REPORT No. FAA-RD-76-17

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# ANALYSIS, FLIGHT TEST & EVALUATION OF HONEYWELL, MCDONNELL-DOUGLAS & RCA AIRBORNE COLLISION AVOIDANCE SYSTEMS (ACAS)

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16. Abstract

As part of its Aircraft Separation Assurance Program, the FAA has evaluated three Airborne Collision Avoidance Systems (ACAS) designed and built by Honeywell, McDonnell-Douglas and RCA. The evaluation consisted of analyses, simulations and maneuver selection logics developed by the Air Transport Association's ACAS Technical Working Group as a standard for comparison. The results show the Honeywell system superior from both a cost and technical performance standpoint.

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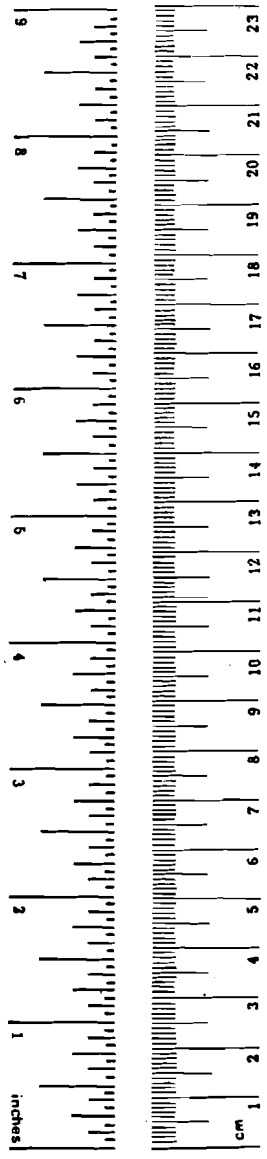
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

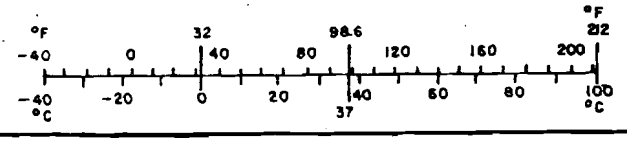
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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# ANALYSIS, FLIGHT TEST & EVALUATION OF HONEYWELL, MCDONNELL-DOUGLAS & RCA AIRBORNE COLLISION AVOIDANCE SYSTEMS (ACAS)

## I. INTRODUCTION

Since the late Fifties, FAA has been searching for an Airborne Collision Avoidance System. Up until the late Sixties, the State-of-the-Art dictated a Time/Frequency (T/F) solution. In the early Seventies, advancements in the State-of-the-Art gave promise of a low cost Interrogate/Transpond (I/T) approach. For the last several years, we have been in the final stages of analyses, test, and evaluation of both kinds of systems, specifically the Honeywell and RCA I/T systems and the McDonnell-Douglas T/F system.

As a result of the analyses and hardware evaluations done to date, it has been concluded that, from a cost and technical standpoint, the Honeywell system is the best of the three systems tested.

## II. THREAT EVALUATION AND MANEUVER SELECTION LOGICS

### A. Background

In late 1966, FAA was about to issue a competitive Request for Proposals for a T/F ACAS for test and evaluation purposes. The Air Transport Association (ATA), in a letter to the FAA Administrator, requested that this planned procurement be cancelled and offered the following alternate:

> The ATA would create an ACAS Technical Working Group (TWG) composed of representatives from the major avionics firms, interested Government agencies, and industry experts in the T/F technology. This group would convene and jointly prepare an ACAS specification to which interested manufacturers would build equipment (at their own expense) for flight testing by the ATA.

In June 1967, the ATA published the results of the TWG's deliberations—Air Navigation and Traffic Control Report No. 117 (ANTC-117), "Airborne Collision Avoidance System, Statement of Airline Policy and Requirements and a Technical Description of the System."

Since that time, there have been many revisions to the document, the latest being Revision 10, dated May 12, 1971. ANTC-117 describes, among other things, the threat evaluation and maneuver selection logics to be utilized to assure safe aircraft separation. It is these logics to which the three manufacturers built their ACASs for air carriers and against which the systems are being compared.

## B. Description of Logics

### 1. General

The threat evaluation and maneuver selection logics described in ANTC-117 are intended to insure separation of aircraft within the following aircraft performance profiles:

| | | |
|---|---|---|
| Horizontal Acceleration | - | 1/2 G |
| Vertical Acceleration | - | 1/4 G |
| Vertical Rate | - | 5000 ft./min. |

Hence, separation assurance was to be provided to pairs of aircraft whose maximum relative horizontal acceleration did not exceed 1 G, whose maximum relative vertical acceleration did not exceed 1/2 G, and whose maximum relative vertical closure rate did not exceed 10,000 ft./min.

In order to achieve this degree of separation assurance, several algorithms involving measured values of separation distance or range (R), separation closing rate or range rate ($\dot{R}$), altitude difference ($\Delta h$), and the rate of altitude closure ($\dot{h}$) of the aircraft in which an evaluation of the threat is being made, are used to generate various cautions and commands to pilots. These cautions and commands cause the pilot to perform certain avoidance or escape maneuvers: to limit or stop turning (also known as roll-out), to limit vertical speeds, and to change altitude. Because relative bearing is not available, escape maneuvers are in the vertical plane.

The algorithms which provide cautionary or command criteria are of two types: (1) horizontal threat criteria, or those based on R, $\dot{R}$, and (2) vertical threat criteria, or those based on $\Delta h$, $\dot{h}$. In principle, since R represents the slant range between aircraft, the R, $\dot{R}$ criteria alone should be sufficient to provide alarms needed for protection against collision. However, it has been found that the use of altitude data is required to reduce the threat volume, and hence the alarm rate, to manageable proportions, and to determine the proper direction for vertical avoidance maneuvers.

The measurement of R, $\dot{R}$ and $\Delta h$ is accomplished by means of RF communications between aircraft. The arrival time of a communications signal (one-way in the case of T/F, two-way in the case of I/T) is used to calculate R, while $\dot{R}$ is obtained from sequentially differencing R measurements and dividing by the time interval between measurements. Each aircraft measures its own altitude and communicates it in digital steps of 100 ft. to other aircraft. Each ACAS equipped aircraft measures its own altitude rate ($\dot{h}$) but does not communicate this data to others. In order to

determine the ultimate escape maneuver, the higher aircraft climbs, the lower of the two dives. To solve the co-altitude problem, the first aircraft determining that a threat exists which requires a climb or dive, chooses a maneuver and biases its altitude transmission 200 ft. in the direction of the maneuver. This insures the other aircraft will make a complementary maneuver and not a cancelling one. In the unlikely event of a three aircraft encounter, the higher climbs, the lower dives, and the middle aircraft flies level.

2. Horizontal Threat Criteria

In the early days of ACAS development, it was proposed that an R, $\dot{R}$ algorithm be based on a quantitity TAU (T), defined by:

$$T = R/\dot{R}$$

representing the time to collision for two aircraft on a non-accelerating collision course. It has since been realized that because of measurement errors and the possibility that aircraft may be accelerating, a modification to this idea was necessary. Thus, ANTC-117 adopted three alarm algorithms based on R, $\dot{R}$. These algorithms, sometimes known as the modified TAU criteria, are as follows, and are depicted graphically in Figure II-1:

$$R + T_2\dot{R} \leq Ro_2 \quad *$$

$$R + T_1\dot{R} \leq Ro_1$$

Where $T_2$, $Ro_2$, $T_1$, and $Ro_1$ are designated constants. In the first algorithm, known as the $T_2$ warning criterion, the constants have the values:

$T_2$ = 40 secs.

$Ro_2$ = 1.8 nmi. (10,940 ft.)

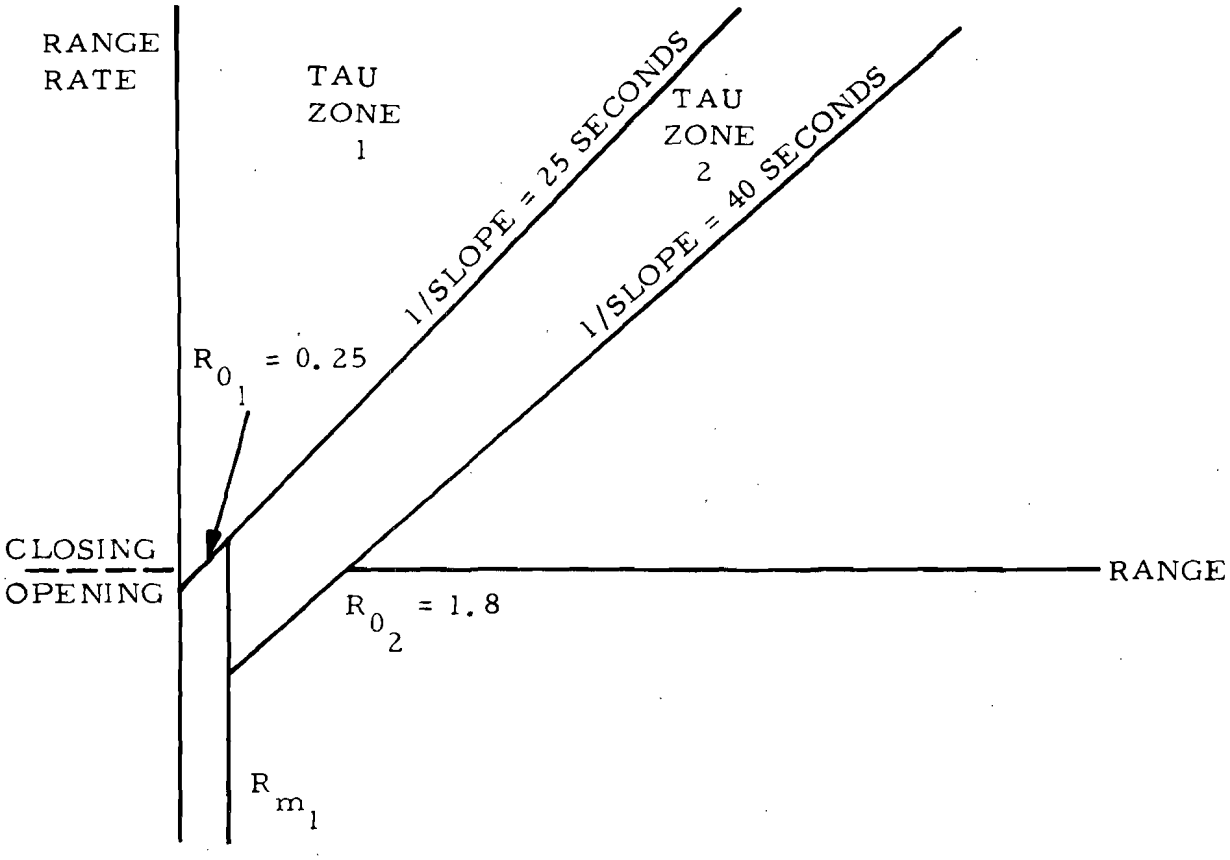
In the second algorithm, known as the $T_1$ alarm criterion, the designated constants have the values:

$T_1$ = 25 secs.

$Ro_1$ = 1/4 nmi. (1,520 ft.)

$TAU_2$ is chosen sufficiently far in advance of $T_1$ to enable aircraft which receive $T_2$ warnings to reduce their vertical and horizontal rates and accelerations before reaching the $T_1$ zone. $TAU_1$ is chosen

* Positive $\dot{R}$ corresponds to increasing range




$R_{0_1}$ = 0.25 NMI = 1,520 FEET

$R_{0_2}$ = 1.8 NMI = 10,944 FEET

$R_{m_1}$ = 0.5 NMI = 3,040 FEET

RANGE AND RANGE RATE THREAT EVALUATION
FIGURE II-1

sufficiently small to reduce the number of commands, yet sufficiently large to enable aircraft receiving $T_1$ commands to make a safe vertical escape maneuver. $TAU_1$ time allowances have been made for pilot reaction, aircraft reaction, missed communications, system cycle time (round time), and maneuver time to acquire safe separation.

Thus, if two aircraft are co-altitude (within 600 ft. for altitudes below 10,000 ft. or within 800 ft. for altitudes above 10,000 ft.), and if measured values of R and $\dot{R}$ satisfy the $T_2$ criterion, the pilot is commanded to limit his turn rate and ascent or descent rate. Compliance with this command reduces the relative trajectory of the two aircraft so that the encounter is approximately horizontal and non-accelerating. Then conditions are assumed to be suitable for the safe use of the more restrictive $T_1$ criterion. Similarly, if a co-altitude situation exists and the measured values of R and $\dot{R}$ satisfy the $T_1$ criterion, vertical commands (climb or dive) are issued.

The third horizontal threat algorithm is:

$$R \leq R_m \quad (3{,}040 \text{ ft.})$$

and is called the minimum range criterion. Its purpose is to protect against the case of very slow closure rates which would not trigger a $T_1$ alarm but which in the presence of measurement errors and possible accelerations, might not leave enough time available for a safe escape maneuver. Thus, a climb or dive maneuver is directed when the slant range between aircraft is 1/2 nmi. or less.

3. Vertical Threat Criteria

The T alarms are implemented only if the encountering aircraft are co-altitude, or it is predicted that they might become co-altitude within thirty seconds. Again, co-altitude is defined to mean that their vertical separation is less than 600 ft. at altitudes below 10,000 ft. and less than 800 ft. at altitudes above 10,000 ft. This definition is based on: (1) an altimeter system error allowance of $\pm$ 150 ft. (3 sigma) below 10,000 ft. and $\pm$ 250 ft. (3 sigma) above 10,000 ft.; (2) the assumption that a safe vertical separation between aircraft is 150 ft.; and (3) what is intended as an allowance for an undetected vertical drift rate of 500 ft./min.

