AGC.

The gated video output, having an amplitude of about 5 volts with AGC operating, is fed to two additional gating tubes in the angle circuits. These circuits separate the elevation pulses from the train pulses, passing each group of pulses to the proper angle channel for lengthening and error determination.

THE TIMING GENERATOR

The timing generator is required to furnish four short pulses of about ten volts amplitude at low impedance. These are a positive pre-transmitter pulse, a positive transmitter keying pulse, a positive pre-gate pulse, and a negative gate or range pulse, these pulses ordinarily occurring in the sequence enumerated. A simplified block diagram of the unit is shown in Figure 12.

The pre-transmitter pulse, or reference pulse, is used to trigger the indicator A-sweep, the range unit, and the lobing-pulse generator located in the angle circuits.

The transmitter keying pulse, occurring after the pre-transmitter pulse by a fixed time delay of about 10 microseconds, is only used to trigger the modulator and represents the instant at which the transmitter pulse occurs.

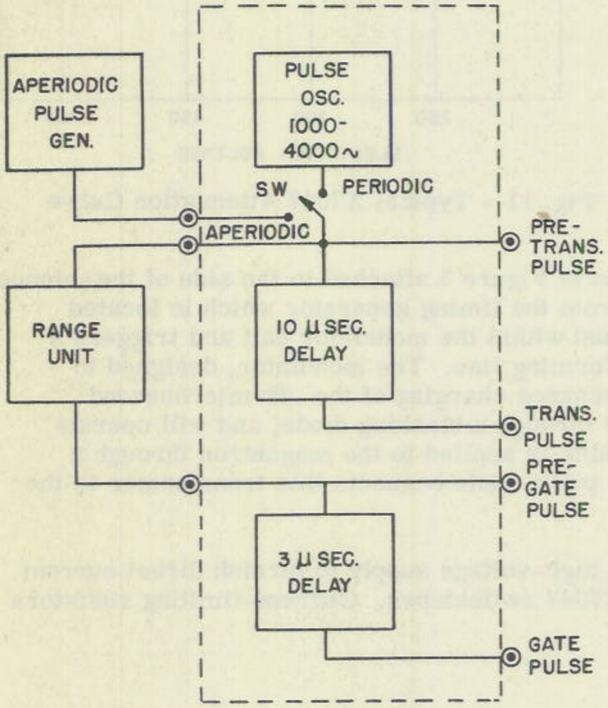

Fig. 12 - Timing Generator Block Diagram

The pre-gate pulse is formed in the timing generator from the range-delay pulse put out by the range unit and is used: (1) to initiate an expanded sweep on the indicator, (2) to key the reference voltage generator in the angle circuits, and (3) to trigger clamping tubes in the pulse-stretching circuits.

The gate or range pulse, which occurs at a fixed time after the pre-gate pulse (about 3 microseconds delay), is used: (1) for the range notch on the indicator, (2) for a gating pulse in the receiver, and (3) for a gating pulse in the automatic range circuits.

A variable-frequency multivibrator in the timing generator establishes a selected PRF between 1000 and 4000 cycles. Adjustable-delay multivibrators govern the delays between pre-transmitter pulse and transmitter pulse, and between pre-gate pulse and gate pulse. Provision is made for aperiodic keying of the system from an external aperiodic pulse generator, which drives the timing generator after the periodic multivibrator is turned off.

AUTOMATIC RANGE

Conventional circuits are employed to develop range-error voltages for automatic range tracking of the servo-driven range unit. This latter unit, however, specially designed for aperiodic operation without time jitter, has novel features which are described in an NRL report. §

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§ King, A. M., NRL Secret Report RA 3A 221A, "An Aperiodic Range Delay Circuit," 4 December 1944

THE INDICATOR

The A-sweep indicator used in this sytem differs but slightly from conventional indicators, the essential difference being that it is required to function uniformly without time jitter at various repetition rates or with random keying. Two sweep lengths are provided on the five-inch tube, twenty thousand and forty thousand yards. A half-microsecond range notch shows continuously on the A-sweep and appears in the center of a 1000-yard expanded portion which may be switched in or out at will. The range notch indicates the position of the receiver gating pulse, and is used to select the target to be tracked. Automatic range, which may be switched on or off, keeps the receiver gating pulse accurately centered on the selected target pip, and, as target range changes, the range notch travels along the A-sweep with the superimposed target pip.

