High-Dynamic-Range Airborne Tracking and Fire Control Radar Subsystems

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***Abstract*—Two high-dynamic-range receiver subsystems for use in airborne radar fire control and tracking applications are described. The X-band dual-channel monopulse tracking receiver operates at 9.36 ± 0.290 GHz with a 6 dB NF and a linear instantaneous dynamic range of 42 dB. A total of 80 dB of RF and IF gain control is programmable with less than $\pm 15°$ phase and ± 1 dB amplitude tracking errors.**

The Doppler radar receiver operating at 9.3 ± 0.15 GHz has a 4.6 dB NF with $\geqslant 80$ dB of instantaneous dynamic range. An 18 dB sensitivity time control (STC) circuit and a 60 dB dump attenuator allow close-in target reception.

I. Introduction

RADAR RECEIVERS used for tracking and fire control in airborne applications require high-amplitude dynamic range capability to linearly process the target returns from short ranges (500 ft), as well as long distances, in the presence of clutter.

To achieve high dynamic range, a low-noise preamplifier is used at the antenna output, preceded by a programmable digital or analog attenuator which reduces strong signal amplitudes, for linear operation. Additional IF programmable attenuation can be used to extend the dynamic range. In a monopulse system which uses two-channel RF reception, good gain and phase tracking over attenuation are required for accurate target tracking. For single-channel pulsed Doppler receivers, a high-dynamic-range receiver is necessary to ensure discriminating the desired target returns from main-beam and side-lobe clutter returns and from distortion products. A sensitivity time control (STC) whereby the receiver gain is varied as a function of time (range), requires extremely rapid attenuator switching and good tracking over the attenuator dynamic range.

The monopulse system described uses this fast automatic gain control (AGC) approach using 80 dB of programmable attenuation to achieve extremely high dynamic range.

A photograph of the complete X-band monopulse receiver is given in Fig. 1.

A block diagram of the monopulse receiver appears in Fig. 2. The two-channel receiver is capable of operating in a radar system with the following modes of operation: terrain following, terrain avoidance, ground mapping, weather mapping, and beacon reception. Although a monopulse tracker can require a sum channel and two difference channels, one in azimuth and the other in elevation, the latter are multiplexed for two-channel operation. The monopulse receiver is used with an amplitude-sensing four-quadrant antenna system. Each of the antenna feeds produces a pattern which is displaced from the antenna boresight axis. The sum and difference patterns intersect on the boresight axis, so that subtracting the two antenna signals results in a sharp amplitude null [1], [2]. The sum signal is hard limited and is used to drive the reference port of the coherent sum detector and the difference channel detector [3].

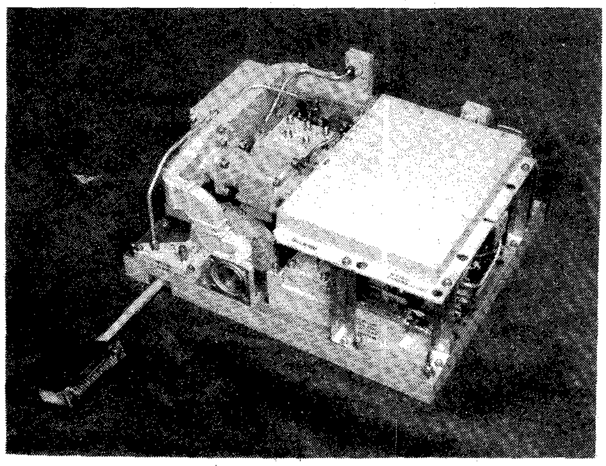

Fig. 1. Monopulse radar receiver.

The phases of the sum and difference channels are compared in the difference, Δ, coherent detector. The polarity of the Δ detector output changes at boresight, so that above boresight a positive error signal is generated and below boresight a negative error is obtained. The Δ coherent detector produces an amplitude output proportionate to the off-axis displacement. Normalization for range and target size is accomplished by the RF and IF step attenuators. The coherently detected sum signals are used to drive the programmable attenuators to produce a constant sum video signal and at the same time normalize the difference video signals. The attenuators match in phase over the full attenuation range so that little error is

Manuscript received March 28, 1989; revised July 13, 1989.
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IEEE Log Number 8930942.

