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ADVANCED GUN FIRE CONTROL SYSTEM (AGFCS). DESIGN STUDY (PHASE I--ETC(U)

APR 77 R L BERG, W J MURPHY, D E SIMMONS

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(AGFCS)

DESIGN STUDY (PHASE II)

ATS RANGE SENSOR DESIGN DESCRIPTION

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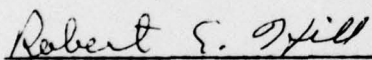
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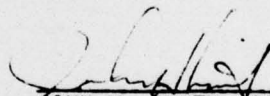
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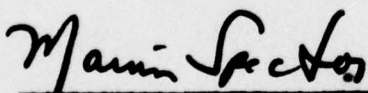
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The Advanced Gun Fire Control System (AGFCS) program is a multi-phase program to investigate technical approaches exhibiting potentially significant improvement in present gun fire control system effectiveness. Phase I, the AGFCS Definition Study, considered the overall design, effectiveness, complexity and mission requirements of a post-1976 air superiority aircraft. The purpose of Phase II, the AGFCS Design Study, was to design an Augmented			

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Tracking System (ATS) for possible fabrication and flight test evaluation in a later AGFCS Program Phase. The ATS includes the range and angle tracking sensors, the computer, and the software used to process the tracking signals. It provides the target-dependent variables required to solve the lead angle equation in a director AGFCS mechanization. The ATS will ultimately serve as the core of an advanced gun fire control system.

The selected configuration serves as the basic element of a modular advanced gun fire control system. Its salient feature is the use of strapdown sensors in both the angle tracking and range tracking systems. The angle sensor is the Bendix Corporation Adaptive Scan Optical Tracker (ASCOT); the range sensor is the General Electric Solid State Radar (SSR-1). Both sensors satisfy the requirements of the ATS application and have adequate technical maturity for timely fabrication and flight test. The principal ATS subsystem and software features are:

- o Principal Subsystems
 - o Bendix Adaptive Scan Optical Tracker
 - o GE Solid-State Radar
 - o ATS Digital Computer
 - o Strapdown Gyro/Accelerometer Package

- o Software Features
 - o Kalman Angle Tracking Filter
 - o Kalman Range Tracking Filter
 - o Director Gun Fire Control Equations

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PREFACE

This report was prepared by the McDonnell Douglas Corporation, St. Louis, Missouri, McDonnell Aircraft Company, Avionics Systems Technology Department under U.S. Air Force Contract F33615-73-C-1319. The program was administered by the Air Force Avionics Laboratory Systems Avionics Division, Wright-Patterson Air Force Base, Ohio. The Air Force project engineer directing the technical aspects of the study was Captain Richard H. Hackford Jr., AFAL/NVA.

This report summarizes the principal program activity of the Advanced Air-to-Air Gun Fire Control System Design Study, Project 7629, Task 762903, from June, 1973 to April, 1974.

The authors were R. L. Berg, who also served as Principal Investigator, Dr. W. J. Murphy, and D. E. Simmons. Contributions to this report from Messrs. J. S. Arnold, R. D. Schoeffel and G. W. Zirkle of McDonnell Aircraft Company are gratefully acknowledged. The authors also wish to acknowledge the technical guidance of Mr. E. A. Rosenkoetter, Manager, Electronics Systems Technology, McDonnell Aircraft.

The authors wish to thank Messrs. R. J. Daugherty and W. C. Feuchter, and Dr. R. R. Olson of Bendix Corporation Aerospace Systems Division; and Messrs. L. W. Burdette and J. J. O'Leary of General Electric Company Aerospace Electronics for their cooperation throughout the study.

Three report VOLUMES are published under separate cover due to their volume and, in the case of VOLUME II, to protect subcontractor proprietary rights. VOLUME II is subtitled ATS Angle Sensor Design Description, VOLUME III is subtitled ATS Range Sensor Design Description, and VOLUME IV is subtitled ATS Software Design Description.

This report was submitted by the authors in April, 1974.

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SECTION 1 INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

This volume describes in detail the ATS range sensor design. It is based for the most part on the subcontractor's final report with some clarification and minor additions added during review and AGFCS Phase II final report preparation. The AGFCS Phase II Augmented Tracking System (ATS) is unique in that the central ATS computer is utilized to optimize angle and range sensor information processing. The range sensor selected for the ATS is the Solid State Range-Only Radar (SSR-1) being developed at General Electric, AESD, Utica, New York. The SSR-1 radar parameters (frequency, power output, etc.) are compatible with the ATS application. Thus the principal subcontracted activity has been addressed to adapting the basic radar to interface with the central ATS computer.

Development of the basic radar has progressed in parallel with the AGFCS Phase II study. Detail design and testing for MIL-E-5400 environments is in process and completed units of the basic design are scheduled for June 1974. Due to this parallel effort, long lead parts on hand will allow delivery of a flight-worthy ATS SSR-1 six months after receipt of an order. As an additional feature of this parallel approach, a breadboard SSR-1 can be made available for demonstration and evaluation in a laboratory environment of the system interface compatibility. A photograph of the basic SSR-1 radar is shown in Figure 1.

1.2 SUMMARY DESCRIPTION

1.2.1 Radar Characteristics

The SSR-1 radar is an X-band, noncoherent, pulsed radar that measures the range and range rate of either closing or opening targets and supplies electrical outputs of range, range rate, and lock-on. The radar is contained in one Line Replaceable Unit (LRU) comprised of the following subassemblies:

- RF Assembly
- Magnetron
- Modulator
- AFC
- IF Amplifier
- Range Tracker
- Power Supply
- Self-Test/Control

It features a strapdown, wide-beamwidth antenna (15°) and has a detection range of 2.65 nautical miles on a 2 square meter target located along the axis of the antenna beam. The main parameters and performance

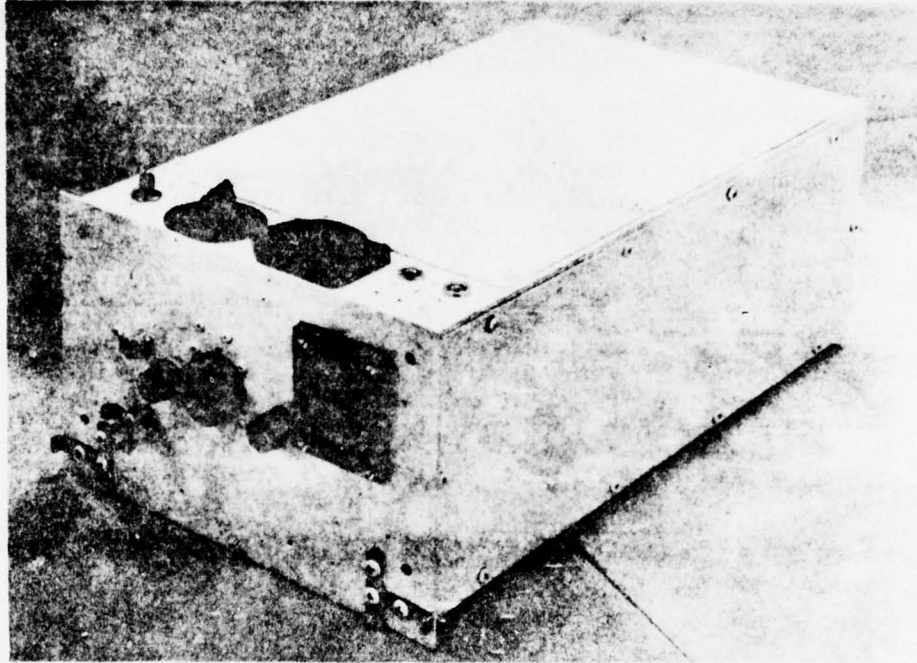


FIGURE 1
SSR-1 RADAR

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characteristics are listed in Table 1 and Figure 2 represents a functional block diagram.

1.2.2 Modes Of Operation

The ATS radar is capable of operating in either an Autonomous or an augmented tracking mode. In the Autonomous mode, the radar updates range and range-rate signals independent of the ATS central computer. In this mode, the radar operates as a conventional alpha-beta tracker, where alpha (α) is a position smoothing constant and beta (β) is a velocity smoothing constant.

In the Augmented mode, the range tracker has been designed to interface with the Kalman Range Tracking Filter in the ATS computer. During Augmented mode operation the radar sets α to 1 and β to 0, and transfers control of range and range-rate updating to the ATS central computer.

