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NATIONAL RESEARCH COUNCIL OF CANADA

RADIO AND ELECTRICAL ENGINEERING DIVISION

A COHERENT PULSE RADAR FENCE SYSTEM

D. W. R. McKINLEY

OTTAWA

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by D.W.R. McKinley

Abstract

This report describes in general terms the design and performance of the first experimental model of the N.R.C. coherent pulse radar equipment. A line of these early warning stations across the north of Canada is visualized to relieve the load on the main defence system. Two fixed, narrow azimuth, vertical fan beams are directed obliquely from each station in the fence, with an average station separation of 30 miles. Coherent pulse and integration techniques are used to distinguish moving targets from permanent echoes. The antenna pattern is 10° in azimuth and cosecant to 40,000 ft. The crystal-controlled transmitter emits 5 KW peak, 20µs pulses on 600 Mc. Automatic alarm of moving targets is provided with coarse range discrimination. No operator is needed but maintenance will be required. Ranges up to 70 miles have been obtained on random aircraft, although formal flight trials have not been carried out yet. Under moderate clutter conditions the system is stable, without false alarms, and operates on aircraft echoes 3 db above noise. In severe clutter the operation is not yet entirely satisfactory.

1.0 Introduction

Early in 1951 the problem of providing early warning of enemy aircraft approaching from the north became particularly acute, when it was apparent that the combined available resources of Canada and the United States were likely to be insufficient to install, and to maintain on a 24-hour basis during peace time, a network of high-power conventional radar stations which could furnish complete coverage across Canada. Several proposals for more elementary radio detection devices were put forward, some of which are under investigation elsewhere. The philosophy behind these proposals was based largely on the logistics of the situation, supplemented by technical considerations such as the detection of low-flying aircraft.

Several high-power, fully-manned stations (AN/CPS-6B, etc., each with a complement of 300-400 men) are already installed or being installed at key spots in the defence zone just north of the Canada-U.S.A. border. Apart from the consideration that the system when finished will not give complete protection from coast to coast, the cost of keeping all these stations on full watch is a cause of some concern. If a forward line of early warning stations were to be established well north of the areas in which the large radars will operate, so that one to two hours' advance notice of a raid should be available, the strain on the main radar system would be greatly relieved. Even the bare information that something was coming would be very useful; any further data, such as position plots, numbers of aircraft, speeds and directions, heights, etc., would add to the value of course, if they can be obtained without adding greatly to the cost and difficulty, but they are not regarded as essential to the scheme. As it is likely that some of the forward line stations would be sited in territory inaccessible during a large part of the year it was considered desirable that the equipment should be as simple and reliable as possible, require a minimum of maintenance, and be capable of automatic operation, i.e., with no operator on continuous watch. Estimates of the station maintenance crew have varied from one to ten men, but in any case they represent a tremendous reduction in both numbers and skill of personnel compared to the large radars.

The Radio Physics Laboratory of the Defence Research Board has developed a long pulse doppler radar system operating on 90-100 Mc. with a broad, flood-lighting antenna pattern facing in the expected direction of attack. This is described in RPL report No. PR8-1. The Eaton Laboratory at McGill University has done considerable work on a C. W. doppler system on 600 Mc, using a narrow, vertical fan beam pattern directed obliquely across the line of attack. A variation of this system is now under way at the RCA laboratories, Montreal, with the assistance of the Eaton Laboratory, in which the transmitter is at one station and the receiver at another, say 30 miles apart, with the narrow beams facing each other. The short pulse doppler radar system developed by the N.R.C. also operates on 600 Mc. and uses the narrow fan beam type of antenna.

In this report no attempt will be made to discuss the general operational research problem which has been considered in detail elsewhere.* The intention is solely to provide a brief description of the first experimental model of the N.R.C. equipment with some assessment of its performance capabilities. Later reports will cover full details, including improvements now being incorporated, and flight trials.

2.0 The Coherent Pulse Radar Set - General Description

Fig. 1 is a simplified block diagram illustrating the operation of the equipment. A 10 Mc quartz crystal unit provides the basic frequency control. The crystal output is multiplied to 50 Mc in a stage that is pulsed by a low-power modulator. Further frequency multiplication and power amplification are done by stages which have steady D. C. on their electrodes, and which are grid-biased beyond cut-off so that no plate or screen currents flow, and no output is obtained except when

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* D.R.B. Operational Research Memo. No. 22A, April 1952, by R.J. Sutherland

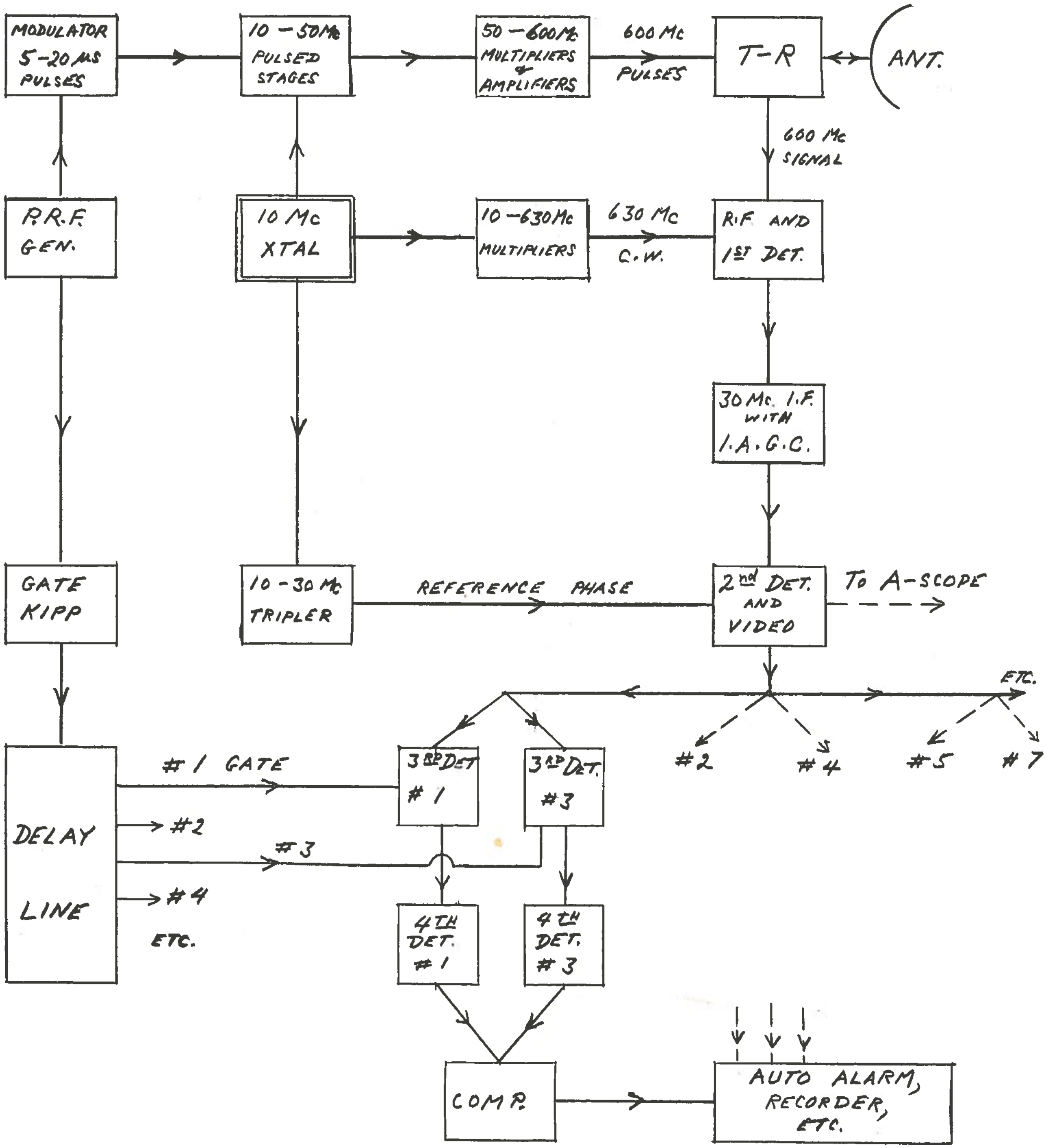


Fig. 1 Block Diagram of Coherent Pulse Radar

the first multiplier is pulsed. The modulator pulse width is variable from 5 to 20 µs, and the pulse recurrence frequency may be changed from 700 to 1200 p.p.s. The peak output power on 600 Mc. is 4 to 5 KW and the average power output may run from 20 watts to about 100 watts, depending on pulse widths and p.r.f.

The transmitter power goes through the T-R unit, which contains both T-R and anti-T-R discharge tubes, and then through a waveguide to the horn-fed parabolic antenna. The horizontal beam-width at half-voltage (actual coverage pattern) is about ten degrees, and the reflector has been designed to provide approximate cosecant coverages to 40,000 feet and 50 miles, with the transmitter power and receiver sensitivity employed.

The receiver signals pass through the T-R switch to the receiver, consisting of a stage of r.f. amplification followed by a silicon diode 1st detector. Local oscillator voltage for the 1st detector is obtained from a multiplier chain, 10-630 Mc. The 30 Mc I.F. amplifier has I.A.G.C. to cope with strong ground clutter. The 2nd detector is supplied with a 30 Mc coherent reference voltage also obtained from the 10 Mc crystal, and the following video stages are Class A amplifiers designed to provide bi-polar video output.