According to ANTC-117, if an aircraft is climbing or diving at a rate greater than 500 ft./min., it is required to extend its co-altitude protection boundary in the direction of its motion by a predicted co-altitude increment. This is determined by multiplying the aircraft's own $\dot{h}$ by 30 seconds.

In addition to the co-altitude zone wherein the T alarms become effective, relative altitude buffer zones are established out to

$\pm$ 3400 ft. In each of these zones, vertical altitude rates are limited, from 2000 ft./min. in the farthest zone, to successively lower values as the zones get nearer. The vertical threat criteria is shown graphically in Figure II-2.

4. Landing/Departure Mode (Desensitization)

ANTC-117 also includes a Landing/Departure Mode, known as desensitization, where the $T_2$ zone, and the dive, and the do not turn commands are inhibited. This is to keep the number of commands and ATC interaction manageable since ATC intentionally brings aircraft close together in this area for landing and departure, and to prevent aircraft from diving into the ground. This mode is shown graphically in Figure II-3.

5. Logic Difference between Three Systems

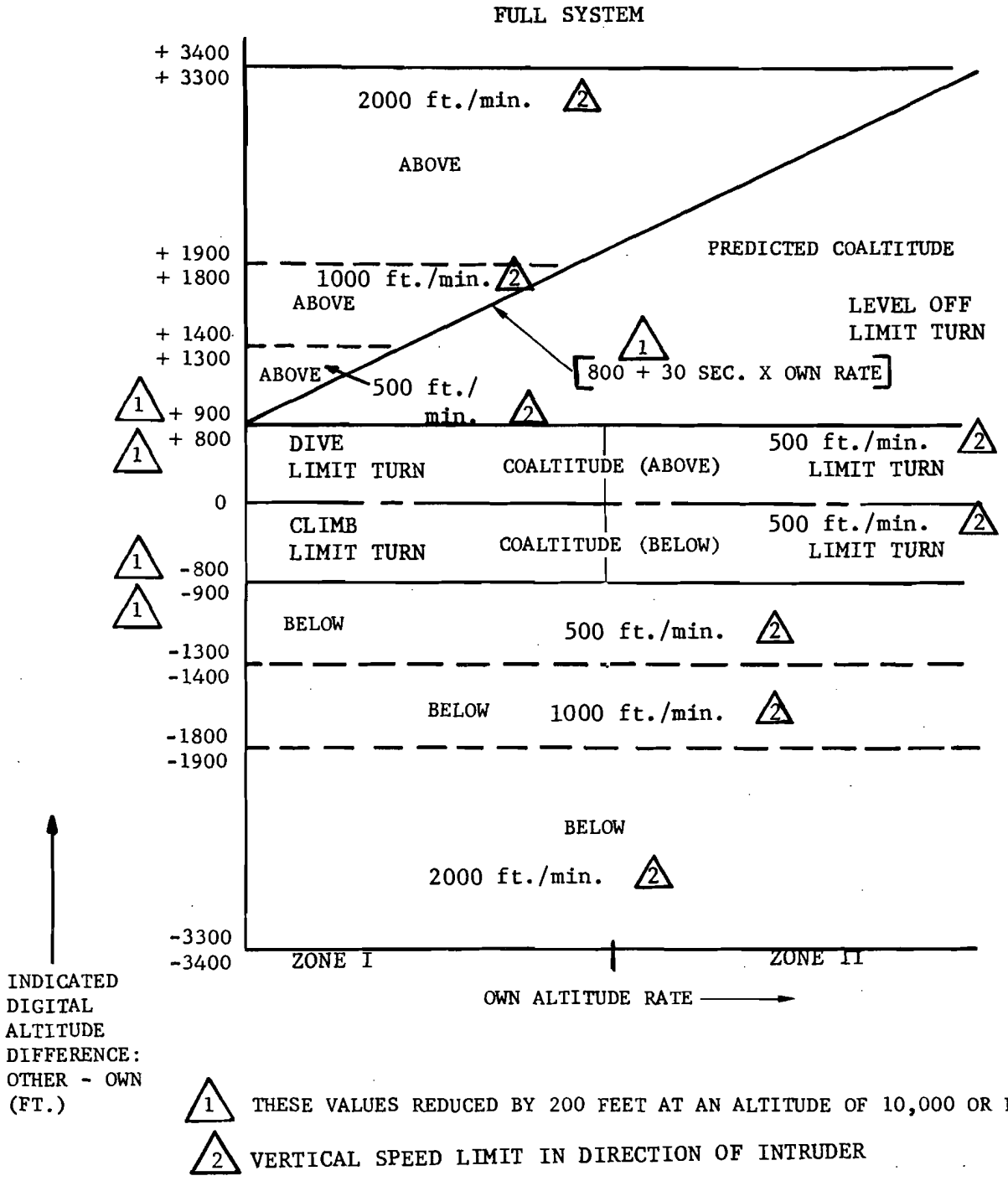
As discussed previously, ANTC-117 was written around a T/F system for airline use. While it allows the existence of ACAS equipments with limited capabilities (to spare general aviation the expense of a full ACAS), it does not describe these systems in the same detail it does the full ACAS. Hence, the major differences between the logics of the three systems under evaluation are in their general aviation equipments. However, since the air carrier equipments are faced with the greater technical problem (longer ranges, higher powers, more fruit, etc.), it is their performance which is used as the primary criteria for comparative evaluation.

## III. EQUIPMENT DESCRIPTIONS

### A. General

As discussed previously, the three air carrier ACASs under evaluation utilize R, $\dot{R}$, $\Delta h$, and $\dot{h}$ to evaluate whether the degree of threat is sufficiently high enough to require a mandatory maneuver. Essentially, the systems determine if a co-altitude situation exists between aircraft (or if the involved aircraft are climbing or descending, whether a co-altitude situation will exist in 30 secs.), and whether the time value of $R-Ro/\dot{R}$ is equal to or less than a predetermined value. If so, appropriate instructions are given to the pilot.

The systems are all cooperative and use the RF frequency band provisionally allocated to the ACAS function in the U.S. (1592.5 MHz to 1622.5 MHz). Altitude data input is obtained from the ATCRBS altitude encoder and the air carrier equipments utilize two antennas (top and bottom) and the same display (a modified instantaneous vertical speed indicator shown in Figure III-1). The general aviation version of each manufacturer is compatible with its carrier version. Additional detailed information on the three systems (over and above the following basic descriptions) can be found in FAA Reports FAA-RD-73-151 and FAA-RD-75-151



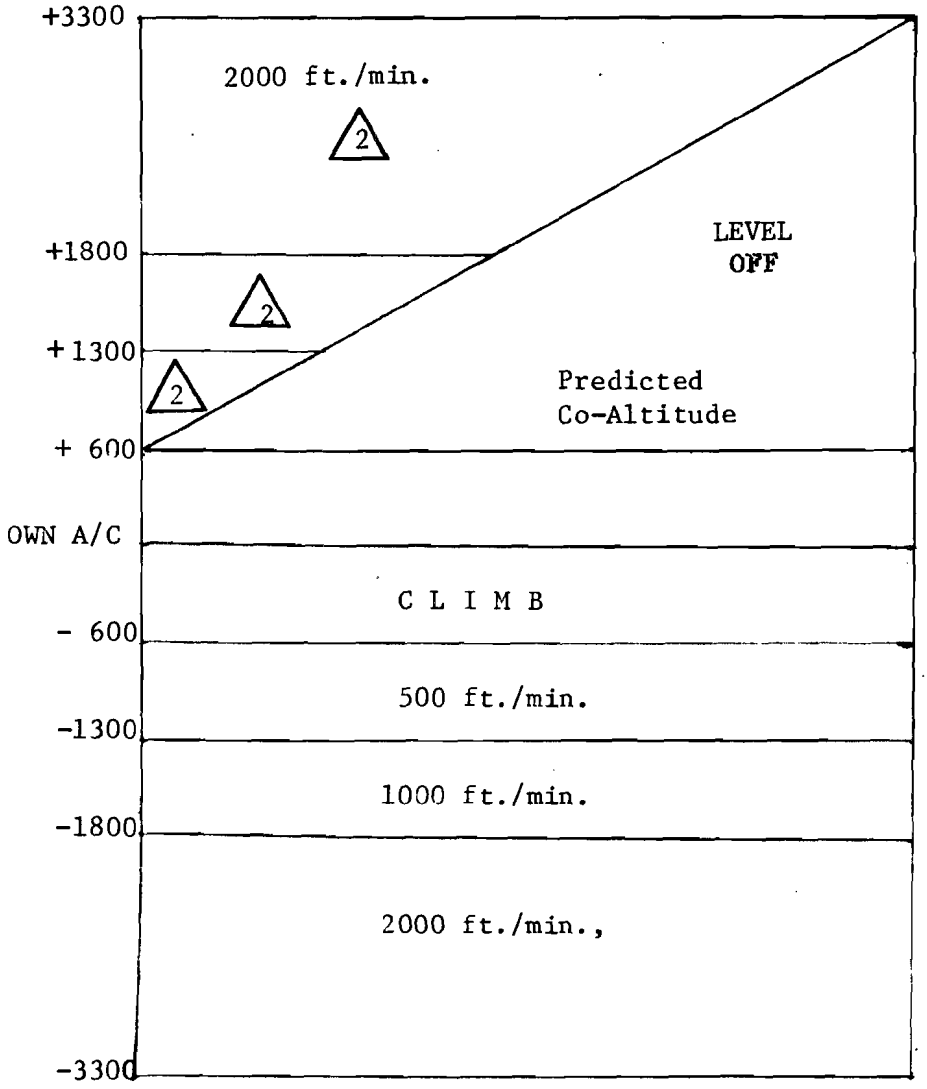

1 THESE VALUES REDUCED BY 200 FEET AT AN ALTITUDE OF 10,000 OR LESS

2 VERTICAL SPEED LIMIT IN DIRECTION OF INTRUDER

NOTE: PREDICTED COALTITUDE IS EXTENDED ONLY IN DIRECTION OF OWN ALTITUDE RATE. THIS FIGURE ONLY ILLUSTRATES OWN A/C ASCENDING.

THREAT EVALUATION ALTITUDE AND ALTITUDE RATE
FIGURE II-2

LANDING/DEPARTURE
MODE




ZONE I

2 Identical to Full System

FIGURE II-3

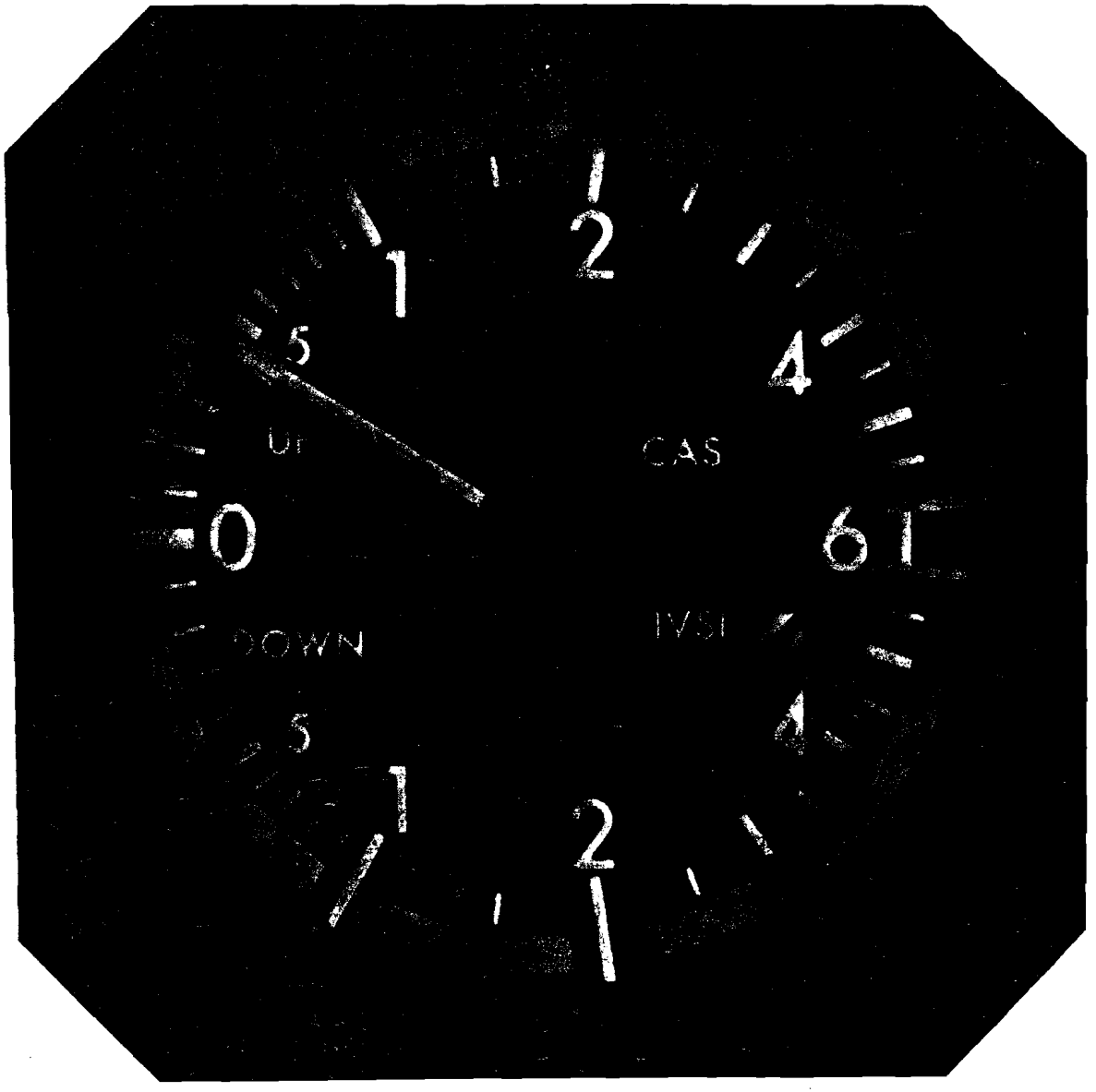



FIGURE III-1 CAS/VSI Indicator in Test Mode.

for the Honeywell system, Reports FAA-RD-73-143 and FAA-RD-75-143 for the McDonnell-Douglas system, and Reports FAA-RD-73-152 and FAA-RD-75-152 for the RCA system (see Appendix A).

