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TCAS I Design Guidelines

V. A. Orlando
J. D. Welch
W. H. Harman
A. R. Paradis

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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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16. Abstract

A description of the FAA airborne Traffic Alert and Collision Avoidance System known as TCAS I introduces the main topic of the report: results of an investigation of simple techniques suitable for the passive and active detection of nearby aircraft by TCAS I. This is followed by a review of the measurement facilities and data used to evaluate the detection techniques.

Techniques for identifying passively detected returns from potentially threatening aircraft, i.e., the rejection or "filtering out" of non-threat aircraft, are described and evaluated. Alternatives for time-sharing the 1090 MHz channel between the TCAS I transponder and the passive detector are described. A candidate passive detector is defined and its performance is evaluated using flight test data.

Predictions of the performance of a low-power TCAS I based on active detection are made via link calculations and flight test measurements.

A summary of results concludes the report.

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CONTENTS

CONTENTS (Con't)

ILLUSTRATIONS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

The Federal Aviation Administration approach to aircraft separation assurance is based on an airborne system known as the Traffic Alert and Collision Avoidance System (TCAS).

Two versions of TCAS have been defined:

TCAS II - A system that provides traffic and resolution advisories. It will be able to operate in all traffic environments foreseen to the end of the century.

TCAS I - A compatible but simpler system that: (1) supports surveillance for TCAS II as well as ground air traffic control, (2) displays the traffic advisory and maneuver intent crosslinked from the TCAS II, and (3) is able to detect the presence of nearby transponder-equipped aircraft.

The TCAS I equipment must be simple enough to be produced at a cost affordable by general aviation users. It must also have such low signal interference characteristics that unrestricted implementation could be permitted with no undesirable interference effects. These considerations have lead to the investigation of passive and low power active techniques for the detection of nearby aircraft.

This report gives the results of a study conducted by Lincoln Laboratory to investigate simple techniques for the passive and active detection of nearby transponder-equipped aircraft. It is intended to provide guidance to designers of TCAS I equipment.

The report begins with a definition of TCAS I functions and components. This is followed by a description of the airborne measurements used to evaluate passive detection techniques. Next, filter criteria that may be used to flag passive detections of potentially threatening aircraft are described and evaluated. Alternatives are identified and compared for time-sharing the 1090-MHz channel between the passive detector and the Mode S transponder included in the TCAS I installation. These results are used to define a candidate passive detector whose performance is evaluated against in-flight target-of-opportunity data. The alternative of using active detection is considered next. A low power active detector is described and its performance is evaluated through link calculations and in-flight measurements. The report concludes with a summary of results.

2.0 TCAS I FUNCTIONS AND COMPONENTS

The three main characteristics of TCAS I are:

1. TCAS I includes a Mode S transponder and an encoding altimeter and is thus able to respond with encoded altitude to interrogations from the air traffic control system on the ground and from airborne TCAS II units.

2. TCAS I has a means for alerting the pilot that a TCAS II aircraft is maneuvering to avoid him. This information is crosslinked from TCAS II to the transponder in the TCAS I aircraft. Thus, the transponder must be a Mode S transponder with an associated pilot display.

3. TCAS I has the ability to detect nearby transponder-equipped aircraft and to alert the pilot when the characteristics of any detection might indicate that it is a threat.

The TCAS I functions are shown in block diagram form in Fig. 2-1. Note that:

1. The transponder detector must operate with both ATCRBS and Mode S equipped aircraft.

2. Some coordination is needed between the transponder detector and the TCAS I Mode S transponder since they operate on the same frequency.

Although together they make up the TCAS I system, the equipment used for transponder detection is functionally independent of the Mode S transponder and the display for TCAS II advisories. Technical aspects of the Mode S transponder and the encoding altimeter other than the coordination provisions noted above are not addressed in this report since the TCAS concept does not require any changes to the existing Mode S design.

2.1 Display of TCAS II Advisories

The inherent communication capability of the Mode S link is used to drive a display in the TCAS I aircraft on receipt of a message from the TCAS II aircraft. When a maneuver advisory caused by a TCAS I aircraft is displayed to the pilot of the TCAS II aircraft, a message is included in the next regular surveillance interrogation to the TCAS I aircraft.

The air-to-air message alerts the TCAS I pilot and indicates where the TCAS II aircraft will be relative to him at the point of closest approach. For example, the "above" message is used when the TCAS II tells its pilot either to climb or to limit his rate of descent. The crosslink message also includes a traffic advisory, that is, information on the range, the relative

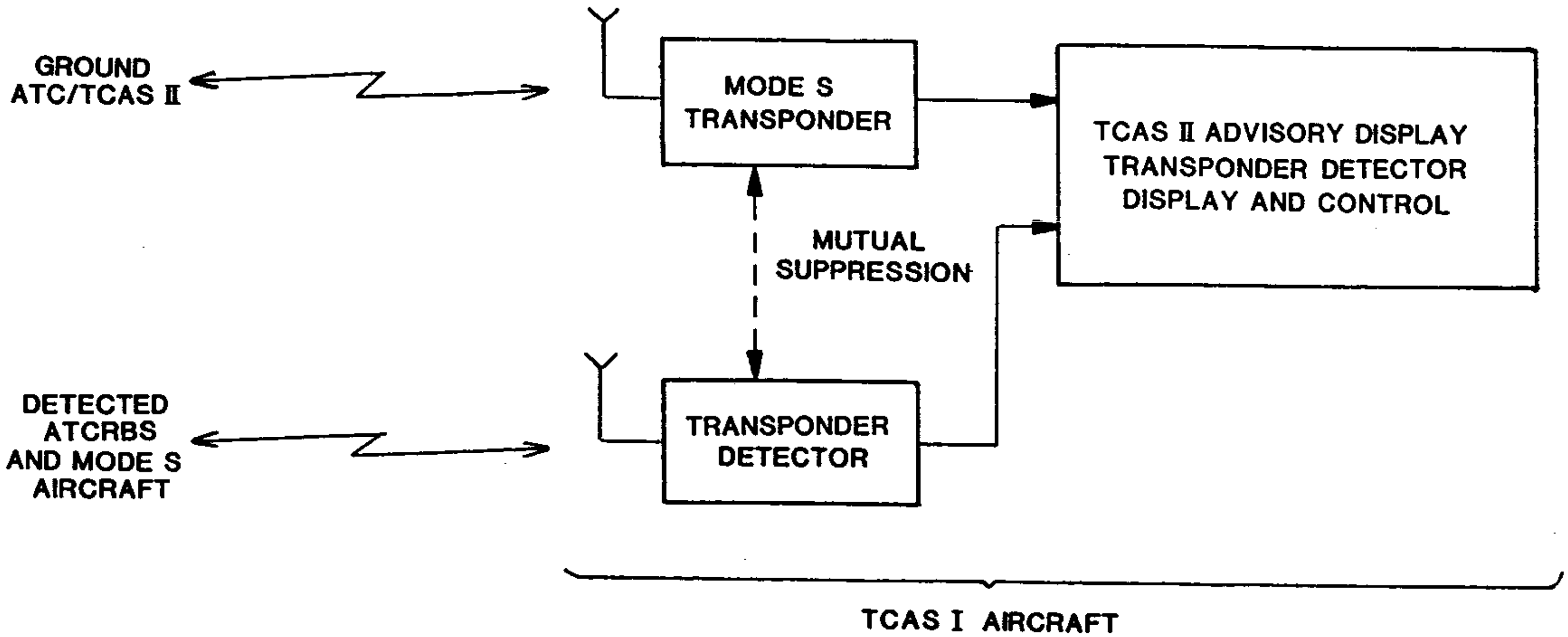


Fig. 2-1. TCAS I block diagram.

altitude, and the relative bearing between the two aircraft. In the example illustrated in Fig. 2-2, the TCAS II aircraft will be above the TCAS I aircraft at closest approach even though it is currently 200 feet below. The range is currently 2.6 nmi and the bearing of the TCAS I aircraft is 30° relative to magnetic north.

2.2 Air-to-Air Transfer of Bearing Information

There are several options for displaying the bearing of the TCAS II aircraft to the TCAS I pilot. Figure 2-3 illustrates the implementation of crosslinked bearing that seems to be least expensive for both the TCAS I and TCAS II aircraft. The TCAS II unit measures the bearing to the TCAS I aircraft and determines its own bearing from magnetic north as it would be seen from the TCAS I aircraft. It need not know the heading of the TCAS I aircraft to do this. This number is crosslinked and displayed directly on a two-digit numeric readout, which could be built into the TCAS I Mode S transponder as shown in the figure. The pilot then uses his directional gyro to determine which direction to look for the target.

Such a display would allow bearing to be displayed almost as accurately in the TCAS I aircraft as in the TCAS II aircraft that makes the measurement. This technique has the advantage that it doesn't require any electrical or mechanical interface between the Mode S transponder and the instrument used for determining heading in the TCAS I aircraft. An alternative would be to display the TCAS II bearing in terms of clock position as seen by the TCAS I pilot. However, this would require an interface between the transponder and the directional gyro to correct for the TCAS I heading.

A second approach exists for Enhanced TCAS II, that is, a TCAS II with a directional antenna having a bearing accuracy capable of supporting horizontal resolution advisories. If such a device could track the TCAS I aircraft in range and bearing accurately enough, it could provide the crosslink advisory relative to the TCAS I track vector which (except for the effect of crab angle) will be the same as clock position relative to the aircraft body axis.

Provision is being made in the TCAS II crosslink format to encode the traffic advisory data using either magnetic north or TCAS I track vector as the bearing reference.

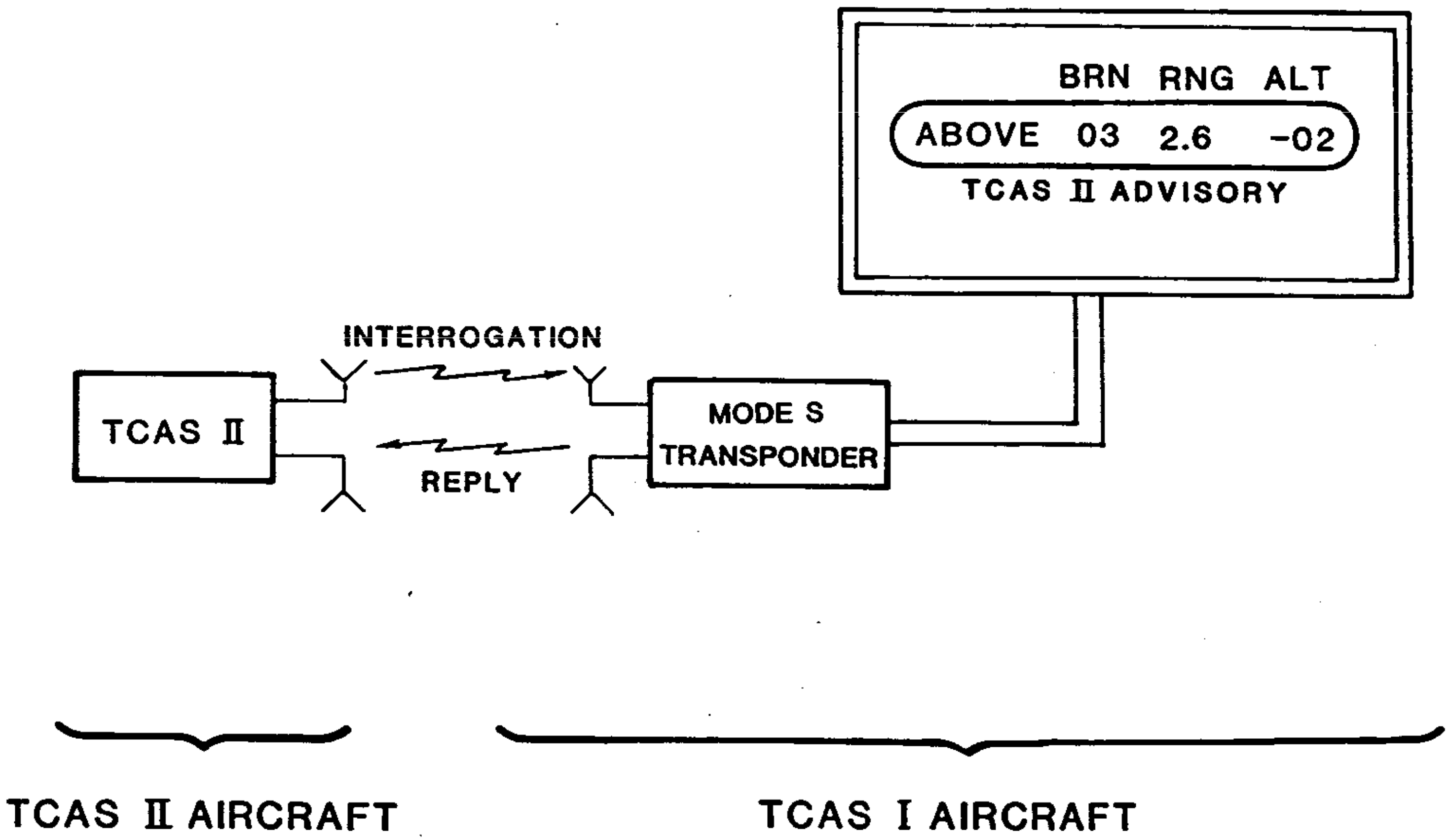


Fig. 2-2. Means of displaying TCAS II advisories.

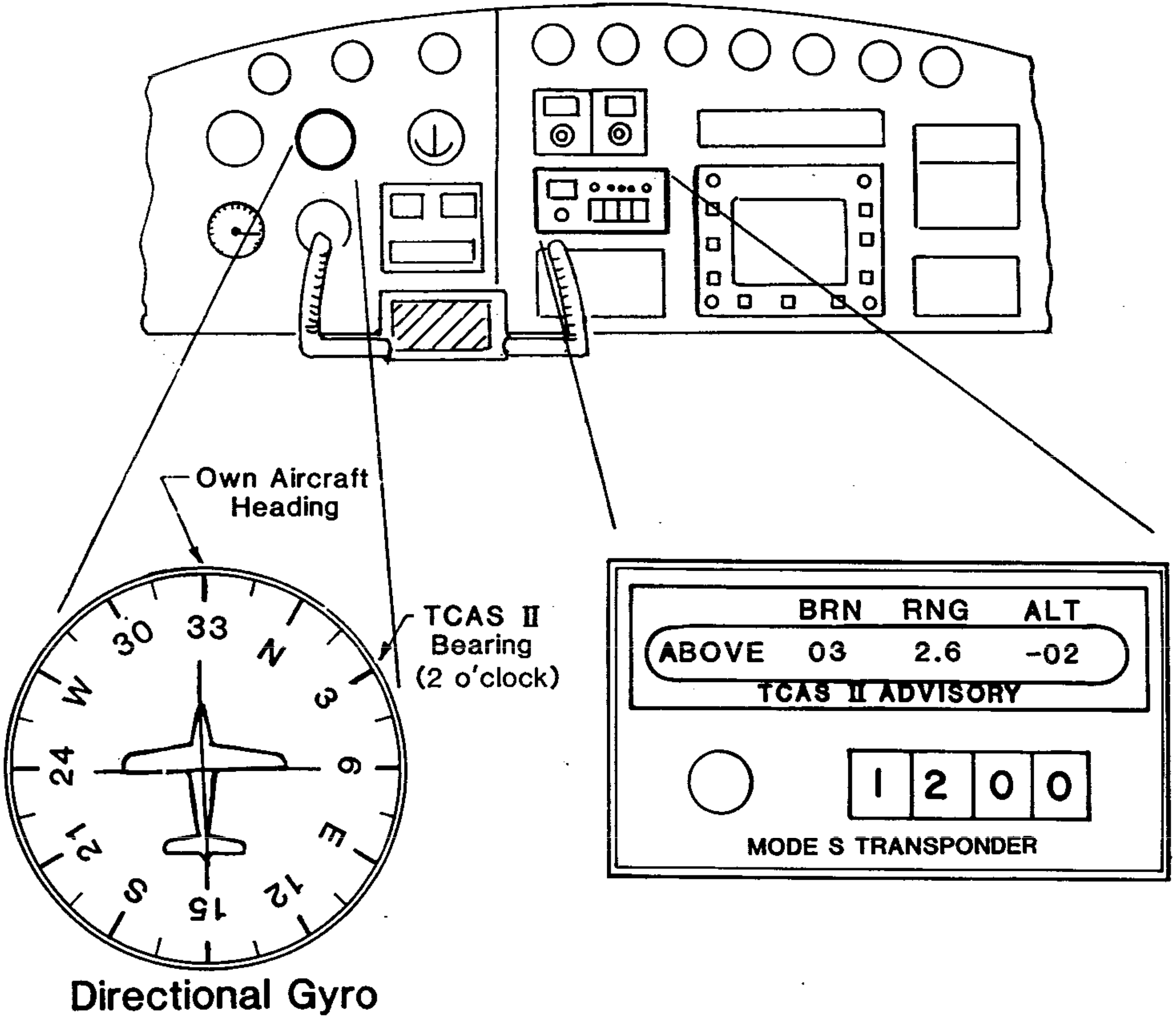


Fig. 2-3. Air-to-air transfer of bearing information.