The video signal may be examined on a conventional A-scope, which is a useful instrument for tuning-up the equipment and for reading accurate target ranges, but it is not an integral part of the system. On the A-scan, noise appears above and below the sweep line, permanent ground clutter echoes appear either above or below the line depending on their relative phase, and aircraft echoes seem to the eye to be bi-polar or "butterfly" signals owing to the doppler change of phase from sweep to sweep. This "butterfly" moving target signal can be identified and followed without difficulty in strong ground clutter. If the 30 Mc reference voltage is switched off the video output becomes mono-polar, as in the conventional radar A-scan, and it is then frequently difficult or impossible to locate aircraft in the clutter.

The transmitter pulse itself may be expressed in terms of a Fourier series of frequencies, each spaced by P. where P is the P.R.F., and with amplitudes given by the usual $\left|\frac{\sin x}{x}\right|$ relation (Fig. 2),

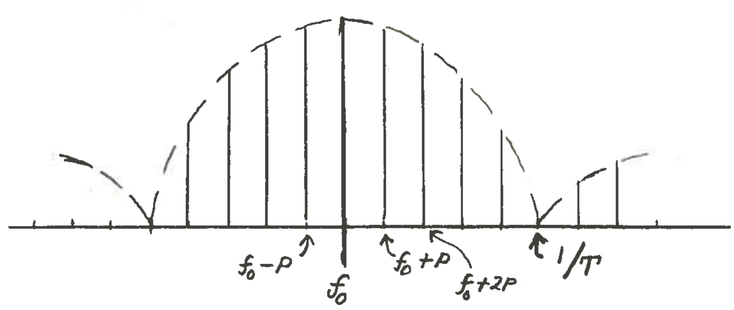


Fig. 2 Spectrum of Transmitted Pulse

spaced about f_o, the unmodulated carrier frequency, with the first nulls occurring at $f_o \pm 1/T$, where T is the pulse width. After the 2nd detector the phase of the output frequencies depends on the arbitrary phase of the reference voltage. In this simplified analysis we shall ignore phase and consider frequencies only. Fig. 3, solid lines, shows the video spectrum of the transmitter pulse, or of the received echo from a fixed ground target.

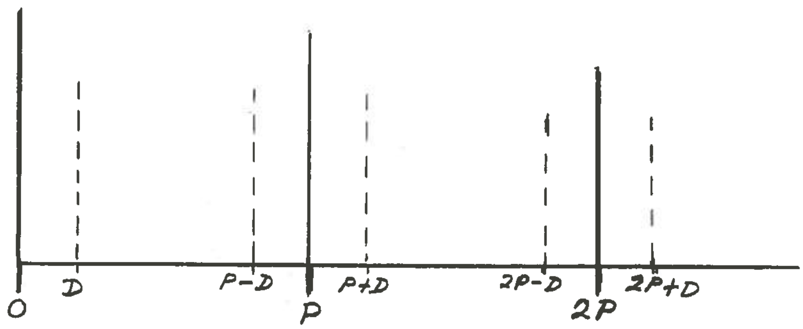


Fig. 3 Video Spectrum

A moving target will produce a doppler shift of all the frequencies of the transmitted spectrum, the shift being towards higher frequency if the target is approaching, and vice versa. The magnitude of the frequency shift, D, is given by $D = \frac{2V\cos\theta}{\lambda}$, where V is the aircraft velocity, λ the carrier wavelength, and θ the angle between the aircraft's track and the line joining the aircraft to the station. For our wavelength of 50 cm we have $D = 1.8V\cos\theta$ where D is in cycles per second, and V is in statute miles per hour. At the 2nd detector an additional series of lines appears in the video frequency spectrum, D, P-D, P+D, 2P-D, etc. as shown by dotted lines in Fig. 3. The doppler video frequencies are identical for an aircraft either approaching or receding on the same track with the same velocity, but the phases will differ for the two cases and, if the information is considered to be of value, a phasemeter can be used to determine the sign of the observed radial velocity.

To separate the doppler information from permanent echoes a conventional band-pass filter may be used to provide attenuation at zero frequency and at P c.p.s. and higher. The effective bandwidth at this stage in the receiver is then that of the B.P. filter but because all the higher order sidebands have been cut off a large amount of energy is not used. If the pulse width is increased a greater proportion of the energy will be concentrated in the first few lines of the spectrum, but the range resolution of the system deteriorates in proportion and a reasonable compromise must be found. Alternatively, a complex filter could be built, having sharp rejection peaks at frequencies P, 2P, etc., which would utilize the higher doppler components, but this is difficult to do in terms of L, C, components. Fortunately, the four-diode switch * provides precisely the desired filter characteristics,

* Waveforms - Chance et al. Radiation Laboratory Series, No. 19, p.519, 1949

in effect (Fig. 4). A gate pulse is supplied to the transformer T, to turn the switch on for 100 µs, i.e., 10 miles, say, at a predetermined

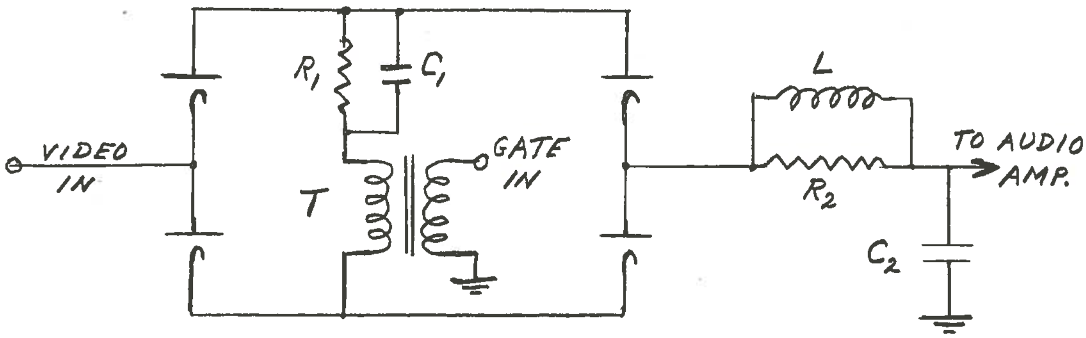


Fig. 4 Four-diode Switch

range on each sweep. R_2, L and C_2 form an integrating circuit with time constants selected to average the video current available during the 100 µs or so in which the switch connects this circuit to the video signal. At the end of the gate pulse the negative bias built up across R_1, C_1, holds the switch open and C_2 remains at its final potential until re-connected by the next gate pulse, Fig. 5. The average voltage

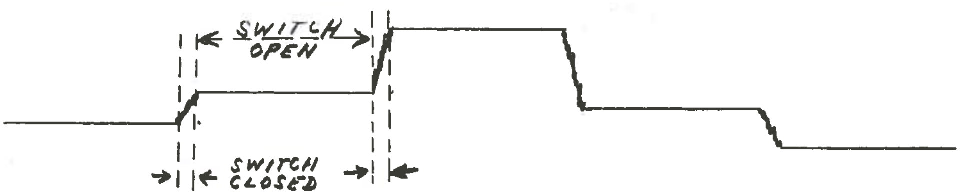


Fig. 5 Voltage on C_2

on C_2 from sweep to sweep, due to noise and permanent echoes in the gate, will remain relatively constant and only random fluctuations of the integrated noise or clutter signals will appear at the output of the A.C. audio amplifier. However, if a regularly varying video signal is present in the gate due to a moving target, the voltage at C_2 will have the form of regular "box-cars", and the envelope of these "box-cars" will be the desired doppler frequency. It may be noted that, if an audio signal generator is connected to the input of the diode switch, the same output amplitude and frequency, namely D c.p.s., will be obtained for generator frequencies of D, P-D, P+D, 2P-D, 2P+D, etc. limited only by the high-frequency characteristics of the switch and amplifier. Thus the switch, together with the audio amplifier whose low-frequency characteristics determine the width of the rejection bands about the video frequencies O, P, 2P, etc., furnishes the desired filter properties. The effective receiver bandwidth at this point is not easily defined because it depends on the combined effect of the integration while the switch is closed and the stationary level while it is open. If the closed-to-open ratio is small the effective bandwidth probably approaches P c.p.s.

Fig. 1 shows two 4-diode switches, here called 3rd detectors, which are supplied with gate pulses obtained at different range positions from a delay line. Six or eight gates may be used to cover a total range of 0-50 miles, with adequate overlap between gates. The output from each audio amplifier is rectified (4th detector) and filtered (time constant $\simeq$ 3 secs.) The resultant D.C. voltages are compared two at a time from non-adjacent channels, thus minimizing long-term variations in general noise level. If an aircraft echo appears in one gate a polarized relay closes, indicating the range block in which the target appears. The relay rings a bell in the station and may also be used to transmit the information automatically via radio or land-line to a remote centre.

Referring to Fig. 1, the P.R.F. generator triggers a monostable multivibrator, or Kipp relay, which produces a pulse variable in width from 50 to 100 µs (approximately 5 to 10 miles). This pulse travels down a 470 µs lumped constants L.C. delay line to a matched load. At selected intervals squaring amplifiers are connected to the line which re-shape the pulse to provide square wave gate pulses at the desired ranges. The leading edges of the gates may be set six miles apart, say, and the gates themselves may be eight miles wide, which is enough overlap to avoid losing weak targets that might occur on the edge of a gate. Because of this overlap channel #1 is not compared with channel #2 but with channel #3 or some other non-adjacent channel.

