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**DESIGN STUDY OF GENERAL AVIATION
COLLISION AVOIDANCE SYSTEM**

Prepared by

**SIERRA RESEARCH CORPORATION
Buffalo, New York**

for Langley Research Center

DESIGN STUDY OF GENERAL AVIATION COLLISION AVOIDANCE SYSTEM

Contract No. NAS1-10653

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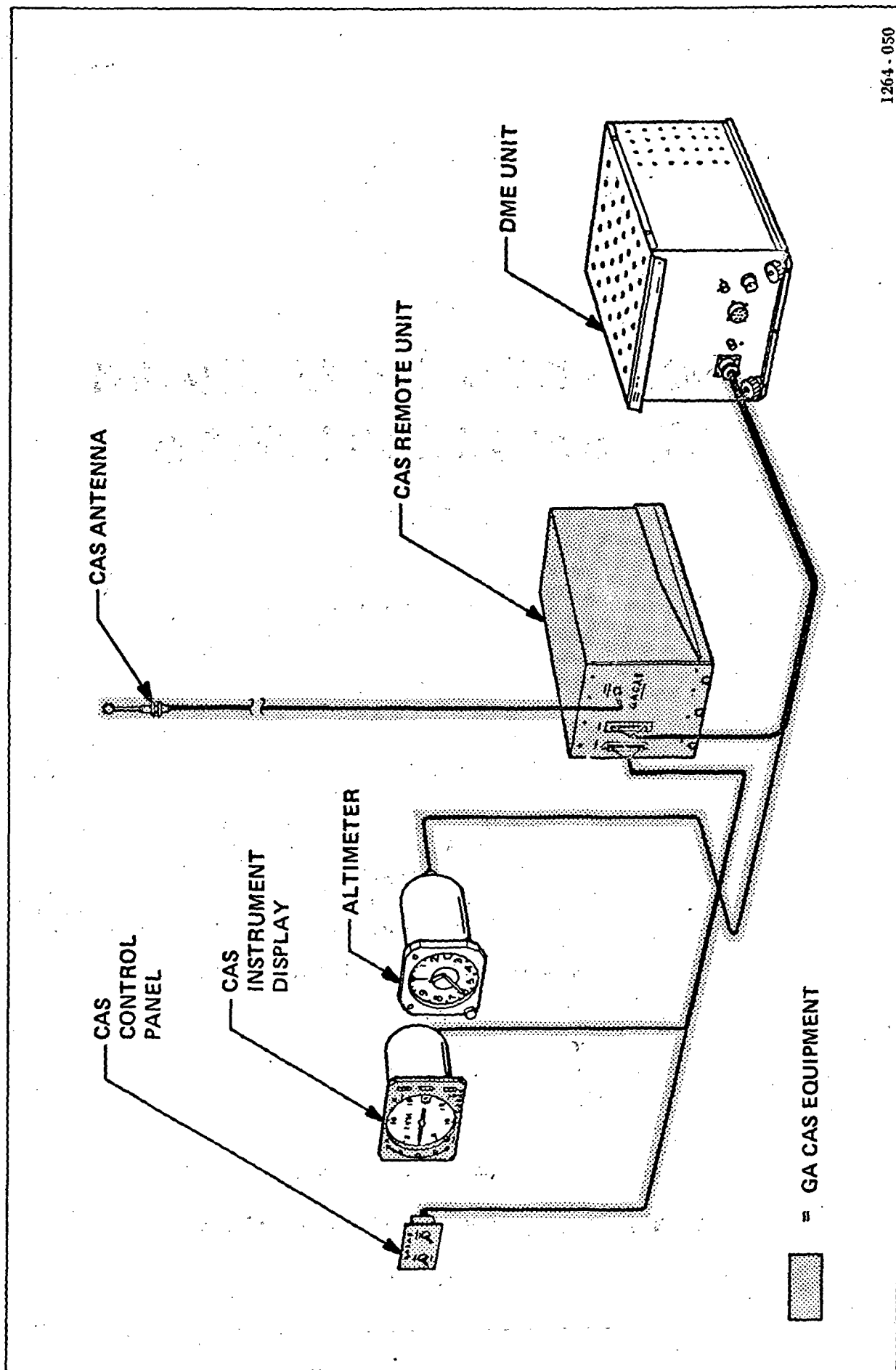
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ABSTRACT

Collision Avoidance Systems for use by single-engine general aviation aircraft must be simple and inexpensive if they are to gain widespread acceptance by general aviation pilots. They also have to be compatible with equipment installed in other aircraft flying in common airspace.

The present report summarizes a seven-month program of work involving selection and design of a Time/Frequency Collision Avoidance System for use in general aviation aircraft. Minor modifications to the ATA Collision Avoidance Specifications are required in order to reduce the design complexity and cost of the GA CAS equipment.

The present simplified GA CAS design utilizes a 1.5 millisecond time slot structure (with accurately synchronized range transmissions) and altitude telemetry which conforms to the ATA CAS characteristics.

Slight modifications to the ATA CAS frequency-switching logic are proposed to permit assignment of approximately 1000 of the 2000 available ATA CAS slots for use by low-flying aircraft.

Simplification of the GA version of Time/Frequency CAS involves deletion of requirements for phase-coherent long-pulse transmissions, doppler processing, and multifrequency reception. Use of synchronous reference pulse transmissions by ground VORTAC stations also permits reduction of transmitter power and receiver sensitivity requirements and deletion of the back-up mode. The transmission of auxiliary data (as biphase modulation of the transmitted pulse) is also eliminated.

Deletion of doppler range rate extraction involves some increase in the protection envelope about own aircraft. However, use of a shorter pulse to distinguish GA CAS transmissions, and inclusion of pilot selection of temporary terminal logic reduces this increment to tolerable proportions.

Detailed system design and associated costing information is provided, which indicates that if there is sufficient user interest, the system target cost to the user will fall below \$1500 within a reasonable time after introduction of the simplified GA CAS equipment on the market.

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ACKNOWLEDGMENTS

This report is primarily the work of M. R. Bates, W. V. Scott, and L. D. Moore. M. R. Bates was responsible for most of the analytical work, W. V. Scott had primary responsibility for the equipment design and costing, and L. D. Moore of Wilcox Electric had primary responsibility for the system RF design. Significant contributions and advice were also received from L. Michnik and A. Seville. The overall effort was directed by J. W. Prast.

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PART ONE
SYSTEM CONSIDERATIONS

SECTION I INTRODUCTION

A. CONTRACTUAL REQUIREMENTS

1. Objectives. The objective of NASA Contract No. NAS1-10653 is stated in NASA Langley Research Center Statement of Work L53-1556 of December 17, 1970. The following extracts constitute the principal requirements and priorities established under the guidance of NASA technical personnel.

"Analyze the overall problem of providing anti-collision protection for all classes of aircraft... in which general aviation aircraft equipped with less costly collision avoidance equipment can participate with aircraft equipped with the ATA collision avoidance equipment."

The Statement of Work calls for maximum utilization of the "computational capability of the ATA collision avoidance system equipment in order to simplify the general aviation collision avoidance system equipment."

"Recommendations of minor changes to ANTC-117 are acceptable, provided they are justified by cost or equipment simplification considerations" because "low cost will be the prime objective."

2. Low Cost. The Statement of Work specifies that "a projected cost of \$1, 500 or less per unit is desirable... The design will attempt to attain a target selling price of \$1, 500 per unit for the minimum configuration."

3. Light Aircraft Equipment. This must be equipment "attractive to the light aircraft owner" featuring "minimum cost and complexity to operate in the airspace normally occupied by light aircraft." It may "reflect the limited capability of general aviation aircraft" and "the capabilities and limitations of light aircraft may be used as a justification for reducing the performance requirements and complexity."

4. System Configuration. "The result will be a system configuration resolved to the block diagram level with signal format, bandwidths, power budget and data processing... The level of detail will be sufficient to allow an accurate cost analysis to be performed and an independent evaluation of the design to be made."

5. Clarifications. An amendment to Solicitation L53-1556 clarified that "this work represents an intermediate step between a conceptual design and the construction of prototype hardware for evaluation." It is also expressed

that NASA desires "not to discourage competition between schemes for producing a low-cost general aviation collision avoidance system."

B. ORGANIZATION OF THIS REPORT

The present report is subdivided into four portions. Part one examines the Time/Frequency Collision Avoidance System from the viewpoint of requirements, possibility for modification to minimize cost for light General Aviation aircraft, and the effects of these modifications on the Air Traffic Control System.

In particular, section II includes the rationale for selecting the principal distinctive features of the system. After discussing the essential features of the Time/Frequency System for Collision Avoidance, selected by ATA, this section discusses changes in certain less fundamental system features. The selected approach deletes dependence on transmission of long phase-coherent pulses and detection of doppler, in order to extract range rate information in encounters involving GA CAS equipped aircraft. Threats are evaluated on the basis of range and altitude separation, although use of distinctive short pulse transmissions by the lower performance GA CAS and incorporation of pilot-selected temporary terminal logic permit use of reduced threat boundaries in such encounters. Moreover, requirements for transmitting or receiving on more than one CAS frequency have been eliminated. Incorporation of synchronous reference pulse transmissions from the ground VORTAC system is recommended as a highly cost-effective method for providing needed CAS synchronization over the conterminous U.S. This approach permits safe reduction in GA CAS transmitted power by allowing such equipment to utilize available higher powered airborne DME and ground VORTAC transmissions for synchronization.

The deletion of requirements for phase coherency, reduction of power, and shortening of the transmitted pulse all contribute to the design of a relatively low-cost transmitter. Other simplifications include reduced requirements for receiver sensitivity and elimination of the asynchronous back-up mode and of auxiliary data transmission. These simplifications in addition to limiting GA CAS receptions to a single frequency and deletion of doppler processing (which were mentioned earlier) permit a CAS equipment design that can meet specified target costs to the user.

A detailed discussion of sync donor requirements and the capabilities of the Ground VORTAC System for meeting these needs is provided in section III.

Detailed system parameters are discussed in section IV, V, and VI. Section IV discusses the single-frequency approach to the GA CAS design, while a detailed discussion of the selected GA CAS threat parameters and of

the required pilot display are presented in section V. Section VI provides a detailed analysis of transmitted power requirements and receiver sensitivities required to provide timely warnings.

The effect of the selected threat logic on airspace requirements is presented in section VII, which focuses on the results of deleting doppler transmission. This section shows that the protected boundaries exhibit some increase over the air-to-air separation required by a safe GA Tau-CAS protected unit. However, the Tau-CAS boundaries would be about 75% as large as for the present GA CAS design. This is not a spectacular decrease and thus appears to justify the use of the less sophisticated threat logic. Section VIII examines various expanded capabilities for the GA CAS.

Part Two contains a detailed design of the selected low-cost Time/Frequency General Aviation Collision Avoidance System for use by light aircraft. Specific itemized costing information is included in sufficient detail to permit technically oriented evaluators to verify the practicability of meeting the contractually specified target costs.

Section I contains a functional description of the resulting GA CAS design.

Section II provides specific detail designs for each of the major functional blocks. Section III provides detailed estimates of the cost of producing each of these functional blocks and of assembling the CAS unit. A projected cost to the user is provided.

The cost estimates are made in two alternative versions: Version A is self-contained, although it requires inputs from an encoding altimeter and an airborne DME, while Version B is intended for those users who have elected to install a quasi-one-way DME with self-contained crystal clock and associated synchronization circuitry.

A first year cost to the user of \$1956 for Version A and \$1572 for Version B are projected. These costs are expected to fall to \$1565 and \$1257, respectively, by the third year.

Conclusions and references appear in Part Three. Appendices follow.

C. GLOSSARY

There are certain non-standard terms and abbreviations that are used in this report and other terms that may be used in a non-standard way. This subsection lists some of these phrases and abbreviations and interprets their use in the present report.

ANTC - Air Navigation/Traffic Control Division of ATA.

ANTC-117 - This references the Airline Air Traffic Control Committee, CAS Technical Working Group document, "Airborne Collision Avoidance System," issued by ANTC division of ATA as ANTC-117 dated June 30, 1967; also the various revisions to this document. References to this document are intended to relate to the Full-CAS equipment as described in the basic document (parts A and B-1 through B-5) and in parts 1, 2, and 3 of Attachment 1. Except where sync donor or back-up mode capabilities are involved, these references also include Limited Equipment, Level 1, as described in part 4 of Attachment 1.

ARINC Characteristic 587 - "Air Transport Time-Frequency Collision Avoidance System," by Aeronautical Radio, Inc., issued September 1, 1970. ANTC-117 is included in the ARINC characteristic. However, 587 applies specifically to Full-CAS equipment.

ATA - Air Transport Association of America.

ATA CAS - An air-to-air (time/frequency) Collision Avoidance System as defined in ARINC Characteristic 587 and in Part A and B-1 through B-5 of ANTC-117 (as revised), and in Sections 1, 2, 3, Attachment 1 of that document, (Full CAS). Except where sync donor or back-up mode capabilities are involved, these references also include Limited Equipment, Level 1, as described in part 4 of Attachment 1.

BUM - The asynchronous back-up mode described in Section B-4 of ANTC-117.

CAS - Air-to-Air Collision Avoidance System.

DME - Airborne distance measuring equipment that is capable of extracting range from ground station replies on the cross-banded TACAN frequency.

Full-CAS - A collision avoidance system defined by ARINC Characteristic 587 and/or by the applicable parts of ANTC-117 listed earlier.

GA - General Aviation aircraft, especially single engine GA aircraft.

Lim-CAS, Limited Capability CAS - Collision Avoidance Systems similar to those defined in part 4 of Attachment 1 to ANTC-117.

Lim-CAS, Level 1 - See Lim-CAS.

Lim-CAS, Level 2 - Level 2 Limited CAS equipment similar to that described in part 5 of Attachment 1 to ANTC-117.

T. F. - Time/Frequency systems, utilizing very precise clock synchronization and assigned slot transmissions to permit non-interfering transmission and "one-way" ranging from time of arrival of the reference pulses.

VORTAC - In this report, the focus is on TACAN or DME stations that can provide ranging information to DEM equipped airborne interrogators. Such equipment includes collocated VOR/TACAN installations, ground TACANS and ground DME installations that do not provide azimuth information on the TACAN frequency.

SECTION II

SYSTEM SELECTION

A. COMPATIBILITY WITH ATA CAS

The selected approach to the design of a low cost collision avoidance system (CAS) to protect light General Aviation (GA) Aircraft against encounters with other (similarly equipped) aircraft and encounters with airliners and other higher performance aircraft is explained in this section. In accordance with contract specifications, it is assumed that the more sophisticated aircraft will be equipped with a Time/Frequency CAS. Such a Collision Avoidance System has been described by the Air Transport Association's (ATA's) Technical Working Group on Collision Avoidance¹ in report ANTC-117, and has been defined in an ARINC document.² Contract specifications permit minor changes from ANTC-117 provided they are justified by cost or equipment simplification considerations. ANTC-117 discusses several versions of Collision Avoidance equipment. These versions include a full CAS for the more affluent users, a limited CAS (Level 1), and other lower level limited systems with reduced capabilities. In this report, the term "ATA CAS" will refer to the full CAS equipment and to the limited system, level 1.

The essential features of the ARINC characteristic may be summarized as follows:

Separate time slots for each aircraft's transmissions.

Multiple frequencies to avoid "ghost"-threats from high-flying aircraft a long distance away.

Sufficient communication range to permit timely detection of potential threats from other equipped aircraft.

Threat evaluation on the basis of range, altitude, and range rate information.

In addition, the following less essential features are included in full CAS equipment specifications:

Telemetry of additional data.

An associated asynchronous Back-Up Mode.

This contractor has examined the detailed system attributes and has classified certain of these as "essential", and others as "desirable" but not

essential. The reasons guiding this selection and the resulting system approach are explained in the following paragraphs.

B. MAINTAINING PROTECTION AGAINST OWN KIND

In making this selection, we first summarized several possible alternative simplified design approaches for GA CAS equipment (refer to table 1). Of the various changes mentioned, the first two approaches (receive-only and transmit-only) do not provide NASA specification mandated protection-against-own-kind (i. e., protection against other aircraft equipped with like equipment). The third basic approach: Use of a single receiving and transmitting frequency for GA CAS, in conjunction with unmodified four-frequency ATA CAS equipment is not attractive because the aircraft utilizing a given frequency would be blind to threats from aircraft assigned to the other three frequencies. This approach could work adequately during initial introduction of equipment, if all aircraft elected to operate on a single frequency. However, only 500 slots are available on each frequency. Thus the system capacity limits might be exceeded as soon as widespread deployment of CAS equipment is achieved.

The fourth approach, that was selected, requires some simple modification of the ATA CAS to yield a viable method for simplifying the GA CAS design. In particular, this approach permits threat evaluation, in encounters with GA CAS equipped aircraft, through use of a single RF frequency.

C. REDUCING COMPLEXITY TO MINIMIZE COST

The ATA CAS has been designed to provide protection between approaching aircraft under a wide variety of anticipated encounters. Significant simplifications are required to permit design of collision avoidance equipment that is fundamentally compatible with the ATA CAS design, but that can be built at significantly reduced cost. These simplifications can either involve a reduction in system capabilities or use of an alternative method for providing similar capabilities.

1. Simplified Threat Evaluation

a. Deleting ATA CAS Threat Evaluation Parameters. An essential approach to the design of a reduced cost GA CAS involves use of less complicated threat-evaluation techniques. Alternative threat evaluation techniques are summarized and compared in table 2. This chart starts with the basic ATA CAS threat evaluation and considers the possibility of eliminating any one (or any pair) of the three basic threat-determining parameters from the CAS. In each case, some increase in the number of unnecessary evasive maneuvers will result. Because of the significant complexity introduced by the doppler measurement, and the restricted effectiveness of doppler measurements at low closing rates, this contractor's approach has concentrated on the deletion of range rate information.

TABLE 1. TECHNIQUES OF THREAT EVALUATION

<u>R-F Approach</u>	<u>Description</u>	<u>Remarks</u>
1. Receive ONLY 2. Transmit ONLY (Synchronized) 3. Reception and Transmission on a single frequency, (existing slot/frequency structure) 4. Reception and Transmission on a single frequency (Modified ATA slot/frequency structure)	Non-emanating systems that can receive CAS transmissions and evaluate threats Transmits on accurate time schedule: Has no threat evaluation This approach deletes the four-frequency capability of a full CAS system Use three-frequency slot structure, with frequency/slot shift at 14,000 feet altitude Assign 1000 slots to low altitude frequency	No protection against own-kind Probably more costly than 1, but still no protection against own-kind No protection against aircraft on other 3 frequencies. Low capacity. (Only 500 slots per frequency) Requires minor Mods to ATA CAS

TABLE 2. TECHNICAL APPROACHES TO GENERAL AVIATION CAS DESIGN

Method	Explanation	Remarks
1. ATA CAS	a. Measure range from time of arrival. b. Measure closing rate from long-pulse doppler. c. Telemeter altitude. d. Use altitude difference combined with range/range rate to evaluate threats.	Doppler measurements help in reducing unnecessary evasive maneuvers, but involve significant cost penalty for hardware. Alternative use of differential range on successive transmissions, might reduce costs but would impose other system changes.
2. Range/Range Rate	Delete Altitude Telemetry.	Moderate cost reduction with elimination of altimeter interfacing. Would introduce excessive unnecessary maneuvers in holding patterns, terminal areas, and near VORTAC sites.
3. Range/Altitude	Delete doppler transmission and processing.	Considerable cost savings
4. Range Rate/Altitude	Delete requirements for precise sync.	Moderate increase in unnecessary evasive maneuvers for low speed aircraft
5. Range Alone	Delete doppler and altitude telemetry.	Lower cost, but significantly increases unnecessary evasive maneuvers
6. Altitude Alone	Rely on altitude telemetry ONLY.	Would involve excessive unnecessary maneuvers in holding patterns, terminal areas, and near VORTAC sites
7. Doppler Alone	Eliminate precise sync for ranging and delete altitude telemetry.	Significant increase in unnecessary maneuvers
8. Inclusion of Azimuth	Needs some sort of direction sensing receptor and/or processor.	Significant increase in unnecessary maneuvers
		Desirable but would increase cost significantly

An interim report compares the threat envelopes of the ATA CAS and of such a range/altitude CAS for single-engine GA aircraft. The interim report has been updated and embodied in section VII of this final report.

b. Inclusion of Azimuth Information for Threat Evaluation. It should be noted that table 2 also mentions two other alternatives. One alternative involves use of azimuth information for collision avoidance. As explained by Morrell,³ rather good accuracy may be required to make effective use of azimuth information for threat evaluation. Nevertheless, use of azimuth in addition to the other threat evaluation techniques might provide useful information to the pilot. Since this is an increase over ATA CAS complexity, it does not provide an attractive approach to an ATA-compatible low-cost CAS design.

c. Alternative Extraction of Closing Rate. Replacement of the doppler measurement of closing rate with an approach that utilizes range change during successive measurements was proposed by TRG and discussed by the CAS Technical Working Group during their deliberations^{4,5,6}. While this approach was not adopted, it still shows promise of providing a viable alternative approach for extracting range rate. This approach would permit deletion of the long doppler pulse and would permit equipped aircraft to extract range rate without requiring the GA aircraft to provide coherent transmissions. The ATA CAS equipped aircraft would have to utilize additional logic and some memory.

These changes would permit higher speed ATA CAS equipped aircraft to conserve airspace by measuring the closing rate to all intruders, while GA CAS (who normally fly at lower speeds in less crowded airspace) could rely on range and altitude measurements for CAS threat evaluation.

While such alternate range rate extraction may cost no more than the doppler measurement, it would require further modifications in the ATA CAS specification. Very good range rate accuracy could be achieved by requiring all clock fine sync phase adjustments to be made in small time increments. (The present 200 nanosecond clock corrections correspond to a 66 ft/sec. closing rate error with a 3-second averaging. Much smaller phase corrections could be utilized, once the clock frequency has been corrected.) In addition, it would be necessary to control slot jumping since two successive range readings have to be secured in the same slot. This may require ground assignment of CAS slots.

None of these changes appear overwhelming for aircraft equipment. However, use of such range rate calculations seems excessively costly for the GA CAS.

The ensuing discussion assumes the use of range/altitude threat logic in all encounters involving the GA CAS.

2. Single-Frequency Approach. In its proposal to NASA, this contractor suggested a modification of the ATA CAS frequency selection logic that would permit reception and transmission of CAS location information on a single frequency at the lower altitudes. This approach involves use of only 3 frequencies for transmitting normal CAS ranging and telemetry information. The approach reserves 1000 of the 2000 slots for use at lower altitude. With minor modifications, the proposed single-frequency system has been embodied as an essential feature of the present GA CAS design.

Before describing these changes in detail, it seems appropriate to review attributes of the General Aviation aircraft which permit the design simplification.

D. GENERAL AVIATION AIRCRAFT PERFORMANCE LIMITATIONS

In designing a minimum configuration collision avoidance system for general aviation aircraft, we are restricting ourselves to aircraft of limited speed and restricted altitude (service ceiling) capabilities. In particular, this equipment is intended primarily for use by single-engine general aviation aircraft.

An examination of general aviation aircraft sales in 1968-1969⁷ reveals that more than half of the single-engine aircraft shipments in 1969 (5102 aircraft shipped out of a total of 10,167) were produced by Cessna. Another 30 percent (3112 aircraft) were produced by Piper. If we ignore the agriculture and trainer aircraft, then Cessna 172, with its maximum recommended airspeed of 131 mph, service ceiling of 13,100 feet and maximum climb rate of 645 feet/min., represents a lower bound on performance specifications for aircraft in current production. The owner's manual⁸ quotes a climb rate of 730 fpm. This climb rate decreases to 310 fpm at 10,000 feet. Similarly, the Piper Cherokee group provides a maximum recommended airspeed of 152-176 mph, a service ceiling of 13,000 to 16,400 feet, and a climb rate of 750-1050 feet/minute.⁹ The lowest climb rate indicated for single engine GA aircraft manufactured in 1967 was 600 fpm, and this rate of climb involved lower-speed agricultural aircraft.¹⁰

If the CAS is to gain acceptance it must not command excessive unnecessary evasive maneuvers. The required protection radius is proportional to the closing speed and inversely proportional to climb rate, as will be explained hereafter. Actual closing speed is no greater than the sum of own airspeed and the intruder's airspeed. A dependable limit on the intruder's airspeed is required to guarantee safe evasions for a reasonably small penetration radius. Thus a limitation on maximum velocity for aircraft utilizing GA CAS is needed

to permit use of restricted airspace in GA/GA encounters. The alternative telemetry of maximum airspeed could be utilized to reduce airspace requirements to a minimum. While attractive, this approach involves some additional hardware complexity and therefore telemetry of own maximum airspeed has not been adopted for the low-cost GA CAS. The restriction on maximum airspeed for aircraft utilizing the lowest cost GA CAS would require somewhat larger expenditures for CAS protection for the more sophisticated, faster flying aircraft.

Requirements for a minimum rate of climb are not clear. It might be appropriate to require an available climb rate of at least 500 to 600 fpm for aircraft equipped with this GA CAS. This would not represent a major limitation, since all but 10% of the GA fleet exceed this climb rate.¹¹ In fact, an overall variation in ratio of climb rate to cruise velocity of between 1/17 and 1/7 for almost all GA aircraft is indicated.¹¹ Even typical trainer aircraft (Cessna 150 and Piper Cherokee 140-C) can provide climb rates of 600 fpm at sea level.¹² the 600 fpm climb rate would not generally be available at the higher altitudes, however. The minimum climb rate is required at low altitudes since a dive maneuver would not be practical near the ground and the climbing aircraft would have to provide safe separation.

While it might appear desirable to mandate a minimum climb rate in order to reduce airspace requirements, this could interfere with the more urgent goal of providing moderate-cost anti-collision protection to a high percentage of all aircraft. Thus it seems appropriate to modify the threat boundaries on the basis of actual performance characteristics of the protected aircraft. This would permit minor parametric changes to provide protection to almost all single-engine GA aircraft.

It is also essential to specify intruder airspeed in the airspace where the GA CAS will be used. Since controlled airspace and the associated jet route structure extends down to 18,000 feet in the East and along the busier air routes, and down to 24,000 feet over the rest of the country, it would seem mandatory to limit the GA CAS equipment for use below such altitudes. Aircraft above 10,000 feet altitude typically fly at high speed so that large protected areas must be utilized in the absence of actual measurements of closing rate.

A natural breakpoint for the lowest cost system occurs at about 10,000 feet MSL since the available climb rate in typical single engine aircraft drops rapidly from about 10,000 feet toward the aircraft's service ceiling. Furthermore, while most single-engine aircraft fly at airspeeds of 175 mph or less, intruder aircraft may fly considerably faster at higher altitudes.

This is not generally true below 10,000 feet MSL since FAA regulation FAR 91.70 prohibits indicated airspeeds in excess of 250 knots below 10,000

feet MSL. (This would involve maximum true airspeeds of 291 knots (335 mph) at 10,000-foot altitude.) It would appear mandatory to limit this general aviation equipment for installation in aircraft having a maximum cruise speed significantly less than 291 knots or 335 mph, and to "red-line" equipment use above 10,000 feet MSL, or to guard a much larger penetration radius above 10,000 feet MSL, since higher intruder airspeeds may be anticipated there.

A somewhat higher altitude cutoff (probably with a somewhat enlarged protected area) could be used if subsequent FAA rule-making establishes airspeed limitations (e.g., in the regions from 10,000 to 14,000 feet and from 14,000 to 18,000 feet MSL).

The following aircraft operational parameters have therefore been utilized in designing the low-cost CAS for single-engine GA aircraft:

Airspeed	Up to 260 ft/sec.,
Climb Rate:	<u>Typically</u> 500 to 600 feet per minute or more,
Protected Flight Altitude:	<u>Maximum 10,000 Feet</u> (corresponding to Federal Air Regulations limiting airspeed).

The significance of these performance limitations is recapitulated in the following summary:

1. Speed

a. Even the best pulse doppler measurements have poor percentage accuracy compared to the 100 to 176 knot airspeeds of typical single engine GA aircraft.

b. Reasonably good estimates of anticipated maximum closing speeds (and climb rate) define the mandatory maneuvering radii for safe evasion.

c. The maximum speed of any aircraft equipped with the GA CAS must be specified for encounters involving such GA intruders. Similarly, the maximum speed of ATA-CAS equipped aircraft in the common airspace must be well defined. Any aircraft flying at excess speeds in the common airspace must maneuver soon enough to provide a safe evasion.

2. Climb Rates

a. Low climb rate aircraft may require longer warning times than full-CAS.

- b. At lowest altitudes, climbing aircraft must provide protection.
- c. At higher altitudes, diving aircraft may provide the requisite protection.

3. Design Altitude

- a. To limit the required protected area, it is essential that the protected aircraft be able to count on prescribed limited speeds for the various categories of intruders.
- b. This suggests designating GA CAS for use below 10,000 feet altitude (250 knots IAS per FAA regs.).
- c. This altitude limitation also limits line-of-sight range to similar low-flying aircraft, which justifies a simplification of the ATA CAS four-frequency-approach.

E. PROPOSED APPROACH

In defining requirements for system compatibility, it is essential to establish the principal attributes of the present ATA CAS system and then focus on the parameters that are unchangeable, those that can be changed slightly, and those that can be left out of the minimum system (refer to table 3). The ATA CAS attributes were summarized in an earlier paragraph. Based on the listed attributes, this contractor suggested the following approach to the design of a low-cost GA CAS in its proposal to NASA:

Restricting the CAS system to a one-frequency operation (for aircraft below 10,000 feet MSL).

Reducing peak power transmissions for the short range threat protection requirements of general aviation aircraft.

Deletion of requirements for long-pulse transmission and doppler detection.

Deletion of additional telemetry.

Deletion of the asynchronous Back-Up Mode.

This still permits adequate threat determination from a combination of range and altitude difference information (as discussed hereafter). Minor changes in ATA CAS design would be required, but these changes would not impose a significant cost penalty if they were adopted before a considerable number of CAS units were deployed in air carriers. An overall comparison

TABLE 3. COLLISION AVOIDANCE SYSTEM FEATURES

Full CAS Parameter Description	Required by GA CAS?	Effect on Minimum CAS Equipment	Effect on Full CAS	Remarks
1. Precise synchronization to an accuracy of 1.6 μ sec., three sigma	Essential	No Change	None	Will require a significant network of ground stations capable of providing sync to general aviation aircraft.
2. 2000 time slots of 1.5 millisecond duration	Essential	Should allocate a significant proportion for use by general aviation aircraft	Modify frequency-selection logic (refer to 3 below)	Since the preponderance of aircraft aloft, especially during peak hours, are general aviation aircraft, it is essential to allocate approximately half the available slots for general aviation use.
3. Transmit and receive on four frequencies	Not essential for low altitude A/C	Use single frequency	Change slot assignment and associated transmission frequency, when passing 14,000 feet pressure altitude. This provides single frequency operation in the common low-altitude airspace. Utilize slightly different sequences of transmitted frequencies than presently proposed.	The four-frequency system was specifically designed for avoiding false threat detection from aircraft that are very far away (but not beyond the radio horizon for high flying aircraft). Such aircraft transmissions would not be a problem for aircraft below 14,000 feet, since earth's curvature would not permit propagation at 475-nautical-mile separations, corresponding to a two-slot propagation delay. (Radio line of sight is approximately 290 nautical miles at 14,000 feet above terrain, and less at lower altitudes.) Uses a three-frequency system for range/altitude transmissions.
4. Generate 2000 watts of peak power for transmission	Not essential for slow A/C	Reduce transmitted power to provide adequate range protection at lower closing speeds	No change	Could reduce power to 100 watts or less since hazard range protection is reduced from 40 nautical miles for two Mach 3 aircraft to 8 nautical miles or less for two aircraft traveling at 300 knots.
5. Transmit on precise schedule. Determine range from time of arrival of received pulse.	Essential for compatibility	No change	No change	Mandatory for threat evaluation.
6. Telemeter altitude as time difference between two pulses. Use received altitude pulse in threat evaluation.	Essential	No change	No change	While the Atlanta VFR Data show little reduction in unnecessary evasive maneuvers resulting from use of altitude discrimination, this would not be true universally (e.g., for aircraft stacked in a holding pattern). For such cases, use of altitude discrimination is essential.
7. Control transmitted long (200 μ sec) pulse frequency to 1 part in 10^8 (short and long term). Determine closing velocity from doppler detection.	Desirable but excessively costly	Delete this requirement for general aviation aircraft flying at low speed (below 10,000 feet MSL). Shorten range pulse to indicate deletion of doppler information.	Full CAS must be able to use existing logic when doppler is available. Range/altitude logic for encounters with general aviation.	Long pulse generation with sufficient stability and the associated doppler measurement at the receiver constitute a major cost increment for the system. Even then, the doppler accuracy at low closing rates is poor. Use of range and altitude as sole threat determiners is feasible at the lower altitudes and closing rates.
8. Digital telemetry in Biphase Barker Code	Not essential	Delete for minimum CAS	No change	While this feature of Full CAS includes attractive capabilities, it does not seem desirable in minimum cost equipment.
9. Backup Mode	Not essential	Delete for minimum CAS	Desirable if ground sync not available.	Unnecessary if adequate ground resync capabilities are provided.

between the ATA CAS design approach and the approach used in the present low-cost GA CAS design is presented in table 3.

A major feature of the ATA CAS is the requirement for precise timing with specific time slots assigned for each aircraft's transmissions, and a specific frequency assigned to each slot. In such a cooperative system, it is mandatory that all participants be precisely synchronized to operate in the same time slot structure, and on the appropriate common frequency. Any significant time-slip could result in interference between the maverick and the other participants in the precisely-ordered system. In particular, early transmissions could result in false threat detection while late transmission, or transmission on the wrong frequency, could prevent other aircraft from detecting a threat.

Thus a compatible CAS for GA must employ common synchronized timing for the ATA-CAS equipment in the air carrier aircraft, and the minimum CAS equipment in the GA aircraft. Either the GA CAS must employ precisely the same timing and frequency control presently mandated for the ATA CAS system, or else minor modifications must be imposed on the full-CAS system and a new common timing and frequency control system adopted.

The various proposed changes and their impact on system complexity were discussed, in the original proposal. Two of the proposed changes are rather obvious and hardly controversial. These changes involve restricting the peak power and deletion of the "additional" digital telemetry transmissions, both of which were considered in the discussion of limited-CAS equipment by the ATA's Technical Working Group on CAS, and embodied in the Sierra-Wilcox limited CAS equipment. Similarly, the Back-Up Mode was generally considered to be a possibly desirable but optional system add-on, so that deletion of this mode and its replacement with a dependable system of ground synchronizing stations should be readily accepted.

All of the proposed system changes have been reexamined during the course of the present study and have (with minor modifications) formed the basis for the overall system design. Thus the study effort was concentrated on specifically exploring the three major changes:

Reduction in transmitted power output.

Deletion of doppler discrimination in encounters with GA CAS equipped aircraft, and the consequent elimination of requirements for coherent transmission.

Use of a single frequency for all GA CAS transmissions and receptions below 10,000 feet MSL.

Specific analyses have been made of the threat boundaries and of the changed airspace requirements resulting from use of the modified threat logic. The major concentration of effort was directed at the specific system design requirements that resulted from the proposed approach.

F. DESIGN ECONOMIES IN GENERAL AVIATION CAS

The proposed modifications to the ATA specification and the performance limitations of the GA CAS permit the selection of relevant areas for design economies. In particular, this contractor has concentrated on the following specific areas:

Use of moderate cost airborne crystal clock for system timing.

Reduction in RF power transmission.

Simplified Transmitter design, eliminating requirements for ultra-precise frequency control with negligible incidental FM (Coherent Transmitter).

No doppler processing.

Reduction of the number of transmitting and receiving frequencies utilized.

Deletion of Back-Up Mode and Data Transmitting capabilities.

These various areas are explored in the following paragraphs:

1. Use Moderate Cost High Quality Crystal Clock. The ATA Collision Avoidance System is time-ordered and uses one-way ranging, which requires precise clock synchronization (sync) for all users. Any time error because of initial setting error or accumulated oscillator drift error causes a corresponding range error.

High quality crystal clocks, capable of performing to an accuracy of one part in 10^8 (or better) are available at reasonable cost. Such units exhibit long-term frequency drift that can be detected and corrected during a sequence of resynchronization intervals. The ARINC CAS characteristics permits use of such crystal clocks in all classes of equipment. Such clocks cannot maintain or pass-on accurate time without frequent resync and update from a higher accuracy unit. Atomic clocks which do not require frequent updating are of course available. However, such units are unduly expensive for most users. The CAS characteristic does provide for air-to-air sync, but as shown in a subsequent section, present traffic patterns make such air-to-air synchronization unreliable over large areas. Deployment of adequate

ground synchronization facilities eliminates uncertainties in time transmissions and permits use of less expensive airborne timing equipment by all categories of users.

Ground navigation facilities can provide adequate sync update to maintain clock time (phase) to an accuracy of 200 to 500 nanoseconds (one-sigma). This permits clock frequency correction to 1 part in 10^8 after 1 minute and to 3 parts in 10^9 after an interval of two-to-five minutes. A method for passing on time with the air of reference transmissions from the VORTAC system was devised by Sierra Research engineers in 1968, and an unsolicited proposal was submitted to FAA. Recognizing the importance of such a system, Sierra Research employed internal funding to build and flight-test a version of the system during 1970. The performance of the system indicated that this approach was quite capable of providing the required synchronization function.

In the Spring of 1971, the FAA contracted with Sierra for the design and fabrication under Contract No. DOT-FA71WA-2571 of a feasibility model of ground and airborne synchronization equipment to permit the ground DME to transmit precisely-timed reference pulses with its normal transmissions and to permit an aircraft to synchronize an on-board clock to the ground-station transmissions. (In addition this contract includes equipment fabrication for extracting quasi one-way range from time of arrival of the reference pulse transmission.) Extraction of time sync for CAS and introduction of quasi one-way ranging for measuring traffic capacity constituted two of the four system changes discussed at the 1971 RTCA Assembly.

The TACAN/DME Subcommittee of RTCA's Special Committee on VORTAC Improvements SC-121, has passed a resolution¹⁴ supporting this "application of time frequency techniques with periodic updating by DME . . ." The SC-121 System Requirements Subcommittee has also endorsed the transmission of accurately timed reference pulses by VORTAC ground-station to permit synchronization of airborne clocks.

Successful use of such crystal clocks requires receipt of synchronization pulses within seconds of takeoff, intermittent receipt of sync update information for one-to-five minutes thereafter, and subsequent resync at intervals not to exceed once every three minutes or so. (Actually, longer delays between sync update are tolerable if the clock frequency is previously corrected to one part in 10^9 or better, or if the protected range boundary is extended outward to compensate for the increased clock error.) Within reasonable limits, somewhat larger sync errors may be tolerated. Thus a relative sync error S_{ab} between aircraft A and aircraft B might increase A's estimate of B's range by CS_{ab} (where C is the speed of electromagnetic propagation), but would then decrease B's estimate of A's range by the same amount. The complementary nature of these range errors helps maintain system safety even with some sync inaccuracy. This feature is most important in encounters when either aircraft can maneuver.

In any event, clock resynchronization must be available at least at five-minute intervals wherever protection is to be provided against encounters between such crystal clock equipped aircraft. The ATA CAS specification assumes that the more affluent users will provide air-to-air synchronization to any crystal-clock CAS equipped aircraft. It will be explained in a later section that presently established flight patterns would not provide adequate resync capabilities (from air-to-air sync) over much of the conterminous United States. This has motivated FAA-sponsored development work to utilize the existing chain of (VORTAC) navigation aids to provide resync capabilities in the airspace where significant numbers of instrument GA aircraft fly.

Based on the successful preliminary results of this development program, the GA CAS design described hereafter assumes the widespread deployment of a ground resynchronization network to permit reliable synchronization of the airborne crystal clock. Thus the design utilizes a high-quality airborne crystal clock together with inputs from an airborne (VORTAC) DME unit which permits error detection and correction.

2. Reduction in RF Power Transmission and in Receiver Sensitivity. One constituent factor that contributes to the cost of the ATA CAS design is the requirement for transmitting enough power and providing sufficient receiver sensitivity so that the aircraft can detect each other in time to provide adequate corrective action. It will be possible to reduce the transmitter power (and receiver sensitivity in the GA CAS) because of the shorter communication range required.

The requisite transmitted power is an inverse squared function of the required communication range (for a fixed receiver sensitivity on the other end). The required range is directly proportional to the maximum closing velocity and to the required warning time. Thus the range is also an inverse function of the available climb/dive rate. The protected range decreases substantially as a result of the reduced speed capability of the GA aircraft (and the limited intruder airspeed in common airspace).

If the intruder is a high-performance ATA-CAS equipped aircraft, then the required warning times (and the ATA CAS receiver sensitivity) are reasonably well defined, so that the lower closing speed provides one estimate of the minimum transmitter output requirement.

Similarly, if the ATA CAS transmits and the GA CAS receives, presently defined ATA CAS power outputs may be utilized in conjunction with estimates of the required warning time to verify GA receiver sensitivity adequacy.

Finally, we must verify the adequacy of reduced transmitter output and receiver sensitivity in encounters between two GA CAS aircraft.

It is evident that a substantial reduction in transmitter power can be tolerated for GA/airliner encounters at typical maximum closing rates of some 700 ft/sec. (as compared to possible closing rates of about 2000 ft/sec. in higher altitude encounters between two subsonic airliners). Selection of specific transmitter power requirements for GA CAS is explained in section VI, after a specific discussion of the threat boundaries. An overall power budget (including the specification of receiver sensitivity requirements) is provided there. This power budget permits timely detection of the GA-CAS equipped aircraft at a range of about 54,000 feet by equipped military high-speed low-altitude VFR aircraft (or by such aircraft flying "heavy wagon" or "oil burner" routes) in the event that the GA aircraft strays into one of these restricted military zones.

It should be noted that one reason for higher power transmission and receiver sensitivity in the ATA defined "limited-CAS" equipment specifications is the need for obtaining synchronization from distant air donors of time sync. Use of a network of ground sync stations on the VORTAC frequency, deletes this requirement for long-range CAS frequency communication.

3. Simplified Transmitter Design. In addition to reducing transmitter power, it is essential to eliminate other significant sources of transmitter design complexity in order to meet the target price requirements. The main source of complexity (and associated cost) in the CAS transmitter is the requirement for transmitting a long (200 μ sec.) pulse with stringent requirements for spectral purity.

For example, a 50 ft/sec. closing rate corresponds to a total doppler frequency

$$f_d = (v/c) f_c = (1.6) (10^9) (50/10^9) = 80 \text{ Hertz}$$

at the CAS carrier frequency of approximately 1.6 GHz. Over a 200 μ sec. interval, this corresponds to a total phase shift of 80 (200/10⁶) cycles = .016 cycles or .016 (360°) = 5.8°.

This introduces very significant requirements for phase stability (incidental phase modulation) over and above the nominal one-part-in-10⁸ carrier-frequency accuracy specified in the ATA CAS document. Decay of system transients, avoidance of effects due to thermal shock during pulsed transmission, power supply droop, and other transient phenomena present significant problems to the equipment designer. Avoidance of such small phase changes in a pulsed system requires significant design sophistication.

Significant savings can be achieved by reducing the pulse width of the transmitted pulse and by deleting these phase coherency requirements. This is achieved by eliminating dependance on doppler range rate in encounters involving GA CAS equipped aircraft.

Instead of doppler, the present GA CAS design uses a very coarse measurement of range rate together with range and altitude difference to determine a potential collision threat. This coarse estimate of closing rate is provided by coding GA CAS range transmissions in the form of a relatively short (30 μ sec) pulse while the ATA CAS transmits a longer (200 μ sec) pulse. Closing rate is estimated from the sum of own and intruders maximum airspeed, (where the single engine GA CAS equipped intruders are restricted to a maximum airspeed of 260 fps, while the ATA CAS equipped aircraft are assumed to fly no faster than 550 fps in common airspace).

Pilot activated Special Terminal Area Logic may be utilized for short intervals in areas where GA and intruder airspeeds can be assumed to be substantially slower than the preceding numbers (which are used for enroute conditions).

ATA CAS equipped aircraft would utilize the Tau threat logic on received long-pulse transmissions (from other ATA CAS equipment), but would utilize similar coarse range rate estimates combined with appropriate range/altitude logic to evaluate threats from general aviation aircraft transmitting shorter pulses.

It is recognized that this approach requires somewhat more airspace than might be required by the ATA's system. However, as will be seen in ensuing discussions, presently achieved doppler accuracies require considerably extended threat boundaries to assure timely detection of potential threats in low-speed encounters. Thus the resulting increase in unnecessary maneuvers seems tolerable compared to the alternative of precluding deployment of CAS in GA aircraft because of the associated excessive cost of a somewhat more discriminatory Tau CAS design.

4. Deletion of Doppler Processing. In addition to simplifying the transmitter design, elimination of the doppler range rate measurement for threat evaluation in encounters involving GA CAS, permits deletion of the doppler discriminator circuitry in the GA CAS. This equipment is no longer required for detecting intruder doppler velocity nor for verifying the purity of own CAS transmissions. The resulting cost savings are again substantial.

It should be noted here that equipment utilizing coherent rf transmissions to permit detection of closing velocity by doppler detection must take special care to ensure the correctness of the rf transmissions. CAS transmission of such doppler rf phases, that are not phase coherent and on

frequency, constitutes a potentially serious hazard. The circuitry needed to check the coherency of the rf transmissions is, in large part, similar to the circuitry utilized in the doppler processing. Therefore, deletion of the doppler processing alone, does not yield significant savings. Deletion of both the coherent rf transmissions and the doppler processing, on the other hand, will result in considerable savings.

5. Reduction in Number of Transmitter/Receiver Frequencies. The present ATA CAS system employs four separate frequency-bands to avoid mutual interference. Thus three 1.5 millisecond slots intervene between successive transmissions on a given frequency. It is shown in section IV that less interference protection is required for aircraft flying at lower altitudes. This permits use of a single intervening slot, with transmissions on different frequencies, between any two cofrequency CAS slots used for low-altitude transmissions, see figure 1. One frequency would be reserved for transmissions by all aircraft flying below 14,000 feet pressure altitude, while two other frequencies would be used with long doppler pulses by all aircraft equipped with ATA CAS units, flying above 14,000 feet pressure altitude. The fourth frequency would be reserved for air-to-air sync of low-flying aircraft.

Aircraft equipped with the minimum system would be fully protected only to 10,000 feet MSL. The common low-altitude frequency would be utilized by these aircraft for all transmissions and for threat monitoring. (Synchronization would be obtained by GA CAS on the VORTAC frequency rather than on CAS frequency.)

As noted in section IV, almost 1000 slots would then be available below 14,000 feet pressure altitude and a like number would be available for higher flying aircraft. The GA CAS equipment would transmit short pulses to permit range/altitude threat evaluation while ATA CAS equipped units would transmit long "coherent" pulses on the appropriate frequency, to permit doppler extraction of range rate.

Since all range/altitude transmissions below 14,000 feet MSL would be on a single common CAS frequency, there would be no requirement for GA CAS equipped aircraft to monitor the other frequencies. Thus no frequency switching circuitry is required, and the GA CAS transmitter and receiver are both fix-tuned units with consequent design simplification.

6. Deletion of Back-Up Mode and Data Transmitting Capabilities. The asynchronous back-up mode (BUM) was introduced to allow CAS protection between aircraft in areas where no sync information is available. With the assumed deployment of synchronization transmissions from the ground VORTAC system, the requirement for a back-up mode largely vanishes. Deletion of BUM capabilities in limited ATA CAS equipment is a recognized possibility.¹⁵

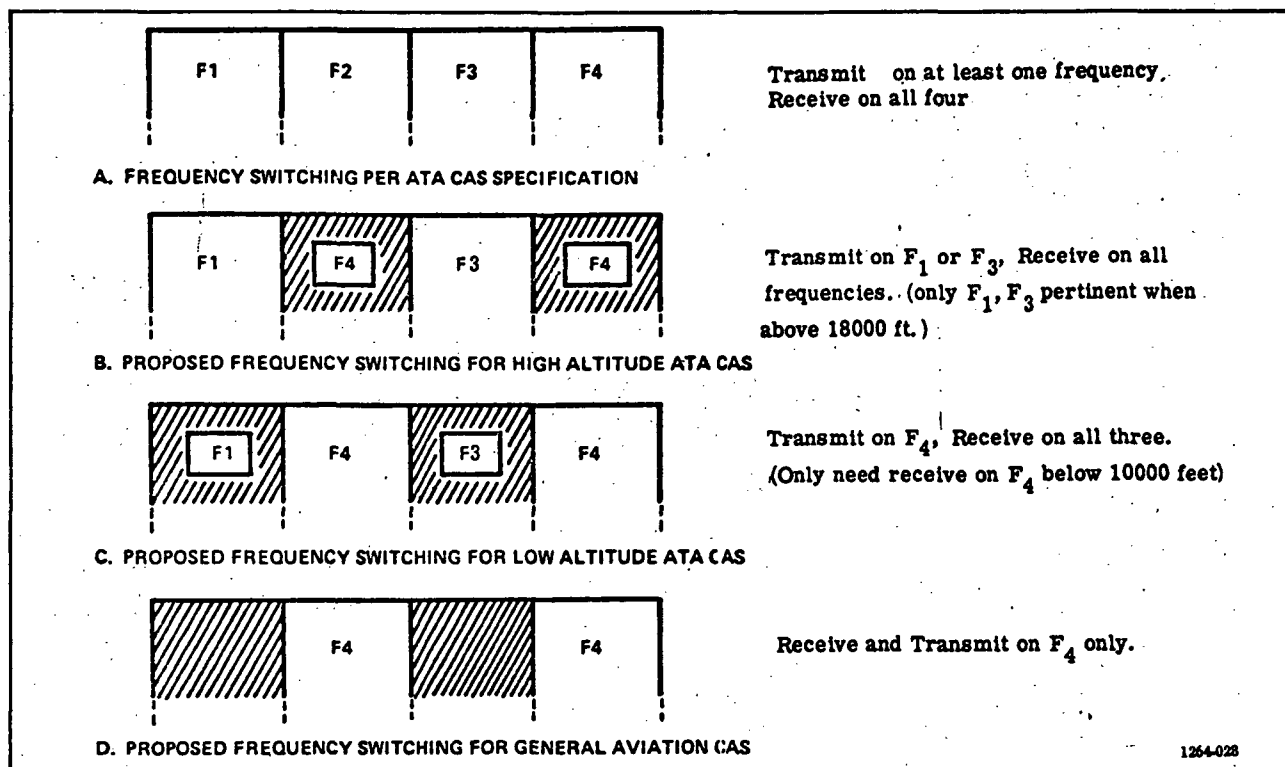


Figure 1. Modified CAS Frequency Switching

The BUM system utilizes an estimate of doppler closing rate to control the timing of reply pulses. Thus deletion of the doppler measurement precludes the use of the ATA CAS BUM by the GA CAS equipped aircraft. Furthermore, all BUM transmissions are on frequency F1 and would not be heard by the GA CAS equipment. The BUM equipment is a source of complexity in the ATA CAS equipment. Thus inclusion of such capabilities in the GA CAS equipment seems unwarranted. Rather, it is suggested that ATA CAS aircraft also utilize the available VORTAC sync signals. Of course BUM may provide additional protection between ATA CAS equipped aircraft in special situations.

Data transmission capabilities are included in the ATA CAS to permit development of a sync hierarchy and for other growth capabilities. Since the GA CAS equipment will rely on the VORTAC system for synchronization, it appears desirable to delete this capability. In any event, the digital data transmission is associated with the long (200 μ sec) pulse transmission, and the GA CAS design is based on the use of much shorter pulse transmissions to distinguish these non-coherent signals and to avoid inadvertent attempts by ATA CAS to develop wrong doppler data from these signals.

The ATA CAS Technical Working Group has always considered this data transmission approval for limited equipment. It is believed that inclusion of data transmission capabilities in the GA CAS would involve an unwarranted cost increment. Thus, this feature has also been deleted.

SECTION III

LIMITED CAS EQUIPMENT AND SYNC DONOR CAPABILITIES

A. GA CAS SYNC REQUIREMENTS

It is vital, to the entire flying community that a substantial proportion of air carrier, general aviation (GA) and military aircraft be equipped with CAS in order to reduce the probability of collisions. The only presently tested equipment for providing air-to-air collision protection to aircraft is the ATA CAS. This time-ordered system uses one-way ranging, which requires precise clock synchronization (sync) for all users. Any time error because of initial clock-setting error or accumulated oscillator drift error causes a corresponding range error.

Atomic clocks of sufficient accuracy to provide very accurate time with an infrequent resynchronization schedule are available but are priced beyond the reach of the typical GA aircraft owner. Moderately priced high-quality clocks are available, but require update at intervals of about 5 minutes to assure adequate range measurement. Resynchronization can be provided by ground stations, airborne units, or even by satellite relay. The latter could provide near universal coverage but would require special receiving equipment and would involve costly installation and maintenance costs.

The ATA CAS specification for Full CAS equipment¹⁵ requires sync donor capabilities (for providing sync to lower hierarchy CAS equipment and, in particular, to any limited CAS units without capability for transmitting data with biphase modulation). At one time it was thought that all airliners would be equipped with such Full CAS equipment having sync donor capabilities. This now appears to be unlikely, since the airline representatives, meeting in administrative session during the August 1971 AEEC general session in Kansas City, voted to write a hardware definition for Air Carrier Limited Level 1 CAS which would probably not include requirements for transmitting sync.¹⁶

Suggestions for requiring sync donor capabilities of all airline CAS equipment have been based on the assumption that this would go a long way toward meeting the sync requirements of the GA community in general and of those aircraft flying limited CAS equipment in particular. Unfortunately, there is no evidence to support the adequacy of such a time-distribution system. In particular, there are many areas in the United States where airline jet aircraft (in fact any IFR-equipped aircraft) appear fairly infrequently.

In such areas, sync update would have to take place at very long range and would require excessive CAS transmitter power to ensure reliable

communication. Even if all air carrier aircraft were uniformly distributed in space and time over the conterminous United States, there would be large gaps without adequate sync coverage. During calendar 1968, some 6.486 million hours were logged by U. S. air carrier aircraft of all categories. If these air hours were uniformly distributed over the 3.022 million square miles of conterminous United States, then the average density during these hours would be

$$\frac{6.486}{3.022 (365) (16)} \frac{\text{aircraft}}{\text{sq. miles}} = 1 \text{ aircraft per } 2721 \text{ sq. miles}$$

This corresponds to an average of one carrier aircraft within a 29.5-statute mile radius of any point over the conterminous United States or one aircraft within a 25.7 nautical mile radius of each such point. This would not provide adequate resynchronization capabilities for GA CAS equipment that is designed to provide a reliable communication range of approximately 9 nautical miles or less. The 9 db reduction in communication margin at 25.7-nautical mile range could reduce the synchronization quality significantly.

However, this assumption of uniformly distributed aircraft is highly idealistic. A more realistic indication of the distribution of sync donors is provided by figure 2 which was reproduced from an FAA document. This figure indicates the number of IFR flight plans filed between paired cities on the PEAK day. If the sync recipient is in the heavily travelled airspace of the northeast (corresponding to the Boston-Chicago-Washington triangle) then airborne sync may be adequate. For the majority of the rest of the country, less than 50 IFR flight plans for travel between most pairs of cities were filed with the FAA's Air Route Traffic Control Centers during their peak day in 1969. Typically, airline flights are concentrated during certain peak hours, and significant gaps occur at other times. Even if 50 flights were evenly distributed over a 16-hour day, an airliner aircraft would only overfly a given ground point on an air route between two such cities once every 19.2 minutes. Thus the closest IFR aircraft (flying at 550 knots) might be 88 nautical miles away from a given GA aircraft. The above estimates assume, conservatively, that all ATA aircraft would carry sync-donor CAS and that all of the IFR flights involve air carriers (actually, of 32,555 Peak Day IFR flights, only 22,319 involved turbine-powered aircraft).