B. Basic Description of Honeywell ACAS

The Honeywell ACAS, Avionic Observation of Intruder Danger Systems (AVOIDS) consists of an air carrier version (AVOIDS I) and a general aviation version (AVOIDS II). They are single frequency (1.6 GHz) I/T systems utilizing identical signal formats. The AVOIDS II equipment has less transmitter power, a simplified threat logic and less equipment redundancy.

The AVOID systems are able to handle high traffic densities through the use of pulse coded RF energy in a specific timing sequence (See Figure III-2). An aircraft in the interrogation mode emits pulse coded information in the form of two pulse pairs. The time separation between the two pulses in the first pair is 0.5 usec. and in the second pair is 0.6 usec. The separation between the first pulse in each pair is 35.5 usec. plus 2.0 ns./ft. of encoded altitude, referenced to -1000 ft. MSL. Aircraft receiving this interrogation compare the altitude of the interrogating aircraft with their own altitude to determine if they are within ± 650 ft. of the interrogating aircraft. If they are, a response is required and a single pulse is emitted by the responding aircraft after a fixed delay. The interrogating aircraft can then determine the range to the intruder by subtracting out the fixed turn-around delays when the responses are received. The fixed delays are incorporated to minimize the deleterious effects of reflected signals (multipath). The different time separation between pulses in the first pulse pair and pulses in the second pulse pair allows the pairs to be discriminated from each other, and also prevents an aircraft from responding to other first pulse pairs after it has received an initial first pulse pair. The range obtained is stored in a specific memory location for further evaluation.

Since more than just a single relative ± 650 ft. altitude band is of interest to the interrogator, he interrogates several bands during each epoch (3.7 secs.) by changing his encoded altitude. The AVOIDS I equipment uses eleven altitude bands below 9600 ft. and ten above, to search out ± 3200 ft. of altitude. The AVOIDS II equipment uses five bands to cover ± 1250 ft. in altitude (See Figure III-3 and III-4). The use of more than the minimum number of ± 650 ft. bands is primarily to limit fruit, since a limited altitude is involved in each interrogation, and to obtain a more accurate altitude positioning of a threat.

Multiple interrogations and responses result in the establishment of dynamic range data. The AVOIDS I system provides a 102,400 ft. range capability--2,048 fifty-ft. range bins--and the AVOIDS II provides a 25,600 ft. range capability--512 fifty-ft. range bins. This data changes from interrogation to interrogation from epoch to epoch. If an aircraft shows a closing rate, its range bin location will move inbound with time.

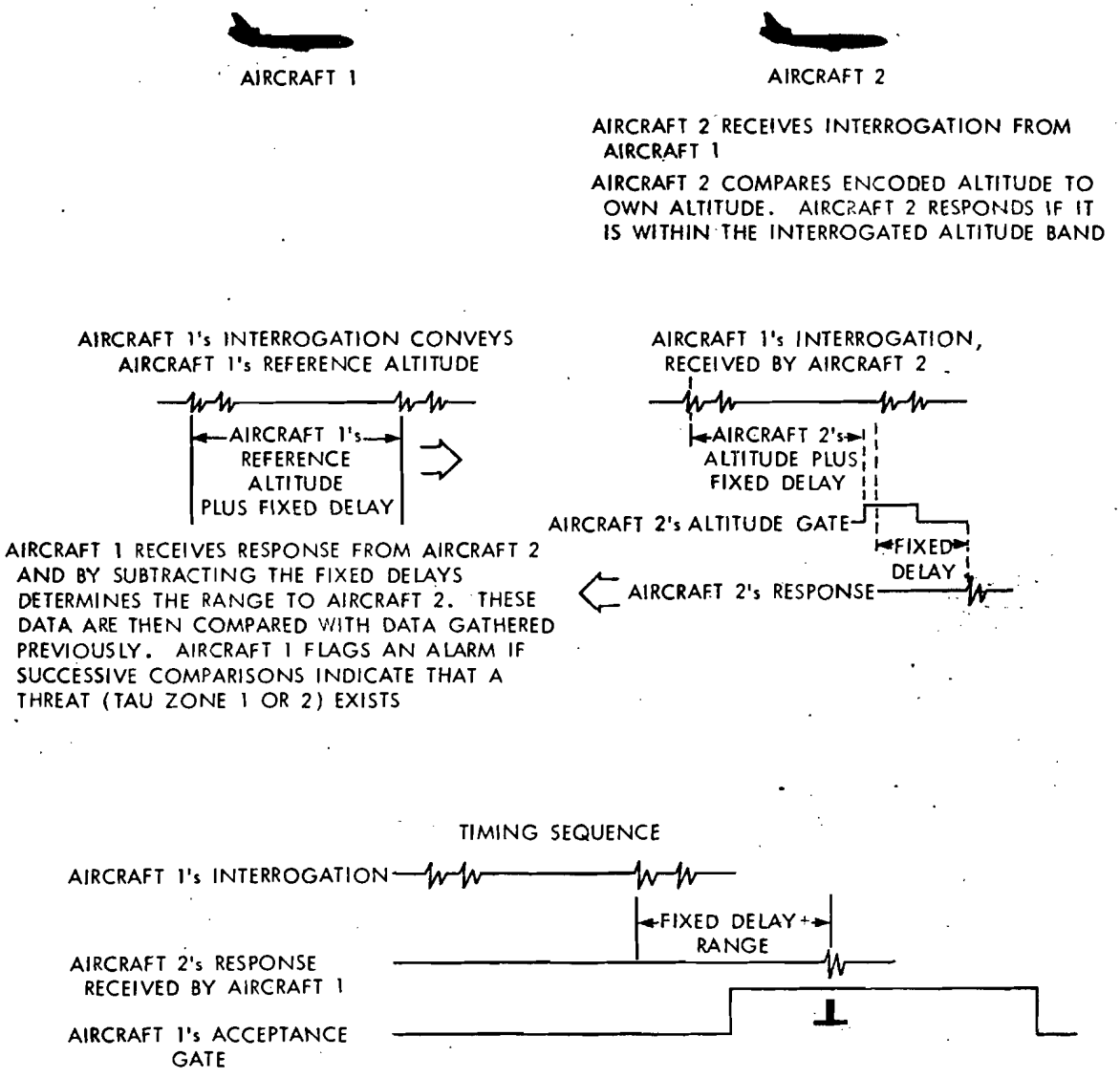



FIGURE III-2

HONEYWELL INTERROGATION/RESPONSE SEQUENCE OF EVENTS

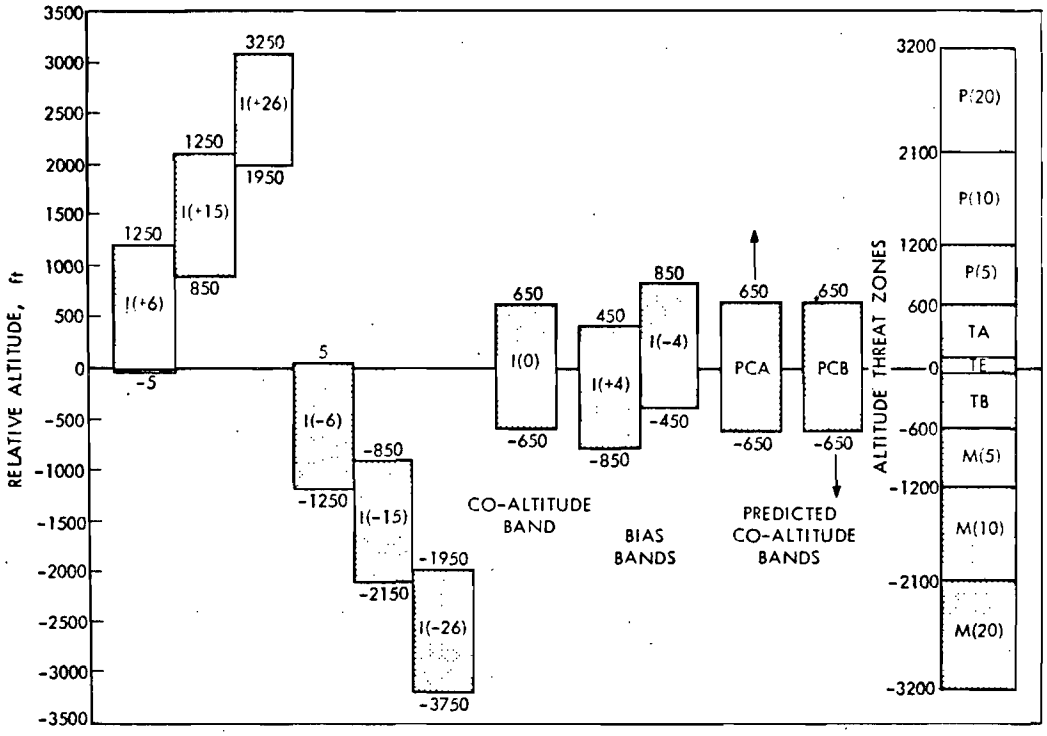



FIGURE III-3 Interrogation Bands and Altitude Threat Zones for AVOIDS-I Below Altitudes of 9600 ft
Note: Above altitudes of 9600 ft, the co-altitude band I(0) is not used.

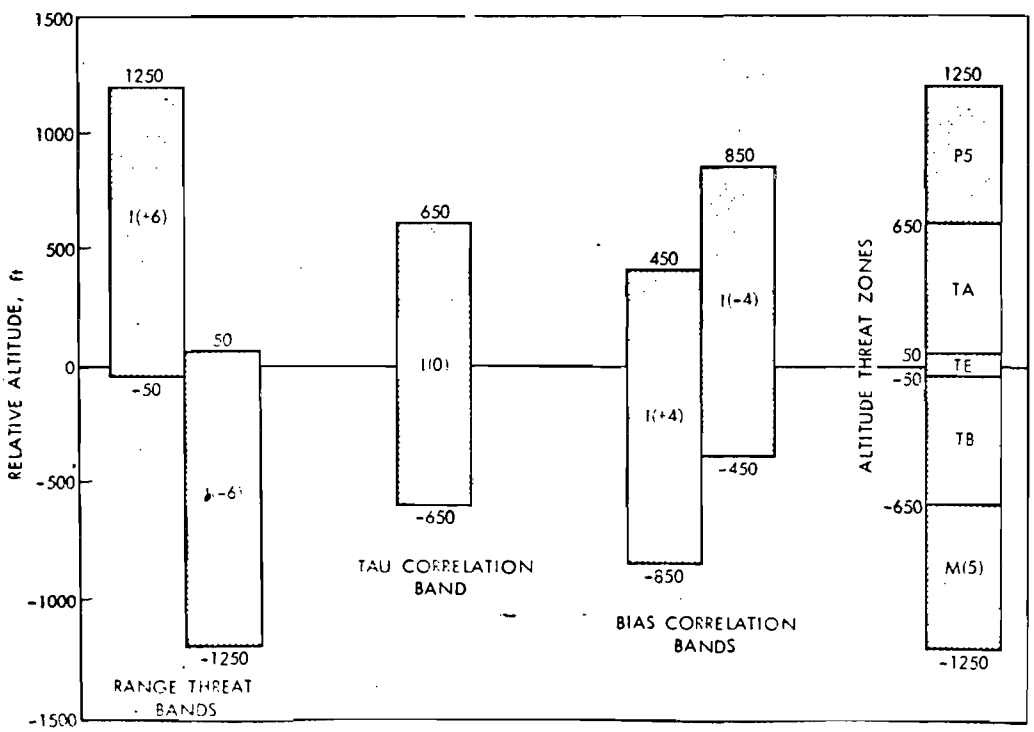



FIGURE III-4 AVOIDS-II Interrogation Altitude Bands

| | AVOIDS I | AVOIDS II |
|---|---|---|
| FREQUENCY BAND | 1592.5 MHz to 1622.5 MHz | Same |
| OPERATING FREQUENCY | 1.6 GHz | Same |
| POWER OUTPUT | | + 58 dBm |
| BELOW 10K ft. | + 58 dBm | |
| ABOVE 10K ft. | + 62 dBm | |
| RECEIVER | Dual RF/IF | Single RF/IF |
| RECEIVER SENSITIVITY | - 74 dBm | Same |
| ANTENNA | 2 (Top and Bottom) | Same |
| ROUND TIME | 3.7 secs. | Same |
| Evaluation Logic | Essentially ANTC-117 | Maximum Range 25,600 ft.; Max. $\dot{R}$ Detectable 903 ft./sec.; $T_1$ & $T_2$ ($Ro_1$ & $Ro_2$ = 0), $R_{m1}$ = 2500 ft.; $Rm_2$ = 6000 ft.; $T_3$ = 2500 ft. $\leq R \leq$ 6000 ft. & -80 ft/sec $\leq \dot{R} \leq$ 50 ft./sec.; No predicted co-altitude.; Altitude constrained to 14,750 ft. |