In practice the noise outputs from the pairs of channels are adjusted so that random fluctuations will not fire the relays. The relays are activated by a 20-volt differential and the overall sensitivity is adjusted so that the greatest peak of integrated noise does not exceed half of this. If the gates normally contain noise only, or noise plus small permanent echoes up to 10 db above noise, long-term stability can be achieved with no false alarms. Under these conditions an aircraft echo 3 db above noise will ring the bell, provided the echo is present for three or four seconds. Aircraft echoes 6 to 10 db below noise, which are invisible on the A-scope, can be detected easily on the central-zero meters in the comparator circuits. However, the relays will fire occasionally on noise if the gain is increased enough to make them operate on signals well below noise level.

Very strong clutter, 20 to 50 db above noise, constitutes a problem for which only partial solutions have been found. In the first place such strong echoes will saturate an ordinary receiver, and logarithmic or I.A.G.C. methods must be employed to keep the signals within bounds. Reasonably satisfactory operation may be achieved with I.A.G.C. although the doppler echo from a moving target, superposed on the large clutter echo, is reduced in proportion to the compression of the large echo. Fortunately, strong clutter usually occurs only at short ranges where the aircraft signals are also strong. A more fundamental difficulty is that heavily wooded terrain, especially in windy weather, can produce very low frequency doppler returns which can only be excluded by increasing the low-frequency cut-off point of the audio amplifiers, at the expense of losing aircraft echoes that may lie in the same frequency band.

2.1 Antenna

Fixed antennas are used, one for each equipment, there being two equipments at each station. A rough plan of the horizontal coverage diagram of three sample stations in the chain is shown in Fig. 6. The

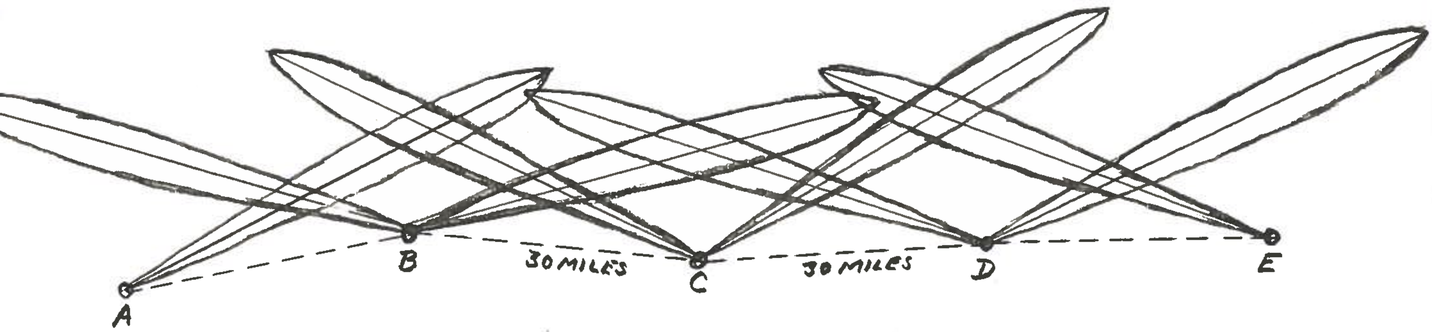


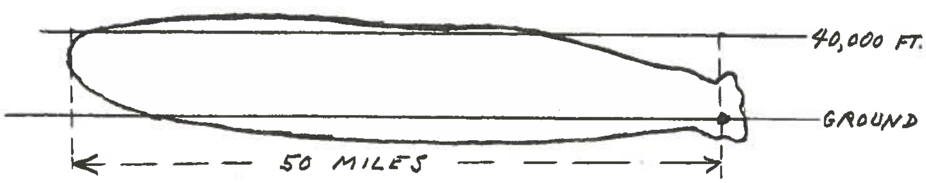
Fig. 6

stations should be sited not more than 25 to 35 miles apart in order to detect very low flying aircraft. The patterns have been drawn 50 miles long, which conservatively represents the coverage of the present equipment. Form an inspection of Fig. 6 it will be apparent that no aircraft can cross the "fence" without intersecting at least two beams, and a fair proportion of targets may be expected to cut three beams. Even if both beams at station C were to go off the air stations B and D will provide good interim coverage. The beams are oriented at angles such that the doppler frequency ($D = 1.8V\cos\theta$) will in general be in the range 20-900 c.p.s. for aircraft flying up to 500 mph on any track. In the limiting case where the aircraft flys directly across the beam ($\theta = 90^o$) the doppler frequency will be zero at the centre of the beam, but even in this case, at the entering and leaving edges of the beam, D will be 16 c.p.s. and 80 c.p.s. for a 100 mph or a 500 mph target respectively. These frequencies are above the low-frequency cut-off of the audio amplifiers, and trials have shown that aircraft flying directly across the beam do operate the alarm effectively, despite the zero frequency response at the point of closest approach. An aircraft could defeat the automatic system (it will still be visible on the A-scope) at one station by flying a perfect circle about that station, but in that case one of the neighbouring stations would trap it easily.

The antenna used is a horn-fed reflector, 16 feet wide by 11 feet high, with the corners cut down to reduce weight and windage. The reflector design deviates from parabolic in the vertical plane in order to provide coverage against high flying aircraft close to the station.

Tracings of actual patterns made at 3,000 Mc on a 1/5 scale model are shown in Fig. 7. These patterns are measured in field strength and thus

Horizontal antenna pattern



Vertical antenna pattern

Fig. 7

represent the coverage diagram using the same antenna to transmit and receive. The horizontal pattern is 10° wide at the half field strength point and shows a considerable number of side lobes which might provide some measure of close in cover at almost any angle. The vertical diagram is the measured free space pattern, which is directed along the ground as indicated; the 40,000 foot level is also shown. In practice an appreciable fraction of the energy striking the ground, depending on the nature of the terrain, will be reflected upwards, reducing the distant low-flying cover, and putting lobes into the pattern, which have the effect of increasing the detection range at some elevations and decreasing it at others. Detailed flight trials will be needed to determine the depth of the lobes at a given site. As will be apparent, the vertical cover to 40,000 feet is reasonably good from maximum range in to about ten miles, where it begins to fall off. It is difficult to design a single antenna that is also capable of covering high aircraft nearly overhead and, at present anyway, it is felt that the adjoining stations can cope with such aircraft.

The experimental antenna at Ottawa is mounted about 30 feet above ground on a rotatable structure, in order to test other potential features of the basic system, such as PPI presentation with clutter rejection. The r.f. energy in this case is fed through a rotating joint. The antenna as used in the radar fence application will be mounted in a fixed position on a short tower, or even on a pair of telephone poles. Sheet aluminum waveguide, scaled directly from standard 10 cm guide, is used between the antenna and the equipment hut because of its negligible attenuation at these frequencies compared to the best co-axial cables. Inside the hut the waveguide is converted to co-axial cable to connect to the pre-plumbed T-R, anti-T-R, unit using RCA 1960 tubes. Co-axial terminals for the transmitter and receiver are provided.

2.2 Transmitter Multiplier Chain

A basic crystal frequency of 10 Mc is used, chiefly because a stock of 10 Mc temperature-controlled crystals was on hand. The output frequency had been determined to be in the range 500-700 Mc from preliminary discussions of the technical, political, and operational considerations, and the final frequency of 600 Mc was selected by both the Eaton Laboratory and the N.R.C. to facilitate the exchange of techniques and components, such as antennas and r.f. plumbing. The final transmitter frequency is reached by multiplying the basic frequency by 5 x 3 x 4 = 60. See Fig. 8. No serious attempt has been made to reduce the number of