Even if all the IFR aircraft had donor capabilities there is a good chance that no donor would be within reliable communication range with the GA aircraft. Many locations are more than 30 miles from the nearest air route connecting major cities. It can be seen from the figure that a substantial portion of the United States would fall outside a 10- to 30-nautical-mile radius about the principal air routes. The GA CAS equipment has been designed with a transmitted output power of approximately 75 watts (peak) to yield a 9-nautical mile detection range for threats at ATA CAS equipped aircraft. The

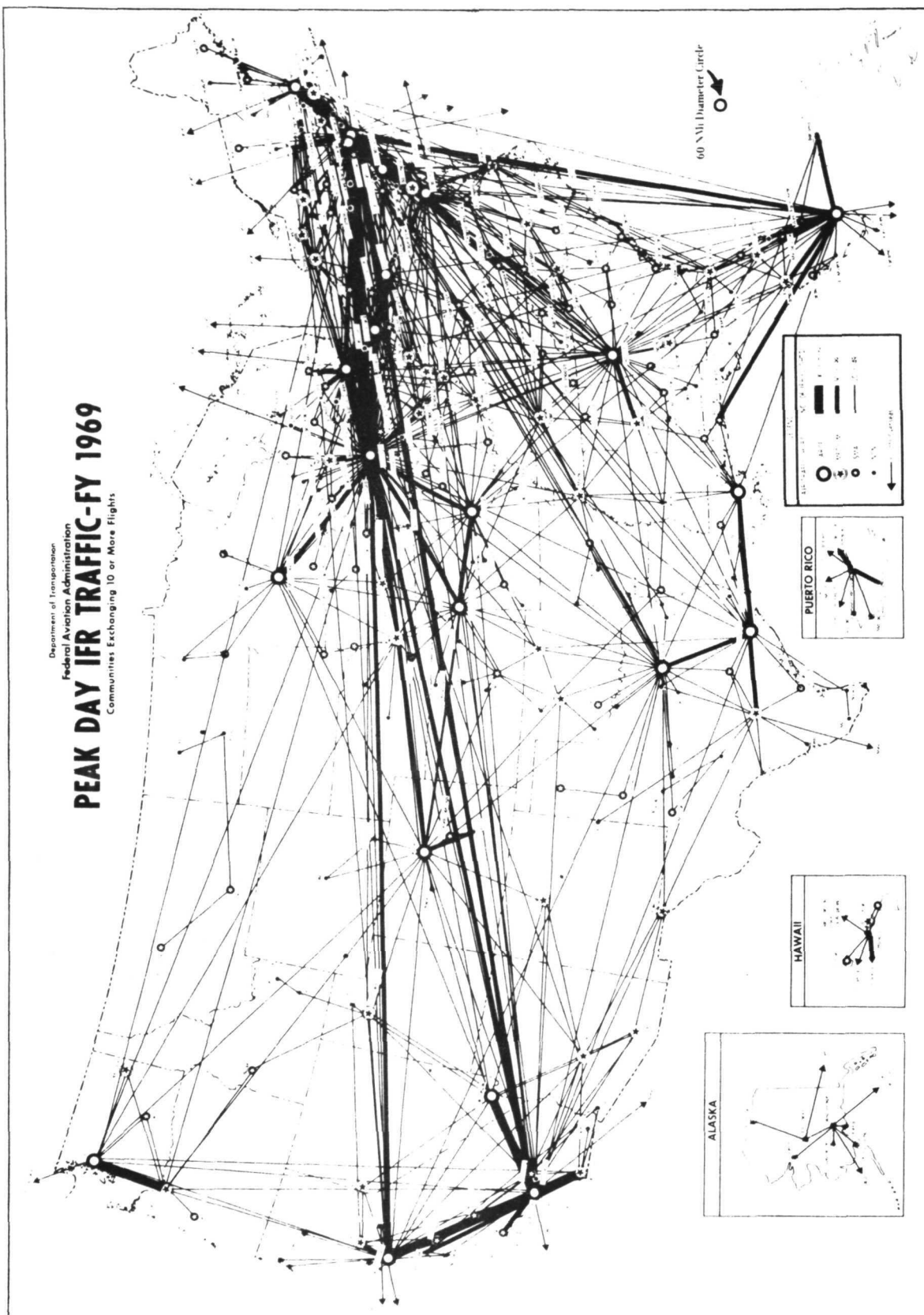


Figure 2. Peak Day IFR Traffic — FY 1969

critical path in extracting sync from airborne sync donors is similarly in the transmission from the GA aircraft to the donor. (Refer to RF Power Calculations, section VI). The associated resync range can be expected to be greater than 10 nautical miles. Resynchronization is not absolutely required every 3-second epoch for system operation. It should be possible to communicate intermittently with less than the 10 db assumed fade margin. Thus the estimated sync range would be 20 to 30 nautical miles.

The maximum allowable time interval between sync updates is the time it takes for a time error of one to two microseconds to accumulate on a clock with maximum permissible offset in frequency. A moderately priced clock with an inherent accuracy of approximately ± 1 part in 10^8 has been selected for this application. However, airborne clock frequency adjustment during sync can correct the frequency to agree with the standard within about 3 parts in 10^9 . Such clocks require updating at intervals of about 5.5 minutes or less to maintain 1-microsecond accuracy. Even the 19.6-minute mean resynchronization interval mentioned earlier would be intolerable. However, statistical variations in aircraft passage intervals, and complete lack of synchronization until an airliner comes on the scene makes this a very hit or miss method for providing collision avoidance protection.

Even in much busier airspace, the present ATA-CAS sync donor approach may cause difficulties when low power CAS-equipped aircraft request sync. The ATA specification requires a capable airborne sync donor to restrict his reply rate to $1/N$, where N is the number of airborne sync donors (with hierarchy and time validation) that any given airborne sync donor may "hear". This restriction was introduced to eliminate possible interference between transmissions of the fine sync triad from different donors. The procedure has potential drawbacks.^{16, 17} This is most readily understood by covering a situation where a large number of potential donors (e.g., 50) are in a busy airspace, just beyond communication range with a sync requester. In addition, one donor is located midway between the requester and the cloud of aircraft. The closest donor, hearing $N = 50$ other donor aircraft, would only transmit sync replies 2% of the time. The other potential sync donors could not reply to the requester if they were out of communication range. Thus the resync rate would drop from once every 3 seconds (or once every 6 seconds) to once every 150 to 300 seconds. If the requester and donor were on antiparallel courses, they might even fly out of communication range by the time that the $1/N$ circuitry allows a sync reply. Similar problems arise if one isolated sync requester is at marginal communication range with a cloud of sync donors, and if one of the donors has a particularly sensitive receiver. Again the presence of the other donors would inhibit most sync replies from the only donor that can hear the sync request.

It is obvious that a large number of appropriately distributed ground stations on the established instrument navigation routes provide an ideal

method for distributing accurate time synchronization to GA aircraft. This approach does not depend on the availability of airborne sync donors to fill gaps left by eliminating ground stations, nor is the ground station sync reply limited to a $1/N$ reply rate. The alternative inclusion of sync donor capabilities in all air carrier aircraft, besides imposing cost and weight penalties (and thereby displacing payload), would not necessarily suffice to provide synchronization to a sufficient percentage of GA aircraft.

However, for economic reasons, it would be necessary to modify virtually all VORTAC stations used by GA aircraft, if the resulting synchronization capability is to be available to these aircraft. At any one time, a GA aircraft listens to just one VORTAC, and this VORTAC station is selected on the basis of FAA-established routes. Use of area navigation equipment will provide considerably greater freedom for selecting VORTAC stations. However, it is not necessary nor recommended that GA-equipped aircraft should first have to purchase area navigation equipment in order to utilize VORTAC sync. If every ground VORTAC is modified to provide sync donor capabilities, then the airborne clock can be synchronized without requiring pilot (or automatic) re-tuning from the navigation DME to one of a limited number of sync DME's.

1. Low Altitude Coverage. It is essential to provide synchronization at the lowest possible altitudes in order to permit use of CAS as soon as possible after takeoff. Figure 3 shows that for an aircraft 500 feet above an assumed smooth earth, an expected line-of-sight path exists for some 28 nautical miles. While there will be locations where the aircraft will not have sync available at the takeoff airport, these locations are minimized by use of the VORTAC navigation system which was specifically deployed to meet air traffic requirements.

2. Associated Benefits. An especially beneficial feature of systems utilizing VORTAC synchronization is that no CAS signals need to be transmitted until the airborne unit is in fine synchronism with CAS time. Present CAS equipment may be coarse synchronized with large propagation delays at ranges where fine sync is not available. The CAS, if not equipped with BUM, would continue requesting sync for extended intervals with possible resultant interference in adjacent slots. If the CAS is equipped with the asynchronous backup mode (BUM) then it could alternate between BUM and fine sync requests. In any event, there is a possibility that a limited CAS unit would transmit in the BUM mode for extended intervals if receiver sensitivity or other minor system degradation inhibited resync capabilities.

The resulting asynchronous transmissions could be detected during "shut-up and listen" cycles and could involve considerable slot jumping and associated interference with the orderly time/frequency transmissions. Synchronization via VORTAC avoids the requirement for a backup mode. By avoiding asynchronous CAS transmissions, this approach eliminates a

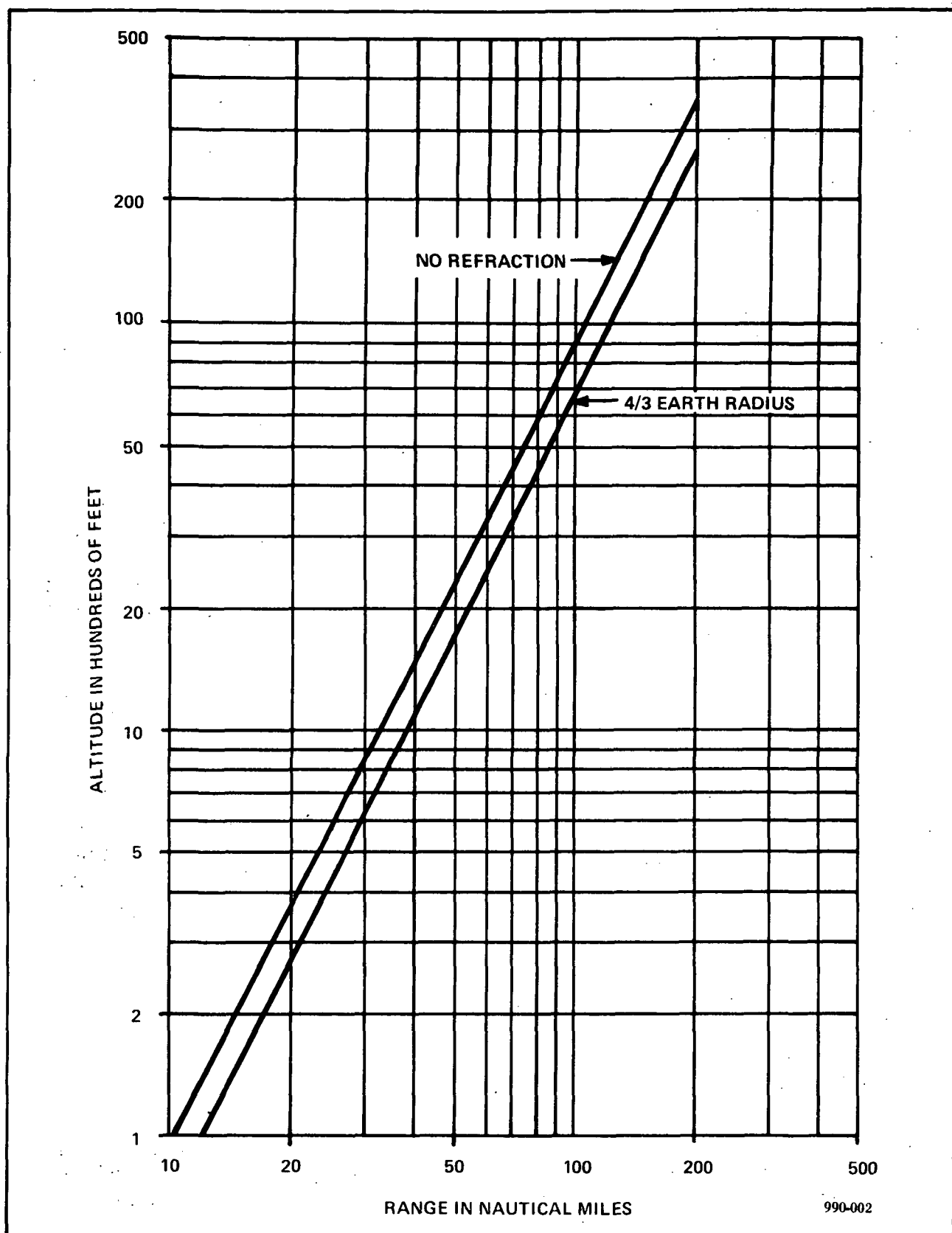


Figure 3. Minimum Altitude for Line-of-sight Air-to-ground Communications

B. GROUND SYNC DONORS

1. Ground Station Distribution. One approach to providing ground sync-donor stations involves the deployment of such a network of stations on a geometrical grid. The desired ground station distribution may be determined by first approximating the conterminous United States with an 870- by 2600-nautical mile rectangle. Assuming the maximum sync range (for the general aviation CAS) to be 30 nautical miles, a ground station deployment in the form of a triangular grid could be considered (see figure 4). This requires 50 stations at 52-nautical-mile intervals, in the east/west direction, parallel to the longer side of the rectangle. There would have to be 19 grid lines at 45-nautical mile intervals in the north/south direction.

Diagram illustrating a network structure with distances in Nautical Miles (NMI):

- GROUND STATION** is connected to a node on the left.
- The horizontal distance from the **GROUND STATION** to the first node is **52 NMI**.
- The network consists of two triangles sharing a common vertical edge.
- The left triangle has sides of **52 NMI** and **30 NMI**.
- The right triangle has sides of **30 NMI** and **45 NMI**.
- The vertical distance between the top and bottom nodes is **30 NMI**.
- The horizontal distance between the two vertical lines is **52 NMI**.
- The distance from the bottom node to the right node is **15 NMI**.

31

miles long sides, are formed. The maximum distance from any point within or on the triangles is 30 nautical miles. A total of approximately 950 ground stations would be required for general aviation sync using this method. Note that a square grid, with dimensions of $30\sqrt{2}$ nautical miles would require some 21 by 62 stations or about 1300 stations. The number of stations would decrease if gaps in coverage were permitted. But even the proposed 30 nautical miles resync range only provides marginal coverage.

Another contractor's report¹¹ indicates that only 600 ground stations are required (see figure 5) for complete coverage (gap $D = 0$) above 1000 feet altitude. The disparity between their estimate and that of Sierra Research results from differing estimates of sync communication range. Figure 5 does not include the communications link as a dependent variable in the determination of the number of ground stations required. However, even the deployment of 600 ground stations would involve considerable expenditure and delay.

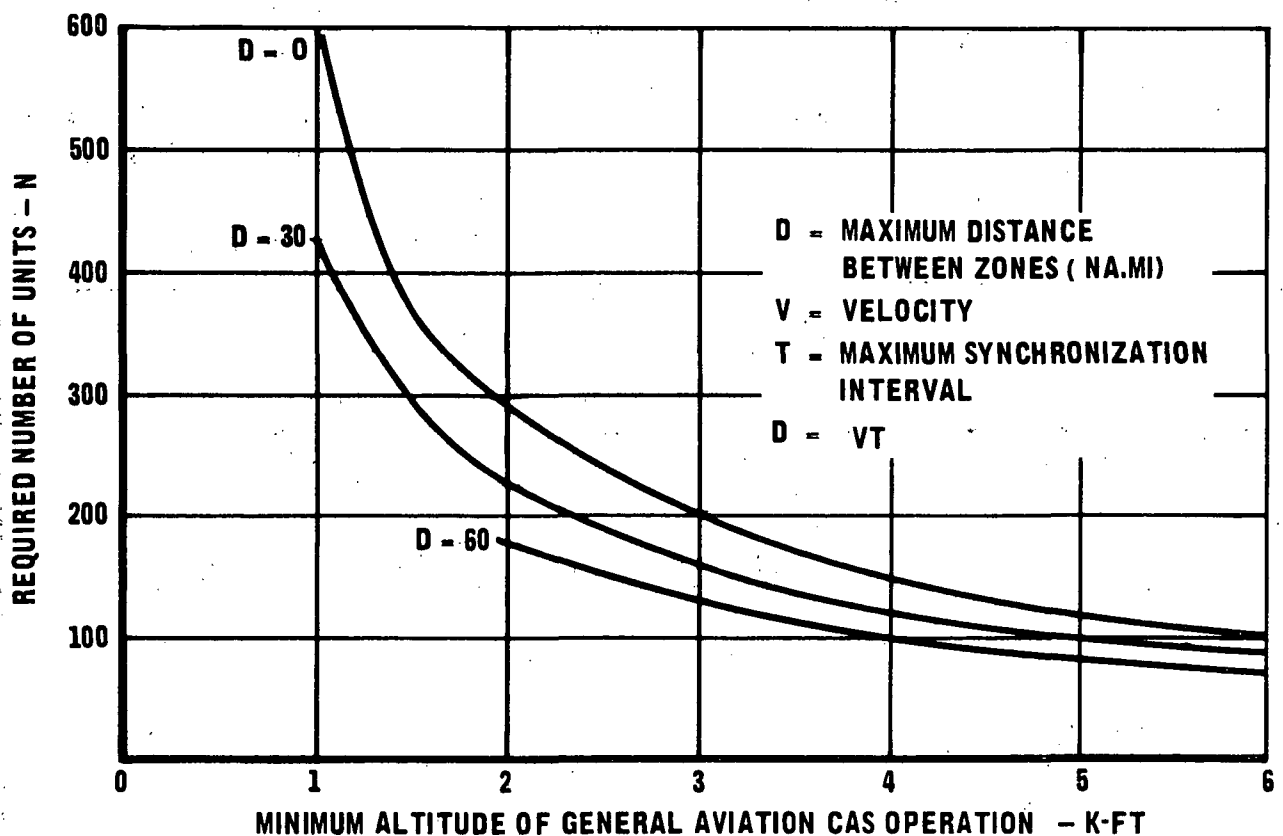


Figure 5. Number of CAS Stations Required for Ground-based Synchronization Network (from reference 11)

If CAS implementation had to await deployment of an extensive network of new CAS-frequency ground stations, the resultant delay would probably scuttle the whole program. Under these circumstances, this contractor has worked with FAA to develop a simple modification to existing ground navigation (VORTAC) facilities in order to transform these stations into a ground donor of time synchronization, without interfering with the stations' intended navigation capabilities.

2. VORTAC Sync Donors. Modifications of the Ground VORTAC network to provide the requisite synchronization function has two major advantages. From an economic point of view, the VORTAC system is already deployed along the most travelled air routes, so that costly shelter and site acquisition for the sync donor stations is not required.

In addition, sufficient communication range and coverage is provided, so that synchronization would be available almost everywhere that GA aircraft fly in significant numbers.

Figure 6 indicates the fine coverage given by the VORTAC network and is one of the primary reasons it was chosen. The ATS Fact Book indicates that in 1967 there were 950 VOR/VORTAC stations in operation (including military and non-federal installations) many of the stations have an operating range of up to 130 nautical miles. This includes 561 VORTAC stations and seven VOR/DME stations. A significant portion of the remaining stations have been modified or are scheduled to be modified to include a DME capability¹⁸. Approximately 1050 FAA-operated stations are expected to have DME capabilities by 1981 (reference 19). These stations provide coverage over the counterminous United States with near-saturation coverage in the regions of maximum air traffic.

In view of the long-range capability (up to 130 nmi) of VORTAC stations, excellent coverage could be achieved by modifying a limited number of ground stations. Even more extensive coverage will become available (especially at low altitude) if a significant number of VORTAC and VOR/DME stations are modified and synchronized.

A method for passing on time with the aid of reference transmissions from the VORTAC system was devised by Sierra Research engineers in 1968, and an unsolicited proposal was submitted to FAA. Recognizing the importance of such a system, Sierra Research employed internal funding to build and flight-test a version of the system during 1970. The performance of the system indicated that this approach was quite capable of providing the required synchronization function.²⁰

In the Spring of 1971, the FAA contracted with Sierra for the design and fabrication under Contract No. DOT-FA71WA-2571 of a feasibility model

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of ground and airborne synchronization equipment to permit the ground DME to transmit precisely-timed reference pulses with its normal transmissions and to permit an aircraft to synchronize an on-board clock to the ground-station transmissions.

The advantage of utilizing VORTAC over other navigation aids for passing on time were summarized²¹ and a detailed discussion of the selected system approach²² was provided to FAA in May 1971. The completed feasibility model of the ground unit is scheduled for shipment to NAFEC on 16 November 1971 for flight test evaluation. The airborne unit, which includes capabilities for extracting quasi one-way range from time of arrival of the reference pulse transmissions, is scheduled for shipment in January 1972.

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SECTION IV

DESIGN OF A SINGLE FREQUENCY GA CAS

A. INTRODUCTION

The ATA's Collision Avoidance System requires each CAS-equipped aircraft to monitor four RF frequencies sequentially in order to assess potential threats. In addition, at least the sync-donor equipment would have to include capabilities for transmitting on each of the four RF frequencies utilized by CAS. Thus, a Full CAS system* is a four-frequency system requiring the generation of eight different frequencies (four different transmit and four different local oscillator frequencies).

In order to reduce costs, Sierra proposed to delete the requirement on the General Aviation CAS for sequentially monitoring four different CAS frequencies. This simplification of the GA CAS equipment is obviously desirable, if it can be accomplished without any deterioration in overall system performance, provided the impact on the Full CAS system is not of great significance. In particular, there must be no deterioration in system capacity, no increased danger of mutual interference, and no loss of capability for evaluating potential threats.

In the ensuing paragraphs, we will summarize the single-frequency discussion from our original proposal and discuss the detailed impact of these changes on the ATA CAS. We will explain the minor modifications in ATA CAS that may be desirable to permit use of a single-frequency system by low-flying GA aircraft, without deteriorating system performance.

It must be emphasized that the proposed single-frequency approach involves specific changes in the ATA CAS.

This report documents the most economical approach to the design of a GA CAS, based on making necessary changes in the overall CAS logic.

B. BACKGROUND

The CAS system, designed by ATA's Technical Working Group on Collision Avoidance utilizes a sequential pattern of transmission on four separate frequencies in order to guard against mutual interference between aircraft within line of sight. These four separate transmitting and receiving

* As used in this report, "Full CAS" and "sophisticated CAS" are used almost interchangeably with "ATA CAS" which includes the ATA's Limited System (level 1) except where sync donor capabilities are required. "GA CAS" refers to the low-cost design under study of NASA.

frequency-allocations are located in the 1.6-GHz band (centered at 1.600, 1.605, 1.610, and 1.615 GHz) and are generally referred to as F_1 , F_2 , F_3 and F_4 , respectively. The system employs a 6-second repetition cycle (see figure 7). This cycle is subdivided into a three-second ground epoch followed by a three-second air epoch. Each epoch is further subdivided into 500 six-millisecond groups of four successive slots where the transmission (and reception) frequencies are successively switched through the frequencies F_1 , F_2 , F_3 , F_4 . Each aircraft transmits on one of the four available frequencies, in an appropriate slot, during the ground epoch and in the corresponding slot during the air epoch. Various slots are reserved for ground stations, test purposes, etc. so that this 2000 slot system has an ultimate capacity to accommodate somewhat less than 2000 aircraft. Approximately 500 slots are available for transmission on each of the four frequencies F_1 through F_4 .

This pattern of frequency-allocations was selected to utilize line-of-sight limitations for preventing mutual interference. In the present one-way CAS system, the signal attenuation with range obeys an inverse square law. Thus every time the range doubles, the power goes down by 6 db. If adequate fade margin is provided, there will be conditions when interference may result from unwanted intermittent good communication at extreme range. By utilizing frequency-switching, an additional increment of attenuation can be introduced. In particular, some 30 db of adjacent channel rejection is assumed in the ATA CAS. (Actual adjacent channel rejection will depend on the filtering employed in the receiver and on the nature of the transmitted pulse modulation.)

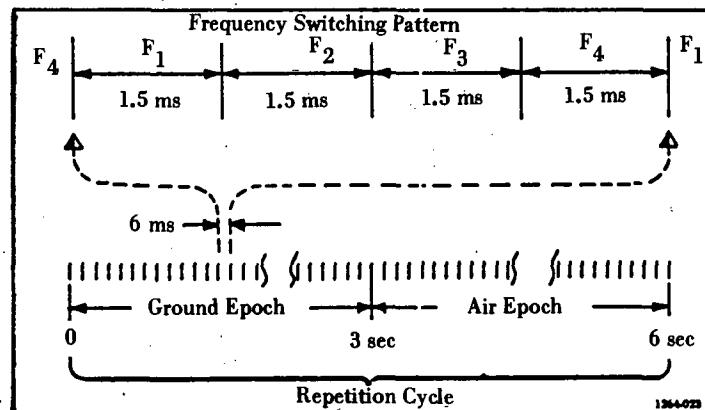


Figure 7. Frequency Switching Pattern in ATA CAS

Line-of-sight refers to the smallest range separation where the intervening earth severely blocks electromagnetic propagation. The line-of-sight distance, $D_1 + D_2$ (see figure 8) can be calculated for two aircraft that are respectively at heights H_1 and H_2 above a perfect spherical earth, by assuming straight-line propagation. By the pythagorean theorem, $(R+H_1)^2 - R^2 = D_1^2$, $(R+H_2)^2 - R^2 = D_2^2$ where R is the radius of the earth. But aircraft are restricted to fly in the atmosphere where H is much less than R so that H^2 can be neglected in comparison with $2RH$. Thus the line of sight is given by:

$$D_1 + D_2 = \sqrt{2RH_1} + \sqrt{2RH_2}.$$

If we just use the earth's radius of 3440 nmi with $H_1 = H_2 = 10$ nmi then $D_1 + D_2 = 2 \sqrt{20 (3440)} = 2 \sqrt{68,800} = 524$ nmi. (All distances are given in nautical miles.)

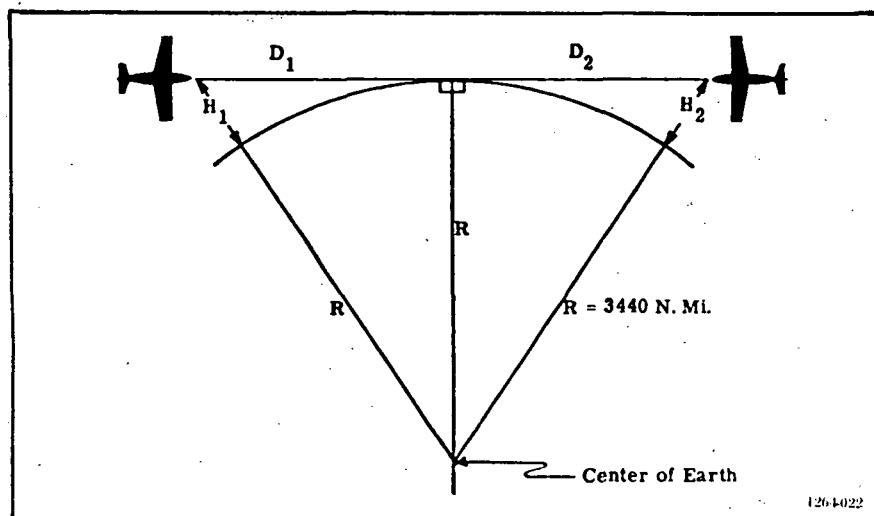


Figure 8. Grazing Line-of-sight Transmission

Refraction effects typically extend line-of-sight coverage. In performing line-of-sight calculations, an "effective" earth's radius of 4587 nmi is used to approximate these refraction effects.²³ With such a $4/3$ radius earth, the line-of-sight becomes:

$D_1 + D_2 = 2 \sqrt{20 (4/3) 3440} = 606$ nmi. Electromagnetic energy travels one mile in $6.19 \mu\text{secs}$, so this corresponds to a one-way propagation delay of $6.19 \times 606 \mu\text{secs}$ or 3.76 milliseconds.

The CAS has been designed for use at a maximum altitude of 87,500 feet, where the 727-nmi line-of-sight range provides a propagation delay of about 4.5 milliseconds. A signal transmitted during the first half of a given slot will arrive at a receiver 727 nautical miles away in the first half of the third following slot. But the frequency switching provides 3 intervening 1.5-millisecond slots where different frequencies are employed (see figure 7). In combination with range attenuation and line-of-sight cutoff, this effectively prevents interference between aircraft transmissions on the same frequency.

C. APPLICABILITY TO GA CAS

Sierra Research Corporation believes that significant cost savings can be realized by limiting all CAS transmissions and receptions by the smaller General Aviation aircraft to a single RF frequency. In order to achieve this simplification it would be necessary to limit all transmissions by potential threat aircraft (i. e., by all aircraft flying in the same airspace) to the selected common frequency.

An apparent solution would involve restricting all threat (range, range rate, and altitude) transmissions by low-flying aircraft to a single one of the four previously mentioned CAS frequencies. ATA CAS logic requires evaluation of threats from all aircraft within ± 3500 feet of own aircraft's altitude. Since the relevant GA aircraft are assumed to fly at altitudes below 10,000 feet, it would be necessary to restrict threat transmissions, by all aircraft below 13,500 or 14,000 feet, to a single CAS frequency. But this only leaves some 500 distinct slots available for use by low-altitude aircraft.

Based on estimates in the Alexander Committee's report ²⁴ there may be a peak of some 1700 aircraft above the Los Angeles Basin, (a 60 by 120 nautical mile area) by 1995. Some 80% of these are projected to be below 10,000 feet. Similarly, some 6250 airborne aircraft are projected within the entire Los Angeles sector. Some 70% of these aircraft are assumed to be below 10,000 feet.

With such a preponderance of low-flying aircraft, it would be absolutely unrealistic to assume that 500 low-altitude slots would suffice for the low-flying aircraft. (It may also turn out that 2000 slots will not suffice for all CAS-equipped aircraft.)

Assigning half the available slots for low-flying aircraft and the rest to high-flying aircraft appears more realistic. This need for more slots, combined with a desire for equipment simplification has motivated us to propose a modified frequency switching system. In particular, it is proposed that every other slot be reserved for use by low-flying aircraft and that all low-flying aircraft be constrained to transmit in one of these reserved slots. A single CAS frequency (F_4) would be used for threat transmissions by all aircraft flying below 14,000 feet. Aircraft flying at 10,000 feet or lower would never have to monitor the other three CAS frequencies for threat evaluation. Thus the GA CAS (which is to be restricted for use by aircraft flying below 10,000 feet) would be a truly one-frequency system, transmitting and receiving on F_4 only.

It remains to show that this change would not cause interference or other problems to the resulting CAS. We consider the line-of-sight transmission path between the highest flying aircraft on F_4 and the highest flying intruder. The aircraft on F_4 may be at 14,000 feet and may interact with aircraft that are up to 3500 feet higher still. In evaluating threats between (transmitting) aircraft at 14,000 feet altitude or less and (receiving) aircraft at 17,500 feet or less, the maximum propagation delay becomes

$$6.19 \left[\sqrt{\frac{8}{3} (3440) (14000/6076)} + \sqrt{\frac{8}{3} (3440) (17500/6076)} \right]$$

$$= 6.19 (\sqrt{21200} + \sqrt{26500}) = 6.19 (146 + 163) = 1915 \text{ } \mu\text{secs or } 1.915 \text{ milliseconds.}$$

Any signals transmitted by the lower-flying aircraft, during the first 1085 microseconds of their assigned slots, would arrive at the higher-flying aircraft in that same slot or in the next subsequent slot (where a different frequency is utilized and therefore the signals can be ignored). The ATA CAS signal transmission format involves completion of all transmissions by the slot occupant within the first 765 microseconds of the slot. The specification reserves a block of up to 350 microseconds for "additional communications and navigation information" (e.g., telemetry of airspeed components as PPM data). This could be reduced somewhat (to 320 microseconds or less) to complete all transmissions during the first 1085 microseconds and thereby avoid any reasonable possibility of interference between transmissions (see ATA CAS Signal Transmission Format, figure 9).

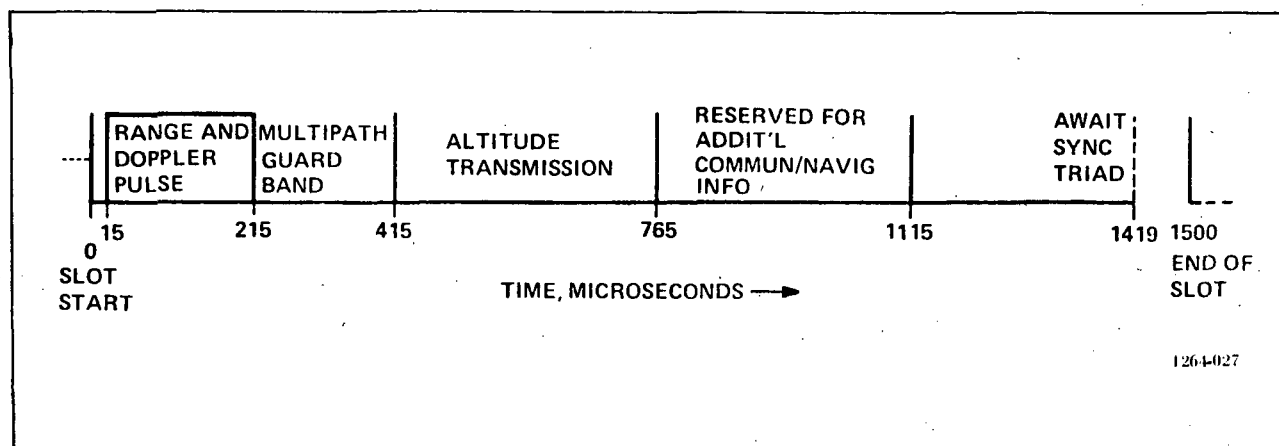


Figure 9. ATA CAS Signal Transmission Format

D. REQUISITE CHANGES IN ATA CAS FREQUENCY SWITCHING

The availability of a 1.9 millisecond guardband (consistent with line-of-sight limitations) motivated our proposal for use by the higher flying aircraft of a single intervening frequency slot between each pair of "F₄" slots to be used by any aircraft flying at or below 14,000 feet altitude (see figure 10). Essentially, this frequency switching technique was suggested in our proposal to permit all aircraft below 10,000 feet to receive and transmit on frequency F₄ only. Aircraft in the buffer zone between 10,000 and 14,000 feet of altitude would have to monitor frequencies F₁ and F₃ (as well as F₄) in order to hear aircraft range transmissions and evaluate threats from aircraft in the region above 14,000 feet altitude. Similarly, aircraft in the region above 14,000 feet altitude might have to monitor transmissions on F₄ (as well as F₁ and F₃) but would only be allowed to transmit range pulses and similar data on F₁ or F₃ in order to provide altitude, range, and range-rate threat information. F₄ replaces F₂ in the ATA CAS frequency switching logic. All CAS-equipped aircraft flying through 14,000 feet of altitude would have to switch slots.

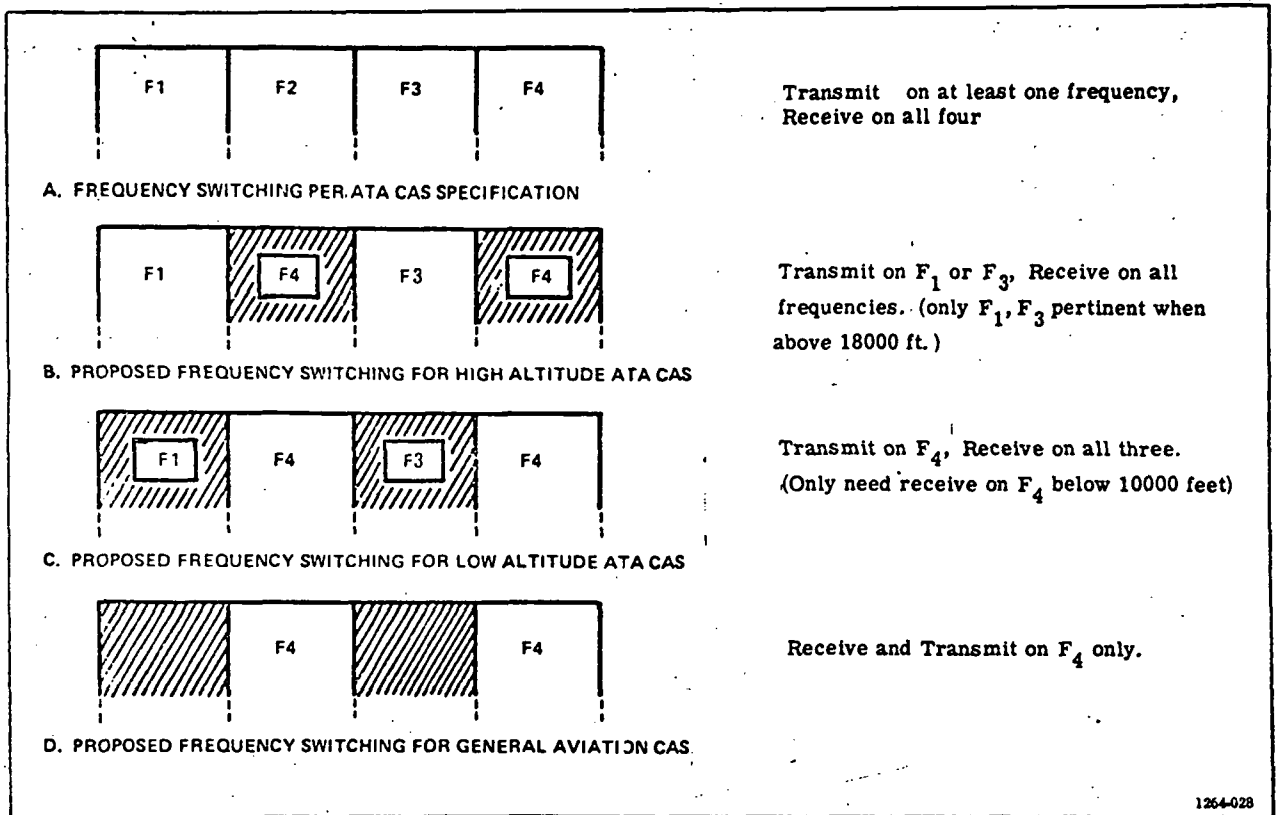


Figure 10. Modified CAS Frequency Switching (for Threat Determination)

As noted earlier, the actual signal in space transmitted from any given synchronized airborne station in the ATA system does not include any threat information beyond the first 765 microseconds of each slot except for a possible set of additional communication or navigation signals that may be transmitted immediately thereafter. This leaves some 400 microseconds of dead time at the end of each given F_4 slot. This delay, in conjunction with the 1500-microsecond guard band provided by the intervening F_1 or F_3 slot, corresponds with the required 1.915 millisecc line-of-sight guard band needed to prevent interference between common frequency transmissions in every other slot.

As noted earlier, a slight (30 microsecond) reduction is desirable in the 350 μ secs. reserved by the ATA CAS for additional communication. Reduction of this reserved time should cause no difficulty since no actual equipment, embodying such additional (pulse position modulation) telemetry has been built as yet. There would be no problem of mutual interference between range and presently-planned telemetry transmissions utilized for threat evaluation in a given slot and the corresponding transmissions two slots later.

E. SYNCHRONIZATION

Since the proposed GA CAS system could not depend on air-to-air synchronization, Sierra Research suggested the use of VORTAC for synchronization. These GA CAS units would synchronize on the appropriate TACAN/DME frequencies rather than using one of the four CAS frequencies.

However, any CAS units that may wish to employ air-to-air synchronization will utilize additional transmissions on one or more of the four CAS frequencies. This is illustrated in figure 11, which shows overall frequency management in the previously-defined ATA CAS, including transmission of sync triads by donors and the reception of such pulses by requestors.

All airborne aircraft must go through the zero to 14,000 foot altitude layer, at least during takeoff and landing. Since we are considering a requirement for use of F_4 in this altitude band, it would appear desirable to include provisions for such aircraft to utilize air-to-air synchronization if they so desire.

When we consider possible use of the frequency F_4 in the air-to-air sync of aircraft below 14,000 feet altitude in the proposed modified GA CAS, then a small probability of interference might be anticipated between the range/altitude transmissions by one aircraft and the air-to-air sync pulses at the very end of the preceding F_4 slot. Specific cases could arise where aircraft within line of sight might receive range pulses from one aircraft and sync pulses directed to another aircraft in an earlier slot. While such interfering

SLOT NUMBER	40	41	42	43	44
SLOT NUMBER MODULO 4	0	1	2	3	0
TRANSMISSION BY SLOT OCCUPANT	F_1	F_2	F_3	F_4	F_1
RECEPTION BY OTHER AIRBORNE CAS UNITS	F_1	F_2	F_3	F_4	F_1
TRANSMISSION BY AIRBORNE DONOR	F_1	F_2	F_3	F_4	F_1
RECEPTION OF SYNC TRIAD BY SLOT OCCUPANT	F_1	F_2	F_3	F_4	F_1

1264-029

Figure 11. Frequency Management per ATA-CAS Specification

sync would generally be of low amplitude, they still could cause some errors in judging initial rise time. It would certainly be preferable not to have such possible interference.

Complete protection against mutual interference is provided through use of the frequency F_2 which had not been previously intended for use in this system. If F_2 is utilized in air-to-air sync of those aircraft utilizing the "earlier" F_4 channel, then all problems disappear. In fact, by restricting any aircraft desiring to utilize air-to-air synchronization to the second channel in each group (where the slot number modulo 4 equals one) and by utilizing F_2 in that channel for any needed air-to-air synchronization, we provide three intervening slots for an overall delay of approximately 6 milliseconds to guard against any possible interference (see figure 12).

By assumption, all low-cost General Aviation CAS would be synchronized utilizing the VORTAC synchronization technique, described in our original proposal, and therefore would not need the air-to-air synchronization capabilities. In fact, in these GA CAS systems, we plan to exclude capabilities for utilizing either air-to-air synchronization (or ground-to-air synchronization, unless that synchronization comes from the VORTAC system) in the interest of simplifying system hardware. There are no technical impediments to the use of both synchronization techniques but this would cost slightly more. Since we are convinced that the VORTAC sync will be required in order to permit synchronization at moderate to long ranges, the deletion of synchronization on the CAS frequency appears to be cost effective for the GA CAS.

The use of frequency F_2 for synchronization purposes (figure 12) involves only minor additional sophistication of the ATA CAS units. It should be emphasized that this approach maintains the concept of a single-frequency (transmit and receive) system in the General Aviation CAS while requiring very little modification of the Full-CAS equipment.

Any Full-CAS equipment utilizing air-to-air sync below 14,000 feet would have to utilize one of the 500 F_4 slots which utilize frequency F_2 for synchronization. (Slot numbers congruent to one modulo 4.) Such ATA CAS systems would have to monitor F_2 in the last quarter of their slots for initial synchronization and during resynchronization. Similarly, any air-to-air donors would have to be able to shift their transmitters to F_2 in the last quarter of every fourth slot in order to provide synchronization capabilities. No air-to-air sync would be provided on frequency F_4 , although ground-to-air sync on F_4 would not cause problems.

F. ALTERNATIVE FREQUENCY ASSIGNMENTS

The proposed frequency management (figure 12) could be improved to simplify the design of the low-cost GA CAS receiver somewhat, by a slight

SLOT NUMBER	40	41	42	43	44
SLOT NUMBER MODULO 4	0	1	2	3	0
TRANSMISSION BY SLOT OCCUPANT BELOW 14,000 FT ALT	NOT USED	F ₄	NOT USED	F ₄	NOT USED
TRANSMISSION BY SLOT OCCUPANT ABOVE 14,000 FT ALT	F ₁	NOT USED	F ₃	NOT USED	F ₁
RECEIVING FREQUENCY GENERAL AVIATION CAS	NOT USED	F ₄	NOT USED	F ₄	NOT USED
RECEIVING FREQUENCY SOPHISTICATED CAS	F ₁	F ₄	F ₃	F ₄	F ₁
TRIAD TRANSMISSION BY AIRBORNE SYNC DONOR	F ₁	F ₂	F ₃	AIR SYNC NOT USED	F ₁
TRIAD RECEPTION BY SYNC REQUESTER	F ₁	F ₂	F ₃	AIR SYNC NOT USED	F ₁

1264-030

Figure 12. Proposed Modified Frequency Management

further departure from the ATA CAS frequency management scheme (figure 11). This is achieved by interchanging frequencies F₂ and F₃ in figure 13. This substitution of frequency F₂ in the present F₃ slots was suggested in our proposal. In that case, the frequency F₃ is never used immediately before an F₄ slot, and less adjacent channel rejection would be required of the GA CAS. While this alternative frequency assignment would appear to show greater change from the ATA's original frequency management proposal, these additional changes are quite minor and should not increase the Full-CAS cost. In fact, none of the proposed changes should cause a significant percentage increase in the cost of a Full-CAS system.

G. COARSE SYNCHRONIZATION

The GA-CAS equipment described in this report would only include the capability to receive on one frequency (F₄). There would be no necessity for receiving transmission on any of the three other frequencies (F₁, F₂, F₃), since all other synchronized aircraft in the common airspace (below 14,000 feet pressure altitude) would transmit range and altitude information on F₄.

SLOT NUMBER	40	41	42	43	44
SLOT NUMBER MODULO 4	0	1	2	3	0
TRANSMISSION BY SLOT OCCUPANT BELOW 14,000 FT ALT	NOT USED	F ₄	NOT USED	F ₄	NOT USED
TRANSMISSION BY SLOT OCCUPANT ABOVE 14,000 FT ALT	F ₁	NOT USED	F ₂	NOT USED	F ₁
RECEIVING FREQUENCY GENERAL AVIATION CAS	NOT USED	F ₄	NOT USED	F ₄	NOT USED
RECEIVING FREQUENCY SOPHISTICATED CAS	F ₁	F ₄	F ₂	F ₄	F ₁
TRIAD TRANSMISSION BY AIRBORNE SYNC DONOR	F ₁	F ₃	F ₂	AIR SYNC NOT USED	F ₁
TRIAD RECEPTION BY SYNC REQUESTER	F ₁	F ₃	F ₂	AIR SYNC NOT USED	F ₁

1264-031

Figure 13. Proposed Alternative Modified Frequency Management

Similarly, since the GA CAS will employ the VORTAC system to provide fine sync, it will not be necessary to transmit or receive on a CAS frequency to achieve synchronization. In particular, the GA CAS will not have capabilities for receiving sync replies on F₃ (or F₂) and will not receive the coarse sync triad on F₁.

Instead, coarse sync information will be transmitted from the VORTAC at 6-second intervals corresponding to the start of "ground-epoch" slot zero. Since synchronization is so fundamental to the design of CAS equipment, it seems appropriate to include some comments on the format of the reference and coarse sync pulses to be transmitted by the VORTAC station. Basic transmissions are in the form of a standard TACAN pulse pair with a constant 12 millisecond spacing.

However, once every six seconds, two successive normal pulse pairs are deleted. A replacement pulse pair, delayed precisely 6 microseconds, and a supernumerary pair, produced precisely 128.8 microseconds thereafter, replace the first deleted pair. A second double pulse pair is transmitted instead of the next successive 12 millisecond pulse pair. The first pair in

this group is also delayed 6 microseconds, while its following supernumerary pair is delayed 140.8 microseconds thereafter (see figure 14). These two double pulse pairs provide successive opportunities for coarse sync, to overcome pulse dropout due to other transmissions from the ground station.

At this moment, the reference pulses do not have priority over other transmissions. However, the normal reply efficiency of the VORTAC is sufficient to permit fast lock-on to the train of reference pulses. The 12 millisecond spacing is an octal multiple of the CAS slot width and is not likely to change significantly. However, it is conceivable that the epoch sync pulses (at 6-second intervals) might be modified in the future.

In any event, this approach (which is scheduled for installation and imminent evaluation at FAA's NAFEC facility near Atlantic City, New Jersey) should suffice to provide complete airborne clock synchronization with fairly simple interface from the airborne DME.

H. BACK-UP MODE

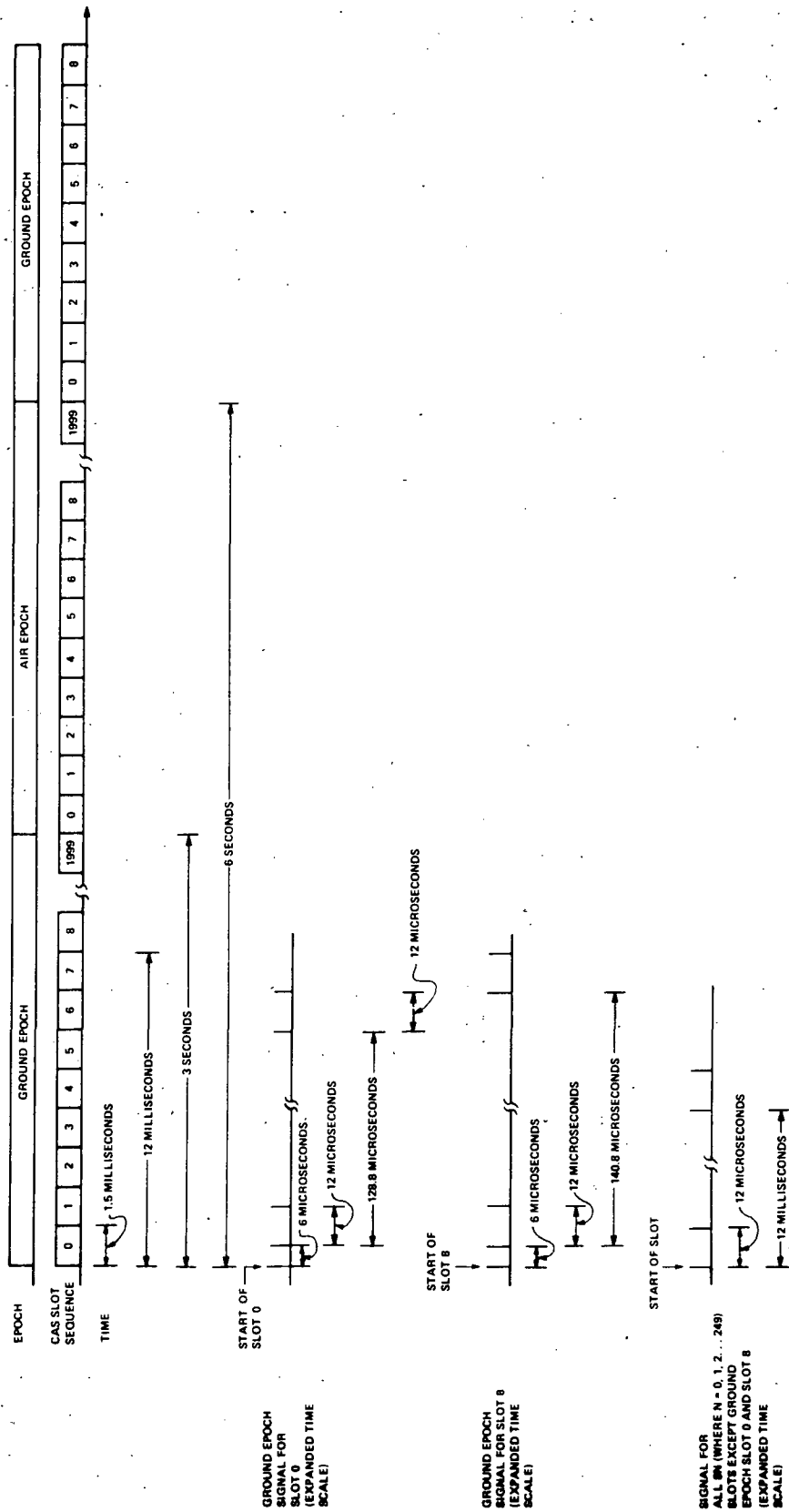
Since no signals can be transmitted or received on F_1 , the simplest GA CAS equipment can not utilize the Back-Up Mode (BUM). This eliminates some protection for GA/GA encounters in areas where no ground VORTAC sync stations are available. However, inclusion of BUM logic would add substantially to system cost and might introduce potential problems of mutual interference between this asynchronous mode and the highly organized Time/Frequency CAS. Capabilities for transmitting and receiving on F_1 (in addition to transmitting and receiving on F_4) could be provided together with BUM logic for an appropriate cost increment.

Of course, it would be possible to modify the basic system to provide (optional) BUM operation on F_4 . Alternatively, the frequency management scheme could be modified to define F_1 as the common frequency below 14,000 feet pressure altitude. Neither approach would have a major impact on system cost, and associated changes in transmitter and receiver design in the GA CAS would not be substantial.

This contractor continues to prefer the frequency management scheme detailed in figure 13.

I. RESERVED SLOTS

Specific slots have been reserved for ground station operation and for special test message transmissions in ARINC Characteristic 587. These 32 slots are defined in appendix I of the characteristic (which is revision 9 of ANTC-117). A significant expansion of these reserved slots to permit their use for ground obstacle avoidance (refer to section VIII) is provided in the



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Figure 14. VORTAC Reference Pulse Format

recent (10th) revision of ANTC-117 (and of ARINC-587). It is obviously essential to assign these ground stations to operate on the common frequency so that they may be heard by GA CAS equipment. This should not present problems.

Of course appropriate logic must be incorporated in the GA CAS to avoid selection of any "reserved slot". The logical design of the equipment, described elsewhere in this report, prevents occupancy of the reserved slots described in revision 9 of the ANTC document. It is obvious that some changes in reserved slot definition will result if the one-frequency GA CAS approach is adopted. The selected obstacle avoidance slots could then be reserved with minor changes in the reserved slot logic that are easily incorporated (refer to section VIII).

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SECTION V

RANGE THREAT PARAMETERS

A. THREAT ZONES INVOLVING GA CAS

In designing the low-cost CAS for single engine general aviation aircraft, it was convenient to utilize system parameters that are appropriate for a Cessna-172, since the 172 is one of the most popular aircraft of this type.

In accordance with present thinking of the ATA Special Working Group on Collision Avoidance, only two threat zones categories are provided. These are a mandatory maneuver zone (Tau 1 in the ATA CAS) and an alert zone (Tau 2). These zones may also be called range zones 1 and 2.

The parameters for the mandatory-maneuver zone (Tau 1 in the ATA CAS) have been selected in accordance with the discussion on threat determination. Four separate range boundaries are suggested, corresponding to:

- En-route encounters with ATA CAS-equipped aircraft,
- En-route encounters with GA CAS-equipped aircraft,
- Terminal-area encounters with ATA CAS-equipped aircraft,
- Terminal area encounters with GA CAS-equipped aircraft.

B. MANDATORY MANEUVER DECISION TIME

1. Methodology. The selection of an appropriate mandatory-maneuver range boundary for these cases has been discussed in an interim report. The maneuver range is chosen as the sum of the range uncertainty plus the product of the maximum anticipated closing velocity by the total time (including sensing, display, pilot, and aircraft delays) required to detect the dangerous situation and change altitude sufficiently to provide safe vertical separation.

The present ATA CAS logic calls for mandatory evasive maneuvers when the ratio, τ , (tau) of range to closing rate falls below a preselected level, and when the indicated altitude separation is inadequate (less than 600 feet below 10,000 feet MSL). The prescribed evasive maneuver is either a climb or a dive (depending on the relative altitude of the intruder). The climb-or-dive maneuver is supposed to be away from the intruder, and specific action is provided to force the two involved aircraft to move in opposite directions. In particular, once a climb or dive maneuver is selected, the aircraft automatically biases its altitude transmissions in the direction of the selected evasive maneuver and maintains this bias for 6 seconds after the threat disappears.

These precautions do not preclude the possibility that both aircraft may be ordered to move in the "wrong" direction. Thus there is always the chance that altimeter and telemetry errors may be sufficiently large to cause a lower aircraft to climb while a higher intruder holds altitude or dives. A worst condition occurs when the various altimeter and telemetry errors cause an aircraft to sense an intruder as precisely co-altitude, while the logic arbitrarily generates a climb command even though the other aircraft is really above.

The amount of vertical motion required in this apparent co-altitude case is just the worst-case altitude error plus a suitable increment for inter-aircraft clearance. In the subsequent discussion, we will estimate the three-sigma root-sum square altimeter and telemetry error and will then add a minimal inter-aircraft clearance estimate to indicate the desired altitude change for a safe evasion.

