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SHORT PULSE TECHNIQUES FOR HIGH DEFINITION RADAR SYSTEMS

REPORT
912

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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SHORT PULSE TECHNIQUES FOR HIGH DEFINITION RADAR SYSTEMS

Abstract

Investigations have been carried out on the problems of producing short pulses and the necessary equipment for utilizing these pulses. Modulators capable of producing pulses as short as 0.02 usec have been built and tested. A receiver with an i-f pass band of 35 Mc/sec and a video amplifier and A-scope with a pass band of 35 Mc/sec have been built and tested. Three different types of magnetrons, 725A, LVX, and 4J50 have been tested on short pulse operation with good results.

Radar operational tests using short pulse equipment indicate that short pulses are quite valuable in combating confusion types of interference and in obtaining good signal definition, but are not recommended for long range operation, or where any types of electrical interference are present.

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SHORT PULSE TECHNIQUES FOR HIGH DEFINITION RADAR SYSTEMS

I. INTRODUCTION

The term "short-pulse technique" as used in this report applies to the investigation and the solution of the following problems: (a) the effect of variation of the pulse length of a radar system on the signals received from various types of targets and such as land signals, airplanes, boats and ships, and from various forms of clutter such as clouds, sea clutter and window; (b) the factors to be considered in the design of components to be used to produce short pulses, and the corresponding receiving and indicating components required to display such pulses; and (c) the effect of short pulses on mapping, signal definition, and minimum range.

The study of short pulses was initiated in Group 44 as a countermeasure against such types of interference as window and false signals, as well as a method of reducing the signal return from clouds. Previous work at longer pulses had shown that the intensity of a signal from a cloud formation could be reduced by using shorter pulses. Since the signal return from window and false signals is of the same nature as that from a cloud, it was felt that this type of interference could be largely eliminated by the use of very short pulses. In addition, it was considered important to determine to what extent the problems of minimum range and signal definition could be solved by the use of very short pulses and correspondingly narrow antenna patterns.

II. GENERAL DESCRIPTION OF SYSTEMS

The work on short pulses has been carried out on three systems, the D2-1, J1-1, and S-2. These three systems are located on the roof of the George Eastman Laboratory where they command a fairly good view of the surrounding vicinity. These sets are not preproduction models for any systems used in the field by the armed forces. They are used primarily in connection with the experimental work carried on by Group 44.

The D2-1 is an experimental X-band system operated at a wavelength of 3.2 cm with a peak power output of approximately 100 Kw. It is completely flexible so that any type of radar equipment can be used in connection with it. The r-f system of the D2-1 is made up of the following components. A 48 inch paraboloid, fed by a dipole antenna array mounted at the end of a waveguide transmission line, is used as the antenna system to furnish a narrow antenna beam, 1.6° wide at the half-power points. A waveguide transmission line approximately 20 feet long and containing three rotating joints is used to transmit the r-f power from the magnetron to the antenna system. The function of three rotating joints is to allow the antenna system to be rotated continuously in azimuth, to be tilted in elevation from -5 to + 75°, and to be changed from horizontal to vertical polarization while the system is scanning in azimuth or elevation. The r-f power is furnished by a 725A magnetron.

The modulator used on this system is a hard tube modulator designed and built especially for short pulse work. It will furnish pulses ranging in length from 0.6 to 0.03 µsec. The peak voltage and current available are 20 kv at 30 amperes.

The receiver used on the system is a special broad band type designed for short pulse work. It has an i-f pass band of 15 Mc/sec centered at 30 Mc/sec. This pass band can be narrowed to 7 Mc/sec and 1.5 Mc/sec by the insertion of the appropriate filter networks. The i-f amplifier has sufficient gain at all pass bands for noise to saturate. The receiver is mounted on the mixer and duplexer in the waveguide transmission line and the video signals are applied at 5 volts maximum amplitude through a 75 ohm cable to the video amplifiers.

The indicators used include three intensity modulated indicators and an A-scope. The intensity modulated indicators consist of a 5-in. m-e EEI with sweep lengths of 5, 50, and 100 miles, a 7-in. m-e PPI with sweep lengths of 10, 30, and 50 miles, and a 7-in. m-m PPI with sweep lengths of 1, 2, and 3 miles. The latter is used for high definition mapping of near-by targets. A 7-Mc/sec non-linear video amplifier is used to drive these tubes. The A-scope consists of a 5-in. cathode ray tube with signals being applied to it by a 10-Mc/sec video amplifier, which has sufficient gain to produce a 3-in. deflection on the scope from an input signal of 5 volts. The sweep speeds available vary from 5 to 0.005 in./µsec, i.e., 150 yards to 100 miles for the full 5 in. sweep.

The central control unit consists of a crystal controlled accurate ranging unit which furnishes the main trigger to the modulator and the indicators, and also a delayed trigger which can be continuously delayed out to 100 miles. This trigger is used to delay the sweep on the A-scope so that any desired portion of the entire range can be presented on an expanded sweep. The trigger repetition frequency can be varied from 250 to 4000 pulses/sec. In addition the control unit furnishes 1 mile and 10 mile rangemarks which can be applied either to the A-scope or the PPI's.

The J1-1 system is an experimental S-band system operating at a wavelength of 9.1 cm with a peak power output of approximately 50 kw. The function of this system is very similar to the D2-1 and it has the same degree of flexibility.

The r-f system of the J1-1 contains the following components. A 48-in. paraboloid fed by a dipole array mounted on the end of a stub-supported transmission line is used as an antenna system to give an antenna pattern of 5° at half power points. The r-f power is transmitted from the magnetron to the antenna by means of a 20-ft. stub -supported transmission line containing three rotating joints. These rotating joints allow the same freedom of motion in the antenna system as is possible in the antenna system of the D2-1. The r-f power is furnished by a 2J25 magnetron.

The modulator used in this system is of convential design, modified to give pulse lengths varying in length from 5 usec down to 0.10 μsec. It is a hard tube type furnishing pulses at a peak voltage and current of 15 kv at 30 amperes.

The receiving and indicating components are also similar to those used in the D2-1. The receiver is identical in passband and gain characteristics, but it has an input designed for an S-band mixer. The indicators used consist of a 7-in. m-e EEI, a 7-in. m-e PPI, and the same 7-in. m-m PPI with the fast sweeps as is used on the D2-1. This indicator is located on the indicator table half way between the two systems and can be used on either system merely by switching selsyn controls and video signals. A 7 Mc/sec video amplifier is used to drive these indicators. The A-scope used on the J1-1 is identical to that used on D2-1.

The central control system on J1-1 consists of a crystal controlled accurate ranging unit which contains two J-scopes (circular trace tubes). A 2000-yard sweep and a 32,000-yard sweep are applied to these tubes, and any desired 2,000-yard section on the 32,000-yard sweep tube can be presented on the fast sweep scope. In addition, any 32,000-yard section extending out to 480,000 yards can be presented on the 32,000-yard scope. This unit furnishes the main triggers for the modulator and indicators. The trigger repetition frequency can be varied from 250 to 4,000 pulses/sec.

The most recent experimental system incorporating advanced design features has been given the designation S-2. It is located on a penthouse on the roof of George Eastman Laboratory at M.I.T. From this position the system has an unobstructed view in all directions except in the direction of the main dome on M. I. T. This system has both an S-band and an X-band radar set built into it. The X-band system was designed primarily for work on short pulses while the S-band system was used mainly on other AJ studies.

The antenna system used on S-2 consists of a 7 x 11 foot cut paraboloid. This is a horizontal grid structure with a grid spacing of 0.5 in. This paraboloid is fed by means of horn type antennas at the ends of the waveguide transmission lines. The total length of transmission line in either system does not exceed 10 feet. This antenna system can scan continuously in azimuth and from -5 to +10 deg. in elevation. Only horizontal polarization can be used, due to the construction of the reflector. The beamwidth is 1.8 deg. in azimuth at half power points on S-band, and 0.6 deg. on X-band.

All r-f and receiving components for both systems are located in a cab which is mounted on the rear of the antenna system. The magnet and magnetron of the S-band system are located in the cab. The modulator is located in the control room and the pulse is transmitted to the magnetron by means of a high-voltage pulse cable and a pulse transformer. The modulator, magnetron, and magnet of the X-band system are mounted in the cab. The high voltage, screen, and bias supplies, and the trigger are supplied by components in the control room and transmitted to the cab components by means of slip rings.

The slip ring assembly used on S-2 consists of four sections. One section contains 70 silver slip rings and silver graphite brushes for use in transferring the low voltage (115 volts) a-c and d-c power. This section also handles all video connections, and systems controls used by the two systems. The second section consists of two larger concentric rings which handle the screen and bias voltage supplies for the X-band modulator. The third section consists of one large ring which supplies the high voltage for the modulator. The fourth section is a coaxial rotating joint which is used to transmit the high-voltage pulse up to the S-band magnetron.

Since this X-band system was designed primarily for short-pulse work, special emphasis has been placed on the components used. The modulator used was specially designed and built for this particular work. It furnishes pulses varying in length from 0.20 μsec down to a minimum of 0.02 μsec to a high power BTL 4J50 magnetron.

The following receiver and indicating units are used. A special wide band receiver with an i-f pass band of 35 Mc/sec is used to receive the very short pulses. The video output from this receiver is fed to a special wide-band (35-Mc/sec) video amplifier and A-scope. This A-scope has sweep speeds varying from 20 to 0.0005 in./μsec, i.e., 40 yards to 1000 miles for the full sweep. The intensity modulated indicator used at present is a 7-in. m-m PPI with sweep lengths ranging from a minimum of 2 miles up to 800 miles. A 12-Mc/sec video amplifier is used to drive this tube.

III. SHORT-PULSE-MODULATOR DESIGN AND RESULTS OBTAINED

The construction of a radar set to be used for short pulse work involves the application of some principles which usually will not cause any trouble if neglected in conventional radar design. These principles will be discussed in connection with the various components whose behavior is determined by them.

As is well known, the pulse length used by any radar system is determined by the modulator which produces the high voltage pulse applied to the magnetron. In designing such a modulator certain important principles should be observed. Fundamentally, a hard-tube modulator is nothing more than a high powered video amplifier. Thus, any principles involved in making a video amplifier with a very wide pass band are applicable to the design of short-pulse modulators. In designing a short pulse modulator, one must first decide on the pulse length and pulse shaping desired. The rise time desired on the pulse will determine the highest frequency response required, and the shape of the pulse will determine what type of pulse forming network is required, i.e., whether a network made up of a small or large number of lumped constant sections or whether a length of cable is needed.

The factors to be observed in the design of short pulse modulators might be summarized in the following manner. All stray capacitances and inductances must be kept at a minimum. All ground leads must be as short, heavy, and common as possible, i.e., if possible, all modulator components and magnetron should be mounted on the same ground and as close together as the necessary high-voltage precautions will permit. All other connecting wires must be as short as possible, i.e., if one wishes to keep the pulse short and properly shaped, long leads should not be used between the modulator and magnetron, or in the modulator itself. Transformer coupling cannot be used for pulses shorter than 0.125 usec, since the present pulse transformers do not have a good enough frequency response to pass shorter pulses. Also they cause ringing on the top of and following the pulses. Such ringing cannot be tolerated if one is interested in minimum ranges. Jitter-free tubes must be used in the triggering circuits, since any such trigger instability will spoil the presentation of the signals observed, unless the modulator furnishes the master trigger for the other units. In a modulator-triggered system, it is impossible to view signals at a minimum range, due to the starting time of the indicators. Modulator tubes should have a high transconductance and very low interelectrode capacity, as well as high power dissipation. High-power triodes are not satisfactory, due to their change in capacitance with change in gain and because so much power is required to drive them properly. Finally, all screen and bias supplies should be well regulated so that the operating characteristics of the tube will not change when the pulse length or repetition frequency is changed.

An ideal short-pulse modulator would be one which produces a very short pulse with a very short rise time, a flat top with no spike at the front edge, and a fairly short decay time with no ringing following the pulses. Some progress has been made toward this goal in the work on short pulses. Three different modulators have been built and tested on systems in connection with this work. The voltage pulses, available in each case, have very short rise times (0.02 µsec), they are reasonably flat on top, the decay time is approdimately 0.2 µsec, and there is no ringing following the pulse. Three different types of pulse forming networks have been used in these modulators with comparable results. These modulators were tested on a 725A, a LVX, and a BTL 4J50 magnetron. Each magnetron operated satisfactorily at all pulse lengths. Contrary to popular belief, the fast rise times on the pulses did not cause the tubes to jump modes. The only time that instability of this type was observable, occurred when excessive spikes were present on the leading edges of the pulses.