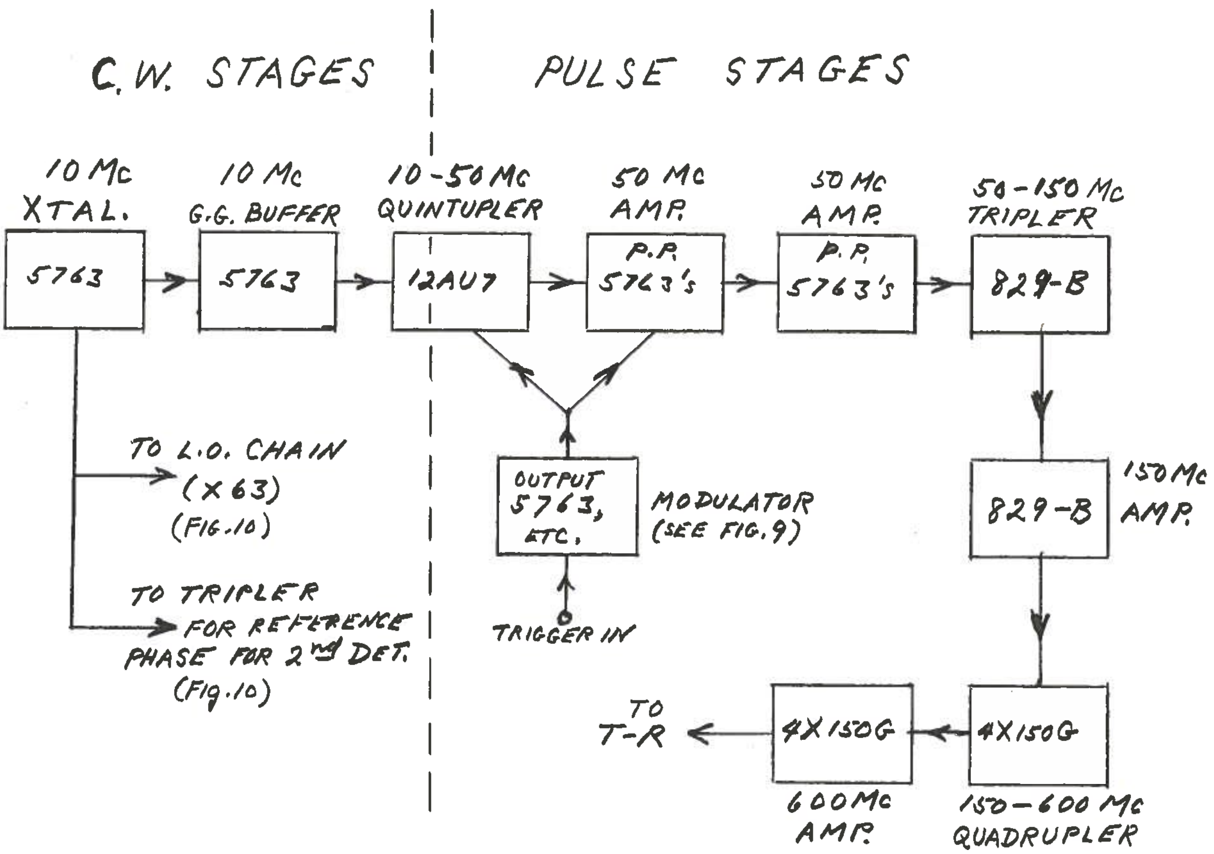


Fig. 8 Transmitter Chain

stages, or otherwise to simplify the circuitry. For example, the second 50 Mc amp. stage was inserted as insurance against inadequate drive, whereas it became apparent that the 150 Mc amp. was far over-driven, and that either the 50 Mc (5763's) stage might be removed, or it might be converted to tripler operation and the 829-B tripler stage deleted. Further simplification could be achieved by starting with a higher crystal frequency.

A conventional pentode crystal stage is used which, in addition to driving the transmitter chain also feeds the receiver chains (see Section 2.3). A triode-connected 5763,with grid grounded, serves as a low-gain buffer stage to drive the pulsed multiplier unit. The modulator and modulated r.f. stages may warrant more detailed discussion. In Fig. 9 the positive pulse from the blocking oscillator P.R.F. generator triggers a Kipp relay. The normally-conducting half of this Kipp is a 5763 triode-connected tube to handle the current and voltage swings needed. Another 5763 acts as a cathode follower to form a low impedance power source for the r.f. tubes. In order to get 400-volts of pulse output to drive the r.f. stages it was necessary to raise the plate voltage on the modulator to 600 volts. However, the currents and dissipations in the modulator tubes are well below ratings and no trouble has developed. A more simple modulator, e.g., a 2D21 with pulse line and pulse transformer, could be devised, but in the experimental set it was desired to change the pulse width continuously from 5 to 20 µs, and at the same time to have a clean, square pulse, which is difficult to do with inductive elements in the circuit.

D. C. bias is developed on the grids of the 12AU7 (Fig. 9) continuously from the 10 Mc input power, and the P.P.5763 stage similarly obtains bias across its grid resistor when pulsed. The peak output power on 50 Mc is of the order of 20 watts, and the output is free of steady 10 Mc signal, at least to 60 db down, which was the limit of the receiver used to test this point.

A second stage of P.P. 5763's was used further to amplify the peak pulse to approximately 100 watts -- probably unnecessarily. This stage operates with 600 V.D.C. on the plates, 300 V on the screens, and -50 V on the grids to bias it just beyond cutoff.

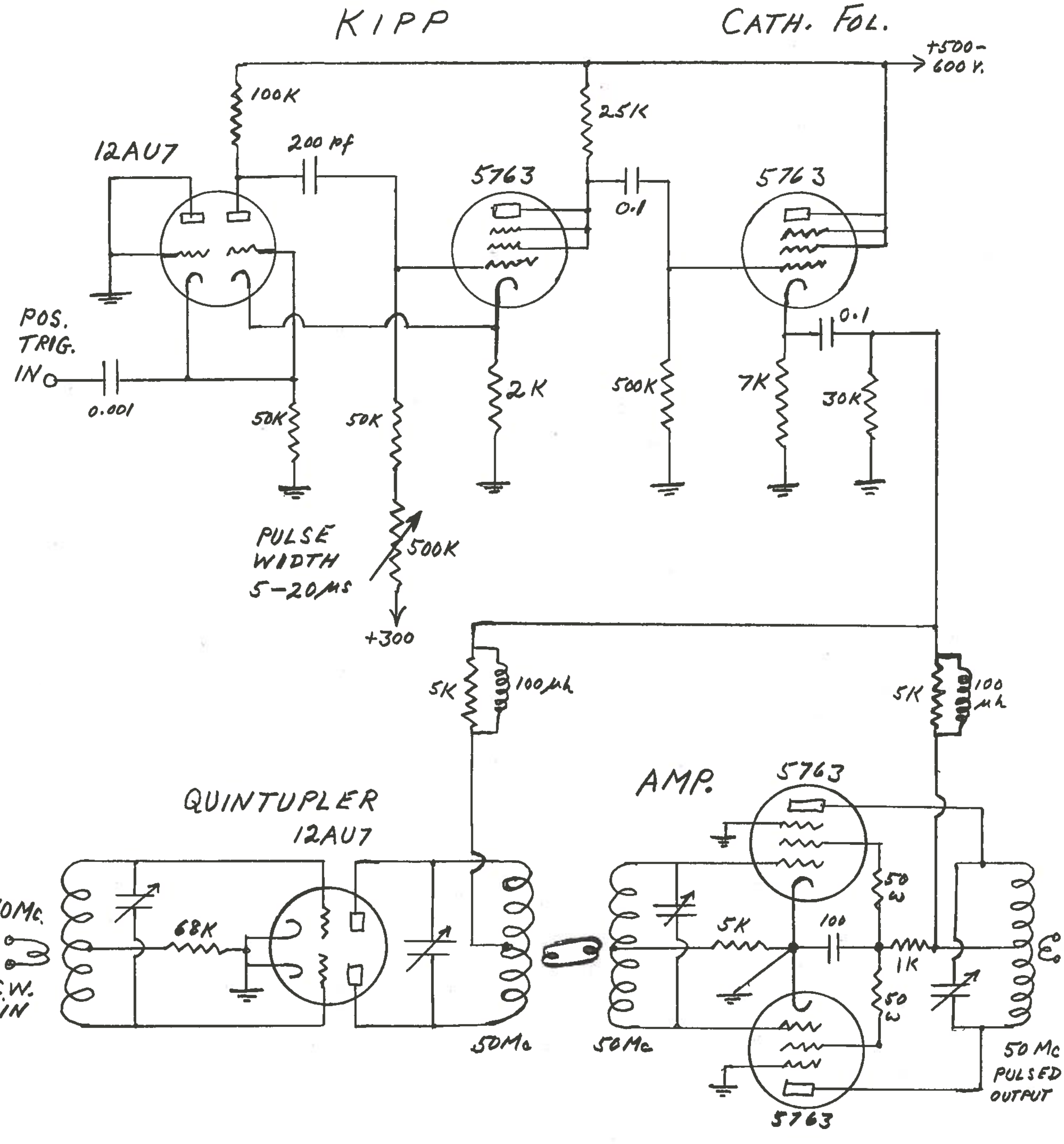


Fig. 9 Modulator and Pulsed R.F. Stages

The 829-B push-pull tripler stage uses lumped LC components in plate and grid, with 1000 V on the plates, 400 V on the screens, and -200 V on the grids. The 829-B push-pull amplifier has a lumped LC input and a parallel line output tank circuit. It has 3000 V on the plates, 400 V on the screens and -200 V on the grids. The peak output power of the 150 Mc amplifier is about 500 watts. The dissipation in these two stages is so small that no forced air cooling is necessary.

The grid input circuit to the 4X150G quadrupler stage is a parallel plate half-wave tank, tuned by a capacity at the end remote from the grid. The cathode is grounded as effectively as possible with a large copper sheet. The screen is by-passed to ground through a ring condenser at the tube socket. In the plate there is a half-wave co-axial tank which is tuned by adjusting the length of the inner tube. Loop coupling to co-axial terminals is provided at input and output tanks. The plate voltage on the 4X150G quadrupler is 3.5KV, screen voltage 400-500 V, and the grid cutoff bias -200 volts.

The final amplifier 4X150G stage has a half-wave co-axial input stage with the grid tuned by adjusting the length of the grid inner conductor. One function of this tank is to ensure that the screen and cathode are at the same r.f. potential (ground), which is done by adjusting the length of the cathode conductor to one-half an electrical wavelength. The plate tank is identical to the one employed in the quadrupler stage. Loop couplings to co-axial fittings are installed in both input and output tanks. The plate voltage is 4KV, screen voltage 1KV, and bias -200 V on this stage. Although these 4X150G stages are operating well below their peak current and average dissipation ratings it is nevertheless necessary to air-cool the anode and cathode elements.

The 4X150G tube is rated by the manufacturer at 7KV peak plate voltage and 4 amps. peak current, with a 4 µs pulse. By reducing the plate voltage to 4 KV and the peak current to 2 amps. we can increase the pulse width to 20 µs and remain well within the plate dissipation rating of 150 watts and also within the limitation of the oxide cathode. The average plate current is 40 ma. at a PRF of 1,000 and pulse width 20 µs. The peak input power is therefore 8KW and the measured output power 5KW. The average output power under these conditions is about 100 watts.