3.0 AIRBORNE MEASUREMENTS

A limited amount of airborne data was analyzed to evaluate techniques identified for passive and active detection. These measurements were based on planned near-miss encounters between test aircraft as well as on encounters with targets of opportunity.

3.1 Test Facilities

Airborne measurements were made using the test facilities described in the following sections.

3.1.1 Airborne Measurements Facility (AMF)

The Airborne Measurements Facility (AMF) provides a means of obtaining recorded data representing pulsed electromagentic signals received on either of the two ATC beacon frequency bands (1030 MHz uplink, 1090 MHz downlink).

The AMF consists of two subsystems. The airborne subsystem, shown in Fig. 3-1, provides for the receipt of signals in the selected band, conversion to digital data samples, and storage on magnetic tape of the digitized signals along with data representing aircraft state and position. The recorded data includes amplitude and pulsewidth separately for signals received on the top and bottom antennas, along with time and angle of arrival.

The AMF is equipped with a beacon interrogator and is therefore capable of emulating active or passive TCAS operation.

The ground subsystem provides a means for playing back the recorded data, an interface that couples the data to an existing mini-computer for data editing and reformating, and a tape transport and associated controller to record the data onto general-purpose computer tape. The resultant tape permits further data processing to take place on a general-purpose computer.

A detailed description of the AMF is given in Ref. 1.

3.1.2 TCAS Experimental Unit (TEU)

The TCAS Experimental Unit (TEU), Fig. 3-2 is an omnidirectional, real-time active TCAS unit. It was built to support development of BCAS and later TCAS, and hence it permits system reconfiguration and variation of system parameters (such as receiver sensitivity), and has data recording capability. For these measurements, the TEU was configured to operate in the passive mode as well as in the normal active mode.

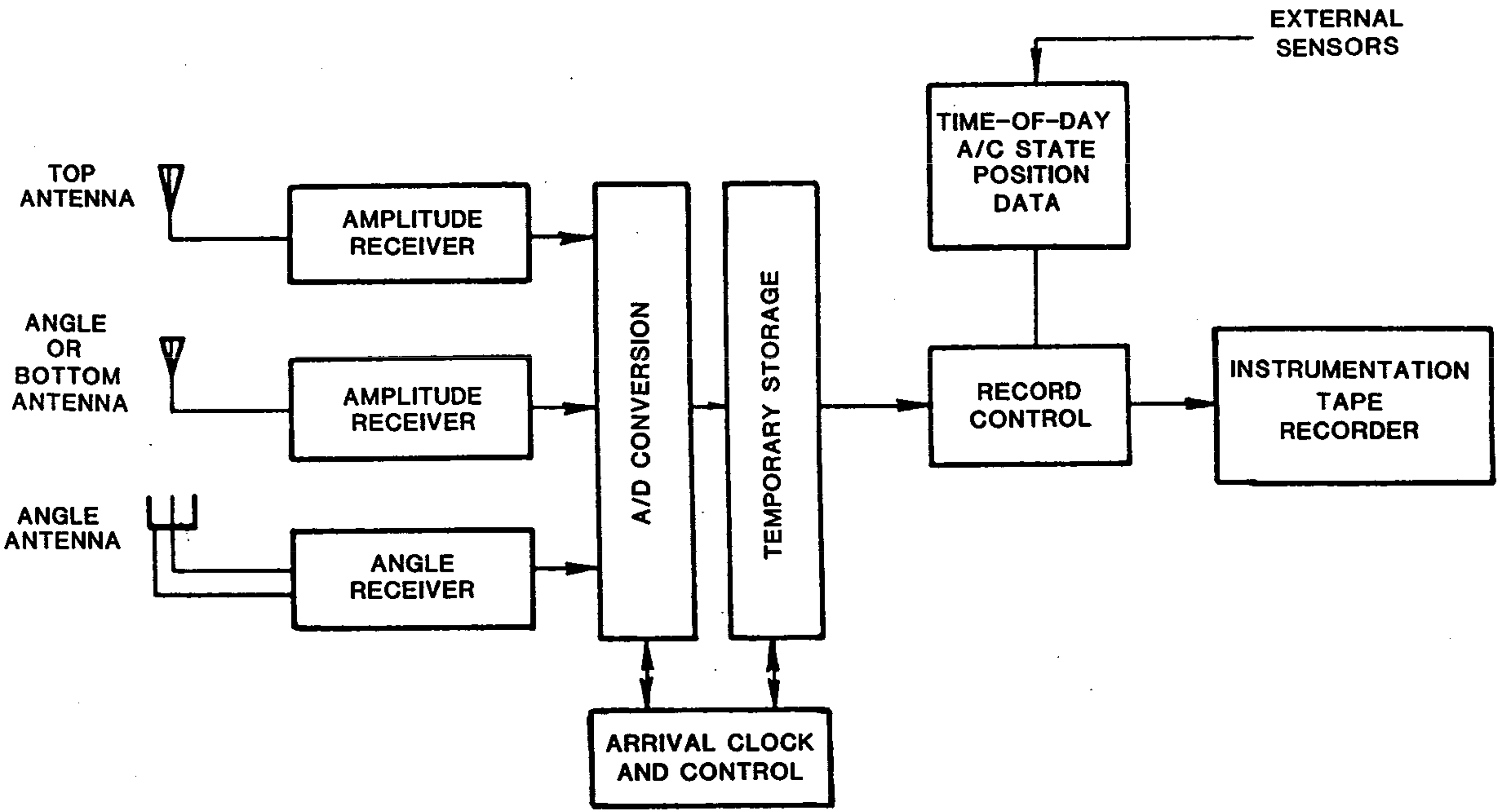


Fig. 3-1. Airborne measurement facility.

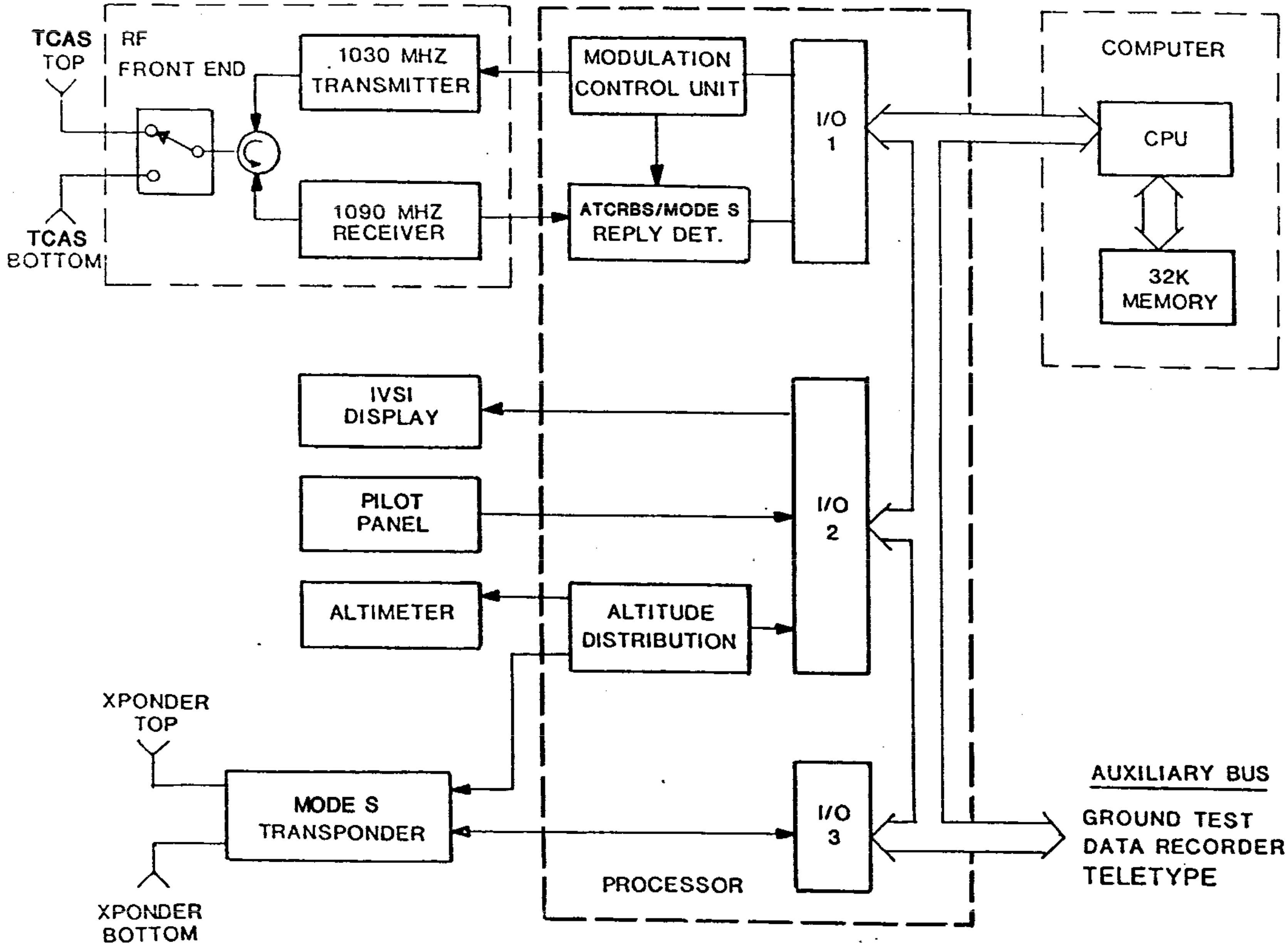


Fig. 3-2. TCAS experimental unit.

3.2 Data Collection Techniques

All of the experiments that required the measurement of received power level were performed with the AMF. Data collection by the AMF was accomplished by interleaving passive and active operation. The active data was used to establish range/altitude truth for evaluation of passive performance measures such as alert rate, false alarm probability, and warning time. The TEU was operated in the passive mode to provide additional information on alert rates, and in the active mode to evaluate the performance of the low-power active interrogator.

3.3 Measurements

Specific details of the test condition and measurement configuration are described in Sections 4 through 7 in connection with an interpretation of the experimental data.

4.0 PASSIVE FILTER CRITERIA

A passive filter is needed to restrict the triggering of pilot alerts so they occur only on transmissions received from potentially threatening aircraft, that is, aircraft that are close in both range and altitude. There are only a limited number of characteristics of a passively received reply that can be used as filter criteria. The most useful appeared to be:

1. Received power: Received power can be used two ways: First the received power can be compared to a fixed threshold to reject transmissions from aircraft at long range. Power may also be tracked to determine how range is changing as a function of time.

2. Aircraft altitude: Transmissions from off-altitude aircraft may be rejected two ways: First by the inherent off-altitude rejection provided by the aircraft antenna patterns, and second by detecting the altitude code and comparing the received altitude to own altitude.

3. Time-after-interrogation: If an aircraft is close and in the same ground interrogator beam as the TCAS I aircraft, range information may be inferred by comparing the time-of-arrival (at the TCAS I aircraft) of its transponder reply with the TCAS I transponder reply time.

Thus there are five distinct techniques for filtering based on these three characteristics. Each of these techniques will be described in this section along with an indication of expected performance.

4.1 Received Power Thresholding

The purpose of power thresholding is to distinguish between aircraft that are within a given volume of local airspace and those that are outside of this volume. Unlike the active mode of aircraft detection, in which replies from distant aircraft can be eliminated on the basis of time delays (i.e., range), passive mode detection does not have a direct measure of detection range.

The use of a power level threshold filter is complicated by the large variance in transponder reply power and transponder antenna gains observed in actual aircraft installations. The variation of the detected power from a population of general aviation aircraft, all at the same range, has been found to be more than 20 db [Ref. 2].

One consequence of the large variation in received power from transponder to transponder is that when the threshold is set to detect most aircraft at a nominal close range, some aircraft will still be detected at long ranges. Table 4-1 summarizes this effect, showing calculated detection performance for a nominal sensitivity setting of -57 dBm based on data from Ref. 2*. It tabulates the range for a given detection reliability for the two types of targets. The detection range is greater for air carrier targets because their transponders are, on average, more powerful.

*A link power budget for a power threshold detector is given in Appendix A.

TABLE 4-1.

RANGE PERFORMANCE (CALCULATED) FOR
RECEIVED POWER LEVEL THRESHOLDING TECHNIQUE

Range For A Given Detection Reliability			
Target Type	Detection Reliability		
	90%	50%	10%
Gen Aviation	1.5 nmi	2.8 nmi	5.5 nmi
Air Carrier	3.3 nmi	5.9 nmi	10.5 nmi

Although this large variation in range is undesirable, it is biased in the right direction, since air carrier aircraft are not only faster but they can be spotted by a pilot at greater distances than general aviation aircraft. Since the ultimate goal of any collision avoidance device is to detect aircraft closing at reasonable speeds in time to alert the pilot of a possible collision, the maximum closing speed that can be handled with a given detection reliability is, in this sense, a more meaningful performance measure than the detection range.

Table 4-2 shows the maximum closing speeds that could be handled while providing a 30-sec warning. The resulting closing speeds at the 50%-reliability range are 340 kt for general aviation and 710 kt for air carrier targets. These are about the highest closing speeds a GA aircraft would expect to encounter. Thus, the nominal sensitivity will provide reasonable warning times for at least 50% of the targets detected. However, the general aviation closing speed handled at the 90%-reliability-range of 1.5 mile is only 180 kt. Thus, some of the targets will not be detected early enough to provide a 30-second warning.

The thresholds could be set to provide higher detection reliabilities, but this would result in more long range detections and also increase the alert rate.