0018-9480/89/1200-1942$01.00

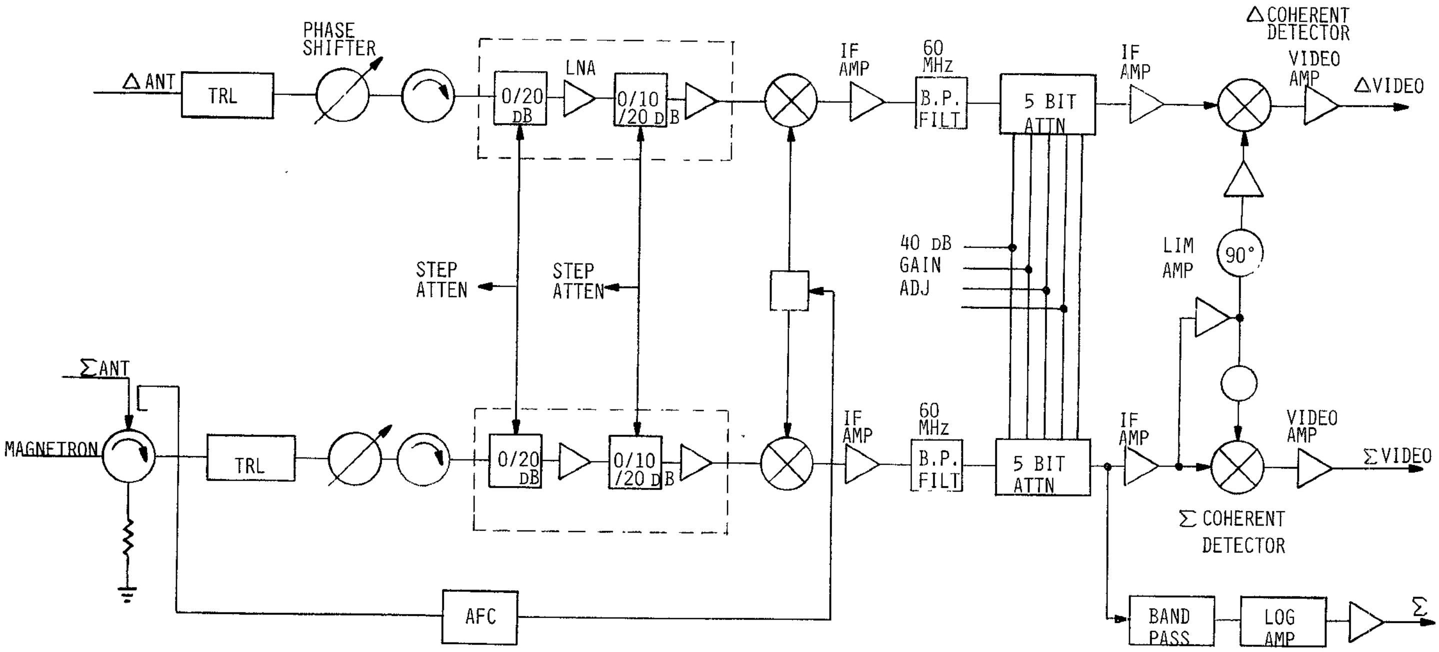


Fig. 2. *X*-band monopulse radar receiver configuration.

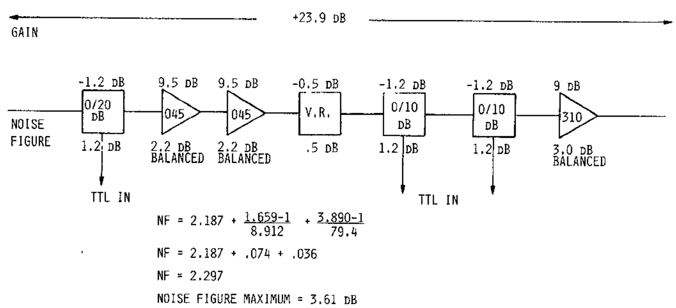


Fig. 3. Simplified block diagram of the LNA/attenuator.