1.2.3 Operational Controls and Displays

The following operational controls and displays have been designed into the ATS radar:

TABLE 1
SSR-1 RADAR PARAMETERS

Antenna

Type	6 in. Horn
Beamwidth Azimuth	15° at 3 dB
Beamwidth Elevation	15° at 3 dB
Aperture Size	6 in.
Gain	21 dB

Transmitter

Transmit Frequency	9375 MHz
Peak Power	8 kW
PRF	1024 Hz
Pulse Width	0.45 microsec

Receiver

IF Frequency	30 MHz
Bandwidth	4 MHz
Noise Figure	8 dB
MDS	-98 dBm

Processor

Search Range (Selectable)	3,000 ft - Gun Mode
	6,000 ft
	24,000 ft - Missile Mode
Search Rate	24,000 ft/sec
Velocity Memory	2 sec
Tracking Accuracy	±50 ft
Lock-On	-91 dBm

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- o OFF - STANDBY - RADIATE: This is the basic power-on control. In STANDBY position, bias voltages are applied along with magnetron filament voltage. After a warm-up period, RADIATE select is enabled and its selection will initiate transmission of RF power.
- o RANGE SELECT: Provides for selection of a 3000, 6000, or 24000 foot maximum search range.
- o SELF TEST: Initiates generation of an internal test target for pre-flight or taxi checks.
- o TARGET REJECT: Allows for breaking lock on presently acquired targets.
- o SELF-TEST GO/NO GO: Provides GO or NO-GO indicator lamp condition based on self-test parameters. Consists of 2 separate lamps.
- o SEARCH: Illuminates indicator lamp when in search.

- o LOCK-ON: Illuminates indicator lamp when radar has acquired and locked on (tracking) a target.
- o THERMAL OVLD: Illuminates indicator lamp when internal LRU temperature has exceeded 160°F.

The computer control functions required for the Augmented mode are summarized below. A detailed description is given in Section 3.0.

- o Augmented Mode Control: Commands radar to go into Augmented mode and transfer control to the ATS computer.
- o Autonomous Mode Control: Commands radar to go into the Autonomous mode and perform own updating of range and range-rate computations.
- o Command Codes: Alerts range tracker to forthcoming computer data requirements. That is, to transfer or to receive from the computer: range and range-rate data, tracker status, signal-to-noise ratio, and range differences.

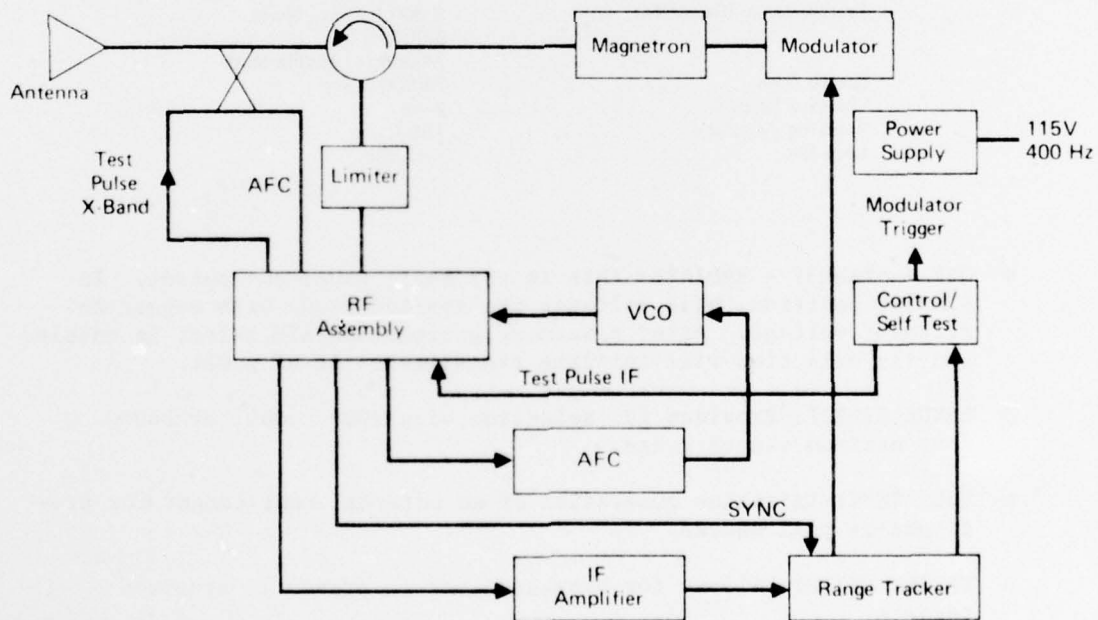


FIGURE 2
SSR-1 RADAR FUNCTIONAL BLOCK DIAGRAM

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1.2.4 Radar Configuration and Reliability

The ATS radar is self contained in one line replaceable unit as shown in Figure 1. Except for the 2J42H Magnetron, the radar is entirely solid state and features high reliability, ease of fault isolation and ease of maintenance. Mechanical characteristics are outlined in Table 2.

Except for the magnetron, the radar is entirely solid state and has no moving parts. It uses fewer than 700 electrical components and has a predicted MTBF in excess of 2000 hours. This prediction is based on reliability experience gained with production radars such as the APQ-113, -114, and -44, which utilize similar components and design techniques as employed in the ATS radar.

TABLE 2
ATS RADAR MECHANICAL CHARACTERISTICS

Weight	23 lb
Dimensions	16.15 in. L 9.06 in. W 5.91 in. H
Cooling Air	None
Pressurization	15 psia (Waveguide Only)
Operating Temperature	-55 to 71°C
Operating Altitude	0 to 50,000 ft
Electrical Power Input	115V - 400 Hz - 1.5A + 28 VDC - 1.0A
Mounting	Hard Mount
Vibration	MIL-STD-810B Curve A

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SECTION 2 AUTONOMOUS OPERATION

2.1 GENERAL

In its Autonomous mode, the ATS radar will perform target range prediction and range-rate update independent of the ATS central computer. The range tracker subassembly contains an internal computer to perform the required update computations.

Adaptation to the ATS application can be understood by first describing the overall autonomous operation. Therefore, an operational scenario follows.

2.2 OPERATIONAL SCENARIO--AUTONOMOUS MODE

Selection of either the Autonomous or Augmented operational modes requires the range tracker circuitry to perform several functions:

- SEARCH
- ACQUISITION
- TRACK
- COAST
- RETURN TO SEARCH (BREAK-LOCK)

2.2.1 SEARCH Function

The SSR-1 is capable of range searching to 3000, 6000, or 24000 feet, selectable from the control panel. During SEARCH, the range gate is swept at 24000 feet/second. Thus, 3000 feet of range is covered in 1/8 second, 6000 feet in 1/4 second, and 24000 feet in 1 second. With this sweep rate and a 1024 PRF, the range gate dwells on a given range segment for 32 pulses. After each 32 pulse packet, the range gate is stepped out in range by 750 feet and searches the next range segment. The range segment is composed of eight (8) 100 foot range gates, as shown in Figure 3. Target detection is performed by a bank of eight capacitors in a sample and hold circuit configuration. In effect, each of these capacitors moves with one of the eight range gates and integrates the target returns for the 32 pulse dwell time. Each capacitor integrates returns from 100 foot increments within the range segment. This is illustrated in Figure 3.

The start of the range gate varies depending upon maximum range selection. For the 3000 and 6000 feet maximum ranges, the range register is reset to zero by positioning gates 4 and 5 at zero range, as shown in Figure 4. When the 24000 feet maximum search range is selected, the range register is allowed to overflow and the start position of the gate on the next range sweep will be positioned out from zero range by the amount of the overflow (0 to 100 feet). This is illustrated in Figure 5.

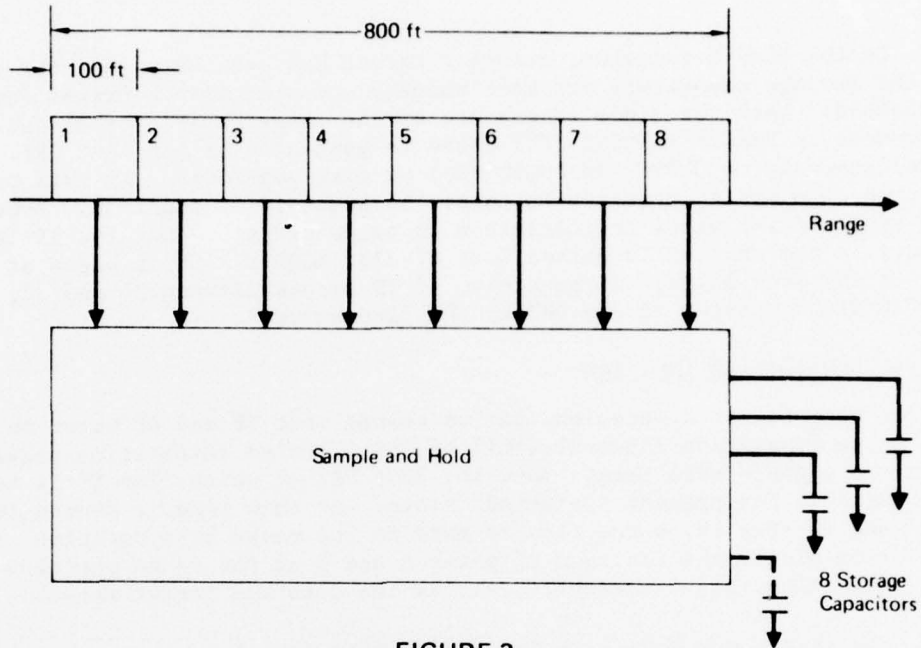


FIGURE 3
RANGE GATE REPRESENTATION

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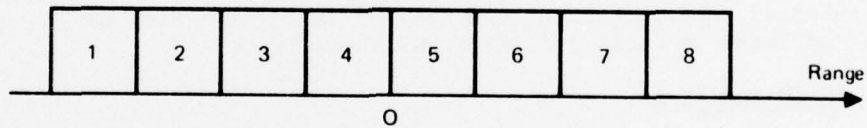