1 µfd storage condensers are used for the plate supplies with 10 K ohms, or more, in series with each condenser from the common high voltage power supply. During discharge the plate resistance appears to be about 2000 ohms. Under these conditions the voltage on the storage condenser drops about 1 per cent during a 20 µs pulse, which is negligible. It was found that small carbon or metallized resistors of 15 to 50 ohms, between the storage condensers and the tube elements would protect the tubes and meters while ascertaining the limits of operating voltages. As these small resistors do not appear to impair the shape of the observed r.f. output pulse they are left in the circuit.

Average power output is measured by matching the power into a 6.3 V. 150 ma pilot light, and measuring the light output with a photocell and meter. Both vacuum photocells and photovoltaic cells have been used. As the average power handling capacity of the photocell-pilot bulb combination is only about 1 watt ± 3 db it is necessary to provide lengths of cables with predetermined attenuations for insertion between the source and the lamp load. The VSWR at the lamp load under matched conditions is 1.2 or better, hence it is likely that the D.C. calibration of the power meter is reliable to ten or twenty per cent at 600 Mc, which is adequate for our purposes.

In the early phases of the project the C.W. portion of the multiplier chain extended to 50 Mc. From the 829-B tripler stage to the final 4X150G stage all plates and screens were pulsed from a high-level modulator. The operation was satisfactory from the viewpoint of r.f. output, but the modulator, using a 5C22 hydrogen thyratron, frequently gave trouble. A very "stiff" voltage divider of 500 ohms was necessary across the modulator output in order to provide the different pulse voltages needed for various tube elements. The resistance divider could presumably have been replaced with a multi-winding pulse transformer, but the design of this transformer would pose a problem. Low-level modulation appears to be equally as efficient as the former high-level modulation in producing crystal-controlled r.f. pulses, and should be more reliable as well as more flexible. A possible disadvantage of low-level modulation is that the high power stages have steady high voltages on them, which could be more dangerous to a careless operator than the same potentials delivered in pulses.

2.3 Local Oscillator Multiplier Chain

The crystal oscillator also feeds the multiplier chain for the local oscillator and the tripler tube which supplies the reference phase for the 2nd detector. See Fig. 10. The seventh harmonic of the 10 Mc basic frequency

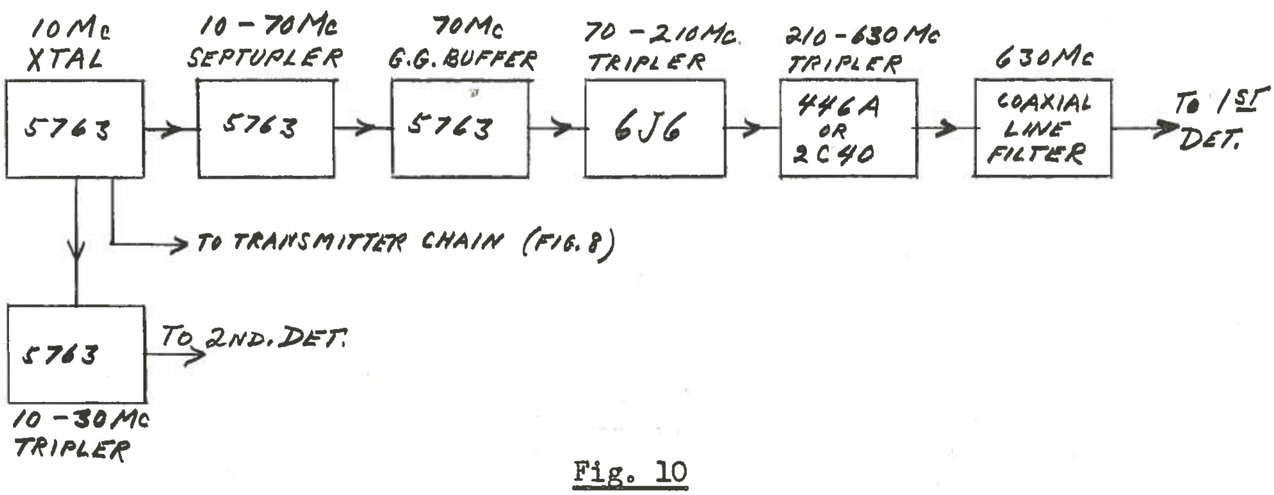


Fig. 10

is generated in the plate tank circuit of the 5763 septupler stage. As the Q of this stage is inadequate to suppress the other harmonics satisfactorily, two additional tuned circuits are added with the buffer stage on 70 Mc. This is a 5763 with cathode input, grid grounded, and screen and suppressor tied to plate. The power gain is about three and there is no tendency for oscillation. A 6J6 with P.P. lumped-constants input and output tanks, triples the frequency to 210 Mc. This stage is the weak link in the present chain as care must be taken not to overdrive the 6J6. The final tripler to 630 Mc is a 446A or a 2C40 lighthouse triode, with a lumped constant series tuned input circuit and a co-axial, plunger-tuned output cavity. It is quite important that the amount of 600 Mc unwanted harmonic content be kept at least 120 db below the 1/4 watt of 630 Mc output. A co-axial filter is needed to achieve this degree of attenuation. It may be remarked that future local oscillator chains will have an entirely different tube line-up. The new I.F. frequency will be 40 Mc and the L.O. frequency 640 Mc, which can be reached by continuously multiplying by 2.

2.4 R.F. and I.F. Receiver Stages

The input r.f. stage uses a 416A grounded grid triode with plunger-tuned co-axial input and output cavities. The plate cavity is link-coupled to the mixer, or 1st detector cavity. The gain of the 416A stage is well in excess of 20 db so that further r.f. amplification before the 1N25 silicon crystal mixer improves the noise factor only imperceptibly. The measured noise factor of the 416A in this arrangement is 7.5 db, which is 3 or 4 db better than that of a 2C40. While the gold-plated 416A is a fairly expensive tube it is felt that its use is warranted, both because of the greatly improved noise factor and because, from its internal design, it should be more reliable and long-lived ---- although we have not yet run life tests to prove this.

The I.F. amplifier consists of four single-tuned stages using 6AK5's with a nominal bandwidth of 200 kc. Each of the last two stages has a feed-back loop to provide instantaneous automatic volume control (I.A.G.C.) using a 1N34 as a diode rectifier and a 12AU7 "boot-strap" cathode follower. Satisfactory compression of signals and ground clutter up to 50 db above noise has been achieved. A control is provided in the grid bias of the second I.F. stage to allow a limited variation in gain. The 200 kc bandwidth is about optimum for a 5 μs pulse but unnecessarily broad when wider pulses are used. However, the coherent-detection or phase-sensitive de-modulation method used in the 2nd detector ensures that the signal to noise ratio in the video is relatively independent of the I.F. bandwidth*, unless cross-modulation should occur in the I.F. amplifier itself due to incorrect operation.

2.5 Second Detector and Video

Several types of balanced detector could be used to provide phase-sensitive bi-polar video output, but the "single-ended" form shown in Fig. 11 has proved simple and reliable. The 30 Mc reference phase voltage creates twenty or thirty volts of rectified D. C. across the

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* Smith, R.A., The relative advantages of coherent and incoherent detectors. I.E.E. Monograph No. 6, Aug. 1951

diodes, and this "bias" is varied about its mean point by the 30 Mc I.F. signal voltage, at a rate depending on the frequency difference, if any.

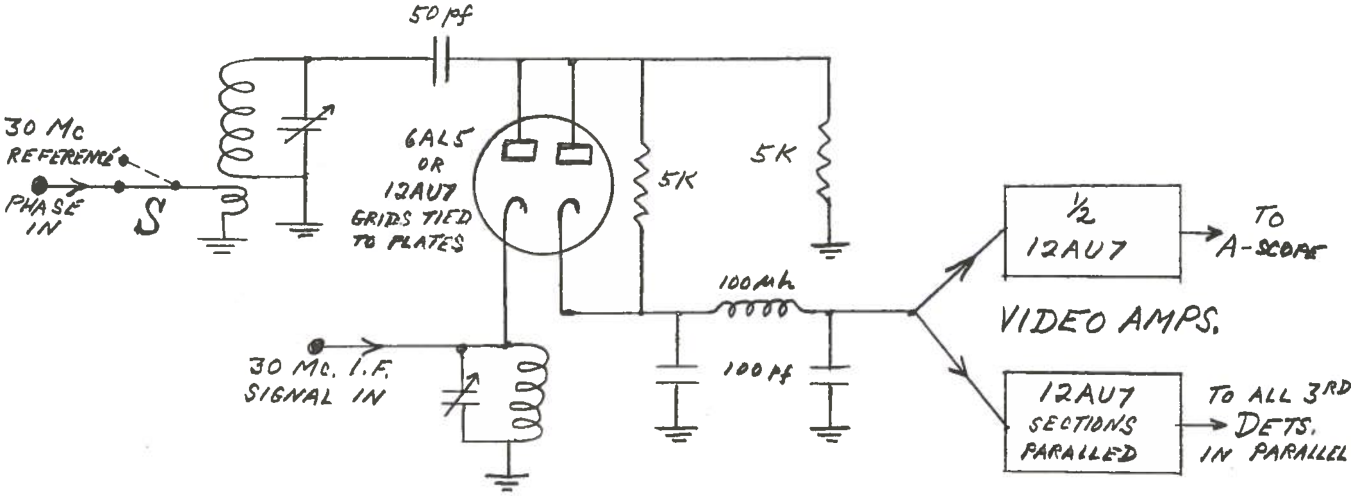

Fig. 11, 2nd Detector and Video

The polarity of the A.C.-coupled video signal at any instant depends on the relative phase between signal and reference voltage. The time constants in the class A video amplifiers must be kept long (e.g. 250 K and 0.1 µfd.) to permit good low frequency response and to reduce overshoot. The output impedance of the parallelled 12AU7 stage is 5 K which is low enough to supply at least eight 3rd detector stages with 5 to 10 V peak video. The switch, S, may be opened to remove the reference phase, in which case the signal input diode acts as a conventional "linear" detector and the video output becomes mono-polar and independent of phase. Occasionally this mode of operation is useful in examining permanent echoes on the A-scope, but it is not employed with the 3rd and 4th det. automatic alarm system.