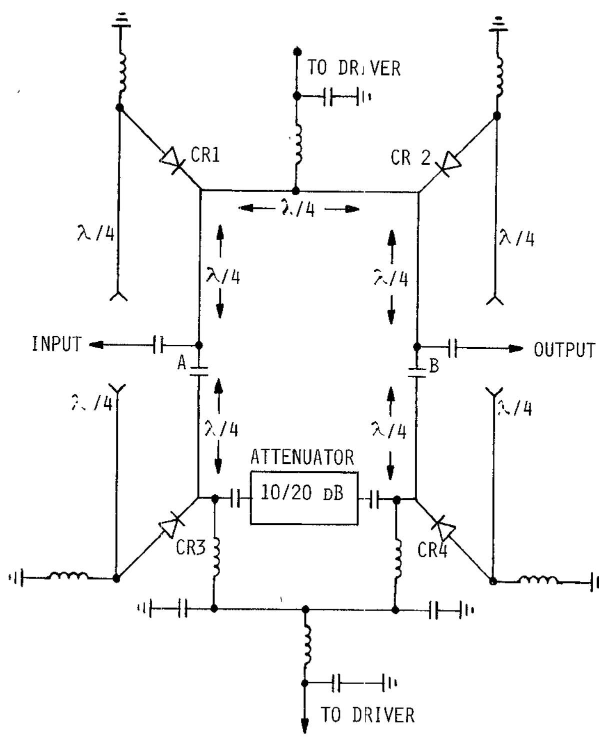


Fig. 4. Circuit diagram for the attenuator stage.

introduced. The use of coherent detectors allows the bandwidth of the system to be set following the video amplifiers; the video amplifier bandwidth is set at 5 MHz. The radar processor control circuits are set to correspond to the pulse width selected.

The monopulse receiver assembly contains a high-power circulator, two channel transmit/receive limiter (TRL) tubes, down-converters, programmable RF and IF attenuators, coherent detectors, AFC circuitry, and a log sum video channel with variable bandwidth. The receiver operates at 9.36 GHz, is frequency agile ± 60 MHz at a 50 Hz rate, and operates over pulse widths of 0.3 to 4.0 μs. To achieve both a maximum sensitivity (< 6 dB NF) and a high operational dynamic range ($+7$ dBm max input), a LNA and programmable attenuator combination are used at the receiver front end [4]. During the transmit period the TRL tube ionizes and shorts the high-power pulses to protect the receiver. Up to 40 dB of attenuation in 10 dB steps is available at the receiver front end. A total maximum gain of 25 dB with 3.40 dB NF is achieved in the preamp assembly. It utilizes three FET amplifier stages cascaded with three p-i-n diode attenuation stages as shown in the schematic of Fig. 3. The circuit diagram of an attenuator stage is shown in Fig. 4. The measured performance of the front end LNA/attenuator assembly is given in Table I. The measured performance of the front end LNA/attenuator gives less than $\pm 7°$ of phase tracking and ± 0.75 dB of gain tracking over the full attenuation range.

An additional 40 dB of programmable attenuation is produced in the 60 MHz IF amplifiers following the bandpass filters. Since the outputs of the difference and sum videos are sampled during pulse widths of as little as 0.3 μs, the programmable attenuators must settle in less than

TABLE I
MEASURED PERFORMANCE FOR LNA/ATTENUATOR

PARAMETER	SPECIFICATION
Frequency Range	9.36 GHz ± 300 MHz
Small Signal Gain	24 dB ± 1 dB @ 25°C
Attenuator	40 dB in 10 dB steps
Gain Flatness vs. Frequency	a) No Attenuation ± .25 dB b) Any Attenuation ± .5 dB
Attenuation Accuracy	± .5 dB 10 dB step ± 1.0 dB 20 dB step ± 1.25 dB 30 dB step ± 2.0 dB 40 dB step
Attenuation Select	3 Bit TTL
Gain Tracking Between Units of a Matched Pair	a) No Attenuation ± .5 dB b) Any Attenuation ± .75 dB
Phase Tracking Between Units of a Matched Pair	a) No Attenuation ± 5° b) Any Attenuation ± 7°
Input/Output VSWR	1.5:1 Max
Power Output at 1 dB Compression	+12 dBm Min
Noise Figure	3.6 dB Max @ 25°C 4.5 dB Max @ 71°C
Attenuation Switching Time	50 nanoseconds Max to within 1 dB
Operating Temperature	-54°C to + 80°C

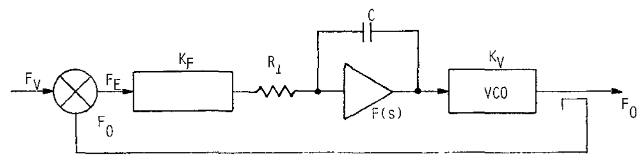
TABLE II
MEASURED PERFORMANCE FOR IF ATTENUATOR