FIGURE 4
RANGE GATE RESET POSITION FOR 3000 AND 6000 FT SEARCH OPTION

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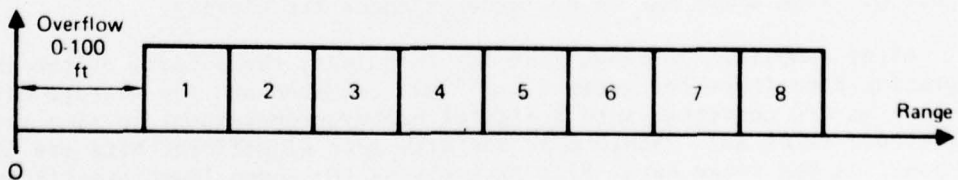


FIGURE 5
RANGE GATE RESET POSITION FOR 24,000 FT SEARCH OPTION

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In the SEARCH function, before a target has been detected, the outputs of the storage capacitors are continuously compared with a preset detection threshold. When the video in any one of the range gates exceeds the threshold, a TARGET PRESENT (TP) pulse is generated on the next PRF. Simultaneously, a DETECTION PULSE (DP) is also generated. At this point in time, the system prepares to enter the ACQUISITION function. However, the system first waits to complete a 16 pulse packet. That is, if TP occurs in the initial 16 pulses (out of 32), ACQUISITION is begun at the end of the 16th pulse. Alternately, if TP occurs between 16 and 32, ACQUISITION is begun at the end of the 32nd pulse.

2.2.2 ACQUISITION Function

For purposes of discussion, let us assume that TP and DP occur on the 20th pulse repetition interval (PRI) of the 32-pulse integration packet. These two signals will remain thru the 32nd PRI at which time TP is reset and DP remains in its present (detected) state. At this time, a coarse incremental range (Coarse ΔR) correction is made in the range gate position. This correction places the centroid of gates 4 and 5 at the range position of the gate indicating target present; i.e., at the detected target range.

The system now goes into the ACQUISITION function. Data are accumulated for 0.25 sec. That is, the system now waits and processes 16 packets of 16 pulses, which is equivalent in time to 256 PRI's. During this time, Fine ΔR corrections are made to the range measurements and range-gate position (if required). The range-rate register, initially set at zero, accumulates data to determine the initial velocity (R) to be used in the TRACK function. At the end of the 256 PRI sufficient data have been accumulated to declare LOCK-ON and begin TRACK.

2.2.3 TRACK Function

During the TRACK function, data are refreshed after each set of 16 PRI samples, which is each 16 milliseconds or at a 64 Hz rate. Range tracker computation, prediction, and update takes 100 microseconds* and is performed during the radar dead time. $\alpha - \beta$ smoothing is employed during these computations to make proper range and range-rate corrections. A diagram of the timing relationship of the TRACK function is shown in Figure 6. Time after PRI 16 has been expanded for clarity.

After sampling the range gate for 16 pulses, the outputs of the integrating capacitors for gates 4 and 5 are compared and the voltage difference is A/D converted into a digital number proportional to fine range difference (Fine ΔR). Since only the nine most significant bits are used to position the range gate, Fine ΔR includes the seven least significant bits of the range register. The measured range register correction, ΔR , therefore, is the difference between Fine ΔR and the seven least significant bits of the range register.

* 50 μ sec for error computation and update (using α and β)
50 μ sec for error prediction and calculation

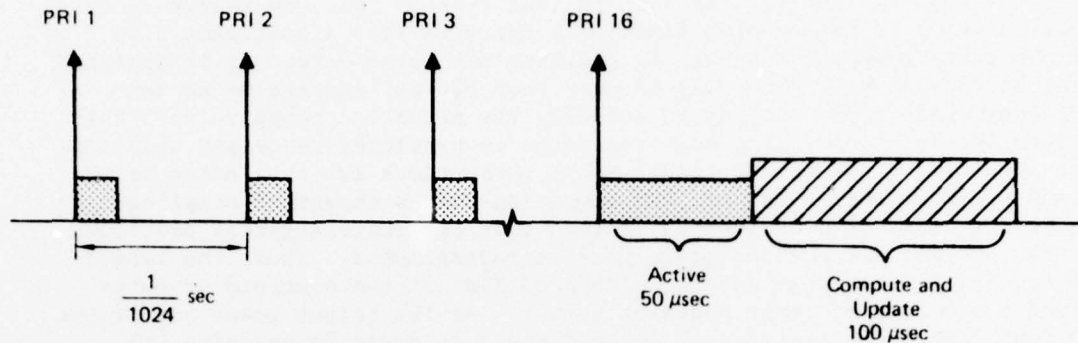


FIGURE 6
TRACK AND COMPUTATION PERIODS

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This measured range correction, ΔR , is used to update predicted range. For smoothing purposes, only a portion of ΔR is added. This portion corresponds to $\alpha \cdot \Delta R$. Therefore, an initial correction is made to predicted range to compensate for the measured error in the current range register contents. A correction is also made to the stored range rate. The range-rate correction is computed as follows:

$$\hat{\Delta R} = \frac{\Delta R \cdot \beta}{T}$$

$\hat{\Delta R}$ = Predicted Range-Rate Correction

ΔR = Measured Range Correction

β = Velocity Smoothing Constant

T = 0.016 Seconds

This range-rate correction ($\hat{\Delta R}$) is added to the range-rate register to update stored range rate.

$$\hat{R}_{\text{new}} = \hat{R}_{\text{old}} + \frac{\Delta R \cdot \beta}{T}$$

Using \hat{R}_{new} , a prediction is made of target range for the end of the next 16 PRF intervals. That is:

$$\Delta \hat{R} = \hat{R}_{\text{new}} \cdot 0.016 \text{ sec.} = \text{change in range due to } \hat{R}$$

and $\Delta \hat{R}$ is added to the range register to establish new target position. Thus, the new predicted range is:

$$\hat{R}_{\text{new}} = \hat{R}_{\text{old}} + \alpha \cdot \Delta R + \Delta \hat{R}$$

It is noted that if $\alpha \cdot \Delta R + \hat{\Delta R}$ is less than 50 feet, no change in range gate position is implemented since only the nine most significant bits of the range register are used to position the range gate. It is expected that $\alpha \cdot \Delta R + \hat{\Delta R}$ will generally be less than 50 feet and the mechanism for range-gate repositioning is actually the predicted range value. This system tracks by comparing measured range to predicted range and updating the predicted range calculation. Range corrections are then added to the range register and it is when the summation over a number of sampling intervals of $\alpha \cdot \Delta R + \hat{\Delta R}$ exceeds 50 feet that the range register overflows at the 50 feet bit and the range gate is repositioned. Thus, the target is tracked by the range gate to within 50 feet of the centroid of gates 4 and 5 by means of range register update. As the target moves out of the 50 feet range, the centroid of gates 4 and 5 is moved by stepping the range gate and the sequence continues.

2.2.4 COAST Function

The previous discussions of TRACK assumed the tracker continuously maintained target lock on. Target scintillation and changes in target aspect angle will cause the video level on the storage capacitors to occasionally fall below the detection threshold level. The COAST function is provided in the SSR-1 to allow for such target signal return fluctuations.

As mentioned in the SEARCH function description, a TARGET PRESENT (TP) pulse occurs when a range-gate capacitor exceeds the detection threshold. During TRACK, this signal also occurs at a 64 Hz rate as long as the video return exceeds the threshold. This pulse is used to reset a free running counter, the terminal count of which represents 2 seconds, and is wired such that terminal count will reset the TRACK flip-flop and return the system to the SEARCH function. As long as the detection threshold is exceeded, the occurrence of TP pulses will prevent this counter from reaching its terminal count. Thus, the tracker can miss a number of target detections before declaring a break-lock. In fact, at a 64 Hz rate, 128 target return samples not exceeding threshold are required for a break-lock condition and return to the SEARCH function.