TABLE III-1 AVOIDS I/AVOIDS II COMPARISON

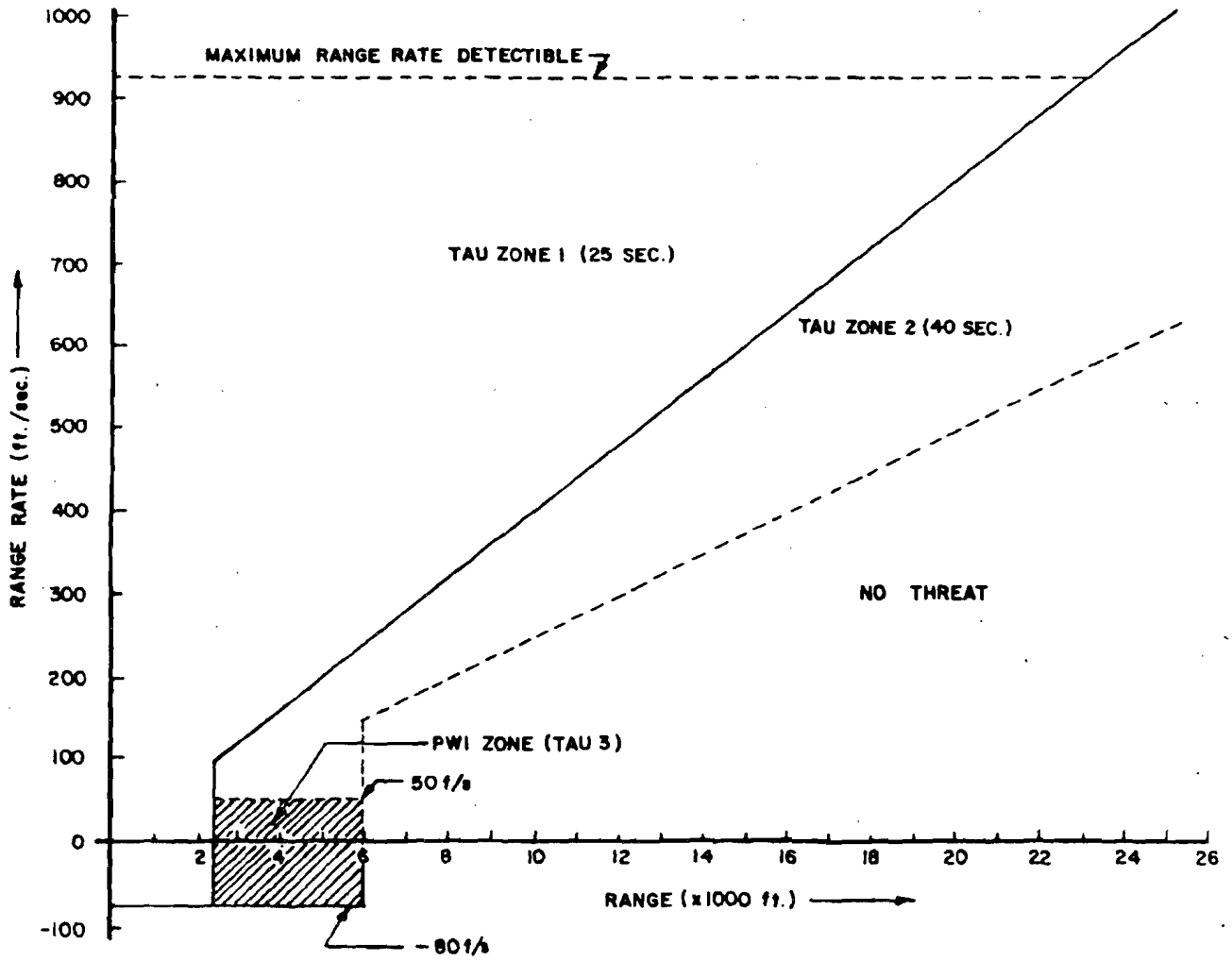
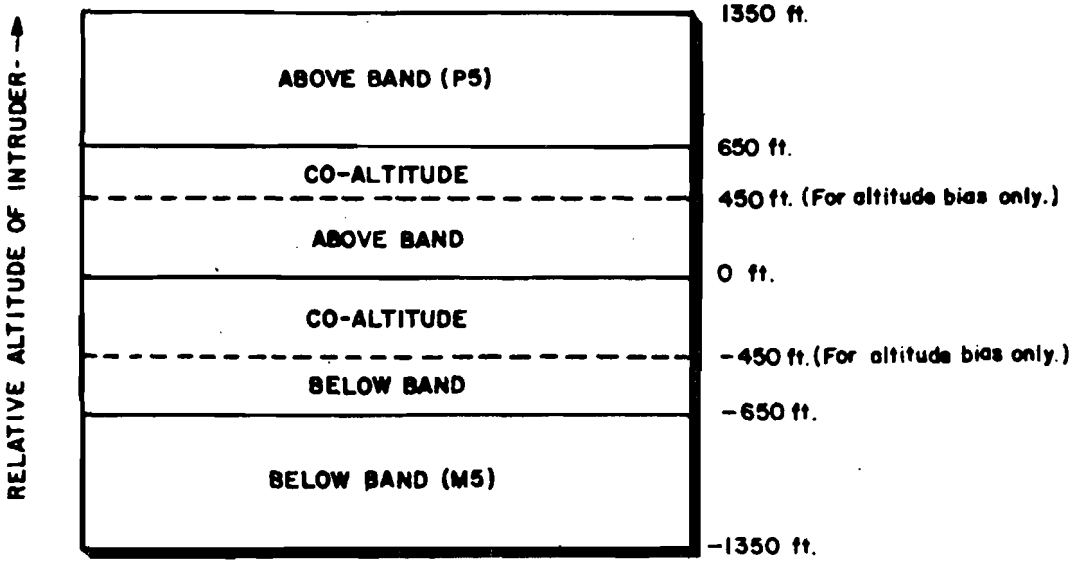



FIGURE III-5 AVOIDS II THREAT ZONE




NOTE: ALTITUDES SHOWN ARE ACTUAL RELATIVE ALTITUDES, NOT DIGITAL ENCODING ALTIMETER ALTITUDES.

FIGURE III-6

AVOIDS II ALTITUDE THREAT ZONE

If the aircraft moves a predetermined number of bins in a predetermined time, the proper instruction will be displayed to the pilot.

Table III-1 is summary comparison between AVOIDS I and II and Figures III-5 and III-6 show the AVOIDS II horizontal and vertical threat criteria respectively.

## C. Basic Description of McDonnell-Douglas ACAS

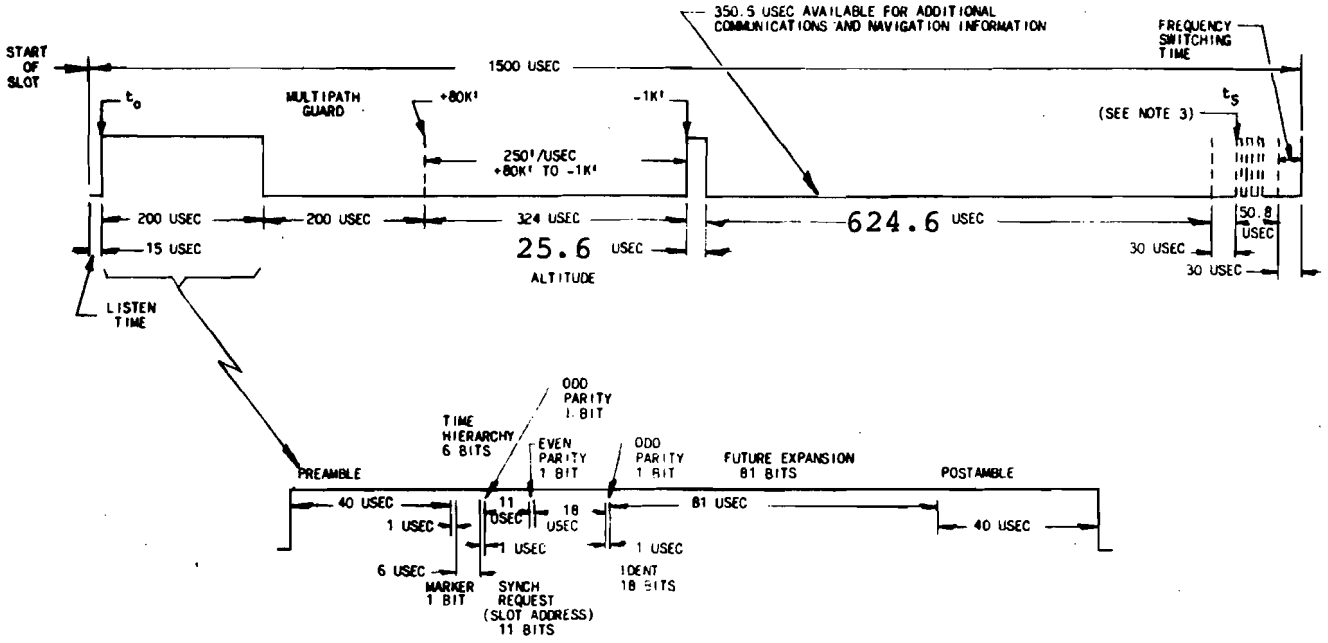
The McDonnell-Douglas Eliminate Range Zero System (EROS) consists of an air carrier version, EROS II and a general aviation version, MINI-CAS. It employs time/frequency multiplexing techniques, with primary time synchronization being supplied by a network of ground stations and secondary synchronization being supplied by EROS II equipments in an air-to-air mode under specified rules. The operating frequencies are 1600, 1605, 1610, and 1615 MHz. A back-up mode is also available which is an asynchronous I/T mode for use in low traffic density areas where time synchronization is not available. The message formats of both systems are compatible, with the MINI-CAS having less transmitter power, a simplified threat logic, a transmission capability on only one frequency and no air-to-air biphase modulated data link.

The method in the synchronous mode by which the necessary information is exchanged is based on the requirement that all participating aircraft carry, as an integral part of the ACAS, a clock whose time is the same (within fractions of a microsecond) as the clocks carried by all other aircraft. This being the case then, a time-ordered sequence is set up as follows:

The system utilizes a three-second cycle called an epoch. Each epoch is divided into 2000 equal time slots of 1500 usec. each. In theory, each participating aircraft is uniquely assigned a time slot for transmitting purposes so that at any instant in time, one and only one aircraft will be transmitting. The start of these transmissions occurs at the precise beginning of each assigned time slot. Therefore, when an aircraft transmits in its assigned time slot, all other aircraft in communication range are listening. Since all aircraft have the same time, and know the start of each time slot precisely, listening aircraft can compute the range to the transmitting aircraft by measuring the time it takes for the transmission to arrive. The listening aircraft then computes the closure rate by sequentially differencing successive range measurements and dividing by the time interval. It determines relative altitude by decoding the altitude information which is encoded by pulse position modulation in the transmission. With this information ($R$, $\dot{R}$, $\Delta h$, and own $\dot{h}$), the listening aircraft are able to evaluate the collision situation in accordance with ANTC-117. The system then cycles through the remainder of the 2000 time slots (transmitting sequentially on frequencies $F_1$, $F_2$, $F_3$, $F_4$, $F_1$, $F_2$, $F_3$, $F_4$. . .) and starts over again. Figure III-7 shows the message format. It is identical for both systems with the exception that MINI-CAS has no biphase modulation. Figure III-8 shows the MINI-CAS vertical threat criteria (the horizontal