In selecting a range boundary for a mandatory-evasive maneuver, it is appropriate to utilize an estimate of the requisite evasion time, which is roughly equivalent to the selection of the time constant "Tau" in the ATA CAS. This total evasion time is the sum of the nominal time required to achieve the desired altitude change, at the selected climb/dive rate, and the time delay between the instant when an intruder reaches the threat boundary and the instant when own aircraft achieves the desired climb/dive rate.

This delay includes the time delay for transmission, reception, and display of the threat, the time delay for the pilot to react, and the aircraft response time delay. Since the ATA CAS equipment alternately transmits from top- and bottom-mounted antennas, (at successive three-second intervals), a full six seconds may elapse between the time that an intruder crosses the threat boundary and the time that the next range/altitude transmission is received from the intruder. We add three seconds for pilot reaction and two seconds for the aircraft to reach its desired climb/dive rate, for a total delay of 11 seconds (in addition to the nominal climb/dive time corresponding to the ratio between the desired altitude change and the climb/dive rate employed).

2. Calculating the Root Sum Squared Altitude Error.

a. Basic Calculation. The root sum squared altitude error is extracted from the combination of the altimeter errors in own and intruder's aircraft, and the truncation errors caused by encoding the altimeter output in 100-foot increments. Three separate cases will be considered, involving two different-quality altimeters that might be utilized by ATA CAS-equipped aircraft and GA CAS-equipped aircraft. A three-sigma RSS altitude error is used, since such an error will not be exceeded with a probability of 99.7%.

b. Use of Quality Encoding Altimeters. The ATA CAS threat logic is based on altimeters with a 150-foot (3σ) error below 10,000 feet MSL. If both the intruder and the GA aircraft have such a 150-foot three-sigma error, and if the altitude is telemetered in 100-foot increments (with a consequent uniformly distributed error of ± 50 feet) then the overall three-sigma altitude uncertainty (in feet) is given by:

$$3\sigma_a = 3 \sqrt{2 \left(\frac{150}{3}\right)^2 + 2 \left(\frac{100}{2\sqrt{3}}\right)^2} = 3 \sqrt{6667} = 245$$

c. Use of Reduced-Accuracy Altimeters. There may be valid reasons to believe that single-engine GA aircraft may elect to buy encoding altimeters that do not quite meet the accuracy specifications envisioned by the ATA's Technical Working Group. If this should happen, it might require some compensatory increase in the range boundaries for all encounters involving such GA CAS-equipped aircraft. While this contractor has no specific reasons for believing that GA encoding altimeters will provide reduced accuracy, it seems desirable to explore the increased altitude uncertainty that would result.

If the encounter is between a GA aircraft (with a 3-sigma altimeter error of 250 feet) and an ATA CAS-equipped aircraft with a 3-sigma altimeter error of 150 feet, and if both altimeters are digitized in 100-foot pressure-altitude increments, then the anticipated 3-sigma altitude discrepancy (in feet) is

$$3\sigma_{a_1} = 3 \sqrt{\left(\frac{150}{3}\right)^2 + \left(\frac{250}{3}\right)^2 + 2 \left(\frac{100}{2\sqrt{3}}\right)^2} = 316$$

In addition, if we should decide to use 250 feet as an assumed three-sigma altimeter error for the GA CAS instrument, then somewhat longer decision times would be required in encounters between two GA CAS aircraft. In particular,

$$3\sigma_{a_2} = 3 \sqrt{2 \left(\frac{250}{3}\right)^2 + 2 \left(\frac{100}{2\sqrt{3}}\right)^2} = 375 \text{ feet.}$$

These various calculations will be employed in the selection of appropriate threat boundaries.

3. Calculation of Total Evasion Time. As noted earlier, the range boundaries are calculated by the sum of a range margin component and the

product of the total evasion time by the maximum anticipated closing rate. The total evasion time is the sum of the nominal evasion time plus an appropriate allowance for delay in evaluating and reacting to the threat. This maximum delay has been calculated as about 11 seconds in a previous paragraph.

The nominal evasion time is just the ratio of the required altitude change to the climb/dive rate. One component of the required altitude change is just the altimeter error. The other component that must be included is the required aircraft-to-aircraft clearance. In particular, the clearance will be a function of the overall dimensions of the aircraft. Tail height of a typical single engine GA aircraft is only about 11 feet. Thus 100 feet should suffice to provide adequate clearance between two GA aircraft. However, the corresponding height of Boeing 707's and 747's is over 39 feet and 72 feet, respectively. The net result is a requirement for 30 to 60 additional feet of clearance. Thus at least 160 feet of vertical clearance is recommended in encounters between a single engine aircraft and an airliner, while 220 feet would be desirable in encounters between two large aircraft. Addition of the appropriate clearances, to the three-sigma altitude errors defined in a previous paragraph, yields the total desired altitude change for any specified encounter. When this estimate is divided by the Cessna's climb rate of 645 feet per minute (10.75 fps) this yields the nominal evasion time requirement. Inclusion of an additional 11-second allowance for delays yields the total evasion time requirements (refer to table 4). This table includes calculations based on both the assumption of using a very accurate (150 foot, 3σ) altimeter and a less accurate (250 foot, 3σ) altimeter by the GA aircraft.

While calculations for both assumptions are utilized and compared, in this report, the more pessimistic calculations have been used in the specific GA CAS system design provided here. Change to the more optimistic numbers could readily be incorporated in the GA CAS design if appropriate mandatory specifications for such encoding altimeters are adopted.

4. Effect on ATA CAS Design. More pessimistic assumptions for GA altimeter errors could have some effect on the design of the ATA CAS. Thus a change from a 150-foot (three-sigma) altimeter error to a 250-foot error, by the GA CAS-equipped intruder, would correspond to a required altitude maneuver of 416 feet rather than 345 feet (as calculated in subparagraph 2). But we also pointed out that encounters with an airliner may require 60 feet of additional height clearance (over the clearance required between a GA aircraft and an airliner). Required clearance between two airlines could require an additional 120 feet of altitude separation. Following this reasoning, the required altitude travel changes from $345 + 120 = 465$ feet for encounters between two airliners to $416 + 60 = 476$ feet for encounters between an airliner and a single engine aircraft. At a steady state climb rate of 2000 feet per

TABLE 4. MANDATORY EVASION DECISION TIMES

Encounter Type	3- Altitude Error (Ft.)	Requisite Interaircraft Clearance (Ft.)	Total Altitude Change Required (Ft.)	Total Evasion Delay at 645 fpm (Secs.)	Sensor, Pilot & Aircraft Delays (Secs.)	Total Evasion Time (Secs.)
1. Based on High-Accuracy Altimeter						
GA/GA	245	100	345	32	11	43
GA/ATA	245	160	405	38	11	49
2. Based on Lower-Accuracy GA Altimeters						
GA/GA	375	100	475	44	11	55
GA/ATA	316	160	476	44	11	55

minute, this 11-foot altitude difference requires less than one second and does not appear to introduce any need for a different decision time.

It should be emphasized that no attempt has been made to consider interaction with trailing vortices of large aircraft. Such vortices would not be encountered in head-on encounters while some additional time margin is provided to the GA CAS-equipped aircraft in the overtake situation.

C. DECISION TIMES IN THE ALERT ZONE

Turn-rates are limited in ATA CAS encounters with "co-altitude" intruders in Tau Zone 2. This prevents undue reduction of warning time while the intruder enters Tau Zone 1 and is detected. The limitation is unnecessary in the GA CAS since range/altitude logic already protects against maximum closing rates. The only requirement in the alert zone is to limit dive/climb rates. Accomplishing this requires no more time of the GA pilot than of the airliner. Thus the 15-second incremental warning used by the ATA CAS equipment should suffice for GA CAS.

The ATA CAS logic also includes a 1.8 nautical mile offset, R_0 so that the Tau 2 (Alert) boundary is given by $R = R_0 + \tau_2 \dot{R}$. The R_0 term corresponds to the incremental distance travelled by both aircraft as a result of closing acceleration after the nominal threat boundary is crossed (refer to Holt and Anderson²⁵). Since the proposed GA/CAS threat evaluation is already based on maximum anticipated closing velocities, it seems unnecessary to include such a term. The only likely exception involves ATA CAS equipped aircraft flying at higher speed, at an altitude just above 10,000 feet MSL. Such aircraft would be slowing down as they approach the 10,000-foot altitude boundary. If we provide 3 seconds of additional alert time (over the 15 seconds provided in the ATA CAS), then this yields an alert display 3 (742) feet early or some 2200 feet early, in encounters with an ATA-CAS equipped aircraft. But this 2200 feet is quite comparable to the extra distance that would be travelled by the intruder during the 33 seconds or less between the time that the "alert logic" is actuated in the GA CAS and the instant when the Tau 2 warning indication is provided by the ATA-CAS. During this interval, even a significant deceleration of 140 knots per minute (4 feet/second^2) would yield a distance change of $a t^2 / 2 = 2.0 (33)^2 \approx 2180$ feet. Thus extending the boundary 2200 feet (in addition to the 1000-foot margin provided as a compensation for range inaccuracy) is conservative in our case. Thus, the alert range boundary will be based on 18 seconds more than the mandatory maneuver decision time. (This provides three complete CAS ground and air epochs.)

D. ANTICIPATED CLOSING VELOCITIES

The mandatory evasive-maneuver range for these various encounters

can be calculated from the product of the decision time by the maximum closing velocity anticipated plus a margin of about 1000 feet to allow for synchronization/ranging errors. Thus it is essential to estimate the peak closing rate under various circumstances. In particular, peak closing rates will be estimated for the single engine GA aircraft in encounters with other GA CAS-equipped aircraft and in encounters with ATA CAS-equipped aircraft. Separate calculations will be made for the case of en-route encounters and terminal area encounters.

1. En-Route Encounters with ATA CAS-Equipped Aircraft. The anticipated maximum closing rate is the sum of the Cessna's 192 ft/sec and the maximum speed of the airliner (or other ATA CAS-equipped aircraft) in the airspace below 10,000 feet MSL. This closing velocity is not completely defined. When Sierra Research submitted its original proposal, it was noted that indicated airspeed is restricted to 250 kts below 10,000 feet MSL in Federal Aviation Regulation 91.70, except as specifically authorized by the Federal Aviation Administrator. A known exception is made for low-level, high-speed training flights by military aircraft in restricted corridors. Such flights are made at speeds up to 500 knots, on low-level "heavy wagon" routes, and at unspecified speeds for "oil burner" and "low altitude high speed VFR" routes. These speeds are substantially greater than anticipated airspeeds for normally-encountered traffic at these altitudes.

While it might be possible to design the GA CAS to provide safe evasions under such higher closing rates, it would impose substantial requirements for added airspace (at such closing rates) on the GA CAS. Thus the present report anticipates that the general aviation pilot will avoid the reserved regions of airspace. As a backup, the high-performance military aircraft should be able to maneuver (if need be) in considerably less time than is practical for the GA aircraft. Section VI verifies the capability of timely receipt of GA CAS transmissions by the fast flying military aircraft, if it is equipped with ATA CAS. The GA CAS threat evaluation is based on assumed flight; by any encountered aircraft, in reasonable compliance with the stated speeds in FAR 91.70.

In recent discussions with personnel from FAA's operational and Air Transport Office, it was noted that turbojet aircraft, flying below 10,000 feet MSL could exceed 250 knots, IAS when conformance to the 250-knot rule would require operation below the "minimum safe airspeed." Apparently this rule introduces excessive buffeting for certain aircraft (707's or 747's) when they depart the terminal in a heavily-weighted condition, e.g., for an overseas flight. This could involve flight at somewhat over 260 knots IAS. We were also informed that certain military jet aircraft may fly at airspeeds of 275 to 280 knots to permit adequate safe control.

In the following analysis of anticipated maximum intruder speeds, it has therefore been assumed that the ATA CAS-equipped intruder may be flying at indicated air speeds that range to 280 knots. This indicated airspeed may correspond to a somewhat higher true airspeed since the indicated airspeed is proportional to the square root of the ram pressure, P_r , where $P_r = .5 \rho V^2$. In this formula, ρ represents the air density, while the airspeed meter is calibrated to read correctly at sea level pressures. Thus the indicated airspeed is given by

$$V_i = \sqrt{2 P_r / \rho_o}$$

where ρ_o is the sea level density of the standard atmosphere, while the equivalent airspeed would be

$$V_e = \sqrt{2 P_r / \rho}$$

so that

$$V_e / V_i = \sqrt{\rho_o / \rho}$$

In particular, at an altitude of 10,000 feet MSL, the density of the standard atmosphere is given by

$$\rho / \rho_o = .7384.$$

Thus
$$V_e = V_i / \sqrt{.7384} = 1.163 V_i$$

An indicated airspeed of 280 knots or 472 fps corresponds to an equivalent airspeed of

$$V_e = (1.163) 472 = 550 \text{ fps.}$$

Thus if we add the Cessna's speed to the maximum assumed speed of the intruder, we obtain a maximum closing speed of $550 + 192 = 742 \text{ ft/sec.}$

2. En-Route Encounters with GA CAS-Equipped Aircraft. It is anticipated that the GA CAS will be restricted for use on slower low-flying (single engine) aircraft. In particular, we assume a maximum true airspeed of 260 ft/sec. for GA CAS-equipped aircraft. This is near the maximum speed of existing single-propeller aircraft. It results in a maximum closing speed of $260 + 192 = 452 \text{ ft/sec.}$ This closing speed will be used in selecting the parameters for encounters between two GA CAS-equipped aircraft.

3. Terminal Area Encounters with ATA CAS-Equipped Aircraft. As noted in our earlier analysis, there is need for a reduced threat boundary radius in the terminal area. Federal Air Regulation 91.70 also restricts aircraft below the lateral limits of (high density) terminal control areas to 200 knots, IAS. These areas normally encompass a radius of 5

statute miles about the airport. It would appear reasonable to assume that the ATA CAS-equipped aircraft would not fly faster than 200 knots IAS in the immediate vicinity of any terminal, and at the low altitudes where single-engine aircraft may be encountered during approach and departure operations. Furthermore, these terminal operations will generally be within 5000 feet MSL. The nominal air density at 5000 feet MSL is 0.8616 times the density at sea level. Thus it is proposed that terminal threat logic be based on maximum indicated airspeeds of $1.69 (200) \approx 338$ fps for ATA CAS-equipped aircraft.

The GA CAS would similarly reduce its own indicated airspeed to about 90 mph, corresponding to 132 fps. Thus we could design for a combined maximum closing speed of $(132 + 338) / \sqrt{0.8616} = 505$ fps. Transition to terminal area logic would require operation of a control, with automatic return to en route logic after a preselected interval.

4. Terminal Area Encounters with GA-CAS Equipped Aircraft. Other GA CAS-equipped aircraft would also tend to operate at somewhat lower speed in the terminal area. It appears desirable to utilize a maximum indicated airspeed of about 120 mph as the maximum approach and departure speeds of the single-propeller GA CAS-equipped aircraft. When added to the 90 mph assumed maximum terminal area speed for the Cessna, this yields a closing speed of

$$(210) \left(\frac{22}{15} \right) / \sqrt{0.8616} = 332 \text{ fps.}$$

Note that the maximum closing speeds that are proposed for selecting the terminal area logic do not quite yield the reduction of the alarm zone to 60% as proposed in our interim report. Such a further decrease could result in a reduced number of unnecessary evasive maneuvers, but would not provide full protection against head-on encounters.

5. Resulting Threat Boundaries. The resulting threat boundaries are summarized in tables 5 and 6 for the cases with a 150-foot 3-sigma altimeter error and 250-foot 3-sigma altimeter error, respectively.

E. ATA CAS TAU ZONES

Since the GA CAS will not transmit a "coherent" long pulse, it will be necessary for ATA CAS either to modify their threat determination procedure in encounters with GA CAS-equipped aircraft, or to utilize differencing of successive range measurements for closing rate measurements.

In the latter case, the ATA CAS threat boundaries could be utilized, although some reduction in threat boundaries might result, if range rate is extracted with improved accuracy.

TABLE 5. SUMMARY OF THREAT PARAMETERS
(BASED ON QUALITY ALTIMETERS*)

Class of Encounter	Closing Speed ft/sec.	Maneuver Decision Time secs.	Maneuver Edry. (Including 1000-ft. Margin)		Alert Decision Time secs.	Alert Edry. (Including 1000-ft Margin)	
			ft.	μsecs		ft.	μsecs
<u>En-Route Logic</u>							
a. With ATA-CAS Equipped A/C	742	49	37, 400	38. 0	67	50, 700	51. 6
b. With GA-CAS Equipped A/C	452	43	20, 400	20. 8	61	28, 600	29. 0
<u>Terminal Area Logic</u>							
c. With ATA-CAS Equipped A/C	505	49	25, 800	26. 2	67	34, 800	35. 4
d. With GA-CAS Equipped A/C	332	43	15, 300	15. 6	61	21, 200	21. 6

* 150-foot, 3-sigma Altitude Error below 10, 000 feet MSL

* 150-foot, 3-sigma Altitude Error below 10,000 feet MSL

TABLE 6. SUMMARY OF THREAT PARAMETERS
(BASED ON REDUCED ACCURACY ALTIMETERS* IN GA AIRCRAFT)

Class of Encounter	Closing Speed ft/sec.	Maneuver Decision Time secs.	Maneuver Bdry. (Including 1000-ft. Margin)		Alert Decision Time secs.	Alert Bdry. (Including 1000-ft Margin)	
			ft.	μsecs		ft.	μsecs
<u>En-Route Logic</u>							
a. With ATA-CAS Equipped A/C	742	55	41, 800	42. 6	73	55, 200	56. 2
b. With GA-CAS Equipped A/C	452	55	25, 800	26. 4	73	34, 000	34. 6
<u>Terminal Area Logic</u>							
c. With ATA-CAS Equipped A/C	505	55	28, 800	29. 2	73	37, 800	38. 4
d. With GA-CAS Equipped A/C	332	55	19, 300	19. 6	73	25, 200	25. 6
* 250-foot, 3-sigma Altimeter Error below 10, 000 feet MSL							

In the following discussion, we assume that the ATA CAS will simply use a range boundary in encounters with GA CAS-equipped aircraft (as is done by the GA CAS) in the reciprocal case. Again assuming two separate cases (one en route case and one terminal area case) we can calculate the relevant range boundaries. In particular, for these higher performance aircraft, we use the established 25- and 40-second warning times for the mandatory evasion time and the alert time respectively. If we employ the maximum anticipated en-route airspeed of 260 feet/second for the GA CAS-equipped aircraft and 550 feet/second for the ATA CAS-equipped aircraft (below 10,000 feet MSL), then the maximum en route closing speed would be $550 + 260 = 810$ feet/second. The corresponding closing speeds in the terminal area would be 338 fps and $22/15 (120) = 176$ fps indicated airspeed for a true closing speed of

$$(338 + 176) / \sqrt{0.8616} = 514 \sqrt{0.866} = 553 \text{ feet/second}$$

at a pressure-altitude of 5000 feet or less. Finally, as noted earlier, somewhat higher speeds may be anticipated above 10,000 feet. It is suggested that 50 kts = 85 feet/second of additional airspeed be assumed in this case. However, 0.5-nautical mile to 1.8-nautical mile acceleration allowance, R_0 , is again not required, since we have already allowed for worst case closing velocity in our estimates. The resulting threat boundaries are summarized in table 7.

These threat boundary estimates are of importance in the present analysis for two reasons. They provide an indication of expected threat envelopes for all interactions with GA CAS-equipped aircraft, and also indicate the required transmission range so that GA CAS signals may be heard by various categories of intruders. Thus GA CAS transmissions must be heard by other GA-CAS equipped aircraft at ranges of approximately 34,000 feet (refer to table 6). ATA CAS transmissions must be heard by GA CAS at ranges of up to 55,200 feet (refer to table 6), while GA CAS transmissions would have to be received by the ATA CAS at ranges of 36,800 feet (refer to table 7).

In this connection, one other type of encounter must be considered. This involves encounters between a military jet flying at high subsonic speeds (in the designated low altitude high speed VFR routes) and a GA CAS-equipped aircraft. As noted earlier, the military aircraft would have to provide the evasive maneuver under these VFR conditions. To do this successfully, the military craft would require a timely alert. Since this aircraft could be traveling at 95 percent of the speed of sound, a true airspeed of up to 1050 feet/second must be assumed. With a maximum GA CAS speed of 260 feet per second, this could result in closing speed of 1310 feet/second. The high performance military aircraft would have to detect the GA aircraft at a range that would be no more than the 25 seconds for the mandatory maneuver zone (or 40 seconds for the alert zone) that are specified for the ATA CAS-equipment. This requires a communication range of at least 53,400 feet for transmissions by the GA CAS and receptions by the military aircraft. This

TABLE 7. SUMMARY OF ATA CAS THREAT
PARAMETERS FOR ENCOUNTERS WITH GA CAS

Class of Logic	Closing Speed ft/sec.	Maneuver Decision Time secs.	Maneuver Bdry. (Including 1000-ft. Margin)		Alert Decision Time secs.	Alert Bdry. (Including 1000-ft. Margin)	
			ft.	μsecs		ft.	μsecs
En-route	810	25	21,300	21.8	40	33,400	34.0
Terminal Area	553	25	13,800	14.2	40	23,100	23.4
Above Terminal Area, 10,000 Feet Altitude	895	25	23,400	24.0	40	36,800	37.4
Encounters Between High Speed Low Altitude Military Aircraft and GA	1310	25	33,750	34.4	40	53,400	54.2

exceeds the 36,800-foot reception range required for reception of GA CAS transmissions by ATA CAS-equipped aircraft, operating at speeds of 280 knots or less. These numbers will be used to define the power transmission requirements for the GA CAS equipment.

F. PILOT DISPLAY

1. Two Aircraft Encounters. The GA CAS pilot display is readily adapted from the ATA CAS threat logic table. Figure 15 shows the proposed GA CAS display logic. Range Zones 1 and 2 respectively, correspond to the "mandatory maneuver zone" and the "alert zone" in the co-altitude case. If a coaltitude (± 600 feet of altitude) intruder is encountered in range zone 1, commands to Climb! Do Not Turn!, or Dive! Do Not Turn! (as appropriate) are displayed to the pilot, and an audible alarm is sounded.

As noted earlier, the range/altitude threat logic of the GA CAS does not require any modification in the threat zones based on aircraft horizontal acceleration. However, stall characteristics recommend leveling out during such climb/dive maneuvers for flight safety. Furthermore, sophisticated CAS units that can extract range rate from successive range measurements for threat evaluation would need to be protected against acceleration by either aircraft. Thus the Do Not Turn command is especially necessary in encounters with ATA CAS-equipped aircraft. However, the Do Not Turn command is also used in encounters between two GA aircraft.

In encounters with co-altitude aircraft (within ± 600 feet of own altitude), in Range Zone 2, the Do Not Turn command appears to be unnecessary

2 AIRCRAFT ENCOUNTER		
INTRUDER'S RELATIVE ALTITUDE	1300	L.C. 500
	600	
	0	1. DIVE 2. DNT 1. L.C.0
	-600	1. CLIMB 2. DNT 1. L.D.0
	-1300	L.D. 500
		RANGE ZONE 1 RANGE ZONE 2

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Figure 15. Threat Logic Table (2 Aircraft Encounter)

since the Range 2 threat zone for the GA CAS is generally beyond the Tau zone limits for the more maneuverable ATA CAS-equipped aircraft. Thus the Do Not Turn command has been deleted in this case. This leaves a command for Don't Climb with an intruder close above, and Don't Dive with an intruder close below. The pilot display has been modified to "Limit Climb (Dive) to 0 fpm" since this causes less confusion for true co-altitude encounters. In that case, either one or the other instruction is displayed, to suggest an upcoming encounter and to avoid staying strictly co-altitude during the approach. Finally, in the non-co-altitude encounters (with an intruder at a relative altitude of 600 to 1300 feet), in both Range Zones 1 and 2, the command "Limit Climb (Dive) to 500 fpm" is displayed. This alerts the pilot to a potential encounter and slows vertical approaches to the intruder according to the latter's relative altitude. It has not appeared necessary to use a command to limit climb (or dive) to 1000 fpm, since the single engine GA aircraft are not normally able to maneuver that fast.

2. Three Aircraft Encounters. As in the case of the ATA CAS the three aircraft encounter logic is patterned directly after the two aircraft logic. Three cases are considered:

Both aircraft above

Both aircraft below

One aircraft above and one aircraft below.

See figure 16, parts A, B, and C. Generally, the display is governed by the more dangerous of the two encounters. A particularly dangerous case results when both intruders are within Range Zone 1, with one intruder co-altitude above, and the other co-altitude below. The pilot display shows limit dive to 0 fpm and limit climb to 0 fpm. (The pilot maintains altitude and sweats.) Note that any simultaneous display of dive and climb limits is an indication of intruder aircraft above and below.

As in ATA CAS, commands of Limit Dive to 200 fpm and Limit Climb to 200 fpm are incorporated when one of the intruder aircraft is co-altitude ± 600 feet but in Range Zone 2, and neither intruder is co-altitude in Range Zone 1. As in the two aircraft encounters, "Do Not Turn" is commanded whenever an intruder is within ± 600 feet of altitude and in Range Zone 1. This display logic has been utilized in the system design described in Part Two of this report.

3. Application to ATA CAS. It appears that the ATA CAS should be able to use an unchanged pilot display in their encounters with GA CAS equipped aircraft, after replacing Tau 1 and Tau 2 violations with the appropriate range violations.

3 AIRCRAFT ENCOUNTER		
RANGE ZONE 1 OR 2 REL. ALT. 600 TO 1300 FT	1. DIVE 2. DNT	1. L.C. 200 1. L.C. 500
RANGE ZONE 2 REL. ALT. 0 TO 600 FT	1. DIVE 2. DNT	1. L.C. 200 1. L.C. 200
RANGE ZONE 1 REL. ALT. 0 TO 600 FT	1. DIVE 2. DNT	1. DIVE 2. DNT
A. BOTH INTRUDERS ABOVE		
1ST INTRUDER ABOVE 2ND INTRUDER ABOVE	RANGE ZONE 1 REL. ALT. 0 TO 600 FT	RANGE ZONE 2 REL. ALT. 0 TO 600 FT
	RANGE ZONE 1 OR 2 REL. ALT. 600 TO 1300 FT	
3 AIRCRAFT ENCOUNTERS		
RANGE ZONE 1 OR 2 REL. ALT. 600 TO 1300 FT	1. CLIMB 2. DNT	1. L.D. 200 1. L.D. 500
RANGE ZONE 2 REL. ALT. 0 TO 600 FT	1. CLIMB 2. DNT	1. L.D. 200 1. L.D. 200
RANGE ZONE 1 REL. ALT. 0 TO 600 FT	1. CLIMB 2. DNT	1. CLIMB 2. DNT
B. BOTH INTRUDERS BELOW		
1ST INTRUDER BELOW 2ND INTRUDER BELOW	RANGE ZONE 1 REL. ALT. 0 TO 600 FT	RANGE ZONE 2 REL. ALT. 0 TO 600 FT
	RANGE ZONE 1 OR 2 REL. ALT. 600 TO 1300 FT	
3 AIRCRAFT ENCOUNTER		
RANGE ZONE 1 OR 2 REL. ALT. 600 TO 1300 FT	1. DIVE 2. DNT 3. L.D. 500	1. L.C. 200 2. L.D. 500 1. L.C. 500 2. L.D. 500
RANGE ZONE 2 REL. ALT. 0 TO 600 FT	1. DIVE 2. DNT 3. L.D. 200	1. L.C. 200 2. L.D. 200 1. L.C. 500 2. L.D. 200
RANGE ZONE 1 REL. ALT. 0 TO 600 FT	1. D.N.T. 2. L.C. 0 3. L.D. 0	1. CLIMB 2. DNT 3. L.C. 200 1. CLIMB 2. DNT 3. L.C. 500
C. ONE INTRUDER ABOVE, ONE BELOW		
1ST INTRUDER BELOW 2ND INTRUDER ABOVE	RANGE ZONE 1 REL. ALT. 0 TO 600 FT	RANGE ZONE 2 REL. ALT. 0 TO 600 FT
	RANGE ZONE 1 OR 2 REL. ALT. 600 TO 1300 FT	

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Figure 16. Threat Logic Table (3 Aircraft Encounter)

SECTION VI

R-F POWER CALCULATIONS

A. POWER REQUIREMENTS

The proposed system must provide adequate communication range for evaluating CAS threats in the following types of encounter:

1. Encounter Between Two GA CAS Equipped Aircraft. An examination of tables 5 and 6 indicates that the maximum hazard range involved in a GA-to-GA encounter is 34,000 feet or 5.6 nautical miles. The output power and sensitivity of the GA equipment must be compatible with this range.
2. GA-CAS Protected Aircraft With ATA CAS Equipped Intruder. Table 6 indicates that the GA CAS must receive signals from the ATA CAS equipped aircraft at a range of up to 55,200 feet. The GA receiver sensitivity must be adequate to meet this requirement.
3. High-Speed ATA-CAS Protected Aircraft With GA-CAS Equipped Intruder. Table 7 indicates that the ATA CAS must receive the signal from the GA CAS at 53,400 feet. The power output of the GA CAS must be sufficient to meet this requirement.

The GA CAS power requirement has been calculated for the first case of a GA CAS encounter with another GA CAS equipped aircraft. This power requirement is based on the use of an inexpensive receiver and associated r-f system design (refer to subsection B). In addition, signal strength computations have been prepared for encounters with ATA CAS equipped aircraft to verify the adequacy of the GA CAS receiver sensitivity and power output in these cases also (refer to subsections D and E). Similar calculations have also been performed for ATA CAS "limited" (Level 1) equipment. It appears that power transmission levels and receiver sensitivity will suffice in these cases also (refer to subsections F and G).

B. GA-TO-GA ENCOUNTER

The proposed system must provide a CAS hazard evaluation for GA-to-GA encounters at ranges of no more than 5.6 nautical miles. A power budget calculation, detailed in table 8, indicates that a transmitter capable of generating 56 watts or more peak power is adequate. The output power of the transmitter selected and detailed in another section of this final report will be a minimum of 75 watts (48.8 dbm) at "end of life" conditions. This relatively low power requirement is a significant factor in achieving a low-cost system.

**TABLE 8. CAS POWER REQUIREMENT CALCULATION
(GA/GA ENCOUNTERS)**

P	=	Transmitter power requirement		
		$\frac{(4\pi)^2 (K)^2 (M)^2 k \text{ TN (BWIF) } R^2 \text{ (SNIF) L F}}{GT \text{ GR } \lambda^2}$		
where:			<u>db</u>	<u>db</u>
$(4\pi)^2$	=	constant expressed in db above unity (20 log 4π)	+22.0	
K^2	=	nautical miles to meters conversion in db above unity (20 log 1852)	+65.4	
M^2	=	wavelength conversion, cm to meters (20 log 100)	+40.0	
k	=	1.38×10^{-23} joules/degree Kelvin (10 log k)		-228.6
TN	=	system input noise temperature = 14500° K (refer to discussion in text)	41.6	
BWIF	=	3 db I-F bandwidth in db above one cycle I-F bandwidth = 2 MHz (10 log BWIF)	+63.0	
R^2	=	system operating range in db above one nmi R max = 5.6 nmi (20 log R max)	+15.0	
SNIF	=	IF signal-to-noise per ATA Spec IF S/N = 15 db (SNIF)	+15.0	
L	=	transmit loss (2 db cable + 1.5 r-f switch, etc.)	+ 3.5	
GT	=	antenna gain on transmit expressed in db above unity, 2 db (-GT db)		- 2
GR	=	antenna gain on receive expressed in db above unit, 2 db (-GR db)		- 2
λ^2	=	wavelength in cm. for 1615 MHz (-20 log λ cm.)		- 25.4
F	=	fade margin 10 db	+10.0	
			275.5	-258.0
				= 17.5 dbw
so that P = 56 watts transmitter power				

The calculations were performed using a 15-db signal-to-noise ratio and a fade margin of 10 db. A 15-db noise figure for the receive system was assumed in order to permit use of a relatively inexpensive receiver. Typical diode mixers with transistorized i-f amplifiers yield noise figures of 8 db or less, allowing 7 db for moderately priced r-f switching, limiting, and preselection components.

In addition to a 2-db cable loss in the transmit system, the power budget calculation includes a 1.5-db transmitter r-f system loss. This margin should be adequate to provide for the duplexer and r-f antenna switch losses for those installations where two antennas are required. Thus, the power output requirement at the output connector is 1.5 db less than 56 watts, or 40 watts.

Following the discussion in the ATA CAS document, we have estimated the noise temperature from the formula:

$$TN = T_a + (T_f) (LR-1) + T_o (LR) (NF-1)$$

where

T_a = antenna temperature = 300°K

T_f = thermal temperature receiving transmission line = 290°K

LR = receive cable loss = 2.0 db

T_o = 290°K

NF = receiver noise factor = 15 db
8 db IF, 7 db r-f switching, etc.

$$TN = 300 + 290 (1.58 - 1) + 290 (1.58) (31.6-1) = 14500^\circ K$$

Since the three temperatures T_a , T_f , and T_o are almost equal in the present application, this formula for TN can be replaced by the simpler formula:

$$TN = T_o (LR) NF$$

with a maximum error of less than 0.01 db.

C. RECEIVER SENSITIVITY

It is appropriate to calculate the sensitivity of the GA CAS receiving system. As defined in the ATA CAS specification, this refers to the minimum power level at the receiver input that provides a 15 db signal-to-noise level.

It is appropriate to calculate the minimum power level at the receiver input that provides a 15 db signal-to-noise level (as also provided in the ATA-CAS specification).

The minimum signal $P_{\min}$ required at the CAS receiver (in order to provide 15 db IF signal-to-noise ratio) can be calculated from

$$P_{\min} = k \text{ TN (BWIF) (SNIF)/LR}$$

where the various terms on the right side of the equation have the same definition as in table 8. In that table, the noise temperature TN, included the overall losses from the antenna output and also included the noise figure of the receiver. Thus division by LR is required so that the cable loss in going from the antenna output to the receiver input is not included twice. The calculations in table 9 indicate a requirement for an input power level of -81 dbm.

TABLE 9. MINIMUM SIGNAL LEVEL CALCULATION

	<u>db</u>	<u>dbw</u>
k		-228.6
TN	= 41.6	
BWIF	= 63.0	
SNIF	= 15.0	
1/LR		- 2.0
$P_{\min}$	=119.6	-230.6 = -111.0 dbw
		= - 81.0 dbm

D. PROTECTED GA CAS ENCOUNTER WITH ATA CAS INTRUDER

As noted previously, table 6 indicates that the GA CAS must receive an ATA CAS at 55,200 feet. It is convenient to call

$$PL = (4\pi)^2 K^2 M^2 R^2 / \lambda^2$$

the path loss and either use direct calculation or a nomogram to calculate this path loss for any range, R, and wavelength, λ . The signal received at the GA CAS can be calculated using the following parameters specified for the ATA CAS in the ANTC-117 document.

P_o = Power output = 62 ± 3 dbm

L_c = Cable loss = 4 ± 2 db

A_G = Antenna gain = 2 db

The signal path is as assumed in figure 17. The minimum specified power output and maximum cable loss will be assumed in the calculations presented in table 10.

TABLE 10. CALCULATION OF SIGNAL RECEIVED AT GA CAS

		<u>db</u>
P_o	59 dbm	
L_c		- 6.0
A_G	+2 db	
Path Loss, 55,200 ft. (from nomograph)		-121.2
Fade		- 10.0
G_R	+2 db	
LR		- 2.0
	<u>63 dbm</u>	<u>-139.2 db</u>
Received signal = +63 dbm -139.2 db = -76.2 dbm		

This signal is greater than the -81 dbm sensitivity of the GA CAS.

E. ATA CAS PROTECTED AIRCRAFT IN ENCOUNTERS WITH GA CAS INTRUDER

As noted in table 7, an ATA CAS may have to receive the signal from a GA CAS at ranges of up to 53,400 feet. This case involves military aircraft flying subsonically at speeds near Mach 1. The signal path and power levels are shown in figure 18. Calculation of the signal strength at the input to the ATA CAS receiver is summarized in table 11.

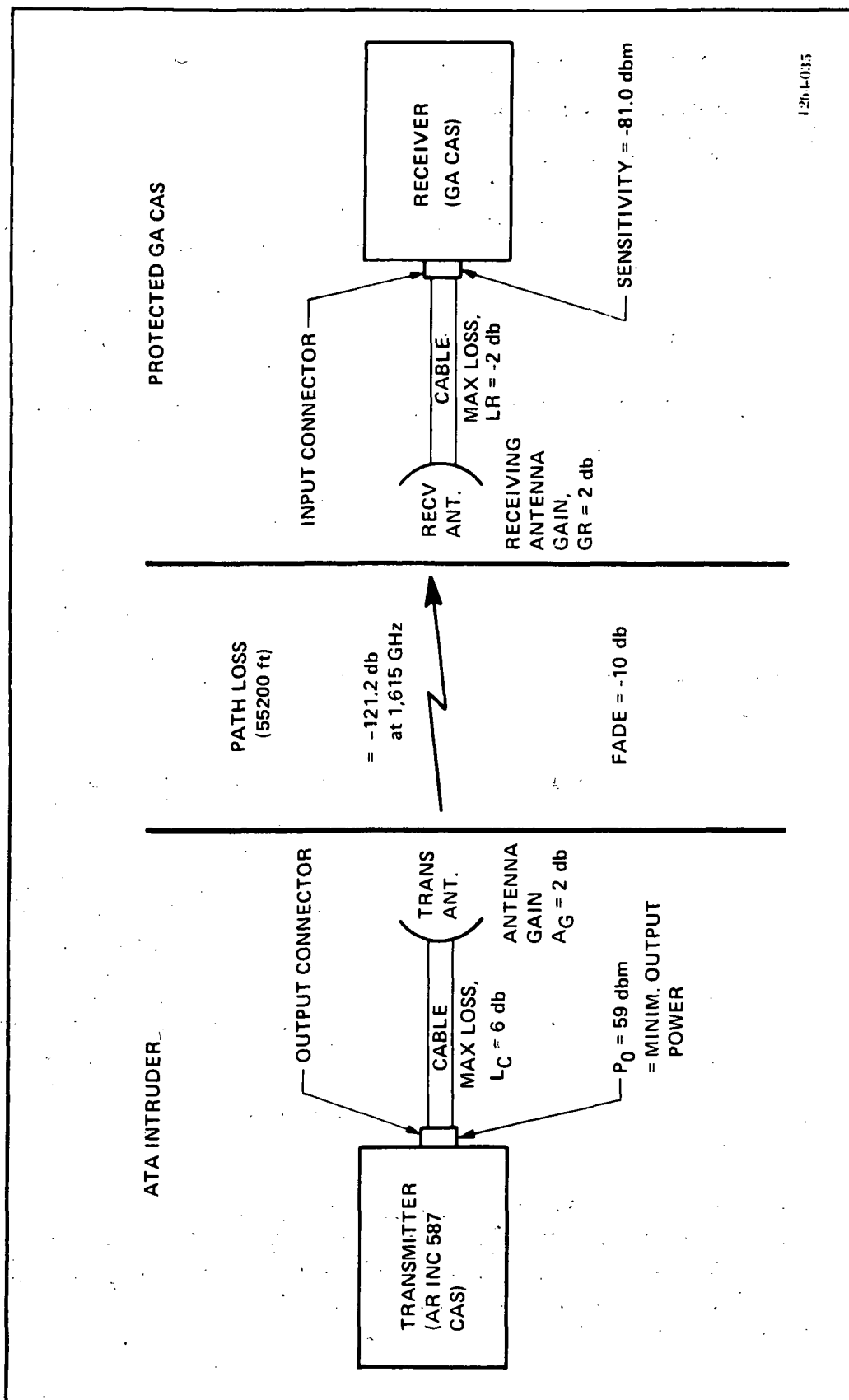


Figure 17. Signal Path and Power Levels, GA/ATA CAS Encounters

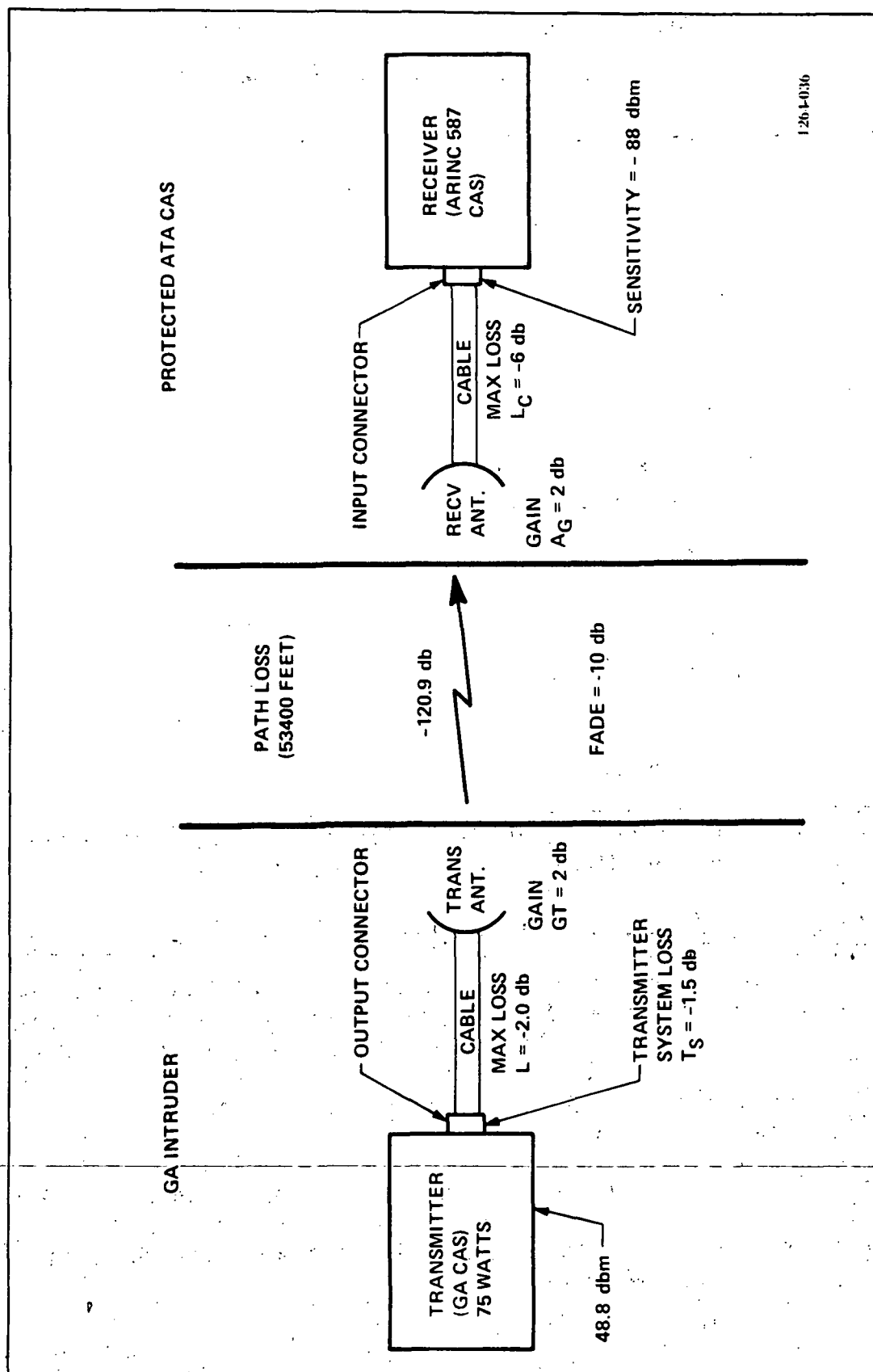


Figure 18. Signal Path and Power Levels, ATA/GA CAS Encounters

**TABLE 12. SIGNAL STRENGTH RECEIVED BY GA CAS
FROM LIMITED ATA EQUIPMENT**

P_O = Power Output = 56 $\pm$ 3 dbm

L_c = Cable loss = 2 db

A_G = Antenna gain = 2 db

The minimum power output will be assumed.
Calculation of signal received at GA CAS:

P_O = 53 dbm

L_c = - 2 db

A_G = 2 db

Path loss, 55, 200 ft. -121.2 db

Fade - 10 db

GR = + 2 db

LR = - 2 db

57 dbm -135.2 db

Received signal is +57 dbm -135.2 db = -78.2 dbm
This signal is greater than the -81 dbm sensitivity
of the GA CAS.

G. LIMITED LEVEL 1 ATA CAS ENCOUNTER WITH GA CAS

Table 7 indicates that an ATA CAS LIM Level 1 must receive the signal from a GA CAS at 53,400 feet. This case involves an aircraft equipped with limited CAS equipment and flying at 600 knots just above 10,000 feet altitude. The signal receiver from the GA CAS is calculated in table 13.

H. DYNAMIC SIGNAL STRENGTH CALCULATIONS

The GA CAS receiver is required to operate over a dynamic range, from a minimum input signal level of -81 dbm to a maximum input signal level of -14.5 dbm. These are power levels into the input connector on the CAS receiver.

Maximum signal levels at the receiver input are calculated in table 14. In this calculation, only the differential terms are presented, and the maximum

signal level is calculated as the sum of the minimum power level in dbw, and the various power and gain level changes.

TABLE 13. SIGNAL STRENGTH RECEIVED BY
LIMITED ATA EQUIPMENT FROM GA CAS

		<u>-db</u>
P_T	+48.8 dbm	
L		- 2.0
T_S		- 1.5
G_R	+ 2.0 db	
Path loss 53,400		-120.9
Fade		- 10.0
A_G	2.0 db	
L_C	<u> </u>	<u>- 2.0</u>
	52.8 dbm	-136.4 db
The received signal of 52.8 dbm -136.4 db = -83.6 dbm is consistent with the specified -84 dbm sensitivity of the Lim CAS equipment.		

TABLE 14. MAXIMUM SIGNAL LEVEL CALCULATION

Range decrease, 5.6 nmi to 0.1 nmi	35 db	
Power increase, 56 watts to +35 dbw	35 dbw	-17.5 dbw
Differential antenna gain	4 db	
Elimination of fade margin	<u>10 db</u>	
	84 dbw - 17.5 dbw =	66.5 db

Thus the maximum received signal level will be -81.0 dbm + 66.5 db = -14.5 dbm.

SECTION VII

THREAT DETERMINATION AND RESULTANT EVASIVE MANEUVERS

A. SUMMARY

This section compares safe threat-boundaries for a range/altitude General Aviation Collision Avoidance System with the corresponding boundaries for a tau/altitude General Aviation Collision Avoidance System, in encounters between General Aviation (GA) and airliner aircraft flying at maximum cruising speeds. The required expansion of threat boundaries to account for anticipated inaccuracies in the range and doppler velocity measurements are indicated. It is explained that the protected region that can be safely utilized in a range/altitude Collision Avoidance System (CAS) is not substantially larger than the corresponding protected region for a tau/altitude CAS in this case.

Recognition of shorter pulse-width transmissions from the GA CAS permits guarding a smaller range circle in encounters between two GA CAS aircraft, equipped with the proposed system.

In addition, a pilot-operated "instantaneous-on" switch permits further reduction of the range circle for short intervals when the aircraft is flying at low speed in the terminal area.

Other possibilities for reduction of required airspace are indicated, for instance, extracting closing rate from the GA CAS transmissions (without the use of doppler). One approach involves telemetry of airspeed and heading while a second approach involves digital processing of closing rate from successive range differences. The digital closing rate measurements should be of comparable accuracy to what can be achieved with present pulse-doppler CAS equipment but the digital equipment would probably be cheaper to build. Adoption of such digital processing by ATA-CAS equipped aircraft would permit their use of smaller protected regions in encounters with GA-CAS equipped aircraft (who do not guaranty the spectral purity of their short pulse transmissions). Telemetry has potentially lower accuracy (unless complex processing is employed) and requires considerable interfacing. Further investigation of such approaches is beyond the scope of the present contract, but may be of interest for users who need more sophisticated equipment to fly in high-density airspace.

B. EQUIPMENT SIMPLIFICATION

In designing a Collision Avoidance System (CAS) for general aviation (GA) aircraft, it is essential to keep the "threat" evaluation techniques and associated hardware design as simple as possible. However, it is also essential to minimize the number of resultant evasive maneuver commands that may be

provided to the pilot. This is required to limit the interaction between the collision avoidance system and the existing ground-based air traffic control system. In proposing a collision avoidance system design study to NASA, Sierra Research elected to eliminate dependence on doppler measurement of range rate as an essential criterion of the "threat" determination, in encounters involving the smaller GA aircraft.

In addition to eliminating the doppler measurement by the general aviation CAS equipment, it was also decided to eliminate the hardware complexity associated with transmission of coherent RF signals. This results in hardware simplifications in the GA CAS through deletion of requirements for careful preservation and monitoring of transmitted signal phase-coherency. Much simpler transmitter design suffices for generation of the shorter pulse durations used for ranging. Without this simplification, potentially expensive procedures would have to be used for testing and manually adjusting the individual transmitters. Elimination of requirements for transmitter coherency also deletes any requirement for precisely monitoring the transmitter frequency, including use of an on-board discriminator. By contrast, use of coherent transmission would require elaborate monitoring provisions in order to ensure that any transmitted long pulse signals were adequate to permit their safe use in "threat" evaluation by aircraft equipped with ATA's full CAS system or with an ATA limited CAS system, (level 1 or 2).

C. IGNORING CLOSING RATE

The ATA CAS system utilizes range and range rate (as well as relative altitude) for threat determination. At high closing rates where range rate can be extracted quite accurately, it is possible to reduce the number of unnecessary maneuvers by providing good discrimination between near-approaches and true collision threats. One-way doppler measurements, performed in Baltimore exhibited one-sigma errors of 47 knots or 80 ft. per second.²⁶ This is not very accurate for low-speed aircraft. Even larger doppler errors could be anticipated in low-cost CAS equipment. Thus, deletion of doppler range rate measurement introduces only a limited number of extra unnecessary maneuvers for low-speed GA aircraft. Nevertheless, it is probable that an aircraft equipped with the proposed limited GA CAS will display alarms and will maneuver somewhat more often than a similar aircraft equipped with a full CAS system.

An ATA-CAS equipped aircraft encountering the GA-CAS equipped aircraft may also maneuver more often. This follows since deletion of requirements for transmitting (and monitoring) long, phase-coherent RF pulses prevents safe extraction of one-way doppler velocity information from the GA CAS transmissions. Of course, the ATA CAS could be modified to extract closing rate from successive range measurements, and thereby avoid some unnecessary maneuvers. This would require some changes in CAS equipment design.

D. AIRSPACE REQUIREMENTS

1. Maximum Protected Region (Tau System). Analyses of the maximum protected area* corresponding to the Tau threat logic may be derived in various ways. Sierra Research has previously employed a non-accelerating model to predict the area where Tau warnings may result.²⁷ For the particular case of a 25-second Tau warning, with own aircraft and co-altitude intruder aircraft speeds of V_1 and V_2 respectively, the intruder has to be located on a circle of radius $25V_2$ centered $25V_1$ feet ahead of own aircraft in order for a true collision to impend in precisely 25 seconds.

A circular protected region about own aircraft can be defined for each set of intruders approaching on a given heading and at a given speed, V_2 (see figure 19). For this case, only the aircraft that is heading directly toward a point $25V_1$ ahead of own aircraft, and which is precisely $25V_2$ feet away is on a true collision course. Appropriate circular protected regions can be defined for each approach heading, and the envelope of these circles is a cardioid²⁶ in the equal speed case ($V_1 = V_2$). In the more general case where $V_2 \neq V_1$, a limaçon of the form: $R = \tau (V_1 \cos B + V_2)$ results (refer to figure 20). When coupled with a proximity warning circle of radius 0.5 nmi, this yields the maximum protected region for the ATA CAS system. However, it is possible to penetrate the Tau cardioid (or Tau limaçon) on certain headings without forcing a Tau alarm.

2. Expanding Protected Region (Tau System). The foregoing discussion was based on the hidden assumption that range and range rate to the intruder are exactly known. However, actual measurements exhibit significant errors.²⁶ If full collision protection is to be provided, it is essential to generate timely evasive maneuvers, even when measurement errors indicate an unrealistically large separation or an inadequate closing rate. Use of uncorrected range and range rate would result in reduced time for performing the evasive maneuver, with a 50% probability. Therefore it is desirable to insert a correction factor into the Tau computation in order to compensate for the component measurement errors.

The estimate of time to closest approach (τ) is obtained from measurement of R (by means of one-way ranging) and from measurement of $\dot{R}$ (by means of one-way pulse doppler). τ is then estimated from: $\tau_e = -R_m/\dot{R}_m$, where τ_e is the estimated time to closest approach while R_m and $\dot{R}_m$ are respectively the one-way range and the doppler velocity measurements.

It is important to calculate the error in the estimate for τ , based on the measurement errors in estimating R and $\dot{R}$. This is easily accomplished. Thus we may write:

*Throughout this section, the warning areas that are discussed and compared correspond to range zone 1 or Tau zone 1, which are the mandatory maneuver zones for the co-altitude case.