2.6 Delay Line Multiple Gate Generator

As mentioned in Section 2.0 the four-diode switch behaves as a filter with the desired frequency characteristics, but a gate pulse is required to turn it on at the same range each sweep. The ratio of signal to noise in the gate naturally improves as the gate is made narrower, and, because the "target block" is smaller, the range discrimination of the automatic alarm system becomes better. However there is an economic limit to the number of gates, and it was felt that six to eight gates covering a 50-mile range would be a reasonable compromise.

Initially, a chain of monostable multivibrators, or Kipp relays, was used to produce a series of gates, each Kipp being fired from the back edge of the preceding one. Blocking oscillators have similarly been used. This had several defects, the most important being that no overlap of the gates was obtainable and an echo straddling the edges of two gates had to be several db stronger than it would otherwise have to be in order to actuate the alarm. Also, a failure anywhere in the chain puts all the remaining gates out of action as well. In another arrangement two independent Kipp chains were used, one staggered half a gate width behind the other. This provided 100% overlap, which is far more than necessary, and increased the complexity considerably.

Most of these difficulties were overcome by the use of a delay line. In Fig. 12, a negative pulse from the P.R.F. generator triggers the Kipp relay. P_1 may be adjusted to produce a positive square wave of duration 5 to 10 miles. This square wave is inverted, and amplified slightly, by the 5763 stage. The negative pulse is applied to a lumped constants delay line consisting of 44 sections, each with a delay of 1 mile. The line is terminated by a resistor equal to its characteristic impedance. Standard commercial 60 mh chokes were used in the experimental

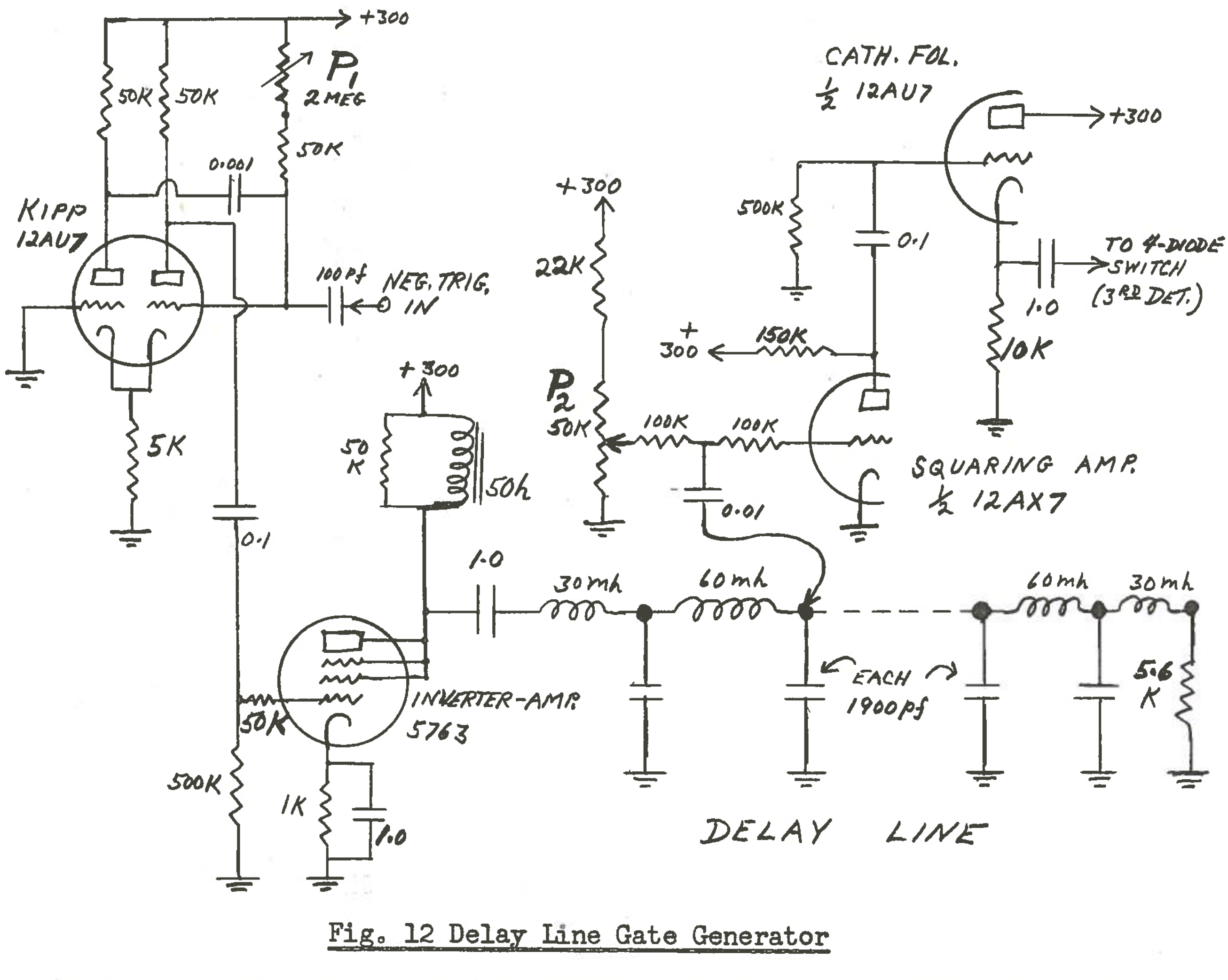

Fig. 12 Delay Line Gate Generator

model, without mutual coupling between sections. Unfortunately, the D.C. resistance of the coils is high and the overall D.C. resistance of the line is about 11,000 ohms. The pulse, therefore, suffers considerable attenuation in travelling down the line and also loses its square shape due to the usual low-pass characteristic of delay lines. Fig. 13 indicates the relative pulse shapes of a nominal 8-mile pulse near the beginning and end of the line. A squaring amplifier (1/2 of a 12AX7) is capacity-coupled to the point on the line at which it is desired to start a

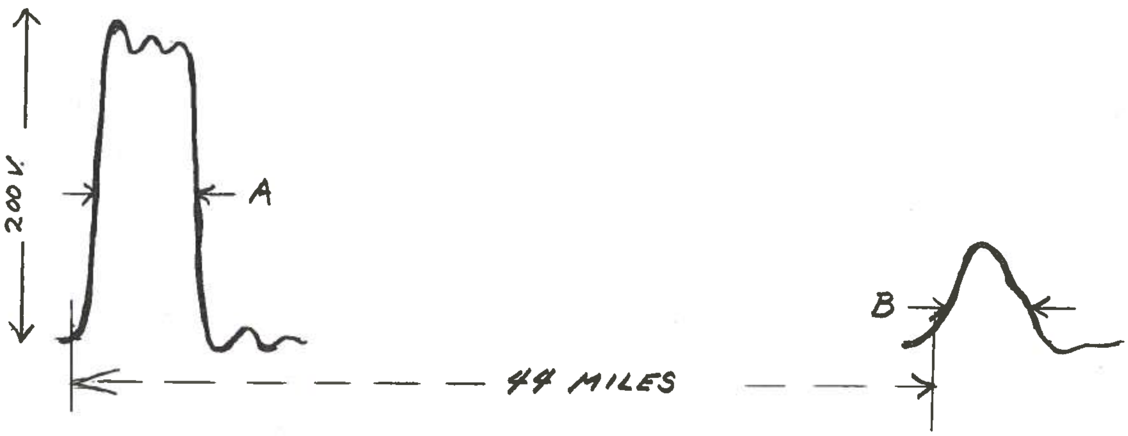

Fig. 13, Pulse Shapes along delay line

gate. This tube has a positive voltage on its grid which is adjustable by P_2. This control determines the point on the negative-going line pulse at which the 12AX7 will start to cut-off, and will have different settings for different positions along the line, see A and B, on Fig. 13. Cut-off is reached very quickly with the high-mu 12AX7 so that the wiggles or rounded characteristics on top of the line pulse are erased and a clean, positive square wave can be obtained from the plate, independently of position on the line. The small baseline overshoot fluctuations on the line pulse are also eliminated by the setting of P_2. The main pulse width control is P_1, of course, but small individual variations in pulse width can be made by the P_2 controls, especially toward the end of the line. The cathode follower tube (1/2 of a 12AU7) provides low impedance output for the transformer of the four-diode switch. The first gate is positioned to open just after the transmitter pulse ceases, i.e., at about 2 miles range.

2.7 Third and Fourth Detectors

A general description of the action of the four-diode switch, or 3rd detector, has been given in Section 2.0, but some further comments on its performance are in order here. Fig. 14 shows the schematic of a 3rd and 4th detector channel with the companion channel in block form.