4.2 Received Power Level Tracking

While the large variance in the received power level of a population of transponders makes it difficult to determine range based on absolute power measurements, one can also measure the power variation observed versus time from a single transponder. The variation in free space loss with range is shown in Fig. 4-1. The significant variation in power with range suggests the possibility of identifying transmissions received from approaching aircraft and rejecting those received from departing aircraft. Another interesting observation is that (if all other link factors are constant) an increase in received power of 6 dB over a time T means that the range to the detected aircraft has decreased to one half its original value and that the range will become zero in the next interval of T seconds if the radial speed remains constant. This indicates that Tau can be expressed as a function of differential received power and measurement time.

An equation* for Tau as a function of differential received power (ΔP) observed over a time (Δt) is shown in Table 4-3. Values of Tau in seconds for several values of ΔP and Δt are also shown.

An example of an air-to-air measurement of received power is shown in Fig. 4-2. Each point plotted represents a measurement of 180 pulses over a period of six seconds. Curves are plotted for the maximum, average and minimum values over the six-second interval. The curves are plotted with

*A derivation of this equation is provided in Appendix B.

TABLE 4-2.

ENCOUNTER SPEED PERFORMANCE (CALCULATED) FOR RECEIVED POWER LEVEL THRESHOLDING TECHNIQUE

Maximum Encounter Speed for 30-Second Warning			
Target Type	Detection Reliability		
	90%	50%	10%
Gen Aviation	180 Kt	340 Kt	660 Kt
Air Carrier	400 Kt	710 Kt	1260 Kt

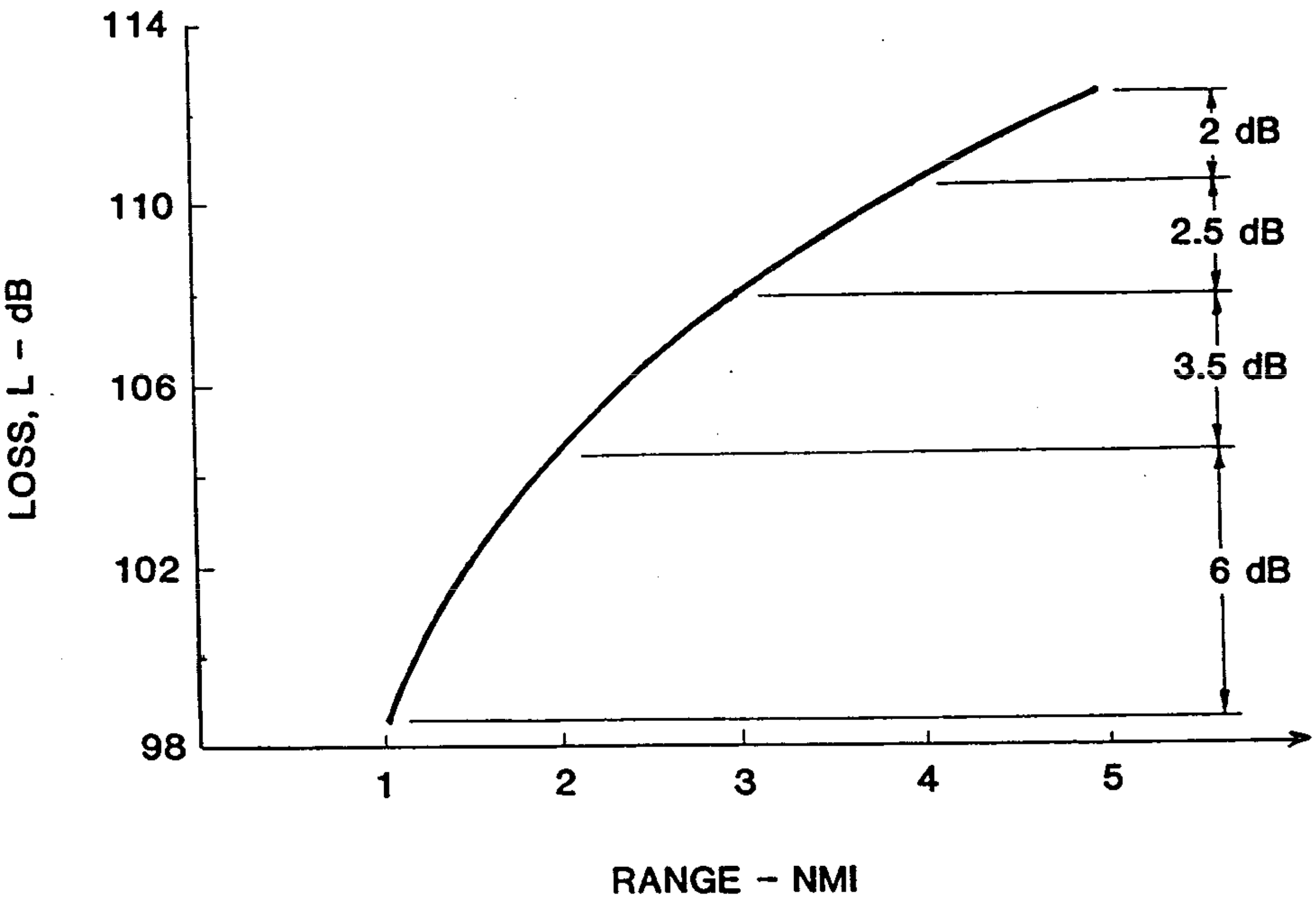


Fig. 4-1. Free space loss at 1090 MHz.

TABLE 4-3.

TAU (τ) DERIVED FROM POWER TRACKING

$$\tau = -\frac{\Delta t}{1 - 10^{(\Delta P/20)}}$$

Power Diff, ΔP (dB)	Time Difference, Δt (Sec)			
	1	4	6	10
6	1	4	6	10
5	1	5	8	13
4	2	7	10	17
3	2	10	15	24
2	4	15	23	39
1	8	33	49	82
0	∞	∞	∞	∞
-1	-9	-37	-55	-92
-2	-5	-19	-29	-49
-3	-3	-14	-21	-34
-4	-3	-11	-16	-27
-5	-2	-9	-14	-23
-6	-2	-8	-12	-20

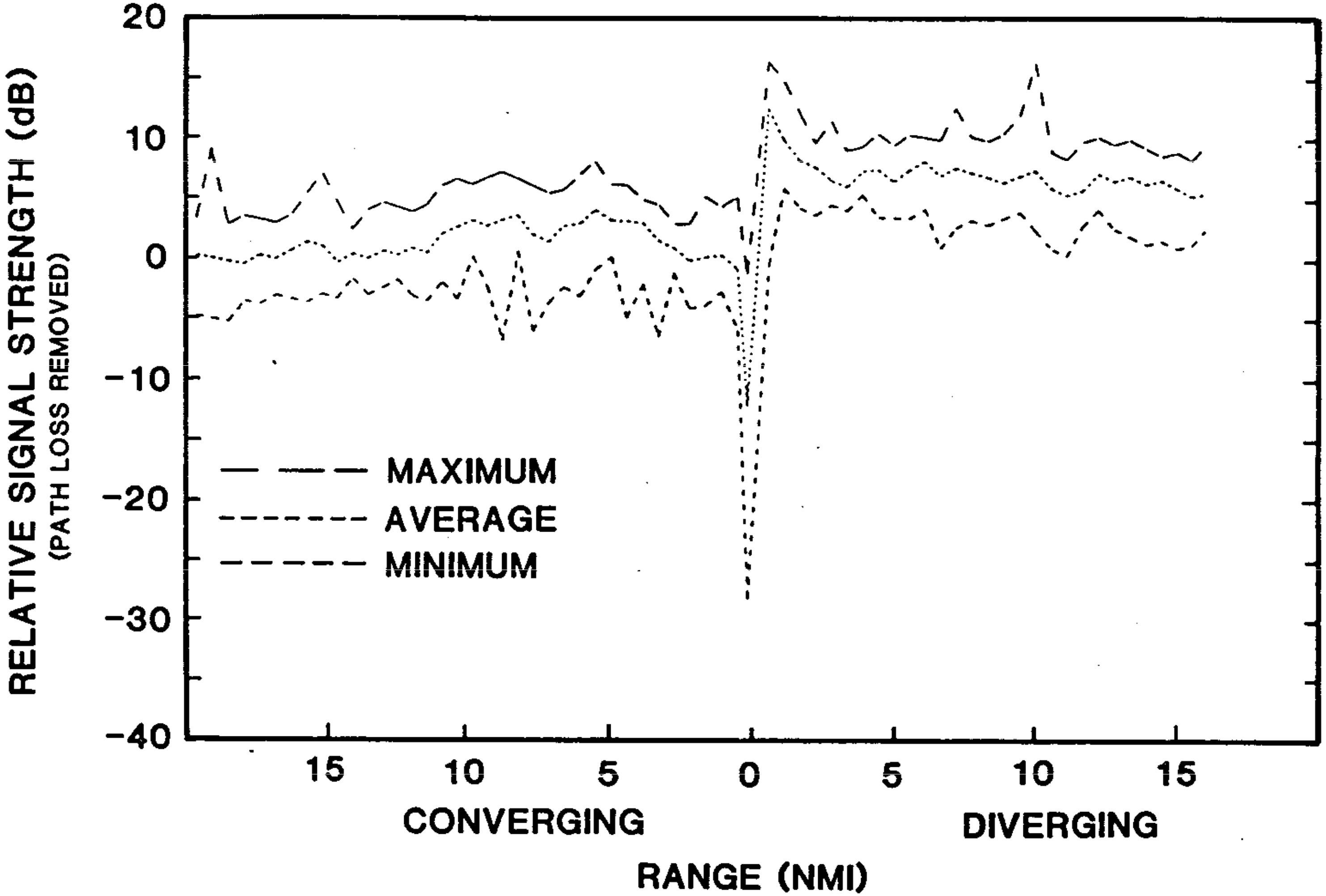


Fig. 4-2. Power tracking performance.

path loss removed and would be horizontal lines if power varied solely as a function of range. In fact, variations of up to 3 dB are observed in the mean value over the 8 nautical mile region that would be of most interest for TCAS I traffic alerts.

In order to evaluate the accuracy of Tau estimation based on power tracking, an analysis was performed on AMF data for seven planned encounters. Encounter characteristics were as follows:

Encounter	AMF Aircraft	Threat Aircraft	Range Nmi	Alt. Kft.	Surface	Type
1	727	Bonanza	+6 to -8	3	Water	H
2	727	Bonanza	+8 to -8	2	Land	O
3	C421	Bonanza	+8 to -8	3	Land	H
4	C421	Bonanza	+8 to -2	4	Land	H
5	C421	C172	+8 to 0	4	Land	H
6	C421	Cherokee	+8 to 0	4	Land	H
7	C421	Piper Cherokee	+8 to 0	3	Land	H

where H = Head-on (0°)
O = Obtuse crossing angle (≈ 135°)

The threat aircraft was actively interrogated at a rate that permitted the AMF to make 180 pulse measurements over a six-second interval. This also permitted range to be measured as a function of time so that true Tau could be calculated. Maximum, minimum and average values for each six-second interval were determined based on the 180 pulse measurements. The estimated value of Tau was based on the average value. A review of the data indicates that the same performance would have been obtained with 15 to 20 pulse measurements over the six-second interval, a sample size that could be obtained from either ATCRBS or Mode S replies.

Data obtained using the top antenna were used for Tau estimation since the top antenna provided more reliable data than the bottom antenna. The results of this calculation for 168 data points are shown in Fig. 4-3.

While it is clear from the figure that there is significant scattering of the Tau estimate, two things should be noted:

1. The estimate of coverging/diverging status is correct most of the time. This is indicated by the relatively small number of calculated values in the second and fourth quadrants of Fig. 4-3.

2. A small value of estimated Tau is usually an indication of a true threat condition, i.e., true Tau less than 30 seconds.

These observations are illustrated in Table 4-4 where the sample measurements are categorized by average power change over a six-second time interval. For example, the first row indicates that of 12 cases where a +6 dB increase in average power was measured in one six-second interval, 10 of the cases occurred where the true Tau was < 30 sec and 2 occurred when the threat aircraft was diverging.

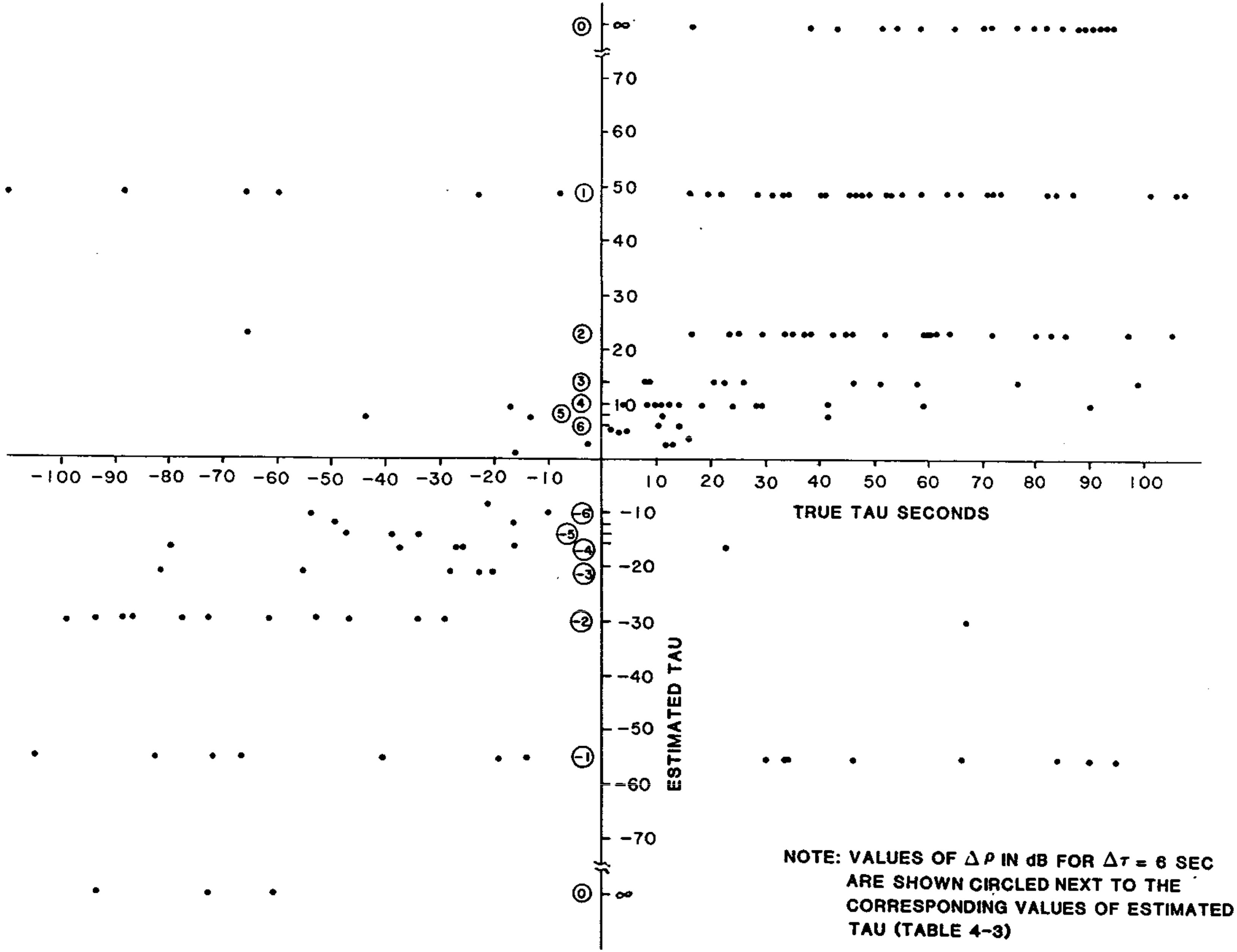


Fig. 4-3. Estimated Tau performance.