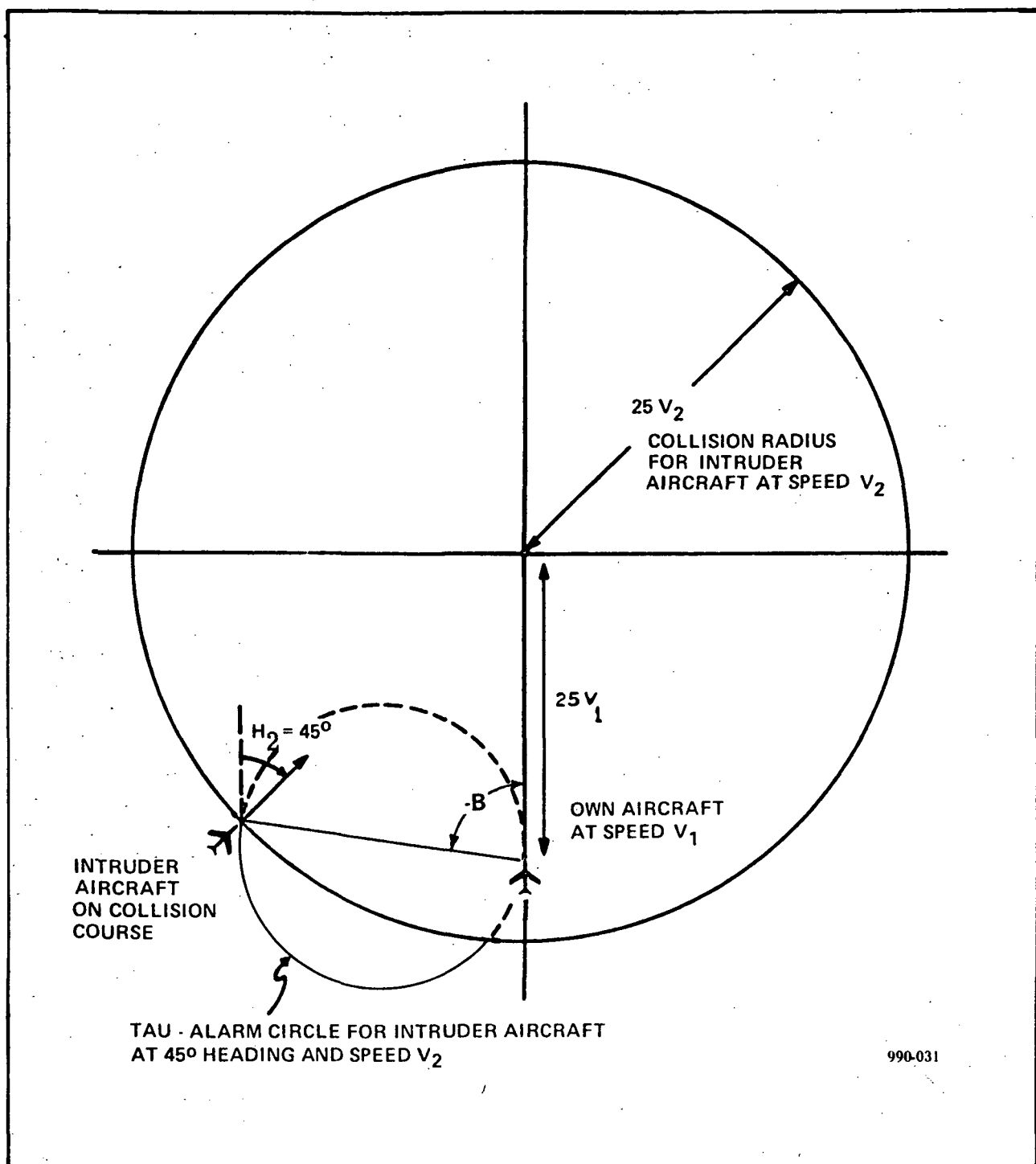


Figure 19. 25-Second Tau-alarm Circle and Collision Circle

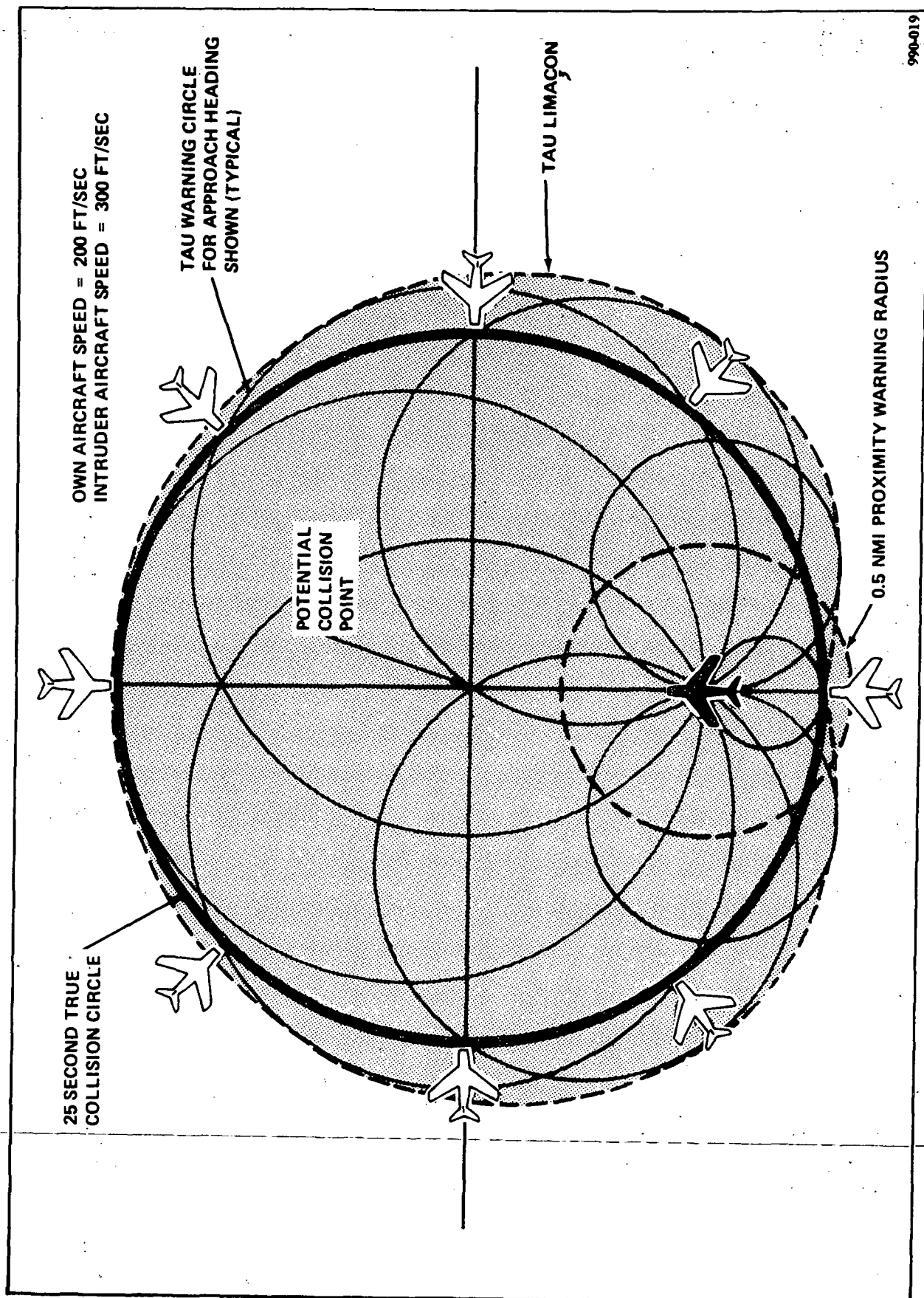


Figure 20. Protected Region -- Unequal Speed Case

$$R_m = R + \Delta R \text{ and } \dot{R}_m = \dot{R} + \Delta V$$

whence $\Delta\tau = \tau_e - \tau$ can be estimated as $\Delta\tau = -R_m/\dot{R}_m + R/\dot{R}$

or

$$\Delta\tau = (-R\dot{R}_m + R_m\dot{R})/\dot{R}_m\dot{R} = (-R\Delta R + R\Delta V)/\dot{R}_m\dot{R}$$

In particular, at the instant when a tau-alarm is defined,

$$\tau = -R_m/\dot{R}_m, \text{ and also } -R/\dot{R} \approx \tau \text{ so that}$$

$$\Delta\tau \approx (-\Delta R - \tau\Delta V)/\dot{R}_m.$$

This calculation emphasizes the strong increase in timing error that results with fixed range and range rate errors at low closing rates, $\dot{R}_m$. Looked at from a statistical point of view (and assuming Gaussian distributions of errors),

$$\sigma_{\Delta\tau} \approx (\sqrt{\sigma^2\Delta V + \tau^2\sigma^2\Delta R})/\dot{R}_m.$$

This indicates that the one-sigma increase in timing error exceeds the larger of $\sigma_{\Delta R}/|\dot{R}_m|$ and $\tau\sigma_{\Delta V}/|\dot{R}_m|$. Furthermore, if either term is substantially greater than the other, the square root of the sum of the squares closely approximates the absolute value of the larger term. It is noted elsewhere in this document that the one-sigma error in extracting range is typically 200 to 500 feet, while the one-sigma error in extracting doppler is approximately 80 ft. per sec. Even with a minimal $\tau = 25$ second warning time, $\tau\sigma_{\Delta V} = 2000 \geq 500 \sigma_R$. Thus

$$\sigma_{\Delta\tau} \approx \tau\sigma_V/|\dot{R}_m|.$$

Actually, the present Tau CAS logic provides a maneuver command if the measured range to the intruder is less than 0.5 nautical miles or if

$$R_m \leq 25 \dot{R}_m + .25(6076) = 25 \dot{R}_m + 1519.$$

This includes a nominal range variation of 1519 feet, which would correspond to a doppler variation of $1519/25 = 61$ ft/sec. It would appear that this system is somewhat under-designed, in view of the rather larger doppler errors predicted by McDonnell Douglas²⁸ and measured by Martin Marietta.²⁶

The present ATA CAS also utilizes a minimum protected range circle of about 0.5 nmi. For very low closing rates, it is this minimum range

(and not the tau calculation) which generates an evasive-maneuver command. In particular, if $R = 0.5 \text{ nmi} = 3038 \text{ feet}$ and $\tau = 25 \text{ seconds}$, the smallest true closing rate that should generate a tau alarm is given by $-\dot{R} = R/\tau = 3038/25 = 122 \text{ fps}$. For such a low-closing rate, the one-sigma timing error is given by:

$$\sigma_{\Delta\tau} = \tau\sigma_v/|R| \approx 25(80)/122 = 16.4 \text{ secs.}$$

Some of this variation is eliminated by the 0.25 nmi offset in the Tau calculation.

If a one-sigma (80 ft/sec) doppler error reduces the measured closing rate from a true 141 ft/sec to an apparent 61 ft/sec, then the threat would be detected at a range of 3038 ft (0.5 nmi). At that instant, the intruder could be $3038/141 = 21.5$ seconds from a collision. With a 2 sigma doppler error at a true closing rate of 221 fps, again yielding a measured closing rate of 61 ft. per sec, the remaining time to closest approach or to collision would be $3038/221 = 13.8$ seconds since the threat would be detected at $R_0 = 0.5 \text{ nmi}$. This 11.2 second warning delay is a very substantial fraction of the nominal 25-second warning time that is supposed to be available for generating an evasive maneuver.

It should be noted that in paragraph B-3c of the pessimistic first draft of the ATA CAS Specifications, dated June 30, 1967, a minimum protected range of 1.5 nmi was provided, and an additional 0.5 nmi was added to the range estimate for all but the 3 highest-hierarchy units. The resulting minimum closing rates that generate a pure tau-alarm may be calculated (with this logic) for the 25 second evasive-maneuver time, yielding:

$$\dot{R}_{\min} = -R/\tau = -9120/25 = -365 \text{ ft/sec. for a 1.5 nmi circle}$$

and

$$\dot{R}_{\min} = -R/\tau = -12160/25 = -486 \text{ ft/sec. for the 2 nmi circle.}$$

In the latter case, the minimum closing velocity that could generate a tau alarm exceeded the maximum closing speed that might be expected between two typical single engine general-aviation aircraft. Based on this threat-logic, the ATA's Tau CAS system effectively corresponded to a range/altitude CAS at the lower closing rates. In particular, this would have been true for any velocities that might be anticipated in encounters between two single engine GA aircraft.

As noted earlier, the present ATA specification is equivalent to a pure 25 second Tau threat evaluation with a 0.25 nmi allowance effectively corresponding to a 61 ft/sec. doppler velocity error. In view of the known inaccuracy of the doppler measurement, it is essential to utilize a somewhat larger allowance. The range offset allowance should correspond to increasing

the measured closing rate by more than the equivalent of 61 ft/sec. A 98% probability of having at least the nominal evasion time available can be assumed by utilizing the measured closing rate plus twice the one-sigma velocity error in determining tau violations. Having assumed that such an allowance would be included in an eventual safely-designed Tau CAS, the calculations of protected region have been performed on the basis of a "two-sigma" expansion of the tau protection. This has been done on the assumption that full collision protection is desired (with very high confidence).

The present Tau CAS utilizes closing rate + 61 fps (or closing rate + $.76\sigma V$) which will not be exceeded 78% of the time, since this is the integral of the Gaussian (normal) probability density function form $-\infty$ to $61\sigma/80$. It might be argued that use of 1.5 sigma to generate 93% confidence, or even use of one sigma to yield 84% confidence, would give "enough" protection. Alternatively, it might be argued that at least a 3-sigma allowance should be utilized to assure "enough" protection. Calculations of protected regions could be made under each of these assumptions, but such alternative calculations have not been included in this study.

3. Protected Region, Range/Altitude System (Maximum Speed Encounters). The maximum protected region for the range/altitude CAS is easier to define (refer to section V). If own maximum airspeed is V_{1m} , and if intruder's maximum airspeed is V_{2m} , then we can define a protected region:

$$R = \tau (V_{1m} + V_{2m}),$$

and provide a warning (evasive command) whenever a coaltitude aircraft approaches within a radius R of own aircraft. The proposed GA CAS equipment is being designed for use below 10,000 feet MSL. In this region, the intruder's airspeed is generally supposed to remain below 250 knots IAS (less than 291 knots = 492 ft/sec true airspeed), in accordance with Federal Air Regulation 91.70. However, some aircraft may fly at 280 knots IAS or 550 ft/sec TAS (as explained in section V). It is therefore appropriate to define $R = T (V_{1m} + 550)$. Complete protection would not be provided against exceptional flights by higher speed aircraft at these lower altitudes (e.g., military oil burner routes). As at present, protection against collision danger could be provided by warning the single engine general aviation pilot not to fly through such reserved regions of airspace, and by requiring CAS-equipped military aircraft to detect any GA intruders and provide timely avoidance maneuvers.

Considering a Cessna 172, the maximum recommended airspeed is 131 mph or 192 ft/second. Thus a value of $V_{1m} = 192$ ft/sec may be used in calculating the protected radius.

4. Expanded Protection Zone (Range/Altitude System). For maximum safety, it would be desirable to increase the protected region slightly. In this case, the added protection can be provided by increasing the protected radius by 2 to 3 times the $1-\sigma$ range error. A 1000 to 1500-foot increase in the protected radius would appear to be conservative, and should be employed in the range/altitude GA CAS. For comparison purposes, it is appropriate to use $T = 25$ seconds for both the Tau CAS and the range CAS design. Thus we could choose $R = 25 (550 + 192) = 18550$ ft. or approximately 2.8 nautical miles as the protected radius for an "ideal" range-CAS system, and increase this radius to 19550 feet, or about 3.2 nautical miles, after adding a 1000-foot allowance for the range error.

5. Comparison of Protected Regions. A comparison of the protected regions for the various cases is presented in figure 21A for the parameter values noted earlier. This comparison is based on flight by a Cessna 172 (at maximum recommended airspeed) in encounters with aircraft flying at maximum anticipated airspeed for encounters below 10,000 feet MSL. It will be seen that in the "ideal" case, the 25-second tau-limacon is significantly smaller than the corresponding range circle. However, when a 4000 foot allowance is made in the threat logic for the anticipated two-sigma doppler velocity error (160 ft/sec), in the case of the Tau CAS, and 1000 ft allowance is provided for the two-sigma range error in the case of the GA CAS, then the improvement due to use of range rate largely disappears. In fact in the expanded tau-limacon, the tau boundary directly in front of aircraft number 1 extends beyond the boundary of the expanded protected range circle corresponding to the GA CAS. However, directly behind aircraft 1, the protected (limaçon) boundary remains well inside the boundary of the protected range circle.

6. Increase in Safe Evasion Times for Low-Performance Aircraft. The previous estimates of protected-areas have employed a 25-second warning-time in comparing the tau logic with the range/altitude logic.

This 25-second warning-time (or any other fixed warning-time estimate) is completely adequate for comparing the protected areas for the two alternative threat-logic determining techniques. However, to obtain a true estimate of the actual sizes of the respective protected areas, it will be necessary to use more realistic estimates of the warning time requirements of the protected aircraft.

The 25-second warning time has been used in the ATA's Tau-CAS design, since their design was based on providing collision protection to fairly high performance aircraft. A similar (25-second) warning time would provide the same degree of "safety" if a range/altitude CAS were to be utilized to protect aircraft of similar performance. However, if a CAS system is to be used to protect a low-performance (single-engine general aviation) aircraft, then the warning time must be increased, regardless of whether tau logic or range/

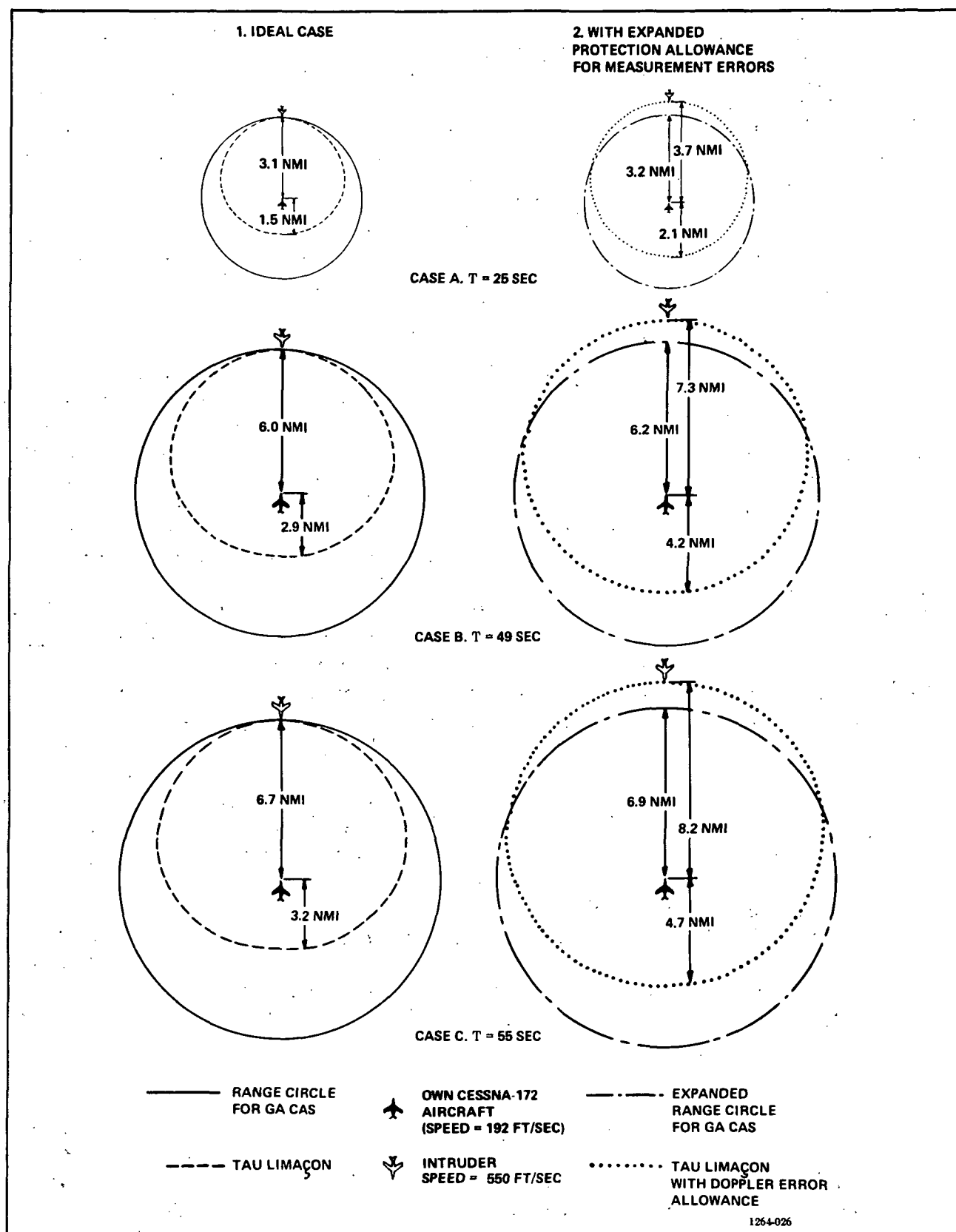


Figure 21. Threat Boundary Comparison: Enroute Encounter Between Cessna and High-Speed Intruder

altitude logic is employed.

As noted earlier, this change in warning time will not change the relative sizes of the respective protected areas. However, the actual dimensions of the tau limaçon and the range circle will grow in direct proportion to the warning time. Therefore it is useful to interrupt the discussion of protected areas in order to examine the single-engine general aviation aircraft's warning-time requirements. This will involve some repetition of the discussion in section V.

Rationale for selecting safe warning times could parallel the parameter selection in the ATA CAS. The ATA specifications mandate vertical evasive maneuvers. Such collision avoidance maneuvers in a vertical plane were deemed safest by Bendix as early as 1958.³ Since many single-engine general aviation aircraft have climb rates that are significantly smaller than the 2000 feet-per-minute envisaged by the ATA's collision avoidance system, it may be necessary to provide significantly longer lead times. Luckily, because of the lower airspeeds involved, overall airspace requirements may not increase unduly.

In designing the air carrier CAS it was possible to assume climb-rate capabilities of up to 2000 feet per minute, although acceleration limitations of approximately $1/4$ g were imposed to avoid maneuvers that might frighten or even injure the air carrier passengers. Such maneuvers permit one aircraft to perform an evasion maneuver which may involve an altitude change of some 465 feet within 25 seconds after crossing the threat boundary. (This includes some 245 feet of 3 sigma altitude error, plus about 220 feet of clearance between air carrier aircraft. With typical aircraft delays, some 4 seconds are required to reach the desired climb rate (with a resultant average climb rate of about 1000 fpm for 4 seconds) while a climb rate of 2000 feet per minute for 12 more seconds provides a total of about $67 + 400 = 467$ feet of altitude change. This leaves approximately 9 seconds for pilot/sensor delays. One half of the interval required for the aircraft to reach its desired climb/dive rate may be lumped into an overall lag of $9+2 = 11$ seconds to simplify the calculation. Since almost half the GA aircraft have climb rates of no more than 800 feet-per-minute under ordinary circumstances, it is apparent that either longer warning times or dependence on both aircraft maneuvering is required in order to avoid potential collision. This could involve doubling the width of the requisite air corridors for a given air speed. Luckily, however, the general aviation aircraft with the climb/rate limitations are also the ones that travel at the slowest speeds and since the requisite corridor is a linear function of the air speed, this may not involve excessive requirements for air space.

In particular, the evasion time may be calculated from:

$$\tau = T_e = \frac{\Delta H}{\dot{H}_s} + T_d \approx \frac{60 \Delta H}{\dot{H}_m} + T_d$$

where ΔH is the incremental climb altitude, $\dot{H}_s$ is the climb rate in feet per second, $\dot{H}_m$ is the corresponding climb rate in feet per minute, and T_d is the sensor/pilot/aircraft response delay.

It may be assumed, as in the ATA specification, the altimeter is accurate to 150 feet (3σ) and that the altitude is reported (telemetered) in 100-foot increments. The "worst" (three sigma) relative error between nominally co-altitude aircraft is approximately:

$$h_{e3} \approx \sqrt{(150)^2 + (150)^2 + 3 \left[\left(\frac{100}{2\sqrt{3}} \right)^2 + 3 \left(\frac{100}{2\sqrt{3}} \right)^2 \right]} \approx 245 \text{ ft.}$$

An additional 100 feet is required to provide minimal clearance between two small aircraft. Thus the maneuvering aircraft may have to climb 345 feet in order to accomplish an adequate evasive maneuver. If we employ the advertised climb rate of 645 fpm for a Cessna 172 as the lower level of attainable climb rates, and add a sensor/pilot/aircraft response delay of about 11 seconds, this yields:

$$T_e = \frac{60 (345)}{645} + 11 = 43 \text{ seconds.}$$

As noted in section V, extra clearance is required in encounters between an airliner and a GA CAS. This suggests a 49-second warning time to allow the GA to avoid the airliner (refer to table 5; section V). Similar calculations based on 250 foot (3σ) altimeter inaccuracy for the GA CAS, correspond to a total warning time of $60 (475)/645 + 11 = 55$ seconds (refer to table 6, section V).

As noted elsewhere, such increases in warning time will result in corresponding increases in the protected area, no matter what sort of CAS logic is utilized. In particular, with a Tau CAS, the protected range for a given closing rate will increase linearly with any increase in evasion time. Furthermore, the minimum protected range R_m and the offset range, R_o , (as used in the ATA CAS characteristic) should also be increased, since both of these range terms serve to overcome possible excessive delay in the tau warnings that may occur at low closing speeds. As noted earlier, a large warning time delay can result at moderately low closing rates (due to doppler

velocity errors) unless R_0 is increased. However, at the lowest closing rates, the minimum range, R_m , provides safe protection. In addition, this minimum range provides protection against horizontal acceleration. The resulting unexpected change in relative aircraft position would increase with required evasion time. It is necessary, therefore, to extend the minimum range, R_m , and the offset range, R_0 with the required warning time, τ .

However, the range expansion due to ranging measurement errors would remain a fixed 1000 feet, and would not increase with warning times. Thus, figure 21A provides a good comparison of the protected areas of a Range/Altitude CAS and a Tau CAS for a short warning time. The threat boundaries in figure 21B and 21C, correspond to larger delays required for safe evasions by GA CAS. These figures employ different scale factors and therefore are nearly identical to the drawings in figure 21A (except for a slight decrease in the relative dimensions of the expanded range warnings circle). Of course, the requirement for longer warning times results in larger protected areas for use by the single-engine general-aviation CAS.

7. Protected Region; Lower Speed Encounters. The preceding discussion concerned the threat boundaries that result when a Cessna-172 is equipped with a range-only GA CAS and encounters an aircraft travelling at maximum anticipated speed at an altitude of 10,000 MSL or less. If the Cessna encounters another small low-speed aircraft, however, the simplest CAS might define threats on the assumption that the intruder is travelling at the same high speed. Under those assumptions, the tau limaçon would shrink significantly while the protected range circle might not decrease. Thus the airspace requirements for an encounter between two slow GA aircraft would be as large as those required between a GA aircraft and an airliner.

As explained in sections II and V, a simple method for reducing airspace requirements in encounters between two GA CAS has been adopted, and the resulting threat boundaries are discussed in a subsequent paragraph. The present discussion, however, is based on the use of common threat boundaries for all intruders.

The protected area about own aircraft may also be excessive when own aircraft flies at speeds significantly below its maximum assumed airspeeds. The resulting threat boundaries are discussed in the following paragraph. In these cases, the tau limaçon shrinks while the range/altitude disk remains unchanged.

The protected regions for these lower speed encounters can be plotted. A case of particular interest results when two GA aircraft, each travelling at 192 ft. per second, meet. If the dimensions of the protected range/altitude disk (for such encounters) were selected equal to the dimensions for the case where the assumed maximum intruder velocity is 550 ft.

per second, then the range disk would remain the same as in figure 21 A, B and C. However, the tau limaçon would shrink substantially. In fact, in this case where intruder speed equals own speed, the closing rate falls to zero on parallel-course encounters. This is illustrated in figure 22 A, B, and C where the ideal tau cardioid and a tau-limaçon that includes a correction term for the assumed two-sigma doppler error, are compared to the ideal and expanded range/altitude disks which protect against encounters with a maximum speed (550 ft/second) intruder. In this case, the figures compare the protected areas for warning times of 25, 43, and 55 seconds, respectively. It can be seen that the resulting expanded protected disk ahead of the aircraft does not extend very far beyond the boundaries of the tau limaçon. However, the significantly lower protected zone behind own aircraft in the tau limaçon permits close in-trail flights to a terminal with consequent faster acceptance rates there.

8. Reducing the Protected Area for Slower Speed Encounters.

a. **Reduced Protection Against Own Kind.** Some reduction in the disk radius can be achieved if it is known that the intruder's maximum airspeed is limited to a number that is significantly less than 550 ft/sec. One approach might involve protection against GA aircraft. This reduces the protected threat zone substantially (refer to figure 23 A, B, and C). Hard-wired protection against own-kind-only might lead to problems in encounters with a high-speed intruder in situations where the intruder cannot provide the safe escape maneuver. This problem is overcome by coding the CAS transmissions appropriately. For example, if the slow speed aircraft that is encountered is a single-engine aircraft equipped with a similar GA CAS, then a relatively short CAS transmission would be utilized, whereas a faster, ATA-CAS equipped aircraft would utilize a 200-microsecond coherent pulse transmission. After receiving a shorter pulse width CAS transmission, the equipment in the Cessna could reduce its protected range to correspond to the maximum anticipated airspeed of a single-engine category intruder. Similarly, if a long (doppler) pulse is received, the GA CAS could utilize a protected area corresponding to the maximum 550 ft/sec. airspeed of the low-altitude intruder. If use of the GA CAS is restricted to aircraft travelling at an airspeed of 260 ft/sec or less, the resultant ideal protected circle would have a radius of $(192 + 260) T_c$ feet where we will consider values of $T_c = 25, 43, \text{ and } 55$ seconds, respectively. As before, the expanded range circle would increase the range protection by 1000 feet to allow for a two-sigma range error, while the tau limacons would move outward by an amount $160 T_c$, corresponding to the two-sigma doppler error (see figure 23 A, B, and C).

It would, of course, be possible to increase the GA CAS system complexity slightly by using pulse-position telemetry to transmit own aircraft's maximum speed, and by changing threat parameters according to intruder's speed telemetry. While this approach might yield some advantages in reduced

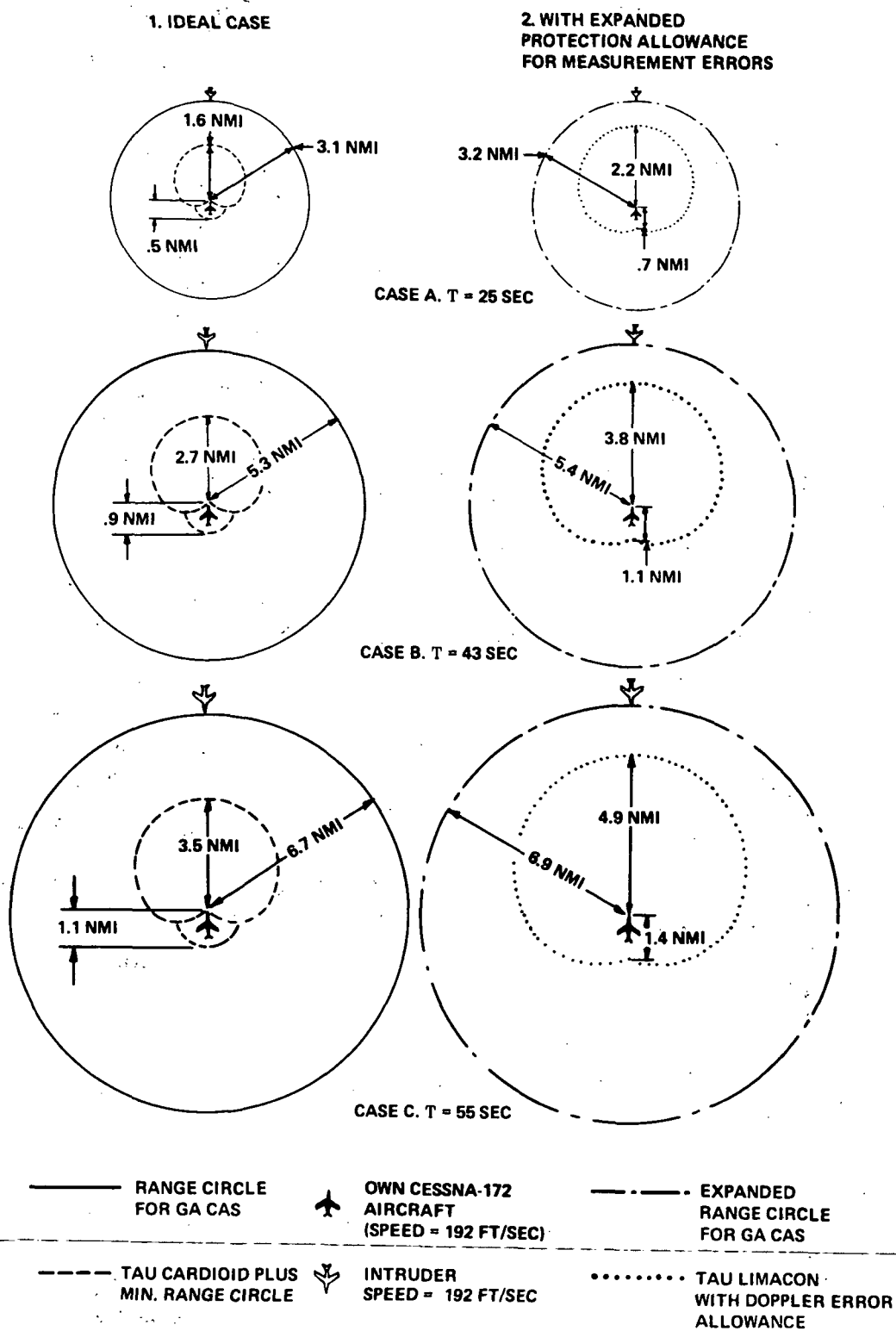


Figure 22. Threat Boundary Comparison: Encounter Between Two Cessnas, Threat Logic Based on 550ft/sec Intruder

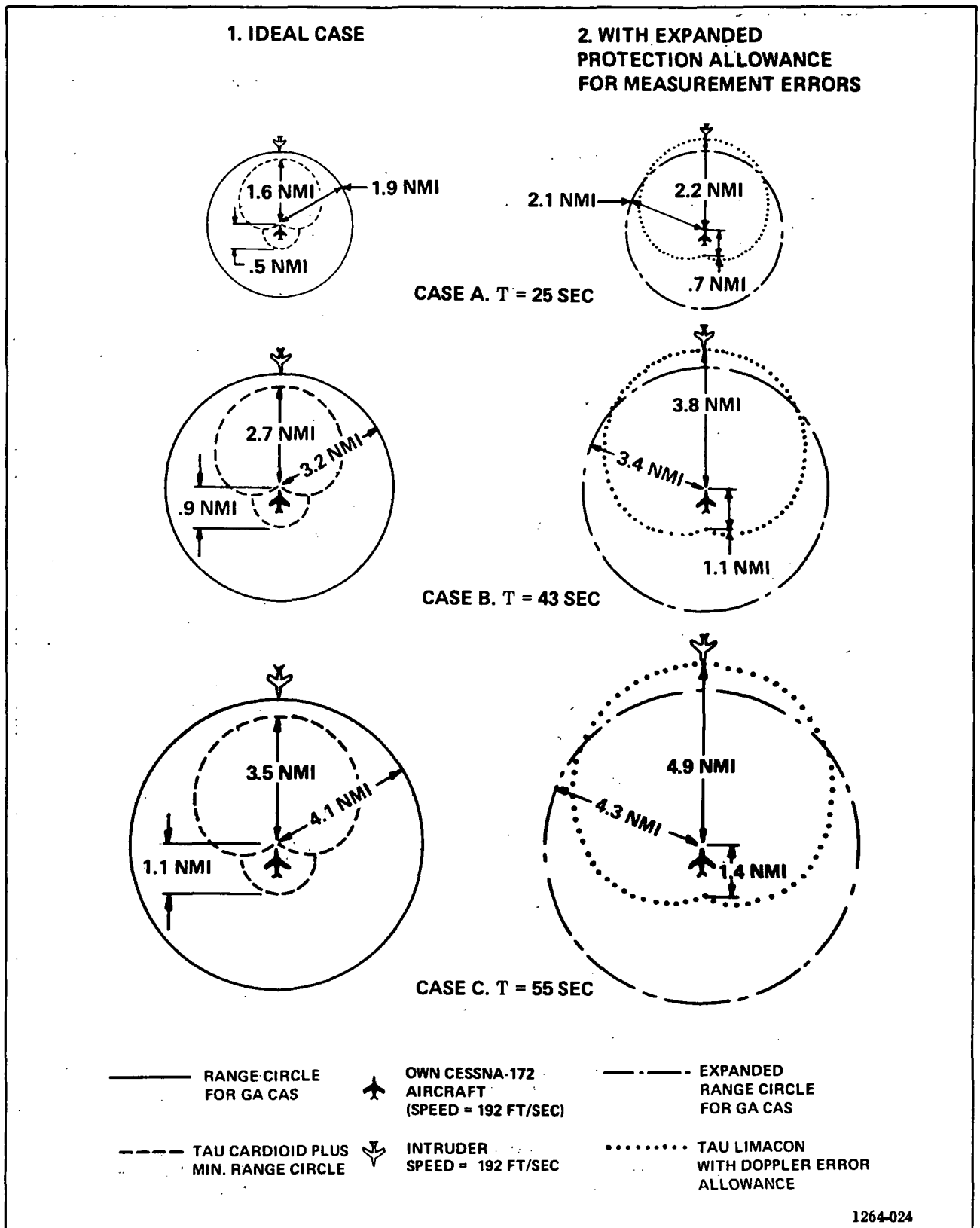


Figure 23. Threat Boundary Comparison: Enroute Encounter Between Two Cessnas, Threat Logic Based on 260ft/sec Intruder

protected regions, the resultant small increase in system complexity discourages adoption of this improvement.

b. **Reduced Protection in Terminal Areas.** The preceding discussion has been limited to aircraft encounters between a Cessna, travelling at maximum recommended speed and an intruder. However, it is common for single-engine aircraft to fly substantially below maximum recommended airspeeds, especially when approaching a destination (or departing from the originating airport). Typical maximum speed of the Cessna, under these circumstances would be about 90 mph or 132 ft/sec. Higher speed aircraft would also reduce airspeed to 200 knots or 338 ft/sec. indicated or less in this area (refer to section V). Assuming that terminal area flight occurs at or below 5000 feet allows designing for true airspeeds of 142 and 363 fps, respectively. It appears practical to reduce the range/altitude protection to conform to these assumed airspeeds in the immediate terminal area. However, the maximum assumed airspeed for other GA intruders has been assumed as 120 mph IAS or 190 fps true airspeed, which is again faster than the 142 fps maximum assumed airspeed of the Cessna.

The threat boundaries for the terminal area logic in such encounters are discussed in subsection E.

While various means may exist for initiating the operation of the "terminal area" switch, it would probably be least complicated to allow pilot selection of this logic. As explained in a later paragraph, we propose that this protection switching logic remain effective for a limited time after pilot actuation and then return automatically to the normal-protection condition. This should help guard against use of limited-protection logic because of pilot oversight.

9. **Additional Comments on Threat Boundaries.** It should be noted that the threat boundaries shown in the various figures correspond to regions where threats might be detected when the actual range and doppler velocity are perfect, but where some margin is included in the system to allow safe evasion with possible range and velocity errors. The boundaries may expand further in specific cases where range is measured low or closing rate is measured high. These cases will not be considered at the present time. Furthermore, the limaçon is a maximum boundary for possible threat detection. It is possible for an intruder, travelling at speed V_2 to penetrate the limaçon on some headings without causing a threat alarm. Nevertheless, the limaçon does give a realistic indication of airspace requirements needed in a tau-system. The limaçon boundary that can be safely used (when appropriate account is taken of the doppler error) is not significantly smaller than the corresponding protected range circle, especially when the intruder and own aircraft are travelling at the assumed maximum speeds, or when the appropriate reduced-range protection areas are utilized.

E. THREAT BOUNDARIES FOR SPECIFIC ENCOUNTERS

1. Range Ratios. In comparing the tau/altitude criterion used in the ATA CAS with the range/altitude criterion proposed for the low-cost General Aviation CAS, we have so far limited our consideration to the overall threat envelopes.

A more detailed comparison is helpful for indicating airspace requirements in specific critical situations. This comparison is based on the estimates of the safe protected range for the selected CAS. The safe protected range, R_G , for a range-altitude threat evaluation corresponds to the safe escape time, τ , multiplied by the maximum anticipated closing rate plus an estimate of range error, with en-route logic. A similar calculation, based on alternative range rate estimates, yields the "terminal" logic. The corresponding safe protected range, R_T , for a tau system is given by the same value of τ times the sum of the measured closing rate and an estimate of the error in the closing rate measurement.

$$\text{Thus } R_G = (V_{mo} + V_{mi}) \tau + k\sigma_R$$

$$\text{while } R_T = R\tau + k\sqrt{\tau^2 \sigma_v^2 + \sigma_R^2} \approx R\tau + k\tau\sigma_v$$

$$\text{so that } \frac{R_G}{R_T} = \frac{(V_{mo} + V_{mi}) + k\sigma_R/\tau}{R + k\sigma_v}$$

where V_{mo} and V_{mi} are respectively own and intruder's maximum anticipated airspeed, σ_v is the one-sigma closing-rate error and σ_R is the one-sigma ranging error of the system, while k is a selected safety factor. Typically, we would use $k = 2$, or $k = 3$, and perform separate calculations for the terminal and en route areas.

At present, the ATA CAS protects a half-nautical mile range circle about own aircraft, regardless of the closing rate measured and also includes a 0.25 nmi bias to account for the doppler errors. The 0.5 nmi minimum range provides timely warnings at low closing rates. The 0.25 nmi bias presumably was to account for the ranging and doppler errors of the Airline CAS. 0.25 nmi would not adequately correspond to the errors noted in the systems tested by Martin Marietta in Baltimore. There, the one-sigma doppler error was estimated at 47 knots or 80 ft/sec., and the one-sigma error was estimated between 200 and 500 feet. Thus for a τ of 25 seconds, and for $k = 3$, the error terms would be:

$$k\tau\sigma_v = 6000 \text{ ft.}, \text{ while } 600 \leq k\sigma_R \leq 1500 \text{ ft.} \quad \text{Even if we use}$$

$k = 2$, we would require a larger minimum protected radius in a Tau CAS.

This would suggest a bias range of at least $25(160) \text{ ft} = 4000 \text{ ft} \approx .66$ nautical miles in the ATA CAS. The smaller threat boundaries employed presumably assume 2.8 times better doppler measurement in the future and do not leave any margin for error. They cause relatively little interaction with the ground ATC but they also would not provide a reasonable degree of safety for a relatively inexpensive doppler processing unit that might be installed in GA CAS aircraft.

In the ensuing discussion, we reexamine the protected ranges that result from use of a safe protection envelope for a hypothetical GA CAS with doppler measurement capabilities.

It will be seen that in comparison to such a GA doppler CAS, the range/altitude GA CAS would utilize the most excess space when the closing velocity is zero and would utilize little or no excess space when aircraft travelling at expected speed, meet in worst case head-on encounters.

2. In-Trail Encounters. In particular, if similar-performance aircraft travel in-trail (as in conventional takeoffs and landings), the ratio of minimum separation dimensions for the two approaches is given by:

$$\frac{R_G}{R_T} = \frac{142 + 190 + 1000/55}{0 + 160} \approx \frac{350}{160} = 2.2$$

This is obviously a significant increase in required airspace. In fact, for a Tau of 55 seconds R_G would be about 3.2 nautical miles. This is similar to presently-utilized separations under radar control, but is somewhat larger than the separation utilized under VFR. Furthermore, if we consider a similar encounter between a Cessna and an aircraft equipped with ATA CAS, the corresponding ratio would be:

$$\frac{R_G}{R_T} = \frac{142 + 363 + 1000/55}{160} = \frac{523}{160} = 3.3$$

In this case $R_G = 4.7 \text{ N. miles}$. In each case, the Tau CAS would rely on its zero measured closing velocity protection of $160(55) = 8800 \text{ ft.} \approx 1.5 \text{ nmi}$ corresponding to the two-sigma velocity error.

3. Anti-Parallel Encounters. It should be noted that another important case was mentioned in the original proposal. This is an anti-parallel encounter that can occur in typical landing and takeoff patterns at uncontrolled airports (see figure 24). As noted in the proposal, such encounters could

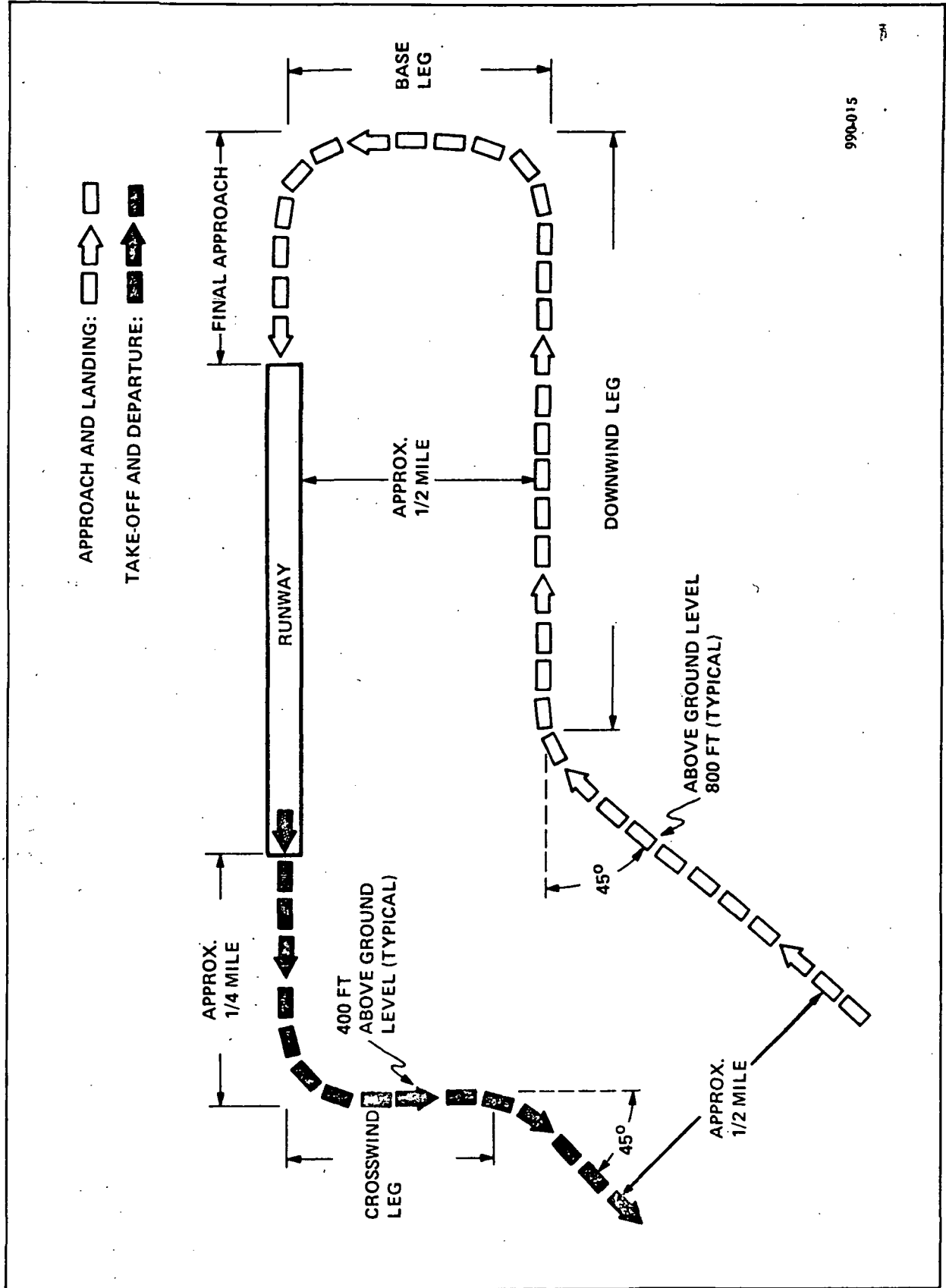


Figure 24. Typical Airport Traffic Pattern

easily require evasive maneuvers whether a range/altitude or a Tau/altitude threat criterion is employed.

Formulas may be derived for the maximum miss-distance that can result in a Tau alarm between two aircraft on antiparallel courses. Suppose that two aircraft are flying at speeds V_1 and V_2 respectively, and that time 0 is referred to the point of closest approach (see figure 25). The separation R at time t is given by:

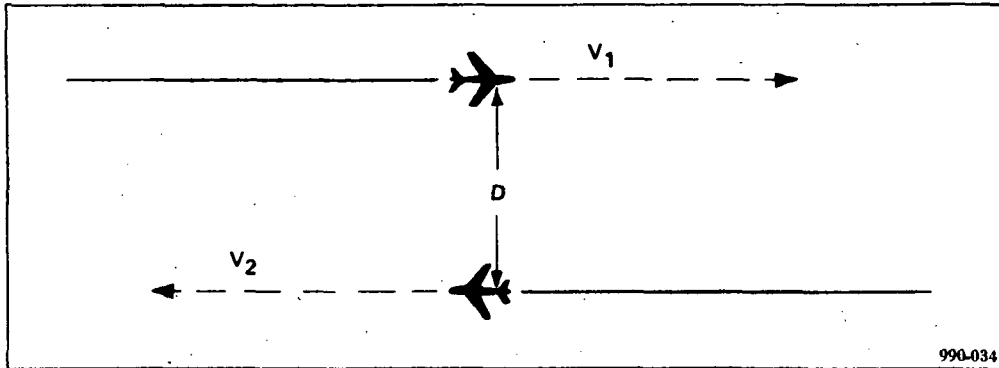


Figure 25. Aircraft on Antiparallel Courses

$$R^2 = D^2 + \left[(V_1 + V_2)t \right]^2$$

while

$$R\dot{R} = (V_1 + V_2)^2 t$$

Let the Tau alarm be defined by

$$\tau = -\frac{R}{\dot{R}} = -\frac{R^2}{R\dot{R}}$$

or

$$-\tau = D^2/[(V_1 + V_2)^2 t] + t, \text{ whence,}$$

$$-\tau = \frac{D}{V_1 + V_2} \left[\frac{D}{(V_1 + V_2)t} + \frac{(V_1 + V_2)t}{D} \right]$$

This negative quantity has a minimum absolute value when

$$\frac{D}{(V_1 + V_2)t} = \frac{(V_1 + V_2)t}{D} = -1$$

$$- \tau = \frac{-2D}{V_1 + V_2}$$

while

$$t = \frac{-D}{V_1 + V_2} = \frac{\tau}{2}$$

If the minimum absolute value of $-R/\dot{R}$ is precisely the Tau-alarm value τ_a , then

$$D = \frac{V_1 + V_2}{2} \tau_a$$

where D represents the maximum miss distance that can generate a Tau alarm between two aircraft on antiparallel courses, while:

$$R^2 = D^2 + \left[(V_1 + V_2)t \right]^2 = D^2 + D^2 = 2D^2$$

$$R = D \sqrt{2}$$

so that the aircraft are at relative bearings of 45° at the instant when the limiting Tau alarm is exceeded (in the no wind case).

The average range at the Tau alarm would increase by $\tau k \sigma_v$, if a suitable range bias is included to compensate for a $k \sigma_v$ doppler error. In that event, the maximum miss distance, M , would increase by approximately $\tau k \sigma_v / \sqrt{2}$ to:

$$M = D + \tau k \sigma_v / \sqrt{2} = \left(\frac{V_1 + V_2}{2} + \frac{k \sigma_v}{\sqrt{2}} \right) \tau$$

For a 55-second τ alarm in encounters between two Cessna 172's, travelling at $V_1 = V_2 = 142$ ft/sec, the maximum miss distance that could generate a Tau alarm is given by $M = (142 + 160/\sqrt{2}) 55 = 14020$ ft = 2.3 N. miles. This is not much less than the 3.2 N. mile protected region provided by the GA CAS with terminal logic, but is substantially better than the 6.9 nmi spacing based on a single range/altitude protected radius.

4. Summary. The spacings, permitted by the various logic categories, are summarized in table 15 and 16. Column A in table 15 indicates the protected range based on the use of range/altitude terminal logic. Column B indicates the minimum terminal miss distance required to avoid a Tau alarm

TABLE 15. REQUIRED INTER-AIRCRAFT SPACING, TERMINAL AIRSPACE

		A	B	C
	Evasion Time	Terminal Range Logic	Anti-Parallel Course Tau Logic Terminal	In-Trail, Tau Logic
	(SECS)	NMI	NMI	NMI
ANTC-117 Assumption				
GA-GA	25	1.5	1.2	.7
GA-AC	25	2.3	1.5	.7*
AC-Quality Altimeter				
GA-GA	43	2.5	2.0	1.1
GA-AC	49	4.2	3.0	1.3*
250-foot Accuracy Altimeter				
GA-GA	55	3.2	2.5	1.4
GA-AC	55	4.7	3.3	1.4*

*Based on the assumption that the higher performance ATA-CAS equipped aircraft flies at the same low speed as the slower GA-CAS equipped aircraft.

TABLE 16. REQUIRED INTER-AIRCRAFT SPACING, ENROUTE AIRSPACE

Evasion Time (SECS)	A En-Route Range Logic	B Anti-Parallel Course Tau Logic (En-Route)	C True Head-On Encounters Tau Logic (En-Route)
	NMI	NMI	NMI
ANTC-117 Assumption			
GA-GA 25	2.0	1.4	2.5
GA-AC 25	3.2	2.0	3.7
AC-Quality Altimeter			
GA-GA 43	3.4	2.4	4.3
GA-AC 49	6.2	3.9	7.3
250-foot Accuracy Altimeter			
GA-GA 55	4.3	3.1	5.6
GA-AC 55	6.9	4.4	8.2

between two aircraft on anti-parallel courses. Column C contains the range separations required between equal-speed in-trail aircraft, when Tau logic is used. (it is unlikely that this situation will generally occur between a single-engine general-aviation aircraft and an airliner, except perhaps in the terminal area.)

In table 16, Column A indicates the protected range using the range/altitude en-route logic. Column B indicates the minimum en-route miss distance required to avoid a Tau alarm between two aircraft on anti-parallel courses. Column C shows the Tau alarm on a true head-on encounter.

Perhaps the most pertinent comparison can be made between the 55-second warning time figures shown in Columns A and B of table 15. While the Tau logic permits spacings that are about 70% to 80% as large as is permitted by the range/altitude CAS, the figures are not grossly different.

Even with the Tau logic, it might very well be necessary to make changes in the presently-accepted procedural turns under some conditions in order to avoid possible evasive maneuver commands in the landing pattern. Such procedural changes are undoubtedly required, but any changes would require FAA rule making and might encounter considerable user resistance.

The 43 to 49-second warning time values corresponding to use of higher quality altimeters by GA aircraft are included to show the effect on threat zones of altitude sensing errors.

Table 17 demonstrates the superiority of the planned use of coarse velocity estimates from pulse length as a modifier of the threat envelopes over plain elimination of doppler detection. We have mentioned one way of reducing the protected range for terminal in-trail encounters at low speed. We now review other available techniques for reducing threat boundaries, as appropriate.

F. METHODS FOR REDUCING MINIMUM SEPARATION FOR IN-TRAIL ENCOUNTERS

1. Available Alternatives. Various methods have been suggested for reducing the protected range in the immediate terminal area (without using doppler) in order to permit shorter interaircraft separations on departure and arrival.

Some of the approaches that might be considered are included in the following list: Possibilities (a) and (c) have been embodied in the present system design, and have been considered earlier.

TABLE 17. REQUIRED INTER-AIRCRAFT SPACING
COMPARISON OF PROPOSED SYSTEM WITH "HARD-WIRED" RANGE LOGIC

	Evasion Time (SECS)	Proposed System		Hard-Wired Range Logic
		A	B	
		Terminal Range Logic	En-Route Range Logic	Terminal and En-Route
		NMI	NMI	NMI
ANTC-117 Assumption				
GA-GA	25	1.5	2.0	3.2
GA-AC	25	2.3	3.2	3.2
AC-Quality Altimeter				
GA-GA	43	2.5	3.4	6.2
GA-AC	49	4.2	6.2	6.2
250-foot Accuracy Altimeter				
GA-GA	55	3.2	4.3	6.9
GA-AC	55	4.7	6.9	6.9

a. Use of Significantly Reduced Range Protection Under Pilot Control. This might involve selecting a "VFR terminal-logic" switch during final approach and departure. The terminal-logic switch would not provide adequate protection against full speed head-on encounters. Luckily, there is some statistical support for assuming that head-on encounters are a very infrequent source of mid-air collisions.²⁹ Perhaps this is because good forward visibility is available under VFR conditions. In addition, aircraft tend to fly at lower speed in the immediate vicinity of a terminal. If this terminal logic approach is employed, it would be highly desirable to include a time-delay circuit to restore en-route logic after a specified time. This would reduce the likelihood of using reduced protection because of pilot error.

b. Telemetry of Each Aircraft's Maximum Airspeed for Use in the Threat Evaluation. If each aircraft telemetered its maximum airspeed, it would be possible for own aircraft to calculate the requisite separation range based on the sum of own (or own maximum) and intruder's maximum airspeed. This would reduce airspace requirements somewhat in the case of an encounter between two GA CAS (see figures 23 A, B, and C for reduced range circle). However, large range separations would be required between an aircraft that can travel at high speed and a GA aircraft.

c. Use of Pulse Width Discrimination for Limited Airspeed Telemetry. Since the GA CAS equipped aircraft transmits a shorter pulse than the full-CAS equipped aircraft, pulse width discrimination can be used to differentiate between the higher and lower speed aircraft (refer to b). This would be relatively simple, and would provide significant reduction in spacing between low-speed aircraft.

d. Telemetry of Faster Aircraft's True Airspeed for Use in Threat Evaluation. An additional reduction in airspace requirements between a GA aircraft and a high-speed aircraft is possible if the latter telemeters his true airspeed. This would require further complications in ATA-CAS equipped aircraft. Furthermore, this would still make use of the sum velocity in an overtake or in-trail flight condition where the difference velocity is applicable. Both this and the preceding approach permit somewhat closer spacing but do not allow very close in-trail flight.

e. Measurement and Telemetry of North and East Components of Airspeed. This could permit much closer spacing when aircraft fly in-trail. Telemetry could be accomplished with the aid of an electrical output from the airspeed indicator, use of a compass-driven resolver, and telemetry provisions. Some reduction in spacing might be achieved by telemetering compass heading alone. Either approach would appear to require considerable development and would probably involve excessive expense for the GA CAS equipment.

f. Use of a Display of Range to Closest Aircraft to Allow Pilot Override of an Evasive Maneuver Command. It would not be difficult to provide a display of range to the closest aircraft. At least one extra digital register and associated comparison circuitry would be needed to extract the requisite range. The approach might not add very much to the system cost, but would add a significant monitoring/scanning burden on the pilot at a time when he already is overloaded.

g. Extraction of Closing Rate Without Doppler. Change in range to the closest aircraft could be divided by elapsed time to yield closing rate. This involves additional logic circuitry to compute range difference after extracting range to the closest altitude aircraft. Some change in threat computation might be required. Some limitations on clock correction rates would have to be added to ATA CAS specifications. The full-CAS units could use very similar logic to extract closing rate to GA aircraft with high accuracy. This might require some additional changes in ATA specifications. In its simplest form, this method would not provide complete protection against more-distant faster-closing aircraft. This approach still appears to be cheaper than the system modifications required to assure adequate operation of a one-way pulse doppler.

h. Two-Step Logic. This would involve range/altitude logic and subsequent checking for closing or opening conditions. It is doubtful whether this could be accomplished without doppler or the circuitry described under subitem g.

i. Front/Back Discrimination. This would tend to reduce the in-trail protected range requirements, but would require two antennas with somewhat directional characteristics and additional circuitry making use of signal strength measurements.