Since the present design of the short-pulse modulator is quite different from that of the first modulator used in this work, a brief survey of short-pulse modulator development as carried out in this group will be given.

The first modulator used was a standard model modified to attempt to produce short pulses. It consisted of a combination of a pulse forming network and a blocking oscillator to produce a low-voltage pulse. This pulse was applied by means of a transformer to a driver tube which in turn was transformer coupled to the modulator. The output was applied to the magnetron through connecting wires about 15 inches long. This modulator was modified to produce pulses varying in length from 5 µsec down to 0.05 µsec. It worked satisfactorily at pulse lengths down to 0.25 µsec, but below this value the pulse had a very poor shape and there was considerable ringing following the pulse. The errors in the design of this modulator were: (a) the driver unit was built on a bakelite chassis with no heavy common ground; (b) transformer coupling caused excessive ringing following the pulse; (c) a pulse transformer was used in the formation of the pulse -- this method is unsatisfactory at pulse lengths shorter than 0.125 µsec due to the frequency response of the pulse transformer, (d) the poor placement of components necessitated long connecting leads, (e) the power supplies for the screen and bias voltages were poorly regulated; and (f) the pulse shape was spoiled by the long connecting leads between the modulator and the magnetron.

Since this first modulator was not satisfacoty a second one was designed and constructed for work on short pulses. In this modulator, special attention has been given toward eliminating the defects listed above. The entire modulator is built on a steel chassis with components placed so that lead lengths are on short as possible. In addition, a change in pulse length from its maximum length of 0.6 usec down to the minimum of 0.03 µsec does not cause the screen or bias voltage to vary more than 2%. The circuit diagram of this modulator is given in Fig. 1. The action of this modulator is as follows: A positive trigger is applied to the first blocking oscillator. This oscillator acts as an isolating circuit so that any size input trigger can be applied without affecting the operation of the modulator. The output trigger from the isolating circuit is applied to a second blocking oscillator which furnishes a high voltage trigger with a very fast rise time (400 volts µsec) to the hydrogen thyratron. The plate of the hydrogen thyratron is coupled to the primary of an air-core transformer. The secondary of this transformer is tuned to the fundamental of the desired pulse while the primary is tuned to some frequency much lower. When the thyratron fires, the secondary of the transformer begins to oscillate at its resonant frequency. It is allowed to oscillate for a positive half cycle, then is sharply damped by a diode connected across it. Due to the 2:1 step up ratio of the transformer, this positive half cycle has a voltage of approximately twice that across the thyratron. This positive high voltage pulse is applied between the grid and the cathode of the driver tube (3E29), and the bootstrapping action drives the grid of the 3E29 beyond the voltage required for plate saturation. Consequently the output taken off the cathode of the tube is a square, flat-top pulse with very steep sides. This pulse is applied directly to the two modulator tubes (5D21's) which in turn pulse the magnetron. The magnetron is mounted adjacent to the output terminals so that the connecting leads are as short as possible. The pulse length is changed by changing the air-core transformer and the 3E29 cathode resistor. These components are mounted on an octal socket which is plugged into the front panel of the modulator.

The maximum power output obtainable from this modulator is limited by the modulator tubes which in this case are incapable of furnishing pulses greater than 20 kv and at peak currents of 30 amperes. Higher voltage cannot be obtained from the type of modulator tube used here because of the internal arcing which occurs between elements in the tube.

The pulse lengths obtained were determined by measuring the voltage pulse on a fast sweep synchroscope, and checking the r-f output by means of the spectrum analyser. The frequency difference between the first minima on each side of the center of the r-f spectrum for the different pulse lengths is given in Table I.

TABLE I. Theoretical and measured frequency differences for the r-f spectra of a magnetron operated at different pulse lengths.

Pulse length in usec	Theoretical frequency difference in Mc/sec	Measured frequency difference in Mc/sec
0.60	3.3	3.5
0.25	8.0	8.0
0.10	20.0	20.0
0.05	40.0	40.0
0.03	66.0	58.0

When the shortest pulse length was used it was impossible to obtain an accurate measurement with the spectrum analyzer because (1) the spectrum analyzer receiver has an i-f pass band centered at 35 Mc/sec, consequently the spectra on the upper and lower side bands overlapped somewhat when the frequency sweep was extended far enough to include the complete spectrum; and (2) the local oscillator in the spectrum analyzer did not give a constant output over the frequency range required for the spectrum presentation. These modulator tests shown in Table I were made using the short-pulse modulator previously described and a 725A magnetron oscillator. Similar results were obtained using a LVX magnetron. The short-pulse modulator is now used in the D2-1 experimental system.

The modulator built for use on the S-2 was based on the results obtained on the D2-1 modulator. One of the limitations of the D2-1 modulator was the high voltage of the pulses obtainable. Since the 725A magnetron was operating at these short pulses at 20 kv without arcing, it was felt desirable to determine the maximum high voltage pulse that the 725A magnetron could stand without internal arcing occurring. Also, since the new BTL high power X-band magnetron was available, it was necessary to have a modulator which could furnish voltage pulses as high as 30 kv. With these requirements in mind, a high-power short-pulse modulator was designed and constructed. The result is a modulator capable of furnishing 35 kv pulses at peak currents of 70 amperes. The pulse length can be varied from 0.20 μsec down to a minimum of 0.02 μsec.

A view of the modulator is shown in Fig. 2. As can be seen, all components are placed in such a way that all lead lengths are at a minimum. A heavy common ground consisting of a brass plate on which all of the components are mounted eliminates any troublesome ground currents. The parasitic resistors in the modulator plate leads were eliminated without introducing parasitic oscillations by connecting all of the plates in common to a heavy brass plate. There were no stray inductances due to lead lengths in the plate circuit because the one terminal of the coupling condenser was connected directly to the brass plate and at the other terminal to the magnetron which, along with the electromagnet was built into the modulator. The viewing scope in the upper corner is used to view the voltage pulse. It has a 3 inch cathode-ray tube with sweep speeds varying from 1 to 12 in./μsec. The magnet used is a water-cooled electromagnet capable of producing a magnetic field of 12000 gauss between pole pieces spaced a distance equivalent to that in a BTL 4J50 magnetron. A closed water-cooling system with forced circulation is used to cool the magnet and the magnetron.

A diagram of the modulator circuit is given in Fig. 3. Its operation is as follows: A positive trigger is applied to the blocking oscillator trigger amplifier which produces a high-voltage, fast-rising (600 volts/μsec) trigger for the hydrogen thyratron (4C35). The hydrogen thyratron fires across the pulse forming network which has been resonance charged through the inductance and diode to a voltage approximately twice that available between the positive and negative supply. When the thyratron fires it short-circuits the pulse forming line and a positive voltage equal to one half that across the line appears across the resistor in the cathode circuit of the thyratron. This voltage remains at this level while the voltage wave travels down to the end of the network and is reflected back out of phase to cancel the voltage across the resistor. The actual resistance which is supposed to match the impedance of the pulse forming network is composed of the 20-ohm resistor in the thyratron cathode circuit and the grid resistance of the modulator tubes when they are driven positive. Since the pulse shaping depends on this matching resistance, it is important to choose the operating condition of the modulator tubes so that the grid impedance will be correct. The positive voltage pulse thus produced is applied directly to the grids of the four 6D21 modulator tubes. The output from these tubes is applied directly to the magnetron.

The pulse-forming networks used in this modulator are made up of sections of high-voltage 50-ohm pulse cable. The shortest pulse (0.02 µsec) is produced by a section of cable 5 feet long. This section is rigidly mounted in the modulator, with a high voltage coupling on the free end. Longer pulses are obtained merely by adding longer sections to the short section. The high voltage couplings change the characteristic impedance of the cable somewhat but not enough to affect seriously the pulse shaping. The maximum pulse length obtainable by this method depends on the length of accessible cable. The maximum pulse length in this modulator was restricted by the size of the coupling condenser between the modulator and the magnetron. At longer pulse lengths, the slight droop caused by the condenser discharge caused some instability in the magnetron operation. The pulse lengths obtained with this modulator were measured by means of the voltage pulse, the r-f pulse and the r-f spectrum. The photographs in Fig. 4 show the voltage pulses and the corresponding r-f pulses.

In the case of both the voltage pulses and the r-f pulses, the ringing observed is caused mainly by the lead lengths in the scopes, and by the cables used to connect the modulator to the scope. One has only to remember the high-frequency components present in such short pulses to appreciate the problems encountered in presenting such pulse shapes properly. The photographs in Fig. 5 show the r-f spectra for the different pulse lengths along with the corresponding voltage pulses.

A modulator using this same circuit but with lower-voltage tubes and a pulse-forming network made up of lumped constants was constructed to test the effect of short pulses on the operation of the LVX magnetron. The circuit used a 3C45 thyratron and a 3E29 modulator tube. The pulse forming networks for the two pulse lengths were made up of three section L-C networks. The photographs in Fig. 6 show the voltage pulses, current pulses, and r-f spectra for the two pulse lengths tried.

The operation of the modulator used on the JL-1 system is very similar to that of the S-2 modulator. Two 5D21 modulator tubes are used and the driver unit consists of a 3C45 hydrogen thyratron with a pulse-forming network made up of lumped constant L-C circuits. The matching impedance for the pulse-forming network is located between the cathode of the thyratron and ground. The cathode of the thyratron is condenser coupled to the grids of the modulator tubes. Resonance charging of the pulse-forming network is not used in this circuit. This modulator furnishes pulses varying in length from 5 μsec down to a minimum of 0.10 μsec. The maximum power output of this modulator is limited by the 15-kv high-voltage supply. However it is adequate for the type of magnetron used.

Rather extensive tests have been made on the operational characteristics of the X-band magnetrons when operated at these various pulse lengths. Maximum power output has been measured as a function of pulse length, magnetic field, and voltage. In general, the results agreed with results obtained at longer pulse lengths. The graph in Fig. 7 shows the relationship of maximum power output to pulse length. The efficiency of the magnetron is also shown for the different pulse lengths.

A summary of the results of these tests is as follows:

(1) The peak power output of the magnetron increased as the pulse length was decreased. The peak power output varies inversely as the square root of the pulse length ratio.

(2) The magnetron could be operated at much higher voltages with the shorter pulse lengths.

(3) The magnetrons were more stable and had a higher output and effieiency when operated at high voltage and low currents than vice versa.

(4) The r-f spectrum had good shaping at all pulse lengths if the voltage pulse was properly shaped.

(5) Most of the magnetrons tested, when operated with short pulses, performed better at higher repetition frequencies.

(6) The shaping of the pulse had a great influence on the stability of the magnetrons. Fast rise times did not cause any instability unless there was a spike on the front edge of the pulse.

(7) The starting time of the magnetron varied between the different types of magnetrons. In general, the 725A magnetron seemed to have the shortest starting time.

IV. RECEIVER AND INDICATOR DESIGN

The i-f bandwidth of any receiver used in a radar system is usually chosen with respect to the pulse length used by the system. In order to have a maximum signal to noise ratio in a radar receiver, it is necessary to have the i-f bandwidth of the receiver set at some optimum value to receive as much energy from the returning pulse as possible without also receiving a large amount of noise. Studies on the optimum bandwidth for receivers indicate that the i-f pass band should be approximately 1.2 times the reciprocal of the pulse length used. Thus, for the very short pulses, wide i-f pass bands are required -- e.g., for a 0.10-usec pulse length the i-f pass band should be 12 Mc/sec, while for the 0.03 usec pulse the i-f pass band should be 36 Mc/sec. The minimum pass band which should be allowed for the video amplifier is one-half that of the i-f pass band. If the video pass band is narrower than this some loss in signal strength will occur as well as very poor pulse reproduction. If one is interested in good pulse reproduction the video pass band should be wider. Also, if a system is to be operated under conditions where off-frequency c-w interference is encountered, the video pass band should be as wide as the i-f pass band. A more complete discussion of this condition is given in a report by Allred.(1)

The receivers used on the D2-1 and the J1-1 systems were designed and built for the reception of pulses as short as 0.10 usec. They have an i-f pass band of 15 Mc/sec centered at 30 Mc/sec. These receivers consist of 14 single-tuned stages arranged in seven sets of staggered pairs. The pass band is changed by inserting a two stage narrow band i-f amplifier in place of the regular amplifier stages numbers 9 and 10. Plate detection is used at the second detector and the video signals from a cathode follower are fed to the video amplifiers at a 5-volt level through a 75-ohm line. Type 6AK5 tubes are used in the i-f section, and 6AG7 tubes in the video section.

The receiver used on the S-2 X-band system is also of special design. It has an i-f pass band of 35 Mc/sec centered at 80 Mc/sec. It consists of 15 stages of 6AK5 i-f amplifiers arranged in three sets of staggered quintuplets. The second detector is a plate detector. The video signals are fed down to the video amplifiers at a 1 volt level through a 70-ohm video cable.