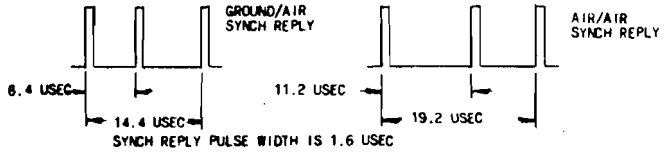
C.A.S. MESSAGE FORMAT

ATTACHMENT 1 - PAGE 1
R/B




NOTES-

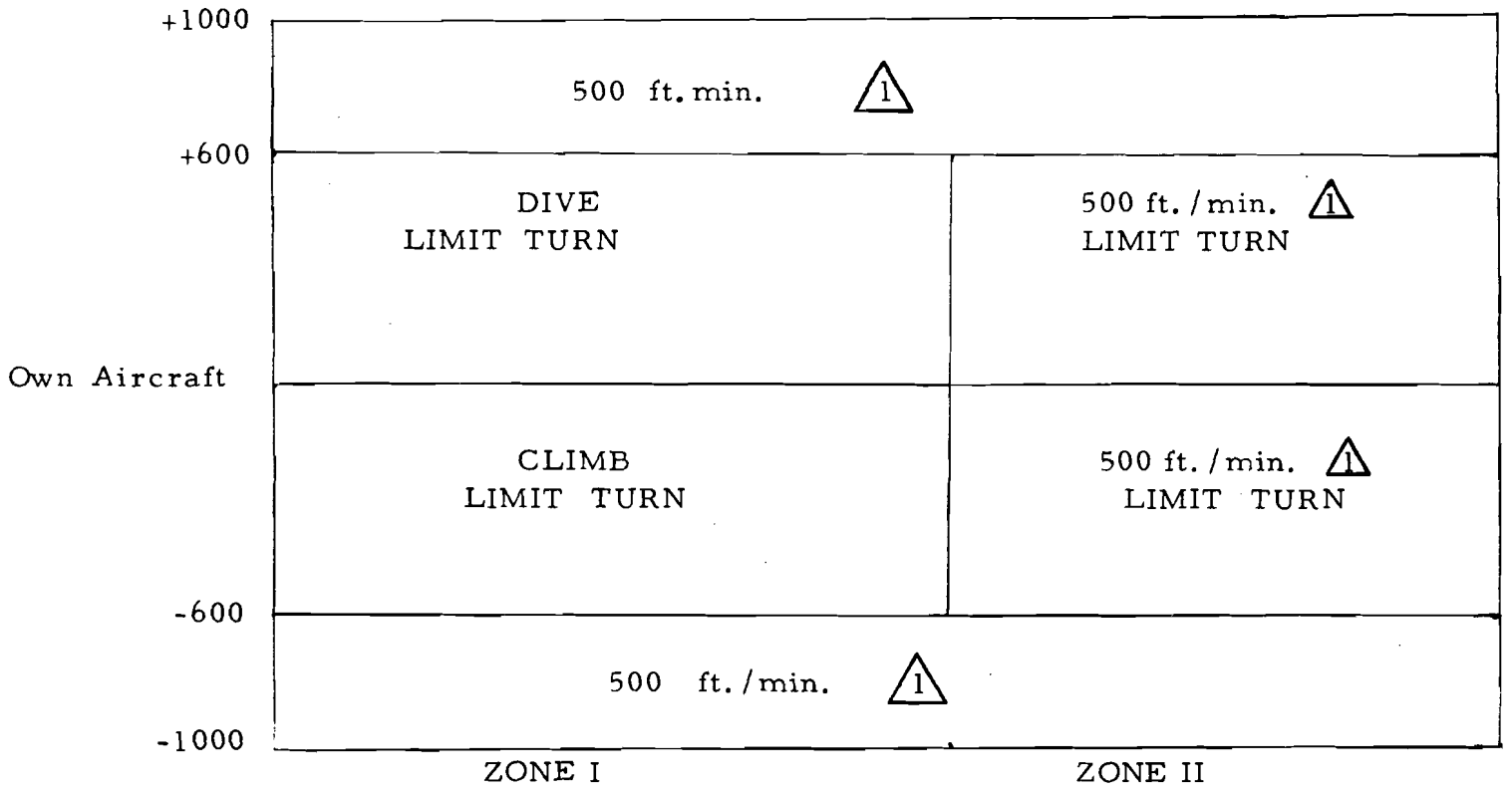
1. "SLOT TIME" - START OF SLOT.
2. $t_o$ - LEADING EDGE OF DOPPLER BURST (15 MICROSECOND AFTER SLOT TIME).
3. $t_S$ - NO ERROR SYNCHRONIZATION RECEIPT TIME (LEADING EDGE OF SYNCHRONIZATION TRIPLET). OCCURS 1419.2 MICROSECOND AFTER SLOT TIME.




4. ALL RANGE, ALTITUDE, BUM RESPONSES AND SYNC TIMING TAKEN AT 50 PERCENT VOLTAGE POINT OF LEADING EDGE OF RESPECTIVE PULSES(S).
5. THE SYNCH REPLY TRIAD SHALL BE TRANSMITTED BY THE SYNC DONOR SUCH THAT IT WILL BE RECEIVED AT THE INTERROGATING AIRCRAFT AT A TIME CORRESPONDING TO DONOR SLOT $t_S$ 1404.2 USEC AFTER DONOR SLOT $t_O$ (SEE ATTACHMENT 1 PARA. 2.8 FOR SYNCHRONIZATION ACCURACY). THIS IS THE ZERO ERROR CASE.
6. THE PREAMBLE AND POSTAMBLE SHALL BE TRANSMITTED AT THE SAME PHASE.
7. EACH BIT OF THE BIPHASE MODULATION; INCLUDING THE MARKER BIT, SHALL BE TRANSMITTED AS NRZ SPACE AS FOLLOWS: FOR LOGIC LEVEL 1 THE PHASE OF THE 1 USEC BURST IS IDENTICAL TO THE PHASE OF THE PREVIOUS 1 USEC BURST. FOR A LOGIC 0 THE PHASE OF THE 1 USEC BURST DIFFERS BY 180° FROM THE PHASE OF THE PREVIOUS 1 USEC BURST.
8. BIPHASE DATA TRANSMITTED MOST SIGNIFICANT BIT FIRST.
9. WHEN BIPHASE DATA IS TRANSMITTED, THE UNUSED EXPANSION BITS MAY BE TRANSMITTED OPTIONALLY AS CW OR BIPHASED, CLOCKED AT A 1 MHZ BIT RATE.

FIGURE III-7

MCDONNELL-DOUGLAS MESSAGE FORMAT




Indicated Digital Altitude Difference: Other-Own (ft.)

FIGURE III-8

MCDONNELL-DOUGLAS MINI-CAS ALTITUDE THREAT EVALUATION

criteria corresponds to ANTC-117 with the exception that $Ro_1$ is zero) and Table III-2 is a summary comparison between EROS II and MINI-CAS.

D. Basic Description of RCA ACAS

The RCA Separation and Control of Aircraft using Nonsychronous Techniques (SECANT) is basically divided into two major categories: (1) equipments which provide full ACAS protection in accordance with ANTC-117 called VECAS (Vertical Escape Collision Avoidance System), and VECAS GA/M (General Aviation/Military); and (2) equipments of lesser capability but compatible with all other equipments. These are called Proximity Warning Indicator (PWI) and Remitter.

RCA intends the VECAS equipment for air carrier and large business aircraft, VECAS GA/M for smaller, high performance general aviation and military aircraft, and PWIs and Remitters for low performance general aviation aircraft.

Basic performance for the VECAS and VECAS GA/M equipments is identical. VECAS GA/M is lower in cost because shorter antenna cable runs permit economies in transmitter and receiver designs and because of possible economies in processing logic for fewer simultaneous targets.

PWIs simply indicate the presence and approximate direction of other aircraft, contain no evaluation logic and have less range (power). A Remitter is simply the transponder portion of a VECAS GA/M which responds to interrogations of VECAS and VECAS GA/M equipments.

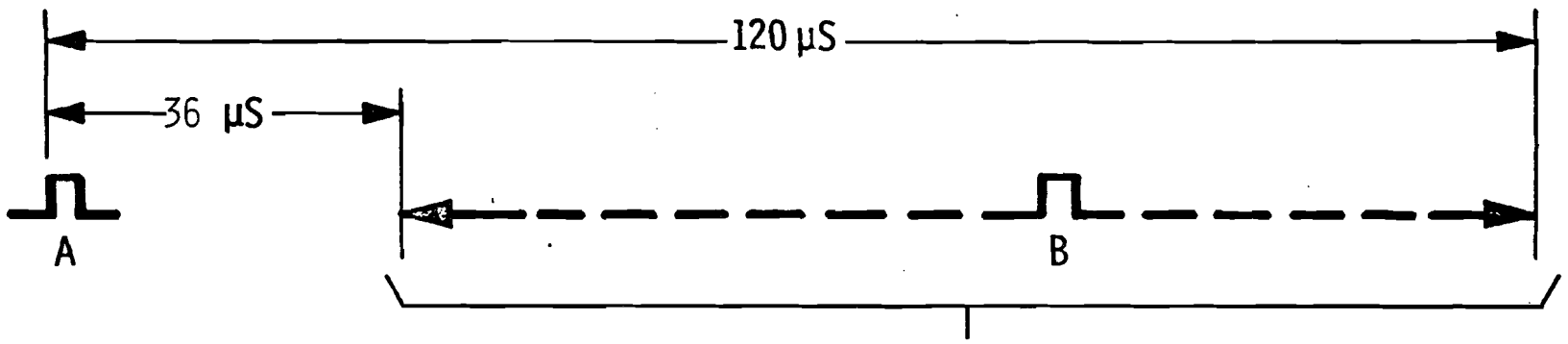
The interrogation wave form of VECAS and VECAS GA/M is shown in Figure III-9 and consists of two 1 usec. pulses separated by a time interval. Altitude is encoded on the time interval as a constant delay proportional to barometric altitude (as in both the Honeywell and McDonnell systems). The interrogators "address" a series of altitude bands by changing the time interval by fixed amounts (2 usec/500 ft. below 10,000 ft., 2 usec/1000 ft. above 10,000 ft.). From 30,000 ft. up, a single delay is used. This technique is similar to the altitude band addressing in the Honeywell system.

The transponders decode the two-pulse interrogation and reply with a single pulse if the decoded 500 ft. (1000 ft. above 10,000 ft.) altitude layer includes the altitude of the transponder. Thus, only transponders which receive interrogations addressed to their altitude layer respond. This reduces the number of overall replies and eliminates garble from transponders at the same slant range but in different altitude layers.

In addition to altitude encoding, the other principal means of reducing fruit are frequency multiplexing and data correlation. Within the frequency band 1592.5 to 1622.5 MHz, VECAS and VECAS GA/M equipments

| | EROS II | MINI-CAS |
|---|---|---|
| FREQUENCY BAND | 1592.5 MHz to 1622.5 MHz | Same |
| OPERATING FREQUENCIES | 1600, 1605, 1610, 1615 MHz | Transmit 1605 MHz<br>Receive All Four |
| FREQUENCY CONTROL | Cesium Beam or Crystal | Crystal |
| MODULATION | Pulse and Biphase | Pulse Only |
| POWER OUTPUT | 1000 Watts ± 3 db | 150 Watts ± 3 db |
| RECEIVER TYPE | Double Conversion Superheterodyne | Single Conversion Superheterodyne |
| RECEIVER SENSITIVITY | -88 dbm, nominal | -78 dbm, nominal |
| RECEIVER NOISE FIGURE | 8 db, maximum | 13 db, maximum |
| ANTENNA | 2 Vertical Polarized Stubs (Top & Bottom) | One Vertical Polarized |
| EPOCH TIME | 3 or 6 secs. | Same |
| EVALUATION LOGIC | Full ANTC-117 | Tau One and Tau Two, No Predicted CO-altitude Only one ± 400 ft. Off-altitude band. Altitude constrained to 10,000 ft., Altitude Rate to 1,000 ft./min. |

TABLE III-2 EROS-II/MINI-CAS COMPARISON




FIRST PULSE REFERENCE

-1000'
34 µS

SECOND PULSE POSITION IN STEPS OF 2 µS

30,000'

SCALE

BELOW 10,000'
2 µS is 500'
ABOVE 10,000'
2 µS IS 1000'

ABOVE 30,000' A SPACING OF 120 µS IS USED BY ALL AIRCRAFT

FIGURE III-9

RCA PULSE PAIR ALTITUDE CODED PROBES

operate on 24 frequency channels separated by 1 MHz. Twelve of the channels are used above 10,000 ft. and 12 below (See Figure III-10).

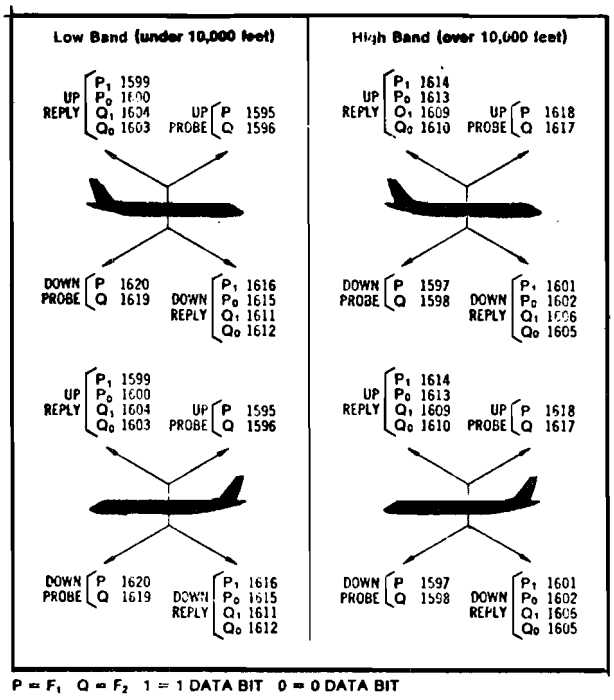
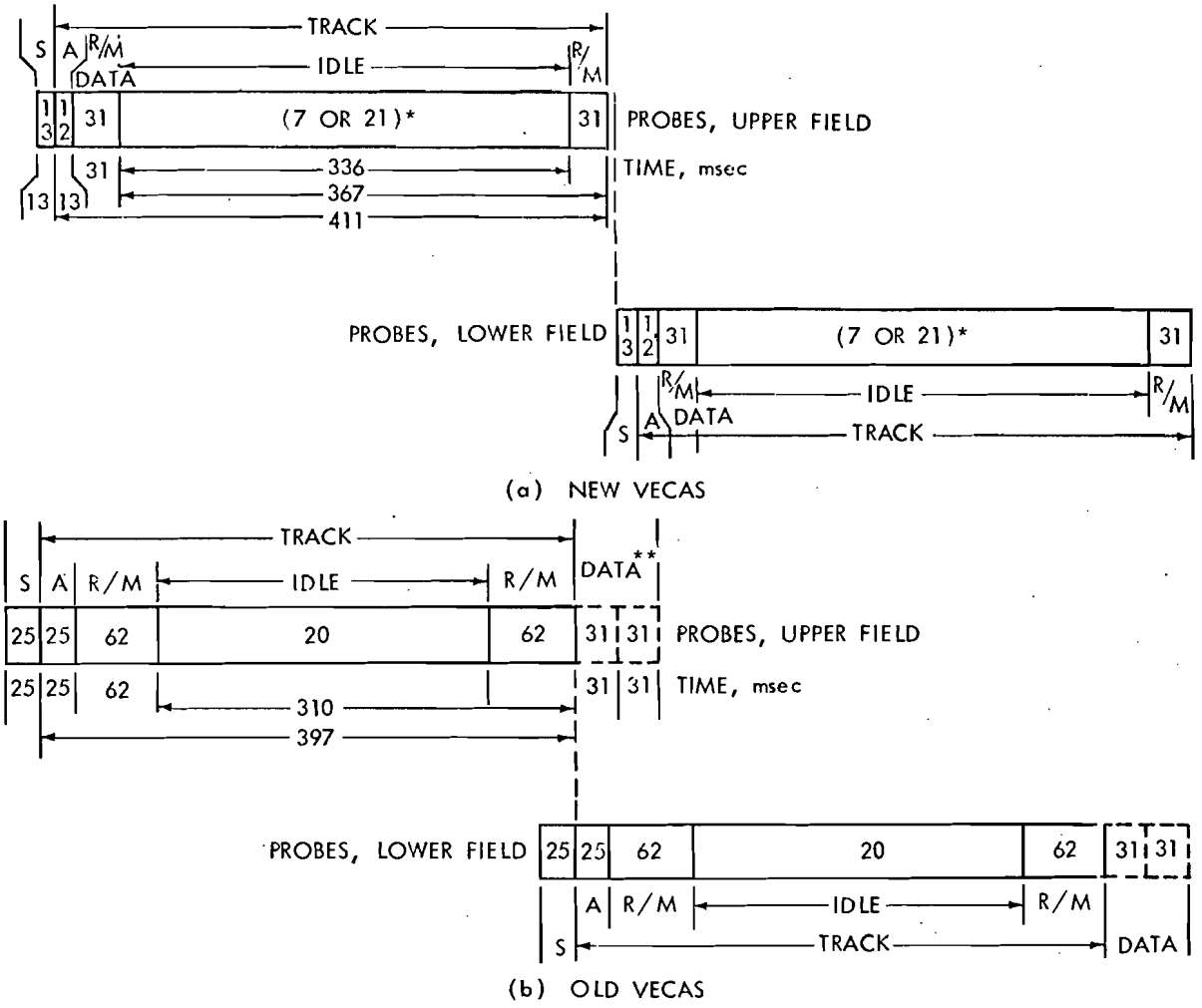