Frequency Range	50 MHz to 70 Mhz
Insertion Loss	4.0 dB, Maximum
RF Power	To +10 dBm Input
Impedance	50 Ω , Nominal
VSWR (All States)	1.35 to 1, Maximum
Attenuation States	2, 4, 8, 16, 16 dB
Attenuation Accuracy	±.50 dB ±5% of Value
Switching Speed	50 nsec, Maximum
Switching Transients	25 mV Peak, Maximum 0mV after 100 nsec
Control	Via 5 line TTL, Logic "1" = Attenuation
Amplitude Tracking (All States)	.5 dB, Maximum
Phase Tracking (All States)	4°, Maximum

50 ns to prevent switching spikes from obscuring the true video signals. The programmable IF attenuator is a special design utilizing FET switches for each bit to minimize switching transients. The overall phase and amplitude tracking of the IF attenuator is better than 4° and 0.5 dB over the attenuation range and operating temperature range as is given in Table II. A built-in automatic frequency control (AFC) circuit maintains the IF at 60 MHz within 0.5 MHz as the magnetron frequency slews ±60 MHz at a 50 Hz rate. The AFC is designed so as to optimize the accuracy at the different system pulse widths.

TABLE III
SYSTEM AFC LOOP PARAMETERS

LO FREQUENCY	9.29 GHz
FREQ. SLEWING	120 MHz at 50 Hz Rate
CAPTURE RANGE	± 15 MHz
FREQ. SETTLING TIME TO WITHIN 100 KHz	.3 μ sec
HOLDING TIME TO WITHIN 250 KHz	4 msec
IF FREQUENCY	60 MHz
IF FREQUENCY ACCURACY	± 250 KHz



$$\frac{f_o}{f_v}(S) = \frac{\frac{K_f K_v}{T_1}}{S + \frac{K_f K_v}{T_1}} \qquad f_v(S) = \frac{\Delta f_v}{S}$$

$$f_o(t) = \Delta f_v \left(1 - e^{\frac{-t K_v K_f}{T}}\right) \qquad \frac{f_e}{f_v}(S) = \frac{1}{1 + \frac{K_v K_f}{S T_1}}$$

$$f_e(t) = \Delta f_v \, e^{\frac{-K_v K_f}{T_1}}$$

$$\text{LOOP BANDWIDTH, BW} = \frac{1}{\frac{2\pi T}{K_v K_f}} = \frac{1}{2\pi T} \ln \frac{\Delta f_v}{f_f}$$

f_f = FINAL FREQUENCY OFFSET AT T, (PULSE WIDTH).
T = PULSE WIDTH
K_v = VCO SENSITIVITY MHz/VOLTS
K_f = DISCRIMINATOR GAIN VOLTS/MHz
T_1 = RC
f_v = INITIAL FREQUENCY OFFSET

FINAL FREQUENCY ERROR	PULSE WIDTH	INITIAL FREQUENCY OFFSET	LOOP BANDWIDTH
200 KHz	.3 μsec	11.6 MHz	2.15 Mhz

Fig. 5. AFC loop analysis.

II. AUTOMATIC FREQUENCY CONTROL

An AFC circuit is normally used in radars incorporating magnetron transmitters to eliminate slow frequency drifts due to temperature, humidity, altitude, VSWR, turn-on warm-up, power supply variation, and aging. For these effects a slow-acting AFC is sufficient, averaging over many transmit pulses for corrections.

Many airborne monopulse radars use a pulsed magnetron, whose frequency can be modulated at a low frequency rate, 100 Hz, typically over a 100 MHz excursion.

The AFC circuit is used to lock an internal VCO to the frequency of the magnetron at each pulse with an offset equal to the receiver IF center frequency. To accomplish this the magnetron frequency must be captured during