In the event of a missed detection, the range tracker will COAST. That is, when TP does not occur, the system rejects any new range information and updates its new range prediction based on previously stored range rate in the range-rate register. Thus,

$$\begin{aligned}\hat{\Delta R}_{\text{new}} &= 0 \\ \hat{R}_{\text{new}} &= \hat{R}_{\text{old}}\end{aligned}$$

Range update is then,

$$\hat{R} = \hat{R}_{\text{old}} \cdot 0.016$$

or

$$\hat{R}_{\text{new}} = \hat{R}_{\text{old}} + \hat{R}_{\text{old}} \cdot 0.016$$

It can be seen, then, that the range gate will coast at the previously predicted velocity. When the TP pulse reappears, new range data are then used in the α - β loop to correct the target range rate and range measurements as discussed in Subsection 2.2.3.

2.3 RANGE TRACKER CIRCUIT DESIGN

The SSR-1 Range Tracker circuitry will be constructed in two multilayer boards with 12 layers each. Standard MSI integrated circuits of the dual-in-line configuration will be used throughout. The following circuits make up the tracker:

Control Circuit:

PRF Counter
Delay and Pulse Shaper
Range Counter
Range Comparator
Computer Clock
Time Counter
Video Integrator

Computer Circuit:

Program Storage Memory and Controls
Arithmetic Unit
Storage Registers

2.3.1 Range Tracker Control Circuit

A block diagram of the control portion of the range tracker is shown in Figure 7. The principal elements are:

PRF COUNTER --used to decode the 5.25 MHz clock to generate a 1.024 KHz radar trigger.

DELAY AND PULSE SHAPER--compensates for variations in transmitter delay and controls the pulse width of the modular sync pulse.

RANGE COUNTER--composed of 3 binary counters operating at a 10 MHz rate; counting from approximately 0 to 48,000 feet each PRI starting at radar main bang.

RANGE COMPARATOR--the range counter number is continuously compared with the range register output in the 10 bit range comparator. Each time the counter reaches the number stored in the range register, a range-gate start pulse is generated and a series of eight range gates, each 191 nanoseconds wide, is generated. Starting the range gate slightly ahead of target range is accomplished by starting slightly ahead of main bang.

COMPUTER CLOCK--the computer clock is created by decoding the PRF counter. These clock pulses are 0.8 microseconds wide, negative going at a 500 KHz rate. In addition, the PRF counter generates the gates required to control computer iterations at 16 or 32 times per interpulse period.

TIME COUNTERS--provides the 1/4 second count for the ACQUISITION function and the 2 second COAST function. Uses the TARGET PRESENT and DETECTED PULSE to put computer in either the ACQUISITION, TRACK, or COAST functions and return to SEARCH in event of loss of target.

VIDEO INTEGRATOR-- contains the eight-gate sample and hold circuitry and associated threshold sensing and controls.

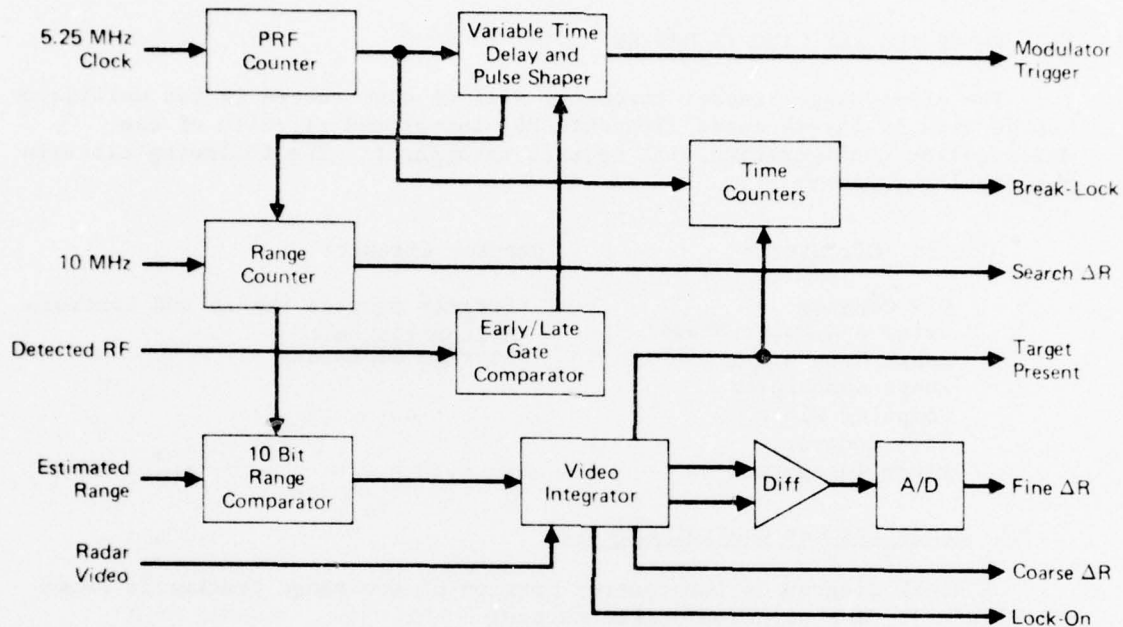


FIGURE 7
RANGE TRACKER CONTROL CIRCUIT

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2.3.2 Range Tracker Computer Circuit

The following describes the range tracker computer subassemblies as illustrated in Figure 8:

PROGRAM STORAGE MEMORY AND CONTROLS--4 eight bit by 32 word programmable read-only memories (PROMs) are connected to form a 16 bit by 64 word program memory. Thus, it requires a 6 bit address to select a single 16 bit word readout. The four least significant bits of address are sequenced by a 4 bit binary counter which is gated on for 16 clocks every 16th PRI.

The memory is divided into 4 fields of 16 words each. The field is selected by the 2 most significant bits of address and the counter sequentially steps the memory through the 16 words in each field.

ARITHMETIC UNIT--A 2-input multiplexer provides for selection of either range or range-rate data for computation and update. This multiplexer's outputs are connected directly to the "A" inputs of the parallel adder. Selection is controlled by the appropriate control bit (A) from the current program instruction being read out of program memory.

A 4-input multiplexer provides for the selection of the "N" register, Fine ΔR , Coarse ΔR , or Search ΔR . This multiplexer's outputs are connected directly to the "B" inputs of the parallel adder. Selection is controlled by the appropriate control bit (B) from the current instruction being read out of program memory.

STORAGE REGISTERS--Two 16 bit parallel/serial shift registers are supplied to store range and range rate. A third register, the N register, is used for temporary storage of partial products and sums. The parallel outputs of the adder are connected in common bus fashion to the inputs of all three registers. The register (s) to receive the adder output is (are) controlled by the appropriate control bit (R, V and N respectively) from the current program instruction.