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(1) C. M. Allred and A. L. Gardner. R. L. Report No. 910

These i-f amplifiers were designed and built following the design theory for wide band i-f amplifiers worked out by H. Wallman(2). The circuits for these two i-f amplifiers are shown in Figs. 8 and 9. A photograph of the 35 Mc/sec receiver is shown in Fig. 10.

The video amplifiers used on the intensity modulated indicators were of standard construction. Shunt peaking was employed to obtain the necessary bandwidth. Type 807 tubes were used in the last two stages. The indicator tubes were all driven in parallel across a 75-ohm terminating resistor. Positive signals were applied to the grids of the indicator tubes. The indicators were connected together by what is called "patchcord technique." The grids of the intensity-modulated tubes were connected to the center conductor of a 70-ohm cable properly terminated at the last tube. The connections between tubes were made by plug-in jacks in such a way that the terminating resistor at any tube was opened when the cable leading to another tube was plugged in.

The type of A-scope used on the D2-1 and J1-1 contains a 5-in. cathode-ray tube with an 8-Mc/sec video amplifier built into the unit. This video amplifier consists of a 6AC7 tube driving a 6V6 phase inverter. The signals from the phase inverter are taken off the plate and the cathode of the 6V6. These signals are applied to the grids of two 6AG7's which in turn drive two 807's. The latter tubes apply the signals to the deflection plates of the cathode-ray tube. Shunt peaking is used on the 6AG7's and the 807's. This amplifier has sufficient gain to give a 3-in. deflection on the screen of the cathode ray tube when a 5-volt signal is applied at the input.

The A-scope and video amplifier used on the S-2 system is the latest design of wide-band video amplifier. This amplifier has a bandwidth of 35 Mc/sec and a voltage gain of 100 which gives a 1-in. deflection on the

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(2) H. Wallman, R. L. Report No. 524

5-in. screen when a video signal of 1-volt is applied at the input. In order to achieve this band-width with amplifier tubes now available it is necessary to run the tubes above their rated plate and screen dissipations. This is avoided by pulsing the tubes in the last two stages at a duty cycle of 30 per cent. The circuit for this amplifier and its accompanying pulsing circuit is shown in Fig. 11. The sweep speeds available on the A-scope of this unit range from 20 in/μsec to 0.0005 in./μsec, i.e., 40 yards to 1000 miles for the full sweep. The pulsed section can be delayed along with the sweep so that signals at any range of the entire sweep can be presented on the fastest sweep.

The video amplifier used on the PPI of the S-2 system is similar to that used on the D2-1 and J1-1 indicators, with the exception that an improved circuit is used which results in a bandwidth of 12 Mc/sec. This amplifier also drives the PPI across a 75-ohm load.

V. OPERATIONAL CHARACTERISTICS OF SHORT-PULSE SYSTEMS

When the use of the short pulses is considered, the first question which arises is what is gained or lost in using them? The net gain or loss depends on the purpose for which they are to be used, as well as such factors as the maximum power obtainable at the different pulse lengths, the maximum power consumption for the different radar units, and the loss in signal to noise ratio in going to shorter pulse lengths.

If the peak power output from a magnetron is kept constant for all pulse lengths, then the energy per pulse is directly proportional to the pulse length. Similarily the energy in the signal return from a solid reflector will vary directly as the pulse length. If the receiver band-width, and sweep length on the indicator of the radar system are kept at an optimum value, then the signal return from a solid reflector would decrease by a factor of 10 if the pulse length were decreased to 1/10. This would mean a loss of 10 db in signal intensity, or a decrease of 45% in range on such a target. This would be disadvantageous to a system primarily interested in a high signal to noise ratio on long-range targets. However, the actual loss need not be this great because the magnetron will give higher peak power out-puts at the shorter pulses and the repetition frequency can be increased due to the lower duty cycle. The increase in signal to noise ratio due to change in repetition frequency is proportional to the square root of the ratio of the repetition frequencies. The increase in peak power output from the magnetron is roughly inversely proportional to the square root of the pulse length as is shown in the graph in Fig. 7. A calculation of the loss in signal strength expected on the D2-1 system is given in Table II.

TABLE II. Calculation of the signal loss expected when the system is operated at 0.03 usec instead of 1 µsec.

Pulse length ratio	$\frac{1\ \text{usec}}{0.03\ \text{usec}}$	14 db
Maximum pulse power ratio	$\frac{40\ \text{kw}}{160\ \text{kw}}$	-6 db
Repetition frequency ratio	$\frac{250}{1000}$	-3 db
		5 db

The resultant loss in going to the shorter pulse is 5 db instead of the 14 db one would expect due to pulse length variation alone.

Since short pulses are used primarily for signal definition, any examination of such signals will be done on expanded sweeps. Tests have shown that the optimum sweep speed to be used on an A-scope or PPI for maximum signal to noise ratio is one in which the signal is approximately 1 mm long. This would correspond to a 10 mile sweep of a 5" cathode ray tube for a 1 μsec signal or a 1 mile sweep for 0.10 μsec, and 0.3 mile sweep for a 0.03 μsec signal. This sweep speed would be quite sufficient for the close examination of signals. However if the sweep speed is doubled or halved, the presentation loss amounts to approximately 1 db on an A-scope, and approximately 0.5 db for a PPI. Thus the optimum condition for viewing signals corresponds to that used in the examination of most signals. However, this is not too important, because such careful examination of most signals is carried out when the signals are much stronger than noise.

Extensive operational tests using the various pulse lengths available have been made on various targets such as planes and land targets. The results agree reasonably well with those predicted. Intensity tests at pulse lengths of 1.0 μsec, 0.25 μsec and 0.1 μsec were made on a TBM airplane. The peak power out-put and the repetition frequency were held constant for all pulse lengths. In addition the sweep speeds on the indicators and the i-f pass band were held at the optimum value for minimum loss. The results are plotted on the graph in Fig. 12. As can be seen, the loss in going from 1.0 μsec to 0.1 μsec corresponds to the value predicted by theory. These measurements were taken in the manner described in a Radiation Laboratory report.(3)

Intensity tests were also made at pulse lengths of 0.25, 0.10, 0.05, and 0.03 μsec on two strong land signals. The peak power and repetition frequency were kept constant at all pulse lengths. The data are given in Table III.

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(3) L. B. Linford, Radiation Laboratory Report No. 64-10

TABLE III. Operational data showing a comparison between the theoretical and observed decrease in signal strength from targets for decreased pulse lengths.

Signal	Pulse length in µsec	Observed signal Intensity in db	Observed difference in db	Theoretical difference in db
A	0.25	15	-	-
	0.10	11	4	4
	0.05	8	3	3
	0.03	5	3	2.2
B	0.25	30	-	-
	0.10	26	4	4
	0.05	25	3	3
	0.03	20	3	2.2

The results agree with the values predicted by theory, with the exception of the 0.03 µsec pulse. The added loss at this pulse length resulted from the fact that the receiver i-f pass band was too narrow (15 Mc/sec was used for 0.10, 0.05, and 0.03 µsec pulses), and to inaccuracies in making the measurements.

The signal return from an air plane or fixed target comes from the front or visible surface of the target. The total energy in a radar pulse is contained in a volume whose cross section is determined by the beam width of the antenna beam, and whose depth is determined by the radar pulse length. In the case of reflection from a solid object, all of the energy incident upon the reflecting surface of the object will be reflected or absorbed. In the case of clouds or window, the signal return comes from a large number of individual reflectors distributed throughout the volume determined by the radar pulse. If the pulse length is decreased, this volume is decreased and hence the number of reflectors, or the effective reflecting area, is reduced. Thus, for clouds or window, the effective reflecting area depends on the size of the cloud and on the radar pulse length used, while in the case of a solid object, the effective reflecting area is independent of the radar pulse length and depends only on the size of the object itself. Hence, the use of short pulses should discriminate between clouds and solid targets in favor of the latter. If the pulse length were reduced from 5 µsec to 0.10 µsec, the signal intensity loss on clouds with respect to land signals should be 17 db. Experimental intensity tests made on clouds and land signals indicated a loss of 18 db. Similar tests on window with respect to an airplane indicate the same results. The PPI photographs in Fig. 13 show how the cloud intensity decreases with decreasing pulse length.

An ideal radar system is one which can paint a PPI picture in which the spot size of the signal on the PPI is identical in size to the corresponding object on an aerial photograph equal in size to the PPI picture. In order for this to be possible, it would be necessary to have an antenna pattern of infinitely narrow beam width; a transmitter which transmits pulses shorter in duration than any object which will give a reflection; a receiver with a pass band wide enough to receive such a pulse, and an indicator with a spot size small enough to distinctly paint the smallest signals received. At the present time, such requirements cannot be met, but a comparison between a radar picture of three years ago with the best presentation yet obtained as shown in Fig. 14 will show how much progress has been made in this direction. The PPI photograph taken three years ago was taken on the experimental S-band system J1-1. The antenna beamwidth was 5 degrees, the pulse length was 1 µsec and the presentation was of a five mile sweep length. The Charles River Basin is just visible in the center of the picture. The most recent photograph was taken on the [illegible] system. The antenna beamwidth was [illegible] degrees, the pulse length was 0.03 µsec and the presentation was of a one-mile sweep length. In this photograph the Charles River Basin is clearly visible, as well as the buildings on the M.I.T. campus.

Since radar systems have an antenna pattern with a finite beam width, a target some distance from the radar system will appear as an arc on the PPI. Since this beam width cannot be decreased at will, one might question the advisability of using a pulse length short enough to make range discrimination much better than azimuth definition at the range of the target being examined. A study of the photographs in Fig. 15 will show how much is gained in signal identification by going to shorter pulses. These photographs show the one-mile azimuth presentation for the J1-1 in going from 5 µsec down to 0.10 µsec.

The related problem of range definition versus azimuth definition is illustrated in Fig. 16. Here, one photograph shows the mapping produced by using a narrow antenna pattern (1.5°) and relatively long pulses (1 µsec), while the other shows the mapping produced by a broad antenna pattern (5°) and short pulses (0.10 µsec). Much more signal definition is afforded by the broad beam and short pulse presentation.

The ideal solution, as stated previously, is to decrease both the beam width and the pulse length. The best example of this obtained thus far is the photograph in Fig. 17. This is a photograph of signals received on the X-band S-2 system at 0.03 µsec pulse length and 0.6° antenna beam and displayed on a two-mile PPI sweep. Since the antenna is located much higher than the surrounding buildings and since the beam is so narrow in elevation, only a limited region around M.I.T. is fully illuminated. This region illuminated depends on the angle of elevation of the antenna system. The accompanying map and aerial photographs show how much can be distinguished on the PPI.

In the use of these very short pulses, very many interesting facts have been observed. In general, buildings and solid objects give a very steady signal return, while trees, boats, birds, and flags give a signal which fluctuates quite rapidly. The smallest targets thus far observable are seagulls, skaters, buoys, lamp posts, flags and row-boats. Subway trains can easily be followed over the Longfellow bridge.

An additional advantage gained by the use of short pulses is the decrease in minimum range. The minimum range on a target obtained on the D2-1 PPI is a turret 25 feet away. The minimum range at which a target is detected on the A-scope is 3 feet. The target was a corner reflector held outside the turret. This minimum range is much less than has been required as yet, but it does indicate that such minimum ranges are possible.

One problem met in the PPI presentation of short pulses on short sweeps starting at the transmitter is that of side lobes and signals caused by secondary reflection from near-by radomes, walls, etc. Since the signal intensity from any target follows the inverse fourth power law, a target near-by will give a much stronger signal than one some distance away, and in some cases, the side lobes from such near-by targets are strong enough to show on the PPI. These side lobe signals and secondary reflections can be eliminated by the use of a sensitivity time control unit. This unit can be used to decrease the receiver gain immediately following the initial pulse, then allowing the gain to increase following an exponential curve. With such a circuit it is possible to present near-by signals unsaturated while noise is showing on the outer edge of the scope. This same unit has been used successfully on the AEW to help reduce the masking of signals due to sea clutter.

As a countermeasure against enemy interference the value of short-pulse radar systems depends on the type of interference. For confusion interference such as clouds, window, and sea return, the use of short pulses is valuable inasmuch as such signals are discriminated against in favor of more solid targets as discussed earlier. In the case of permanent echoes, short pulses are valuable in that they make possible greater signal definitions and hence decrease the possibility of confusion caused by large blocks of solid signals. The ability to identify certain factories, gas tanks, off-shore signals, is very valuable in aerial navigation. The photographs in Figs. 15, 16, and 17 amply illustrate this fact.