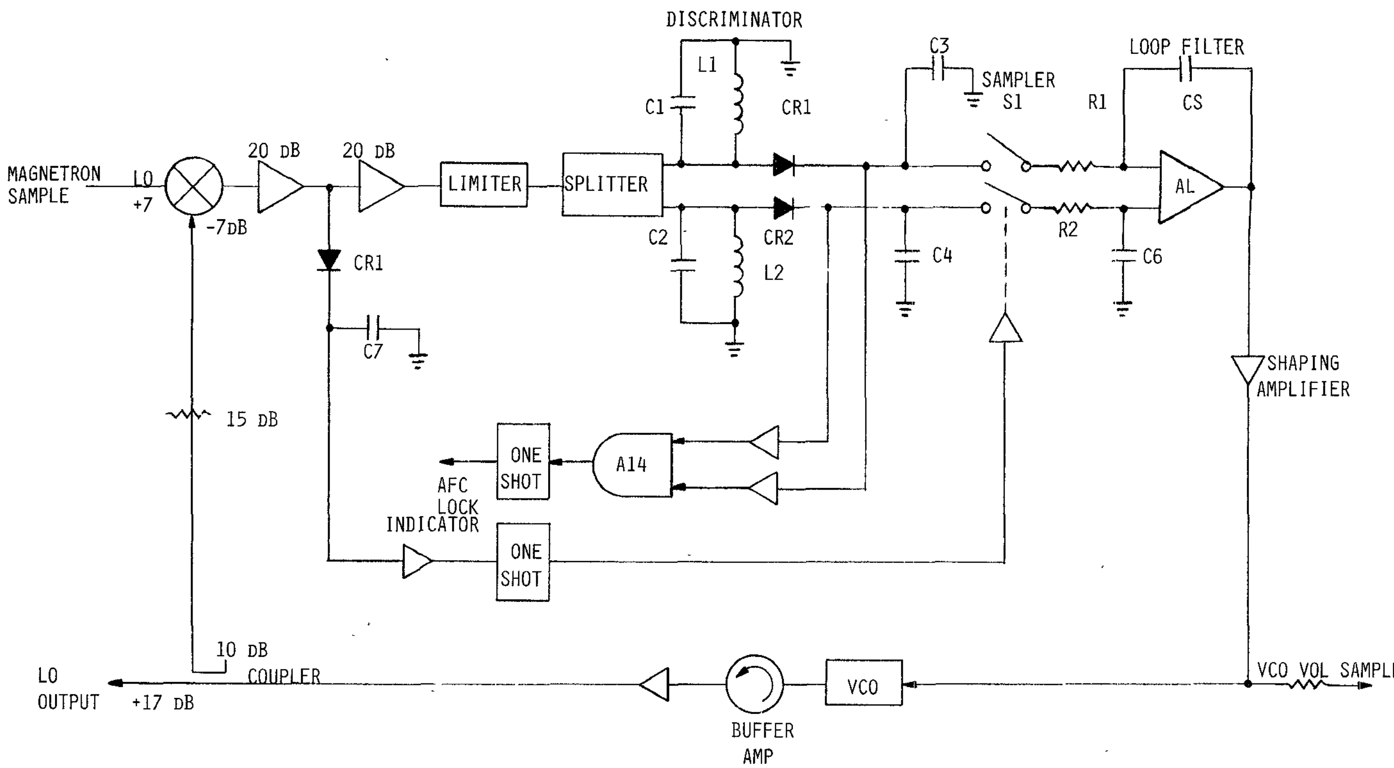


Fig. 6. Block diagram of AFC circuit.

each transmit pulse interval, < 0.3 μs, and held closely during the interpulse period (up to 4 ms).

An instantaneous AFC-type loop is used in which the error correction is completed before the pulse has ended. Extremely wide bandwidths are required in the discriminator and amplifiers in order for negligible delay to be obtained in these elements. The discriminator has a 30 MHz bandwidth, while the shaping amplifier bandwidth is better than 20 MHz.

The capture range of the loop must be designed to be broad enough to accommodate the expected maximum frequency change in the interpulse period resulting from the 100 MHz frequency slewing of the magnetron.

The capture range is directly dependent on the bandwidth of the discriminator curve and is limited by the desired frequency accuracy and the IF operating frequency. Narrower discriminator bandwidths result in tighter accuracy specifications but smaller capture ranges.

The performance parameters of the AFC loop required by the system are shown in Table III.

An analysis of the AFC loop during the sampling interval appears in Fig. 5 along with the calculation of the required loop bandwidth.

The AFC loop is a first-order loop using a fast active integrator to achieve the required settling time. Any additional time delays or lags in the circuit must be minimized to keep frequency ringing low. The sample and hold circuits are designed for wide bandwidth and low droop during the interpulse period. The 60 MHz IF frequency accuracy is determined by the discriminator crossover accuracy and the temperature stability. Careful design is required to attain the discriminator bandwidth for the required capture range and the 60 MHz IF offset frequency accuracy of ±250 kHz over the operating temperature.