2. Selection of Alternatives. It will be seen that most of the alternative methods for reducing spacing during in-trail flight in the immediate terminal area would add excessively to the cost of a GA CAS, while others require excessive pilot effort. This contractor believes that only two of the approaches are simple enough to permit their inclusion in lower-cost GA CAS equipment. These approaches would consist of (a) reducing range protection in the terminal area under pilot control, and (c) use of pulse-width discrimination for limited airspeed telemetry. Both of these features have been included in the system design.

It would appear that significantly closer in-trail spacings could be achieved with either method (e) or method (g). However, these approaches would be more expensive and would not be included in the simplest GA CAS equipment. Detailed investigation of these approaches for a full CAS or a more sophisticated GA CAS is undoubtedly desirable. However, these approaches do not fall within the scope of the present contract.

SECTION VIII

ADDITIONAL CAPABILITIES

A. GROUND EXTRACTION OF AIRCRAFT LOCATION

The Time/Frequency CAS approach utilizes precisely-timed transmissions by all participants. Thus any (ground) receiving station that is similarly synchronized to common time can extract relevant ranging information from time of arrival of the CAS transmissions and can decode the telemetered altitude information. If such information were received at two or more intercommunicating ground stations, it would be possible to combine the information in a computer which extracts aircraft position in three dimensions. Alternately, azimuth information could be extracted from signal strength measurements using a very rapidly (electronically) scanned antenna or from a multiplicity of fixed narrow beam antennas. This information could be displayed to ground traffic-control personnel to permit aircraft monitoring and could also be used by such personnel in the terminal area to display and control approaching aircraft. Use of this information for monitoring requires the deployment of ground clocks, synchronized to CAS time, with associated receiving, logic, and display circuitry to indicate the relevant positional information to the ground personnel. (These clocks and receivers could also be collocated at VORTAC or TVOR sites for system economy.)

The GA CAS described in this report radiates sufficient power to assure accurate range measurement at 9 nautical miles (with a 10 db fade margin) through use of an ATA CAS quality receiver and an associated omnidirectional antenna. Some increase in communication range can be achieved by suitable ground station design. For example, ANTC-117 specifies ground station cable losses of 1.1 db and a ground antenna gain of 6.15 db. This provides a net gain of approximately 9 db, over the power estimates used to calculate the communication range in ATA/GA CAS encounters. A consequent reliable communication range of more than 25 nautical miles results (even with a 10 db fade). This should suffice for terminal area operations.

Use of the received CAS signals for en route monitoring (either as a supplement or replacement for ATCRBS) may prove more difficult. There it might be necessary to increase transmitted power from the aircraft or else utilize an array of directional horns and associated fixed or switched receivers to increase the communication range. The communication range can be increased substantially by utilizing an electronically scanned narrow beam antenna. This approach is attractive since it may permit extraction of azimuth information from a single 30 microsecond pulse transmission if the beam scanning is sufficiently rapid. This ultra high-speed scanning requires

an all electronic phased array antenna system which would be excessively expensive at this point in time.

The alternative of a substantial increase in transmitted power to allow extraction of aircraft position with the aid of omnidirectional antennas does not seem to be cost effective. In fact, replacement of ATCRBS by a combined Time/Frequency CAS/ATCRBS using VORTAC sync would not be attractive if it reduced the availability of suitable backup equipment to the basic airborne navigation system. Nevertheless, ATCRBS operation has been less than completely satisfactory, and alternatives or improvements to ATCRBS should be considered.

In any event, the possibility of extracting precise positioning information in the terminal area is attractive since this additional capability could be provided without any change in required airborne hardware. The approach would require substantial deployment of ground station equipment in critical terminal areas. Long delays in deploying ground receiving and display equipment would not interfere with the operation and utility of the CAS.

Of course, installation of CAS in aircraft would become more attractive if unmodified CAS equipment could also be used to provide other essential services to the operation of that aircraft, such as improved surveillance and vectoring in the terminal area.

Actual use of the time/frequency system to provide aircraft positioning information in the terminal area would be assisted by ground assignment of the aircraft's CAS slot. This would permit direct identification of the positioning transmissions with the aircraft from which they emanate. Such ground assignment of slots would obviate the need for "shut up and listen" circuitry, and would therefore eliminate some of the potential sources of delay in the threat determination. Since such ground assignment of slots would not be immediately available, the present GA CAS logic design includes shut-up-and-listen capabilities. Eventual elimination of this logic would result in minor system simplification.

B. OBSTACLE AVOIDANCE

A proposal has been made to set aside certain CAS slots for use as obstacle avoidance beacons. Synchronized transmissions from such stations could be used to define an avoidance circle about the ground obstacle (hill or tall building) in the vicinity of the terminal area. Appropriate adjustment of the transmission time by the ground station would permit generation of a circular protected zone of appropriate radius about the obstacle. Similarly, slight adjustment of the beacon's transmitted altitude could modify the altitude protection. Since these transmissions would be in preassigned slots, it is feasible to add logic in the protected CAS aircraft to give the aircraft a

climb command (and thus prevent a low-flying CAS from generating a command to tunnel under a high obstacle). Since obstacle avoidance capabilities are required by low slow-flying aircraft, doppler range rate measurement is not needed. This suggests deployment of cheaper obstacle avoidance beacons emitting short non-coherent transmissions in assigned slots on the appropriate CAS frequency. Since these stations would have to be heard by the GA CAS, all such transmissions should be on the common frequency (F4).

The most recent draft of the ATA CAS technical description³⁰ sets aside specific slots for use as obstacle avoidance beacons. If these beacons are to be heard by the GA CAS, then they would have to operate on the common frequency. Simple logic would prohibit use of these slots for normal CAS operation and would force generation of a climb command even when the aircraft is below the obstacle altitude. It was not convenient to conform to the slot selection called out in the latest spec revision since the specific reserved slots and the associated frequency assignments would have to be modified to conform to single-frequency use for all low altitude operations. Embodiment of the needed logic would be readily accomplished and would not significantly affect cost or complexity of the GA CAS.

C. ONE-WAY DME

The present GA CAS design is based on the use of ground VORTAC which emits a carefully timed sequence of reference bursts for synchronization. Once the airborne clock is synchronized, it is possible to extract range to the ground station from time of arrival of the reference bursts. Excellent ranging accuracy is achievable in this manner since a quite high "one-way" range update rate is provided. (Sierra Research Corporation's current sync equipment for FAA transmits a reference pulse every 12 milliseconds. The very accurate airborne clock acts like a flywheel to permit continued range measurements at this high data rate even though the ground station is only interrogated at infrequent intervals (e.g., once or twice per second) to measure and correct clock phase and frequency errors.

This approach permits significantly reduced interrogation of the ground stations with resultant significantly increased VORTAC capacity for providing DME information to aircraft. Present VORTAC stations can provide a maximum of 2700 range replies per second which can accommodate a maximum of about 90 to 110 airborne interrogators (at a normal data rate of about 30 interrogations per second in "track" and a higher data rate in "search"). Significant growth is anticipated in the number of DME equipped aircraft aloft, both as a result of the shift to area navigation and as a result of projected growth in the number of aircraft flying IFR. Under these circumstances the need for a viable method for providing DME information to increasing numbers of aircraft has been recognized. While various other alternatives have been put forth, it is generally recognized that the one-way

approach is the only one that can provide undegraded service to a mix of aircraft equipped with DME's of current design, and with suitably modified DME equipment.

This capability for one-way DME requires a highly accurate airborne crystal clock and associated time synchronization logic. It therefore seems quite appropriate to include the costs of the crystal clock and associated timing and sync circuitry in the cost of the DME unit. In fact, one of the cost estimates for the GA CAS assumes the use of such a quasi one-way DME and therefore does not include the clock costs in the CAS.

D. STATIONKEEPING

Under the chairmanship of J. W. Prast, ATCAC's System 4 Subcommittee studied distributed air traffic control. This group suggested³¹ a need for air-to-air navigation in order to permit safe spacing between aircraft and to provide overtake and merge capabilities. Sierra Research is presently producing Time/Frequency stationkeeping equipment for the Air Force, which could provide many of the required capabilities.

It would appear desirable to provide such stationkeeping capabilities to the pilot, including azimuth measurement and an associated situation display (showing relative location of other essentially co-altitude aircraft). Unfortunately, extraction of azimuth is relatively costly, and relatively wide bandwidth and ultra-accurate synchronization would be required in this approach. While it might be possible to embody stationkeeping capabilities in more expensive CAS equipment (with some effort), it seems unlikely that such features could be included in moderately-priced equipment for use in single engine General Aviation aircraft.

E. DATA TRANSMISSION

The ATA's Full-CAS includes data transmission in the form of bi-phase modulation of the long (doppler) pulse, plus limited capabilities for data transmission (in the form of pulse position modulation) near the end of the slot. While time (and r-f power) may be available for data transmission with the GA CAS message, this approach would again complicate the system somewhat.

Perhaps the most relevant data for transmission would include aircraft identity and maximum airspeed.

Need for transmitting aircraft identity would be obviated by unique ground assignment of transmitting slots, as suggested in an earlier paragraph. This would also eliminate many potential future problems when a considerable number of CAS units are deployed and where slot jumping to avoid coslot

occupancy could result in a significant probability of double occupancy of the successive new slot selections.

Transmission of maximum airspeed as pulse position information is possible in the time between 750 and about 1000 microseconds after the start of the range pulse transmission. This information could be used to modify the threat boundaries. Embodiment of encoding or decoding equipment in the GA CAS would require some increment in cost, and this feature has therefore not been included.

F. OPERATION ABOVE 10,000 FEET

The overall GA CAS equipment was initially designed for use by single engine GA aircraft operating below 10,000 feet pressure altitude. This altitude limitation is not a problem in most parts of the conterminous United States, where very few single engine GA aircraft fly above this altitude. In fact, the big peak in GA altitude assignments is at about 5,000 to 6,000 feet. In accordance with table N of Ref. 15, of 692 peak day IFR departures in fiscal 1969, 634 single engine aircraft received tower altitude assignments below 6,000 feet, 45 had assignments between 6,000 and 9,999, while only 12 had assignments above 10,000 feet. However, a tabulation of VFR flight plans³² for calendar 1969 indicates 35,453 flight plans were filed for single engine GA aircraft. Ignoring the 801 aircraft cleared to fly "on top" and the 2510 aircraft with unknown altitudes, there were 18,922 aircraft assigned to altitudes below 6,000 feet, 11,283 to altitudes between 6,000 and 9,999 feet, and 1,939 aircraft assigned to fly above 10,000 feet. 1,078 of these higher flying aircraft were cleared for altitudes of 10,000 to 10,999 feet, and only 79 flew above 14,000 feet. These higher altitude flights include the small aircraft that fly over the Rocky Mountains.

There does not appear to be any reason for prohibiting such flights by GA CAS equipped aircraft if they remain substantially below the 14,000 foot upper altitude limit where the selected common frequency (F_4) is utilized. Such flights would not provide complete CAS protection since the typical single engine aircraft has little reserve power to climb at altitudes near their service ceilings. Thus the diving aircraft would have to provide safe separation in GA/GA encounters. (In losing altitude, such aircraft would have to avoid ground obstacles.) Such GA/GA encounters at or above 10,000 feet altitude do not require additional threat range (refer to section V) nor additional transmitter power (refer to section VI).

Encounters between GA and ATA CAS equipped aircraft could be detected by the CAS equipment (refer to power calculations at end of section VI). The ATA CAS might have to utilize slightly larger threat boundaries than those employed below 10,000 feet, since the larger aircraft could fly at high subsonic speeds in this area. However, the power transmitted by the GA CAS

suffices for this application (as was verified for the case of high-speed military aircraft flying in special restricted zones). Similarly, it would be desirable to expand the threat boundaries for the GA CAS (in encounters with these faster flying aircraft). This would involve a range increase of about 30% to 40%, which could be accommodated in the available power budget. Again, the more maneuverable faster aircraft may have to provide the safe separation, especially if the GA aircraft is at a higher altitude.

The expanded threat zone would not involve significant interference with traffic since considerable space is available in such en route areas. Furthermore, faster flying aircraft would be expected to fly significantly above any mountain passes or other regions when high flying low performance GA aircraft might have to operate.

Thus the GA aircraft could operate above 10,000 feet with reasonable CAS protection if this operation should prove necessary. Simple changes in the threat boundaries for encounters between GA and ATA CAS aircraft above 10,000 feet pressure altitude could be embodied easily. However, such logic has not been included in the present design.

PART TWO
DETAILED HARDWARE DESIGN AND COST ANALYSIS

SECTION I

FUNCTIONAL DESCRIPTION

This section defines a functional description of the proposed General Aviation Collision Avoidance System (GA CAS) and is presented in block diagram format in figure 1.

Initially, the system is turned on without sync attained. The sync logic inhibits the transmit and receive logic until sync is attained. Aircraft power is converted to supply the voltages required for the digital and analog circuitry. Altitude data is taken from an on-board source and converted to a pulse position code in the altitude and pulse measurement logic.

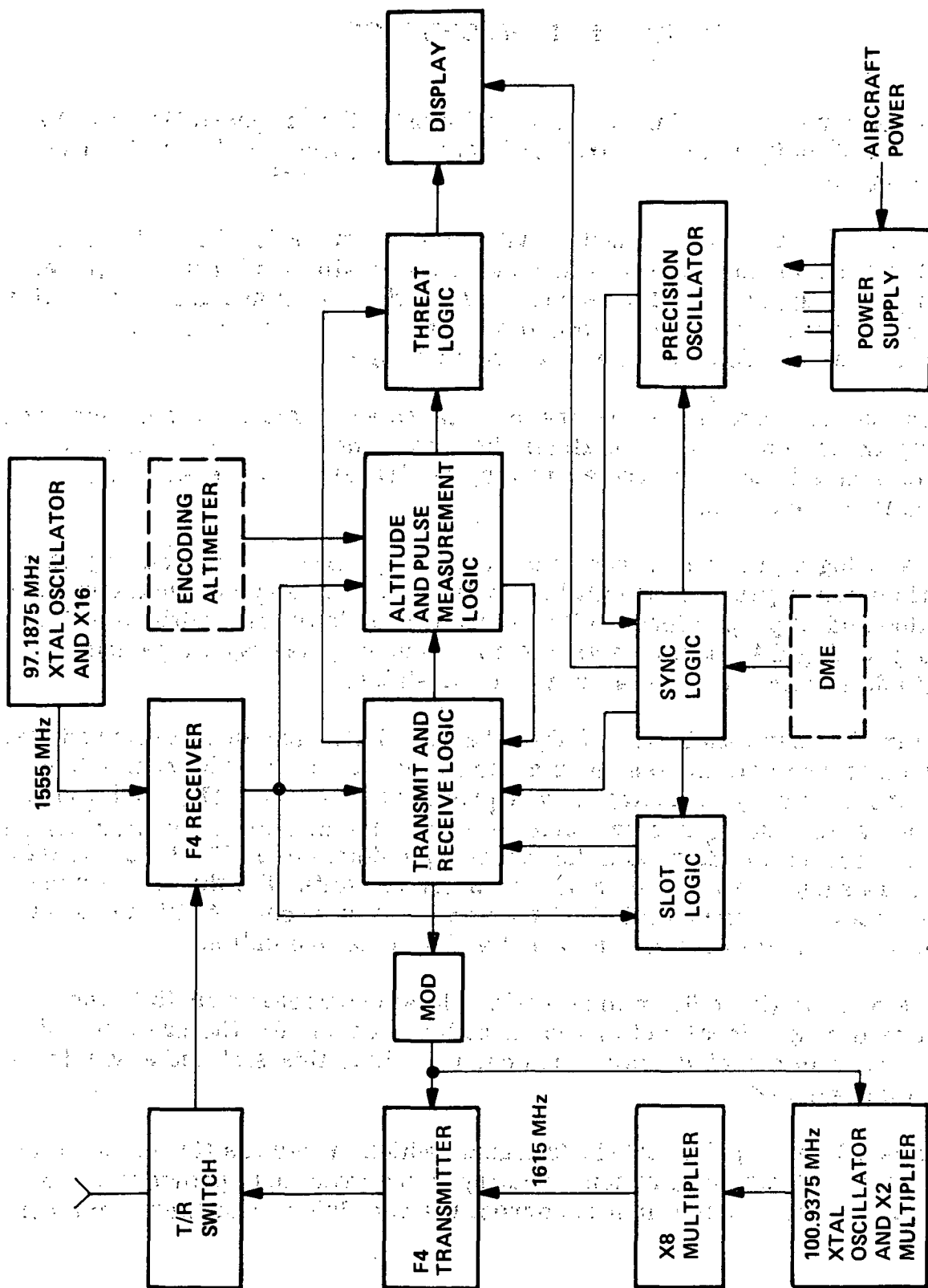
When the sync logic receives fine and coarse sync data from the Distance Measuring Equipment (DME) and aligns the local time base with the ground station time base to the required accuracy, the transmit and receive logic inhibit signal is removed.

The slot logic provides a local slot once every three seconds during which a fixed-time range pulse and an altitude pulse that is time-positioned from the range pulse and is proportional to the aircraft altitude is transmitted on F_4 . Other cooperating CAS participants can now measure one-way range and altitude to determine the local aircraft threat status.

During all other usable slots (other than local slot and some reserved test slots) other aircraft transmissions may be received. It must be remembered that with the frequency switching format proposed, a suitable (F_4) slot appears every other slot. The F_4 receiver detects the r-f, the altitude and pulse measurement logic verifies the data, and the threat logic determines if a threat exists. If a threat is such that a climb or dive command results, the threat logic adds a 200-foot bias to the transmitted altitude only. Any threat condition causes the display to activate with both an aural and a visual indication.

The slot logic (in addition to selecting slots) occasionally inhibits the transmitter during a local slot and looks at the receiver for the presence of video. If video is detected, more than one user is in this slot and a new local slot must be selected.

The oscillator supplies a 5-MHz signal, which drives the timing chain in the sync logic. Time comparison circuitry in the sync logic provides a frequency control error with which to correct the oscillator frequency to the sync source.



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Figure 1. General Aviation Collision Avoidance System Block Diagram

SECTION II

DETAILED DESCRIPTION

A. R-F ASSEMBLY

1. Function. The r-f assembly provides a duplexing function to permit receiving and transmitting on the same antenna, a low pass filter to suppress transmitter harmonically generated signals, a limiter to prevent mixer overload, a preselector for eliminating out-of-band interference signals, a local oscillator filter to eliminate unwanted signals from the local oscillator signal source, and a balanced mixer for detection of the r-f signal.

2. Description. The r-f assembly characteristics are described in Specification SP7115-0100 of appendix A. Proposals were received from various suppliers of r-f assemblies on detail techniques for providing the function described.

B. TRANSMITTER POWER AMPLIFIER

1. Function. The power amplifier provides approximately 24 db of gain to the 1615 MHz signal from the X8 multiplier to obtain the required minimum power output of 80 watts.

2. Description. The power amplifier characteristics are described in Specification SP7115-0103 of appendix B. Proposals were received from various suppliers of power amplifiers on detailed techniques for providing the function described. Note that the specification calls for a minimum of 150 watts power output to allow about 3 db of tube degradation.

C. ANTENNA

The antenna is a simple quarter-wave monopole structure that has a nominal input impedance of 50 ohms with a voltage standing wave ratio (VSWR) of 1.5:1 or less. The antenna is vertically polarized and should be located to provide as nearly omnidirectional coverage as possible.

During local flight tests of the Sierra-Wilcox limited CAS, some qualitative experiments were conducted to determine typical antenna coverage and the following results were noted:

1. A top antenna on the fuselage of the Cessna 180 gave good all around CAS threat coverage but provided poor ground sync coverage when the aircraft was headed toward the ground station. The reason for this poor coverage was attributed to the upward slope of the Cessna 180 fuselage in level flight and was somewhat validated by noting good coverage when outbound from the ground

station and even good coverage when a 90° turn was made except when directly over the ground station. Only the top antenna was used in this experiment.

2. A bottom antenna on the Cessna 180 also gave good all around CAS threat coverage but provided poor sync coverage when the aircraft was on a heading tangential to the ground station and with the landing gear obstructing the path to the ground station. The landing gear was assumed the most likely cause of the signal loss and was validated by making small turns and noting the reacquisition of the signal.

The bottom antenna also provided poor ground sync coverage but in the opposite direction of the top antenna. When the aircraft was outbound, poor ground sync coverage was noted but inbound to the ground station good ground sync coverage was noted.

3. On the Beech Baron, the top fuselage coverage for CAS threat coverage was good but ground sync coverage was very poor. Good ground sync coverage was not noted until the antenna was placed on the top of tail where excellent all around coverage was noted. The only problem noted on the tail location was when the aircraft was heading toward the station and either the fuselage or a wing would shield the antenna. No problems with ground sync reception were noted on the bottom antenna of the Beech Baron.

While these tests were qualitative, they do indicate that several locations provided CAS threat coverage with one antenna. Since the system defined herein does not require synchronization data on the CAS antenna, no problem is foreseen on the use of one antenna; however it is suggested that a separate program be funded to conduct quantitative tests before implementation. Circuitry for the use of two antennas is included for those that require it, but costing is based on only one antenna.

D. VARACTOR MULTIPLIER

1. Function. The varactor multiplier provides an X8 multiplication of the 201.875 MHz, 600-milliwatt signal from the exciter to feed the power amplifier of the transmitter with a 1615 MHz signal.

2. Description. The varactor multiplier characteristics are described in Specification SP7115-0102 of appendix C. Proposals were received from various suppliers of r-f assemblies on detail techniques for providing the function described.

E. PRECISION OSCILLATOR

1. Function. The precision oscillator provides a highly stable 5 MHz signal source for the precise timing required for the time/frequency system.

defined. A frequency control input is provided to frequency-synchronize the oscillator to the system frequency if sync data is available.

2. Description. The precision oscillator characteristics are described in Specification SP7115-0101 of appendix D. Proposals were received from various suppliers of precision oscillators on detail techniques for providing the function described.

F. LOCAL OSCILLATOR SIGNAL SOURCE

1. Function. The local oscillator signal source uses a standard oscillator and appropriate multipliers to generate a 1555 MHz signal, at a power level of 4 milliwatts, into the mixer part of the r-f assembly.

2. Description. Figure 2 shows a block diagram of the local oscillator signal source and schematic 7115-0517 shows the circuit diagram of the local oscillator signal source. A basic crystal controlled transistor oscillator at 97.1875 MHz feeds a buffer/multiplier transistor stage that provides isolation for the oscillator and a X2 multiplication to 194.375 MHz. The output of the buffer/multiplier drives a step recovery diode (SRD) X8 multiplier to produce the 1555 MHz local oscillator signal at the 4 milliwatts power level required by the mixer in the r-f assembly.

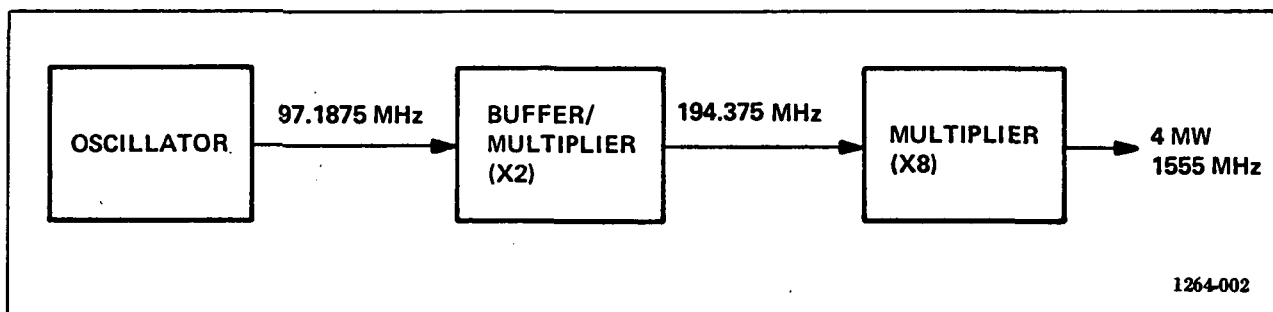
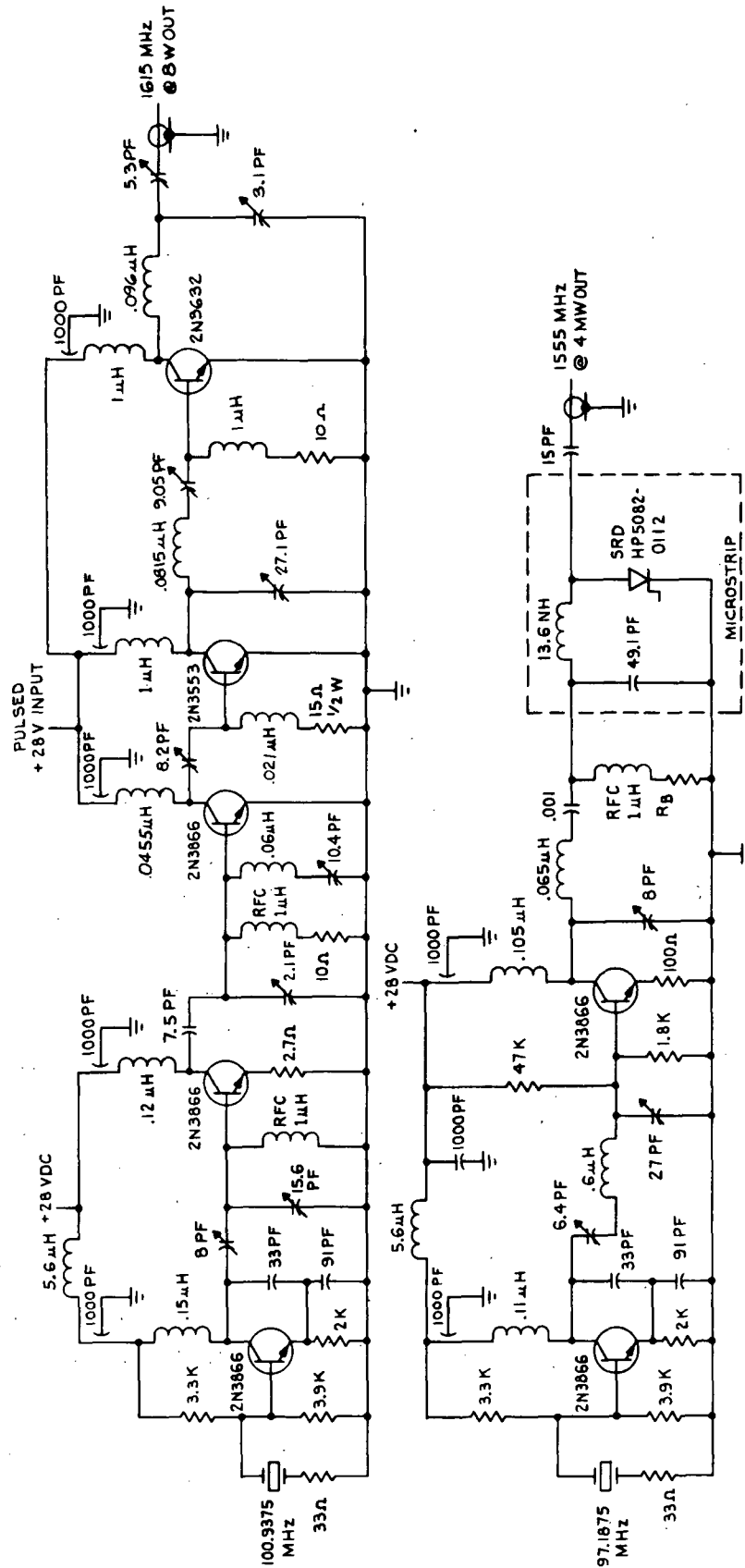


Figure 2. Local Oscillator Signal Source Block Diagram

G. EXCITER SIGNAL SOURCE

1. Function. The exciter signal source uses a standard oscillator and an appropriate multiplier to generate a 201.875 MHz signal, at a power level of 8 watts, into the X8 multiplier for the transmitter signal source.

2. Description. Figure 3 shows a block diagram of the exciter signal source and schematic 7115-0517 shows the circuit diagram of the exciter signal source. A basic crystal controlled transistor oscillator at 100.9375 MHz feeds an amplifier which isolates the oscillator and provides a gain of 10 db. The amplifier output drives a transistor multiplier (X2) which produces



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a 201.875 MHz that in turn is amplified by 10 db to produce an output power level of 2 watts which is fed into a 6 db gain amplifier to produce an output of 8 watts in a 50 ohm load. Pulsed 28 vdc power is applied from the modulator to conserve power significantly since the duty cycle is very low (0.000018) and 8 watts of power are required.

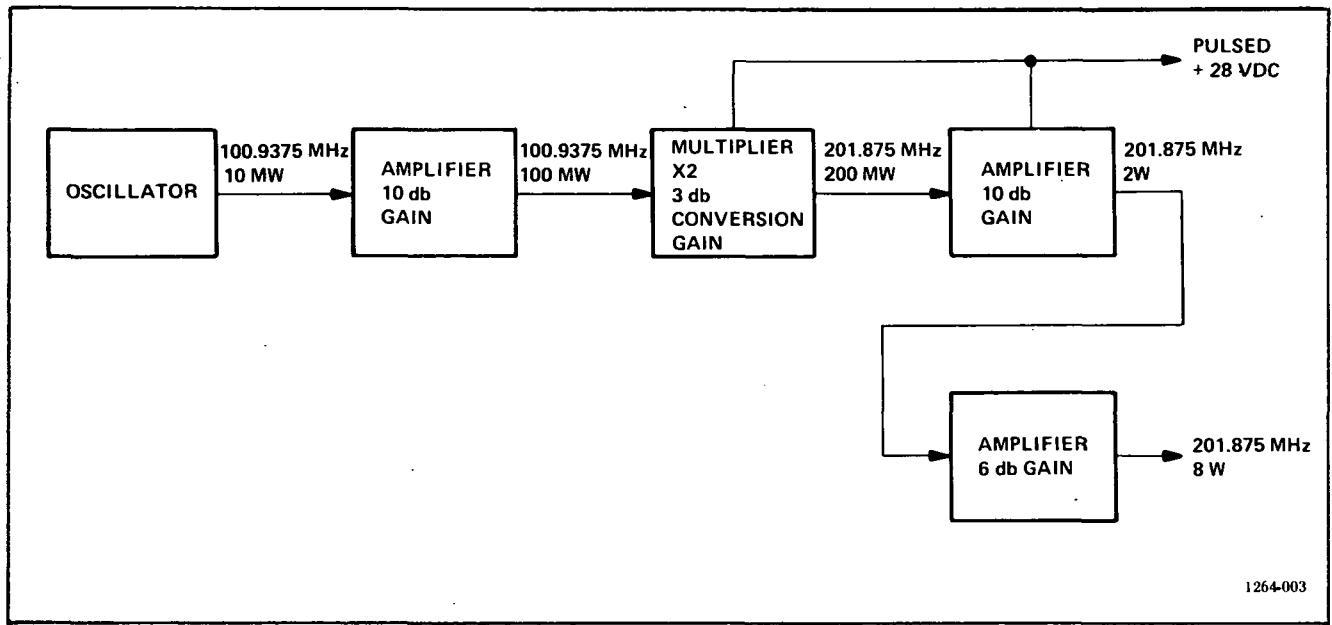


Figure 3. Exciter Signal Source Block Diagram

H. POWER SUPPLY

1. Function. The power supply converts the standard aircraft +13.75 vdc or +27.5 vdc into the necessary voltages and currents that are required for the various circuits in the equipment. The power supply also provides line and load regulation as well as aircraft power transient protection.

2. Description. Figure 4 shows a block diagram of the power supply and schematic 7115-0537 shows the circuit diagram of the power supply. A switching regulator is used as an efficient line regulator over the expected $\pm 10\%$ variation of the 13.75 vdc or 27.5 vdc input voltage to provide 10 vdc to the d-c to d-c converter. A conventional regulator could be used but is much less efficient and although they cost less to build, the cost of higher dissipation creating heat is more than offset. Also, when switching installations from a 13.75 vdc to a 27.5 vdc power source, no changes in power hook-up are required. The d-c to d-c converter changes the 10 vdc to the voltages at the stated currents as follows:

a.	+5 Volts dc @ 3 Amps	15.0	watt
b.	+22 Volts dc @ 280 MA	6.2	watt
c.	6.3 Volts rms @ 2 Amps	12.6	watt
d.	+1400 Volts dc @ .02 MA (Avg)	0.028	watt
e.	+28 Volts dc @ 250 MA	7.0	watt
f.	-18 Volts dc @ 50 MA	0.9	watt
g.	+15 Volts dc @ 50 MA	0.75	watt

Total Power Required from Supply 42.48 watts

a. Power Requirements. As can be seen in the preceding paragraph a total of 42.48 watts must be supplied to the circuitry. With a d-c to d-c converter efficiency of 80%, this means that 53 watts must be supplied to the d-c to d-c converter and with an 80% Switching Regulator efficiency, the total power supplied is 66.3 watts.

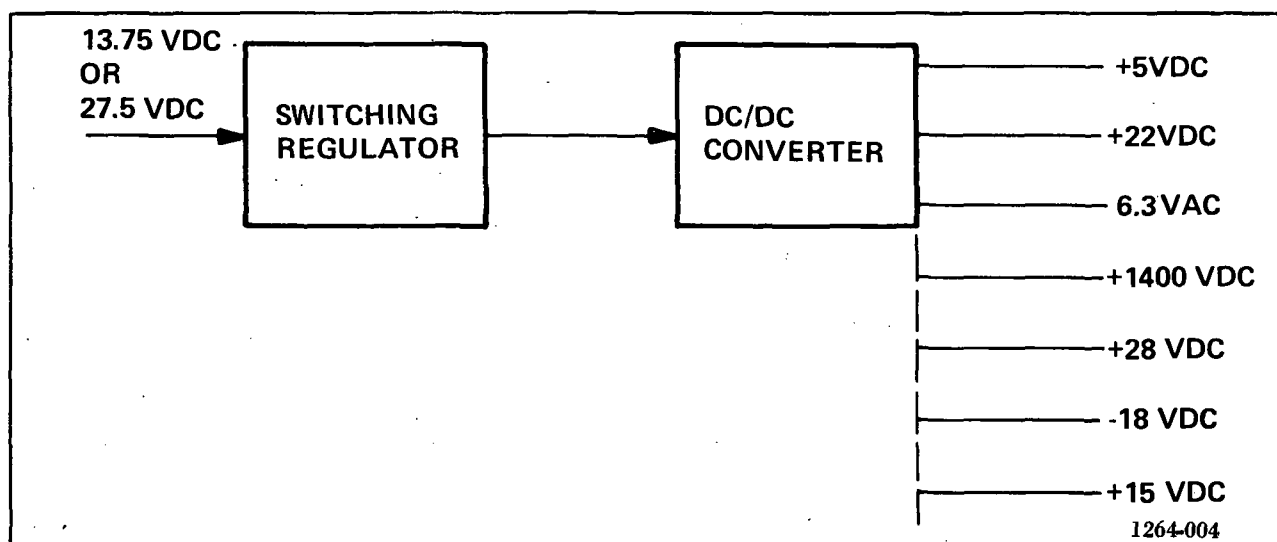


Figure 4. Power Supply Block Diagram

b. Switching Regulator. Figure 5 shows a block diagram of the Switching Regulator elements. The input voltage range is from 12.375 vdc to 30.25 vdc when a 10% line variation is allowed. To provide an output regulation of 10%, an output voltage of 10.0 vdc was chosen to be consistent with the nominal 12 vdc and 31 vdc input variation.

Since a switching regulator operates essentially as a switch, input and output voltages need only differ by the saturation voltage of the series switch transistor. Some switch considerations for the series transistor and driver transistor are as follows:

- (1) Low saturation voltage to keep dissipation down during on condition ($V_{ce\ sat} < 1$ Volt).

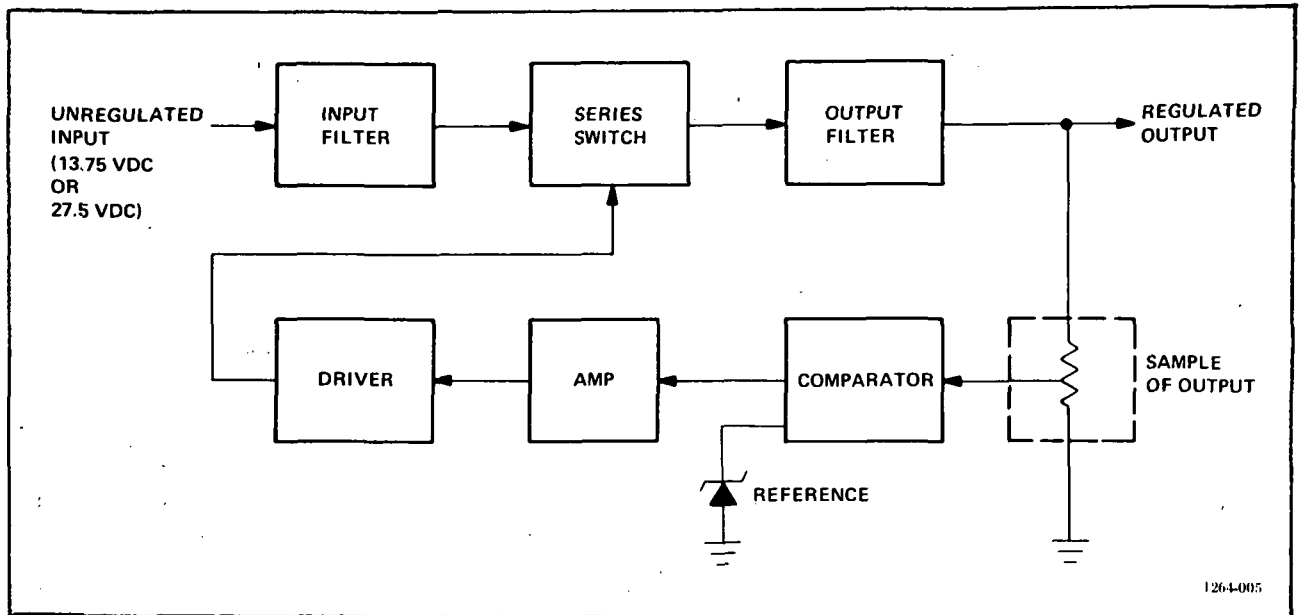


Figure 5. Switching Regulator Block Diagram

- (2) Collector to emitter breakdown voltage must be $\geq V_{\text{input}} - V_{\text{output}}$.
- (3) Collector current rating ≥ 1.5 times the d-c output current for the series transistor and a collector current rating $\geq 1.5/10$ times the dc output current for the driver transistor for reliable operation.
- (4) Fast switching speed to keep switching losses to a minimum (turn-on and turn-off < 1 microsecond).

The frequency of the switching regulator is determined by:

- (a) Output filter components,
- (b) Output load,
- (c) Gain and hysteresis of comparator,
- (d) Input voltage.

The values shown on the schematic 7115-0537 were experimentally determined to give a frequency of operation of 10-40 KHz depending on load and/or input voltage. The frequency chosen represents a compromise between efficiency and size of filtering components, that is, if frequency of operation is increased, filter components get smaller, but switching losses get greater.

All of the transistors in the switching regulator operate in a switching mode, i.e., on or off. Resistor values for bias are calculated assuming a current gain of 10-20 at saturation, (depending on manufacturers' specifications at current level being used).

Transient protection is provided by the 33-volt Zener diode firing and turning off the series switch and driver for the duration of the transient.

c. D-C to D-C Converter. The d-c to d-c converter inverts the 10 VDC from the switching regulator and converts this signal to fixed load voltages as required by conventional rectifiers.

The inverter shown in figure 6 is a conventional square wave,

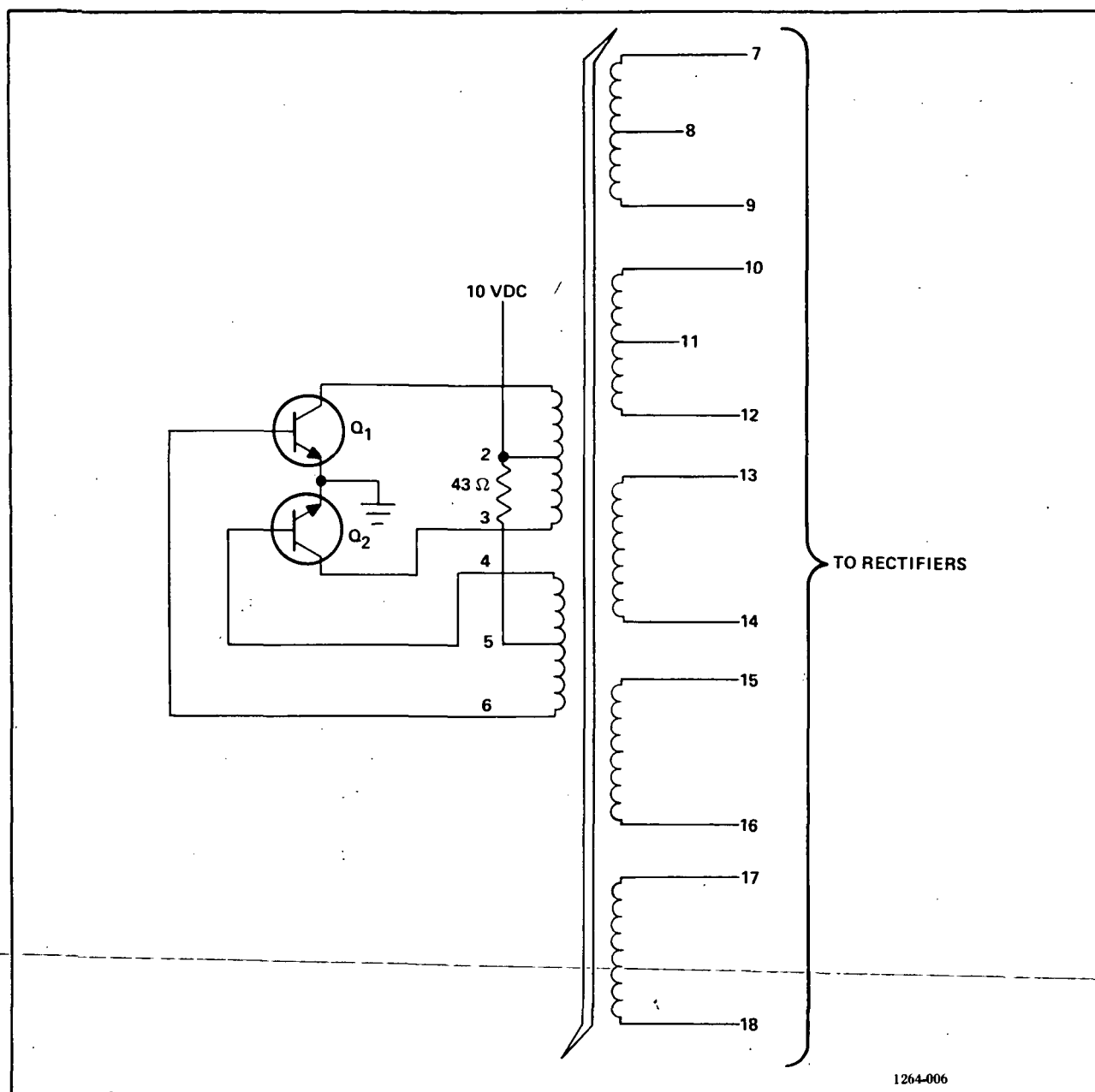


Figure 6. Inverter Circuit Diagram

saturable core, free-running multivibrator. Frequency of operation is about 10 KHz which represents a compromise between size (of both transformer and filtering components) and efficiency. Q_1 and Q_2 must have low saturation voltages (≤ 1.0 volt), have voltage breakdown $B_{V_{CE0}} \geq 20$ volts, have switching speeds $\leq 1.0 \mu\text{sec}$, and be capable of switching collector currents of at least 6.5 amps without secondary breakdown. The transformer must provide the necessary secondary voltages and currents, must be designed to operate at about 10 KHz in a saturating mode with 10 vdc input to the inverter, and should be as efficient as possible.

The rectifiers are standard design and values of filter components used to filter secondary voltages are experimentally determined to provide an acceptable level of ripple. Choke input filters are used to prevent excessive "spike" currents from being generated when the filter capacitors are being charged with a square wave voltage.

I. VIDEO AMPLIFIER AND NOISE AGC

1. Function. The video amplifier and noise AGC circuit receives the low level video signal from the i-f amplifier and, after appropriate signal conditioning, provides a standard logic output for signal processing. In addition, a noise detection/amplifier circuit provides a noise AGC for i-f amplifier gain control.

2. Description. Figure 7 shows a block diagram and schematic 7115-0522 shows the circuit diagram of the video amplifier and noise AGC. The requirements of the circuit are as follows:

Approximately 40 db of gain is required to bring the i-f amplifier output level up to a value that is sufficient to drive the threshold circuit at the minimum signal input.

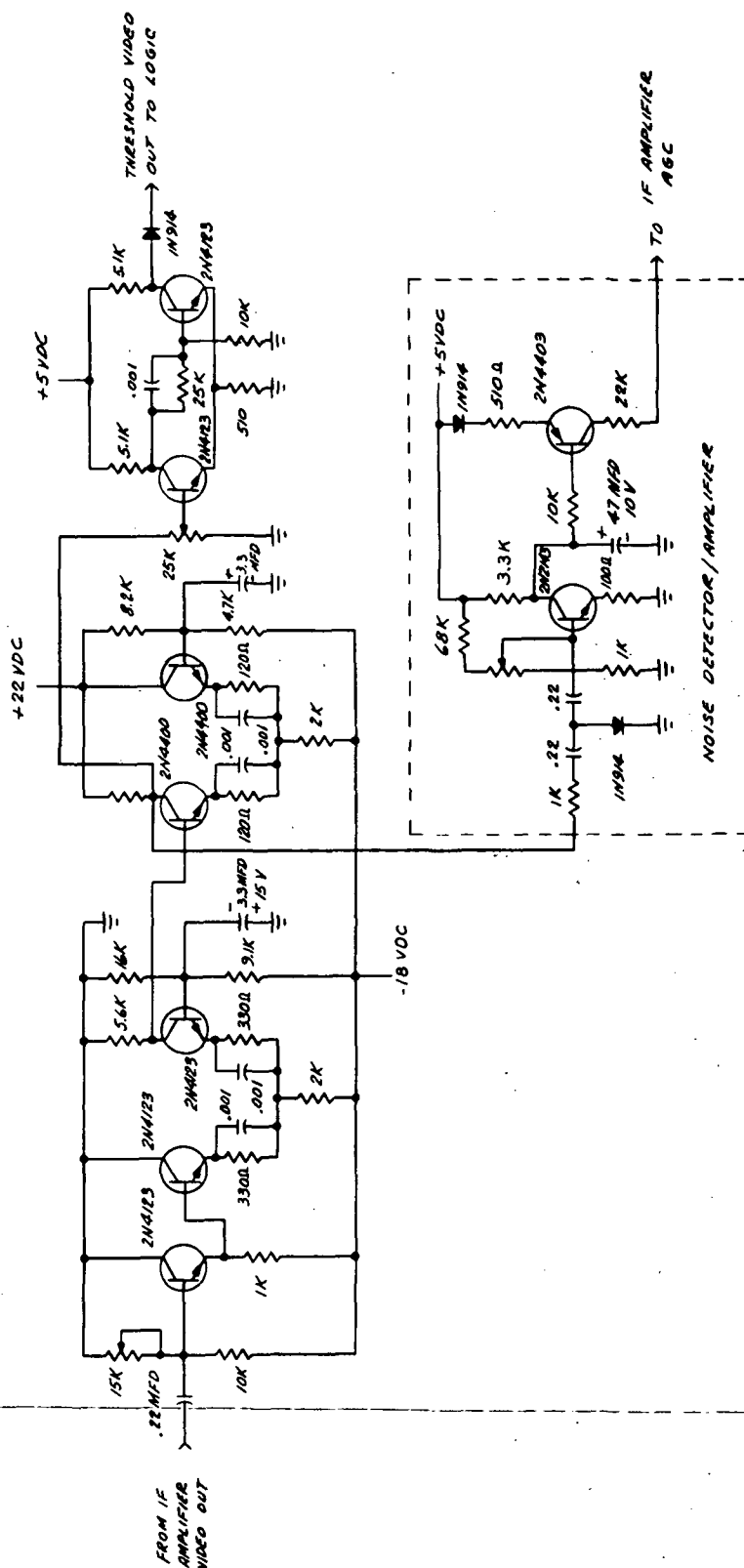
Approximately 20 db of dynamic range is required since the logarithmic/linear i-f amplifier will vary the 20 db for an input level variation of 80 db to the receiver.

No pulse stretching or compression since pulse width tests are made for signal validation.

The threshold circuit must detect signals that are at least 10 db above noise.

The noise AGC must hold the gain of the i-f amplifier constant.

a. Video Amplifier. The video amplifier is identical to that which was used in the Sierra/Wilcox test and evaluation CAS flown in the Air



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Transport Association sponsored tests at Baltimore. The circuit is a conventional differential amplifier with negative feedback added to provide the necessary linearity without stretching the video pulse. To provide the 20 db dynamic range, it is necessary to operate with the high V_{cc} voltage (+22 and -18 vdc).

The thresholding is accomplished with a conventional schmitt trigger which has the capability of being adjusted at a signal-to-noise ratio of 10 db to allow thresholding. Fixed thresholding is acceptable as long as the i-f gain is held constant.

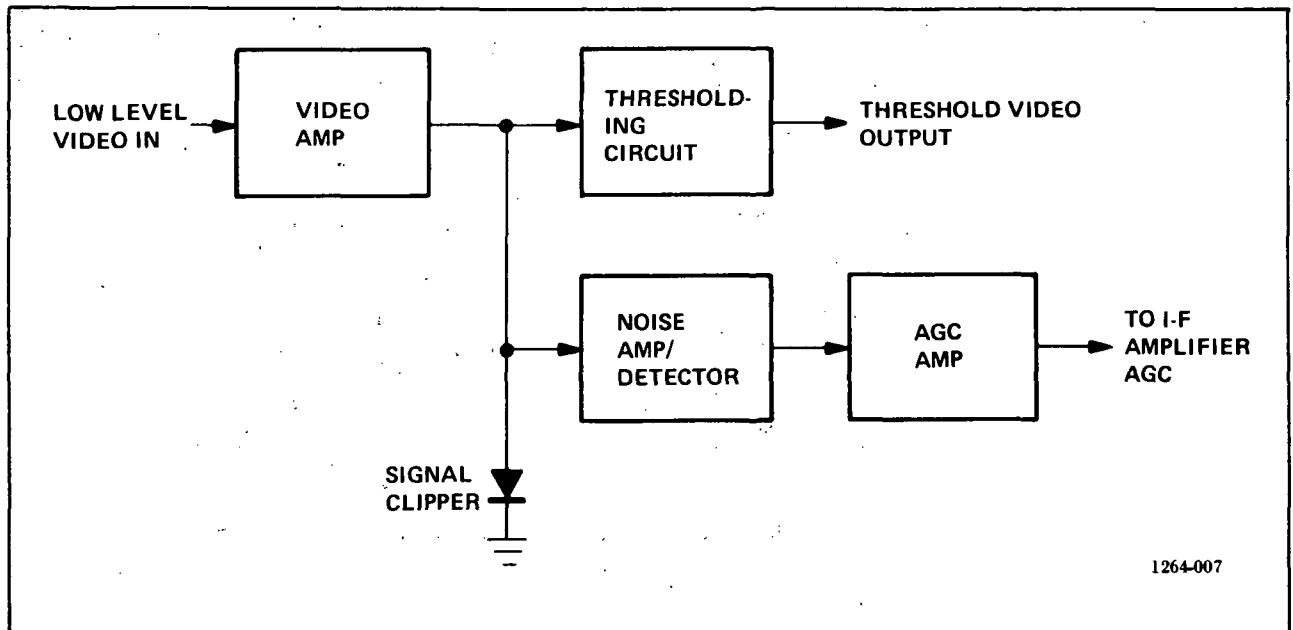


Figure 7. Video Amplifier and Noise AGC

b. Noise AGC. The AGC circuit holds the i-f gain constant by detecting the noise level out of the video amplifier and producing a d-c voltage to vary the gain of two stages of the i-f amplifier. The signal fed to the noise AGC circuit contains both signal and noise; therefore, a clipper is used to eliminate the signal at a level just above the noise. Some signal may be present at the noise detector/amplifier but, because of the low duty cycle, will not contribute significantly to the gain control voltage. The AGC circuit has a very long time constant to provide a correction voltage that is essentially a function of noise level or i-f gain.

J. I-F AMPLIFIER

1. Function. The 60 MHz difference frequency from the mixer is amplified by the i-f amplifier, and provides a video signal to the video amplifier that is a logarithmic function of the receiver input signal level. The i-f amplifier also provides the band-limiting function of the receiver with a band-pass filter (BPF).

2. Description. Figure 8 shows a block diagram of the i-f amplifier and schematic 7115-0527 shows a circuit diagram. The i-f amplifier and BPF provide 12 to 14 db of gain; the remaining 6 stages of amplification provide 14 to 18 db of gain each, which results in an overall gain of from 96 to 122 db of gain. Approximately 100 db of gain is necessary for inexpensive detection, and it is very unlikely that the worst case gain of 96 db would ever occur with a normal distribution of transistors. Since it is quite likely that gains in excess of 100 db will be realized, gain control is included in the 2nd and 3rd i-f stage to allow adjustment to the desired gain. The transistor (2N4123) on schematic 7115-0527 acts as a variable resistor in the emitter circuits of the 2nd and 3rd stage. The gain of these stages decreases with increasing emitter current. Controls for receiver adjustment are located on the video amplifier and noise AGC circuit diagram to provide for 20 to 30 db of i-f gain difference.

The approach used is to broadband all amplifier stages to minimize passband shift with temperature or signal level. The selectivity of the i-f amplifier is then determined by a bandpass filter inserted between the first and second i-f stage.