TABLE 4-4.

POWER TRACKING MEASUREMENT PERFORMANCE

(Based on Δt = 6 Seconds)

ΔP dB	True Tau < 30 sec	True Tau > 30 sec	True Tau Opposite Sense	Probability That True Tau < 30 sec	Prob. of Correct Conv/Div. Category
> 6	10	0	2	0.83	0.83
5	1	1	2	0.25	0.50
4	10	3	1	0.71	0.93
3	5	5	0	0.50	1.00
2	4	19	1	0.17	0.96
1	4	24	6	0.12	0.82
0	1	22	0	0.04	-
-1	1	7	7	0.07	0.53
-2	0	11	1	0.0	0.92
-3	0	6	0	0.0	1.00
-4	1	4	1	0.17	0.83
>-5	0	9	0	0.0	1.00
Total Data Points	37	111	21		

Table 4-4 suggests parameters for a relative power detector. Rules and performance are as follows:

Characteristic Estimated (Based on Δt = 6 sec)	Correct‡	Total‡	Performance
Threat Detection (Tau < 30 sec):			
Alert when $\Delta P > +4$ dB	21	30	70%
Converging/Diverging:			
Use sign of ΔP	125	146	86%
Use sign of ΔP if $\lvert\Delta P\rvert > 1$ dB	89	97	92%

‡From Table 4-4.

An indication of warning times for this threat detector can be obtained by noting the values of true Tau for which ΔP was > 4 dB over a six-second interval for the seven encounters analyzed. This is shown in Fig. 4-4.

It should be noted that power tracking requires reply-to-reply correlation. This correlation is easy for Mode S replies because of the unique address code. It is somewhat difficult for Mode C or discrete code Mode A replies and very unreliable for other ATCRBS cases when there are enough aircraft present to result in a finite probability that two or more targets have the same code.

4.3 Antenna Pattern Filtering

Measurements of typical transponder antenna patterns [Refs. 3,4,and 5] indicate that if both the transponder antenna and the passive transponder detector antenna are bottom mounted, the vertical coverage of the passive detection system described in paragraph 4.1 is restricted by antenna patterns and air frame blockage to roughly ± 5000 ft if the target is a GA aircraft, and ± 12000 ft if it is an air carrier aircraft as shown in Fig. 4-5.

Air-to-air measurements demonstrating this filter effect are shown in Fig. 4-6A and -6B. These measurements were made using the AMF in an active omnidirectional TCAS mode*. Data from four whisper/shout levels for both top and bottom antennas were used to establish range/altitude truth. Next, regions where the lowest power interrogations elicited replies were determined and recorded**. The lowest power interrogation was used for this purpose in order to cause the air-to-air link to become marginal off-altitude and at long range in order to reveal antenna pattern effects. Normal receiver sensitivity was used for all whisper/shout levels. Note that this approach illustrates antenna pattern filtering on the transmit link only. The results apply to the receive case as well since the same antenna is used.

*The equipment was flown in a Cessna 421 from Boston to New York at 8000 feet and returned at 9000 feet.

**Interrogation power was 4 watts referred to the antenna.

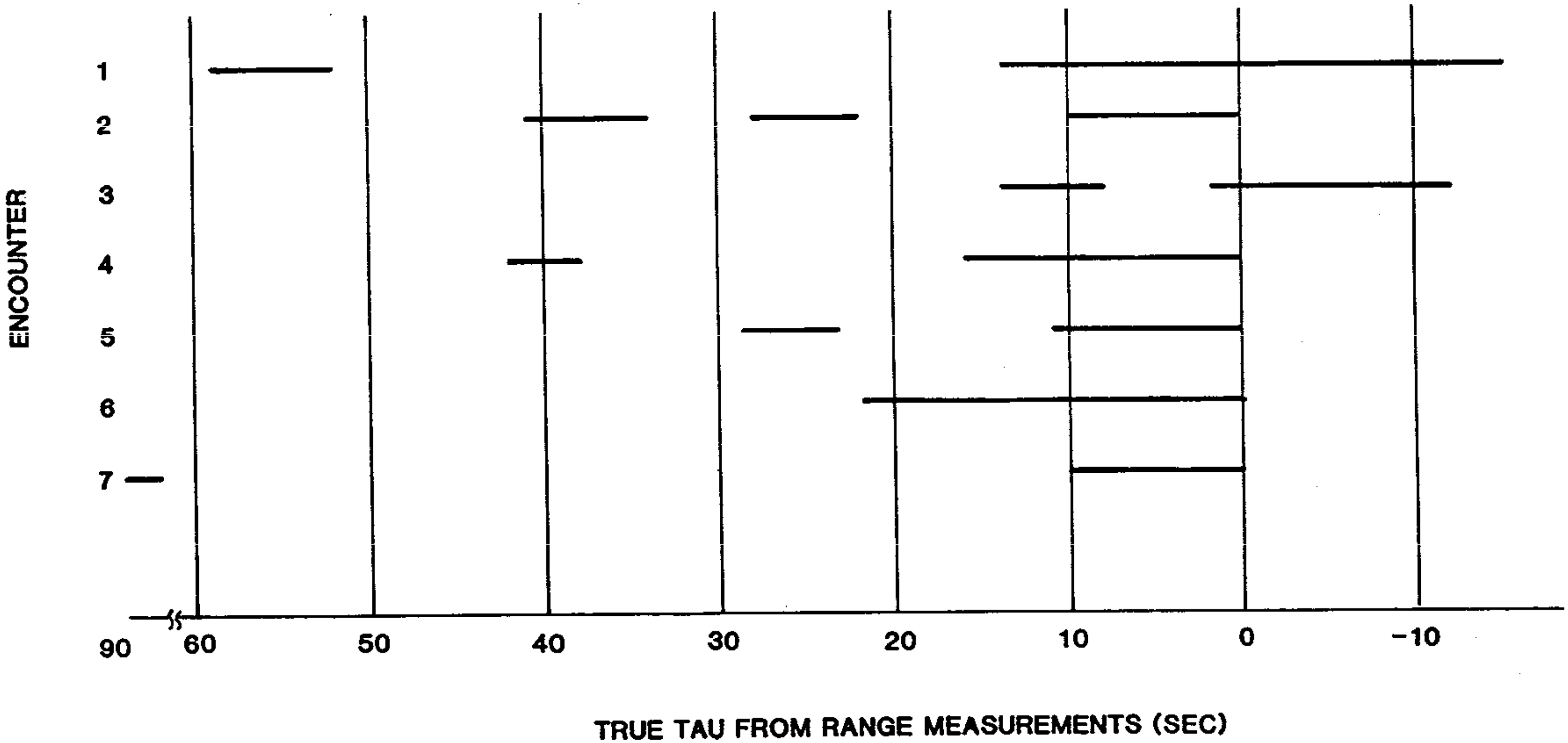


Fig. 4-4. Values of true Tau for which ΔP ≥ 4 dB over a six-second interval.

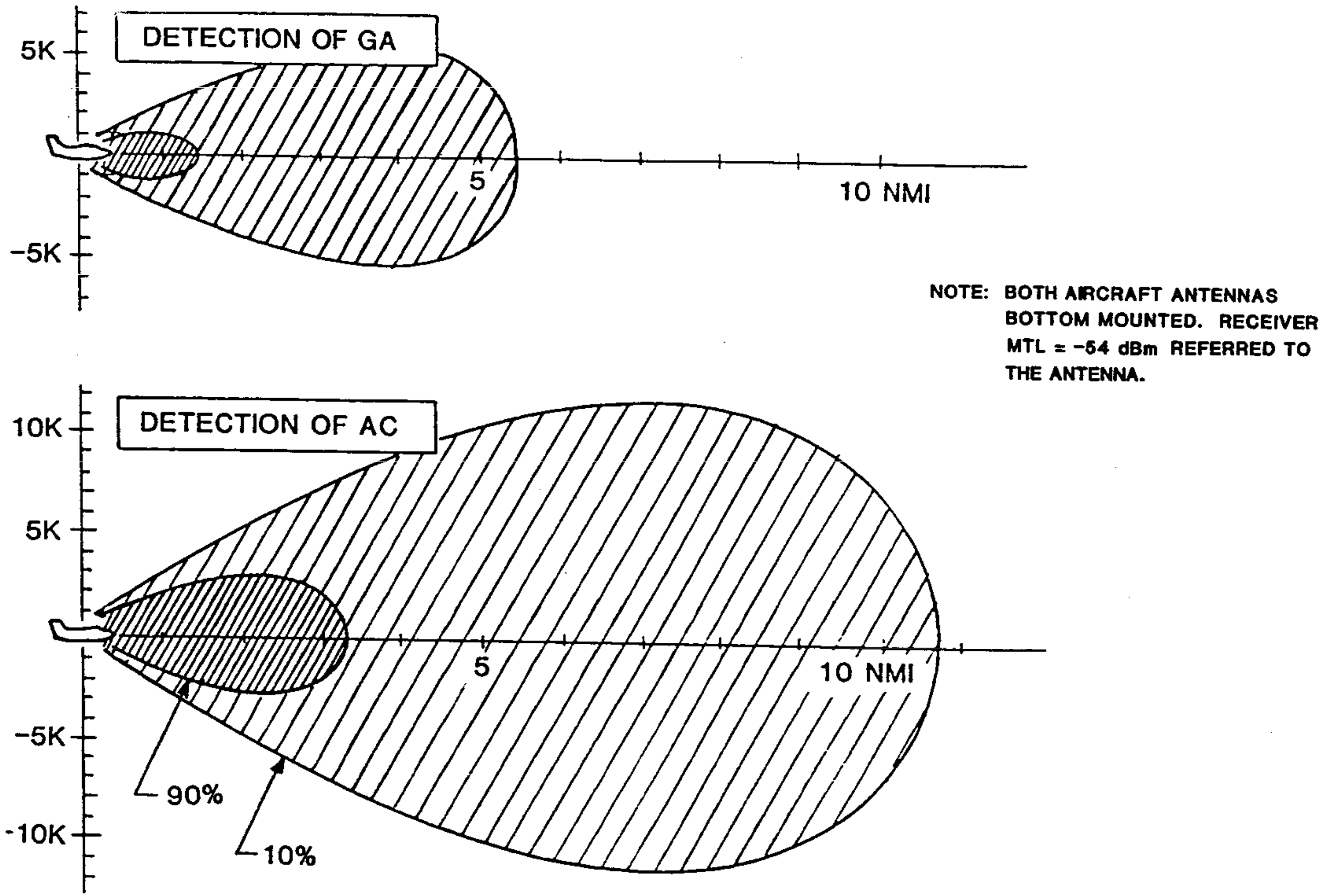


Fig. 4-5. Antenna pattern filtering.

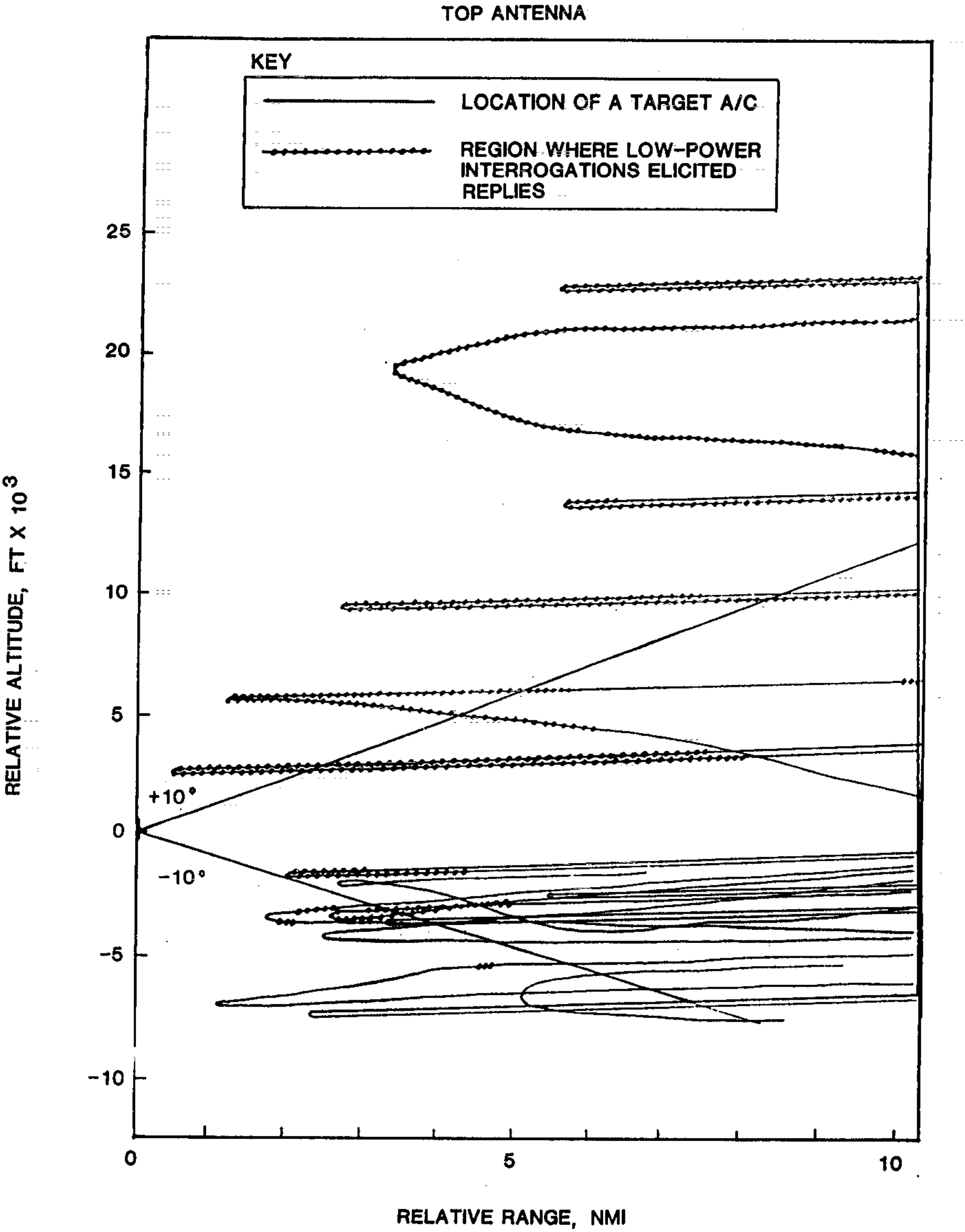


Fig. 4-6A. Antenna pattern filtering results, top antenna.