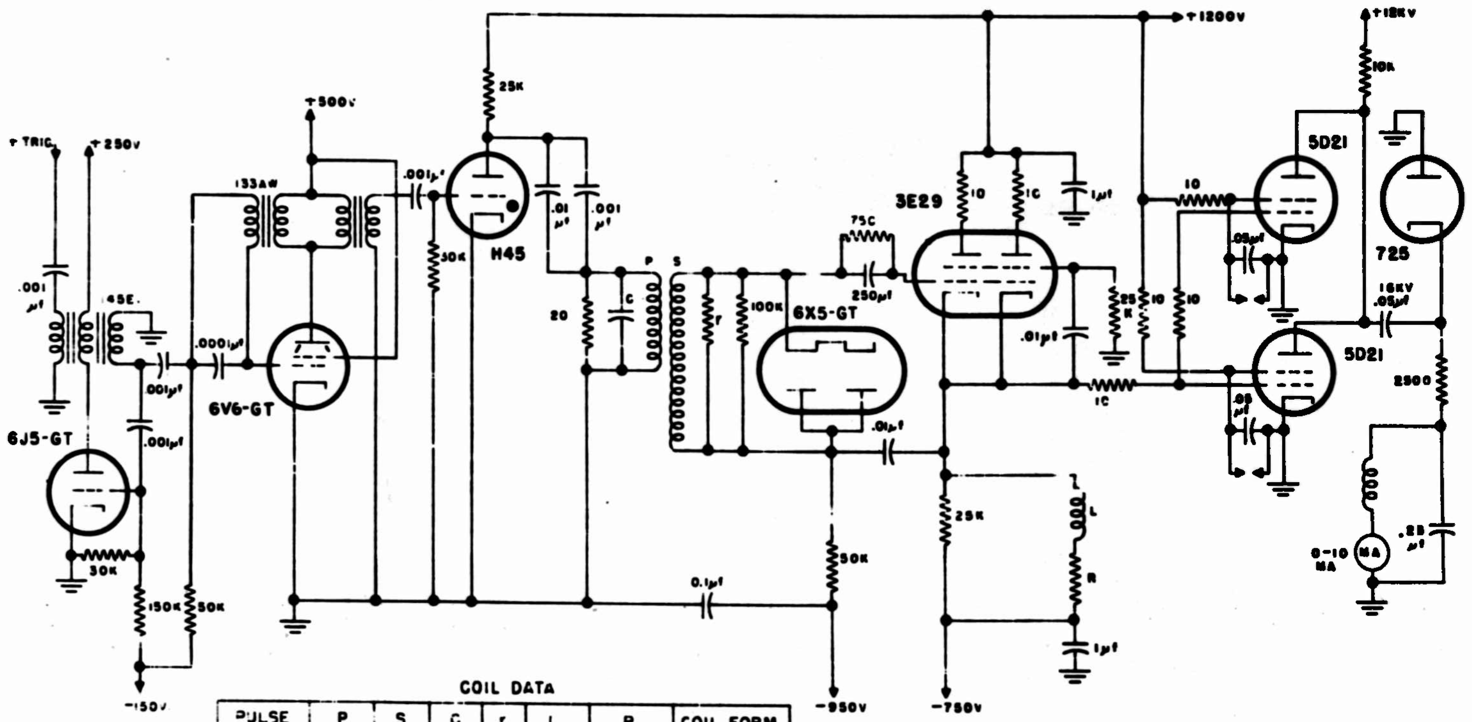
Unfortunately, enemy interference is not limited to such forms as mentioned previously. Other types of interference include various forms of c-w jamming, railings, noise, and false signals. The wide band receivers necessary for short pulses are quite vulnerable to these types of jamming because they will receive such signals over their entire pass band. Other countermeasures such as back biasing, railing suppression, and fast time constants must be used in the receivers under such jamming conditions.

Since the uses to which a radar set can be put are many and varied, the choice of pulse length depends on the function of the radar set. If the radar system is an early warning system where maximum signals to noise is most important, it would be unwise to use short pulses. On the other hand, if the set is to be used in navigation, fire control, or in such tasks where accurate ranging and signal definition are most important, short pulses would be very valuable.

If a system is to serve one specific purpose then the pulse length best suited for that purpose should be used. If the system is to be used for a variety of purposes, then several different pulse lengths should be available.

Vernal Josephson
November 30, 1945

LIST OF FIGURES



COIL DATA

PULSE	P	S	C	r	L	R	COIL FORM
1.0µ SEC	100T	400T	—	500	300µh	500 OHMS	1"
0.25 "	25 T	100T	—	200	50 "	200 "	1"
0.10 "	8 T	35T	.002	1000	20 "	100 "	3/4"
0.05 "	3 T	12 T	.002	—	20 "	100 "	3/4"
0.03 "	1½T	6 T	.002	—	10 "	100 "	3/4"

NOTE: THE CATHODE LOAD OF THE 3E29-L&R IS MOUNTED ALONG WITH THE PULSE LENGTH COIL ON A TUBE BASE WHICH IS PLUGGED INTO THE FRONT OF THE UNIT.

ALL RESISTORS ARE IN OHMS.

FIG. I CIRCUIT DIAGRAM OF SHORT PULSE MODULATOR

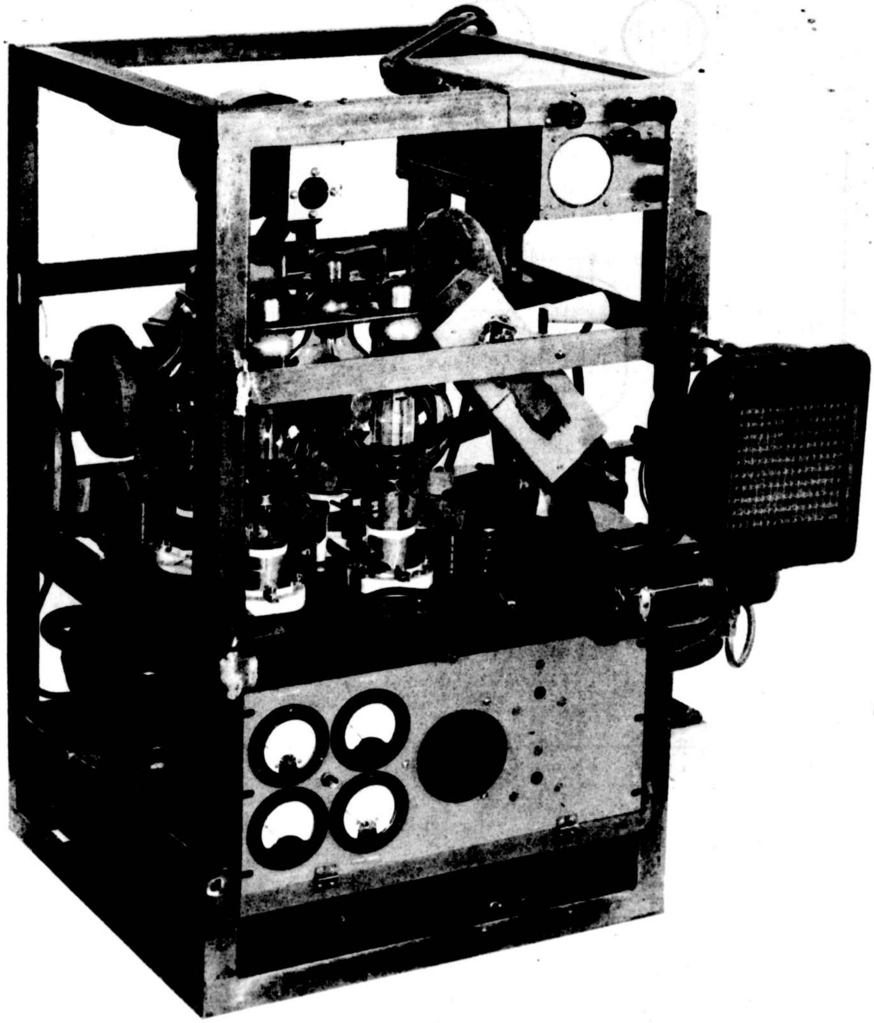


FIG. 2 — PHOTOGRAPH OF S-2 SHORT PULSE MODULATOR

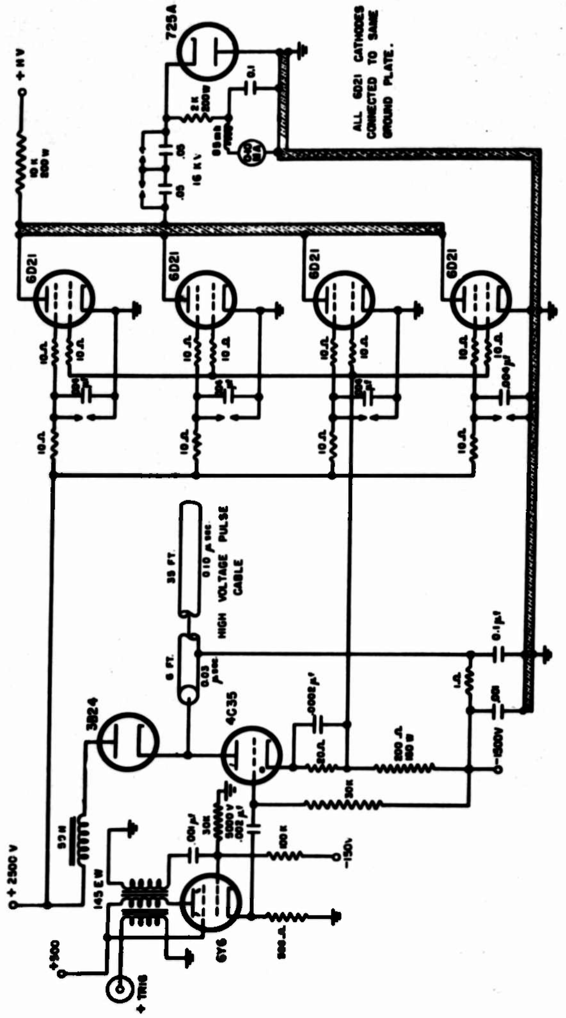
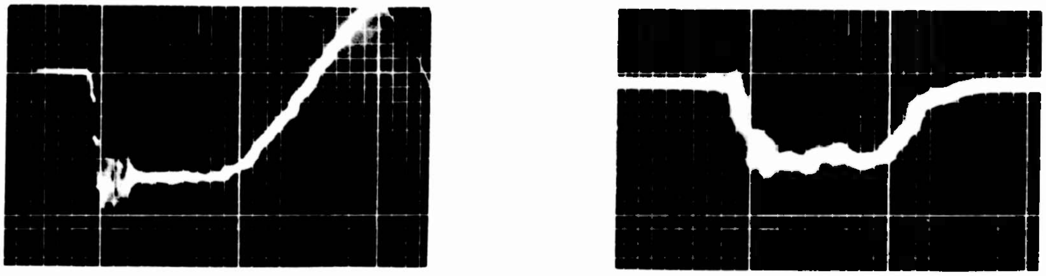
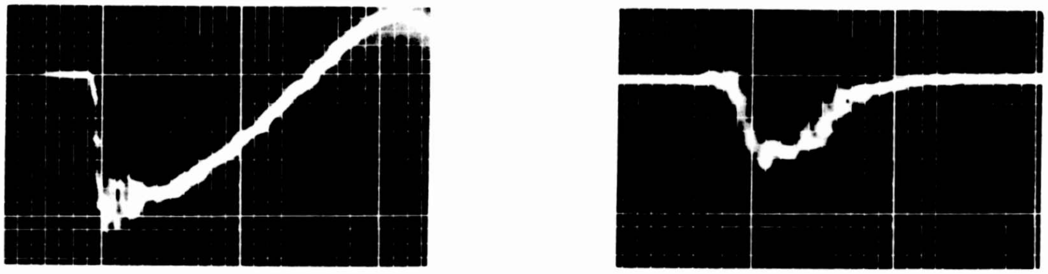