THE ANGLE CIRCUITS

The angle circuits, or more explicitly, the angle-error detection circuits, perform the function of converting lobed, gated video pulses into d-c angle-error voltages. In describing the operation and functions of the unit, the production of a d-c error voltage for a single plane, say bearing, will be considered, and pulse-to-pulse, sequential lobing, with periodic keying will be assumed.

Since a common first detector and a common receiver is used in the present system, the signals from each of the four lobes appear successively at the video output of the receiver. A selected-signal gating tube then furnishes the angle circuits with gated echo pulses. With pulse-to-pulse lobing, four pulses complete a lobing cycle, and gating tubes at the input to the angle circuits separate the train and elevation pulses and direct each pair of pulses to the proper channel. After the separated pulses are amplified, "boxcars" are formed in each channel by pulse-stretching for the period between two pulses. The lengthened pulses are then brought to the demodulator bridge through a phase-inverter stage which is capacitively coupled to the bridge. A synchronized square-wave reference voltage generated by flip-flop circuits is used to drive the bridge. Figure 13 shows the basic circuit used.

With echo signals returning from a target which is slightly off to one side of the antenna axis, the energies received in the two bearing lobes will differ in amplitude, while, being on target in elevation, the energies in the two elevation lobes will each have the same amplitude. The boxcars of each channel are applied to terminals of separate bridge demodulators, while a common reference square -wave voltage drives both demodulators. The difference in the amplitude of the boxcars for bearing produces a change in the average d-c level at the error-voltage output of the bridge demodulator, while the polarity of this voltage, indicating the sense of the error, is dependent upon which of the two boxcars is larger. Figure 14 is an experimental plot of this d-c error voltage in the bearing plane, taken as the antenna was trained across a fixed target.

Figure 15 is a block diagram of the angle circuits, while the significant wave forms and their time relationships for one lobing cycle are shown in Figure 16.

Since the pulses which control the electronic switchtubes are initiated in the angle circuits by a triggering pulse from the timing generator, and since the demodulator reference voltage is synchronized from these same lobing pulses, the lobing rate can be changed simply by using a dividing circuit in the trigger-pulse line. Thus, with the

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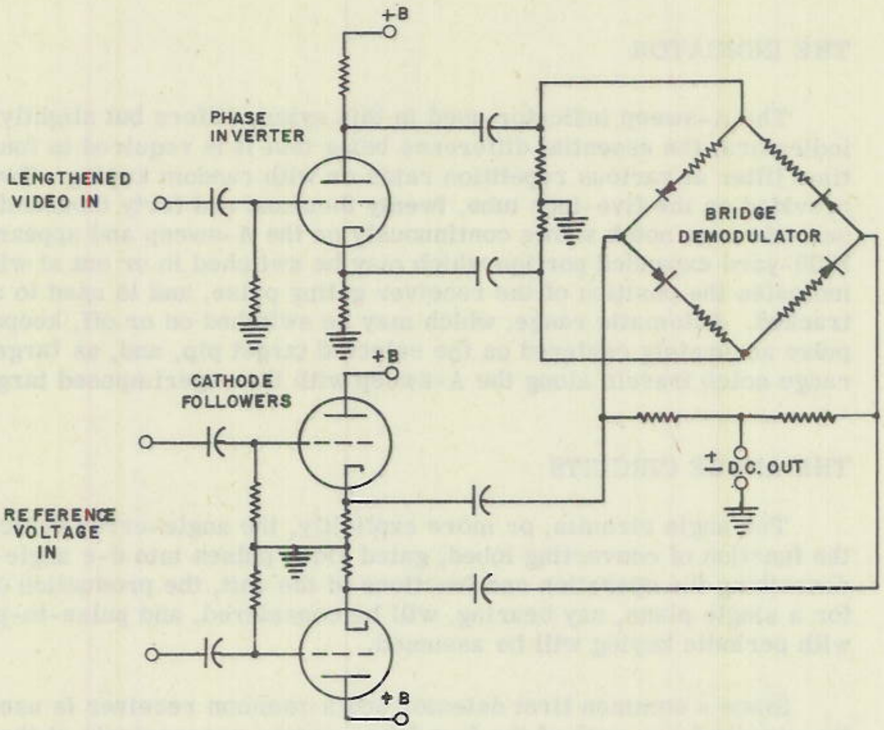