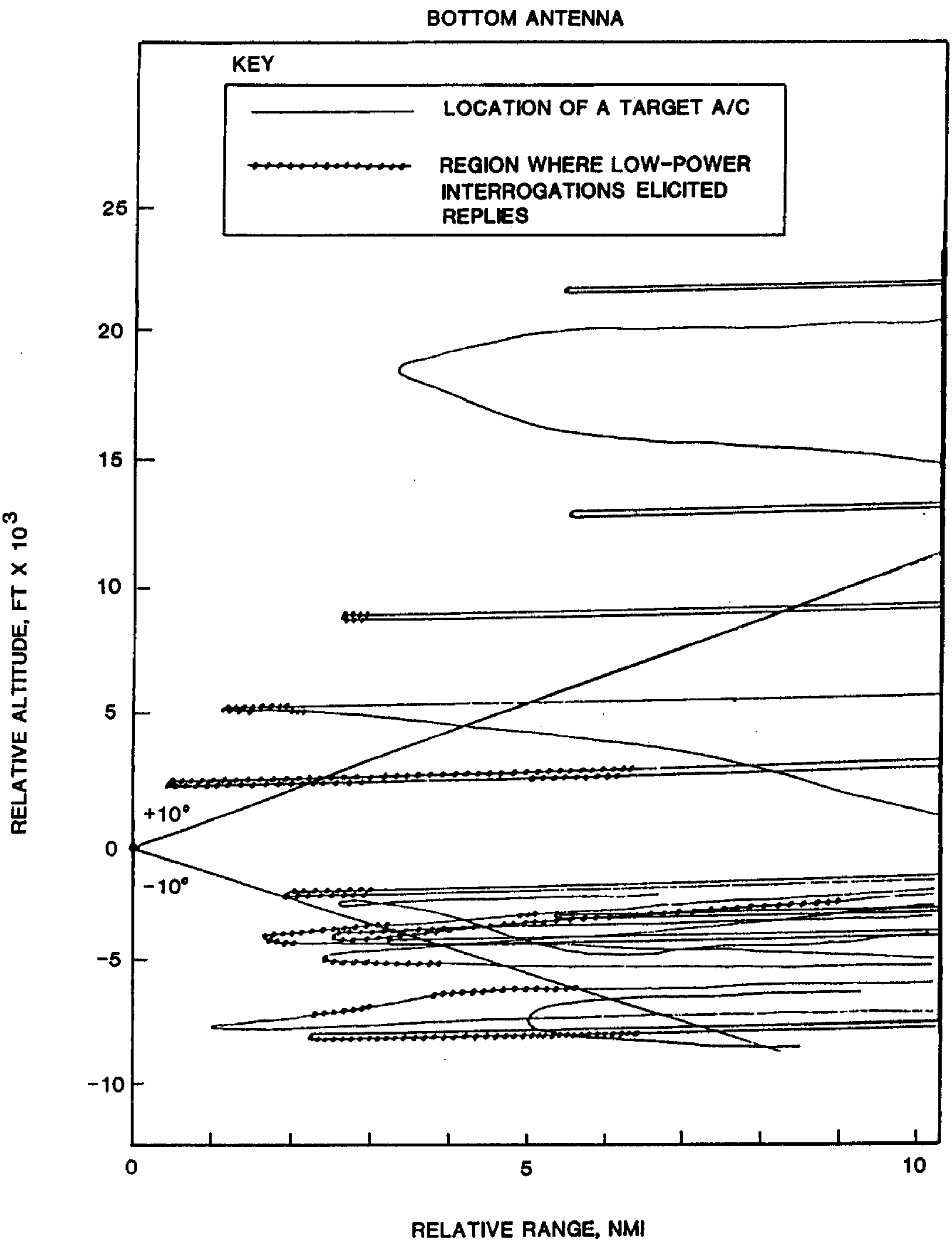


Fig. 4-6B. Antenna pattern filtering results, bottom antenna.

A comparison of Figs. 4-6A and -6B indicates the expected filtering effect when using the bottom AMF antenna. The results with the top AMF antenna (Fig. 4-6A) are indicative of the extended high-altitude coverage that would result from a top antenna installation on the TCAS I aircraft. Antenna pattern filtering would clearly be ineffective with diversity-equipped Mode S transponders. However, these transponders will normally be equipped for altitude reporting so that they can be handled by the next type of filter considered.

4.4 Altitude Code Filtering

The second way to filter off-altitude targets is to determine the code contained in the detected reply. This detection is more reliable if a top-mounted antenna is used since this improves the protection from code errors due to multipath.

Mode A replies are of no value since they contain no altitude data. However, ATCRBS replies are not uniquely labelled as Mode A or C. Some Mode A replies can be rejected by checking the code bits and rejecting those that contain illegal altitude codes. Illegal Mode C codes are those in which any of the following conditions are TRUE for the pulse positions indicated:

$$
\begin{aligned}
D_1 &= 1 \\
C_1C_2C_4 &= 000 \\
C_1C_2C_4 &= 101 \\
C_1C_2C_4 &= 111 \\
X &= 1
\end{aligned}
$$

(The reply pulse labelling for an ATCRBS reply is shown in Fig. 4-7.)

Rejecting these combinations will not eliminate all Mode A replies. Fortunately, all 1200 code replies will be discarded since their codes have all C pulse positions equal to zero. Further, the probability of a discrete Mode A code causing an altitude alert appears small and has not been observed in the data analyzed.

Mode S replies are uniquely labelled as containing identity or altitude code and therefore are well suited to altitude code filtering. The Mode S coding provides for error detection if replies are tracked.

The overlay of a ± 1000 foot altitude code filter on the antenna patterns of Fig. 4-5 is shown in Fig. 4-8. The acceptance volume compared to antenna pattern filtering is also shown. It is seen that additional alarm reduction occurs for all aircraft that report altitude when off-altitude codes are rejected, but the technique appears most useful when detecting the higher-power air carrier aircraft, which are all equipped for altitude reporting.

Altitude code filtering reduces the alert times for threats that are changing altitude. This protection could be restored by altitude tracking to the extent that reply-to-reply correlation can be done successfully.

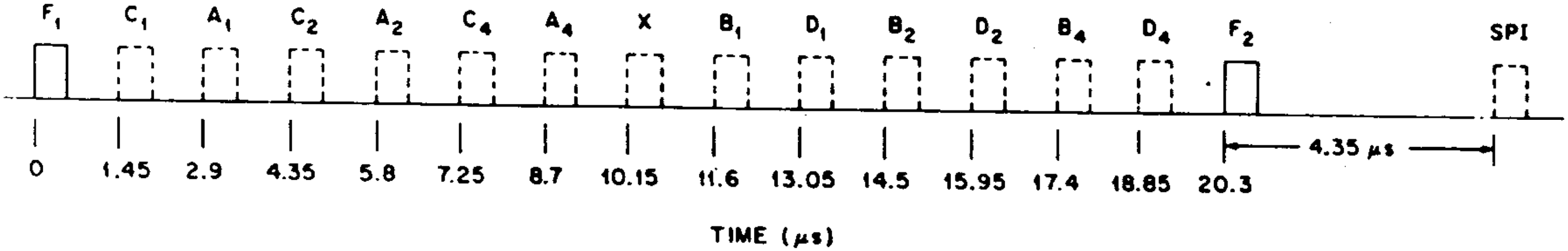
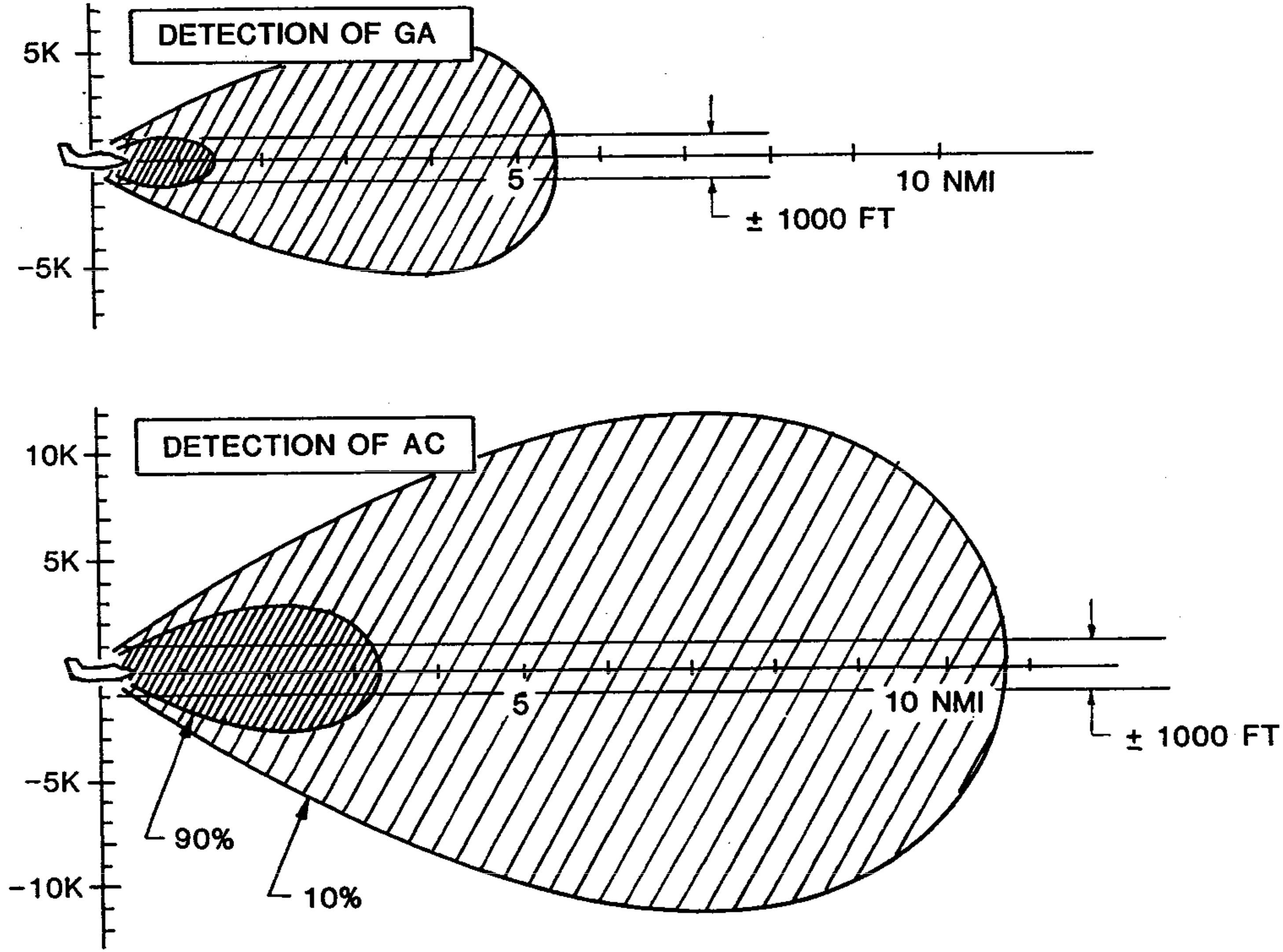


Fig. 4-7. ATCRBS reply pulse labelling.



ALTITUDE CODE FILTER DETECTION VOLUME COMPARED TO ANTENNA PATTERN FILTERING

± 1000 FT GA = 26 % AC = 12 %

Fig.4-8. Altitude code filtering.

4.5 Time-After-Interrogation

The principle used in time-after-interrogation filtering is shown in Fig. 4-9. A TCAS I aircraft (A) and a threat aircraft (B) are both illuminated by the beam of a ground interrogator. The ATCRBS interrogation arrives first at the TCAS I aircraft and a short time later at the threat aircraft. The reply generated by the threat aircraft is seen to arrive at the TCAS I aircraft in the interval following the TCAS I reply.

The fact that the TCAS I aircraft replies to the same interrogation as the threat aircraft limits the closest range from which replies can be received due to what can be called the "ATCRBS blind spot effect". An example is shown in Fig. 4-10. In this example both aircraft are at the same range from the ATCRBS interrogator and thus reply at the same time. The reply from the threat aircraft overlaps the reply from the TCAS I aircraft and thus cannot be detected.

The general geometry for the ATCRBS blind spot effect is shown in Fig. 4-11. Two envelopes are shown. The outer is the blind spot envelope for which the threat reply would overlap some portion of the TCAS I reply, the inner envelope is for the clear detection of only the F2 pulse of the threat reply. It is obvious that a pulse detection approach must be used if the blind spot envelope is to be kept small enough to allow detection of aircraft within 2 miles.

The outer envelope also gives an indication of how the acceptance volume changes relative to the location of the ATCRBS interrogator. If the listening window is set to accept pulses from aircraft up to 2 nmi farther away from the interrogator than the TCAS I aircraft, the acceptance volume increases as the threat range decreases with respect to the ATCRBS interrogator.

With one ATCRBS interrogator, this technique provides a useful reduction in acceptance volume compared to the power thresholding technique. When a second interrogator is considered, the effectiveness of the filter is seen to decrease as shown in Fig. 4-12. Note that the resultant blind spot for two interrogators is the intersection of the individual blind spots and hence is reduced compared to a single interrogator blind spot. The resultant acceptance volume, however, is the union of the acceptance volumes for each sensor and therefore is seen to increase.

The actual performance of the filter in a multi-interrogator environment is dependent on the range and azimuth from the TCAS I to the interrogators as well as interrogator beamwidth. However, with more than 3 or 4 interrogators, the time-after-interrogation filter appears to provide very little additional filtering compared to the power thresholding technique.

An example of this multi-interrogator effect is shown in Fig. 4-13 that compares the alert rate measured by the AMF at 8500 feet in the Boston area using only power thresholding, or power thresholding and time-after -interrogation filtering. For these measurements the time-after-interrogation acceptance window was set at 2 nmi. The figure shows nearly equal alert rates for either technique, a result expected in the high interrogator density of the Boston area.

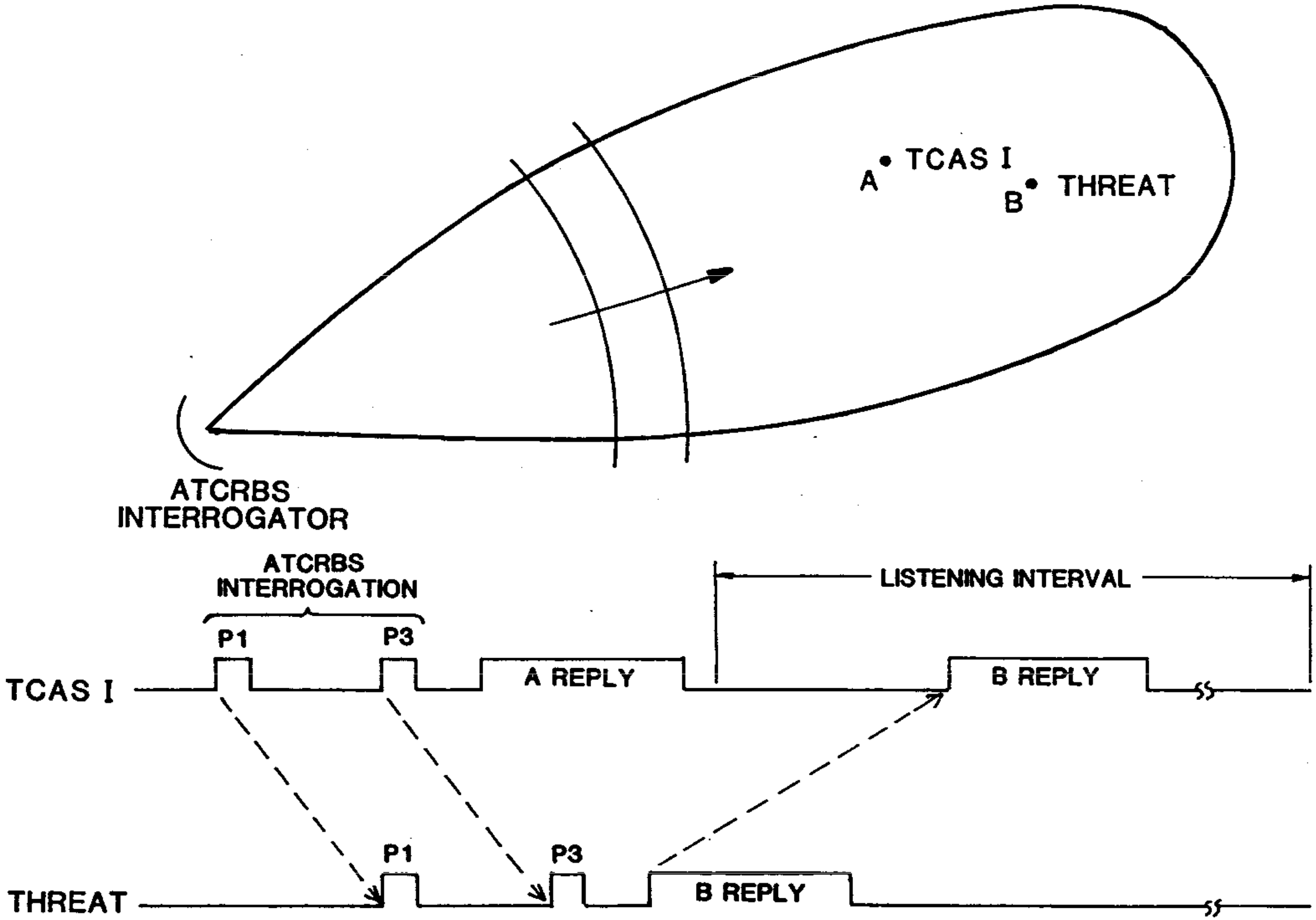


Fig. 4-9. Time-after-interrogation filtering.