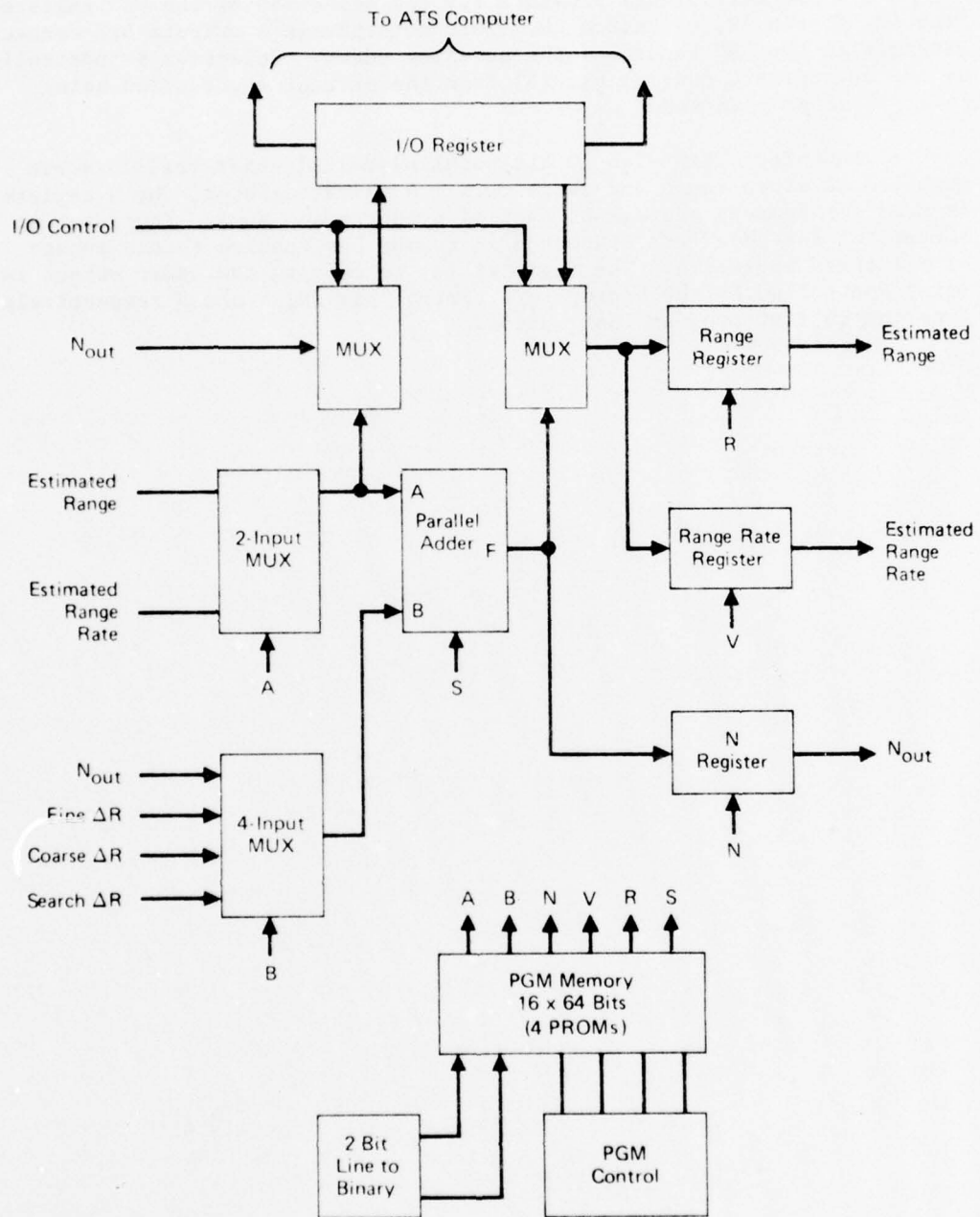


FIGURE 8
RANGE TRACKER COMPUTER CIRCUIT

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SECTION 3 AUGMENTED OPERATION

3.1 GENERAL

The ATS SSR-1 is designed to interface with the ATS Kalman Range Tracking Filter via the ATS Computer. As such, when commanded, it will transfer complete control of the TRACK function to the ATS computer. This operational mode is referred to as the Augmented mode.

In the Augmented mode, the radar's signal-to-noise ratio (SNR) is computed and transmitted to the central computer. This computation is performed by the addition of an A/D converter to the Automatic Gain Control (AGC) circuitry in the radar. AGC level appropriately scaled provides a measure of SNR for use in setting the range measurement error variance in the Kalman Range Tracking Filter.

3.2 OPERATIONAL SCENARIO - AUGMENTED MODE

In the Augmented mode, the sequence of operations is the same as in the Autonomous mode except that the ATS central computer takes control of both range and range-rate update during TRACK. The sequence of functions is still as follows:

SEARCH
ACQUISITION
TRACK
COAST
RETURN TO SEARCH (BREAK-LOCK)

Initiation of the Augmented mode is commanded by the central computer. This establishes the range tracker operational mode. When the ATS computer transfers control back to the SSR-1, another discrete signal is required to restore the Autonomous mode.

3.2.1 SEARCH Function

The SEARCH function is the same in either the Augmented or the Autonomous mode. That is, it is performed by the SSR-1 as described in Subsection 2.2.1. This eliminates the need for sending radar signals to the computer for performance of radar control functions. Thus, during SEARCH, the radar control lies with the SSR-1.

3.2.2 ACQUISITION Function

ACQUISITION proceeds as in Subsection 2.2.2 similar to the Autonomous mode. This allows the SSR-1 to establish initial range and range-rate estimates prior to transferring control to the ATS computer. The occurrence of the LOCK-ON discrete initiates TRACK and transfers control to the ATS computer.

3.2.3 TRACK Function

Although control has been held by the SSR-1 up to this time, the ATS computer has been receiving measured range, range-rate, and radar status discretely. Therefore, once control is transferred, the computer has the latest radar data. The SSR-1 contains a simple serial input-output circuit which is used to communicate commands and data to and from the central computer.

During TRACK, the SSR-1 range register is updated by the central computer. When the Augmented mode is selected α is set to 1 and β is set to 0. Thus, the range register receives the full error value in range and provides a true measure of target range. The range-register contents are transmitted to the ATS computer where the Kalman Range Tracking Filter is updated. This updated range is then predicted and used to update the SSR-1 range register. Measured range, range rate and range register correction are transmitted from SSR-1 to ATS computer at a 64 Hz rate. In sequence, the ATS computer inputs to the SSR-1 predicted range and range-rate. At the end of the 16 pulse sampling period, the radar will output measured range.

3.2.4 COAST Function

The COAST function in the Augmented mode is similar to that of the Autonomous mode described in Subsection 2.2.4. Under Augmented operation, a COAST bit is sent to the ATS computer to signal the loss of a TARGET PRESENT pulse in the previous data sample. The ATS computer then continues to load the range register but with range predictions based upon extrapolated range from the ATS Kalman Range Tracking Filter.

In summary, the difference between Autonomous and Augmented operation is that in the Augmented mode all filtering and prediction is performed by the ATS central computer using the Kalman Range Tracking Filter. The order and means by which data are updated and transferred is determined by the ATS computer software and system interface.

3.3 ATS RADAR/COMPUTER INTERFACE

A representation of the ATS Radar/Computer Interface is shown in Figure 9. Signal transfer across this bus takes place primarily in the Augmented mode where the ATS computer performs data update and prediction. The interface consists of six twisted pairs transmitting complementary TTL signals. The four inputs consist of data and an interrupt to the ATS computer to advise it that data is available. The inputs and outputs utilize 9615 and 9614 integrated circuits complying with MIL-M-38510. The clock rate for the interface is a nominal 1 MHz but is not critical and can be 300 KHz to 2 MHz.

3.3.1 Commands

The number of data items to be transferred between computer and tracker necessitates the use of an 8 bit command word. This command word represents the following:

Transmit Measured Range Correction, Status, and Signal-to-Noise Ratio
 Autonomous Mode
 Augmented Mode
 Transmit Range Data
 Receive Range Data
 Transmit Range-Rate Data
 Receive Range-Rate Data
 Extra Bit

The ATS central computer will transmit this 8 bit serial command to the tracker prior to each transaction. Clock pulses will also be furnished by the computer to enter commands into an 8 bit shift register.

When the transaction is "Receive Data", the computer will transmit the 16 data bits along with computer clock pulses. An "Execute" pulse then follows the data. Thus, data is entered into the range tracker. When the transaction is "Transmit Data", the central computer will follow the command transmission with an "Execute" pulse. The 16 computer clock pulses then follow. Thus, data is entered into the central computer. The "Execute" pulses represent parallel data transfers into and out of the Input/Output (I/O) registers. The clock pulses provide for serial transfer into the I/O registers or into the central computer.

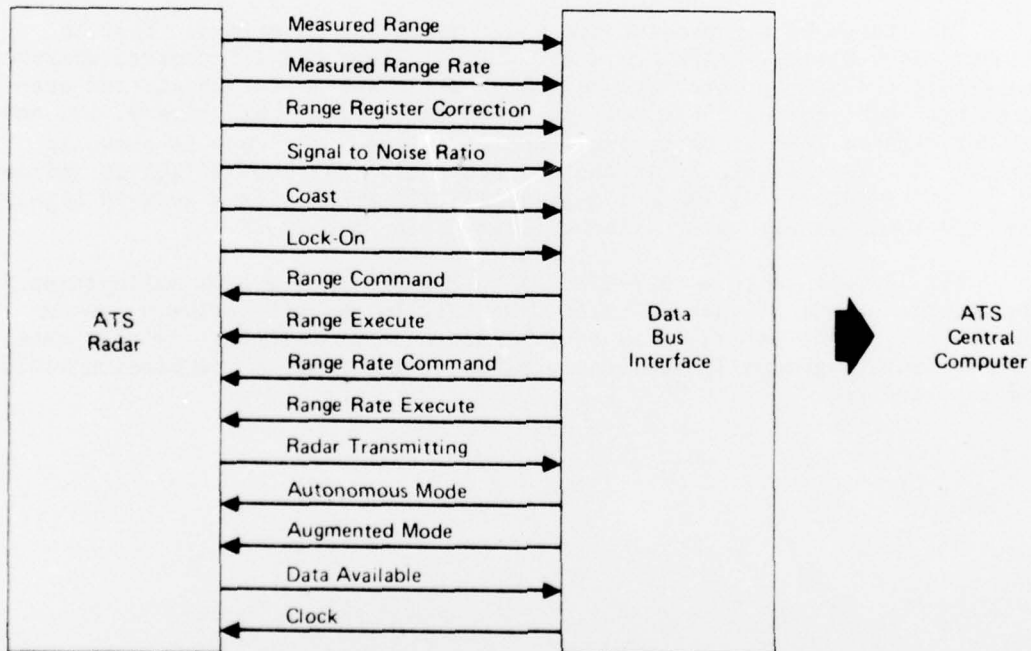


FIGURE 9
 ATS RADAR/COMPUTER INTERFACE

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3.3.2 Data Words

Data words are 16 bits long with bit 1 being the least significant bit (LSB). The data word structure is shown in Table 3. The most significant bit (MSB) of the range word is 12000 feet, while the least significant bit is approximately 0.4 feet. Those range word bits below 2.9 feet have no significance, however, since radar resolution is 2.9 feet and the system cannot step the gate in that small of an increment, but are necessary to avoid underflow errors.