The two channels whose outputs are to be compared must not be adjacent because they are overlapped 20 to 50 per cent, hence an aircraft occurring in both channels at the overlap position would cause both outputs to increase together, with no resultant differential. With eight gates in use the channels can be combined in pairs, starting from zero range, either as 1, 3: 2, 4: 5, 7: 6, 8, or as 1, 5: 2, 6: 3, 7: 4, 8: or with other hybrid variations. The first-mentioned arrangement is probably preferable inasmuch as the channels at close range are grouped together and similarly those at long range. Thus the long-range channels

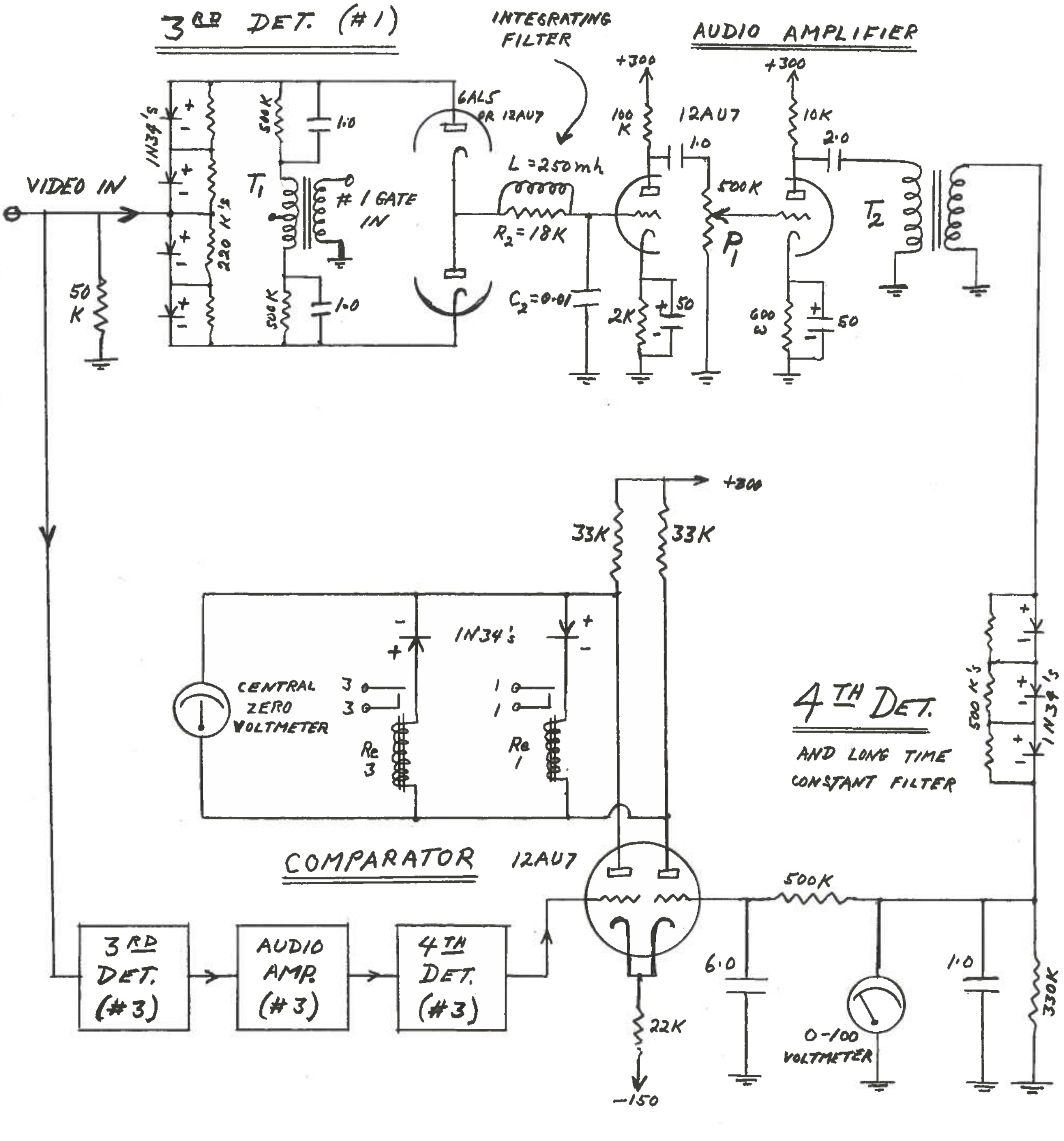

Fig. 14. Third and Fourth Detectors, and Comparator

may be operated at maximum sensitivity since they have little clutter in them. Fig. 1 and Fig. 14 both show Channel #1 compared with Channel #3.

The transformer T_1 is a Hammond type 903 audio transformer, 500 ohm one-to-one ratio, which was the best available to pass the 50 to 100 µs square wave pulse. The two input diodes of the switch can be replaced by 1N34 germanium diodes as shown, but the output diodes should be high vacuum tubes because there must be a minimum of leakage from the filter circuit, L, C_2, R_2, when the switch is off. Inferior performance may be had by removing the input diodes altogether and feeding the video to the centre tap of T_1. The back bias from the pulse amounts to 100 volts across the bridge to hold off the diodes.

The filter constants, L = 250 mh, R_2 = 18K, C_2 = 0.01, were determined empirically as being close to optimum for an 8-mile gate. To test the switch and filter a second 10 Mc crystal was used which could be tuned several hundred cycles about the original crystal frequency. The test crystal frequency was tripled, pulsed and fed into the I.F. amplifier. Thus an artificial aircraft echo was produced which could be varied in doppler frequency from zero to a few thousand cycles and positioned where desired in range. Using the above filter constants, the voltage output at the 4th detector was measured as a function of D, the Doppler frequency. (See Fig. 15, solid line.) The waveform present

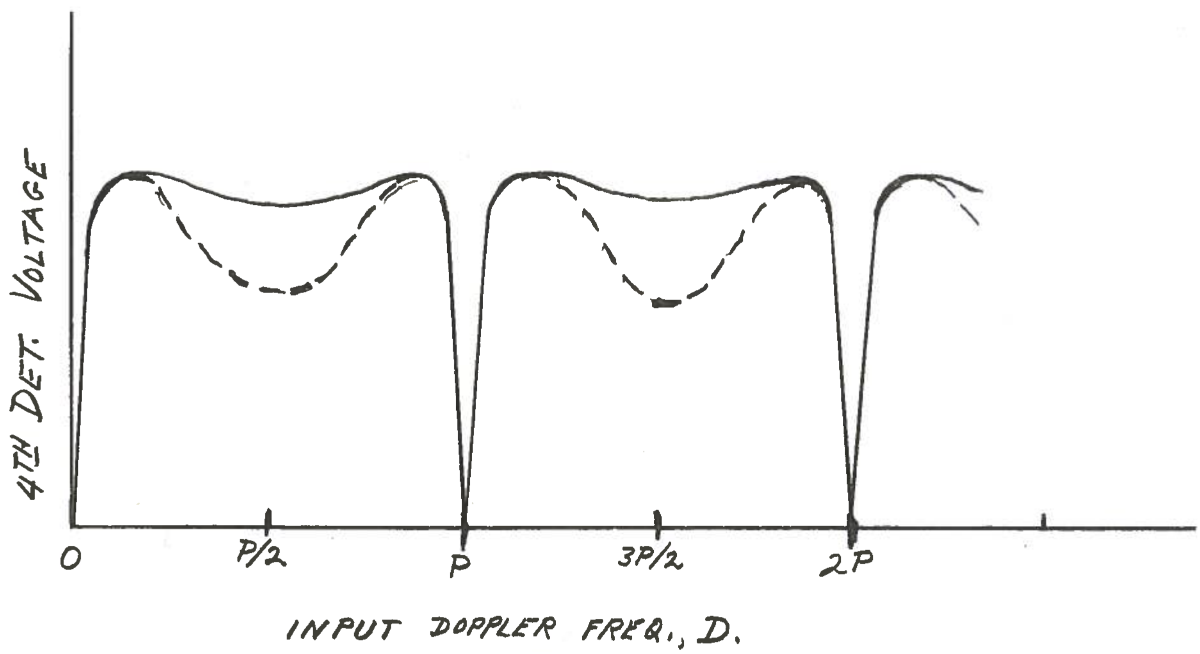

Fig. 15

in the audio amplifier after the 3rd detector has a strong fundamental component that begins at zero with D = 0, rises to P/2 as D reaches 1/2 P and falls to zero frequency again as D reaches P. The same audio frequency cycle repeats as D goes from P to 2P cycles, and so on. Obviously, the audio frequency is the combination of the D and P - D components, and near

D = P/2 the waveform is badly distorted. This is of no consequence at all to this system because the 4th detector rectifies and smoothes whatever doppler waveform is present.

The low-frequency rejection near zero frequency and the rejection slots at P, 2P, etc, depend entirely on the low-frequency pass characteristic of the audio amplifier. If the amplifier were D. C.-coupled the rejection bands would become infinitesmal. To suppress low-frequency flutter from permanent echoes it would be desirable to cut off the amplifier sharply at 5 cycles, say. In the one shown in Fig. 14 no attempt has been made to obtain sharp cut-off, other than to series-tune the primary of T_2. At 5 cycles the output is 10 db down and falls to zero at zero frequency. It may be necessary to re-design the low-frequency characteristic to cope with fluctuating strong clutter.