TABLE IV
X-BAND MONOPULSE RECEIVER MEASURED PERFORMANCE

Operating Frequency	9.36 ± .290 GHz
Frequency Agility	± 60 MHz at 50 Hz Rate
Pulsewidth	.3 to 4.0 μsec
PRF	2000 PPS to 250 PPS
Single Sideband Noise Figure	6 dB at 20°C 6.5 dB at 71°C
Image Rejection	20 dB
Linear Instantaneous Dynamic Range (8 MHz IF BW)	42 dB
Log Channel Instantaneous Dynamic Range	80 dB
Gain Control	
Front End	40 dB in 10 dB Steps
IF	40 dB in 2 dB Steps
Phase Tracking Between Sum and Difference Channel	± 15° Over -54 to +71°C & ± 60 MHz of Center Freq.
Amplitude Tracking Between Sum and Difference Channels	± 1 dB over all Attenuation Ranges
Supurious Signals	-60 dBc
Two Tone, Third Order Responses (-30 dBm Input)	-45 dBc

III. AFC LOOP DESCRIPTION

A block diagram of the AFC loop appears in Fig. 6.

A sample of the magnetron frequency is mixed with the internal LO to produce an IF frequency centered at 60

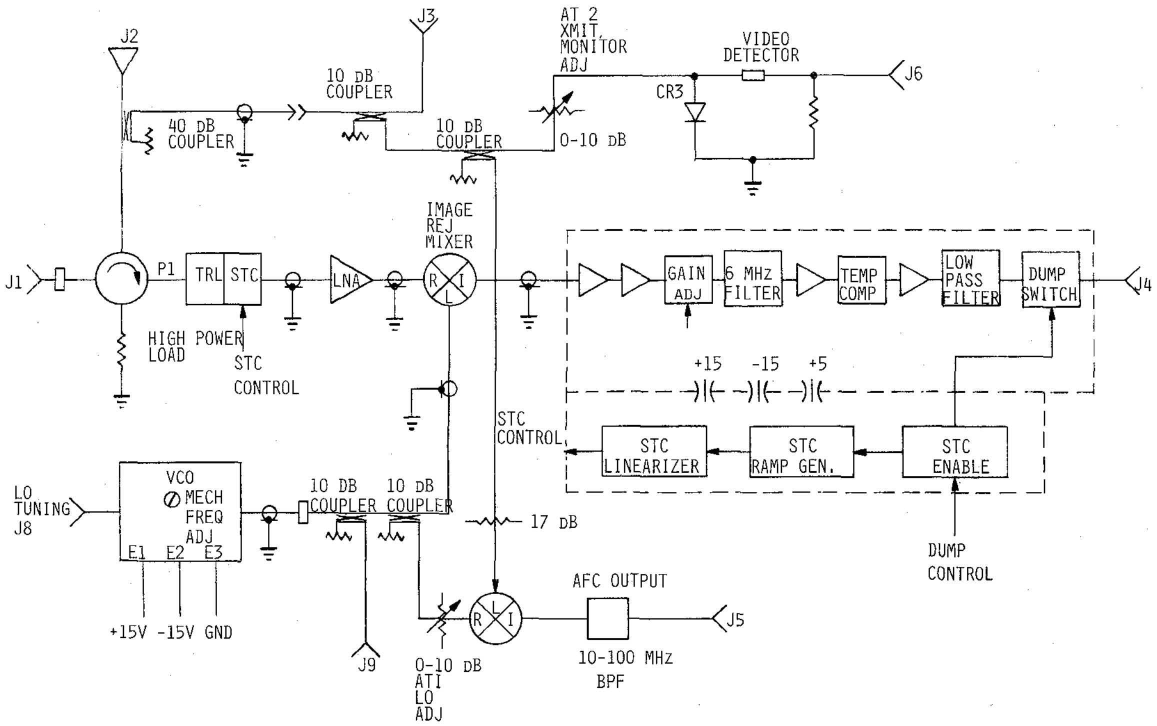


Fig. 7. Fire control radar microwave assembly block diagram.

MHz. After amplification, the signal is limited to remove amplitude fluctuations and then applied to an FM discriminator. The discriminator consists of two tuned circuits, one peaked at 90 MHz (30 + 60 MHz), the other tuned to 30 MHz (60 − 30 MHz).