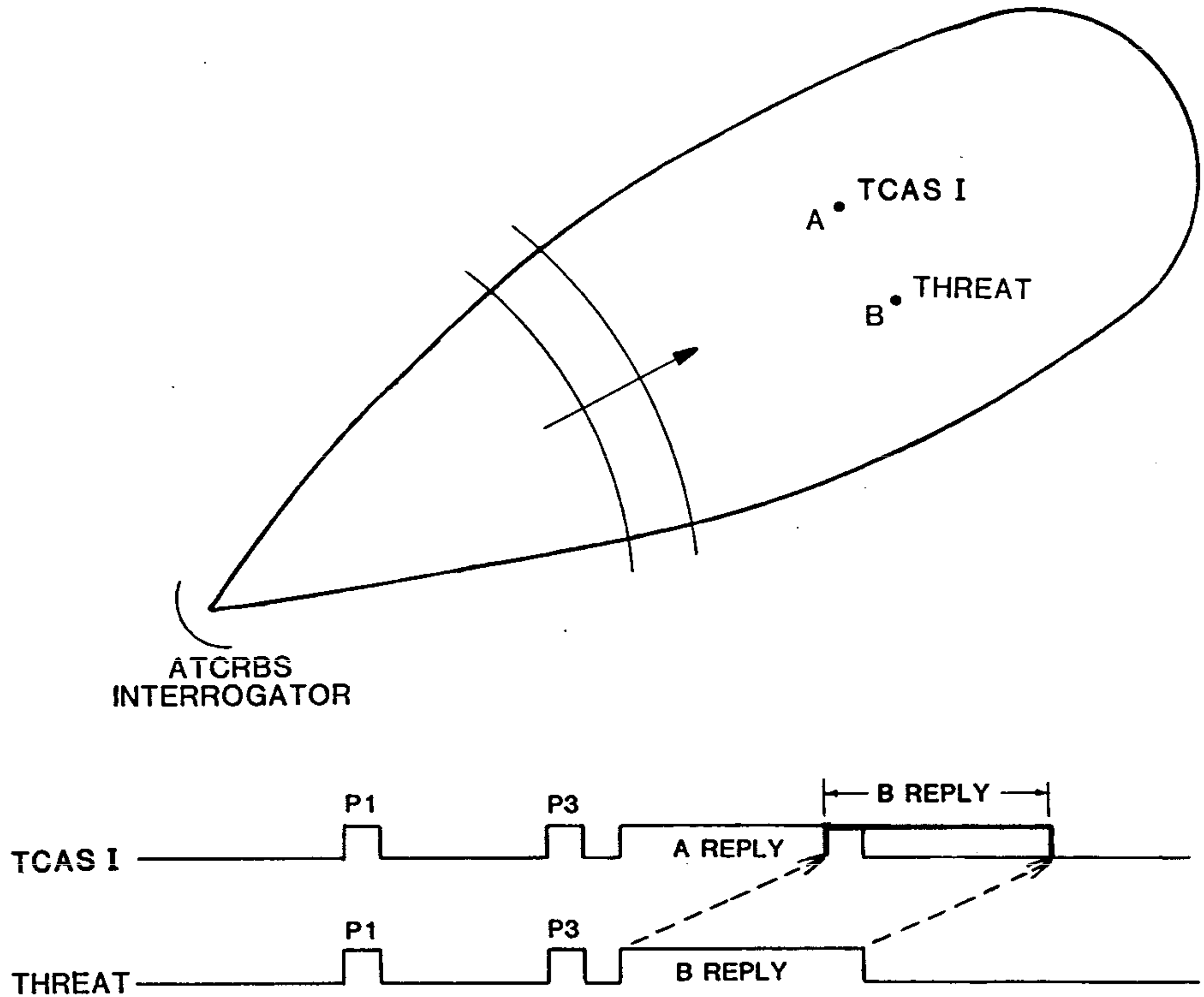


Fig. 4-10. Time-after-interrogation ATCRBS blind spot effect.

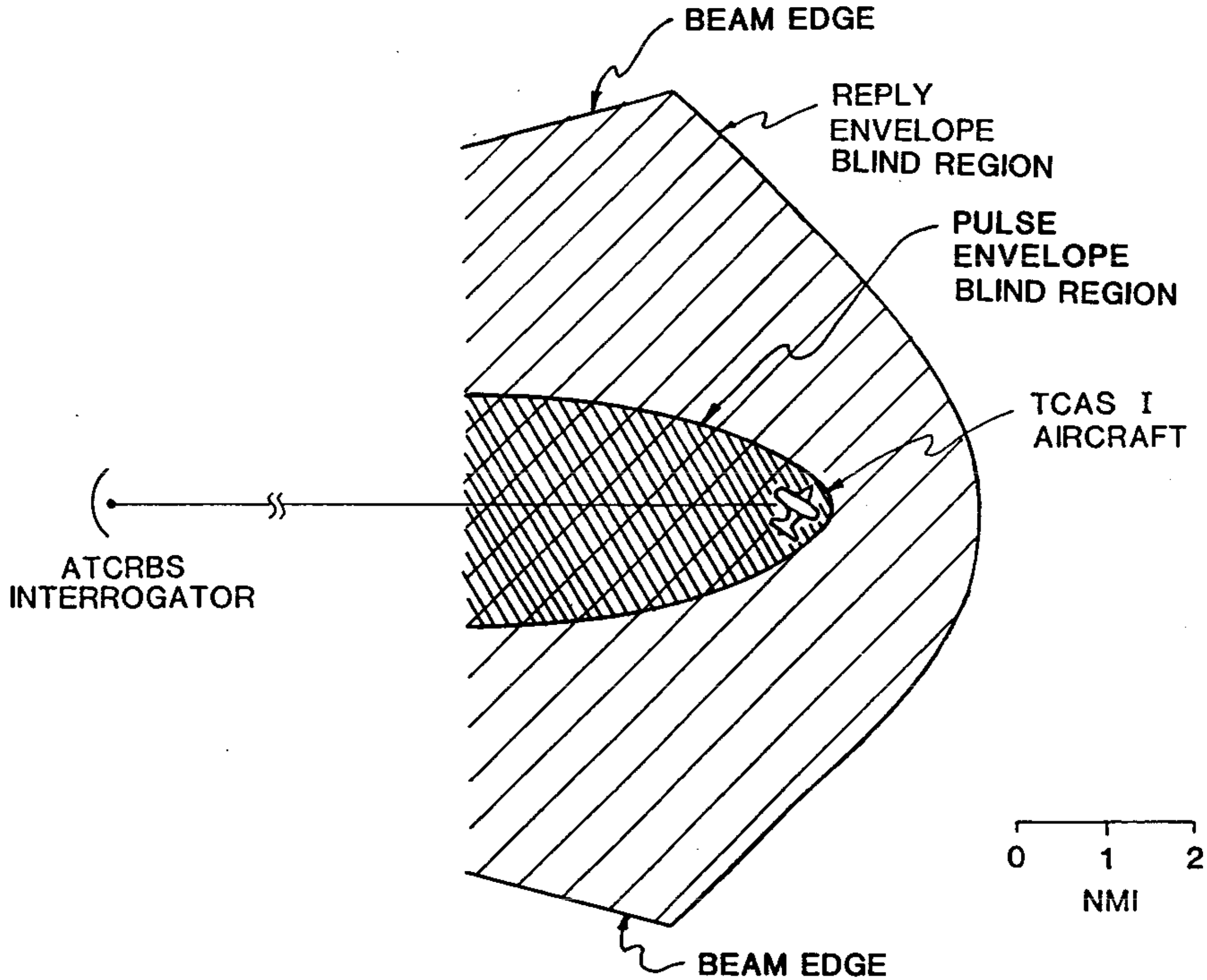


Fig. 4-11. Time-after-interrogation blind spot geometry.

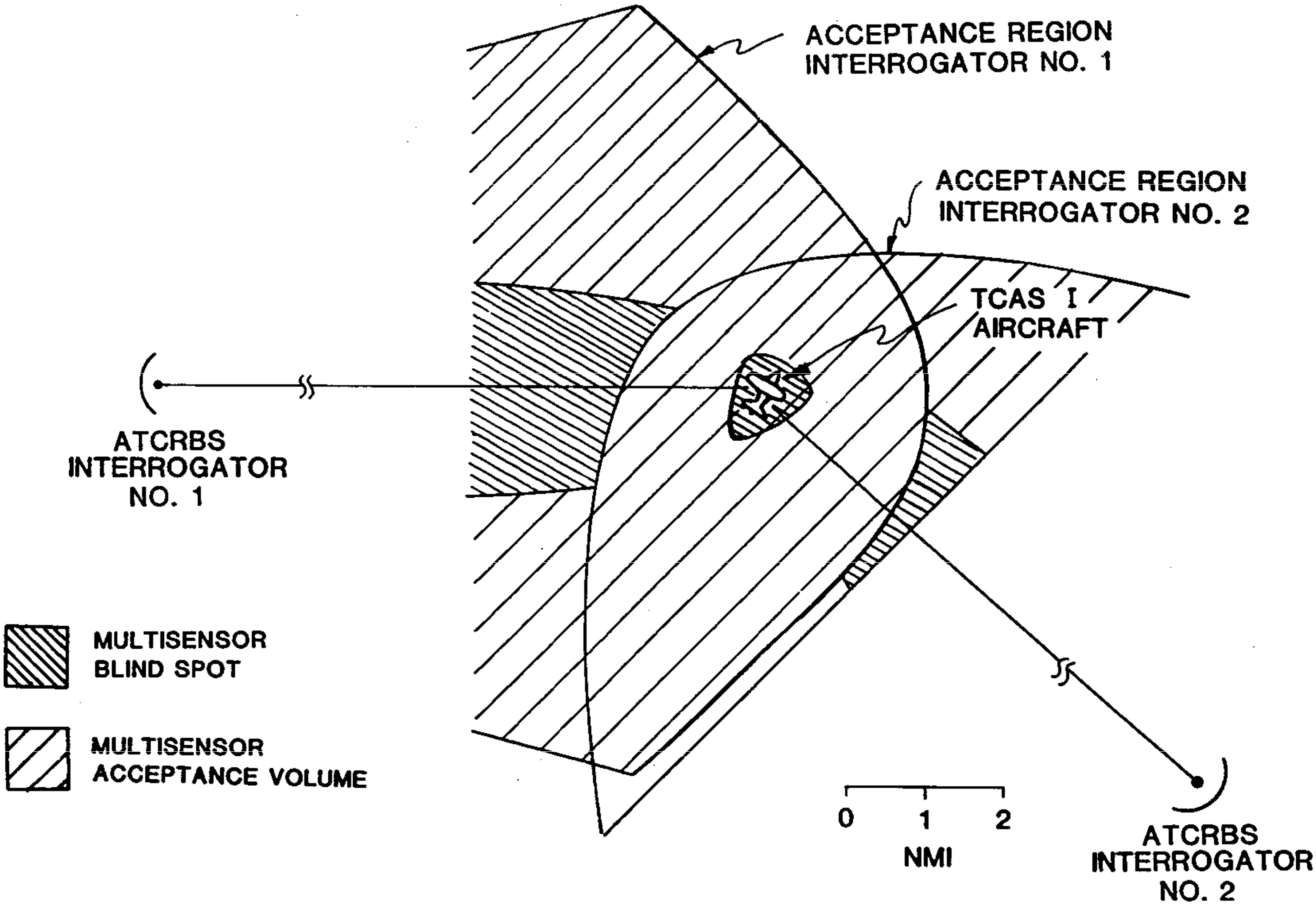


Fig. 4-12. Time-after-interrogation filter performance due to multiple interrogations.