For range rate (velocity), the first or LSB is 23.4 feet/second while the 7th or MSB is 1497.6 feet/second. Bit 8 in the range-rate word is a sign bit, as in the 8th bit of the ΔR , Status and SNR word. This is a requirement since the system operates on two's complement arithmetic. Bits 9 through 16 of the range-rate word are unused and are filled with the sign of range rate.

Bits 1 through 8 of the ΔR , Status, and SNR word are used for ΔR transmission. The first or LSB is .36 feet while the 7th or MSB is 23.4 feet. The 8th bit is the sign of ΔR . Bits 9, 10 and 11 denote the Status, i.e., the DETECTED PULSE, LOCK-ON and COAST signals. Bits 12 through 15 transmit the SSR-1 16-pulse SNR. The 12th or LSB is 3 db (power) while the 15 or MSB is 24 db.

The Status bits represent the radar operating functions. That is SEARCH, ACQUISITION, TRACK, or COAST. This allows the ATS central computer to select the appropriate data and computation scheme for update and prediction. Referencing Table 3 it is noted that Status word bits 9, 10, and 11 represent a code of operating function status. The code is shown in Figure 10. From Figure 10 it can be seen that: (1) ACQUISITION is initiated by DETECTED PULSE; (2) TRACK requires DETECTED PULSE plus a LOCK-ON Signal; and (3) COAST cannot occur without first having had TRACK.

BIT 16 represents a SELF-TEST FAILURE which is a system malfunction. Due to the nature of the Self-Test Circuitry in checking primary system parameters, a one in BIT 16 is equivalent to radar failure. In this case, combat tactics generally applied to radar failure during the mission would be resorted to.

**TABLE 3
DATA WORD STRUCTURE**

Bit Number	Range Word (ft)	Range Rate Word (ft/sec)	ΔR , Status & SNR Word	
LSB 1	0.36	23.4	0.36	ΔR ft
2	0.73	46.8	0.73	
3	1.46	93.6	1.46	
4	2.93	187.2	2.93	
5	5.85	374.4	5.85	
6	11.72	748.8	11.72	
7	23.44	1497.6	23.44	
8	46.88	Sign	Sign	
9	93.75	Not Assigned ↓	Detected Pulse	Status
10	187.50		Lock-On	
11	375.00		Coast	
12	750.00		3	SNR dB
13	1,500.00		6	
14	3,000.00		12	
15	6,000.00		24	
MSB 16	12,000.00	↓	Self-Test Failure	

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Radar Function	Status Word Bit Number and Title	9	10	11
		Detected Pulse	Lock-On	Coast
Search		0	0	0
Acquisition		1	0	0
Track		1	1	0
Coast		1	1	1

**FIGURE 10
RADAR STATUS WORD CODE**

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SECTION 4 DETECTION PERFORMANCE

4.1 DETECTION RANGE

The calculation of detection range is approached in steps due to the fact that many different intercept situations are possible. The first step consists of the calculation of Marcum's range, R_o . This is the range at which the signal-to-noise ratio for a single received echo is unity. Since this system integrates 32 pulses, the ratio of R/R_o for moderate probabilities of detection is quite close to unity. Because of this, the value of R_o in this application is quite indicative of system performance. The specific performance calculations with different detection criteria, different angle with respect to the antenna boresight and different closing rates are based on the R_o value.

4.2 R_o CALCULATION

The radar range equation is:

$$R_o^4 = \frac{G^2 P_t A_t \lambda^2}{(4\pi)^3 K T B N F L_t}$$

where:

R_o is the single pulse, unity signal-to-noise range

G is the antenna gain

P_t is the transmitted peak power

A_t is the target area

λ is the wavelength of the transmitted signal

K is Boltzmann's constant

T is the absolute temperature

B is the system bandwidth

NF is the receiver noise figure

L_t is the total losses

R_o for a 2 square meter target has been calculated for the SSR-1. Radar parameters are summarized in Table 4, and the on-boresight R_o calculations are listed in Table 5.

**TABLE 4
RADAR PARAMETERS**

Parameter	SSR-1 Radar
Frequency, (MHz)	9375
Peak Power, (kW)	8
Pulse Length, (μ sec)	0.45
PRF, (Hz)	1024
Antenna Aperture, (in.)	6 in. Circular
Receiver Bandwidth, (MHz)	3
Azimuth Beamwidth, (deg)	15
Elevation Beamwidth, (deg)	15
Antenna Gain, (db)	21

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**TABLE 5
R₀ ON-BORESIGHT CALCULATIONS**

Parameter	SSR-1 Radar (dB)
G^2	42
P_t	39
λ^2	-30
A (2m ²)	3
(3 π) ³	-33
KT	204
B	-65
NF	-8
L _r	-2
L _{m4}	-2
R ₀ (dB)	<u>148</u>
R ₀ (dB)	37
R ₀ (KM)	5.0
R ₀ (NM)	2.7

Total Loss $L_t = L_r + L_m$
 L_r = Radome Loss
 L_m = System Loss

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4.3 SINGLE SCAN PROBABILITIES

R_0 values give the range at which the single return signal-to-noise ratio is unity. Depending upon the number of returns integrated, there will be a probability of detection and a probability of false alarm which may be calculated at this particular range for a single scan. Since the SSR-1 is a range-only radar, the term scan refers to the scan or search of the range gates, rather than the more common meaning of an angular scan of an antenna across a target.

The probability of detection is dependent upon the false alarm rate which is selected. Physically, this is determined by the setting of the detection threshold in the range tracker. For this system, a false alarm rate of 10^{-6} was selected. This 10^{-6} probability of false alarm applies to each search gate so that for the 8 gates the probability is 8×10^{-6} . Multiplying this by the 32 search observations per second then gives a probability in one second of a false alarm of 2.56×10^{-4} or a probable time between false alarms of 3906 seconds (somewhat above 1 hour).

The probability of detection at R_0 is dependent upon the target scintillation model assumed as well as the number of hits integrated. As previously stated, the number of hits is 32. For a probability of false alarms of 2.56×10^{-4} using this 32 hit integration, the probability of detection at R_0 is 0.5 for a nonfluctuating target and 0.38 for a fluctuating target (Swerling Case 1). Curves for a single scan probability versus R/R_0 for these two types of targets are shown in Figure 11. These show that an 85 percent probability of detection in a single scan is obtained on a non-fluctuating target at about 94 percent of R_0 , while this is achieved on a fluctuating target at only 64 percent of R_0 . If a lower probability of false alarms such as 10^{-8} or 10^{-10} is desired, the range values are reduced by about 7 percent or 12 percent, respectively.

4.4 CUMULATIVE DETECTION PROBABILITY

Cumulative probability of detection is a function of target range, range rate, Marcum range and the time between scans. For the SSR-1 a cumulative probability of detection of 85 percent is obtained at a range of 2.65 nautical miles for a closing range rate of 1000 feet/second and a 1 second scan time.

4.5 OFF BORESIGHT EFFECTS

The detection ranges calculated above assume that the target is on the antenna boresight. To the degree that this is not true, the detection range performance is degraded. A case of interest is that where the target is at the half power or 3 db point of the antenna beam. This results in an overall 6 db reduction in received signal which results in a 30 percent reduction in detection range.