FIG. 3 CIRCUIT DIAGRAM OF S-2 SHORT PULSE MODULATOR



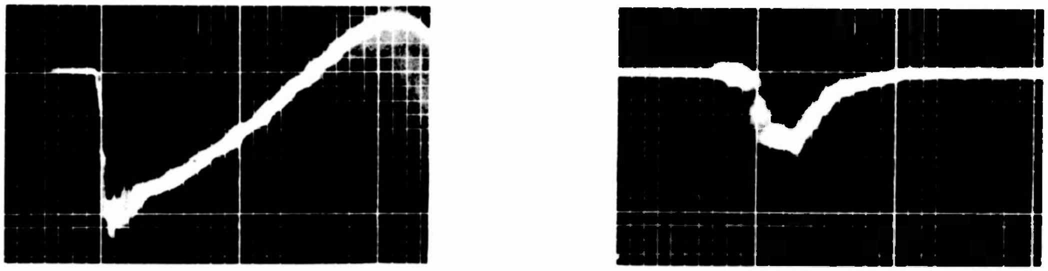
0.10 μSEC VOLTAGE PULSE

0.10 μSEC R.F. PULSE



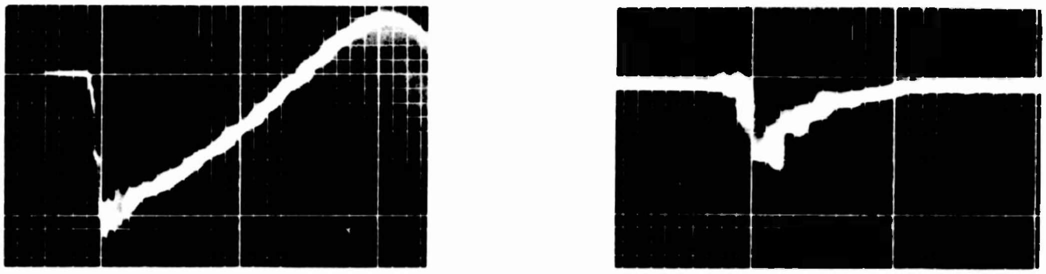
0.05 μSEC VOLTAGE PULSE

0.05 μSEC R.F. PULSE



0.03 μSEC VOLTAGE PULSE

0.03 μSEC R.F. PULSE

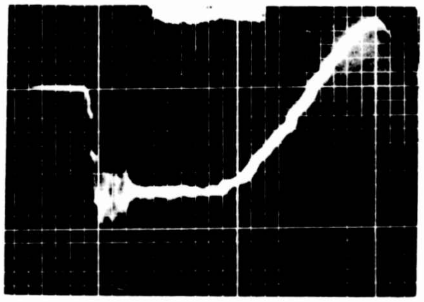


0.02 μSEC VOLTAGE PULSE

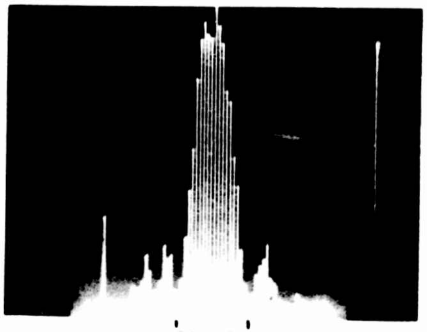
0.02 μSEC R.F. PULSE

FIG. 4 – VOLTAGE AND R.F. PULSE SHAPES OBTAINED FOR THE PULSE LENGTHS AVAILABLE ON THE S-2 MODULATOR AND ITS 4J50 MAGNETRON.

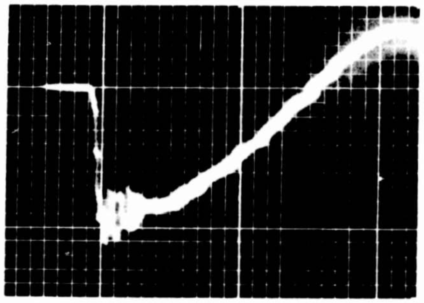
SCALE = 0.10 μSEC/INCH



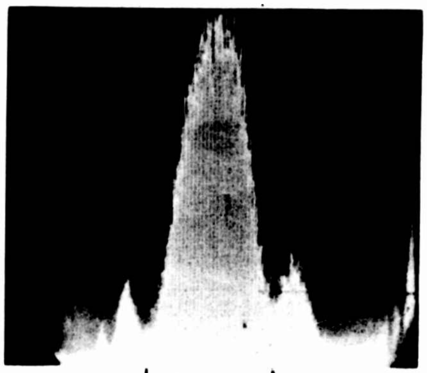
0.10 µ SEC VOLTAGE PULSE



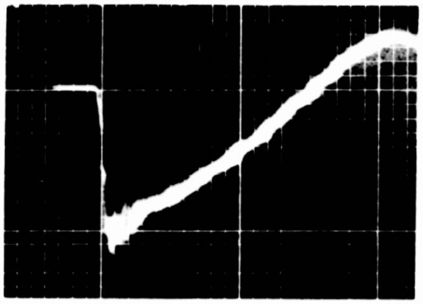
0.10 µ SEC R. F. SPECTRUM



0.05 µ SEC VOLTAGE PULSE

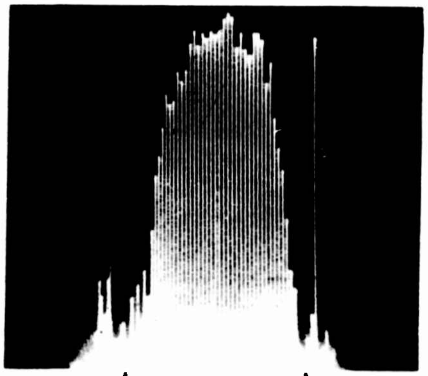


0.05 µ SEC R. F. SPECTRUM



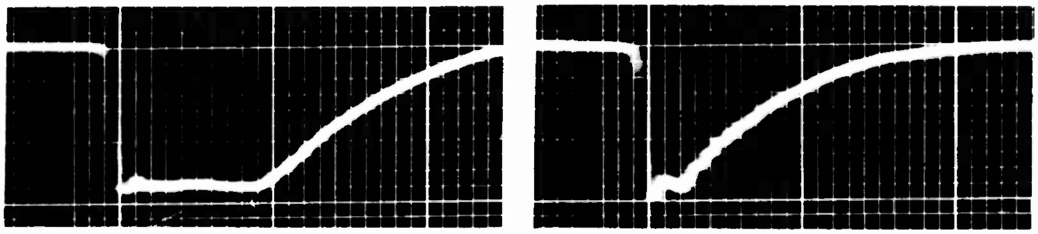
0.03 µ SEC VOLTAGE PULSE

SCALE = 0.10 U SEC/INCH

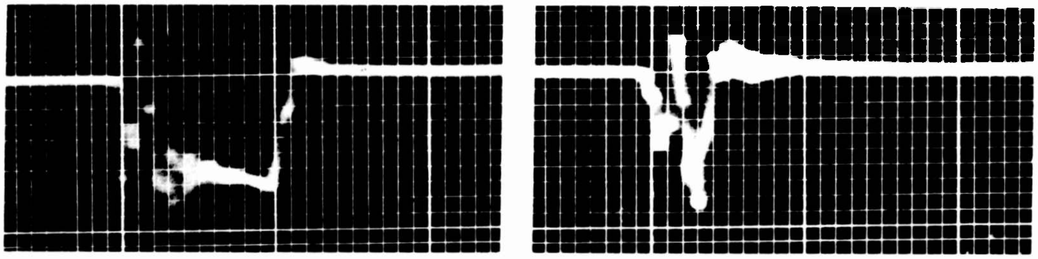


0.03 µ SEC R.F. SPECTRUM

FIG. 5 — VOLTAGE PULSES AND CORRESPONDING R.F. SPECTRA FOR DIFFERENT PULSE LENGTHS ON THE S-2 MODULATOR AND ITS 4J50 MAGNETRON.



0.10 μ SEC VOLTAGE PULSE   0.03 μ SEC VOLTAGE PULSE



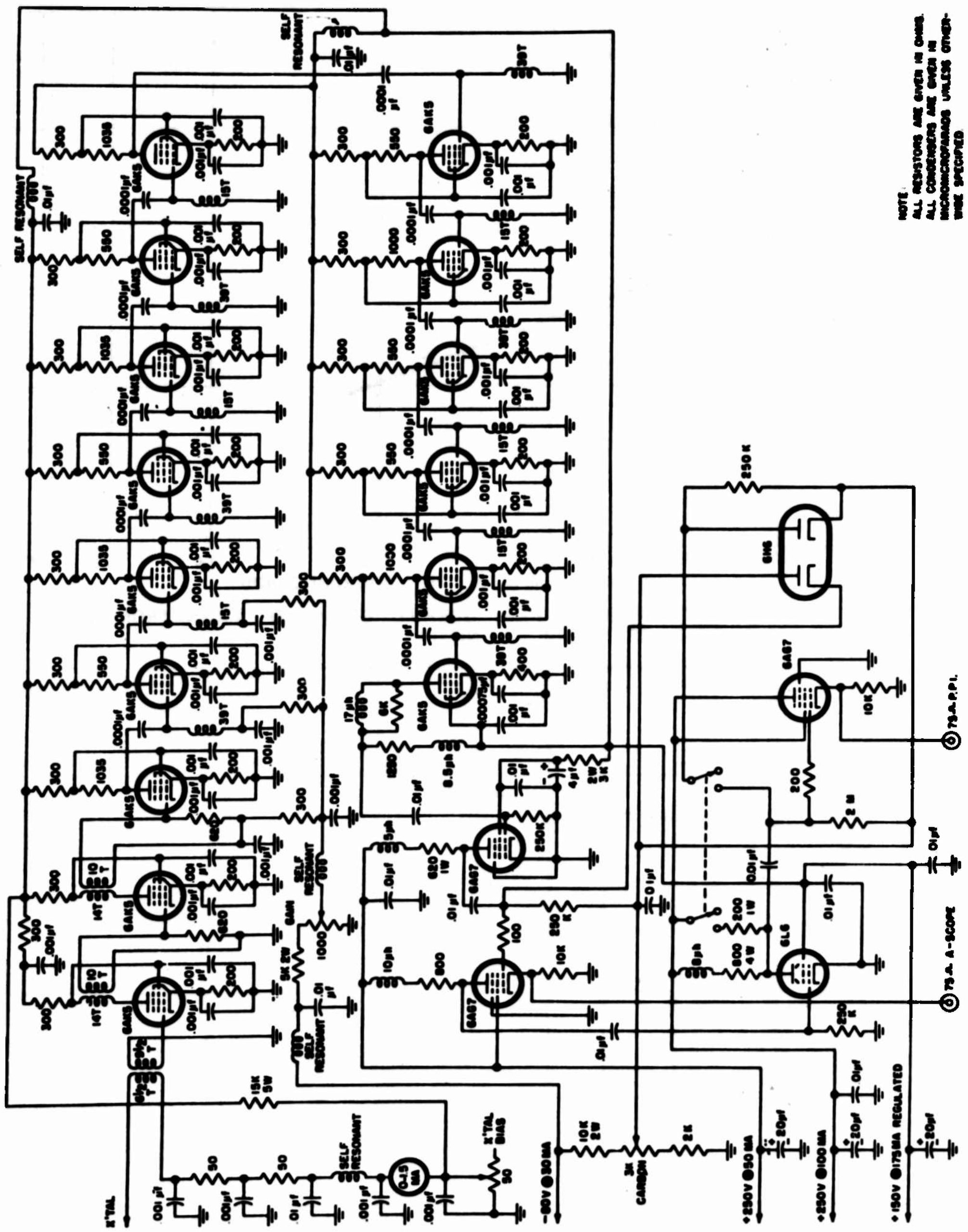
0.10 μ SEC CURRENT PULSE   0.03 μ SEC CURRENT PULSE

SCALE = 0.10 μ SEC/INCH

20 MC/SEC   70 MC/SEC

0.10 U SEC R. F. SPECTRUM   0.10 U SEC R. F. SPECTRUM

FIG. 6 — VOLTAGE AND CURRENT PULSES AND R. F. SPECTRA FOR TWO PULSE LENGTHS OBTAINED WITH ALVX MAGNETRON.