Fig. 13
Basic Diagram
of Bridge Angle Circuit

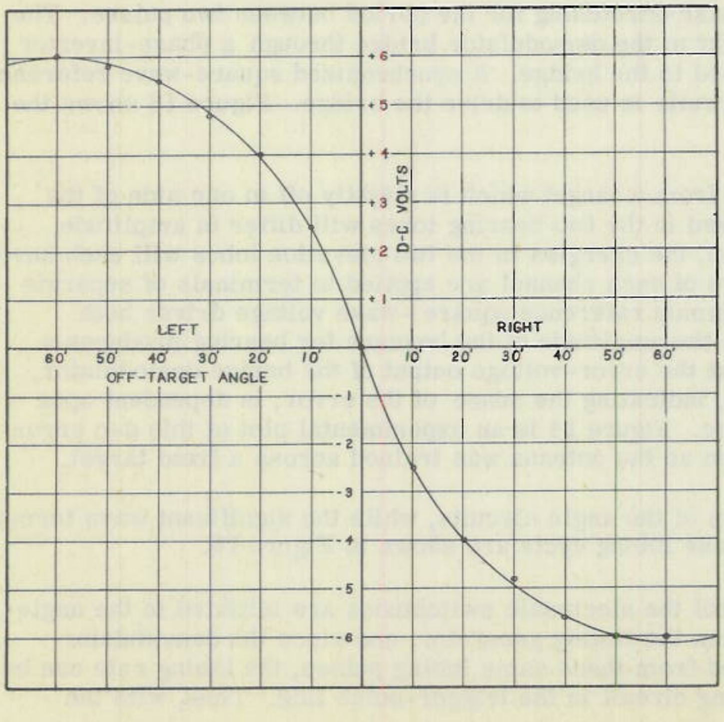

Fig. 14
Experimental Plot
of d-c Error Voltage

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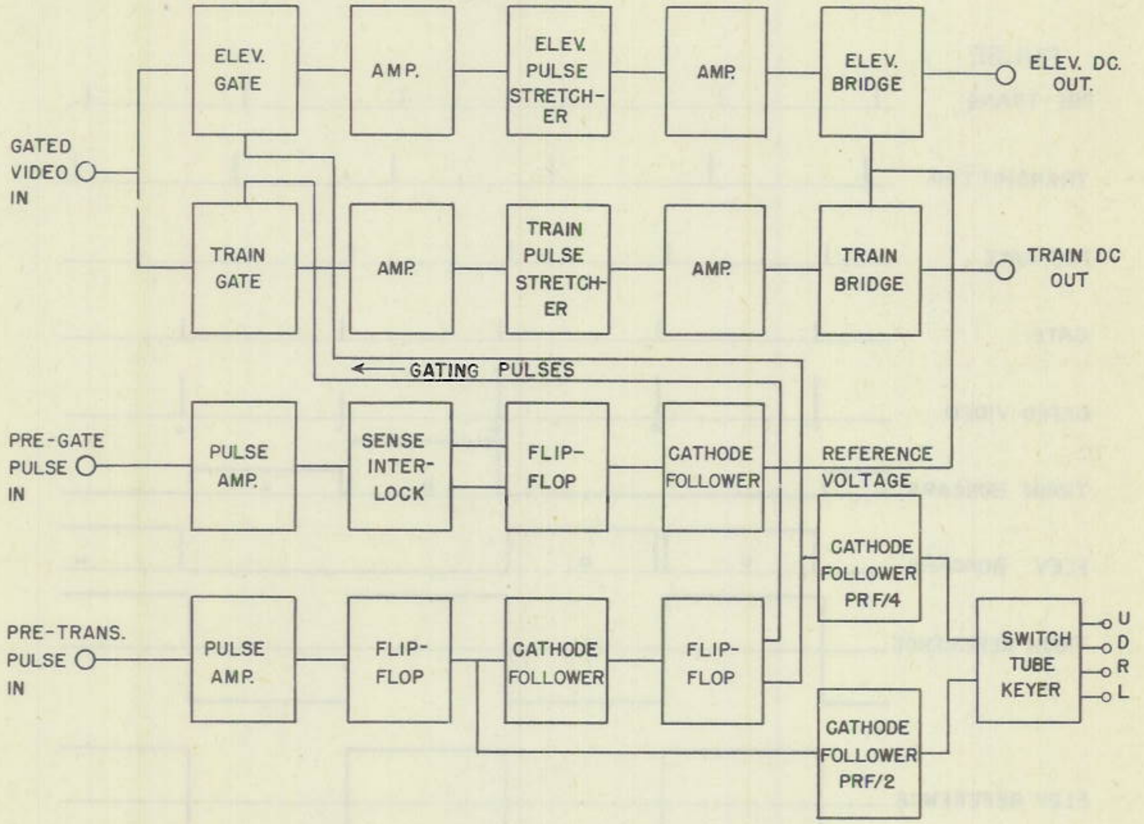