FIGURE III-10

RCA FREQUENCY MULTIPLEXING

Within an altitude band above and below 10,000 ft. each group of 12 frequencies is divided into two subgroups of 6 frequencies each. Each of the latter subgroups is assigned to operation on either the top or bottom antenna. Finally, within each subgroup of 6 frequencies, 2 frequencies are assigned for probes (interrogations) and 4 for replies. Each probe has two reply frequencies associated with it. That is, a transponder receiving a probe on one given frequency will respond with a reply on one of two associated reply frequencies. The use of two reply frequencies for each probe frequency permits a transponder to superimpose coded binary messages on the replies. In this manner, the transponders altitude is encoded in the reply message.

The VECAS interrogator cycles through a sequence of steps: search for targets, tracking and fine range measurement, altitude decoding, and threat evaluation for each 500 ft. or 1000 ft. altitude layer. This timing diagram is shown in Figure III-11. After the cycle is completed, it proceeds to the next altitude layer until all layers from which threats can develop are covered. The complete process to cover up to 10 layers takes a maximum of 4.26 seconds.




LEGEND:

S = RANGE SEARCH
A = TRACKER ACQUISITION
R/M = RANGE MEASUREMENT

*Number of idle probes is seven for operation below 10,000 ft, 21 above 10,000 ft. Data = synchronous data transmission always on first R/M, and only on second R/M after detected error on first R/M. At end of second R/M there is a 2-msec evaluation.

**Data transmission only if track detects alarms, in which case other field transmissions are delayed 62 msec.

FIGURE III-11

TIMING DIAGRAMS FOR NEW & OLD RCA VECAS FOR RANGE SEARCH, TRACK, & DATA

During search, the interrogator sends a series of jittered probes with a nominal period of 1 ms. These probes are pseudo-randomly coded on the two-probe frequencies being used for the particular altitude zone and antenna. Replies from a target transponder will be correlated with the probe frequency; that is, for a given probe frequency, valid target replies should only be on the associated reply pair of frequencies. Such valid replies are summed as "plus ones" in a counter, and there is a counter for each range bin. If a reply is received on a frequency associated with the other probe frequency, a "one" is subtracted from that range bin's counter. Since fruit replies (those stimulated by other interrogators) are expected to add equally "plus ones" and "minus ones", their contribution in the counter should, on the average, cancel out, whereas valid replies will always increase the count. If, at the end of a series of probes, the counter exceeds a predetermined threshold value, a target is declared in the appropriate range bin.

Following the detection of targets in the range correlator, the VECAS logic assigns one of 32 trackers (16 for VECAS GA/M) to acquire each target in the occupied range bins. After acquisition of a target by a tracker, a precision range measurement is made by averaging the ranges measured for each of a series of 31 probes. The range measurement, with 31 more probes is repeated after a delay of about 0.37 seconds. The difference between the two averaged measurements is used to estimate the range rate for use with ANTC-117 logic. The altitude of the transponder is then decoded and the threat evaluation performed. Table III-3 is a summary comparison of VECAS and VECAS GA/M equipments.

## IV. DESCRIPTION OF ANALYSES AND TESTS

### A. General

The three ACAS systems have undergone testing involving mathematical analyses, computer fast-time and real-time (with controllers in the loop) simulations, and hardware bench and flight testing. Some of the analyses and simulations were applicable to all the systems as they were directed at ANTC-117 logics. Other analyses and tests were specifically directed to the individual systems. This section of the report presents a brief description of the analyses and tests conducted and a summary of the results. For a more detailed treatment of the analyses and tests, the reader is referred to the reports listed in Appendix A, "References".

### B. ACAS/ATC Simulations

In an effort to quantify and better understand the interaction between ACAS and the air traffic control system, NAFEC has performed both fast-time and real-time (with controllers in the loop) simulations. ANTC-117 logics existing at the time of the simulations were utilized and hence were applicable to all three systems.

| | VECAS | VECAS GA/M |
|---|---|---|
| FREQUENCY BAND | 1592.5 MHz to 1622.5 MHz | Same |
| CHANNEL BANDWIDTH | 1 MHz | Same |
| NO. OF CHANNELS | 24 | Same |
| PULSE WIDTH | 1 usec | Same |
| RADIATED POWER PROBE | 16 watts | Same |
| RADIATED POWER REPLY | 16 watts | Same |
| RECEIVER THRESHOLD (at antenna) | | |
| Probe (below 10,000 ft.) | -85.5 dBm | Same |
| Reply (below 10,000 ft.) | -88.5 dBm | Same |
| Probe (above 10,000 ft.) | -91.5 dBm | Same |
| Reply (above 10,000 ft.) | -94.5 dBm | Same |
| ANTENNA | 2 (top and bottom) | Same |
| ROUND TIME | 4.26 sec. | Same |
| NO. OF TRACKERS | 32 | 16 |
| EVALUATION LOGIC | Essentially ANTC-117 | Tau One and Tau Two, Only one altitude rate limit (1000 ft./min.), Altitude rate to 4000 ft./min. |

TABLE III-3

RCA VECAS/VECAS GA/M COMPARISON

1. Fast-Time Simulations

Briefly, traffic data was gathered from various ARTS facilities and stored in a computer. ANTC-117 logic was also stored in the computer such that when any of the ARTS tracks were in conflict with any other (in accordance with ANTC-117 criteria) the computer would record the number and type of these conflicts. This was an "After-the-fact" kind of investigation in that the ARTS tracks were not perturbed as a result of the ACAS logic. One of the major goals of these investigations was to determine where the Landing/Departure Mode (desensitization) of ANTC-117 should be initiated, from the standpoint of reducing interaction with air traffic control.

It is concluded that the switch point between full ANTC-117 logic and the Landing/Departure Mode should be different for each terminal area studied. In addition, it is necessary that the switchpoint for individual terminal areas should change in accordance with ATC procedures in effect. This makes the solution to the switching problem both difficult and awkward. Pilot and/or controller inputs to the system may be necessary.

2. Real-Time Simulations

Two lengthy real-time simulations, with controllers in the loop, were run to further explore the nature of ACAS/ATC interaction, and specifically the effect on the controller. The simulated ATC environment was a high density terminal area, patterned after Chicago O'Hare, which provided for simultaneous approaches to parallel runways. Various switch-points from full logic to Landing/Departure Mode were studied. These simulations were real-time, in that controllers were controlling the traffic, simulator pilots were flying the "aircraft" in accordance with controller instructions, and in the event of an instruction initiated by the ACAS logic, the computer would maneuver the aircraft in accordance with the instruction. Upon cessation of the ACAS instruction, the controller/pilot would regain primary control of the aircraft.

Not surprisingly, it was found that the further out from the runways the Landing/Departure Mode was initiated, the less interaction with ATC there was. With the switchpoint sufficiently distant, operations rates were unaffected and controllers readily adapted to the situation. However, no attempt was made to determine what level of protection the various switchpoints afforded. Again, one conclusion reached is it is highly unlikely that a standard optimum switchpoint procedure for all terminal areas will be practical. The "how" of the switchpoint will be difficult and awkward.

C. Institute for Defense Analyses (IDA) Review of ANTC-117

Under contract to the FAA, the Institute for Defense Analyses conducted an independent assessment of the adequacy of the threat evaluation and

maneuver selection logics as described in ANTC-117, Revision 10, for the aircraft performance parameters specified. (Report No. FAA-RD-75-72, See Appendix A) Major conclusions were: (1) the threat criteria do not allow sufficient time for the required escape maneuver in all circumstances; (2) the alarm criteria for threat evaluation will probably result in alarm rates which are intolerable by any standards, i.e., several $T_1$ alarms per minute for an aircraft in dense traffic at the center of the 1982 LAX Basin, and (3) a single modified T alarm criterion could provide as much protection in encounters among ACAS equipped aircraft. Such a single T criterion would have a smaller alarm rate than that resulting from the $T_2$ warning now specified.

## D. Institute of Telecommunications Sciences (ITS) Radio Altimeter Interference Study

Within the United States, the Radio Frequency band 1592.5 to 1622.5 MHz is provisionally assigned for the collision avoidance function. Two foot-notes to the OTP "Manual of Regulations and Procedures for Radio Frequency Management" apply to this band. They are as follows:

Foot-note US39. "Within the band 1535 to 1660 MHz, radio altimeters are permitted to use only the portion 1600 to 1660 MHz and then only until such time as international standardization of other aeronautical radio-navigation systems or devices requires the discontinuance of radio altimeters in this band."

Foot-note US39A. "The band 1592.5 - 1622.5 MHz is allotted provisinally, but on a primary basis, for the collision avoidance function, noting the continued use of existing altimeters in the band 1600 to 1660 MHz."

Since radio altimeters present one of the major possible sources of RF interference to the ACAS systems, the Institute of Telecommunications Sciences, with FAA funding, undertook a test program to determine how severe this interference would be. The tests are not yet complete. Results of the reduction of data collected to date follows.

### 1. Systems Tested to Date

(See Table IV-1, next page)

| Military Altimeters | | | | |
|---|---|---|---|---|
| Model | User | Nominal Operating Frequency (MHz) | Emission Type | Peak Power (dBM) |
| AN/APN-133 | USAF & USN | 1640 | Pulsed CW | 47-48 |
| AN/APN-155 | USAF | 1630 | Swept CW | 30 |
| AN/APN-159 | USAF & USN | 1630 | Pulsed CW | 58-60 |

| Civilian Altimeters | | | | |
|---|---|---|---|---|
| Model | Manufacturer | Nominal Operating Frequency (MHz) | Emission Type | Peak Power (dBM) |
| TRN-70 | Bonzer | 1630 | Pulsed CW | 30 |
| GAR | In Flight Devices | 1630 | Pulsed CW | 37 |

TABLE IV-1

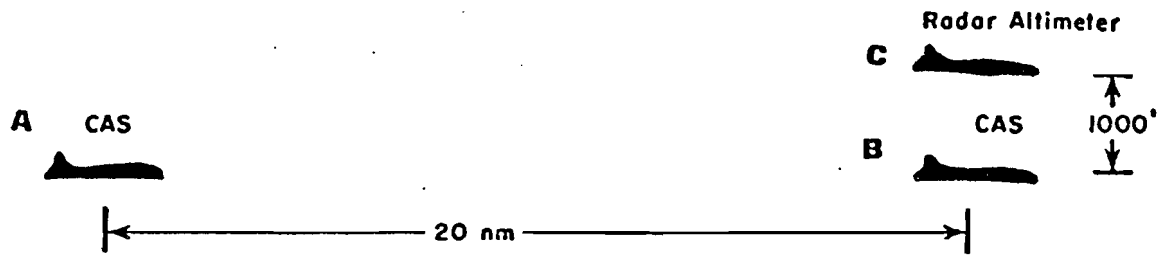
(EQUIPMENTS TESTED TO DATE)

2. Methodology

The ACAS equipments were "hot bench" tested in the laboratory with each of the above altimeters providing interference in stepped levels to determine the Interference to Signal (I/S) level at which each ACAS failed because of interference from a specific altimeter. Interference signal levels sufficient to cause ACAS performance degradation were determined by reducing digital data tapes recorded by instrumentation connected to the ACAS. Failure of the ACAS being tested was determined to be the I/S ratio at which essential information was missed by the ACAS due to the interferring signal.