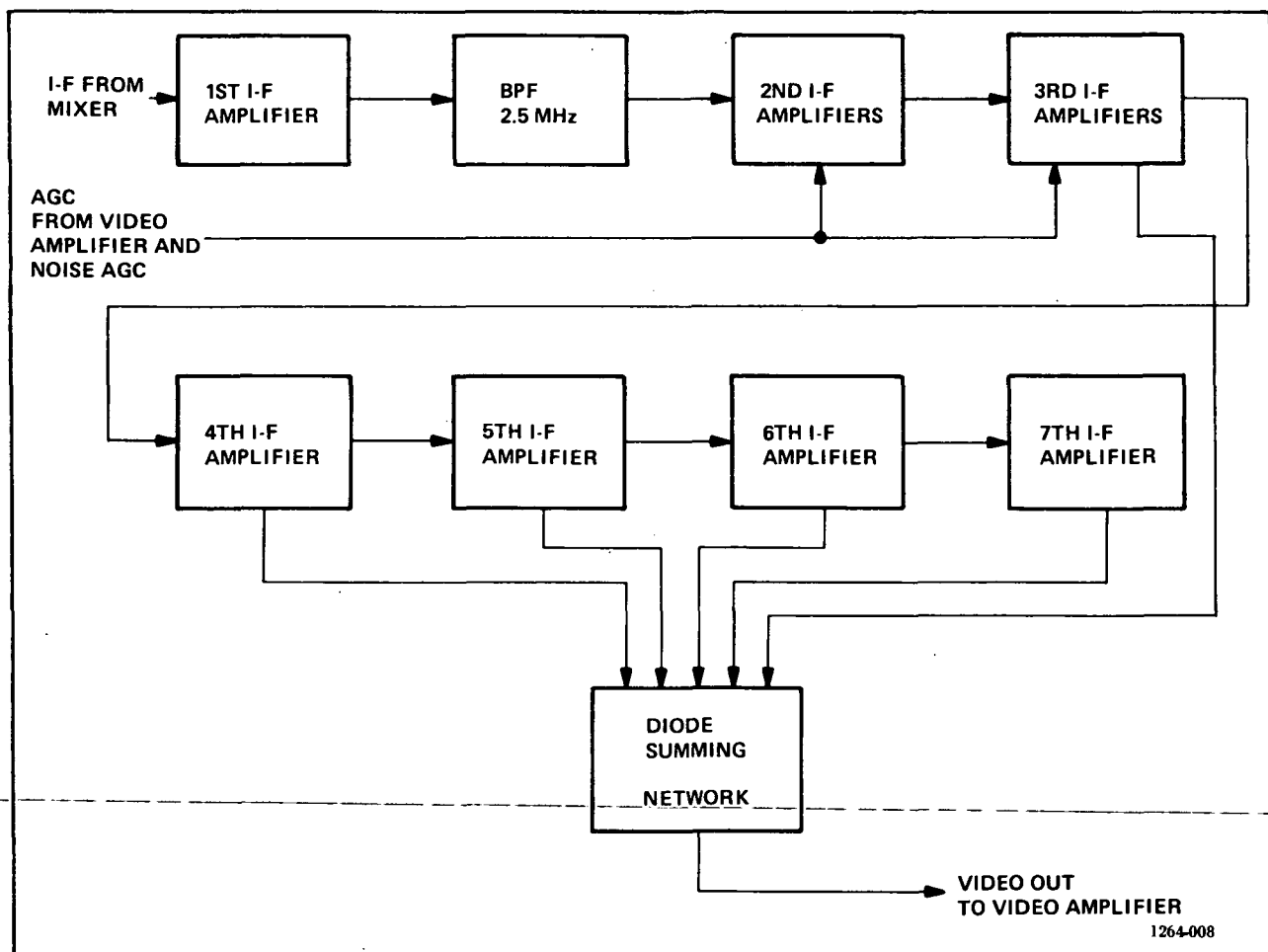
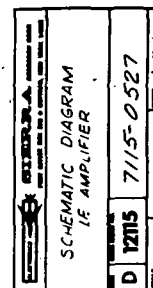
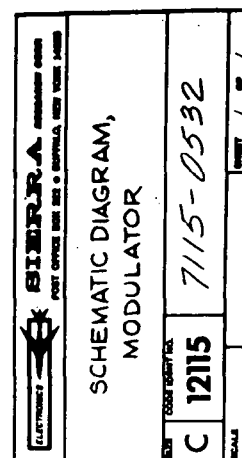


Figure 8. I-F Amplifier Block Diagram



1. ALL RESISTORS $\frac{1}{4}$ WATT UNLESS OTHERWISE NOTED.

NOTES:



a. Modulator. Experience has shown that shaping of the transmitted pulse can be accomplished best by shaping the r-f pulse before it is fed into the power amplifier. The power amplifier is then biased into conduction just before the r-f drive is applied, and left on just slightly longer than the r-f drive. Figure 10 shows the timing sequence.

The transmit logic provides the start and stop of any transmitted pulse exactly $1.0\ \mu\text{sec}$. early to provide an adjustment range in the modulator for transmit delay changes, as well as the normal modulator function of turning on and controlling the transmitter. Transmitter turn-on and turn-off delays of $0.3\ \mu\text{sec}$. can be controlled independently with the circuit shown which assumes a minimum OFF-ON or ON-OFF delay of $0.4\ \mu\text{sec}$. and a maximum OFF-ON or ON-OFF delay of $0.7\ \mu\text{sec}$. The circuitry shown was successfully used in the Sierra/Wilcox CAS equipment flown in the Air Transport Association sponsored flight test.

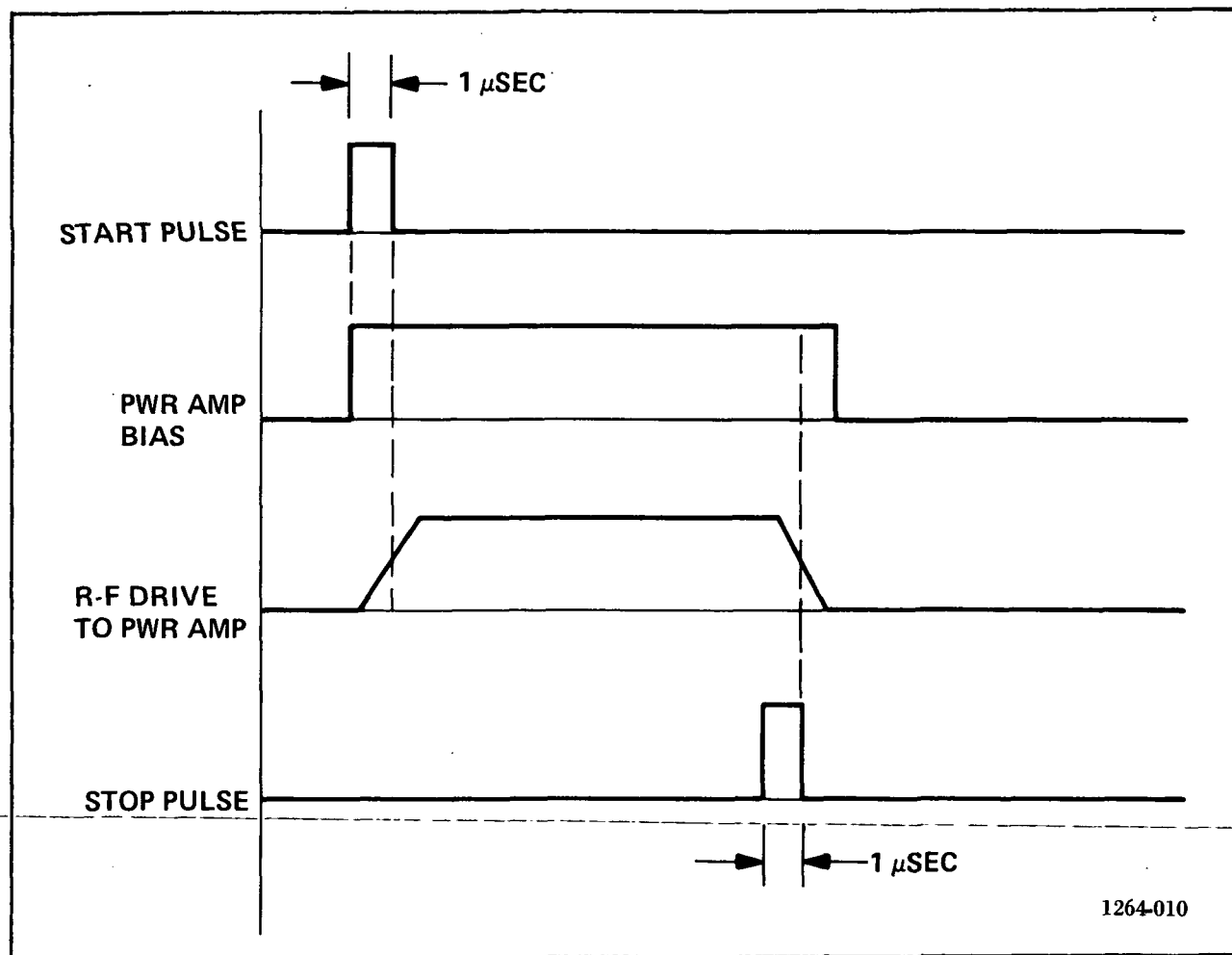


Figure 10. Modulator Timing Sequence

Turn-on delay of 120 seconds for transmitter tube filament warm-up is provided by the transmit logic and is used to inhibit any transmitter or exciter turn-on signals.

b. **Antenna Switch Driver.** The antenna switch driver accepts a logic control level from the synchronization logic, and appropriately controls either the top or bottom antenna. The "on" antenna requires a 5-volt signal at 100 milliamperes, and the "off" antenna requires a back-bias of -18 volts. The circuit shown on schematic 7115-0532 provides these required values.

L. ALTITUDE AND PULSE MEASUREMENT LOGIC

1. **Function.** The altitude and pulse measurement logic performs the following:

Converts the ICAO code from the encoding altimeter into a binary code.

Provides a pulse position signal relative to aircraft altitude to the transmit logic for transmission of altitude data in "local slot".

Provides pulse verification of either a 30- or 300-microsecond pulse for the receive logic in all F_4 slots except those reserved for test purposes and local slot.

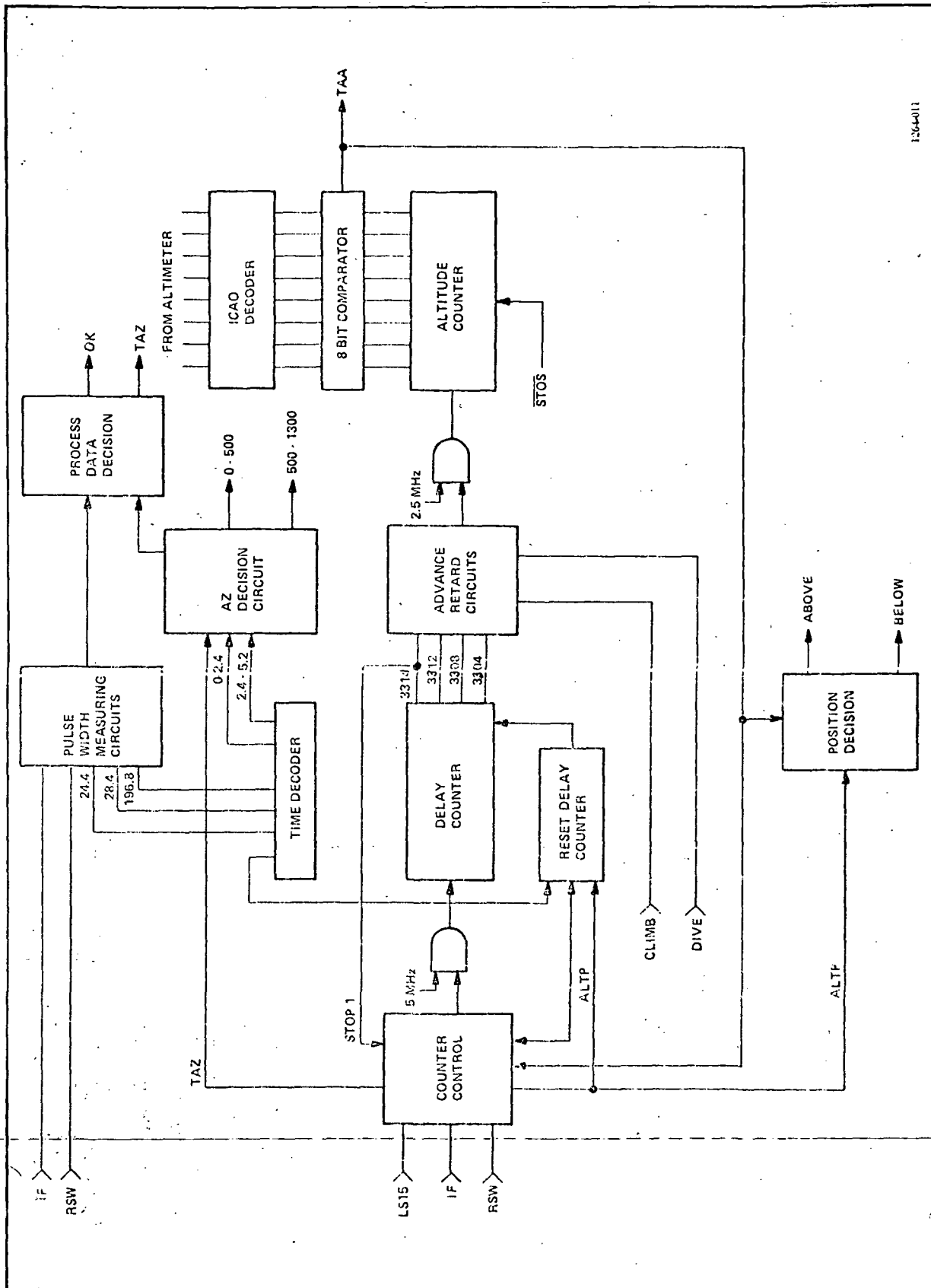
Provides pulse verification of the 25.6-microsecond altitude pulse for internal altitude logic use.

Provides above/below, altitude zone, sample command, and a valid data signal to the threat logic, depending upon received information.

2. **Description.** Figure 11 shows a block diagram and schematic 7115-0547 shows a detail logic diagram of the altitude and pulse measurement logic.

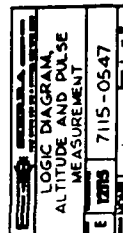
a. **Transmit Mode.** In the transmit mode, the circuit simply provides a pulse position signal (relative to aircraft altitude) to the transmit logic. The signal is only transmitted in the aircraft "local slot". Figure 12 shows the timing relationship of the altitude transmission.

Signal LS15, which occurs 15 microseconds after the start of local slot, starts the delay counter counting at a 5 MHz rate and is used to delay the start of the altitude counter. The 662.8-microsecond (count 3314) length of the delay counter is chosen as a convenient value to correspond to an altitude of 14,300 feet. This delay length is chosen to allow processing of received data up to this maximum altitude. However, since the general avia-



1364011

Figure 11. Altitude and Pulse Measurement Logic Block Diagram



1. ON ALL DUAL IN LINE PACKS, +5V IS CONNECTED TO PIN 14, GROUND IS CONNECTED TO PIN 7, ON ALL 7400, 7401, 7402, 7403, 7404, 7405, 7406, 7407, 7408, 7409, 7410, 7411, 7412, 7413, 7414, 7415, 7416, 7417, 7418, 7419, 7420, 7421, 7422, 7423, 7424, 7425, 7426, 7427, 7428, 7429, 7430, 7431, 7432, 7433, 7434, 7435, 7436, 7437, 7438, 7439, 7440, 7441, 7442, 7443, 7444, 7445, 7446, 7447, 7448, 7449, 7450, 7451, 7452, 7453, 7454, 7455, 7456, 7457, 7458, 7459, 7460, 7461, 7462, 7463, 7464, 7465, 7466, 7467, 7468, 7469, 7470, 7471, 7472, 7473, 7474, 7475, 7476, 7477, 7478, 7479, 7480, 7481, 7482, 7483, 7484, 7485, 7486, 7487, 7488, 7489, 7490, 7491, 7492, 7493, 7494, 7495, 7496, 7497, 7498, 7499, 7500, 7501, 7502, 7503, 7504, 7505, 7506, 7507, 7508, 7509, 7510, 7511, 7512, 7513, 7514, 7515, 7516, 7517, 7518, 7519, 7520, 7521, 7522, 7523, 7524, 7525, 7526, 7527, 7528, 7529, 7530, 7531, 7532, 7533, 7534, 7535, 7536, 7537, 7538, 7539, 7540, 7541, 7542, 7543, 7544, 7545, 7546, 7547, 7548, 7549, 7550, 7551, 7552, 7553, 7554, 7555, 7556, 7557, 7558, 7559, 7560, 7561, 7562, 7563, 7564, 7565, 7566, 7567, 7568, 7569, 7570, 7571, 7572, 7573, 7574, 7575, 7576, 7577, 7578, 7579, 7580, 7581, 7582, 7583, 7584, 7585, 7586, 7587, 7588, 7589, 7590, 7591, 7592, 7593, 7594, 7595, 7596, 7597, 7598, 7599, 7600, 7601, 7602, 7603, 7604, 7605, 7606, 7607, 7608, 7609, 7610, 7611, 7612, 7613, 7614, 7615, 7616, 7617, 7618, 7619, 7620, 7621, 7622, 7623, 7624, 7625, 7626, 7627, 7628, 7629, 7630, 7631, 7632, 7633, 7634, 7635, 7636, 7637, 7638, 7639, 7640, 7641, 7642, 7643, 7644, 7645, 7646, 7647, 7648, 7649, 7650, 7651, 7652, 7653, 7654, 7655, 7656, 7657, 7658, 7659, 7660, 7661, 7662, 7663, 7664, 7665, 7666, 7667, 7668, 7669, 7670, 7671, 7672, 7673, 7674, 7675, 7676, 7677, 7678, 7679, 7680, 7681, 7682, 7683, 7684, 7685, 7686, 7687, 7688, 7689, 7690, 7691, 7692, 7693, 7694, 7695, 7696, 7697, 7698, 7699, 7700, 7701, 7702, 7703, 7704, 7705, 7706, 7707, 7708, 7709, 7710, 7711, 7712, 7713, 7714, 7715, 7716, 7717, 7718, 7719, 7720, 7721, 7722, 7723, 7724, 7725, 7726, 7727, 7728, 7729, 7730, 7731, 7732, 7733, 7734, 7735, 7736, 7737, 7738, 7739, 7740, 7741, 7742, 7743, 7744, 7745, 7746, 7747, 7748, 7749, 7750, 7751, 7752, 7753, 7754, 7755, 7756, 7757, 7758, 7759, 7760, 7761, 7762, 7763, 7764, 7765, 7766, 7767, 7768, 7769, 7770, 7771, 7772, 7773, 7774, 7775, 7776, 7777, 7778, 7779, 7780, 7781, 7782, 7783, 7784, 7785, 7786, 7787, 7788, 7789, 7790, 7791, 7792, 7793, 7794, 7795, 7796, 7797, 7798, 7799, 7800, 7801, 7802, 7803, 7804, 7805, 7806, 7807, 7808, 7809, 7810, 7811, 7812, 7813, 7814, 7815, 7816, 7817, 7818, 7819, 7820, 7821, 7822, 7823, 7824, 7825, 7826, 7827, 7828, 7829, 7830, 7831, 7832, 7833, 7834, 7835, 7836, 7837, 7838, 7839, 7840, 7841, 7842, 7843, 7844, 7845, 7846, 7847, 7848, 7849, 7850, 7851, 7852, 7853, 7854, 7855, 7856, 7857, 7858, 7859, 7860, 7861, 7862, 7863, 7864, 7865, 7866, 7867, 7868, 7869, 7870, 7871, 7872, 7873, 7874, 7875, 7876, 7877, 7878, 7879, 7880, 7881, 7882, 7883, 7884, 7885, 7886, 7887, 7888, 7889, 7890, 7891, 7892, 7893, 7894, 7895, 7896, 7897, 7898, 7899, 7900, 7901, 7902, 7903, 7904, 7905, 7906, 7907, 7908, 7909, 7910, 7911, 7912, 7913, 7914, 7915, 7916, 7917, 7918, 7919, 7920, 7921, 7922, 7923, 7924, 7925, 7926, 7927, 7928, 7929, 7930, 7931, 7932, 7933, 7934, 7935, 7936, 7937, 7938, 7939, 7940, 7941, 7942, 7943, 7944, 7945, 7946, 7947, 7948, 7949, 7950, 7951, 7952, 7953, 7954, 7955, 7956, 7957, 7958, 7959, 7960, 7961, 7962, 7963, 7964, 7965, 7966, 7967, 7968, 7969, 7970, 7971, 7972, 7973, 7974, 7975, 7976, 7977, 7978, 7979, 7980, 7981, 7982, 7983, 7984, 7985, 7986, 7987, 7988, 7989, 7990, 7991, 7992, 7993, 7994, 7995, 7996, 7997, 7998, 7999, 8000, 8001, 8002, 8003, 8004, 8005, 8006, 8007, 8008, 8009, 8010, 8011, 8012, 8013, 8014, 8015, 8016, 8017, 8018, 8019, 8020, 8021, 8022, 8023, 8024, 8025, 8026, 8027, 8028, 8029, 8030, 8031, 8032, 8033, 8034, 8035, 8036, 8037, 8038, 8039, 8040, 8041, 8042, 8043, 8044, 8045, 8046, 8047, 8048, 8049, 8050, 8051, 8052, 8053, 8054, 8055, 8056, 8057, 8058, 8059, 8060, 8061, 8062, 8063, 8064, 8065, 8066, 8067, 8068, 8069, 8070, 8071, 8072, 8073, 8074, 8075, 80

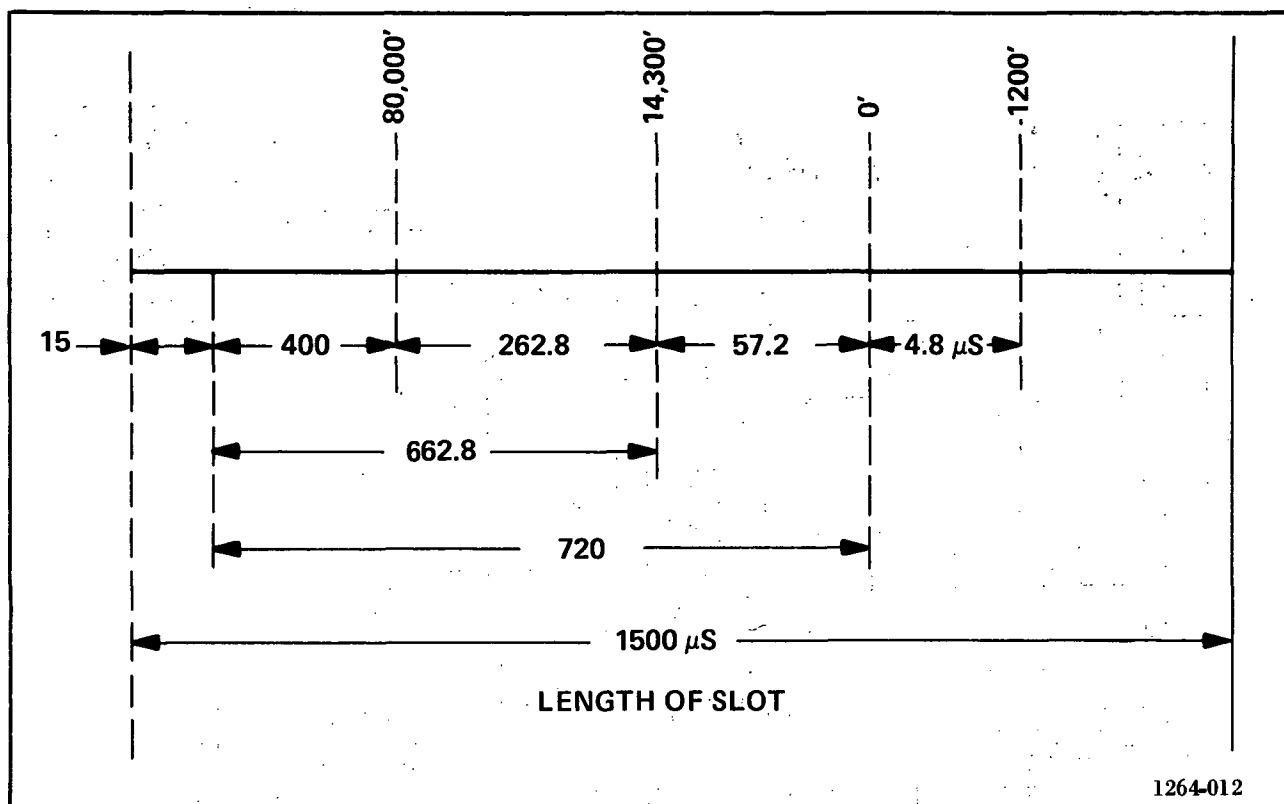


Figure 12. Altitude Transmission Timing Diagram

tion CAS is red-lined above 10,000 feet, only 10,000 feet would have been required for transmission. To compensate for modulation and transmitter delays and to provide altitude bias for complimentary maneuver commands, the altitude counter is actually started at three different counts by the advance/retard circuit as follows:

- (1) If no "dive" or "climb" command exists, a count of 3308 (corresponding to 661.6 microseconds) starts the altitude counter. The 1.2 microseconds early start is to compensate for the modulator and transmitter delay.
- (2) If a "climb" command exists, a count of 3304 (corresponding to 660.8 microseconds) starts the altitude counter. The 2.0 microsecond early start is to provide the 1.2 microseconds early start to compensate for the modulator and transmitter delay and to provide a 0.8-microsecond early bias (corresponding to 200 feet higher altitude) required by the CAS specification to guarantee complimentary maneuvers.
- (3) If a "dive" command exists, a count of 3312 (corresponding to 662.4 microseconds) starts the altitude counter. The 0.4-microsecond late start is to provide the 1.2-microsecond early start to compensate for the modulator and transmitter delay and to provide a 0.8 late bias (corresponding

to 200 feet lower altitude) required by the CAS specification to guarantee complimentary maneuvers.

In all cases, the delay counter is reset at a count of 3314.

Depending upon the three aforementioned conditions, the advance/retard circuit provides an enable level and allows the 2.5 MHz clock rate to be applied to the altitude counter. Each clock pulse of 400 nanoseconds duration corresponds to a 100-foot increment of altitude. The altitude counter, reset by the STOS signal to a count of 14,300 feet, will start to count down. The altitude counter consists of a special divide-by-five for the 3 least significant bits and normal binary for the 5 most significant bits. Its output is applied to an 8-bit comparator which compares each count of the altitude counter, to the pressure altitude from the encoding altimeter in the aircraft. Only the 8 least significant bits of information from the encoding altimeter are used because of the limited altitude of a general aviation aircraft. Of the 8 least significant bits applied to the ICAO decoder, the 5 most significant bits are converted from a gray code to a binary code and the 3 least significant bits are specially decoded for ease of comparing with the 3 least significant bits of the altitude counter. When the outputs from the altitude counter agree with the outputs from the ICAO decoder, a TAA signal will be applied to the transmit logic causing an r-f signal to be transmitted.

b. Receive Mode. In the receive mode, the circuit provides verification for 30- or 200-microsecond range pulses, and 25.6-microsecond altitude pulses in all received slots. In addition, the circuit assesses the relative altitude separation between own aircraft and all participants to provide the necessary threat logic inputs to assure safe separation. Significant differences, between the transmit mode and receive mode, are that the delay counter runs two or three times each active slot, and no altitude bias is used.

Signal THV (Threshold Video), from the video amplifier, in conjunction with RSW (Received Slot Window) start the delay counter and the pulse verification logic. The RSW signal, occurring in every slot except "local slot", starts at 15 microseconds after start of slot (corresponding to a range of 0 nautical miles) and lasts for 62 microseconds (corresponding to a range of 10 nautical miles). Only range pulses in this window are relevant for threat evaluation.

After the delay counter has been started by the appropriately gated range pulse, or a following altitude pulse during the next start of the delay counter, the time decoder provides 28.4-microsecond, 196.8-microsecond, and 24.4-microsecond gates off the delay counter to verify that after a range or altitude pulse has started, no THV signal drop-out occurs for the duration of the gates. If any one pulse fails, it disables the process data decision circuit so that the information in that particular slot will not be pro-

cessed. Therefore, the acceptance criteria for a range pulse is 100 percent signal from the start of the signal to 28.4 microseconds for a 30.0-microsecond range pulse or to 196.8 microseconds for a 200-microsecond range pulse. In addition, the acceptance criteria for an altitude pulse is 100 percent signal from the start of the signal to 24.4 microseconds for a 25.6-microsecond altitude pulse.

THV occurring in a General Aviation CAS slot will also cause the delay counter to count out a fixed delay of 662.8 microseconds as it did in the transmit mode. This corresponds to a count of 3314 and will be gated through the advance retard circuit to start the altitude counter, and to reset the delay counter to 0. The altitude counter will count down from 14,300 feet until it agrees with the altitude information from the altimeter. At this time, a TA signal will be applied to the counter control circuit and the position decision circuit.

After the altitude counter has started, the first THV assertion signal will generate an ALTP signal that is assumed to be the intruder aircraft altitude pulse. A time comparison of TA (own aircraft altitude) and ALTP (intruder aircraft altitude) is made to assess whether the intruder is above or below and if the intruder is close enough in altitude to be considered a threat. Also, the THV pulse is tested 100 percent from start to 24.4 microseconds later to verify that it is an altitude pulse.

Three cases must be considered when measuring the altitude of an intruding aircraft as follows:

- (1) Intruder aircraft above,
- (2) Intruder aircraft below,
- (3) Intruder aircraft co-altitude.

In the case where the intruder aircraft is above, the THV altitude information will again start the delay counter. In this case the signal TA will be generated after signal ALTP so that the position decision circuit will decide the intruder aircraft is above. The time decoder has an output equal to 2.4 microseconds which is equivalent to 600 feet in altitude. If the signal TA comes during this time, the 0-600 foot output of the AZ decision circuit will rise to a "1" level signifying the intruding aircraft is between 0 and 600 feet. If TA comes between 2.4 and 5.2 microseconds, which corresponds to 600 to 1300 feet, the 600-1300 output of the AZ decision circuit will be at a "1" level. If TA comes after 5.2 microseconds, it disables the process data decision circuit.

In the case where the intruder aircraft is below, the signal TA will start the delay counter for the second time. Signal ALTP will be generated after TA so that the position decision circuit will indicate the intruder aircraft is below. Again, the time decoder has a 0-600 foot output and if signal ALTP comes during this time, the 0-600 foot output level will rise to a "1". If ALTP comes between 600 and 1300 feet, the 600-1300 foot level will rise to "1". If ALTP comes after 1300 feet, it disables the process data decision circuit. Also in this case, ALTP resets the delay counter to enable it to count to 24.4 microseconds in order that the altitude THV pulse width may be measured. Recall in the first case the THV altitude information started this action.

In the case where the intruder aircraft is exactly co-altitude, signals TA and ALTP coincide and enable the AZ decision circuit in the 0-600 foot time. The position decision circuit will decide if the aircraft is above or below depending upon which signal TA or ALTP occurred first. In addition, the delay counter will be appropriately started to provide the 24.4 microsecond altitude THV pulse width check.

In the receive mode, the altitude and pulse measurement logic provide the threat logic in each active slot with an altitude zone (AZO), an above/below decision (ACB), an appropriate sample time after all data has been received (DE15), and a signal that the range and altitude pulses did not fail a pulse width test and the altitude pulse occurred in a time corresponding to 1300 feet or less of altitude separation (OK). Also, in the receive mode, the altitude and pulse measurement logic provide the transmit and receive logic in each active slot with a 30- or 200-microsecond received range pulse decision.

M. THREAT LOGIC AND DISPLAY

1. Function. The threat logic and display circuit determines when a threat from another aircraft exists and commands appropriate pilot action to eliminate the threat.

2. Description. Figure 13 shows a block diagram of the threat logic and display, Figure 14 shows the commands and advisories to be displayed for each type of encounter and schematic 7115-0542 shows a detail logic diagram on the schematic diagram but are physically located on the display that will be discussed later.

The CAS system will display to the pilot nine different commands depending on the information received from intruding aircraft. Two types of encounters are provided for: (a) The 2 aircraft, and (b) the 3 aircraft.

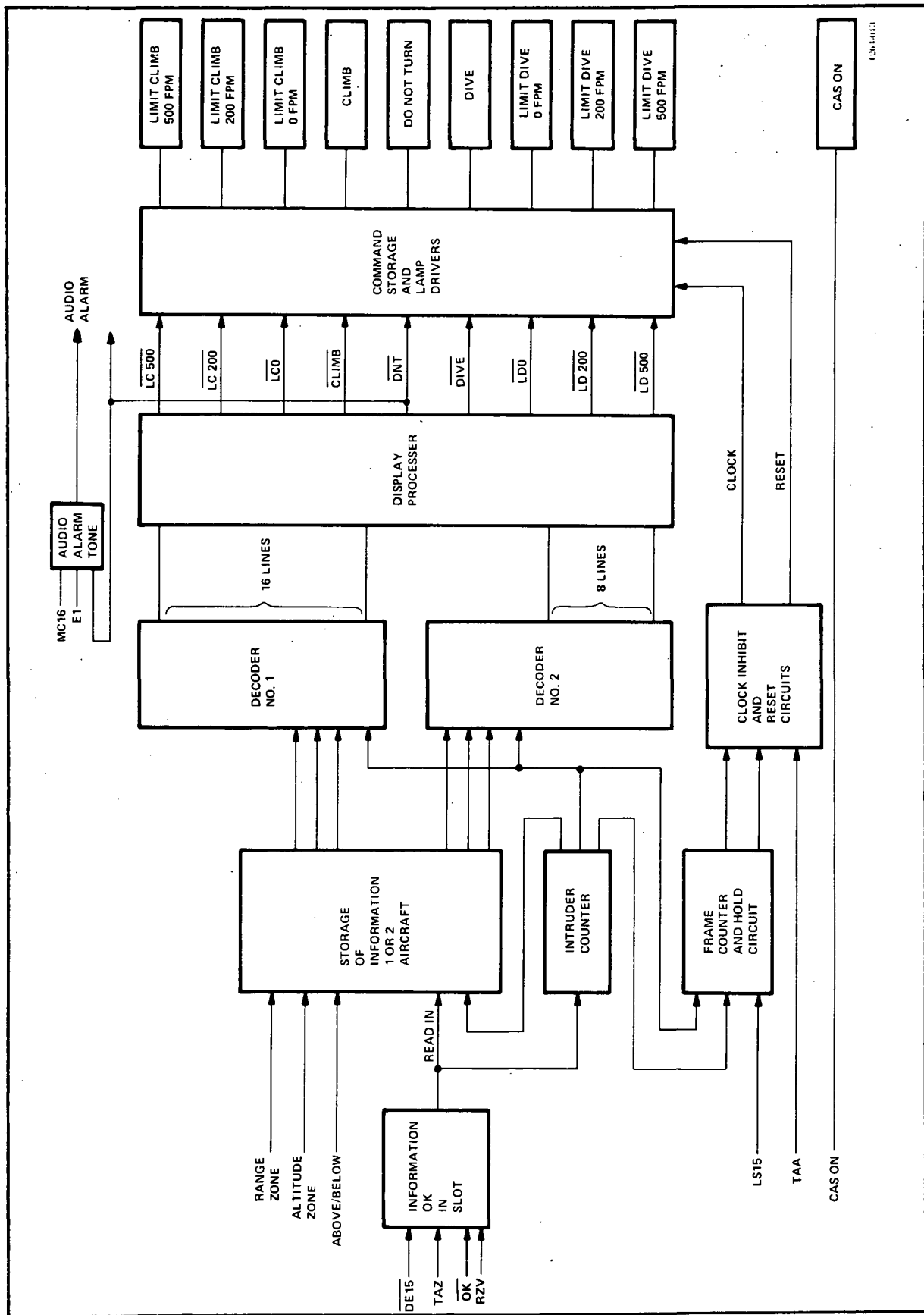
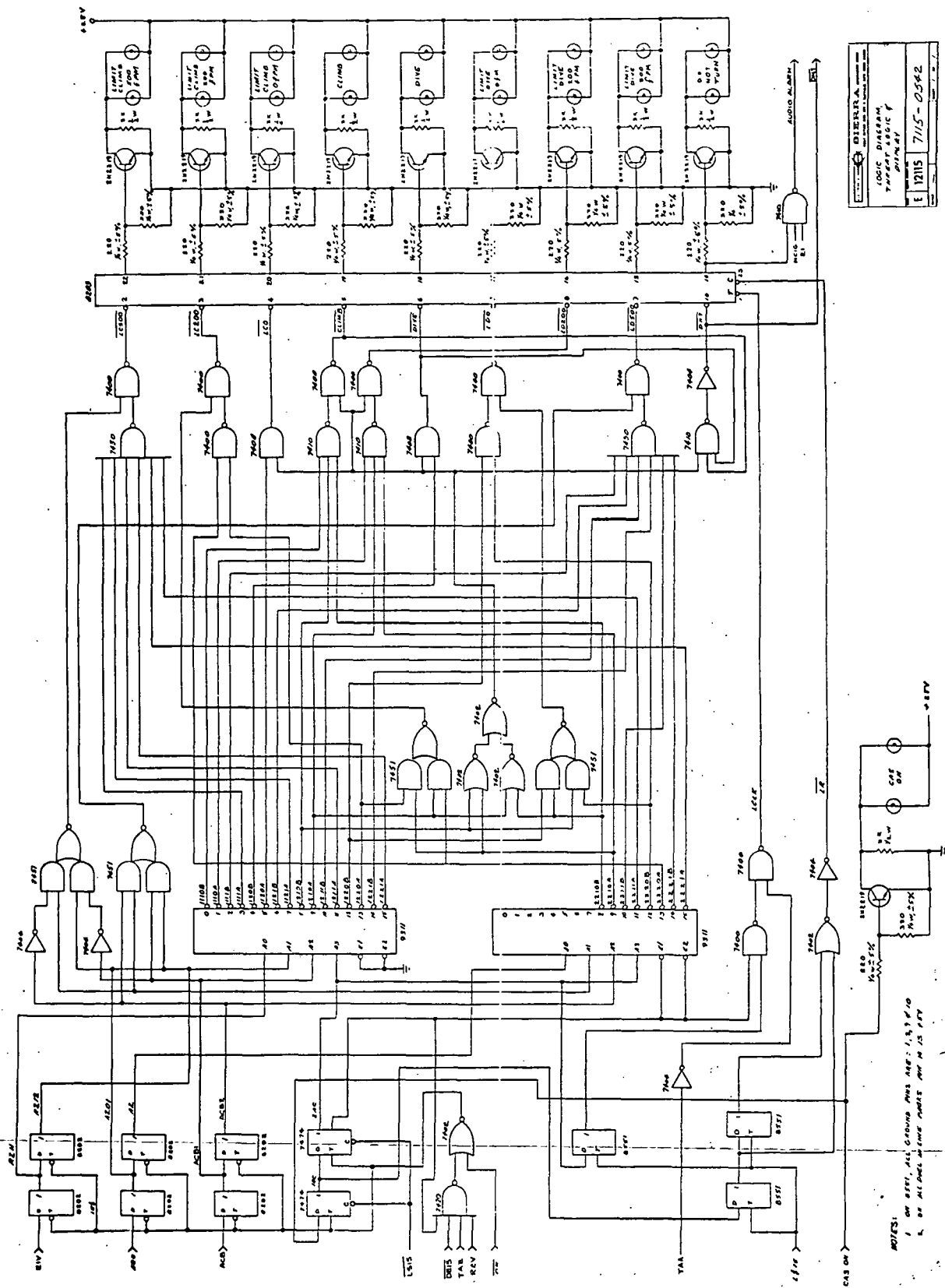


Figure 13. Threat Logic and Display Block Diagram



The two aircraft encounter means that one intruding aircraft is in the collision circle surrounding the threatened aircraft, and the three aircraft encounter means there are two intruding aircraft in this collision circle.

In figure 14, the two-aircraft encounter has the altitude position of the intruding aircraft plotted on the ordinate and the range of the intruding aircraft plotted on the abscissa. The three-aircraft encounter has one intruding aircraft plotted on the ordinate and the other intruding aircraft plotted on the abscissa.

The following abbreviations are used in figure 14.

ACA: Intruding Aircraft Above
ACB: Intruding Aircraft Below
AZO: Altitude Zone Zero (0-600 ft.)

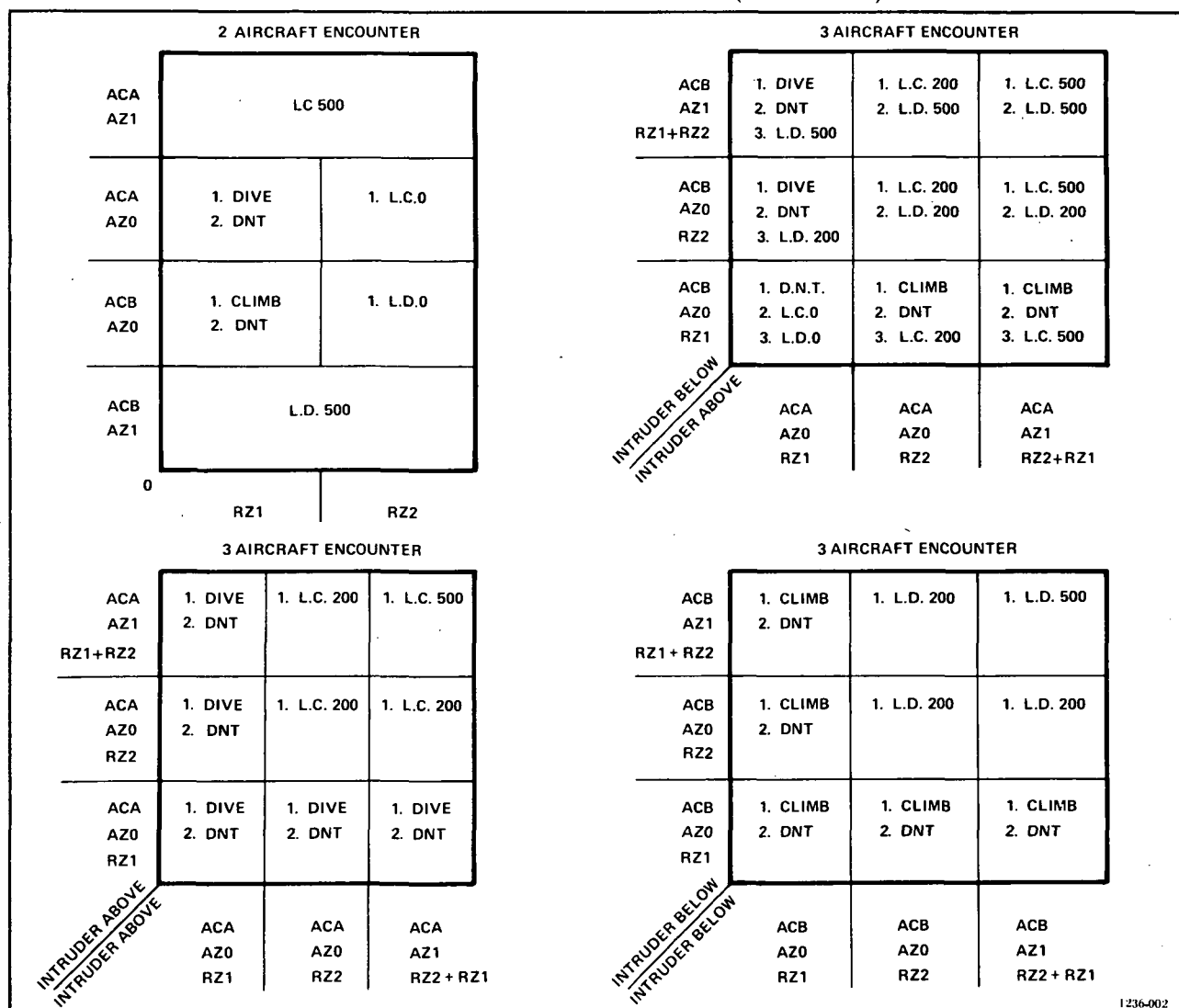


Figure 14. Commands and Advisories

AZ1:	Altitude Zone One (600 ± 1300 ft.)
RZ1:	Range Zone One
RZ2:	Range Zone Two
LC0:	Limit Climb to 0 fpm (feet per minute)
LD0:	Limit Dive to 0 fpm
LC200:	Limit Climb to 200 fpm
LD200:	Limit Dive to 200 fpm
LC500:	Limit Climb to 500 fpm
LD500:	Limit Dive to 500 fpm
DNT:	Do Not Turn
RZ1 + RZ2	Range Zone 1 or Range Zone 2

The range and altitude information is stored in a 2-bit shift register called "storage of information 1 or 2 aircraft", if the "CAS ON" signal exists (figure 13). The "CAS ON" signal indicates that the power is turned on, synchronization has been obtained, and the unit has passed self test. The information to be stored is clocked into storage provided it has passed all the tests described in the altitude and pulse width measurement system. This is determined by the information OK in slot circuit. The intruder counter counts the number of intruders. When this amount gets to two, it inhibits any intruder information from being stored.

The output of the storage 1 or 2 intruder aircraft is fed to decoder 1 and decoder 2. Decoder 1 is used in the 2 aircraft encounter and both decoders are used in the 3 aircraft encounter.

Decoder 1 and decoder 2 feed the display processor which determines the light or lights to be illuminated from the decoding done by decoder 1 and decoder 2. The output of the display processor is clocked into command storage in every local slot provided at least 1 intruding aircraft is detected in the 1999 slots prior to local slot. If no intruding aircraft is detected after 2 times through the 1999 slots, the command storage logic is set to 0 turning out all command lamps. The frame counter and hold circuits count this time and the clock inhibit and reset circuits perform the reset and clocking action.

The 10 blocks on the extreme right of figure 13 are the 9 command/advisory indicators and the "CAS ON" indicator.

The threat logic and display also generates an audible alarm by providing a 666.7 Hz tone, gated on for 3.0 seconds and then off for 3.0 seconds, any time an intruder aircraft is detected in the 0-600 foot altitude zone and is in range zone 1. The audible alarm signal is to be used for connection into the aircraft alarm. The communications receiver usually has audio jacks provided for interconnection. Another output from the threat logic and display is the $\overline{\text{DNT}}$ signal which is used in the slot control logic to inhibit the "shut-up-and-listen" function normally used to detect co-slot occupancy.

N. SLOT CONTROL LOGIC

1. Function. The slot control logic selects and stores a local slot number, generates a local slot signal for the transmit and receive logic, selects and stores an alternate slot, and determines if someone else is using either the local or alternate slot. Should either the local or alternate slot be busy, a new slot is automatically chosen for operation.

2. Description. Figure 15 shows a block diagram and schematic 7115-0507 shows a detail logic diagram of the slot control logic.

a. Shut-Up-and-Listen. The random count generator, count select, and the divide-by-seven and inhibit circuitry provides a random average interval of fourteen local slots to quench any transmissions for one local slot for the purpose of determining if someone else is occupying the same local slot. The random interval is required to assure that two participants do not shut-up and listen at the same time. The random count generator is a simple heads or tails circuit that is driven by any thresholded video (THV) from the receiver. The heads or tails (HT) output is used to count (H) or not count (T) each local slot (LS). The divide-by-seven and inhibit circuitry counts the count select output. When a count-of-seven is reached and no inhibit ($\overline{DNT} = 1$) exists, the shut-up and listen (SUL) signal is made active and the normal range and altitude pulse is quenched for that local slot. Since the random count generator will have half heads and half tails, only every other LS gets counted on the average which gives an average interval of 42 seconds between the shut-up and listen intervals. Should a threat condition exist (any intruder detected in range zone 1 and altitude zone 0), the SUL signal activation is inhibited by $\overline{DNT} = 0$ from the threat logic and display. After any active shut-up and listen slot, the divide-by seven and inhibit is reset to preclude more than one shut-up and listen in a row.

b. Slot Selection. Both the local slot (LS) and alternate slot (AS) selectors are 10-bit comparators that select 1 out of 1000 possible slots. The slot counter in the synchronization logic provides one set of comparator inputs for each slot selector while the alternate slot counter (10-bit binary counter) provides the other set of comparator inputs for the alternate slot selector and the local slot storage (10-bit storage register) provides the other set of comparator inputs for the local slot selector. One bit, S1, does not require a comparison since for all F_4 slots it is by definition a logical 1. After a slot is selected, it is continuously examined to verify that it is an allowable slot and that it is not occupied by someone else.

c. Alternate Slot Control. At start up, the alternate slot counter is permitted to come up in any state and will thereafter be controlled by the change alternate slot circuit unless it comes up in one of the unused 48 counts (2000 of 2048 counts of the slot counter are used). Should this occur, the

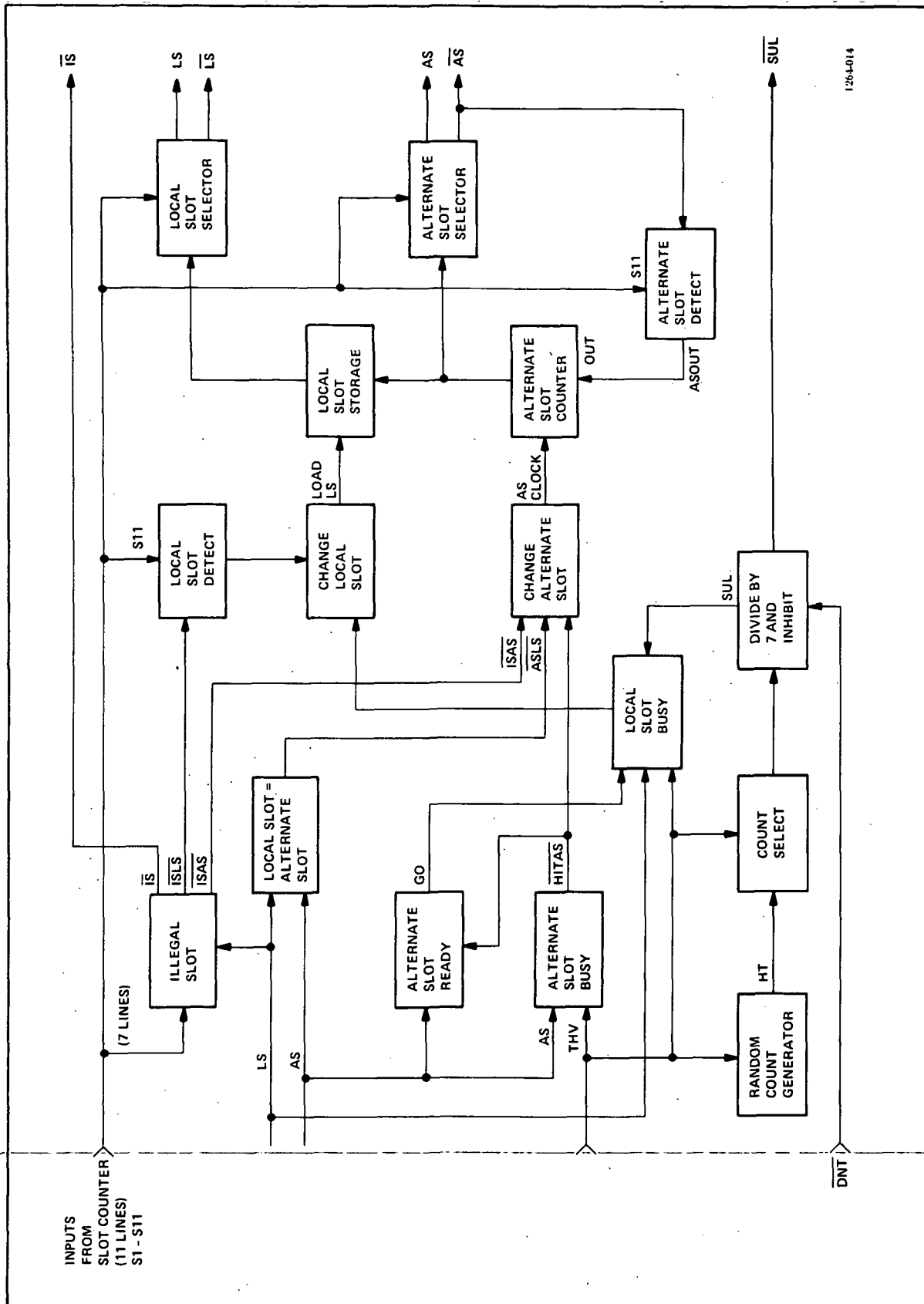
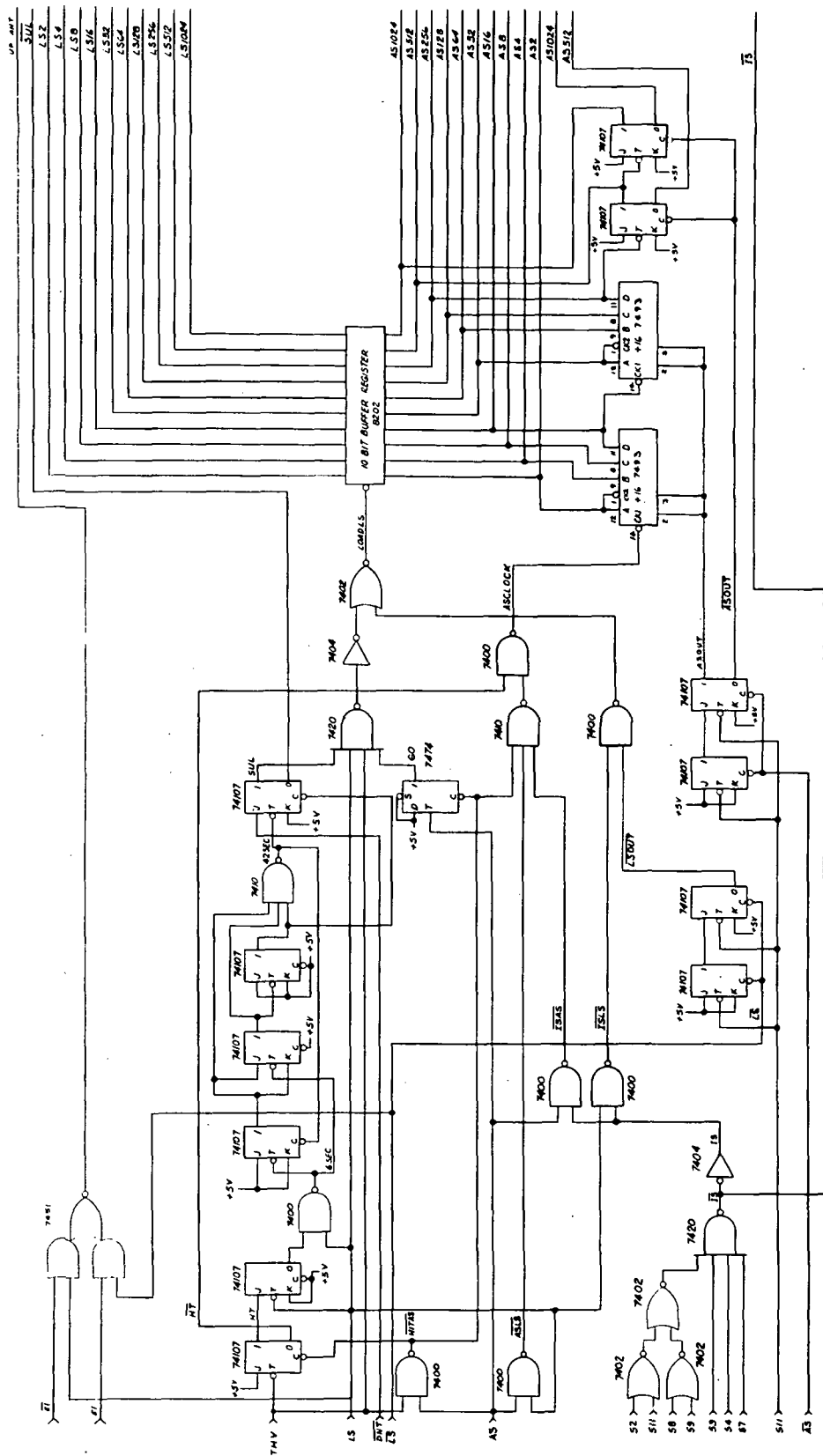
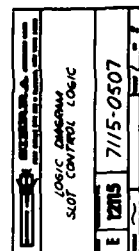


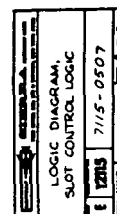
Figure 15. Slot Control Logic Block Diagram



NOTES:

1. ON ALL DUAL-IN-LINE PACKS, 15V IS CONNECTED TO PIN 1, 16V IS CONNECTED TO PIN 2, 17V IS CONNECTED TO PIN 3, 18V IS CONNECTED TO PIN 4, 19V IS CONNECTED TO PIN 5, GROUND IS CONNECTED TO PIN 10.





alternate slot selector will not generate an alternate slot (AS) and in two slot counter overflows, the alternate slot detect circuit will reset the alternate slot counter to its lowest state.