Fig. 15 - Block Diagram of Angle Circuits

trigger pulses from the divider being at some sub-multiple of the PRF, the number of video pulses received per lobe will be dependent on the dividing ratio. The actual lobing rate will be dependent upon the dividing ratio and the PRF. For example, with a PRF of 1920 cps, lobing rates between 480 and 30 cps can be had by switching the dividing ratio over the range from 1 to 16. Synchronism is automatically maintained in all circuits as the lobing rate is changed to various sub-multiples of the PRF.

THE SWITCHTUBE KEYER

Located remotely at the antenna mount, the switchtube keyer, driven by square waves developed in the angle circuits, provides four properly-timed high-voltage rectangular pulses for operation of the Type X7047 switchtubes. Two square-wave lobing pulses, one having half the frequency of the other, are combined in the keyer to form the 75 percent duty-cycle pulses of different phases required for sequential lobing. Since the switchtubes operate with their frames grounded and require a negative keying voltage, the keyer has a separate power supply with the positive grounded and the negative connected to the cathodes of the triode keyer tubes. The switchtubes are shunted across the plate loads of the keyer tubes through series stabilizing resistors.

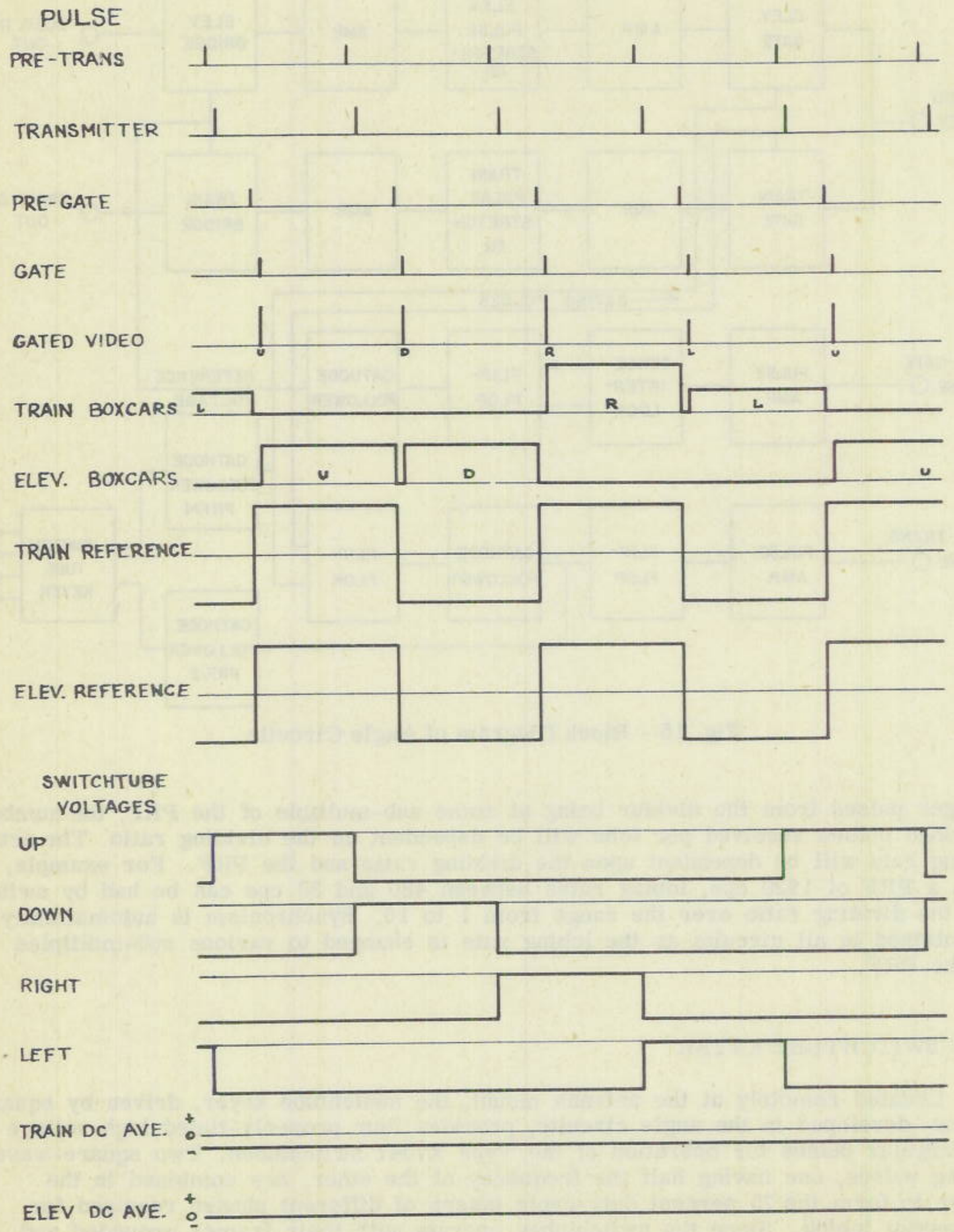

Fig. 16
Significant Wave Forms and Time Relationships

THE ANTENNA MOUNT CONTROL SYSTEM

Amplidyne control of reversible d-c motors is employed for train and elevation drive of the antenna mount. The initial control voltages, which may be derived from the servo positioning controls, from a "joystick" control, or from error voltages developed in the angle circuits, are fed through suitable equalizer networks and to high-gain, stabilized d-c amplifiers. The outputs of these amplifiers, in turn, serve to control the amplidynes.

The joystick control is provided on the antenna mount for optical target acquisition, while servo control is provided at the radar operating position for acquisition by use of search-radar target position information. Both one-speed and 36-speed synchros are used to transmit train and elevation data accurately to the operating position.

PRELIMINARY TRACKING PERFORMANCE

While preparations for thorough tracking tests at various lobing rates are still in progress, preliminary automatic tracking runs have resulted in very good performance of the system. Miscellaneous military and commercial planes have been used as targets in these runs, though without prescribed courses. Several of these runs have been filmed with a camera mounted on the antenna, and analysis of a typical film has indicated unusually good output data.

Results of the system testing and performance will be included in a future report following conclusion of these tests.

PROPOSALS

It is planned to use the present experimental system to conduct an investigation of the accuracy of angle-error data collected at various sequential lobing rates from 30 to 1000 cps and at different PRF's. Lobing will be synchronized at frequencies which are sub-multiples of the PRF. Correlations of angle tracking accuracy and lobing rates will then be made.