These laboratory measured I/S ratios were then used to show separation distances at which interference to the ACAS would occur from the various altimeters, in accordance with the scenario shown in Figure IV-1. Aircraft A and B are both equipped with an ACAS. Aircraft C is equipped with a radar altimeter. Aircraft A is overtaking aircraft B & C, who are flying at the same heading and

velocity. Free space transmission loss was used as well as estimated antenna patterns and gains.




Scenario 1

FIGURE IV-1

In addition to the above tests, the problem of co-location of ACAS and radar altimeters on the same aircraft was investigated in a limited manner to determine the magnitude of the problem. This is important since for ACAS to be effective, all aircraft should be equipped. This was accomplished experimentally by equipping two NAFEC Gulfstream aircraft with the McDonnell-Douglas EROS II and MINI-CAS systems, one aircraft with the Bonzer TRN-70 altimeter and the other with the AN/APN-155 military altimeter. The altimeter antennas were mounted on the bottom of the aircraft, about 10 ft. from the bottom ACAS antenna. Coupling between the altimeter antenna port and the top ACAS antenna port was measured in flight and showed 78 db and 81 db isolation on the two aircraft. Isolation between the altimeter antenna and the bottom ACAS antenna was 55 db and 63 db respectively. The experiment was performed by flying the two aircraft, initially separated by 12 nmi. horizontally and 500 ft. vertically, at each other until they "met." The course was flown once with the ACAS operating normally and neither of the altimeters turned on. A second run was made with the Bonzer altimeter turned on and a third run was made with the Bonzer off and the AN/APN-155 on. The experiment was first performed with the EROS II in operation and then repeated for the MINI-CAS.

3. Results

The results of the testing discussed previously are shown below:

a. Laboratory Tests

Table IV-2 lists the I/S ratios at which the various ACASs failed due to interference from the indicated altimeters, as measured in the laboratory.

| | AN/APN-133 | AN/APN-155 | AN/APN-159 | Bonzer TRN-70 | In-Flight Devices GAR |
|---|---|---|---|---|---|
| EROS II | 29 | 12 | 26 | -3 | 35 |
| MINI-CAS | 45 | 30 | 30 | 20 | 33 |
| VECAS | > 53 | > 35 | > 54 | 26 | > 42 |
| AVOIDS I | > 58 | 12 | > 63 | 8 | > 60 |

TABLE IV-2 LABORATORY I/S RATIOS CAUSING ACAS INTERFERENCE

b. Laboratory Tests Extrapolated to Separation Range

In accordance with the scenario shown in Figure IV-1, Table IV-3 shows the theoretical separation distance in nautical miles that could exist between the two ACAS equipped aircraft for the ACAS to operate properly in the presence of a specific radar altimeter. Distances less than these values result in satisfactory ACAS operation. For example, using the values shown for EROS II and the APN-133, from 20 nmi. separation to 9.5 nmi. separation, interference occurs. At less than 9.5 nmi. separation, the ACAS signal becomes strong enough to override the interference. Separations shown as greater than 20 nmi. simply means that from separations of 20 nmi. and in, the I/S ratio is always such as to insure proper ACAS operation. At some point greater than 20 nmi., the I/S ratio will become large enough to cause ACAS malfunction.

| | APN-133 | APN-155 | APN-159 | TRN-70 | GAR |
|---|---|---|---|---|---|
| EROS II | 9.5nm | 11.0nm | 1.2nm | 2.5nm | >20 nm |
| MINI-CAS | >20 | > 20 | 2.5 | >20 | >20 |
| VECAS | 15.5 | 20 | 4.5 | 9.5 | >20 |
| AVOIDS I | >20 | 4.5 | > 20 | 4.5 | >20 |

TABLE IV-3 I/S RATIOS EXTRAPOLATED TO SEPARATION DISTANCE

c. ACAS/Altimeter Co-Location Flight Tests

Both the EROS II and MINI-CAS, mounted on the same aircraft with the TRN-70, were seriously interferred with when the TRN-70 was in operation, over the entire course flown. Altitude, range, and range-rate information were either inaccurate or unavailable, rendering the ACAS display in both aircraft unusable. The interference from the APN-155 was less severe than that from the TRN-70, but the EROS II and MINI-CAS were rendered inoperable on the co-located aircraft.

4. Conclusions

Based on the available data, the radar altimeters tested do cause objectional interference to the ACAS systems, with the APN-159 and TRN-70 being the worst offenders. The EROS II is the most susceptible to the altimeter interference with the VECAS and AVOIDS I being less susceptible.

The experiment involving the co-location of ACAS and the radar altimeters on the same aircraft indicate a great deal more than normal isolation between the two systems would be required to make them operable on the same aircraft, if indeed it could be accomplished at all.

It is doubtful whether retuning or band limiting the altimeters would reduce the interference to a negligible level. The interference problem is one of degree; the only absolute solution would be removal of the altimeters from the band.

E. ARINC Research Corporation Cost Analysis

1. General

Since the choice of an ACAS system for a U.S. National Standard cannot be based on technical factors alone, ARINC Research Corporation, under contract to FAA, performed a cost analysis to provide a basis for assessing the economic impact of ACAS implementation on the various aviation communities. (Report No. FAA-EM-76-1, See Appendix A) Separate cost evaluations were developed for general aviation, commercial aviation, and the military. The classes of equipment studied included both the air carrier and general aviation versions of the Honeywell, McDonnell-Douglas, and RCA systems.

2. Methodology

The cost analyses required the development of detailed cost and reliability data peculiar to each of the ACAS systems and the development of ACAS implementation cost factors that apply equally to the three ACAS concepts. System costs based on these data were

then evaluated with the aid of an economic cost model. The cost and reliability data describing each of the three systems provided the basis for the economic comparison of the systems. Since these data were critical to the success of the study, two different sources were used. First, the three manufacturers were requested to provide detailed cost and reliability data on their systems; then the general aviation versions of each of the systems were subjected to a uniform pricing evaluation by independent general aviation manufacturers, General Aviation Electronics (GENAVE) and National Radio Company (NARCO).

3. Results

Tables IV-4 through IV-8 show the ARINC cost data for one year in 1975 dollars. While the GENAVE and NARCO derived data were slightly different, they both maintained the same relative ranking, that is Honeywell is the least costly, RCA the most costly, and McDonnell-Douglas in the middle. This relative ranking was maintained even when a number of the basic assumptions and data inputs were varied. Costs associated with any required ground stations are not included.

TABLE IV-4 AIR CARRIER COSTS*

| | Honeywell | McDonnell-Douglas | RCA |
|---|---|---|---|
| Electronics | $ 6,322 | $ 7,004 | $ 7,938 |
| Installation | 4,227 | 4,227 | 4,227 |
| Non-Recurring | 103 | 160 | 164 |
| Recurring Logistics | 337 | 302 | 358 |
| TOTAL COST (ONE YEAR) | $10,989 | $11,693 | $12,687 |

* Costs include a simplex collision avoidance box, two indicators, and two antennas

## TABLE IV-5 MILITARY (HI PERFORMANCE) COSTS*

| | Honeywell | McDonnell-Douglas | RCA |
|---|---|---|---|
| Electronics | $ 5,776 | $ 6,458 | $ 7,392 |
| Installation | 8,252 | 8,252 | 8,252 |
| Non-Recurring | 391 | 514 | 471 |
| Recurring Logistics | 781 | 767 | 776 |
| TOTAL COST (ONE YEAR) | $15,200 | $15,991 | $16,891 |

* Costs include a simplex collision avoidance box, two antennas and an average of 1.5 indicators (50% of the aircraft would have two, the other 50% one)

## TABLE IV-6 MILITARY (LOW PERFORMANCE) COSTS*

| | Honeywell | McDonnell-Douglas | RCA |
|---|---|---|---|
| Electronics | $ 591 | $1,016 | $1,175 |
| Installation | 2,479 | 2,479 | 2,479 |
| Non-Recurring | 100 | 208 | 196 |
| Recurring Logistics | 882 | 952 | 918 |
| TOTAL COSTS (ONE YEAR) | $4,052 | $4,655 | $4,768 |

* Costs include a simplex collision avoidance box with an integral display and two antennas

TABLE IV-7 GENERAL AVIATION (HI PERFORMANCE) COSTS*

| | Honeywell | McDonnell-Douglas | RCA |
|---|---|---|---|
| Electronics | $6,434 | $7,320 | $ 8,496 |
| Installation | 1,925 | 1,925 | 1,925 |
| Recurring Logistics | 22 | 19 | 24 |
| TOTAL COST (ONE YEAR) | $8,381 | $9,264 | $10,445 |

* Costs include a simplex collision avoidance box, one indicator, and two antennas

TABLE IV-8 GENERAL AVIATION (LOW PERFORMANCE) COSTS*

| | Honeywell | McDonnell-Douglas | RCA |
|---|---|---|---|
| Electronics | $ 930 | $1,610 | $1,863 |
| Installation | 226 | 226 | 226 |
| Recurring Logistics | 23 | 39 | 32 |
| TOTAL COSTS (ONE YEAR) | $1,179 | $1,875 | $2,121 |

* Costs include a simplex collision avoidance box with an integral display and two antennas

## F. Institute for Defense Analyses (IDA) Capacity Studies

### 1. General

In 1973, in an attempt to discover how the three proposed ACAS systems might work in a high-density environment, the FAA contracted with IDA to perform an independent study of the communication capacity capability of the systems when operating in a predicted 1982 traffic environment for the Los Angeles Basin. (See Appendix A for Report Numbers) Under this effort, IDA was enjoined from directing any effort to determine the adequacy or effectiveness of the ANTC-117 threat evaluation and maneuver selection logics. Rather, they were directed to put particular emphasis on the relationship between traffic density and missed alarms (accepting the hypothesis that an intruder is not a hazard when in fact he is, in accordance with ANTC-117) and false alarms (accepting the hypothesis an intruder is a hazard when in fact he is not, according to ANTC-117). Consideration was to be given to the ACAS systems' communications reliability and synchronous & asynchronous garble.

### 2. Traffic Environment

The traffic model used for evaluation purposes was a forecast of the instantaneous peak traffic in the Los Angeles Basin in 1982, as prepared by FAA's Aviation Forecast Division, dated April 27, 1971. It was a static model, and gave the three dimensional position of each aircraft with the LAX airport as the origin of the coordinate system. General Aviation, air carrier, and military traffic estimates were distributed into local vs. itinerant and IFR vs. VFR. The total traffic was 807 aircraft, classified by type and distributed in altitude as follows:

| | < 10,000 ft. | > 10,000 ft. |
|---|---|---|
| General Aviation | 599 | 127 |
| Air Carrier | 29 | 15 |
| Military | 20 | 17 |
| TOTAL | 807 | |

IDA reported on the analysis of the systems in 1974 and suggested modifications to correct some deficiencies uncovered. On-going work by the manufacturers themselves as well as hardware evaluation by the Naval Air Development Center of Honeywell and RCA air carrier equipment, led to additional changes in the systems. Therefore, FAA again contracted with IDA (July 1974) to revise the analyses in accordance with the changes made.

## 3. Results

### a. General

Generally, the results of the IDA analyses show that any of the three systems can form the basis of an ACAS system, provided the ANTC-117 logics are valid. However, many detailed problems were uncovered, all of which could be remedied or alleviated with appropriate modifications.

### b. Honeywell Analyses

Major conclusions reached as a result of the Honeywell analysis are as follows:

(1) Non-threatening aircraft with a range-rate which is close to that considered threatening were found to be the major cause of false alarms in the AVOIDS tracking filter. This is due to the fact that at range-rate close to threatening range-rates, the range bins associated with the TAU filter (which must all be full for further threat processing) can be nearly all filled by the non-threatening aircraft. This then makes it more probable that the remaining bins can be filled by fruit. As a result, the false alarm rate is sensitive to the distinction which is made between a false alarm and an alarm which is displayed too early in time or at too great a range, and the shape of the range rate distribution of non-threatening aircraft. Analyses has shown the total false alarm rate in the 1982 LAX Basin would be about one per hour if alarms issued within about four epochs of the $T_2$ boundary are excluded. This increases to about seven per hour if alarms issued within about two epochs of $T_2$ are excluded. These estimates assume all aircraft were exposed to the most dense traffic region of the LAX 1982 model and are therefore conservative.

(2) Due to transponder blockage, it is estimated that the probability of no delay in the $T_2$ warning is .97. The probability of a one epoch delay (i.e., 3.7 secs.) is about 0.015, the probability of a two epoch delay also about 0.015, and the probability of a delay of three or more epochs about 0.0007.

### c. McDonnell-Douglas Analyses

Major conclusions reached as a result of the McDonnell-Douglas analysis are as follows:

(1) Use of range difference measurements for range-rate estimation introduces bias errors between the actual TAU alarm boundary in the range rate versus range plane. This leads, in most cases of level flight, to early alarms. However, situations resulting in false alarms do exist. Despite the fact that the error, at short ranges, exceeds the specified value by wide margins, there is only an 8 to 10 percent increase (depending on relative speeds) in the overall alarm rate.

(2) Reduced air-to-air synchronization relay range due to aircraft antenna gain nulls, a short rundown time in synchronous status due to limited airborne clock stability, and the backup mode interference/garble and alarm rates are all inter-related and manageable problems, if an adequate relationship between air carrier and MINI-CAS equipments is maintained throughout the aircraft population.

d. RCA Analysis

Major conclusions reached as a result of the RCA analysis are as follows:

(1) The probabilities of acquiring a non-existent target (false alarm) and of not acquiring a true target (missed alarm) are both less than 2% at the maximum hazard range and considerably smaller at closer ranges.