NOTE:
ALL RESISTORS ARE GIVEN IN OHMS.
ALL CONDENSERS ARE GIVEN IN
MICROMICROFARADS UNLESS OTHER-
WISE SPECIFIED

FIG. 8 CIRCUIT DIAGRAM OF 15 MC/SEC RECEIVER

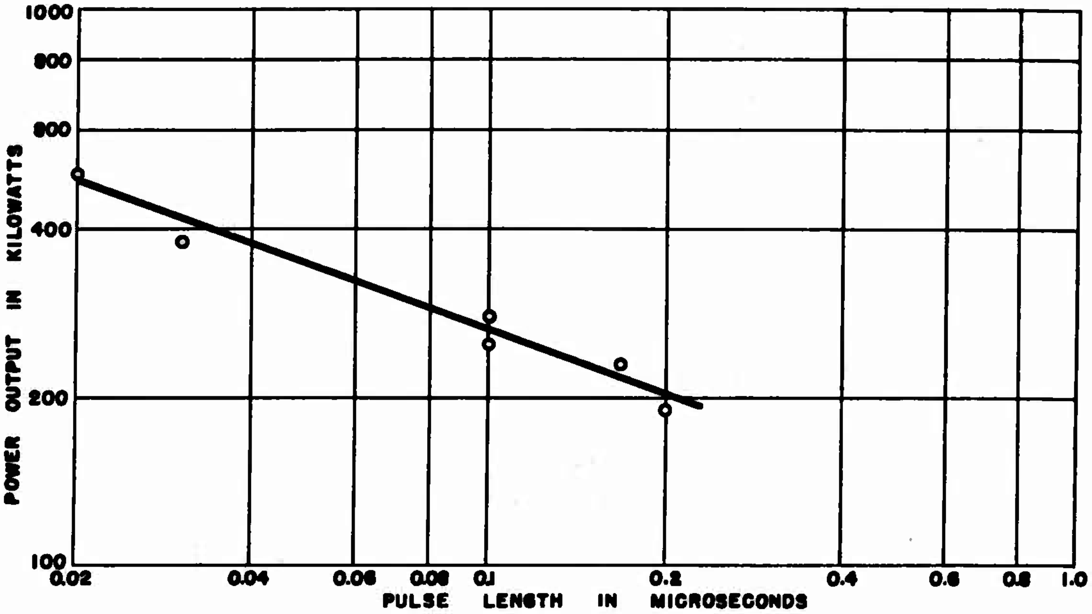


FIG. 7a – MAXIMUM PULSE POWER OUTPUT OF 4J50 MAGNETRON AS A FUNCTION OF PULSE LENGTH.

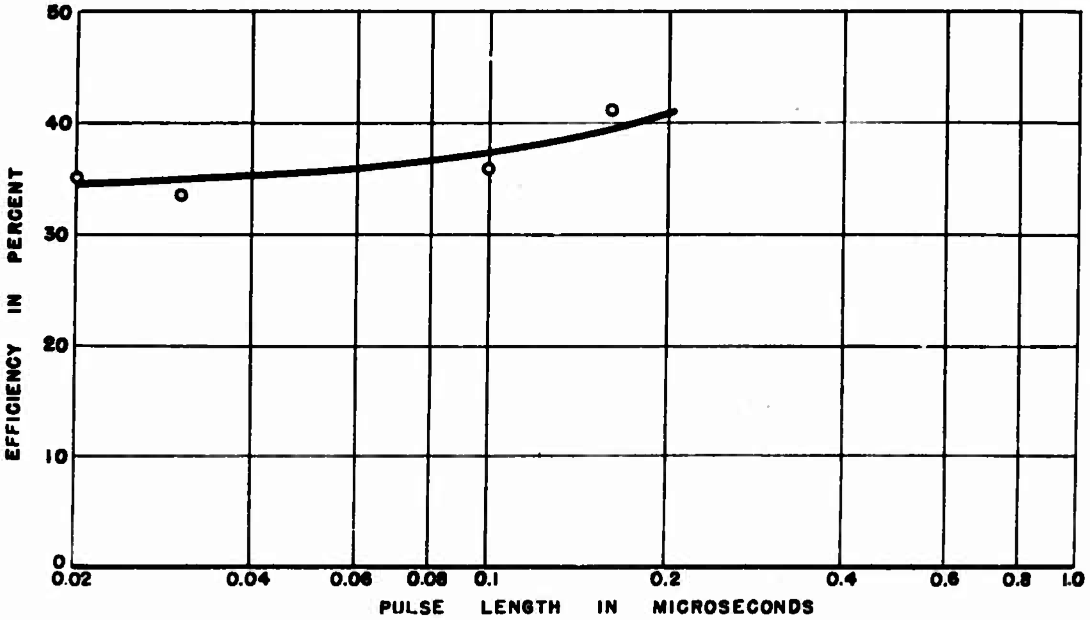


FIG. 7b – EFFICIENCY AT MAXIMUM PULSE POWER OUTPUT OF 4J50 MAGNETRON AS A FUNCTION OF PULSE LENGTH.

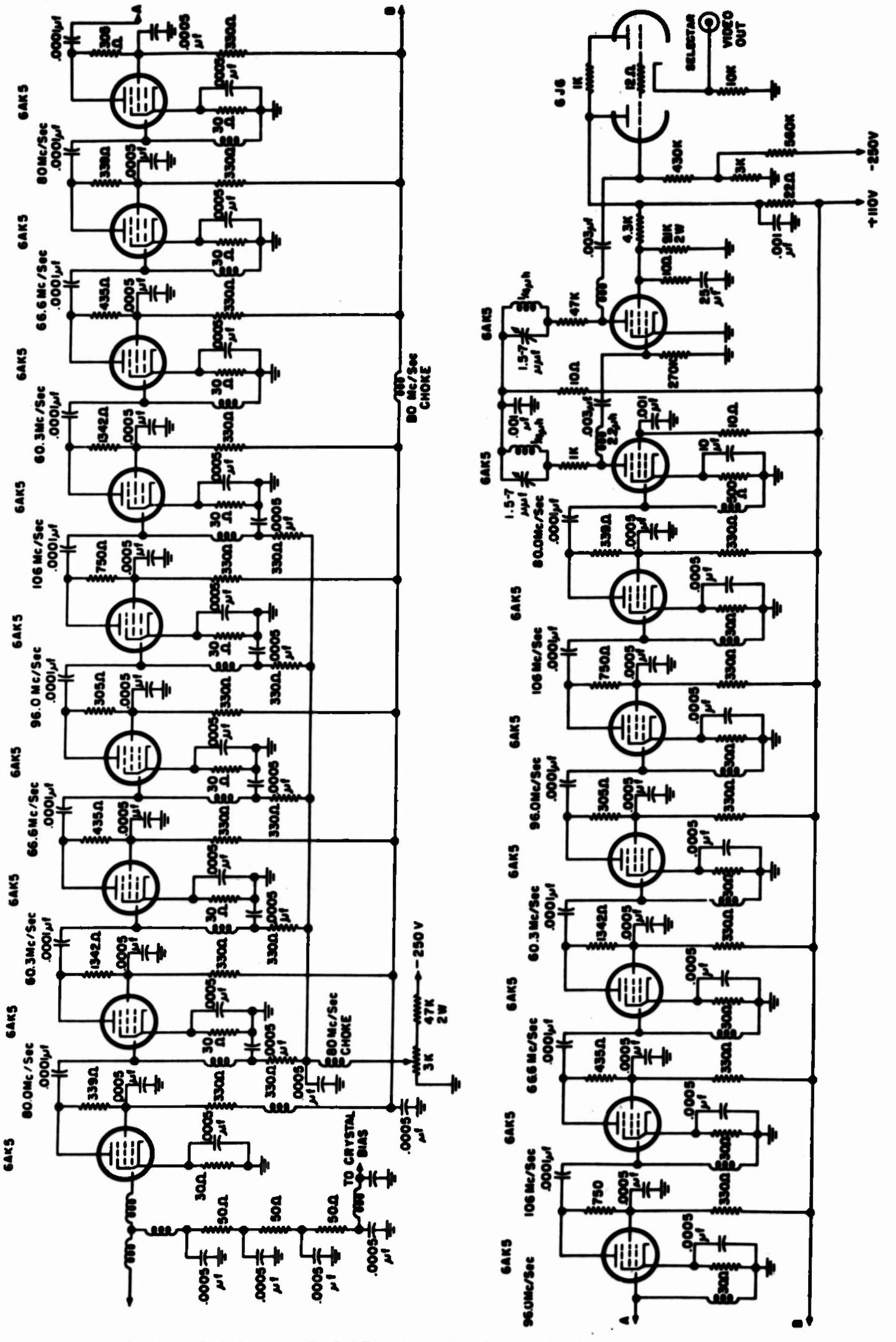


FIG. 9 CIRCUIT DIAGRAM OF 35 MC/SEC RECEIVER

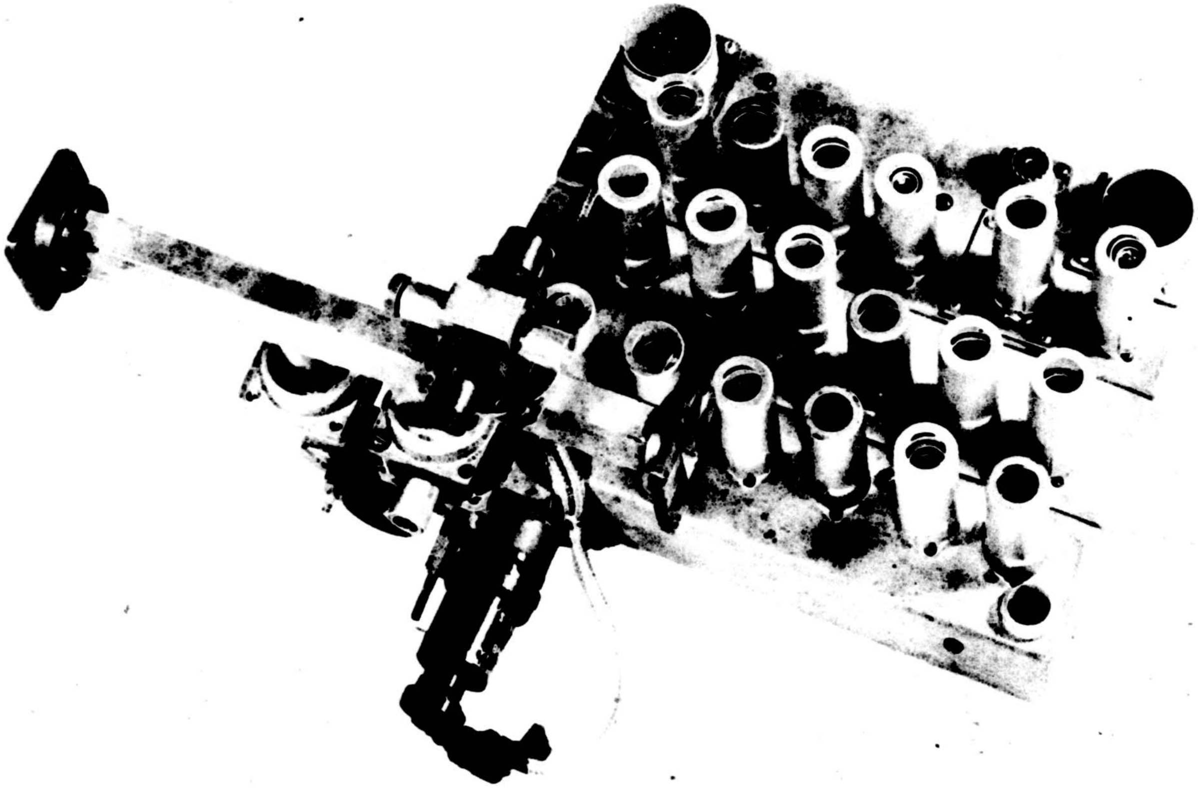


FIG. 10 — 35 MC/SEC WIDE BAND RECEIVER.