A proposed variation of the system described in this report utilizes two receiver channels with each channel carrying the information from the lobes of one plane only. Thus train and elevation signals are handled independently, and reception can take place on one lobe of each plane simultaneously. This not only increases the rate at which data can be obtained with a given PRF, but simplifies the circuitry of the angle circuits and the switchtube keyer.

When operating aperiodically, it is important that all fixed delays remain constant to avoid time jitter between the various keying pulses. In the present timing generator, however, some undesirable jitter does exist during aperiodic keying due to slight variations in pulse shapes within the unit with variations in PRF. It is planned to overcome this difficulty in a new timing generator which will eliminate delay multivibrators in favor of delay lines.

Experience in target acquisition with the system has indicated the desirability of having the A-sweep separate from the expanded sweep and arranged so that both may be observed simultaneously. A new indicator will utilize a dual-beam cathode-ray tube as a double-trace indicator. The upper sweep will be the regular A-sweep having three ranges of ten-, twenty-, and forty-thousand yards. The lower sweep is to be a precision sweep of 1000 yards centered about the range notch, This type of indicator will simplify target acquisition, allowing observation of new targets which may appear on the A-sweep, while the expanded portion permits continuous observation of the character of the echo from the target being tracked.

While the Type X7047 tube represents the first successful development of an r-f attenuator tube of this type, two other types are currently under development and when completed will broaden the possible applications of electronic r-f switching or attenuating. One new type is a broad-banded low-power tube which may replace the Type X7047 in most applications, since it will be fixed-tuned to operate over a 9-percent band while otherwise providing similar performance. The second type is a high-power device for transmitter switching, expected to handle 100-kw peak power, with development to continue toward tubes of still higher power capabilities. Such a high-power switching device, which can be controlled electronically, will offer a welcome solution to the problem of transmitter lobing for radar-guidance applications. Construction of such a radar system is proposed, pending completion of satisfactory switchtubes.

ACKNOWLEDGEMENTS

The proposal for an automatic radar system employing electronic lobe switching to obtain high lobing rates was originated by Mr. J. H. Greig.

The authors recognize and particularly appreciate the cooperative efforts of Mr. W. S. Sunderlin and of the many other persons who have been involved in this project.

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