In normal operation the alternate slot counter is a binary counter driven by the change alternate slot circuit. There are three criteria for moving the alternate slot as follows:

- (1) Illegal slot for alternate slot (ISAS)
- (2) Alternate and local slot equal (ASLS)
- (3) Alternate slot busy (HITAS).

The first condition occurs because some slots are reserved for test purposes by the ANTC-117 specification. For the one-frequency system defined, these reserved slots are as follows:

$$\text{Slots } 79 + 128 N \text{ (N = 0, 1, 2, 3)}$$

$$\text{Slots } 1101 + 128N \text{ (N = 0, 1, 2, 3)}$$

The illegal slot circuit determines when this condition occurs and activates the change alternate slot circuit.

The second condition normally occurs each time a new local slot is selected which will be discussed later. If the selected alternate slot is the same as the local slot, the local slot = alternate slot circuit activates the change alternate slot circuit and a new alternate slot is selected.

The third condition occurs when thresholded video (THV) occurs in the alternate slot selected. This condition will exist when someone else is using the particular slot as his local slot. As soon as the alternate slot busy is detected, it activates the change alternate slot circuit and a new alternate slot circuit and a new alternate slot is selected.

d. Local Slot Control. The local slot storage circuit is a 10-bit storage register and is permitted to come up in any state at start-up and will be controlled by the change local slot circuit thereafter. Should a decision to change the local slot occur, the change local slot circuit causes the contents of the alternate slot counter to be read into the local slot storage and a new alternate slot is chosen. There are three criteria for moving the local slot as follows:

- (1) Illegal slot for local slot,

- (2) No local slot,
- (3) Local slot busy.

The first condition occurs because some slots are reserved for test purposes by the ANTC-117 specification. For the one-frequency system defined, these reserved slots are the same as those previously listed under the discussion on Alternate Slot Control. Should the illegal slot circuit determine that one of these prohibited slots has been selected, the change local slot circuit is activated and new local slot is selected.

The second condition occurs when the local slot storage gets to one of the 48 unused counts. If no local slot is generated in two slot counter overflows, the local slot detect circuit activates the change local slot circuit and a new slot is chosen.

The third condition occurs when another system user is also using the same local slot. For the local slot busy circuit to activate the following conditions must prevail:

A previously determined vacant alternate slot has been chosen (GO).

The shut-up-and-listen (SUL) signal is active,

The local slot is active,

Threshold video (THV) is active.

Should all these conditions be met, local slot busy circuit will activate the change local slot circuit and a new local slot will be selected.

O. TRANSMIT AND RECEIVE CONTROL LOGIC

1. Function. The transmit and receive control logic primarily provides start and stop control signals to the modulator for transmission of range and altitude pulses and assesses received video range pulses to provide the threat logic with signals signifying that an intruder range pulse has been detected in a particular range zone. Secondly, the transmit and receive control logic provides control signals to the altitude and pulse measurement logic for starting the altitude pulse transmission circuitry in local slot and for gating only relevant received data into the pulse measurement circuitry.

2. Description. Figure 16 shows a block diagram and schematic 7115-0512 shows a detail logic diagram of the transmit and receive control.

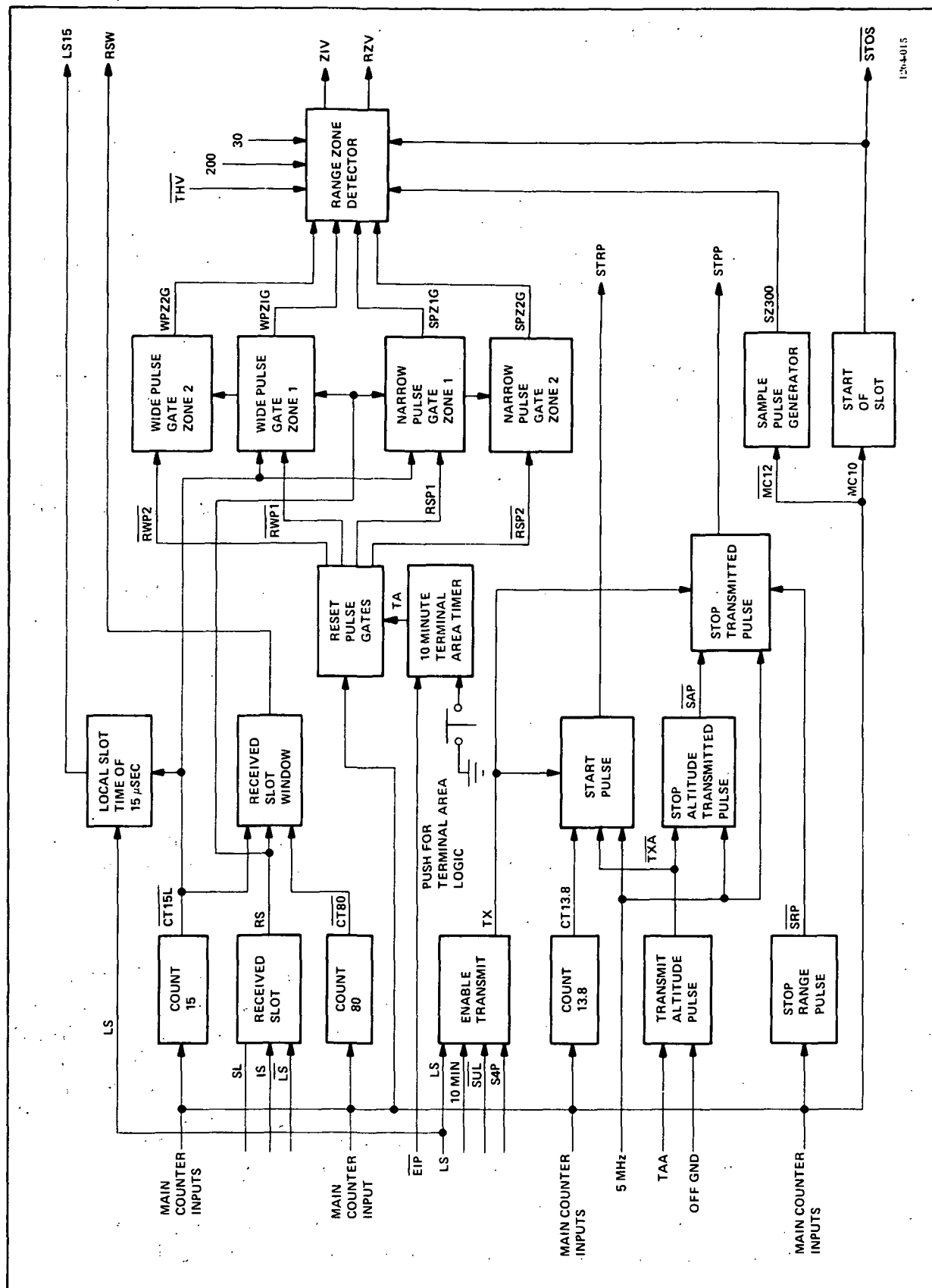
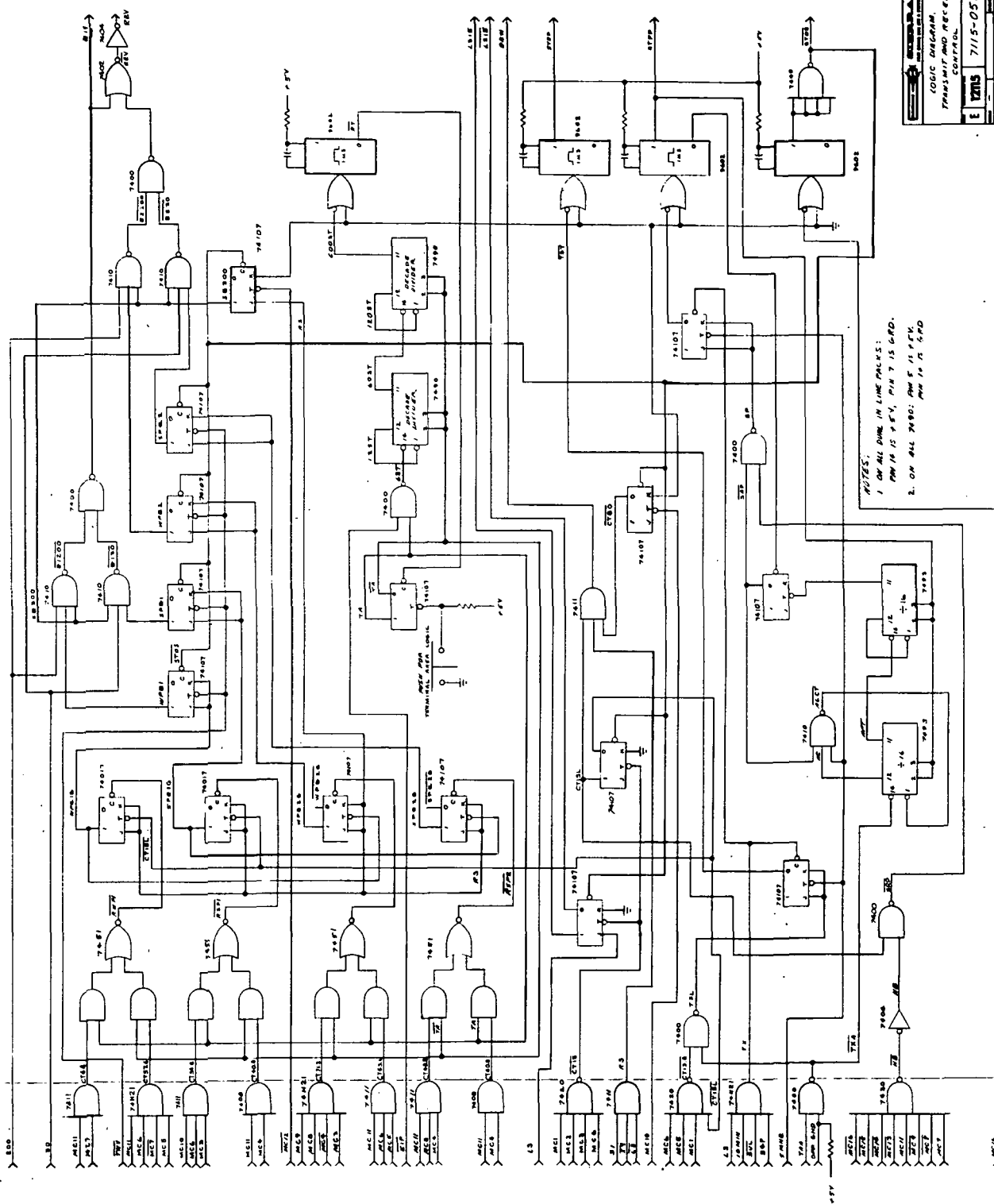


Figure 16. Transmit and Receive Control Logic Block Diagram



NOTES:
 1. ON ALL DUNE IN LINE PULSES:
 PPM IN 15 W 8V, PPM 7 15 W 8V.
 2. ON ALL 7400: PPM 5 11 W 8V.
 3. ON ALL 7400: PPM 14 15 W 8V.

LOGIC DIAGRAM
TRANSMIT AND RECEIVE
CONTROL

7115-0512

7115-0512

a. Start and Stop Transmitted Signals. The start transmitted pulse and stop transmitted pulse circuit, shown in figure 16, provides the modulator with a start and stop control pulse, one microsecond early, to compensate for modulator and transmitter delays. The enable transmit circuit allows transmissions to take place only when the following conditions are met:

Local slot (LS) is active

Warm-up period (10 minutes) has been completed after power was applied

Shut-up and listen ($\overline{\text{SUL}}$) is not active for this local slot

Fine sync (S4P) has been obtained

A range pulse transmission must have a pulse width of 30.2 microseconds, and r-f out at 15.0 microseconds from the start of local slot. The count 13.8 circuit, with inputs from the main counter in the sync logic, provides the start transmitted pulse with a gate level at 13.8 microseconds from the start of slot. Combined with the 5-MHz clock rate, it generates a start transmitted pulse at 14.0 microseconds from the start of local slot. With modulator and transmitter delays at 1.0 microsecond, the r-f is then generated at 15.0 microseconds from the start of local slot. The stop range pulse circuit, with inputs from the main counter in the sync logic, provides the stop transmitted pulse with a gate level at 44.0 microseconds from the start of slot, and combined with the 5-MHz clock rate, it generates a stop transmitted pulse at 44.2 microseconds from start of local slot.

The altitude pulse transmission is identical to the range pulse transmission, except that the start signal (pulse width of 25.6 microseconds) is provided by the altitude and pulse measurement logic (TAA), with no altitude pulse transmitted if the aircraft is on the ground. The transmit altitude pulse circuit allows the TAA signal to start the transmission of an altitude pulse only if the strut switch (or similar control) is closed. Since the start signal is variable as altitude changes, a separate counter is required to provide the stop signal for the altitude pulse. This counter is provided by the stop altitude pulse circuit, which is a controlled binary divide-by-128 of the 5-MHz clock rate. When the counter reaches a count of 128 (corresponding to a time of 25.6 microseconds), the stop altitude pulse circuit generates a signal which activates the stop transmitted pulse circuit and turns off the transmitter.

b. Range Zone Detection. The range zone detector provides the threat logic with a zone one violation (Z1V) signal and a range zone violation (RZV) for combining with the altitude data for threat evaluation. If both Z1V and RZV are true a range zone 2 is used in the threat logic. Range values for

the different zones are discussed in Part One, section V, paragraph D.

The range zone detector receives gate inputs as shown in figure 17, and a sample pulse (SZ300) to enable either or both the Z1V and RZV signal. Note that both range zone 1 gates are started at 15.0 microseconds after the start of slot, and both range zone 2 gates are started at the end of each range zone 1. All range gates are reset by the reset pulse gates circuit. Also note that the resets of all gates can be shortened for terminal area logic by the pilot activates pushbutton switch and 10-minute timer. This gives about a 70 percent reduction in all range alarms as discussed in Part One, section V, paragraph D. The gate inputs in conjunction with the threshold video (THV) cause an active range zone which could be the result of a 200-microsecond or 30-microsecond range pulse from an intruding aircraft. The active range zone is combined with the 30- or 200-microsecond signal from the altitude logic to finally generate the Z1V or RZV or both signals.

c. Control Signal Generation. The local slot time of 15 microseconds circuit provides the altitude logic with a precisely timed start signal for local slot transmission of an altitude pulse.

The received slot window circuit provides the altitude logic with a gate during each slot that can contain received range and altitude information. The received slot circuit allows all F4 slots (S_1), except test slots ($\overline{IS}$) and local slot ($\overline{LS}$), to be included in the received slot window. In each of these slots, the received slot window is started at 15.0 microseconds after slot start (range = 0), and stopped at 80.0 microseconds (by the count 80 circuit) which corresponds to a window whose length is slightly over 10 nautical miles. Threshold video which does not occur in this window will not be processed.

P. SYNCHRONIZATION LOGIC

1. Function. The synchronization (sync) logic accepts range and special time reference pulse information from a DME in the aircraft and precisely aligns the time base in the sync logic. Once the time base is in accurate alignment, the CAS transmitter is enabled and the normal collision avoidance function can be provided. After time base alignment has been achieved, the sync logic continuously validates that the time is correct. If an error is found or the sync data lost, the sync logic turns off the CAS function and searches for sync data. In addition, the self test monitor is included in the sync logic. Signals provided by the sync logic are as follows:

Slot counter outputs to the slot control logic,

Main counter outputs to the transmit and receive control logic for transmission and reception of data,

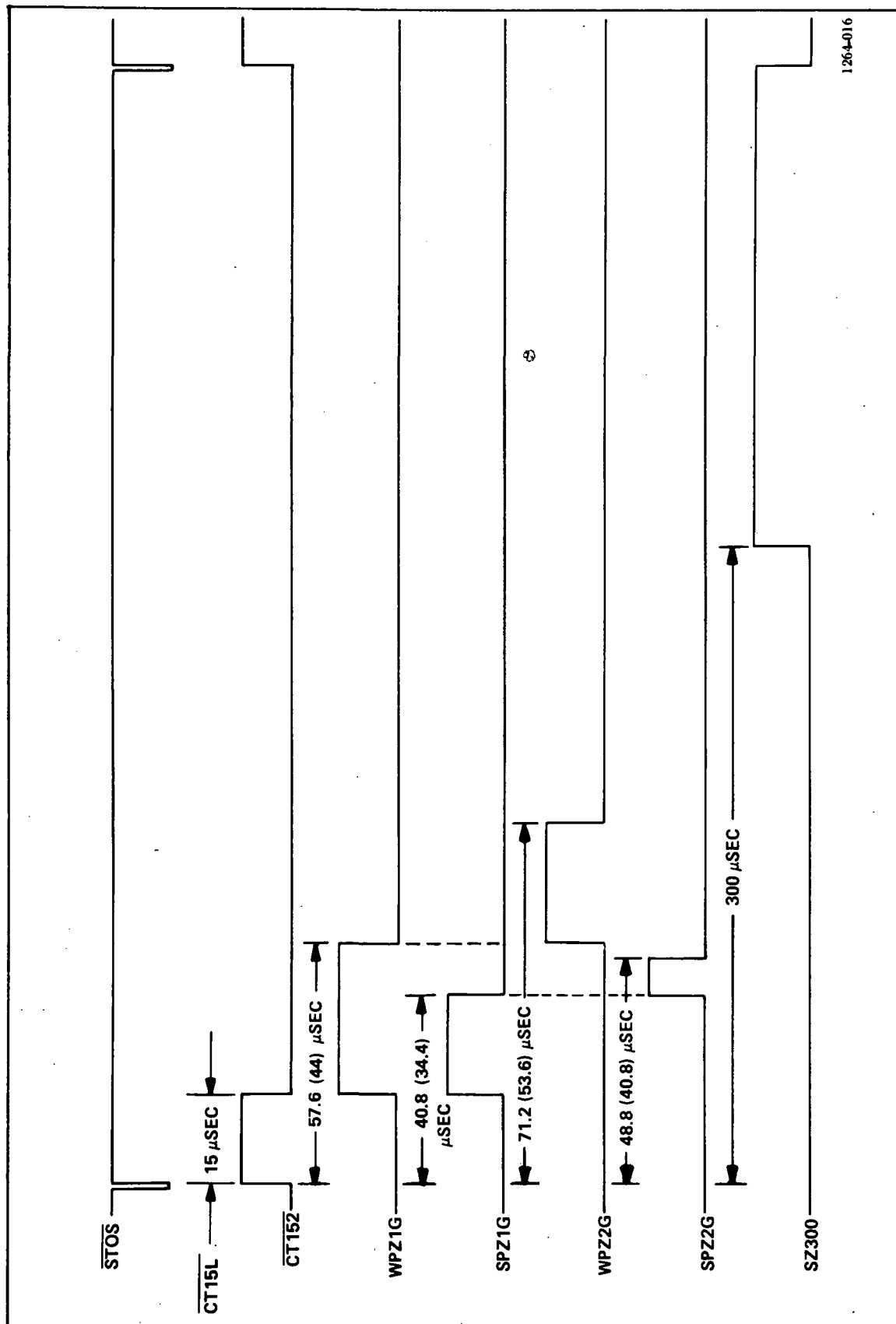


Figure 17. Range Zone Detector Gate Inputs

10-minute warm-up delay for transmitter and precision oscillator.

CAS ON to display.

2. Description

a. Sync. Figure 18 shows a block diagram of the synchronization logic and schematic 7115-0502 (sheets 1 through 6) shows a detail logic diagram of the synchronization logic.

The major functions of each of the 6 sheets that make up the synchronization logic are as follows:

Sheet 1

Half-amplitude detector of DME video
DME interface for:
(1) Track
(2) DME video
(3) Range delay counter drive (1.6172 MHz)
(4) Pulse pair decode
Shaping circuit for 5 MHz
D/A converter for VCO frequency control

Sheet 2

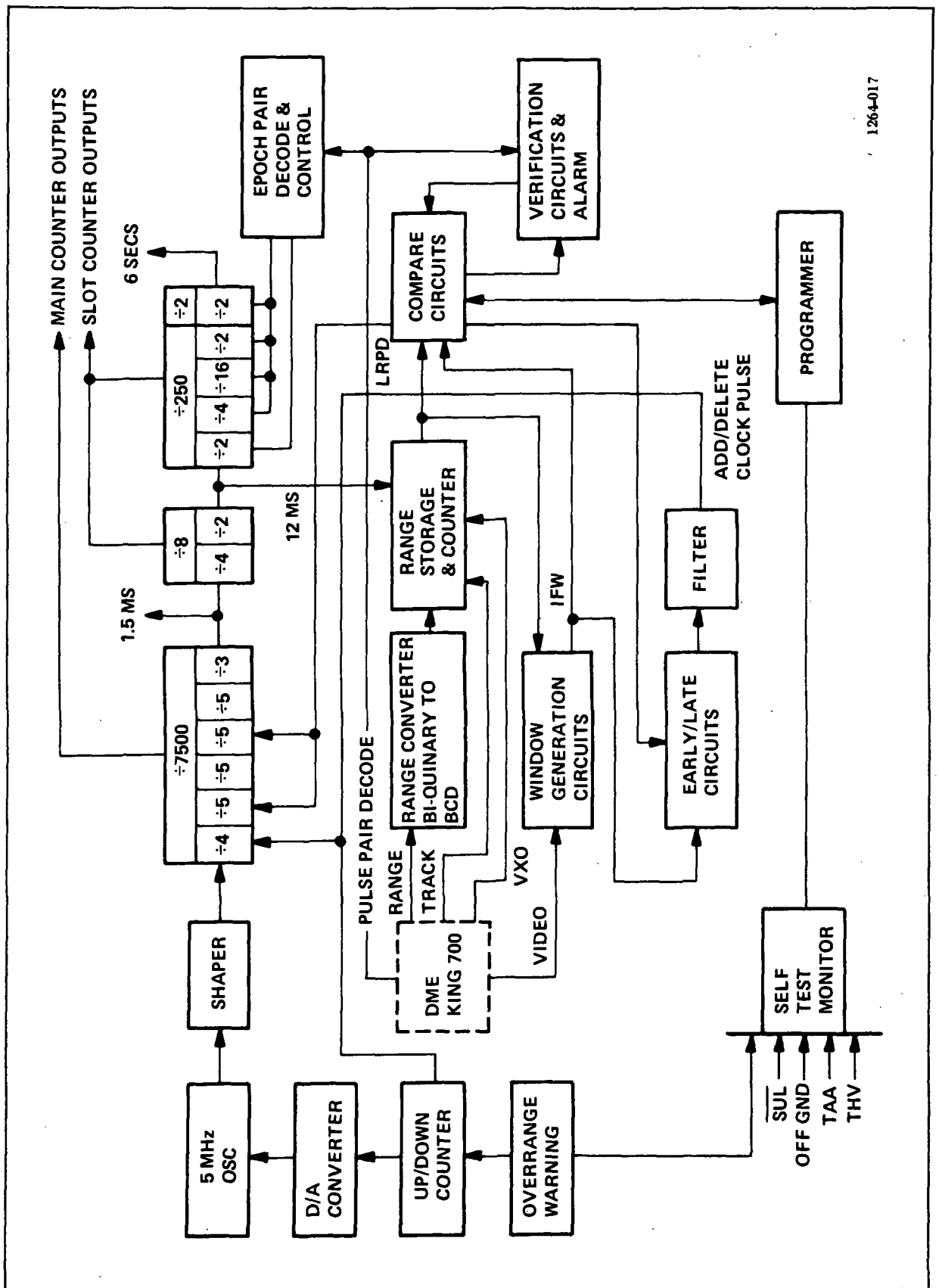
Main counter
Slot counter
Epoch counter
Local range delay counter initiation
Epoch pulse decoder and reset
Counter correction

Sheet 3

Bi-quinary to decimal conversion
Range delay counter
Video sampling

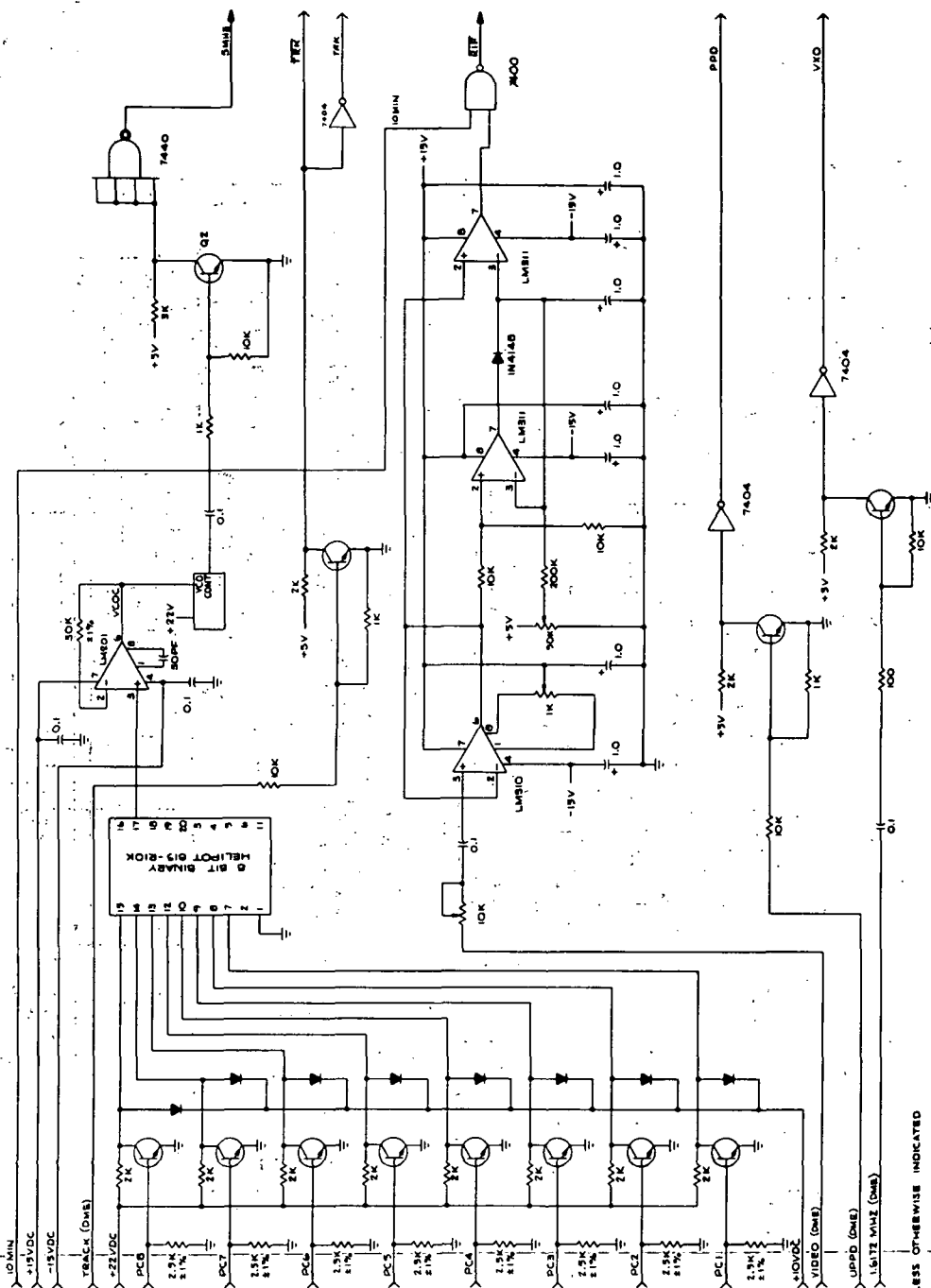
Sheet 4

Determines if local time is early or late
Generates digital frequency control value
Provides a 10-minute warm-up timer
Generates a power-on reset for initialization
Performs self-test monitor

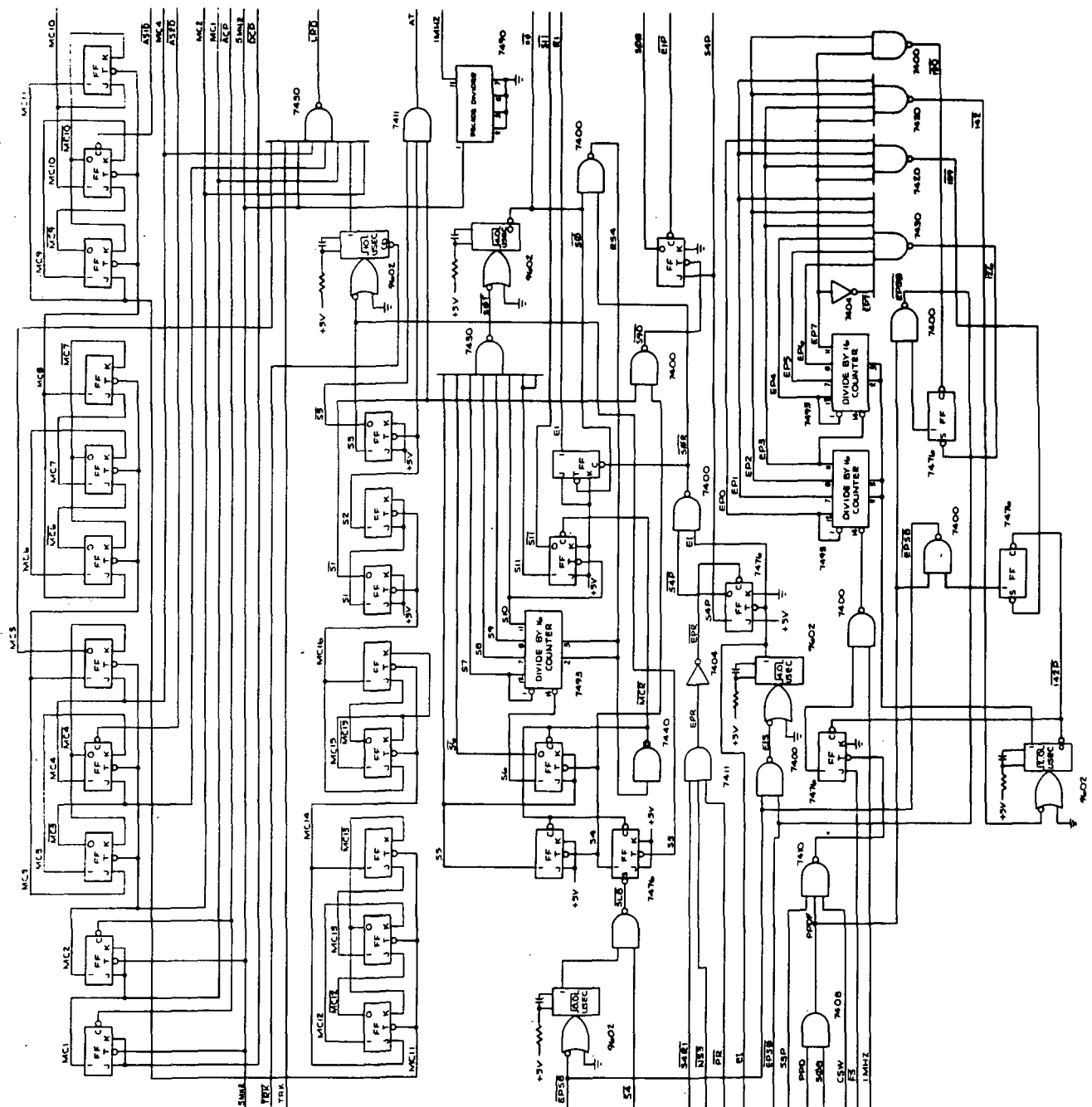


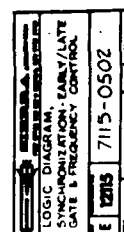
1264-017

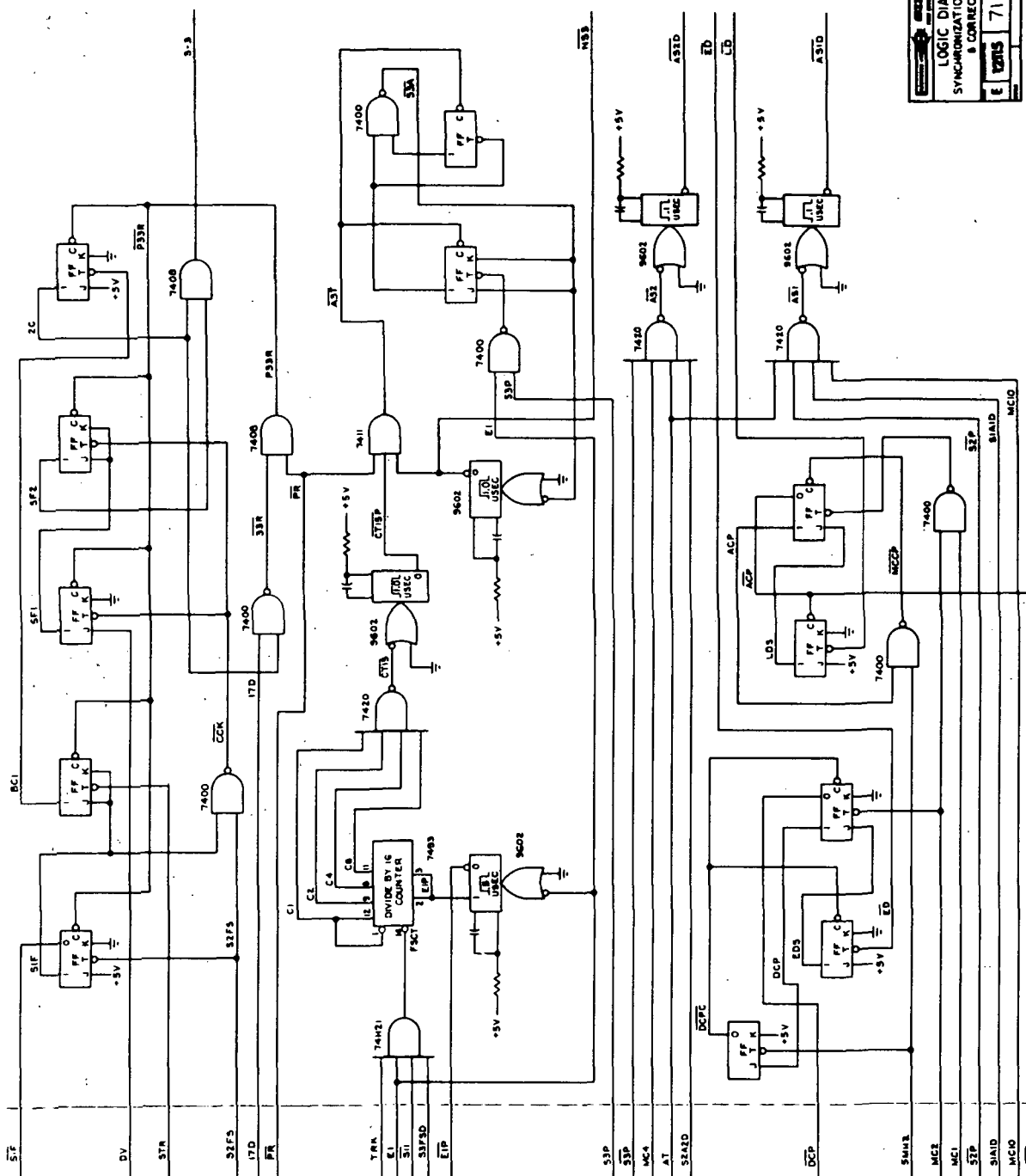
Figure 18. Synchronization Logic Block Diagram

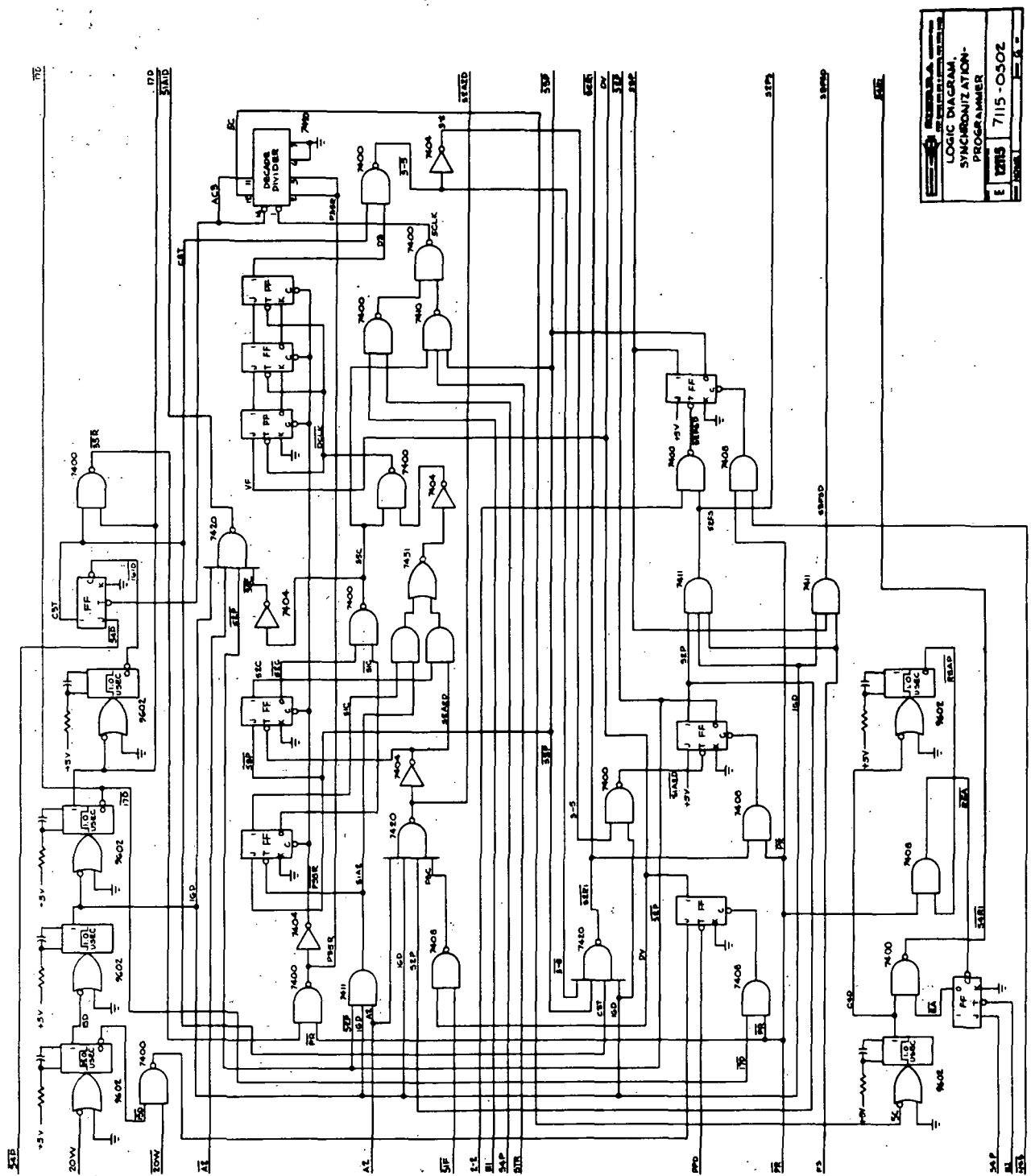


- NOTES: UNLESS OTHERWISE INDICATED
1. INTERPRET DRAWING IN ACCORDANCE WITH STANDARDS PRESCRIBED BY MIL-D-1000.
 2. PARTIAL REFERENCE DESIGNATIONS ARE SHOWN FOR COMPLETE DESIGNATION. PREFIX WITH UNIT NO. OR SUBASSEMBLY DESIGNATION.
 3. ALL CAPACITANCE VALUES ARE IN MICROFARADS, $\pm 20\%$, 50V.
 4. ALL RESISTANCE VALUES ARE IN OHMS, $\pm 5\%$, $\frac{1}{4}$ WATT.
 5. ALL DIODES ARE HP 5082-2800.
 6. ALL TRANSISTORS ARE 2N9004.
 7. ALL FLIP FLOPS ARE 74107.
 8. ON ALL DUAL-IN-LINE PACKS, +5V IS CONNECTED TO PIN 14, GROUND IS CONNECTED TO PIN 7. ON ALL TRANSISTORS, GROUND IS CONNECTED TO PIN 1. ON ALL DIODES, GROUND IS CONNECTED TO PIN 1. ON ALL 7400 AND 7404, +5V IS CONNECTED TO PIN 5, GROUND IS CONNECTED TO PIN 10.









Sheet 5

Makes advance or retard decision for timing chain correction
Verifies sufficient sync data is received to control
programmer

Sheet 6

Generates sampling times
Determines what condition of sync exists and controls logic
accordingly

The 5-MHz precision oscillator drives a divide by 7500 main counter which generates the 1.5 millisecond (ms) slot timing required for CAS. This drives a divide-by-8 counter that supplies the 12 ms local reference pulse required for comparison with the received 12 ms reference pulse which is continuously transmitted by the modified VORTAC station. The 12 ms local pulse drives a divide-by-250 and a divide-by-2 counter which generates a 6-second epoch pulse. The divide-by-8 and divide-by-250 counters make up the slot counter.

The range output of the King 700 DME is in a modified biquinary format. This is converted to ten's complement BCD. Table 1 shows the truth table and Boolean functions of this conversion for the tenth nautical mile range output. The units and tens of nautical mile outputs are converted in the same way.

TABLE 1. TRUTH TABLE AND BOOLEAN FUNCTIONS

Count	Modified BiQuinary						Complemented BCD			
	TS1	TSA	TSB	TSC	TSD	TSE	B ₁	B ₂	B ₃	B ₄
0	0	1	0	0	0	0	1	0	0	1
1	1	1	1	1	0	1	0	0	0	1
2	0	0	1	0	0	0	1	1	1	0
3	1	1	1	1	1	0	0	1	1	0
4	0	0	0	1	0	0	1	0	1	0
5	1	0	1	1	1	1	0	0	1	0
6	0	0	0	0	1	0	1	1	0	0
7	1	1	0	1	1	1	0	1	0	0
8	0	0	0	0	0	1	1	0	0	0
9	1	1	1	0	1	1	0	0	0	0

NOTES:

IF TS1 = 1, set B₁ to a one

IF $TSC \cdot \overline{TSE} + \overline{TSB} \cdot TSE = 1$, set B₂ to a one

IF $TSC \cdot \overline{TSE} + TSA \cdot TSD = 1$, set B₃ to a one

IF $TSB \cdot TSD = 1$, set B₄ to a one

The converted range information is strobed into the range counter by the local 12 ms reference pulse (STR). The range counter is a 3 decade BCD up counter. A single flip-flop is used to keep track of the hundreds place. When the counter overflows, a new local 12 ms reference pulse is generated (RLCR) which is delayed in time by the one-way range to the VORTAC station. This signal is routed to the compare circuits where it is compared with the received 12 ms reference pulse.

RLCR is also routed to the window generation circuits where it initiates a 4-microsecond (μsec) and 20- μsec window. The windows and the video from the DME are gated and form FS which is compared with the RLCR signal (see figure 19).

In order to generate a $\pm 2\text{-}\mu\text{sec}$ window about the local reference pulse, the 12 ms local reference pulse (STR) is required to be decoded 2 μsec to compensate for receiver time. This will most always require the 12 ms reference pulse to be decoded some time after the normal decode time. With a receiver delay of 3.5 μsec , the reference decode time would be 12001.5 μsec (or 1.5 μsec after the start of each 12 ms period).

There are four modes of operation. In mode 1 (search mode) only the 20- μsec window is used. If the received 12 ms pulse is not detected in the window, the compare circuitry commands the timing chain to advance in time by 20 μsec . If any verified pulse pair occurs in the window, the advancing of the master timing chain is stopped and a 3-out-of-5 test is started. If three of the next five decisions of the compare circuit support the trial case in progress, the compare circuit assumes that the received 12 ms reference pulse has been found. At this time, the programmer is forced into mode 2.

In mode 2, both the $\pm 2\text{-}\mu\text{sec}$ and 20- μsec windows are in use. The timing chain is now being advanced in time by 0.8- μsec steps. If a verified pulse pair is detected in the $\pm 2\text{-}\mu\text{sec}$ window, the advances to the timing chain are stopped and the 2-out-of-2 verification circuit is initiated. If two of the next two decisions of the compare circuit support the trial case in progress, the 12 ms received reference pulse is now assumed to be within the $\pm 2\text{-}\mu\text{sec}$ window. The compare circuit now forces the programmer into mode three, which is fine sync. During mode 2, the 20- μsec window is also in use. This continuously insures that the verified received pulse pair is indeed within the 20- μsec window and that the system has not locked on to a received reference pulse that does not exhibit the 12 ms fixed spacing characteristic of the sync signal.

In mode 3, early-late decisions are made. The video occurring in the $\pm 2\text{-}\mu\text{sec}$ window is continuously compared with the local 12 ms reference pulse. If the received reference pulse arrives first four times in a row, the local time is considered late and a pulse will be added to the timing chain.

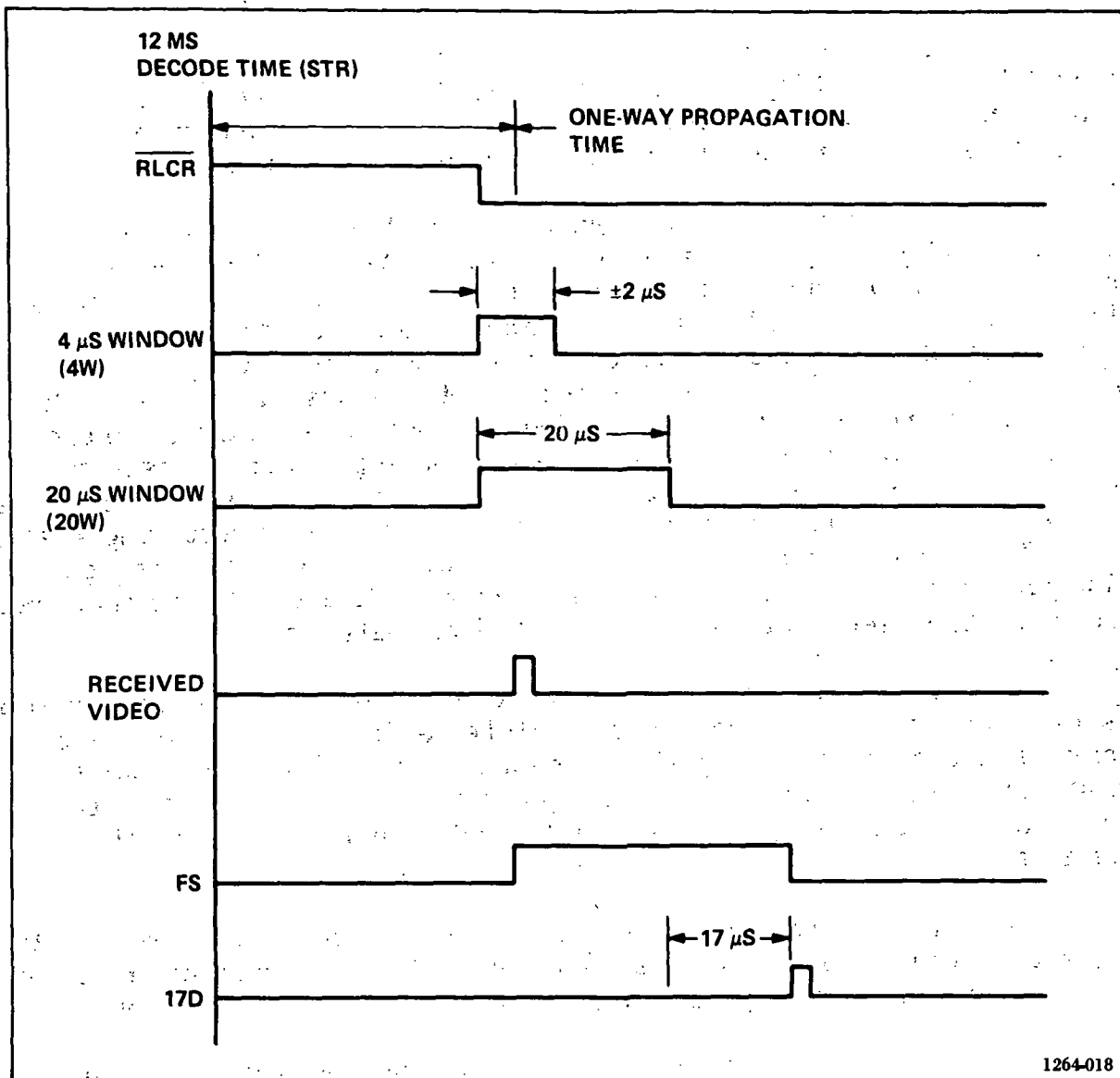


Figure 19. Time Comparison Diagram

At the same time, the frequency of the oscillator will be increased by 1.56 part/ 10^9 . In the case of an early decision, a pulse will be deleted and the frequency of the oscillator will be decreased by 1.56 part/ 10^9 .

The frequency correction is accomplished by a D/A converter which drives the VCO input of the oscillator. The D/A is controlled by an up/down counter. When the counter is incremented, the corresponding voltage change causes an increase or decrease in frequency of the oscillator.

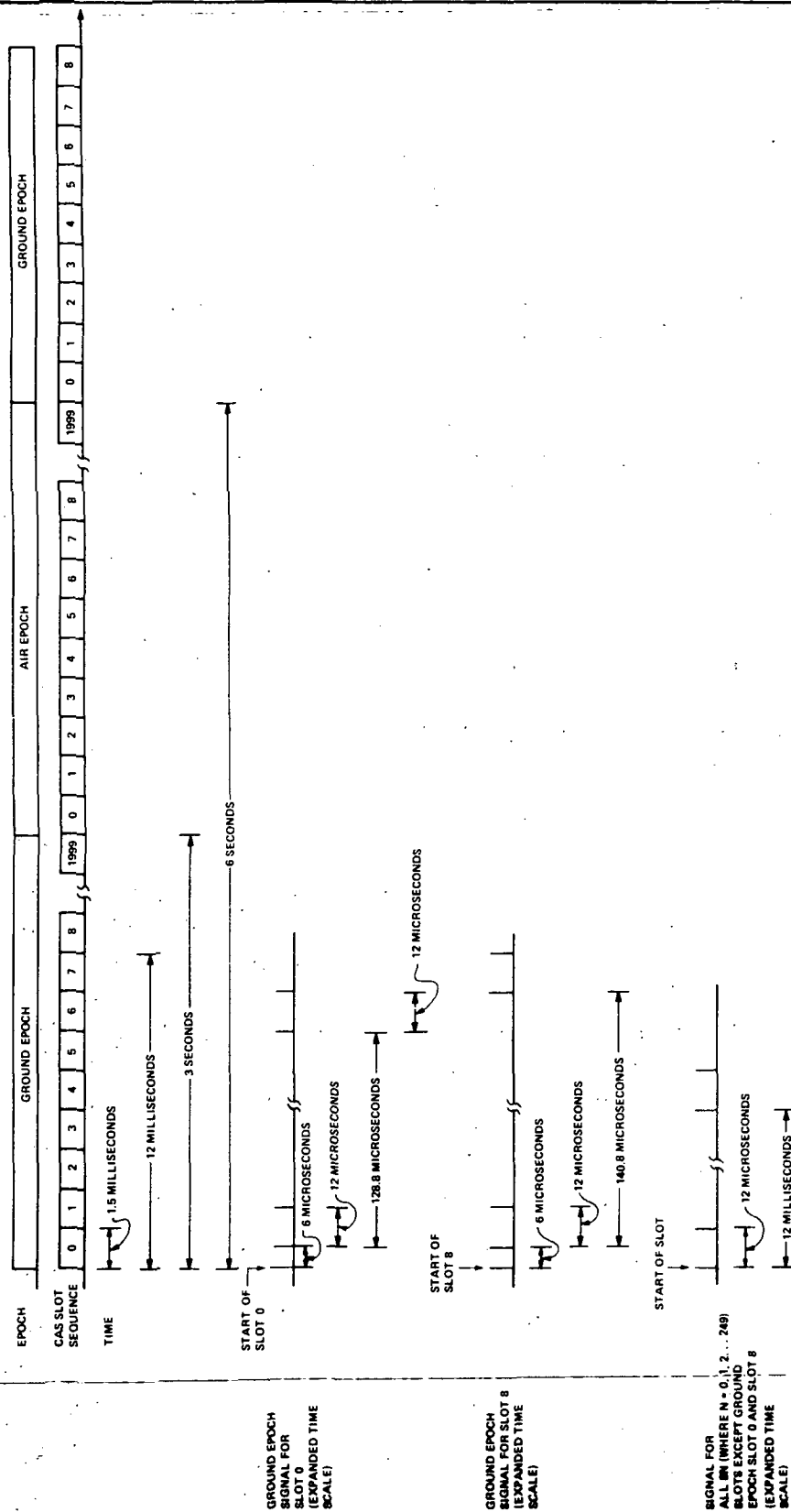
Once fine sync is achieved, two additional circuits, the fine sync alarm and the epoch sync circuits are initiated. When in fine sync, the ± 2 - μ sec window is continuously monitored. If 16 reference pulses are not detected within the window in a 1.5-second sample each 6 seconds, the system resets back to mode 2 when two successive failures occur. In mode 2, if insufficient sync data to pass the 3-out-of-5 test is present, the system is reset back to mode 1 and search is enabled. When fine sync has been attained, the epoch pair decoder is activated. Two sets of epoch pulse pairs are transmitted by the modified VORTAC system every 500th, 12 ms reference pulse. The first set of epoch pairs occurs at slot zero, with the second pair occurring at slot eight. The slot zero pulse pairs spacing is 128.8 μ sec and the slot eight pulse pairs spacing is 140.8 μ sec (see figure 20). In addition, the epoch pulse pairs start 6.0 μ sec later than the normal 12 ms pulse pairs.

If the slot zero pulse pairs are detected, the slot counter will be reset at this time and the programmer will be set to mode 4. Once the programmer is in mode 4, one epoch pair decode is required each minute to maintain the programmer in mode 4. Should at least one epoch pair decode occur each minute, the system is reset to mode 3 and normal operation continues.

If slot zero is not detected in mode 3, slot eight is searched for. If detection occurs, the slot counter is reset to slot eight, and the programmer will set to mode 3. Both epoch pair decodes are used for verification.

In mode 4, both the epoch sync verification circuit and the fine sync alarm continuously monitor their respective windows. If the fine sync alarm is triggered, both epoch and fine sync modes are cleared. If epoch sync verification fails, just the epoch sync mode is cleared.

b. Self Test. Sheet 4 of logic diagram 7115-0502 shows the self-test circuitry that provides a positive test on a very large percentage of the circuitry. This assures the pilot that the CAS is operational by signalling CAS on, only if it passes the self-test criteria. At the end of each local slot, the results of the tests made are summed and provide drive to the CAS ON indicator if all tests passed. In each slot zero, the drive to the indicator is set to the failed condition. The criteria and the conditions tested are as follows:



- NOTES:
1. ALL PULSES AND PULSE PAIRS ARE STANDARD TACAN SIGNALS EXCEPT FOR TIMING.
 2. SOME PULSE PAIRS WILL BE MISSING BECAUSE OF PRIORITY COUNTDOWN.
 3. TIMING SHOWN WITH NOMINAL 50.0 MICROSECONDS TRANSPONDER BEACON DELAY.

1264-32

Figure 20. Synchronization Reference Pulse Timing Diagram

If the slot logic programmed a shut-up and listen ($\overline{\text{SUL}}$), the CAS ON is passed as good since not all self-test data is available.

If the frequency control counter is close to either end of the control range ($\overline{\text{OV}}$), the CAS ON is failed and CAS operation is not allowed. An oscillator calibration adjustment is needed.

Mode 4 (S4P) of the programmer must be true to signify the unit is in good sync alignment and all sync logic is operational.

A range pulse is detected in local slot (ROK) which signifies that the transmit and receive logic, the transmitter, and the receiver are functioning. Power output of the transmitter, receiver sensitivity, or pulse verification is not performed for the purpose of self test.

An altitude pulse is transmitted in local slot (AOK) which signifies that the altitude logic is functioning in the transmit mode. Should the aircraft be on the ground, the AOK signal is passed as good since no altitude transmission is possible while on the ground.