(2) While excessive roundtime has been reduced by the addition of many trackers, under certain circumstances, roundtime could still be excessive.

(3) Range error measurements may deteriorate by an unacceptable amount when multiple targets appear in a single range bin (interval of 500 ft.), an event which can occur with greater frequency than indicated by the traffic density because of the presence of virtual as well as true aircraft targets.

G. Flight Test and Evaluation Program

1. Participants

FAA, under interagency agreements with the Naval Air Development Center, Warminster, Pennsylvania, funded for the procurement, flight test and evaluation of the Honeywell and RCA air carrier and general aviation ACAS equipments. FAA directly procured the McDonnell-Douglas air carrier and general aviation equipments and performed the flight test and evaluation at NAFEC.

Subsequent to the flight test and evaluation of the AVOIDS I and VECAS equipments, system design changes were made to both and incorporated into the AVOIDS II and VECAS GA/M equipments which had not yet been delivered. Flight testing of the AVOIDS II equipment was completed at NADC by October 1, 1975. The VECAS GA/M equipment is currently undergoing bench testing at NADC. Flight testing of the EROS II and MINI-CAS equipments was completed at NAFEC in October 1975.

2. Commonalities

ANTC-117 logics were used as the basis for evaluation for all air carrier equipments. Identical flight test patterns were utilized

for all equipments and range and range-rate calibration flights were performed on the Navy's Patuxent River phototheodolite range for the Honeywell and RCA equipment and at the NAFEC phototheodolite range for the McDonnell-Douglas equipment.

3. Differences

Besides the differences in test organizations and locales, there were minor differences in the test instrumentation. Both the Honeywell and RCA equipments were flown with simulators capable of injecting fruit into the system up to that level estimated for the 1982 Los Angeles Basin if all aircraft were ACAS equipped. Since the McDonnell-Douglas system does not suffer from a "mutual interference" problem, and since analysis did not indicate system capacity to be a problem, no such simulator was used in its flight test. The NADC testing also included slightly higher closing velocities.

4. Description of Flight Tests

The primary objectives of the flight tests were to:

a. Determine the communications reliability of the RF link as a function of range and antenna aspect angles

b. Determine the range and range-rate accuracies

c. Determine conformance with ANTC-117 TAU zone and altitude zone boundaries

d. Examine the capabilities of the vertical maneuver escape logic

To accomplish these objectives, a wide range of flight patterns were run covering closure rates of zero to approximately 800 knots. These patterns included traffic geometries encompassing 360° around the participating aircraft to test for adequate hazard detection in all directions. Flights above and below 10,000 ft. were flown as well as two and three aircraft encounters.

Aircraft used in the NADC tests were as follows:

| TYPE | NUMBER | AIRSPEED |
|---|---|---|
| P-3A | 1 | 190 to 350 knots |
| NC117 | 1 | 120 to 180 knots |
| RA3B | 1 | 220 to 400 knots |

Aircraft used in the NAFEC tests were as follows:

| TYPE | NUMBER | AIRSPEED |
|---|---|---|
| Gulfstream | 2 | 140 to 250 knots |
| Convair 880 | 1 | 190 to 350 knots |

5. Results

a. General

Subsequent to the flight testing of the Honeywell AVOIDS I and the RCA VECAS, the systems' designs were changed. These design changes were incorporated in the Honeywell AVOIDS I and II and the RCA VECAS and VECAS GA/M. The data from tests of the modified equipments shows the Honeywell system change improved $\dot{R}$ accuracy and reduced the level of false alarms, and the RCA system change decreased the $\dot{R}$ accuracy.

b. RCA

(1) VECAS

The VECAS provided the necessary avoidance warnings in a manner consistent with the requirements of ANTC-117. The pilots were able to execute the necessary avoidance maneuvers.

The required communication range was exceeded for all encounter angles except the head-on case above 10,000 ft., which was marginal when extrapolated to a 1200 knot range-rate. Analysis shows that there was an imbalance in the theoretical threat range at the 10,000-foot altitude boundary. Aircraft on opposite sides of this boundary do not have the same theoretical communications range.

Round reliability (proper commands and advisories) from the point at which initial communication range was established to the point of closest approach was greater than 90% for all encounter angles for most simulated traffic conditions, and without the benefit of round-to-round memory. The tolerance of the data link to fruit replies above 10,000 ft. was greater than 350,000 replies per second per field above threshold, and below 10,000 ft. was greater than 40,000 replies per second per field above threshold.

The accuracies of the trackers were:

| TRACK TYPE | RANGE IN FEET | | RANGE-RATE KNOTS | |
|---|---|---|---|---|
| | MEAN | 1 SIGMA | MEAN | 1 SIGMA |
| Half Track | 142 | 95 | 0.88 | 20.5 |
| Full Track | 105 | 70 | 1.09 | 8.6 |

The warning time mean and standard deviations expressed as percentages of the TAU Two and TAU One thresholds, (theodolite reference) were:

| TAU ONE | TAU TWO |
|---|---|
| Mean = -7.3% | Mean = -7.4% |
| Sigma = 13.7% | Sigma = 7.1% |
| N = 92 | N = 87 |

From the above, it can be seen that the TAU Two warning times provided by the VECAS on 87 encounters were found to be 7.4% late on the average with a standard deviation of 7.1%. The TAU One warning times on 92 encounters were found to be 7.3% late on the average with a standard deviation of 13.7%.

The TAU Two advisories were generated at greater than 40 seconds before collision. The TAU One commands were generated within one round of the desired time. The minimum round-time was 4.5 seconds below 10,000 ft. and 6 seconds above 10,000 ft. The contribution to roundtime of each target is usually 0.3 second for test track plus either 0.4 second for half-track or 0.8 for full-track. The use of two trackers for co-half-zone targets in the same correlator sector reduced the roundtime contribution of these targets.

Multipath tracks of a real target occurred infrequently, and their effect on average roundtime was insignificant. Other multipath tracks occurred at low altitudes where the VECAS replied to its own interrogations.

(2) VECAS GA/M

The VECAS GA/M equipment is currently undergoing bench testing at NADC. Very little data has been reduced, but based on this data, and on factory acceptance, it appears that in redesign efforts to correct other problems, the $\dot{R}$ accuracy has suffered. The one sigma value now appears to be on the order of 40 knots.

c. Honeywell

(1) AVOIDS I

The AVOIDS I provided the necessary avoidance warnings to the pilots. The warnings were consistent with the requirements of ANTC-117, and provided the pilots with sufficient time to execute the necessary avoidance maneuvers.

The required communication range was exceeded for all encounter angles at the speeds flown, and for all extrapolated 1200 knot range rates above 10,000 ft. for all of the flights involving the NC117 vs. either the RA-3B or P-3. The same results were achieved for all of the flights involving the RA-3B above the P-3. For the flights involving the P-3 above the RA-3B, the communication ranges were marginal when extrapolated to a 1200 knot range rate, above 10,000 ft., at encounter angles of -120 and 180 degrees.

The pilot display reliability was 98.2%.

The air-to-air communications link when operating with fruit had an error rate which was too high and caused an excessive number of false alarms.

The range and range rate accuracies (Theodolite reference) were:

| | RANGE | | RANGE RATE | |
|---|---|---|---|---|
| GROUP | MEAN %OF RANGE | SIGMA FEET | MEAN KNOTS | SIGMA KNOTS |
| All Data | +2.5 | 154 | +10 | 11 |
| Data Without Fruit | +2.7 | 132 | + 9 | 10 |
| Data With Fruit | +2.1 | 197 | +13 | 13 |

The warning time mean and standard deviations expressed as percentages of the TAU Two and TAU One thresholds (theodolite reference) were:

| TAU One | | | TAU Two | | |
|---|---|---|---|---|---|
| Mean | = | 0.4% | Mean | = | 0.5% |
| Sigma | = | 4.1% | Sigma | = | 4.1% |
| N | = | 47 | N | = | 48 |

(2) AVOIDS II

The AVOIDS II equipment was evaluated against itself and was also flown against the AVOIDS I equipment after it had been modified to improve its performance. Incomplete reduction of data recorded in the AVOIDS II vs. AVOIDS II flights indicates the equipment is performing in accordance with the logic implemented as shown in Figures III-5 and III-6. No false alarms were detected and multipath has not shown itself to be a problem. Communications reliability is on the order of 96.5% with the display reliability being greater than 99%. The range and range rate accuracies were:

| | RANGE | RANGE RATE |
|---|---|---|
| Mean | 83 ft. | 9 knots |
| Sigma | 94 ft. | 7 knots |

Warning times (expressed as percentages of the TAU Two and TAU One thresholds) indicate that 95% of the time, the TAU Two warning ranged from 14.5% late to 16.1% early. The TAU One warnings ranged from 11.8% late to 21.8% early.

d. McDonnell-Douglas EROS-II and MINI-CAS

Data reduction accomplished to date shows the EROS II equipment provided the necessary avoidance warnings in a manner consistent with the requirements of ANTC-117. The MINI-CAS operated in accordance with the logic implemented (no $Ro_1$ off-set, one off-altitude band only, and no predicted co-altitude band).

The air-to-air communications reliability for EROS II vs. EROS II was above 95% before TAU Two, and above 98% at TAU Two and TAU One. For the MINI-CAS vs. MINI-CAS, these figures were 96% before

TAU Two, above 98% at TAU Two and above 99% at TAU One. For the EROS II vs. MINI-CAS, these figures were greater than 91% before TAU Two, and greater than 97% at TAU Two and TAU One.

The range and range rate accuracies (theodolite reference) were:

| | RANGE | | RANGE RATE | |
|---|---|---|---|---|
| | Mean (nmi.) | Sigma (nmi.) | Mean Knots | Sigma Knots |
| EROS II | .03 | .035 | -5 to 10 | 15 |
| MINI-CAS | .01 | .035 | -5 to 15 | 10 |

The warning time mean and standard deviations expressed as a percentage of the TAU One and TAU Two thresholds were:

| | WARNING TIME | | | |
|---|---|---|---|---|
| | TAU ONE | | TAU TWO | |
| | Mean | Sigma | Mean | Sigma |
| EROS II | -14.8% | 9.6% | -1.3% | 4.0% |
| MINI-CAS | - 8.1% | 11.0% | -1.6% | 3.7% |

Both ground-to-air communication reliability for synchronization and synchronization accuracy were more than adequate.

## V. SUMMARY OF ANALYSES AND TESTS

### A. ACAS/ATC Interaction

The simulations performed at NAFEC and the analysis of ANTC-117 conducted by IDA, cast doubt on the validity of ANTC-117, at least insofar as acceptable alarm rates are concerned. More effort is necessary in this area and will require a trade-off between protection provided and the number of alarms tolerable. This problem is applicable to all three systems.

### B. RF Frequency Compatibility

The radar altimeters analyzed present interference to the three ACAS systems, with the EROS II being the most susceptible. Co-location of an altimeter and an ACAS on the same aircraft is the worst situation and may be intolerable.

C. IDA Capacity Analyses

From a communications viewpoint and assuming the validity of ANTC-117, it appears that all three systems could operate satisfactorily in the Los Angeles Basin traffic model utilized. The McDonnell-Douglas system suffers from a bias error in the TAU measurement under certain circumstances which serves to increase the alarm rate. This error is insignificant in the Honeywell and RCA systems. The RCA system can, under certain circumstances, have an excessive roundtime and the fruit level is a function of the distribution of VECAS, VECAS GA/M, Proximity Warning Indicators and Remitters. Unlike the Honeywell and McDonnell-Douglas systems, not all aircraft receive positive commands. The escape maneuver is required to be accomplished by the VECAS and VECAS GA/M equipped aircraft.

D. ARINC Research Cost Analyses

The ARINC Research Company cost analysis shows the Honeywell AVOIDS systems enjoy a clear economic superiority over the McDonnell-Douglas and RCA systems.

E. Flight Test and Evaluation

The flight test and evaluation of all systems indicate they all meet ANTC-117 requirements. The Honeywell system was superior in performance to the other ACAS systems.

F. Summary Evaluation Table

Table V-1 is a summary of the three systems based on data available at the writing of this report.

## VI. CONCLUSIONS AND RECOMMENDATIONS

A. It is concluded that the Honeywell AVOIDS I and II systems are superior to the McDonnell-Douglas and RCA systems.

B. It is recommended that additional effort be made to optimize the ANTC-117 threat evaluation logic from the standpoint of protection vs. alarm rate. The problem of ANTC-117 compatibility with the ATC system needs additional effort. Analysis indicates the alarm rates attendant with current logic are too high and unsatisfactory, especially in high density terminals.

C. If an ACAS is to be implemented, it is recommended that action be started to remove the radar altimeters from the 1600 to 1660 MHz band.

D. If an ACAS is to be implemented, it is recommended that further effort be conducted to determine the mutual impact of other existing or planned services in or near the ACAS frequency band (i.e., AEROSAT, etc.).

| | HONEYWELL | McDonnell-Douglas | RCA |
|---|---|---|---|
| GROUND STATION SYNCHRONIZATION REQUIRED | NO | YES | NO |
| ALL AIRCRAFT PROVIDED WITH POSITIVE COMMANDS | YES | YES | NO |
| COMMUNICATIONS ON ALL ANTENNA COMBINATIONS | YES | NO | NO |
| RANGE RATE ACCURACY | BEST | MIDDLE | WORST |
| DEGREE OF DESIGN MATURITY | HIGH | MEDIUM TO HIGH | LOW |
| COST | LOWEST | MIDDLE | HIGHEST |

TABLE V-1

SUMMARY EVALUATION

# APPENDIX A

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