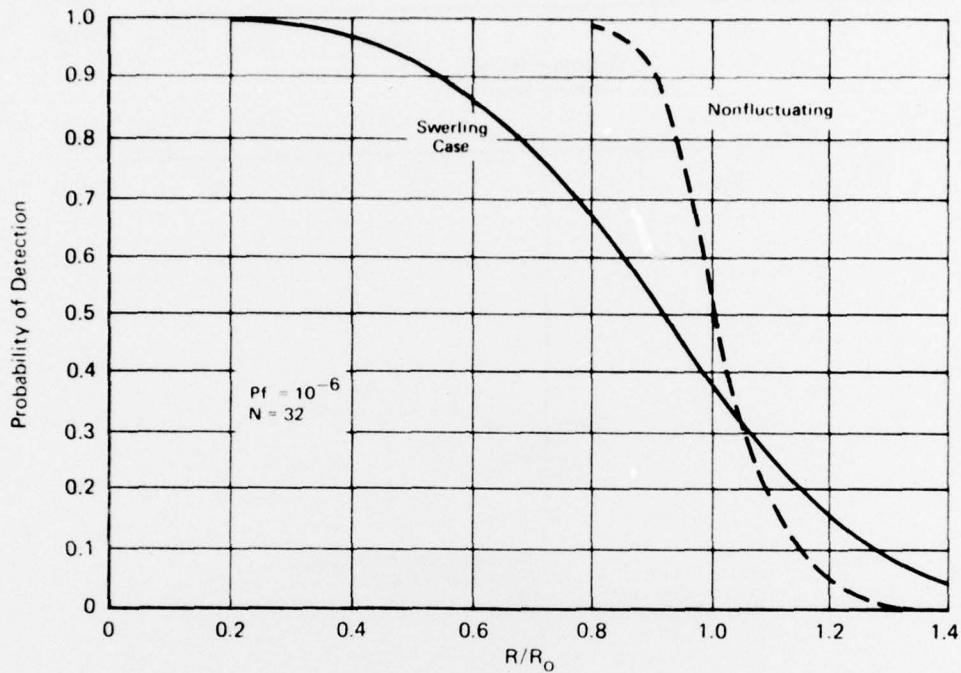


FIGURE 11
SINGLE SCAN PROBABILITY OF DETECTION vs R/R_0

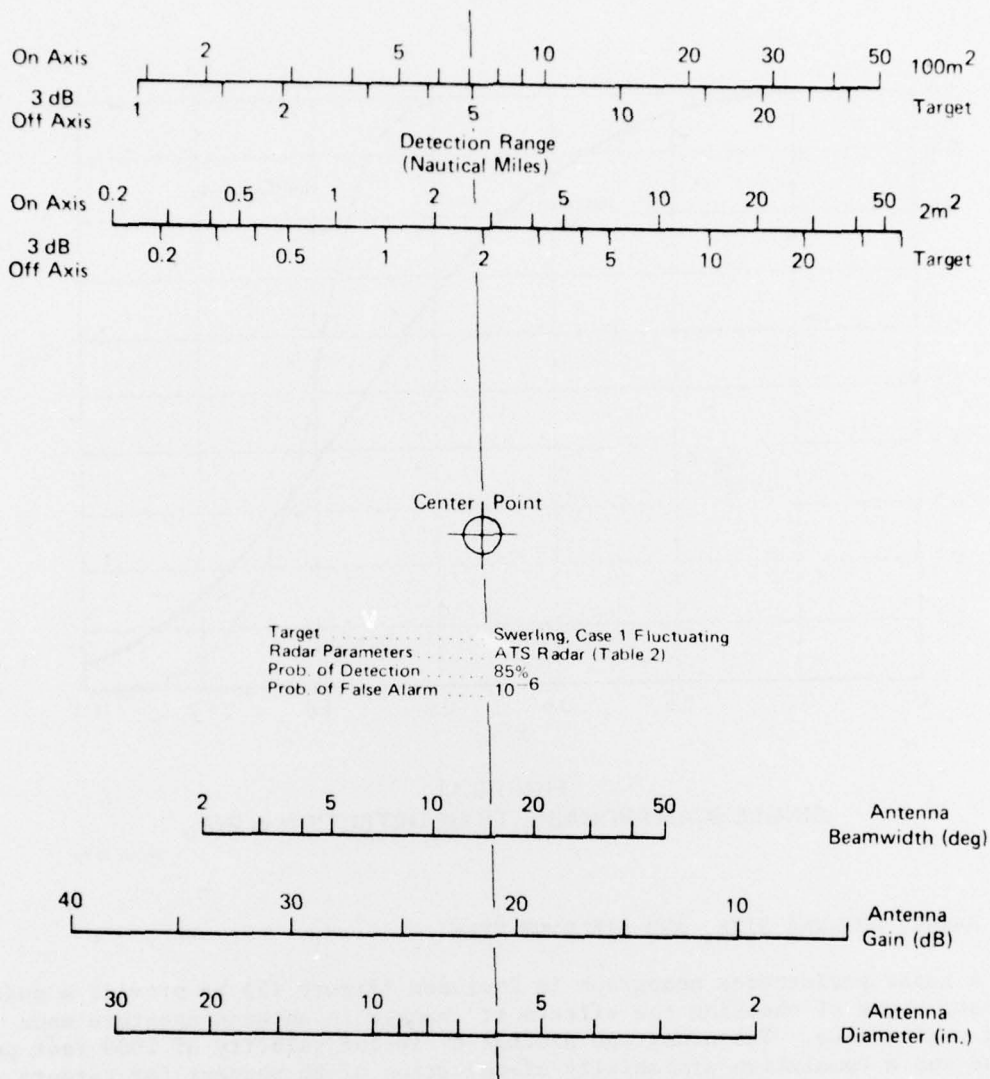
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4.6 RANGE, ANTENNA SIZE, AND FIELD OF VIEW

A radar performance nomograph is included (Figure 12) to provide a quick and easy means of checking the effects of changes in antenna aperture upon radar performance. The nomograph assumes a closing velocity of 1000 feet per second and a cumulative probability of detection of 85 percent for targets located at the half power point of the radar beam (3 db off-axis).

4.7 SUMMARY

The actual detection range for the ATS radar will be determined by several factors. The most significant of these are the effective reflecting areas of the target, the relative velocity between the ATS aircraft and the target and the position of the target within the radar antenna beam. For a 2 square meter target closing at a rate of 1000 feet per second, the 85 percent cumulative probability of detection range will vary from 1.85 nautical miles at the 3 db point of the radar beam to 2.65 nautical miles at the beam center.



This nomograph can be used to consider the effects of changes in the antenna aperture upon the detection range and antenna beamwidth of the ATS Radar.

For example: Assume the proposed six inch horn antenna is used. Place a straight edge along the line defined by 6 on the Diameter line and the Center Point. This intersects the other lines as follows:

- 100m² Target, On-Axis (nm) 7.1
- 100m² Target, 3 dB Off-Axis (nm) 5.0
- 2m² Target, On-Axis (nm) 2.65
- 2m² Target, 3 dB Off-Axis (nm) 1.85
- Antenna Beamwidth (deg) 15
- Antenna Gain (dB) 21

FIGURE 12
SSR-1 PERFORMANCE NOMOGRAPH

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SECTION 5 ERROR ANALYSIS

5.1 GENERAL

This section contains an analysis of the range errors expected in the ATS SSR-1. The range tracker control circuit of the radar measures the difference between the range gate position and the actual range (see Figure 7). The measured range difference will include any errors in the radar and any errors in the range gate positioning. Errors in range gate positioning are eliminated by the method in which the total range measurement is generated. The purpose of this analysis is to quantify the errors in the radar.

Assuming that tracking is already in progress, a predicted range has been entered in the range register. A measurement starts when the sync generator simultaneously starts the 10 MHz counter and initiates a pulse transmission by the transmitter. Since there are variable delays in the transmitter, a sample of the transmitted energy is brought back, compared with the counter, and used to adjust a variable time delay if necessary. The transmitted pulse is then radiated, reflected by the target, and returns to the receiver at a time delay of roughly 2 nsec per foot of the range. Gates 4 and 5 sequentially sample the return signal and their difference is averaged. If the return was centered in the two gates, the result will be zero. However, if there was a time (or range) difference, a DC voltage will exist. These differences are averaged over 16 radar transmissions and then converted into a digital measurement of the difference between the target return and the transition time of gates 4 and 5; i.e., Fine ΔR .

An explanation of the manner in which the 16 bit range word is used is in order. First bits 1 to 3 (having values of 0.36 to 1.46 feet) are not felt to have any real meaning since they are far less than any expected resolution or accuracy of the system. They are, however, used in order that no underflow exists when a velocity update is made in the Autonomous Mode. For the 23 foot per second velocity LSB to have any effect in the 1/64 sec updates of range, the range register must be able to accumulate the 0.36 foot increments.

Second, only the 9 most significant range bits are used in the 10 MHz counter; i.e., to position the range gate. Accordingly, the A/D output of range difference (Fine ΔR) includes the seven least significant bits of the range number. The measured range register correction then is the difference between the output of the A/D converter and the seven LSBs of the range number. It is this measured range register correction which is added to the range register in Augmented Mode to provide a total range measurement.

Errors described herein are evaluated as to RMS (root mean square) amplitude and, in general, it is assumed that errors which have nearly the same correlation time are combined in an RSS (root sum squared) manner.

Correlation time is that time period over which a knowledge of the error value at one time would have some value in predicting the error at another time. It also has the interpretation that averaging a number of readings of the same variable taken during that time period will have little effect in reducing the error. The correlation time can be considered a function of the reciprocal of a noise bandwidth of the error.

The importance of the error correlation time can be seen by considering the effect of different correlation times on the calculation of range rate. A short correlation time such as one of less than 1 millisecond is produced by receiver noise. Accordingly, this error will average down from pulse to pulse (at a 1024 PRF) and its effect on the range-rate estimation will be small in comparison to the RMS value seen on a single received pulse. It also can be seen that an error due to receiver delay, which would have a correlation time of days, would have no effect on the range-rate estimate. It would effect the range estimate, however.

Although errors with both short (millisecond) and long (days) correlation times can be tolerated in a range-rate calculation, an error with a correlation time of 1 second can have a very serious effect. The wander of the center of reflection on the target (range glint) is an example of an error which can have such a correlation time.

5.2 SOURCES OF RANGE ERROR

Sources of range error in the SSR-1 are:

1. Clock and propagation errors
2. RF to clock time errors
3. Radar signal-to-noise errors
4. Receiver time gain stability
5. Variation in IF and Video amplifier delays
6. A/D window variations
7. Differential gain in early and late video
8. A/D converter bias or offset
9. Noise pickup in video circuits
10. Target reflection characteristics.