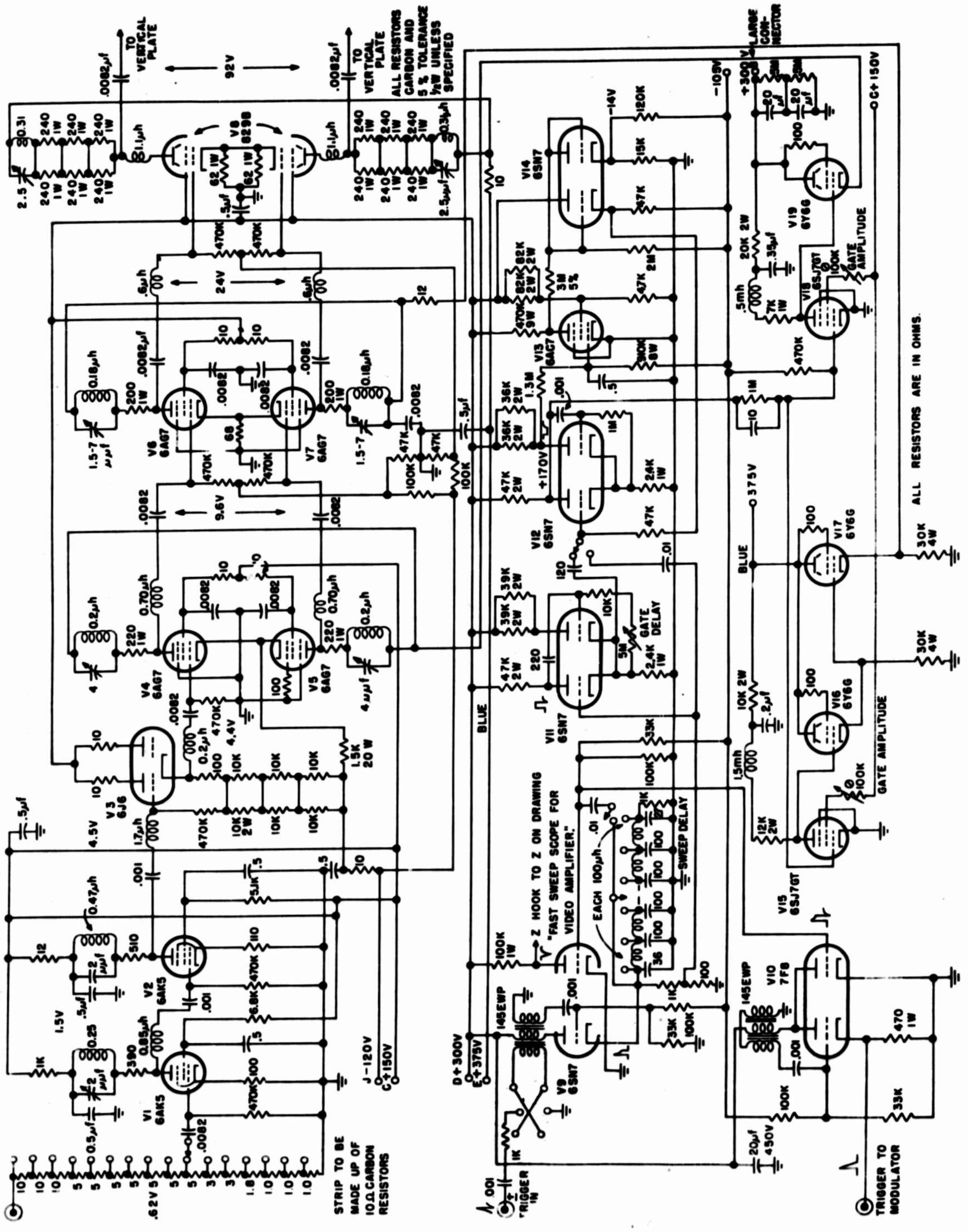


FIG. 11 DIAGRAM OF 35 MC/SEC VIDEO AMPLIFIER

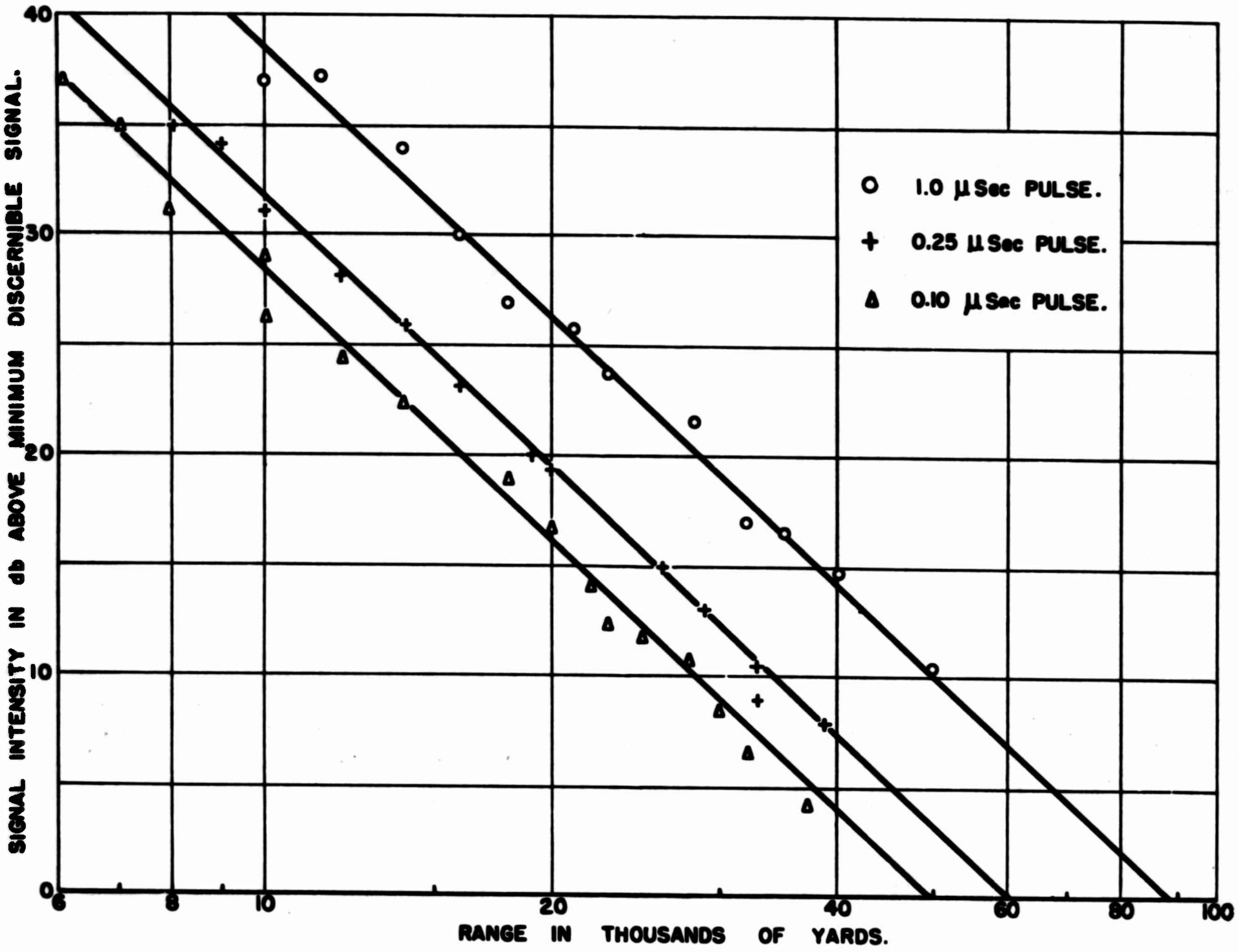
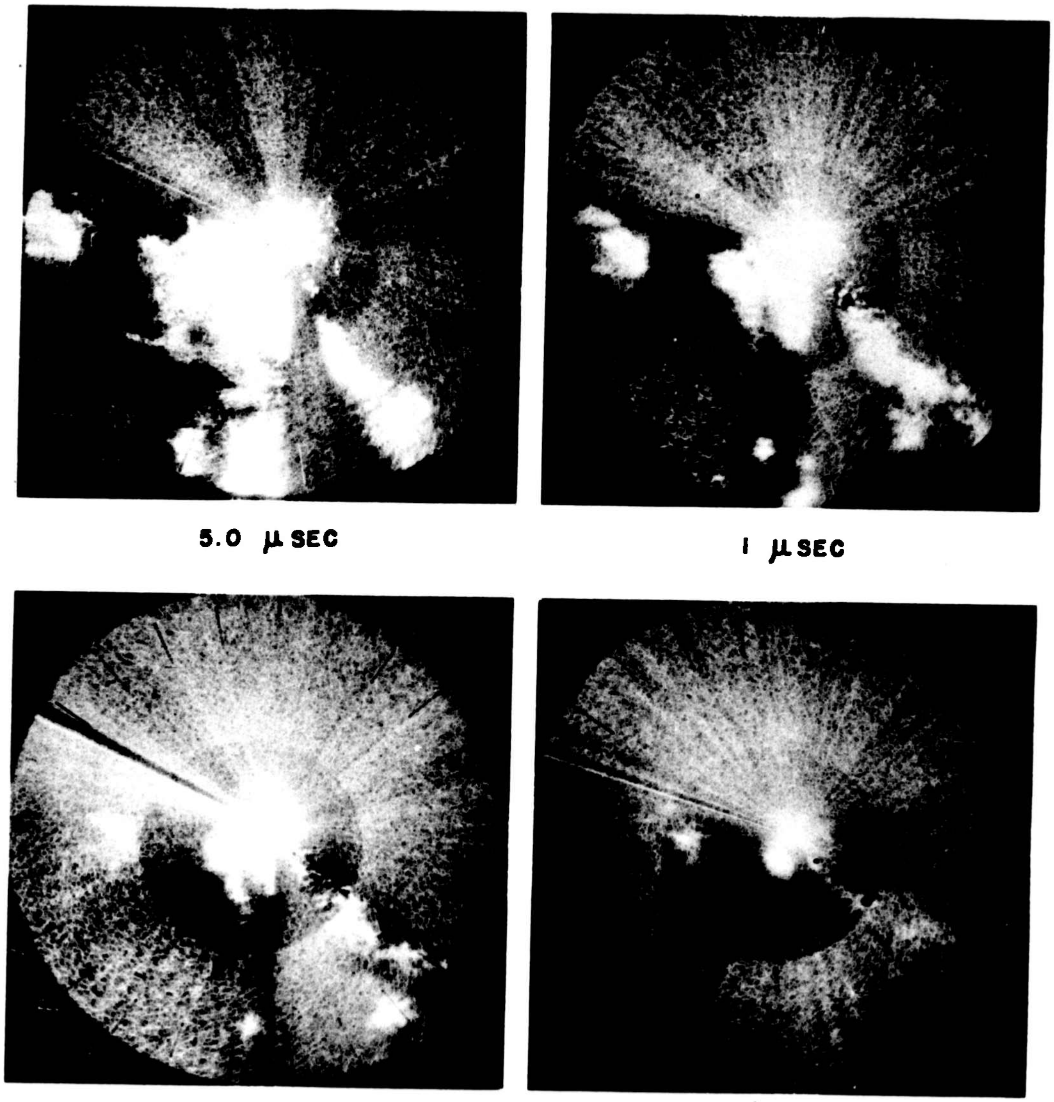


FIG. 12 — MAXIMUM EXTRAPOLATED RANGES OBTAINED BY THE D2-1 ON A TBM PLANE FOR THREE DIFFERENT PULSE LENGTHS.