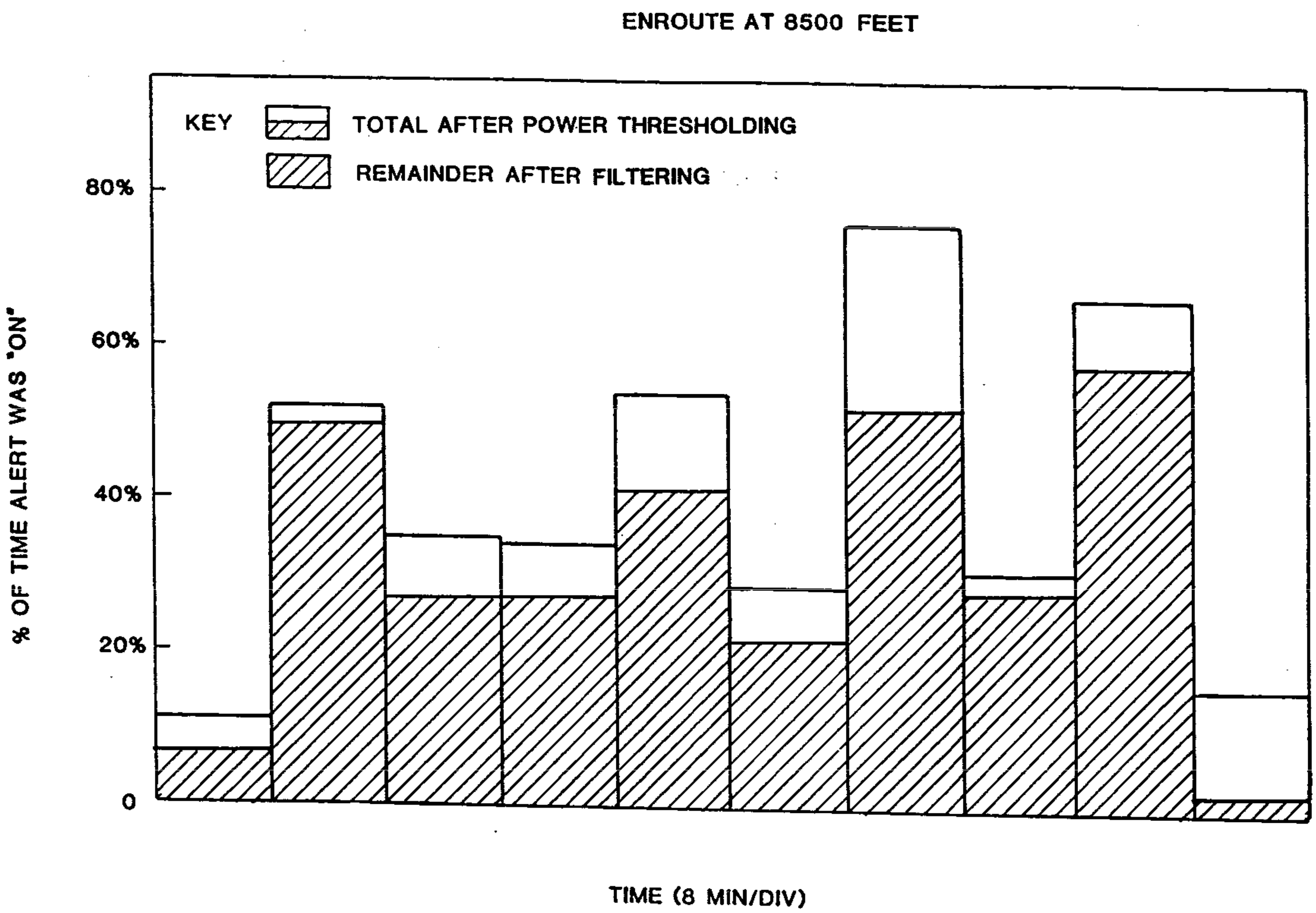


Fig. 4-13. Time-after-interrogation filtering performance - Boston area.

A serious false alarm mechanism for the technique occurs for ATCRBS targets at altitudes up to around 5000 ft. At these altitudes, backscatter multipath from the TCAS I transponder's reply may have sufficient amplitude to be detected in the listening window. An example of the effect is shown in Fig. 4-14. The figure gives backscatter signal strength for altitudes from 700 to 5000 feet over land as measured by the AMF on board a Cessna 421 aircraft. The subplot for each of the 10 measured altitudes is a scattergram of received pulse amplitude as a function of time over a period of 20 seconds. The pulse amplitude is quantized in 1-dB steps. Each dot indicates that one or more pulses were received at the indicated signal strength at some time during the listening interval following the TCAS I transponder reply. (The pulse times are irregularly spaced because they correspond to the reply times of the local transponder, which is in the coverage region of more than one interrogator.) A substantial number of pulse detections above the -57 dBm threshold are seen to occur up to 4500 feet with some pulses still detected at 5000 feet.

The time-after-interrogation technique applies also to the detection of a Mode S-equipped threat. The TCAS I equipment detects the Mode S interrogation and opens the listening window after the Mode S turn-around delay of 128 μsec as shown in Fig. 4-15. Since the TCAS I aircraft does not reply to the threat's discrete Mode S interrogation, there is no blind spot or backscatter multipath effect for Mode S replies.

Since Mode S transponders will normally be discretely interrogated by no more than two or three Mode S sensors, this filtering technique may remain effective even in areas of high Mode S sensor density.

4.6 Evaluation of Filter Criteria

Two of the techniques studied appear unsuitable for further consideration due to difficulties in handling ATCRBS replies.

Power Tracking - Reply correlation is needed to support power tracking. As indicated earlier, this correlation becomes very unreliable for non Mode C and non discrete code replies in higher density airspace where filtering is needed most.

Time-After-Interrogation - At low altitude, ATCRBS detections will be unreliable due to backscatter multipath. At high altitude the performance will be reduced due to the fact that the TCAS I will become visible to more interrogators. The filter will be least effective in an area with a high interrogator density. This is precisely the area where filtering is needed most since a high interrogator density usually implies a high traffic density.

The three remaining filter criteria (power level thresholding, antenna pattern and alitude code filtering) will therefore form the basis for the measurement of passive detector performance presented in Section 6.

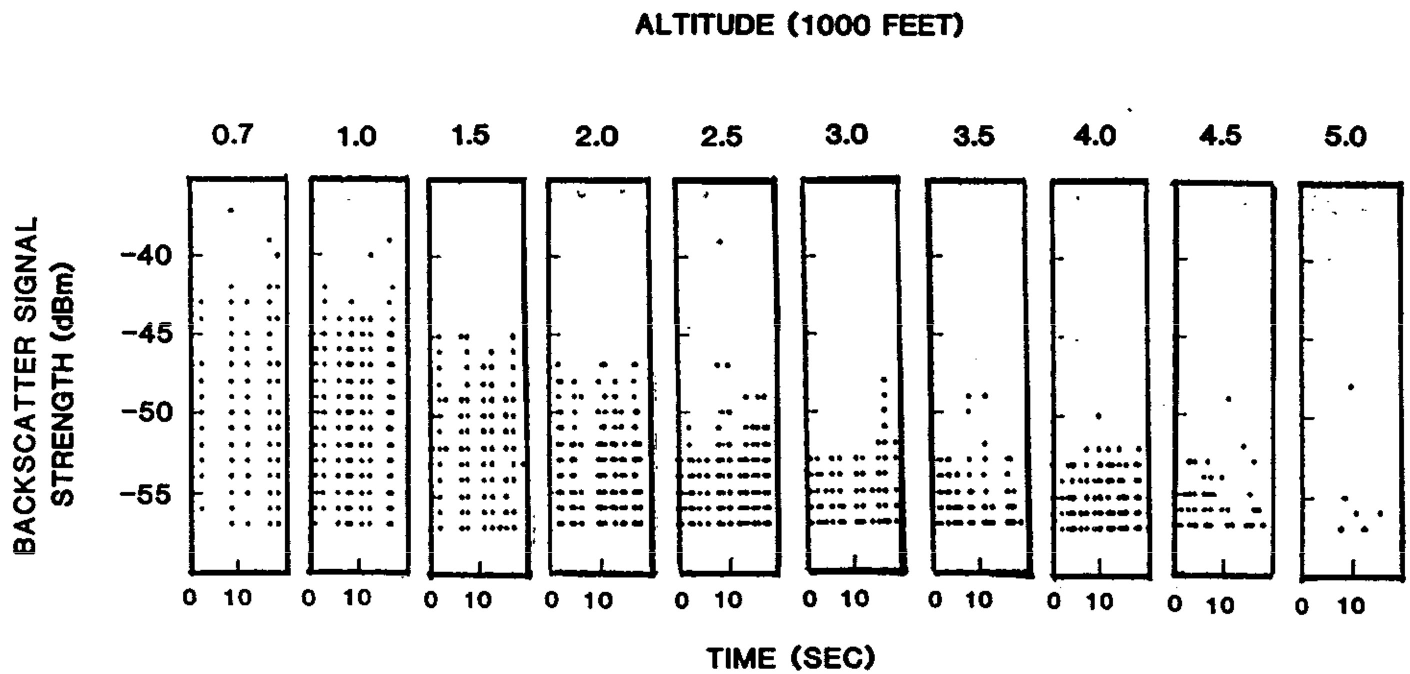


Fig. 4-14. 1090 MHz reply backscatter.

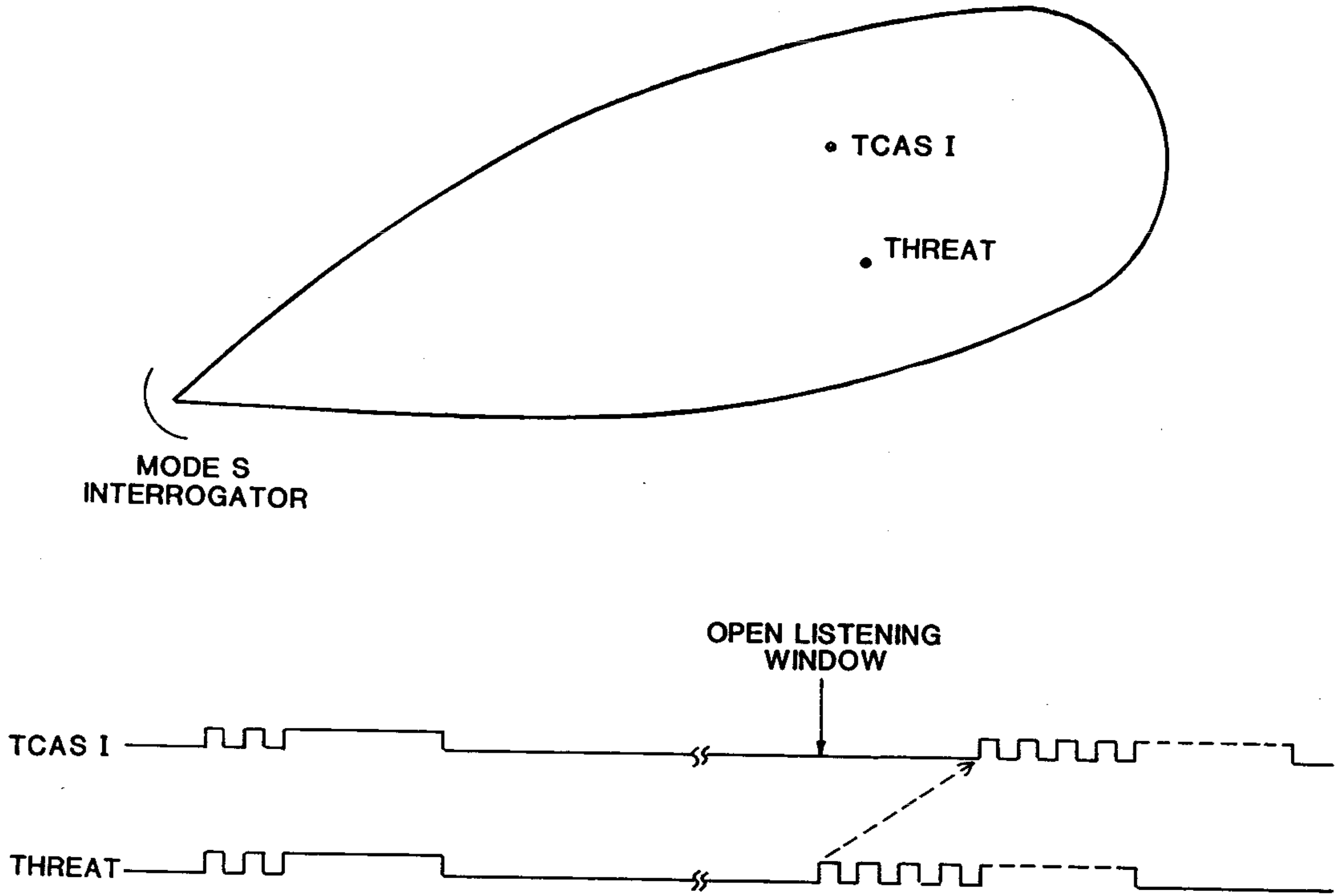


Fig. 4-15. Mode S Time-after-interrogation.

5.0 PASSIVE LISTENING ALTERNATIVES

5.1 Transponder Interface

Since the TCAS I transponder transmits and the passive detector receives on the same frequency, it is obvious that some coordination of activities is required. Either the passive detector must suppress the TCAS I transponder or the TCAS I transponder must suppress the passive detector.

The consequences of this interface choice are discussed in this section.

5.2 Sampled Listening

If the TCAS I detector suppresses the TCAS I transponder (called sampled listening), there is no ATCRBS blind spot or backscatter multipath effect. However, since the transponder is turned off when the detector listens, the sampling must be limited to avoid a decrease in transponder round reliability. The limit for decreased round-reliability due to TCAS II activity has been set at 2%. TCAS I should also meet this limit. Therefore, sampled listening will provide a very low probability of reply detection.

5.3 Gated or Continuous Listening

If the TCAS I transponder suppresses the passive detector (called gated or continuous listening), there is an ATCRBS blind spot and backscatter multipath effect. However, there is no restriction on listening time since detector listening has no effect on transponder round-reliability.

It should be noted that (as shown in Fig. 5-1) the ATCRBS blind spot effect for continuous listening is reduced compared to the geometry defined in the time-after-interrogation filter. This results from the fact that as the ATCRBS interrogator beam scans there will generally be interrogations to which the threat transponder replies and the TCAS I transponder does not. The blind spot is therefore reduced to a radial wedge from the interrogator. The width of this wedge is dependent on the relative reply run lengths of the two transponders.

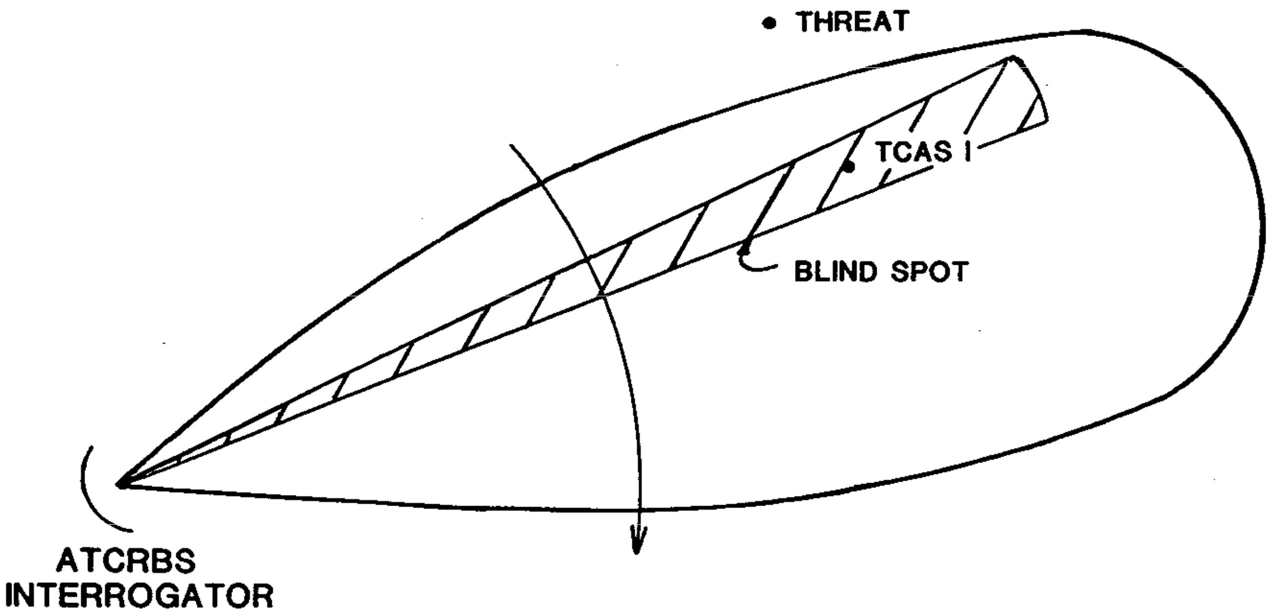


Fig. 5-1. Continuous listening - ATCRBS blind spot effect.