The detected signal is applied differentially to the loop filter to produce a discriminator S curve centered at 60 MHz. The loop acts to set the pulses out of each tuned circuit at equal levels during the nulling process. The loop filter output feeds a shaping amplifier which acts to linearize the voltage versus frequency curve of the VCO. The shaping amplifier drives the varactor input of the VCO which completes the loop. The sample-and-hold circuit is used to hold the loop null point during the time that input pulses are absent. This requires a fast-acting sampler along with a low-leakage hold circuit. Note that these requirements are conflicting and will have to be carefully balanced. The lock detector functions by comparing the pulse levels at the detected discriminator output for equality.

IV. Monopulse Measured Performance

The measured performance of the integrated X-band monopulse receiver is presented in Table IV [5].

An overall system noise figure of 6 dB was obtained at 20°C, rising to 6.5 dB at 71°C. A linear instantaneous dynamic range of 42 dB with 80 dB of programmable gain was achieved with low two-tone intermodulation products (−45 dBc) and spurious responses (−60 dBc). Total phase tracking between channels over all attenuation settings, over a temperature range of −54° to +71°C, and over a 120 MHz frequency band was ±15°. Total amplitude tracking over the same conditions was ±1 dB.

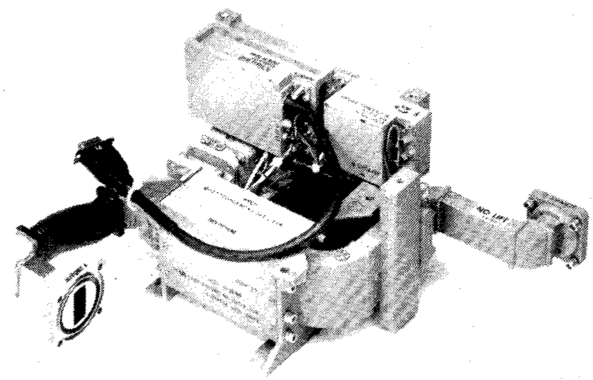


Fig. 8. Doppler radar assembly.

V. Doppler Radar Description

The elements of the X-band Doppler radar subsystem are shown in the block diagram of Fig. 7. They include a fast recovery multisection TRL tube and a precise STC circuit for range-controlled attenuation. Other components are a high-power low-loss circulator, a low-noise FET amplifier, an image rejection mixer, and an AFC circuit for frequency lock of the LO onto the magnetron transmit pulse.

A photograph of the completed integrated subassembly appears in Fig. 8. The combination of the low-noise GaAs FET amplifier preceding the image rejection mixer improves the single-sideband (SSB) noise figure without degrading the overall receiver dynamic range. A time-sensitivity attenuator (STC) preceding the low-noise amplifier attenuates strong, close-in radar returns by a minimum of 18 dB. This prevents overloading of the receiver front end

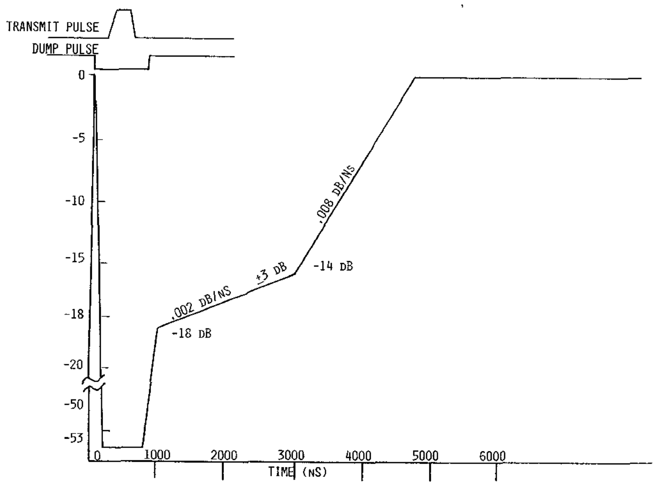


Fig. 9. S.T.C. timing.

TABLE V
FOUR-PORT CIRCULATOR PERFORMANCE

OPERATING FREQUENCY	9.3 ± .15 GHz
POWER	140KW Peak
RF VSWR	
PORT 1	≤1.15 (with TRL short circuited and a 2:1 load VSWR on Port 2)
PORT 2	≤1.2:1
PORT 3	≤2:1
INSERTION LOSS	
PORT 1 TO PORT 2	.8 dB max

for target returns as close as 500 ft and maintains an instantaneous dynamic range of 80 dB.