The time constant of the filter circuit must be large enough to ensure that a signal at the beginning of the gate will be fully integrated. On the other hand, if the constant is too large the circuit appears to act as a low pass filter and to attenuate doppler signals in the centre of the pass band, as shown by the dotted curve of Fig. 15. The series inductance, L, helps both to increase the voltage available at C_2 for a given video input, and to improve the integration, without attenuating the higher doppler frequencies. Further analysis and experimental work is indicated before the action of the switch and integrating filter can be said to be fully understood. However, it is not difficult to determine workable values for specific cases.

Returning to Fig. 14, the 4th detector consists of three 1N34 diodes in series feeding a filter of time constant $\simeq$ 3 secs. Normally, the rectified noise output is set at about 50 volts at this stage. A D.C. differential amplifier, or comparator tube, with an effective gain of 5, is used to compare the outputs of two channels. Balance under no-target conditions is achieved by adjusting P_1, or its companion in channel #3, and is indicated on the central zero voltmeter. A polarized relay may be used in the comparator plate circuit to indicate which channel has a target but not enough such relays were available. As a substitute ordinary 2 ma, 20 V relays were used with series rectifiers of appropriate polarity. The contacts 1, 1: 3, 3, are connected to pilot lights, bells, etc, and may key the communications system directly. As one example, a series of tones could be used; 5 c.p.s. to indicate the range block 2-10 miles, 10 c.p.s. the block 8-16 miles, 15 c.p.s. the block 14-22 miles, etc. Or in this example, the range blocks could be designated "A" (6±4 miles), "B" (12±4 miles), "C" (18±4 miles), up to "H" (48±4 miles), with "W" or "E" prefixed to indicate the West or East beam. The usual range accuracy may be taken to be half the gate width, although it becomes much better for a target in the overlap of two gates. In the experimental set-up the relays actuate individual pilot lights, individual pens of an Esterline-Angus multi-pen recorder, and a common alarm bell.

The "band-pass" of the 4th detector is about 1/3 c.p.s. The effective band-pass at the 3rd detector is estimated to be 1,000 c.p.s. or slightly more. Hence, the overall noise band of the receiver may be taken to be about $\sqrt{1000/3}$ cycles, or the order of 20 c.p.s.

3.0 Performance of the System

No formal flight trials have yet been undertaken with the system described here. However, many hours of informal tests have been run, using random aircraft flying the air routes or circuiting the local airports at unknown altitudes. The gates have been tried 10 miles wide, with 8 miles separation, 8 miles wide with 6 miles separation, and 7 miles wide with 5 miles separation, with increasingly better sensitivities. Using 8-mile gates positive automatic alarm was obtained in the 44-52 mile gate on aircraft which were scarcely visible on the A-scope. Other aircraft have been followed on the A-scope, beyond the range of the gates, to 70 miles.

The stability of the gates beyond 20 miles is quite satisfactory. The short range channels do give trouble, especially when the antenna is looking north of Ottawa over the wooded Gatineau hills, which produce ground clutter up to 40 db above noise with a strong fluctuating component. The country to the south is more regular and little difficulty is experienced from permanent echoes in that direction. It is probable the short range channels will require modification of their low-pass characteristics, as mentioned in Section 2.7 to enable them to operate satisfactorily under all clutter conditions.

No special provisions have been made yet for the inclusion of anti-jamming devices. Noise jamming, or C. W. jamming, might be expected to have the usual bad effects, although the two-channel comparison techniques will help to mitigate against this, since the noise or C. W., if not too strong, simply raises the level in all gates equally. However, if the system is jammed by enemy airborne transmissions, it is felt that its major function will actually have been performed, namely, the warning that something is coming. Referring back to Fig. 6, it was the intention to direct the beams to the north of the line of the stations, but the system works just as well if the beams are to the south (with a few minutes' less warning time). The enemy would thus be less able to stand off from the fence at long range and jam it.

4.0 Alternative Schemes for Automatic Operation

Before the four-diode switch method was tried a high quality 1000-cycle low-pass filter was used which rejected the P.R.F. and all higher components. The doppler signal was then at such a low level that a high-gain audio amplifier had to be used, with its attendant hum troubles.

A walking gate has also been used with moderate success. A goniometer or a continuous potentiometer, driven at one or one-half revolution per second moved a gate continuously across the range sweep. The gate, approximately two miles wide, was fed into a single channel four-diode switch with the time constants appropriately reduced. As this gate swept slowly out in range (slowly relative to the P.R.F. and to the expected doppler frequencies) a moving target produced an audio component and a sharp rise in 4th detector voltage (the 4th det. time constant also being much smaller) which triggered a buzzer circuit. Permanent echoes with no A.C. component had no effect. Range information about targets could be transmitted automatically by transmitting a beep on every slow sweep at zero range and then measuring the time interval between that beep and the echo buzzer. The method was not very satisfactory for several reasons. First, a doppler echo had to be at least 6 to 10 db above noise to register in the short time the gate was straddling the target, second, the target could easily fade momentarily as the gate reached it, third, slow variations in noise level and gain had critical effects, there being no self-compensation available as is obtained in the present system by comparing the outputs of two gates.

5.0 Doppler Frequency Discrimination

As mentioned in Section 2.0 the phase of the video doppler signal from an aircraft depends on whether the target is approaching or receding. In this radar fence system a knowledge of the sign of the velocity is not likely to be of much value, although it could be obtained with some additional circuitry, because most tracks will pass through the beams nearly normal to the line of sight, and a small change in angle of direction could reverse the sign of the velocity. In fact, an aircraft flying exactly normal to the beam produces first an approaching doppler and then a receding doppler for either direction of flight on the path. An indication of direction of flight, if it is required, can be obtained by noting the difference in time of detection by two or more stations.

Gating in range has been employed in this system to isolate targets into range blocks and to improve the signal to noise ratio. Gating in frequency could also be employed, i.e., doppler frequency filters could be added to the outputs, further to improve the detectability. However, for aircraft tracks nearly normal to the beam the doppler frequency changes so rapidly that little benefit should be expected from frequency filters. Band pass audio filters could be of value for the higher doppler frequencies which should not change greatly while the aircraft is in the beam. However, to add $\underline{n}$ filters to each gate of this system already containing $\underline{m}$ range channels would require (at first glance anyway) $\underline{nm}$ filters and $\underline{nm}/2$ output devices, and the circuit complexity would increase tremendously. Gating in frequency alone, without gating in range, should yield detection sensitivities comparable to the present range gating system. However, a knowledge of the doppler frequencies, which is all that frequency gating could supply, is of little or no value, whereas the information that the target is in block "WF", say, at a range of 36 miles ± 4 miles, is considered to be quite useful.

6.0 Other Applications of the Basic Equipment

It is considered that the basic equipment described here, up to and including the second detector, may be of value in stations where more facilities for operation and maintenance are available, and where more information is required.

For example, the antenna may be rotated continuously to give excellent conventional P.P.I. coverage to 60 miles or more, using only the present low-power 5 KW transmitter. A barrier-grid storage tube may be added to provide clutter-free P.P.I., as the system already has the necessary coherent pulse feature built in. Mercury delay line M.T.I. could also be used but it is felt that at 600 Mc, and with pulse widths from 2 to 5 µs, the storage tube would be the equal of the delay line and it is much more simple.

With these thoughts in mind we are building a high-power (100 KW) linear amplifier to add to the basic system, and are investigating the possibilities of storage tubes.

7.0 Acknowledgments

This report covers in a sketchy manner, some of the preliminary experimental work on the N.R.C. coherent pulse radar fence system. No attempt has been made to present sufficient information to enable anyone to make a Chinese copy of the gear. Photographs, assembly drawings, and full circuit diagrams will be left to later reports. It is perhaps understandable, if not altogether commendable, that the features most emphasized in this discussion were usually those with which the author was personally involved. Several others contributed greatly to the experimental work. In particular, E. L. R. Webb designed and built the 4X150G amplifier and the plate tank circuit for the 4X150G quadrupler. J. R. Kenney built the R.F. and I.F. portions of the receiver. R. A. Dingwall designed the high-level modulator used in the early trials. A. G. McNamara's assistance has been helpful in the circuit work. The antenna was designed by F. V. Cairns, and the T-R unit and other R.F. plumbing was done by W. Lavrench. The job could not have been finished without the men who wrapped up the breadboard gear into neatly-wired boxes; S. M. Panagapko, A. Petch, R. S. McLean and several others. Advice, and even good-natured heckling,were provided from time to time by persons not directly connected with the project; W.B. Lewis, G. A. Woonton, P. M. Thomson, R. S. Rettie and others. Mr. B. G. Ballard, Director of the Division, has ensured that the project would progress as expeditiously as possible, commensurate with our other defence commitments. The Defence Research Board, although not contributing directly, have expressed a keen and continuous interest in the work, and have been of great assistance in arranging contacts, e.g. with the R.C.A.F. who will be providing target aircraft. The operational research analysis of the general problem, made by R. J. Sutherland, of D.R.B., has been useful to us in planning the equipment characteristics.

The project is now in the hands of Mr. Webb, head of the Air Force Section of the Radio and Electrical Engineering Division, N.R.C., who has undertaken to build two complete systems (much better engineered than the original model) and to instal one at Ottawa and the other at Arnprior, 35 miles west of Ottawa. These stations will serve as two examples of links in the radar fence, and a program of flight trials and life tests will be commenced this summer to demonstrate the advantages and deficiencies of the system.