Q. MECHANICAL PACKAGING, DISPLAY, AND INSTALLATION

The GA CAS is intended for a use in a wide variety of aircraft, thus, the requirement is for an inexpensively packaged unit that is easy to install. Since a pilot display is required, it is tempting to consider packaging the unit in an instrument case with an integrated display. However, when considering the size of the unit and the lack of instrument panel space, a remote installation of the electronics is almost mandatory. By remoting the electronics and integrating the display with a vertical speed indicator (an instrument that almost all general aviation aircraft have) only the control function requires any instrument panel space. A small (3/4-by-1-1/2-inch) panel with two switches mounted on it provides the control required.

The GA CAS is comprised of three independently mounted sections plus the antenna installation: (1) a remote unit contains all the electronics; (2) an instrument display provides the pilot command and advisory information; and (3) a control panel for turning the unit on and off and to provide the choice of terminal area operation at the discretion of the pilot.

1. Remote Unit. The remote unit contains the entire electronic system comprised of power supply, transmitter, receiver, logic, and precision

frequency source. Four connectors are mounted on the front plate for connection to the upper and lower antenna (if both used) control panel, and instrument display. Mounting is accomplished by bolting a small rack to the airframe for remote unit support. The remote unit itself can be removed or installed in the rack by removing the connectors and two wing nuts (much like a standard ATR mount). A single unit protection cover is easily removed with a common screw driver. Figure 21 depicts the remote unit and associated rack.

Construction is modular for ease of repair and reduction of manufacturing costs. The remote unit utilizes an I-beam type of construction. A master interconnect board is sandwiched in the center of the I-beam with male interconnects protruding into the left and right compartment. All connections (except r-f) are made through the master interconnect board, including connection to the two cable connectors on the front plate.

Critical circuit separation is accomplished by the I-beam construction. Two independent compartments that are shielded from each other provide r-f to logic isolation. The left compartment is for logic and power supply; the right side is for r-f.

Both antenna connectors are mounted on the r-f front end assembly. This assembly is mounted behind the front plate on the rf side and the connectors protrude through clearance holes for access. This direct connection eliminates additional cable/connector loss.

All of the integral r-f assemblies are interconnected via coaxial cable and connectors. This provides adequate control over radiation, coupling, and losses.

2. Instrument Display. A flat, black molded frame of durable material houses all of the warning lights. It mounts around the Instantaneous Vertical Speed Indicator (IVSI) or a Vertical Speed Indicator on the front of the instrument panel. Three mounting screws are used to sandwich the instrument panel between the CAS Instrument Display and the IVSI, therefore providing a mount. Figure 22 depicts the instrument display.

A thin G-10 printed circuit board (PCB) for all signal routing is permanently molded into this frame. In addition, a small cable (that is electrically attached to the PCB) exists at the rear of the frame for connections to the remote unit. This cable is routed through a clearance slot in the instrument panel during mounting. A connector is permanently attached to the opposite end of the cable.

Grain-of-wheat type incandescent bulbs are mounted to the PCB for warning light illumination. Expected life of these bulbs is 5000 hours. Each warning section is illuminated by one bulb except the MAX CLIMB, NO TURN,

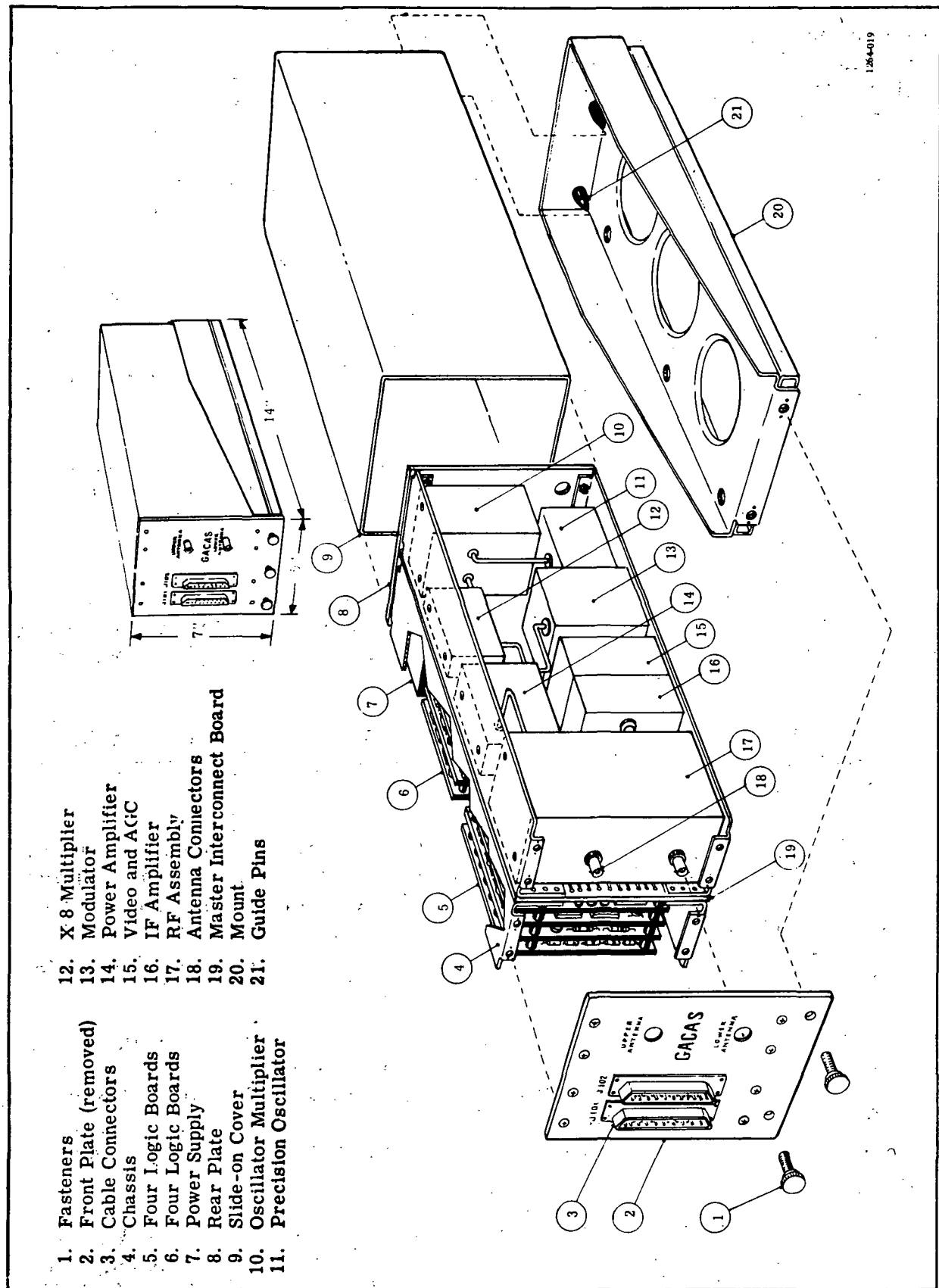
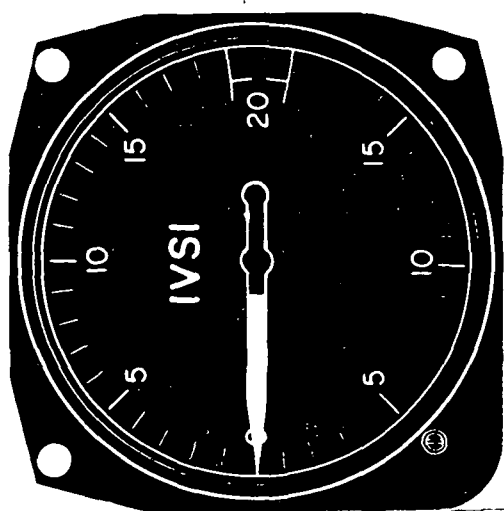
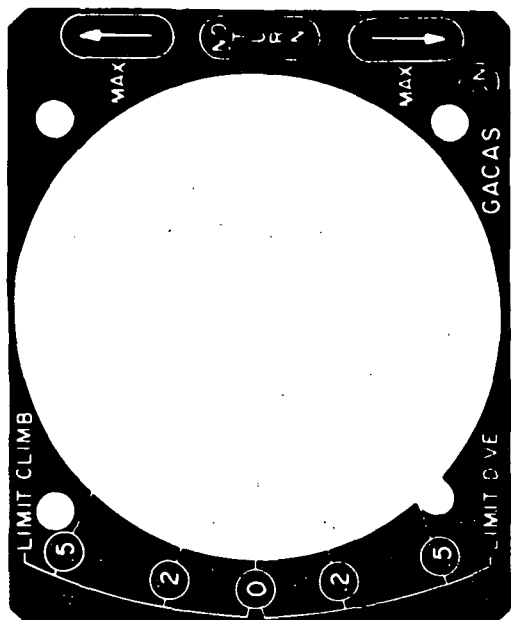


Figure 21. Remote Unit and Associated Rack



BASIC IVSI



INSTRUMENT DISPLAY



IVSI AND INSTRUMENT DISPLAY MOUNTED

13644030

Figure 22. Instrument Display

and MAX DIVE sections, which have two. In a final assembly operation, translucent caps are cemented over bulb clearance hole or slot. The following colors are used for these indicators:

ON	Green
MAX CLIMB	Red
NO TURN	Red
MAX DIVE	Red
.5	Amber
.2	Amber
0 (zero)	Amber

A clearance slot is provided in the lower left corner of the frame for access to the IVSI zero adjustment screw.

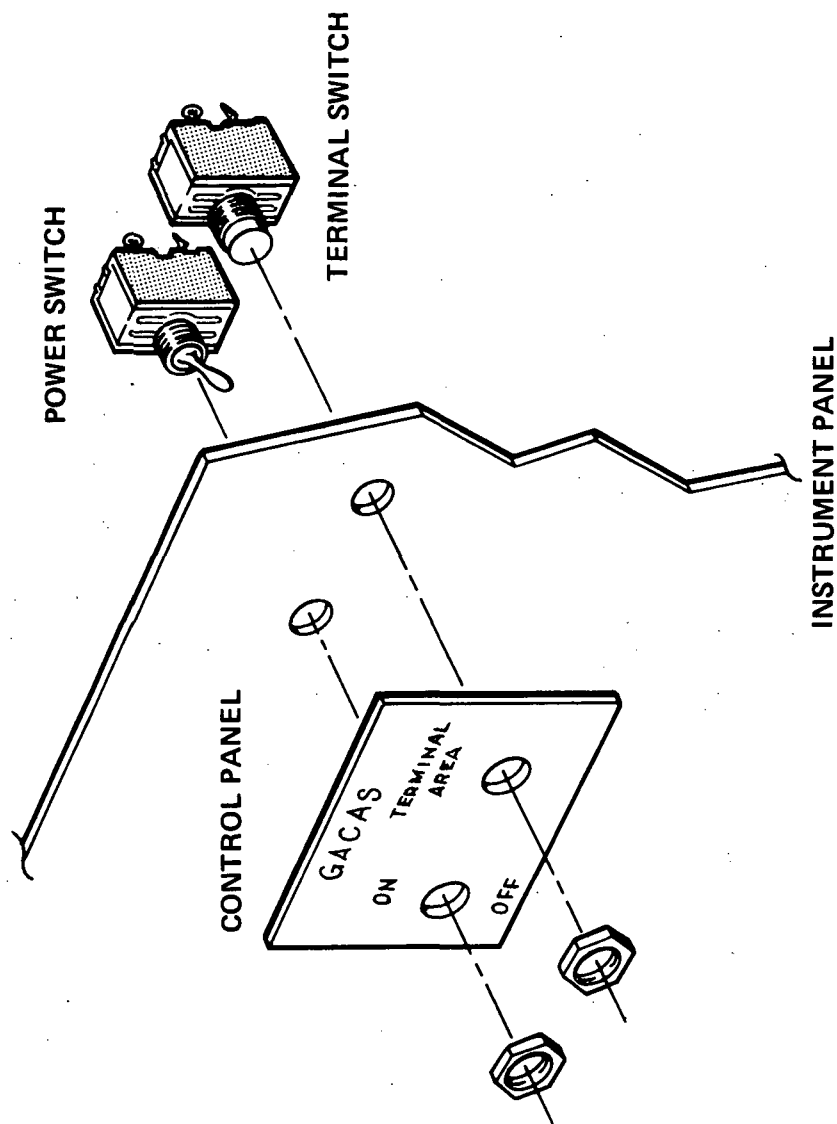
3. Control Panel. Two switches (power and terminal area) are mounted in a convenient place on the instrument panel. Two 1/4-inch holes are drilled 3/4-inch apart and the switches are inserted from the rear. A 3/4-inch high by 1-1/2-inch wide panel with mating 1/4-inch holes spaced 3/4-inch apart is then placed over the switch shafts and the nuts secured. All pertinent nomenclature is inscribed on this panel. Figure 23 depicts the control panel.

R. ENVIRONMENT

The GA CAS is designed to operate continuously in the following environment:

Ambient Temperature	-15° C + 50° C
Altitude:	15,000 feet or less
Humidity:	95% @ 50° C for 48 hours
Shock:	Peak acceleration of 6G for time duration of 10 milliseconds in all axis.
Vibration:	10 - 55 Hz constant total excursion of 0.01" from 10 - 55 cps with maximum acceleration of 1.5 G in all axis.

Additionally, the unit will withstand storage temperatures of from -40° C to +71° C.



1264-021

Figure 23. Control Panel Installation



SECTION III

COST ANALYSIS

A. GENERAL

The cost analysis for production versions of the GA CAS described herein is made by combining the labor costs, overhead burden, material costs, general and administrative allowances, and profit. The overhead burden, general and administrative allowances, and profit percentages used were obtained by averaging a small sample survey of the industry. The cost estimates assume a modern production facility with such capabilities as wave soldering and automatic testing of components and assemblies considered standard practice. Also, it is assumed that high quality parts, material, and assembly techniques are used consistent with the general aviation industry. Additionally, an assumption of at least 5000 units per production facility was made.

Nonrecurring costs have not been included because it has been assumed that only very large quantity production runs can be economically justified. If GA CAS as defined herein is implemented, it will be a very large scale which makes the nonrecurring costs insignificant. In reference 33, it is predicted that 137,000 single engine aircraft will exist in 1974 and a very large percentage of these must be CAS equipped to make the system useful. With even half of the 137,000 single engine aircraft equipped and an estimated \$300,000 to \$500,000 development cost, it can be seen that the nonrecurring costs are in the \$5 to \$8 per unit range.

Included in the cost analysis is a detailed special assembly costs, material cost details, labor estimates, and cost to the user estimates based on various marketing schemes.

B. SPECIAL ASSEMBLY COSTS

Table 2 lists the cost of special assemblies that require special tooling and expertise to design and produce. A specification was written for each item and these specifications are included in appendixes A through D. Vendors that have the expertise to design and produce the special assemblies were contacted for cost and design information and the cost of the lowest estimate was used. Since the cost of the special assemblies have normal profit and overhead-attached-already, the user cost is determined by adding on the cost of the special assemblies after all other costs are computed. Some costs for assembly time and test time is included for these special assemblies. A make-or-buy decision would have to be made on the special assemblies by the producer depending upon his capabilities.

C. MATERIAL COST DETAILS

Table 3 shows a summary of the material cost. Tables 4 through 11 list the material cost estimates for the GA CAS described herein. Each of the tables provide the detail build-up of material costs for that module, and provide the source of the cost by code letters. The code letters are defined as follows:

- 1 - Wilcox Electric Co. standard cost.
- 2 - Telephone or wire quote from supplier used for special components with low-quantity usage.
- 3 - Catalog cost used for common components with low-quantity usage.
- 4 - Sierra Research Corporation estimate based on similar material currently used.

D. LABOR ESTIMATES

The labor estimates detailed in table 12 were derived by an Industrial Engineer using an estimated standard time to accomplish the task and then add an allowance for losses such as touch up, rework, spoilage and repair. Table 13 shows a summary of the direct labor cost.

To obtain costs for direct factory labor, the labor hours were multiplied by Sierra Research Corporation average labor rate for the category of labor used. These average labor rates are as follows:

- | | | |
|--------------------------|---|--------------|
| 1. Model shop technician | - | \$3.79/hour |
| 2. Test technician | - | \$4.04/hour |
| 3. Bench assembler | - | \$2.24/hour. |

E. SPECIAL VERSION OF GA CAS

Should the aircraft already be equipped with a one-way DME capability that is currently being built and tested by Sierra under an FAA contract, some cost reduction is possible since the precision oscillator and sync logic would already be in the aircraft. The reductions possible by this deletion are as follows:

MATERIAL

1. Logic cost reduction (Note 1)	\$105.99
2. Precision oscillator	<u>108.50</u>
Total Material Cost Reduction	\$214.49

LABOR

3. Test technician reduction (Note 2)	\$ 1.62
4. Bench assembly reduction (Note 3)	<u>8.96</u>
Total Labor Cost Reduction	\$ 10.58

Note 1: Delete the circuitry on Logic Diagram 7115-0502

Note 2: Delete 0.4 hours of test technician labor at \$4.04/hour.

Note 3: Delete 4.0 hours of bench assembly labor at \$2.24/hour.

TABLE 2. SPECIAL ASSEMBLY COSTS

Transmitter Power Amplifier	\$ 87.50
R. F. Assembly	130.00
Varactor Multiplier	<u>112.30</u>
Total	\$329.80

TABLE 3. MATERIAL COST SUMMARY

Logic	\$177.37
Miscellaneous (Display, Controls, etc)	55.80
Exciter Signal Source	36.48
Local Oscillator Signal Source	21.48
Modulator	12.24
Video Amplifier and Noise AGC	16.01
IF Amplifier	44.46
Power Supply	81.74
Precision Oscillator	<u>108.50</u>
Total	\$554.08

TABLE 4. MATERIAL COST FOR LOGIC

Descripton	Quantity/ Module	Cost/ Unit	Total Cost/ Item	Cost Source
P. C. Board	8	\$1.00	\$8.00	4
Spacers	32	0.10	3.20	4
Connector Pins (Female)	120	0.015	1.80	4
Resistors (Carbon)	97	0.04	3.88	4
Capacitors (Mica)	36	0.10	3.60	4
Transistors (2N3904/2N2219)	24	0.29	6.96	4
Ladder Network (Helipot 815-R10K)	1	4.87	4.87	2
Diodes (HP5082-2800)	8	0.50	4.00	2
Linear I. C. (National LM201)	1	7.50	7.50	2
Linear I. C. (National LM310)	1	4.85	4.85	2
Linear I. C. (National LM311)	2	3.90	7.80	2
Digital I. C. (7400)	18	0.18	3.24	2
Digital I. C. (7402)	4	0.20	0.80	2
Digital I. C. (7404)	11	0.20	2.20	2
Digital I. C. (7408)	5	0.20	1.00	2
Digital I. C. (7410)	7	0.18	1.26	2
Digital I. C. (7411)	7	0.20	1.40	2
Digital I. C. (7420)	6	0.18	1.08	2
Digital I. C. (74H21)	4	0.25	1.00	2
Digital I. C. (7430)	4	0.18	0.72	2
Digital I. C. (7440)	2	0.18	0.36	2
Digital I. C. (7451)	8	0.18	1.44	2
Digital I. C. (7454)	10	0.18	1.80	2
Digital I. C. (7474)	8	0.39	3.12	2
Digital I. C. (7476)	3	0.44	1.32	2
Digital I. C. (7490)	8	0.79	6.32	2
Digital I. C. (7493)	10	0.79	7.90	2
Digital I. C. (7496)	1	1.23	1.23	2
Digital I. C. (74107)	47	0.40	18.80	2
Digital I. C. (8280)	3	1.30	3.90	2
Digital I. C. (8551)	1	3.25	3.25	2
Digital I. C. (Fairchild U7B902259X)	3	0.45	1.35	2
Digital I. C. (Fairchild U6A900859X)	1	0.20	0.20	2
Digital I. C. (Fairchild U6N931159X)	3	1.95	5.85	2
Digital I. C. (Fairchild U7B931259X)	1	0.85	0.85	2
Digital I. C. (Fairchild U7B960259X)	13	1.55	20.15	2
Digital I. C. (Fairchild U4M451059X)	1	10.25	10.25	2
Digital I. C. (Signetics N820 N)	2	4.95	9.90	2
Digital I. C. (Signetics N8203N)	1	5.25	5.25	2
Digital I. C. (Signetics N8241A)	2	0.83	1.66	2
Digital I. C. (Signetics N8284A)	1	1.15	1.15	2
Digital I. C. (Signetics N8285A)	2	1.08	2.16	2
		Total	\$177.37	

TABLE 5 . MATERIAL COST FOR MISCELLANEOUS ITEMS

Description	Quantity/ Module	Cost/ Unit	Total Cost/ Item	Cost Source
Indicator, Panel	1	\$33.05	\$33.05	4
Raw and Bulk Material	1	8.75	8.75	4
Connectors and Fasteners	1	8.25	8.25	4
Master Interconnect Board	1	2.00	2.00	4
Antenna	1	3.75	3.75	1
		Total	\$55.80	

TABLE 6 . MATERIAL COST FOR EXCITER SIGNAL SOURCE

Description	Quantity/ Module	Cost/ Unit	Total Cost/ Item	Cost Source
91 PF Dura Mica DM10 Cap	1	\$.075	\$.08	1
33 PF Dura Mica DM10 Cap	1	.075	.07	1
5.5-18 PF Disc Trimmer	5	.563	2.82	1
2 - 8 PF Disc Trimmer	3	.563	1.69	1
9 - 35 PF Disc Trimmer	2	.563	1.13	1
1000 PF Stand Off Cap	5	.15	.75	3
1/4 W 5% Carbon Comp Res	8	.03	.21	1
2N3866 Transistor	3	1.23	3.69	2
2N3553 Transistor	1	1.75	1.75	2
2N3632 Transistor	1	11.80	11.80	2
5.6 μ H Wee Ductor	1	.40	.40	1
1 μ H RF Choke	1	.40	.40	1
Misc. Airwound Coils	7	.13	.91	1
P.C. Board	1	4.50	4.50	1
Chassis	1	3.00	3.00	1
RF Connector	1	.93	.93	1
Misc. Hardware		.45	.45	1
100.9375 MHz Crystal	1	1.90	1.90	1
		Total	\$36.48	

TABLE 7. MATERIAL COST FOR LOCAL OSCILLATOR SIGNAL SOURCE

Description	Quantity/ Module	Cost/ Unit	Total Cost/ Item	Cost Source
33 PF Dura Mica DM10 Cap	1	\$.075	\$.08	1
91 PF Dura Mica DM10 Cap	1	.075	.07	1
15 PF Dura Mica DM10 Cap	1	.075	.08	1
.001 MFD Ceramic Disc Cap	2	.061	.12	1
1000 PF Stand Off Cap	2	.15	.30	3
2 - 8 PF Disc Trimmer	1	.563	.56	1
5.5 - 18 PF Disc Trimmer	1	.563	.56	1
9 - 35 PF Disc Trimmer	1	.563	.57	1
1/4 W 5% Carbon Comp Res	7	.03	.21	1
2N3866 Transistors	2	1.23	2.46	2
HP5082-0112 Step Rcvry Diode	1	4.75	4.75	2
5.6 μ H Wee Ductor	1	.40	.40	1
1 μ H RF Choke	1	.40	.40	1
Misc. Airwound Coils	4	.13	.52	1
PC Board with Microstrip Circuitry	1	6.00	6.00	1
97.1875 MHz Crystal	1	1.90	1.90	1
Chassis	1	2.50	2.50	1
		Total	\$21.48	

TABLE 8. MATERIAL COST FOR MODULATOR

Description	Quantity/ Module	Cost/ Unit	Total Cost/ Item	Cost Source
270 PF Dura Mica DM10 Cap	5	\$.075	\$.38	1
51 PF Dura Mica DM10 Cap	2	.075	.15	1
100 PF Dura Mica DM10 Cap	1	.075	.08	1
190 PF Dura Mica DM10 Cap	1	.075	.07	1
4.7 MFD 35 V Tantalum Cap	1	.34	.34	1
150 MFD 35 V Aluminum Cap	1	1.78	1.78	3
1/4 W 5% Carbon Comp Res	19	.03	.57	1
10 K 1/2 W Multi-Turn Pot	2	1.15	2.30	3
2N4400 Transistor	2	.30	.60	2
2N4403 Transistor	1	.38	.38	2
2N4921 Transistor	1	.79	.79	2
2N4123 Transistor	3	.16	.48	2
5402 Quad 2 Input Nor	2	.41	.82	2
PC Board	1	3.50	3.50	1
		Total	\$12.24	

TABLE 9. MATERIAL COST FOR VIDEO AMPLIFIER AND NOISE AGC

Description	Quantity/ Module	Cost/ Unit	Total Cost/ Item	Cost Source
.001 MFD Ceramic Disc Cap	5	\$.061	\$.31	1
0.1 MFD 100 V Mylar Cap	2	.28	.56	1
0.22 MFD 100 V Mylar Cap	3	.24	.72	1
3.3 MFD 15 V Tantalum Cap	2	.36	.72	3
47 MFD 10 V Tantalum Cap	1	.43	.43	3
1/4 W 5% Carbon Comp Res	37	.03	1.11	1
1 W 5% Carbon Comp Res	2	.06	.12	1
15K 1/2 W Multi-Turn Pot	1	1.15	1.15	3
10K 1/2 W Multi-Turn Pot	1	1.15	1.15	3
2N4123 Transistor	8	.16	1.28	2
2N4400 Transistor	4	.30	1.20	2
2N4403 Transistor	3	.38	1.14	2
1N914 Diode	5	.043	.22	1
PC Board	1	5.90	5.90	1
		Total	\$16.01	

TABLE 10 . MATERIAL COST FOR IF AMPLIFIER

Description	Quantity/ Module	Cost/ Unit	Total Cost/ Item	Cost Source
.001 MFD Ceramic Disc Cap	20	\$.061	\$1.22	1
15 pf Dura Mica DM10 Cap	5	.075	.37	1
51 pf Dura Mica DM10 Cap	3	.075	.22	1
43 pf Dura Mica DM10 Cap	2	.075	.15	1
2.2 pf Ceramic Stack Pole Cap	1	.04	.04	1
1.2 pf	1	.04	.04	1
1.7 pf	1	.04	.04	1
47 pf Dura Mica DM10 Cap	1	.075	.08	1
1/4 W 5% Carbon Comp Res	43	.03	1.29	1
2N4259 Transistor	1	1.38	1.38	2
2N3292 Transistor	6	.95	5.70	2
2N4123 Transistor	1	.16	.16	2
5.6 μ h Wee Ductor	8	.40	3.20	1
18 μ h Wee Ductor	1	.40	.40	1
.13 μ h Tuneable Coil Q2100	4	.95	3.80	1
IF Interstage Transformer (Tuneable)	5	.95	4.75	1
IF Last Stage Coil (Tuneable)	1	.95	.95	1
.36 μ h Tuneable Coil Q3100	1	.95	.95	1
1N914 Diode	5	.043	.22	1
Chassis & Cover	1	5.72	5.72	1
RF Connector	1	.93	.93	1
PC Brds	3		12.10	1
Misc. Hardware		.75	.75	1
			<u>\$44.46</u>	

TABLE 11 . MATERIAL COST FOR POWER SUPPLY

Description	Quantity Module	Cost/ Unit	Total Cost/ Item	Cost Source
0.1 MFD 100 V Mylar Cap	2	\$.28	\$.56	3
0.5-.5 Dual Sect. 1000 V Cap	1	2.01	2.01	3
150 MFD 50 V Aluminum Cap	1	1.65	1.65	1
390 MFD 15 V Aluminum Cap	1	1.78	1.78	3
1000 MFD 7 V Aluminum Cap	1	2.24	2.24	3
100 MFD 35 V Aluminum Cap	2	1.73	3.46	3
47 MFD 35 V Tantalum Cap	1	1.07	1.07	1
100 μ H 7 Amp Choke	2	3.00	6.00	1
25 μ H 3 Amp Choke	1	1.25	1.25	1
1 MH 0.4 Amp Choke	2	2.10	4.20	2
1 MH 0.1 Amp Choke	1	2.10	2.10	2
Inverter Power Transformer	1	16.75	16.75	1
1/4 W 5% Carbon Comp Res.	6	.03	.18	1
1/2 W 5% Carbon Comp Res.	5	.04	.20	1
1 W 5% Carbon Comp Res.	1	.06	.06	1
2 W 5% Carbon Comp Res.	1	.08	.08	1
6.5 W 1% Wire Wound Res.	1	.45	.45	1
1/2 W Multi-Turn Pot	1	1.15	1.15	3
2N3790 Transistor	1	3.85	3.85	2
2N4036 Transistor	1	.80	.80	2
2N4403 Transistor	1	.38	.38	2
2N4403 Transistor	1	.30	.30	2
2N3714 Transistor	2	2.28	4.56	2
702 OP Amp IC	1	2.10	2.10	2
1N3899R Rectifier	1	4.90	4.90	2
1N914 Diode	2	.043	.09	1
1N746A Zener Diode	1	.20	.20	2
1N754 Zener Diode	1	.21	.21	2
1N4934 Zener Diode	1	.95	.95	2
1N4744 Zener Diode	1	.95	.95	2
1N4746 Zener Diode	1	.95	.95	2
MR830 Motorola 3A Rectifier	2	1.60	3.20	2
1N4933 1 Amp Rectifier	8	.75	6.00	2
SFM20 Semtech HV Rectifier	2	.98	1.96	2
PC BCD	1	3.90	3.90	1
Misc. Hardware	1	1.25	1.25	1
			<u>\$81.74</u>	

TABLE 12. LABOR ESTIMATES

	Metal Shop Technician (hrs)	Test Technician (hrs)	Bench Assembly (hrs)	Packing (hrs)
Final Assembly		1.5	1.576	
Front Panel Assembly			0.093	
Front Plate	0.201			
Cable and Connector Assembly			0.3	
Chassis Assembly			0.15	
Right Beam	0.526			
Left Beam	0.526			
Rear Plate	0.101			
Master Interconnect Board			0.4	
Slide On Cover	0.226			
Mount Assembly	0.250			
Mount	0.297			
Mount (Base)	0.132			
Guide Pins	0.264			
Printed Wiring Boards		1.0	12.0	
Power Supply		0.2	1.5	
Exciter Signal Source		0.1	1.9	
Local Oscillator Signal Source		0.1	1.6	
Modulator		0.25	0.74	
Video Amplifier and Noise AGC		0.2	1.425	
I. F. Amplifier		0.7	2.83	
Cable Sub-Assembly			0.70	
Packing				0.05
Totals	2.523 hrs.	4.05 hrs.	25.214 hrs.	0.05 hrs.

TABLE 13 . LABOR COST SUMMARY

Labor Class	Total Hrs.	Labor Rate	Cost
Model Shop Technician	2.5	\$3.79	\$ 9.48
Test Technician	4.0	4.04	16.16
Bench Assembly	25.2	2.24	56.45
		Total	\$82.09

F. CCST TO THE USER

1. General. To develop a cost to the user for the equipment described herein, it is necessary to combine the labor cost with an attached overhead, the material cost, a general and administrative fee for such costs as advertising, warranties, and future development, profit, and finally distribution costs.

2. Factory Selling Price. All but the distribution costs make up the factory selling price and with some estimates on the labor overhead, general and administrative fee, and profit, the estimated factory selling price can be well determined. Table 14 shows a factory selling price for the GA CAS described herein. Also shown in table 14 is the factory selling price for the special version of the GA CAS where the precision oscillator and timing chain have been deleted as described in paragraph E. For the discussion, the version with the precision oscillator and clock will be called Version A and the one without the precision oscillator and clock will be called Version B.

3. Distribution Channels. There are three major distribution channels that a manufacturer can use to get his product to the general aviation market as follows:

a. Sell directly to an aircraft manufacturer for factory installation of the equipment. A larger discount is usually offered by the avionics manufacturer in this distribution channel because orders are placed annually and in lot sizes of about 100. Demand is well known and the avionics manufacturer does not tie up inventory or take any risk in producing the units. In addition, any installation is easier to make as the aircraft is in assembly - especially wiring and panel mounting. Typical discounts of 50% are given from one manufacturer.

b. Sell to a distributor that also sells aircraft. The distributor normally has the installation made and adds this cost on to the list price of the equipment. The advantage of selling to a distributor is primarily one of quantity since dealer lots usually run 6 to 10. The distributor must either install the equipment or pay someone else to install it and this cost is passed on to the buyer on top of the list price. Typical discounts of 45% are given from one manufacturer.

TABLE 14. FACTORY SELLING PRICE

	<u>Version A</u>	<u>Version B</u>
Labor	\$ 82.09	\$ 71.51
Overhead (150%)	<u>123.14</u>	<u>107.27</u>
Labor and Overhead	\$ 205.23	\$ 178.78
Material (Note 1)	<u>498.67</u>	<u>339.59</u>
Factory Cost	\$ 703.90	\$ 518.37
General and Administrative (15%)	<u>105.59</u>	<u>77.76</u>
Selling Cost	\$ 809.49	\$ 596.13
Profit (20%)	<u>161.90</u>	<u>119.23</u>
Selling Cost and Profit	\$ 971.39	\$ 715.36
Special Assemblies	<u>329.80</u>	<u>329.80</u>
Factory Selling Price	\$ 1301.19	\$ 1045.16
Note 1: The material cost listed is 90% of the total bill of materials quote which is consistent with industry experience that 10% lower average material cost can be negotiated at time of manufacture.		

c. Sell to a dealer that normally runs a servicing shop. The dealer usually installs the equipment and the cost of installation is added to the list price of the equipment as in the case of the distributor. No quantity advantage is available to the producer. Typical discounts of 40% are given from one manufacturer.

It is not possible to compute the distribution cost for each of the channels - especially the one involving the aircraft manufacture. Assuming he installs avionics on the aircraft at the time of manufacturer and then sells to a distributor, how does he discount that small portion off the list price of the unit? He must cover labor costs for handling, installation, etc. and some profit but how much? For the distributor and dealer it would be easier to estimate the distribution costs but the number would vary widely depending on the quality and service back-up provided by the distribution channel.

Fortunately, in the real world, distribution costs do not have to be determined directly to obtain a user cost as shown below in the selling price discussion.

4. Selling Price: The avionics manufacturer through his sales literature or quotes to customers develops a list price for his equipment. This published list price, as in the automotive industry, is only a figure the seller may use during the negotiation of a sale. The published list price does not necessarily reflect the manufacturing or distribution costs of the product. The seller will usually offer the largest off list amounts on equipment that does not fail under the normal warranty period and on equipment that has features (such as additional capability, safety, and price) that allow a high inventory turnover rate.

5. Typical User Cost. Since some 137,000 single engine aircraft will exist in 1974 and a very large percentage of these must be CAS equipped to make the system useful, as was assumed in section III paragraph A, the only practical distribution channel is through the dealer for a majority of users. In a small survey of existing dealer practices, it was found that many dealers now will usually make a sale at between 10% and 20% off list and installation done at the dealer costs. Additionally, as shown in reference 34, the list price of similar equipment as it is widely accepted and used, tends to fall at about 15% per year.

To determine the acquisition cost to the user, more conservative assumptions have been made as follows:

- a. Manufacturer gives dealer a discount of 40%,
- b. Shipping charges are \$5.00 per unit,
- c. List price falls 5% per year for the first 3 years,
- d. Dealer gives 10% off list to user the first year, 15% off list to user the second year, and 20% off list to user the third year.

Following is an estimated cost to the user for Version A and Version B for the first three years with the assumptions listed above.

<u>Estimated Cost to User for First Year</u>		
	<u>Version A</u>	<u>Version B</u>
Factory Selling Price	\$1301.19	\$1045.16
Shipping	5.00	5.00
Dealer Discount	<u>867.46</u>	<u>696.77</u>
List Price	\$2173.65	\$1746.93
Off List to User (10%)	<u>217.37</u>	<u>174.69</u>
Cost to User	\$1956.28	\$1572.27
<u>Estimated Cost to User for Second Year</u>		
	<u>Version A</u>	<u>Version B</u>
List Price (reduced 5%)	\$2064.97	\$1659.58
Off List to User (15%)	<u>309.75</u>	<u>248.94</u>
Cost to User	\$1755.22	\$1410.64
<u>Estimated Cost to User for Third Year</u>		
	<u>Version A</u>	<u>Version B</u>
List Price (reduced 10%)	\$1956.28	\$1572.24
Off List to User (20%)	<u>391.26</u>	<u>314.45</u>
	\$1565.02	\$1257.79

PART THREE

CONCLUSIONS

On the basis of this study, it is concluded that the projected \$1500 target cost can be met, although one version would be somewhat more expensive when it first appears on the market.

Meeting the target cost requirements would not be feasible without some significant simplifications in the CAS design. In particular, no really inexpensive approach to doppler range-rate extraction appears consistent with required system safety.

It is possible to simplify the GA version of Time/Frequency CAS by deleting requirements for phase-coherent long-pulse transmissions, doppler processing, and multifrequency reception. Use of synchronous reference pulse transmissions by ground VORTAC stations also permits reduction of transmitter power and receiver sensitivity requirements and deletion of the back-up mode. The transmission of auxiliary data (as biphasic modulation of the doppler pulse) is also eliminated.

Deletion of doppler range rate extraction involves some increase in the protection envelope about own aircraft. However, use of a shorter pulse to distinguish GA CAS transmissions, and inclusion of pilot selection of temporary terminal logic reduces this increment to tolerable proportions.

It may be possible to reduce the threat protection in terminal areas somewhat further; however, this might not provide absolute collision protection against head-on encounters.

The detailed cost estimates, presented here, indicate that if there is sufficient user interest, the system target cost to the user for either version will fall below \$1500 within a reasonable time after introduction of the GA CAS equipment on the market.

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PART FOUR

APPENDIX A
SPECIFICATION FOR GENERAL AVIATION
COLLISION AVOIDANCE SYSTEM
RF ASSEMBLY

SIERRA RESEARCH CORPORATION
POST OFFICE BOX 222 • BUFFALO, NEW YORK 14225

TECHNICAL DATA

BY W. V. Scott
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DATE 12 November 1971
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REPORT NO. SP7115-0100 MODEL

**SPECIFICATION FOR GENERAL AVIATION
COLLISION AVOIDANCE SYSTEM
RF ASSEMBLY**

REVISIONS

DATE	PAGE NO.

SPECIFICATION FOR GENERAL AVIATION COLLISION AVOIDANCE SYSTEM RF ASSEMBLY

General Description

The RF assembly described by this specification consists of a SPDT switch, a three-port circulator, a limiter, a preselector, a balanced mixer, a local oscillator bandpass filter, and a transmitter lowpass filter (see figure 1). The assembly is to be an integrated package utilizing strip line techniques wherever practical. The interfaces with the assembly shall consist of: two antenna connections, a transmitter input, an IF output, and a local oscillator input.

The RF assembly will be used in an airborne box that is intended for use in general aviation type aircraft with temperature-controlled non-pressurized environment.

Please suggest any minor modification of these requirements that may result in significant cost savings.

System Performance Specifications

The RF assembly will meet or exceed the electrical specifications listed below, when subjected to the required environmental conditions.

Transmit Mode

- | | |
|--|---|
| 1. Frequency | 1615 MHz |
| 2. Transmitter Input VSWR | The input VSWR shall be 1.5:1 maximum for any terminating impedance. The VSWR shall remain within a 1.1:1 VSWR circle over the temperature range of -10°C to +50°C. |
| 3. Peak Power Capability | 150 Watts |
| 4. Average Power Capability | 3 mw |
| 5. Insertion Loss - Transmitter to Antenna | 1.5 db Max. |
| 6. Isolation - Transmitter to Mixer | 60 db Min. |
| 7. Low Pass Filter Harmonic Rejection | 40 db Min. |

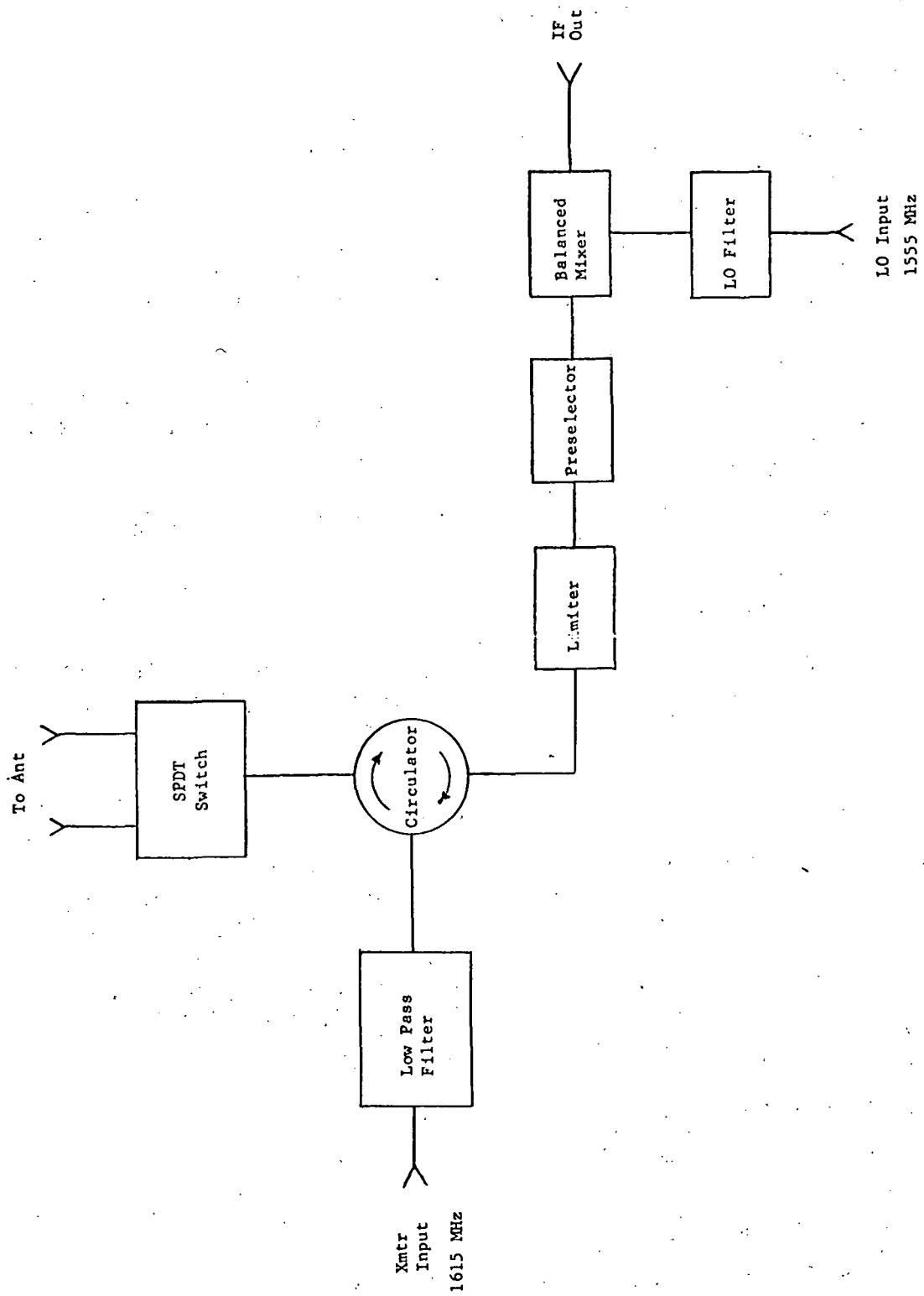


Figure 1

Receiver Mode

1. Preselector Center Frequency	1615 MHz
2. Preselector 3 db Bandwidth	6 MHz Min.
3. Image Rejection ($f_o \pm 120$ MHz)	60 db Min.
4. Half Image Rejection (1585 MHz)	60 db Min.
5. Out-of-Band Frequencies Rejection ($f_o + 120 - 60$ MHz)	60 db Min.
6. Passband Ripple	1.0 db Max.
7. Receiver Input VSWR	1.5:1 Max.
8. Noise Figure (3 db IF)	12 db Max.
9. IF Impedance	150 ± 25 ohm 12 ± 3 pf
10. LO Input VSWR	1.5:1 Max.
11. LO Input Power	2.0 mw Min.
12. Isolation-LO to Antenna	60 db Min.
13. LO Filter Rejection @ 1361 MHz and 1749 MHz	20 db Min.
14. LO Frequency (Fixed Tuned)	1555 MHz

NOTE: All connections to be OSM female.

Environmental Requirements

1. Temperature Range	-15°C to +50°C
2. Altitude	15,000 ft. test
3. Humidity	48 hrs. @ 95% and +50°C
4. Shock	Apply three shocks to the equipment, mounted in each of the following positions: A. Normal upright. B. Suspended upside down. C. At positions such that the first major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plane of the table.

D. At positions such that the second major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plane of the table.

A peak acceleration of at least 6 G shall be reached in approximately 5 1/2 milliseconds. The total time duration shall be 11 ± 2 milliseconds.

5. Vibration

Equipment shall be vibrated from 5 to 55 Hertz with amplitude excursion of .010" and maximum acceleration of 1.5 G. Vibration shall be for a minimum of one hour in each of the three major orthogonal planes. Vibration frequency shall vary at a rate not to exceed 1.0 octave/minute.

Physical Requirements

1. Size

Please specify.

2. Weight

Please specify.

APPENDIX B
SPECIFICATION FOR GENERAL AVIATION
COLLISION AVOIDANCE SYSTEM
TRANSMITTER POWER AMPLIFIER

SIERRA RESEARCH CORPORATION
POST OFFICE BOX 222 • BUFFALO, NEW YORK 14225

TECHNICAL DATA

BY W. V. Scott
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**SPECIFICATION FOR GENERAL AVIATION
COLLISION AVOIDANCE SYSTEM
TRANSMITTER POWER AMPLIFIER**

REVISIONS

DATE	PAGE NO.

SPECIFICATION FOR GENERAL AVIATION COLLISION AVOIDANCE SYSTEM TRANSMITTER POWER AMPLIFIER

General Description

The power amplifier described by this specification will be used in a low-cost airborne Collision Avoidance System intended for use in general aviation type aircraft with temperature controlled, non-pressurized environment.

It is anticipated that this amplifier will be a two tube coaxial cavity or stripline resonator type configuration; however, in the interest of cost savings other approaches (e.g., lumped constant, microstrip) will be given equal consideration provided performance specifications are met.

Please suggest any minor modification of these requirements that may result in significant cost savings.

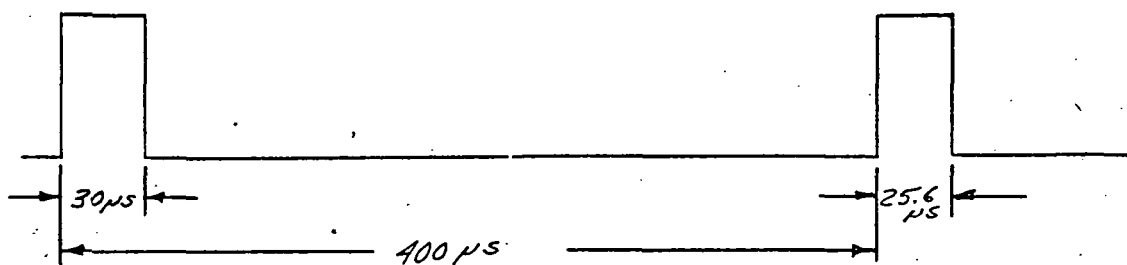
Performance Specifications

The transmitter power amplifier will meet or exceed the electrical specifications listed below when subjected to the required environmental condition.

Electrical Specifications

- | | |
|---|---|
| 1. Frequency | 1615 MHz |
| 2. Bandwidth (3 db) | 8 MHz min. |
| 3. Peak Pulse Power out
(Pulse width = 30 μ s) | 150 watts min. |
| 4. Power Gain (@ 150 w out) | 30 db min. |
| 5. Modulation | Cathode Pulsed |
| 6. Modulation Pulse Characteristics | Please Specify |
| 7. Input VSWR | 1.5:1 (ref. to 50 ohm) |
| 8. Load VSWR | The load VSWR shall be 1.5:1 maximum. The load VSWR shall remain within a 1.1:1 VSWR circle over the specified temperature range. |
| 9. Duty Cycle (see figure 1) | .002% |

CAS MESSAGE FORMAT
(Shown at Maximum Duty Cycle)



Rep. Rate= 1/3 HZ

Figure 1.

- | | |
|---|--|
| 10. Harmonics | 20 db down min. |
| 11. Pulse Rise Time | 0.1 μsec. max. |
| 12. Pulse Decay Time | 0.1 μsec. max. |
| 13. Pulse Droop | 2% max. |
| 14. Input/Output RF Connectors | OSM Female |
| 15. Tube Life | 2000 hrs. min. with not more than 3 db loss in power out |
| 16. Plate and Filament Voltage and Current Requirements | Please specify |

Physical Requirements

- | | |
|-----------|----------------|
| 1. Size | Please specify |
| 2. Weight | Please specify |

Environmental Requirements

- | | |
|----------------------|---|
| 1. Temperature Range | -15°C to +50°C |
| 2. Altitude | 15,000 ft. test |
| 3. Humidity | 48 hrs. @ 95% and 50°C |
| 4. Shock | Apply three shocks to the equipment mounted in each of the following six positions:
A. Normal upright. |

- B. Suspended upside down.
- C. At positions such that the first major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plan of the table.
- D. At positions such that the second major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plan of the table.

A peak acceleration of at least 6G shall be reached in approximately 5 1/2 milliseconds. The total time duration shall be 11 ± 2 milliseconds.

5. Vibration

Equipment shall be vibrated from 5 to 55 Hertz with amplitude excursion of .010" and maximum acceleration of 1.5 G. Vibration shall be for a minimum of one hour in each of the three major orthogonal planes. Vibration frequency shall vary at a rate not to exceed 1.0 octave/minute.

APPENDIX C
SPECIFICATION FOR
VARACTOR MULTIPLIER

SIERRA RESEARCH CORPORATION
POST OFFICE BOX 222 • BUFFALO, NEW YORK 14225

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SPECIFICATION FOR VARACTOR MULTIPLIER

REVISIONS

DATE	PAGE NO.

SPECIFICATION FOR VARACTOR MULTIPLIER

General Description

The varactor multiplier described by this specification will be used in a low-cost airborne Collision Avoidance System intended for use in general aviation type aircraft with temperature-controlled, non-pressurized environment. The multiplier is to be of stripline construction were practical and economical.

Please suggest any minor modification of these requirements that may result in significant cost savings.

System Performance Specification

The varactor multiplier will meet or exceed the electrical specifications listed below when subjected to the required environmental conditions.

- | | | |
|----|--------------------------------------|-------------|
| 1. | Output Frequency (Single Freq.) | 1615 MHz |
| 2. | Input Frequency (Single Freq.) | 201.875 MHz |
| 3. | Multiplication Factor | X8 |
| 4. | Power Out (@ 2 W In) | 150 mw Min. |
| 5. | Fundamental Frequency Suppression | -30 db Min. |
| 6. | Suppression of 7th and 9th Harmonics | -25 db Min. |
| 7. | Non-Harmonic Components | -55 db Min. |
| 8. | Input VSWR (Ref to 50) | 2:1 Max. |
| 9. | Output Impedance | 50 |

NOTE: RF Connectors to be OSM female.

Environmental Requirements

- | | | |
|----|-------------------|------------------------|
| 1. | Temperature Range | -15°C to +50°C |
| 2. | Altitude | 15,000 ft. test |
| 3. | Humidity | 48 hrs @ 95% and +50°C |

Environmental Requirements (cont)

4. Shock

Apply three shocks to the equipment mounted in each of the following six positions:

- A. Normal upright.
- B. Suspended upside down.
- C. At positions such that the first major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plane of the table.
- D. At positions such that the second major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plane of the table.

A peak acceleration of at least 6 G shall be reached in approximately 5 1/2 milliseconds. The total time duration shall be 11 ± 2 milliseconds.

5. Vibration

Equipment shall be vibrated from 5 to 55 Hertz with amplitude excursion of .010" and maximum acceleration of 1.5 G. Vibration shall be for a minimum of one hour in each of the three major orthogonal planes. Vibration frequency shall vary at a rate not to exceed 1.0 octave/minute.

Physical Requirements

- 1. Size
- 2. Weight

Please specify.

Please specify.

APPENDIX D
SPECIFICATION FOR
HIGH STABILITY OSCILLATOR

SIERRA RESEARCH CORPORATION
POST OFFICE BOX 222 • BUFFALO, NEW YORK 14225

TECHNICAL DATA

BY W. V. Scott
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SPECIFICATION FOR HIGH STABILITY OSCILLATOR

REVISIONS

DATE	PAGE NO.

SPECIFICATION FOR HIGH STABILITY OSCILLATOR

General Description.

The high stability oscillator described by this specification will be used in a low-cost airborne Collision Avoidance System intended for use in general aviation type aircraft with a temperature-controlled, non-pressurized environment.

Please suggest any minor modification of these requirements that may result in significant cost savings.

System Performance Specification.

The high stability oscillator will meet or exceed the electrical specifications listed below when subjected to the required environmental conditions.

- | | |
|---|--|
| 1. Frequency | $5.0 \text{ MHz} \pm 1 \times 10^{-8}$ at nominal bias and 25°C |
| 2. Frequency Stability | |
| (a) Aging | $\pm 5 \times 10^{-9}$ /day |
| (b) Short Term | $\pm 1 \times 10^{-10}$ /second |
| (c) Supply Voltage | $\pm 1 \times 10^{-8}$ for a ± 0.5 volt change in supply voltage |
| (d) Resistive Load Change | $\pm 1 \times 10^{-9}$ for $\pm 10\%$ resistive load change |
| (e) Capacitive Load Change | $\pm 1 \times 10^{-9}$ for $\pm 10\%$ capacitive load change |
| (f) Temperature | $\pm 1 \times 10^{-8}$ for an ambient temperature change from -15°C to $+50^{\circ}\text{C}$ |
| (g) Vibration | $\pm 5 \times 10^{-9}$ |
| (h) Shock | $\pm 5 \times 10^{-9}$ |
| (i) Orientation | $\pm 1 \times 10^{-8}$ for all positions with respect to the gravity vector |
| 3. Warm-up Time (after four hours off referenced to the turn-off frequency and at -15°C) | $\pm 5 \times 10^{-7}$ in 10 minutes
$\pm 5 \times 10^{-8}$ in 15 minutes |

- | | |
|----------------------|---|
| 4. Output | 1.0 VRMS or greater into 1 K ohm and 50 pF load with less than 10% distortion |
| 5. Input Power | $\pm 22 \pm 0.5$ vdc 6 watts maximum for normal operation; 10 watts maximum for warm-up |
| 6. Frequency Adjust | $\pm 2 \times 10^{-6}$ settable to $\pm 5 \times 10^{-9}$ |
| 7. Voltage Control | |
| (a) Range | $\pm 2 \times 10^{-7}$ |
| (b) Slope (positive) | $40 \times 10^{-9}/\text{volt} \pm 8 \times 10^{-9}/\text{volt}$ |

NOTES:

1. All inputs and outputs to be solder hook terminals.
2. Voltage control terminals shall not be internally D-C referenced to any other circuit.

Environmental Requirements.

- | | |
|----------------|---|
| 1. Temperature | -15°C to +50°C |
| 2. Altitude | 15,000 ft. test |
| 3. Humidity | 48 hours @ 95% and +50°C |
| 4. Shock | Apply three shocks to the equipment mounted in each of the following six positions: |
| | (a) Normal upright |
| | (b) Suspended upside down |
| | (c) At positions such that the first major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plane of the table. |
| | (d) At positions such that the second major orthogonal axis of the equipment successively forms angles of plus 90° and minus 90° (two positions) with the plane of the table. |

A peak acceleration of at least 6 G shall be reached in approximately 5-1/2 milliseconds. The total time duration shall be 11 milliseconds.

5. Vibration

Equipment shall be vibrated from 5 to 55 Hz with amplitude excursion of .01" and maximum acceleration of 1.5 G. Vibration shall be for minimum of one hour in each of the three major orthogonal planes. Vibration frequency shall vary at a rate not to exceed 1.0 octave/minute.

Physical Requirements

1. Size

Please specify

2. Weight

Please specify