The receiver gain reduction curve (STC) versus time is such that at 1 μs after pulse transmisson a minimum of 18 dB of attenuation is provided. It then slopes linearly with an accuracy of ± 3 dB to 14 dB attenuation at 3.0 μs, and to 0 dB attenuation at 5.0 μs. The receiver gain reduction curve (STC) versus time is given in Fig. 9.

For low-noise performance, the losses of the high-power circulator and the TRL/STC are minimized, as shown in the component performance specifications of Tables V and VI. A minimum of 60 dB of dump attenuation at the 60 MHz IF output is provided during the transmit pulse. This prevents any possible overloading by transmit transients of the radar's 80 dB dynamic range signal processor.

VI. DOPPLER MEASURED PERFORMANCE

The measured performance of the complete Doppler radar receiver subsystems is presented in Table VII.

At maximum gain (no STC) an overall system noise figure of 4.6 dB was met at 25°C.

Instantaneous dynamic range of 80 dB with -35 dBc maximum spurious level was measured. The fast STC and quick recovery of the TRL tube allow reception of received signals within 1 μs of the start of the transmitted pulse.

TABLE VI
TRL/STC PERFORMANCE

INPUT POWER	140 KW Peak
INSERTION LOSS (OFF CONDITION)	<1.2 dB
RECOVERY TIME (To - 10 dB)	< .8 μ sec
INSERTION LOSS MAX	>53 dB

TABLE VII
DOPPLER RADAR RECEIVER MEASURED PERFORMANCE

Operating Frequency	9.3 ± .15 GHz
Pulse Width	.4 ± .04 μsec
PRF	2500 PPS or 1500 PPS
Frequency Agility	± 50 MHz at 100 Hz Rate
Received Signal Levels	-103.7 dBm to -10 dBm
Noise Figure	4.6 dB at 25°c
Instantaneous Dynamic Range	≥ 80 dB
Spurious Signals	> 35 dBc
Image Rejection	15 dB Minimum
Gain	22 dB nominal
STC	18 dB 1 μsec after transmit pulse; decreases linearily to 0 dB in 5.0 μsec
Dump Attenuation	>60 dB Fast Recovery

VII. CONCLUSION

For monopulse radar, the fast AGC approach utilizing RF and IF programmable attenuators with coherent detectors can provide high-dynamic-range monopulse receiver performance. Careful design of the attenuators for rapid switching and tracking in phase and amplitude over all attenuation states and with temperature is essential for accurate system nulls.

For pulsed Doppler radar, close-in target tracking was achieved using a fast recovery TRL and front-end STC circuit. Accurate control of the time-varying gain allows optimum performance of the radar in the presence of strong returns and over a high instantaneous dynamic range.

REFERENCES

[1] S. M. Sherman, *Monopulse Principles and Techniques.* Dedham, MA: Artech House, 1984, ch. 1, pp. 13–16.

[2] G. W. Stillwell, A. M. Madni, and L. A. Wan, "Sensitivity analysis of a 15.0 GHz monopulse radar receiver using a logarithmic amplifier detection scheme," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1985, pp. 200–203.

[3] A. M. Madni and G. Stillwell, "Design consideration in the development of monopulse radar receivers," in *Dig. IEEE Aerospace Application Conf.*, 1987, pp. 1–15.

[4] A. M. Madni, F. Mesghali, P. McDonald, and L. A. Wan, "Phase and amplitude matched LNA/attenuator pair provides monopulse receiver performance," in *Proc. Military Microwaves 88 Conf.*, 1988, pp. 274–279.

[5] A. M. Madni, P. T. McDonald, R. K. Hansen, and L. A. Wan, "High dynamic range airborne tracking and fire control radar subsystems," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1989,D pp. 439–442.

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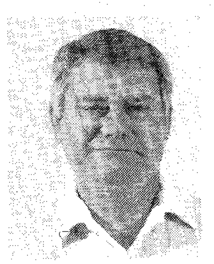

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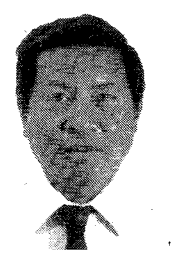

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