5.2.1 Clock and Propagation Errors

Clock and propagation errors stem from the tolerance on the crystal oscillator in the radar (50 ppm) and the variation in the speed of light in the atmosphere. The speed of light or radar energy is a direct function of the index of refraction n . For radar purposes, this is measured in terms of a normalized and magnified unit N where:

$$N = (n - 1) \times 10^6$$

so that N represents the error in radar range in parts per million.

The variations in N which are of concern here are illustrated by the following examples:

<u>ATMOSPHERIC CONDITION</u>	<u>N</u>
Vacuum	0
Sea level, 0% relative humidity	270
Sea level, 100% relative humidity	330
40,000 foot altitude, 50% relative humidity	65

If a design center value of 200 is used, which corresponds to the normal velocity of propagation at 10,000 foot altitude, maximum variations in N of 130 will be encountered. The maximum expected errors due to propagation and oscillator timing amount to about 150 ppm or an error of 2.5 feet at the Marcum range of 16400 feet. For analytical purposes, this is taken as an RMS error of 0.8 feet.

It can be seen that this error consists primarily of that due to altitude changes and accordingly it is felt that a correlation time of 5 minutes is a suitable figure for the error.

5.2.2 RF to Clock Time Errors

RF to clock time errors are caused by: 1) jitter in the turn-on time of the transmitter; 2) unbalance in the gate and phase comparator (used to lock the modulator sync to the range tracker clock); 3) noise pickup on the detected RF line; and 4) offset due to the combination of RF detector nonlinearity and nonsymmetry in the transmitted pulse. Some of these result in errors which are independent from pulse to pulse, while others tend to resemble bias errors in that they have a correlation time of days. The 1 millisecond component of the error is primarily that due to power supply ripple and magnetron jitter and is expected to be 5 nanoseconds RMS or 3 feet. The error due to modulator pickup on the detected RF line and unbalance in the comparator circuits is expected to have an RMS amplitude of 10 feet and a correlation time of 1 day.

5.2.3 Radar Signal-to-Noise Error

Radar signal-to-noise error is described by the relationship,

$$E = C * T / (2 * K * (SNR) ** 0.5)$$

where E is the RMS error, C is the velocity of light, T is the radar pulse width, SNR is the signal-to-noise power ratio and K a constant with a value of 1.0 to 1.5. K is determined by the exact shapes of the transmitted pulse and the tracking gates as well as the receiver bandwidth. For the purposes of this analysis the worst-case value of unity is used. SNR is an inverse function of the fourth power of range in the usual case where the noise is established by the front end of the radar receiver. This condition is generally true from the maximum range in to about 20 percent of the maximum range. At still shorter ranges, noise sources at the back

end of the receiver and in the video circuits begin to dominate and further reductions in range do not produce an improvement in SNR.

For the characteristics of this system at R_0 , where $SNR = 1$, the single pulse RMS error is 200 feet for a 2 square meter target. From this the errors due to signal-to-noise ratio at various ranges are:

<u>SINGLE PULSE</u>			<u>16 PULSE</u>	
<u>Range Feet</u>	<u>Error Feet</u>	<u>SNR, db</u>	<u>Error Feet</u>	<u>SNR, db</u>
16400	200	0	50	6
8000	50	12	13	18
4000	13	23	3	29
2000	10	30	3	35

The correlation times for these errors are 1 millisecond for the single pulse case and 16 milliseconds for the 16 pulse case. However, an additional complication stems from the fact that these numbers are based on an average minimum target cross section, whereas a real target will have a return which fluctuates above and below its average value (scintillation). The fluctuation will have something close to a Rayleigh distribution and will have a correlation time in the order of 1 second depending upon target motion. This results in a degradation in overall accuracy since the effect of increased error during nulls in target return has a larger effect than that of the decreased error during peaks of target return. To some degree, this effect is improved by the fact that severe nulls in target return cause the signals to drop below the AGC (Automatic Gain Control) threshold in the radar and thus reduces the scale factor of the radar output. To a degree then, this attenuates those outputs with a large error content. Since the computer is also being supplied with the fade signal in the status word, this can be partially compensated in the ATS computer.

For small targets or long ranges, it must be noted that the target return will fall below the AGC threshold. This is due to the fact that the AGC threshold must necessarily be above the detection threshold. The range digits up to ± 23 feet are handled in an analog manner through the A/D converter. If a target return is just at the detection threshold or about one half the AGC threshold, the input to the A/D converter will be about half what it should be. In other words, this condition will result in a 22 foot range difference being measured by the A/D converter as being only 11 feet. This situation will then result in about a 3 feet RMS error at 16400 feet with a correlation time depending upon range rate but generally having values near 100 msec.

From the above considerations a reasonable value for RMS error versus range for the 16 pulse case with a 16 millisecond correlation time is:

<u>Range Feet</u>	<u>RMS Error, Feet</u>
16400	65.6
8000	22.9
4000	6.5
2000	3.2

5.2.4 Receiver Time Gain Stability

Receiver time gain stability is a short range error which results from the finite time required for the receiver to return to full gain after a transmitted pulse. This variation in receiver gain vs time results in greater attenuation of that portion of the signal in the early gate than that in the late gate. Targets at close range accordingly appear to be at a greater range. It is estimated that at a range of 500 feet this outward shift will be approximately 80 feet. At a range of 1000 feet the effect will be about 13 feet, and at 1500 feet and more it will be under 3 feet. A reasonable empirical equation for this error in the range of 500 to 2000 feet is:

$$(2000 - R / 650) * * 4$$

The correlation time for this error will depend upon range rate, but for analysis purposes is given a value of 10 seconds. Compensation is included in the ATS computer program to account for this effect but some portion of this error is unpredictable and as such could not be eliminated. The RMS value of the remaining error would amount to 35 feet at 500 feet and 3 feet at 1000 feet. For normal closing rates, it is expected that the correlation time for this remaining component would be about 3 seconds.

5.2.5 Variation in IF and Video Amplifier Delays

IF and video amplifier delay variations are based on the unpredictable part of the overall delay; overall delay is in the order of 300 nanoseconds. The maximum variations of this delay are about 75 nanoseconds and accordingly an RMS deviation of 25 nanoseconds is expected. This corresponds to 13 feet RMS error. The correlation time of this error is in the order of one week.

5.2.6 A/D Window Variations

Gate delay variations in the clock to the video gates consist primarily of two components. One is that due to power supply ripple and noise for which a correlation time of 1 millisecond is applicable. The other is that due to logic delays and accordingly is substantially a function of temperature and component aging for which a correlation time of one hour seems appropriate.

The 1 millisecond component is expected to have an RMS value of 15 nanoseconds or 6.5 feet. Averaged over 16 pulses to give a correlation time of 16 milliseconds, this is reduced to a value of 3.3 feet. The variations due to temperature and other effects with a correlation time of one hour should have an RMS variation in time of 25 nanoseconds or 13 feet in range.

5.2.7 Differential Gain in Early and Late Video

Differential gain in the early and late video is produced by changes in the resistance and switching time of the video analog gates, offset and drift in the buffer amplifiers and comparators, and differences in capacitive feedthrough. The overall accuracy in such circuits is typically about 3 percent which corresponds to 3 feet RMS. The correlation time for this error is one day.

5.2.8 A/D Converter Bias and Offset

A/D converter accuracy includes the effect of scaling errors which for the SSR-1 are 3 feet RMS. The correlation time for this error is typically one week. In addition, the granularity of the converter produces an RMS error of 1.3 feet. Although in any dynamic case it might seem that this error would be independent from output to output, the exceptions to this are significant. Accordingly, a correlation time of 100 milliseconds is assigned rather than 1 millisecond.

5.2.9 Noise Pickup in Video Circuits

Video noise pickup is expected to be about 30 millivolts RMS. Since video signals of about 3 volts peak will be used, this will correspond to an error of 2.0 feet RMS and will be independent from pulse to pulse, giving a correlation time of 1 millisecond.

5.2.10 Target Reflection Characteristics

Target reflection characteristics produce errors due to the fact that the apparent radar center does not coincide with the center of gravity of the target and changes the return time. In general, the RMS value of this error is 20 to 25 percent of the physical depth of the target, accordingly, for a normal fighter aircraft, an RMS error of about 10 feet would be expected. The correlation time for the error depends upon the rate of the change of aspect angle of the target and to a lesser extent on the size of the target. For a large target, with a constant aspect, correlation times of tens of seconds would be expected. For a large target with a large angular rate, the time might be under 0.1 second. The bandwidth of this error is correlated with the bandwidth of signal amplitude variations and can be estimated from amplitude data to the extent that these are not eliminated by the action of the radar AGC circuit. Where the amplitude variations are removed by AGC, the AGC voltage still retains this information.