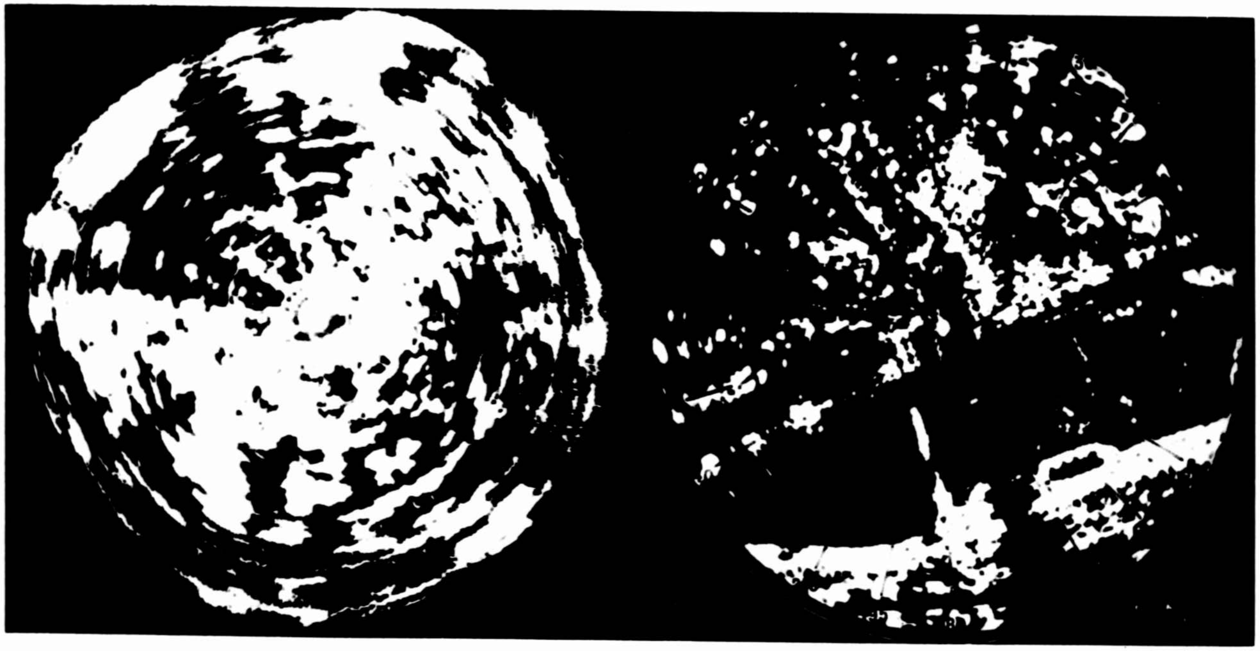
5.0 μ SEC

1 μ SEC

.25 μ SEC

05 μ SEC

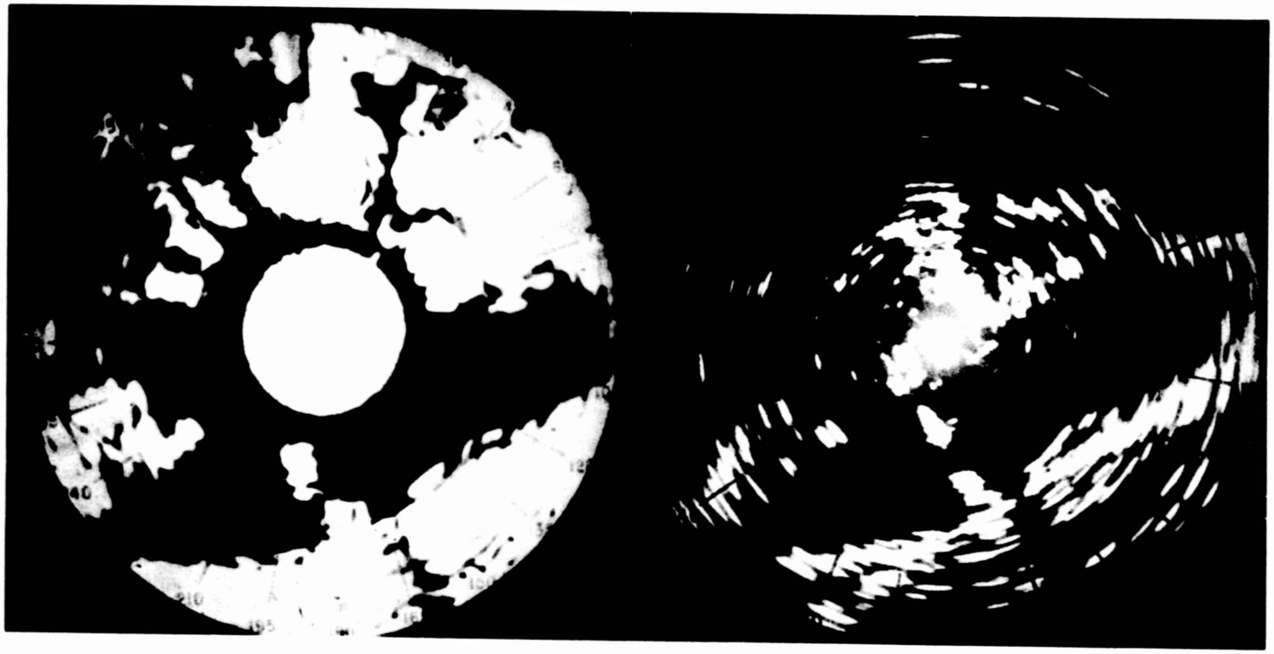
FIG. 13 – PHOTOGRAPHS SHOWING THE DECREASE IN CLOUD SIGNALS WITH DECREASING TRANSMITTER PULSE LENGTH.



(a)

(b)

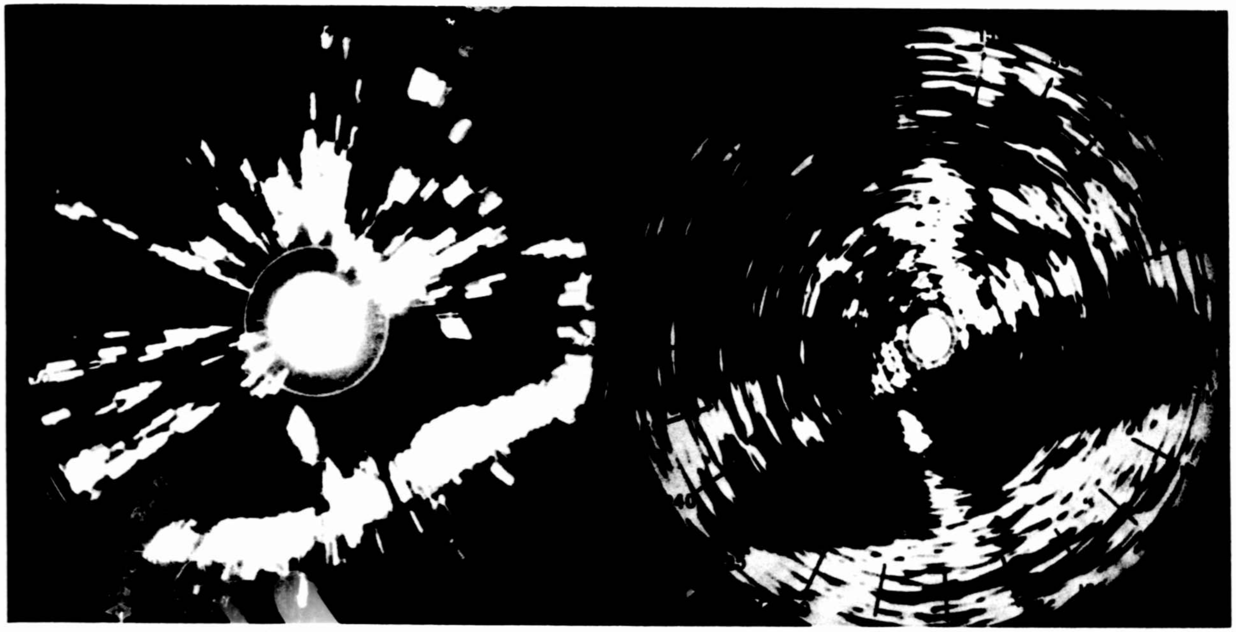
FIG. 14 – (a) JI-I PPI PHOTOGRAPH TAKEN IN 1942
(b) D2-I PPI PHOTOGRAPH TAKEN IN 1945



(a)

(b)

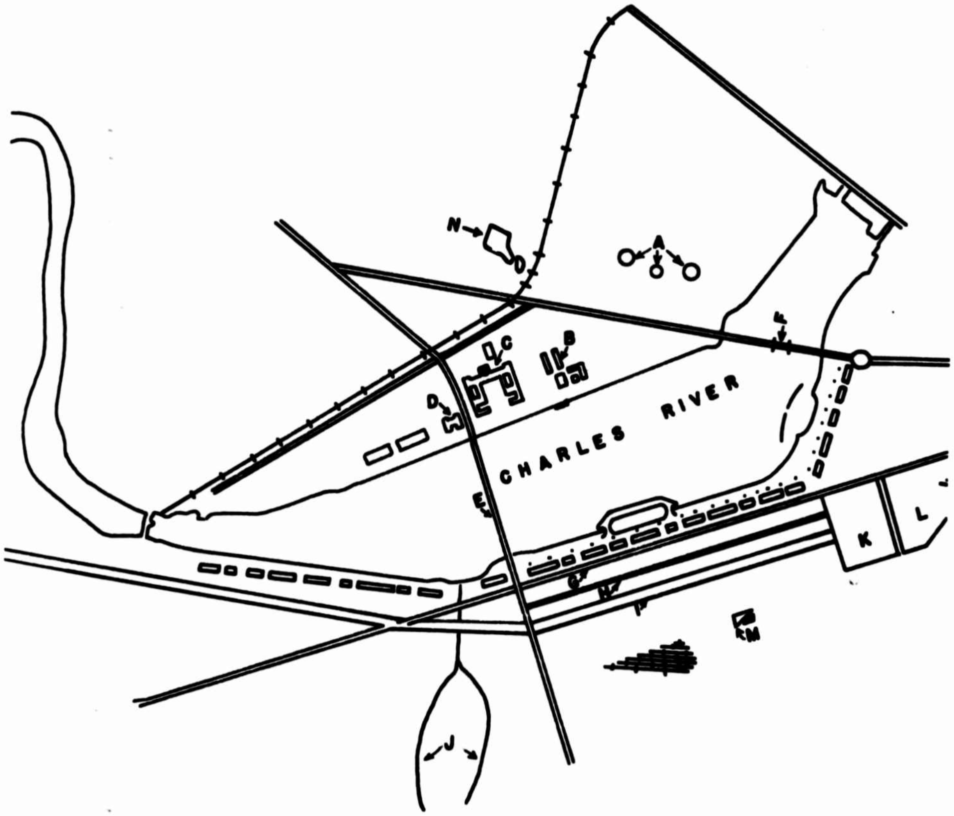
FIG. 15 – J1-1 PPI PHOTOGRAPHS TAKEN AT (a) 1 μSEC AND (b) 0.10 μSEC PULSE LENGTHS.



(a) 1.5° beam 1 μsec pulse (b) 5° beam 0.10 μsec pulse

FIG. 3- PPI PHOTOGRAPHS SHOWING THE RELATIVE MERITS OF
(a) AZIMUTH DEFINITION AND (b) RANGE DEFINITION.

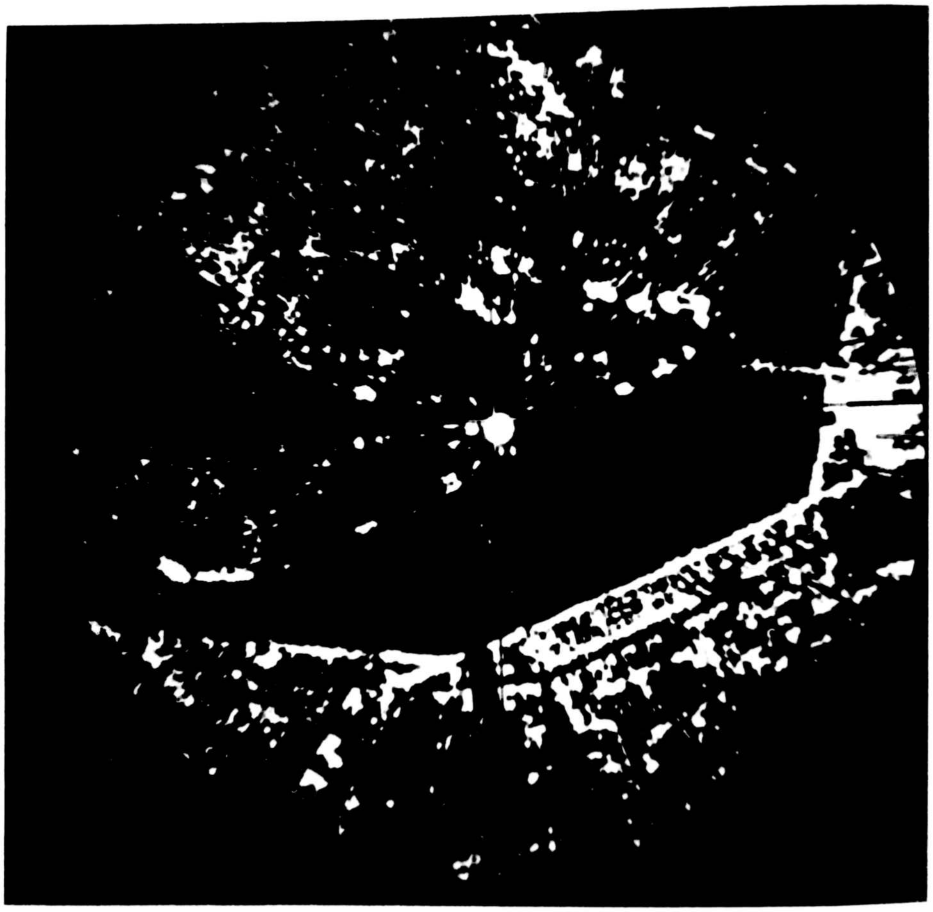
c.



A GAS TANKS
B DORMITORY
C TECHNOLOGY
D GRADUATE HOUSE
E HARVARD BRIDGE
F LONGFELLOW BRIDGE
G BEACON STREET
H MARLBOROUGH STREET
I COMMONWEALTH AVENUE
J FENWAY
K PUBLIC GARDENS
L BOSTON COMMON & STATUE
M COPLEY SQUARE
N LEVER BROS. FACTORY

b.

FIG. 17 - COMPARISON OF S-2 PPI WITH AERIAL PHOTOGRAPH AND MAP.



a.

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ABSTRACT:

Investigations have been carried out on the problems of producing short pulses and the necessary equipment for utilizing these pulses. Modulators capable of producing pulses as short as 0.02 micro sec have been built and tested. A receiver with an IF pass band of 35 mcps and a video amplifier and A-scope with a pass band of 35 mcps have been built and tested. Three different types of magnetrons, 725A, LVX, and 4J50 have been tested on short pulse operation with good results. Radar operational tests using short pulse equipment indicate that short pulses are quite valuable in combating confusion types of interference and in obtaining good signal definition, but are not recommended for long range operation, or where any types of electrical interference are present.

(23) * Modulators ; Pulses Pq/1

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AIR TECHNICAL INDEX

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