6.0 CANDIDATE PASSIVE DETECTOR

6.1 Characteristics

The results of Sections 3 and 4 indicate that the most capable candidate for a simple TCAS I passive detector would have the following features:

1. Continuous listening except during own transponder replies.

2. Received power thresholding with a nominal sensitivity of -57 dBm.

3. Antenna pattern filtering or altitude code filtering. If the latter is used it should (1) reject replies outside a nominal ± 1000 foot band, (2) reject replies with invalid altitude codes, and (3) accept replies with empty Mode C brackets.

It does not appear feasible to use both antenna pattern and altitude code filtering in a passive detector with a single antenna. The bottom-mounted antenna location required for antenna pattern filtering will lead to frequent multipath-induced bit errors in the detected Mode C code. Bit errors of this type will cause the detected code to report the wrong altitude or (more likely) convert the altitude code into an illegal pattern. In either case the rejection of these corrupted replies will lead to a missed alarm. Since altitude code filtering offers higher performance than antenna pattern filtering, the code filter (and hence a top-mounted antenna) will be used in the candidate passive detector.

In order to allow the pilot to adapt the detector to local conditions, it may be necessary to provide for pilot control of the nominal sensitivity and altitude filtering settings.

Experience with passive detection has indicated a high alarm rate if an alert is triggered on every accepted reply. False brackets are frequently synthesized by pulses of closely-spaced ATCRBS replies. It is therefore desirable to set a minimum threshold on the number of replies per second that must be received to trigger an alert. Since a terminal sensor elicits approximately 12-16 replies per beam dwell and may use a mode interlace of AAC, the highest fixed threshold that can be used when there is only a single interrogator is 4 Mode C replies in a one-second interval. Note that this reduces the probability of detecting aircraft that are near the edge of the blind spot.

In higher interrogator densities false alarm performance would be enhanced through the use of a variable threshold. This threshold can be established by monitoring the rate of Mode C interrogations received at own transponder and adjusting the detection threshold to be compatible with the received rate. This latter technique may be necessary in order to accommodate the low reply rates that will be elicited by a Mode S sensor using ATCRBS monopulse techniques (two Mode C interrogations per 3 dB beamwidth).

If altitude code filtering is used, phantom elimination logic in the ATCRBS reply detector [Ref. 6] may be used as an alternative to the adaptive threshold. The phantom eliminator should detect and suppress the synthesized empty brackets and thus permit the use of a fixed threshold of 2 replies in a one second interval, which is compatible with Mode S interrogation rates.

Once an alert has been triggered, the alert device should stay on for some minimum period to provide the pilot the opportunity to observe it, and to avoid continuous retriggering in the case where the replies are being elicited by a single interrogator and thus are only received once per scan. An alert time-out of 5 seconds has been selected to be compatible with a terminal antenna scan time. A longer time-out, required to maintain an alert on the slower enroute scan time, was not used since it would prolong the effect of any false alarms.

A possible realization of a detector having these capabilities is shown in Fig. 6-1. A 1090 MHz receiver converts the RF transponder reply pulses into video pulses. These are fed to an amplitude comparator which is used to establish a detection threshold. This comparator can also be used to desensitize the unit each time the transponder on the TCAS-I aircraft transmits so the detector does not alarm on its own transponder replies. Since time-after-interrogation filtering is not used, the detector should remain suppressed for an additional 40 microseconds to avoid triggering the detector on reflections from own transponder replies. Pulses that pass the detection threshold are then fed to ATCRBS and Mode S reply decoders which look for a valid pulse sequence and, if a valid sequence is detected, extract the altitude code from the reply. The altitude code is then compared to own aircraft's code. If the reply altitude is outside of a predetermined altitude band or if it is an invalid altitude code, the reply is rejected. If the reply is in the band, or if the reply comes from an ATCRBS transponder which is not equipped with an encoding altimeter, the reply is accepted and an alarm is triggered if the detection threshold is exceeded.

The ALARM LOGIC controls the triggering and duration of the alarm. The pilot control of sensitivity feeds back to control both the detection threshold sensitivity and the width of the altitude acceptance band.

It is also possible to include a direction finding capability in the passive transponder detector. This requires some sort of array of antenna elements on the aircraft. One possible realization of a passive transponder detector with direction finding capability is shown in Fig. 6-2.

A four-element array is mounted on the top of the aircraft. Behind the array is a passive RF combiner network consisting of stripline hybrid junctions. The output of the hybrid network is a pair of RF lines, labeled Sum (Σ) and Difference (Δ). These lines feed a pair of phase-matched receivers. The IF outputs of the receivers are fed to a phase comparator to

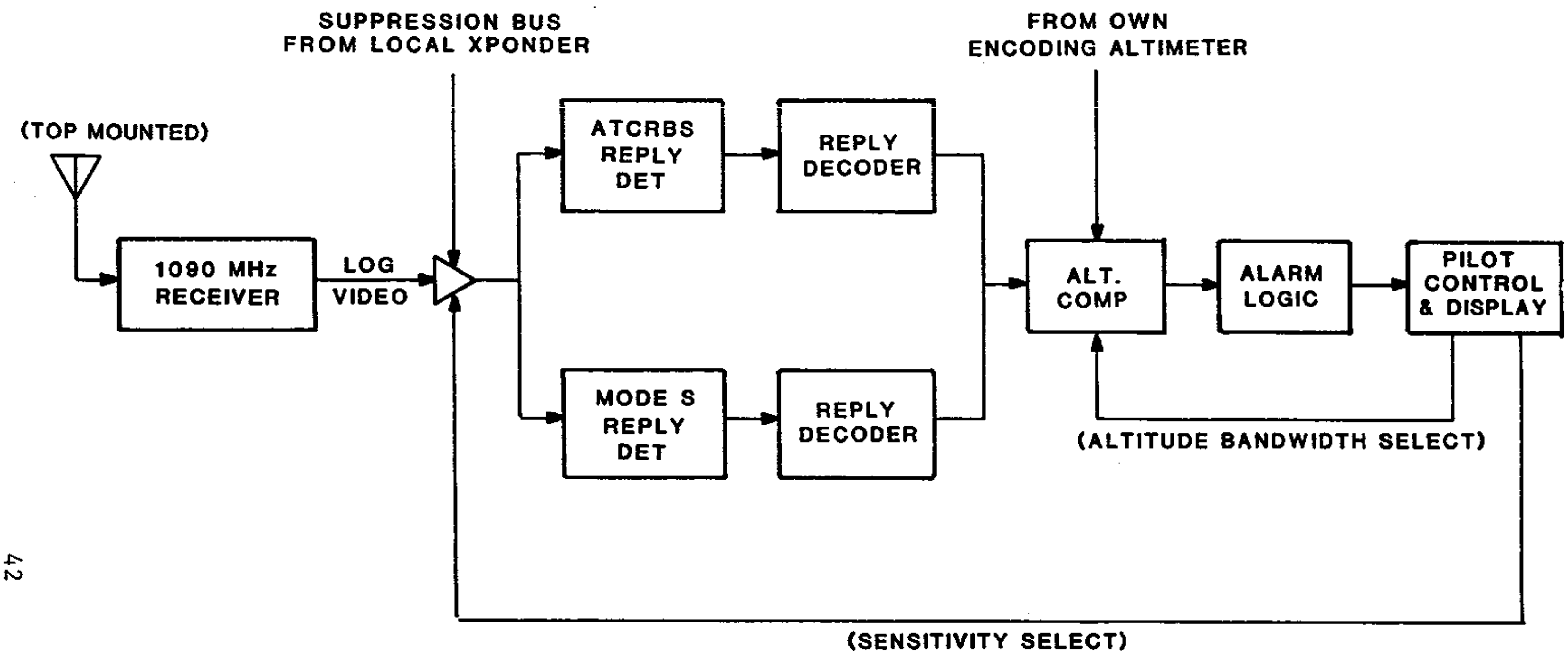


Fig. 6-1. TCAS I passive transponder detector possible realization.

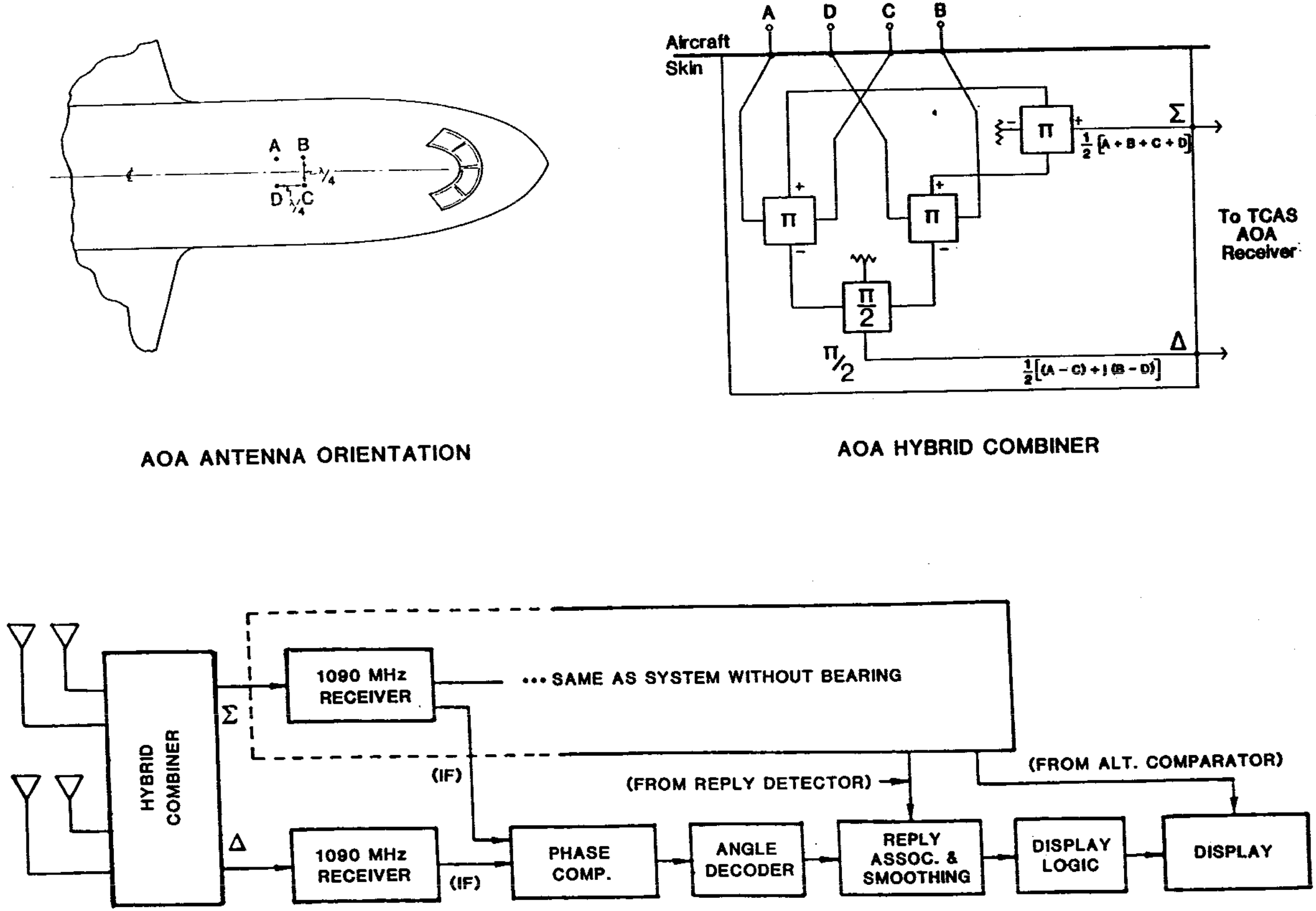


Fig. 6-2. TCAS I passive transponder detector with bearing, possible realization.

determine the angle of the received pulse. The sum-channel receiver has a video output which drives a set of circuits equivalent to those shown in the block diagram for the detector without bearing. Thus everything outside of the upper box (partially dashed) of the block diagram in Fig. 6-2 is required for direction finding.

The analog phase signal obtained from the phase comparator is converted to a digital signal in the ANGLE DECODER. This processor includes an analog-to-digital converter and a look-up table for calibrating the phase signal. The angle estimates for individual pulses are associated with replies and averaged to obtain a reply angle estimate. This estimate is then converted into a form appropriate for driving the display.

Angle-of-arrival processing to provide bearing for the TCAS II crosslink advisory is under development by Lincoln Laboratory. Results of this development (which will be published in the near future) are directly applicable to TCAS I for measurements made at the reply level.

Limited experience during flight testing has indicated that angle-of-arrival information would greatly increase the utility of the passive detector.

6.2 Passive Detection Performance Measurements

Two sets of in-flight performance measurements on targets-of-opportunity were analyzed in order to quantify the performance of the candidate passive detector.

1. Active/Passive - The AMF was configured to interleave active interrogations with passive listening once per second. The active data provided the true target information needed to evaluate passive detection acquisition range, warning time and false alarm probability. The passive data alone was used to measure the alert rate in the Boston area.

2. Passive Only - The TEU was programmed to operate as a real-time TCAS I equipment. TEU data was used to measure alert rates on two flights from Boston to Washington.

6.3 Active/Passive Measurements

AMF data on targets-of-opportunity was collected at 8500 feet in the Boston area. The equipment and data analysis parameters emulated the characteristics of the candidate passive detector described in paragraph 6.1. The following results are based on an analysis of one-hour and twenty minutes of AMF data.

6.3.1 Data Description

An example of the type of data collected with the AMF is shown in Figs. 6-3 through 6-7. Each figure shows data for approximately a five-minute segment of the AMF flight.

Active Traffic Environment (Fig. 6-3) - Mode C pulse trains received in response to the active interrogations are plotted as a function of range. Interrogations were made at nominal TCAS power (250 watts at the antenna) but receiver sensitivity was set at -57 dBm to obtain the benefit of power thresholding for the passive measurements. Four aircraft are shown in the figure. Aircraft A, B, and D are Mode C equipped as evidenced by the data pulses between the received brackets. Aircraft B and D are within the ± 1000 foot acceptance window for altitude code filtering. Aircraft C is reporting empty brackets and is therefore a non-Mode C aircraft.

Passive Non-Mode C Replies (Fig. 6-4) - The number of passively received non-Mode C replies per second is shown for each second of the flight segment. A comparison of Figs. 6-3 and 6-4 shows that these non-Mode C replies were received from aircraft C. The time extent of the passively received replies is somewhat longer than for the active case due to the fact that active measurements were made on the basis of a single reply while passive measurements were made using many replies, due to the high interrogation rates in the Boston area.

Passive In-Band Mode C Replies (Fig. 6-5) - The data are presented in the same format as the previous figure. The passively received in-band Mode C replies are seen to be received from aircraft B and D of Fig. 6-3.

Passive Out-of-Band Replies (Fig. 6-6) - The out-of-band Mode C replies plotted are seen to be received from aircraft A and B of Fig. 6-3.

Passive Illegal Mode C Replies (Fig. 6-7) - Mode A and garbled Mode C replies from all four aircraft contribute to the high reply rates shown in the figure.

Figures 6-4 through 6-7 demonstrate the effectiveness of altitude code filtering in sorting replies into the four altitude code categories.

6.3.2 Performance Results

The 80 minutes of AMF data yielded approximately 2000 aircraft-seconds of data on 35 different aircraft. In order to increase the sample size, calculations of acquisition range and warning time were performed on the total set of aircraft regardless of the results of altitude filtering. The following performance measurements were calculated from this set of data.

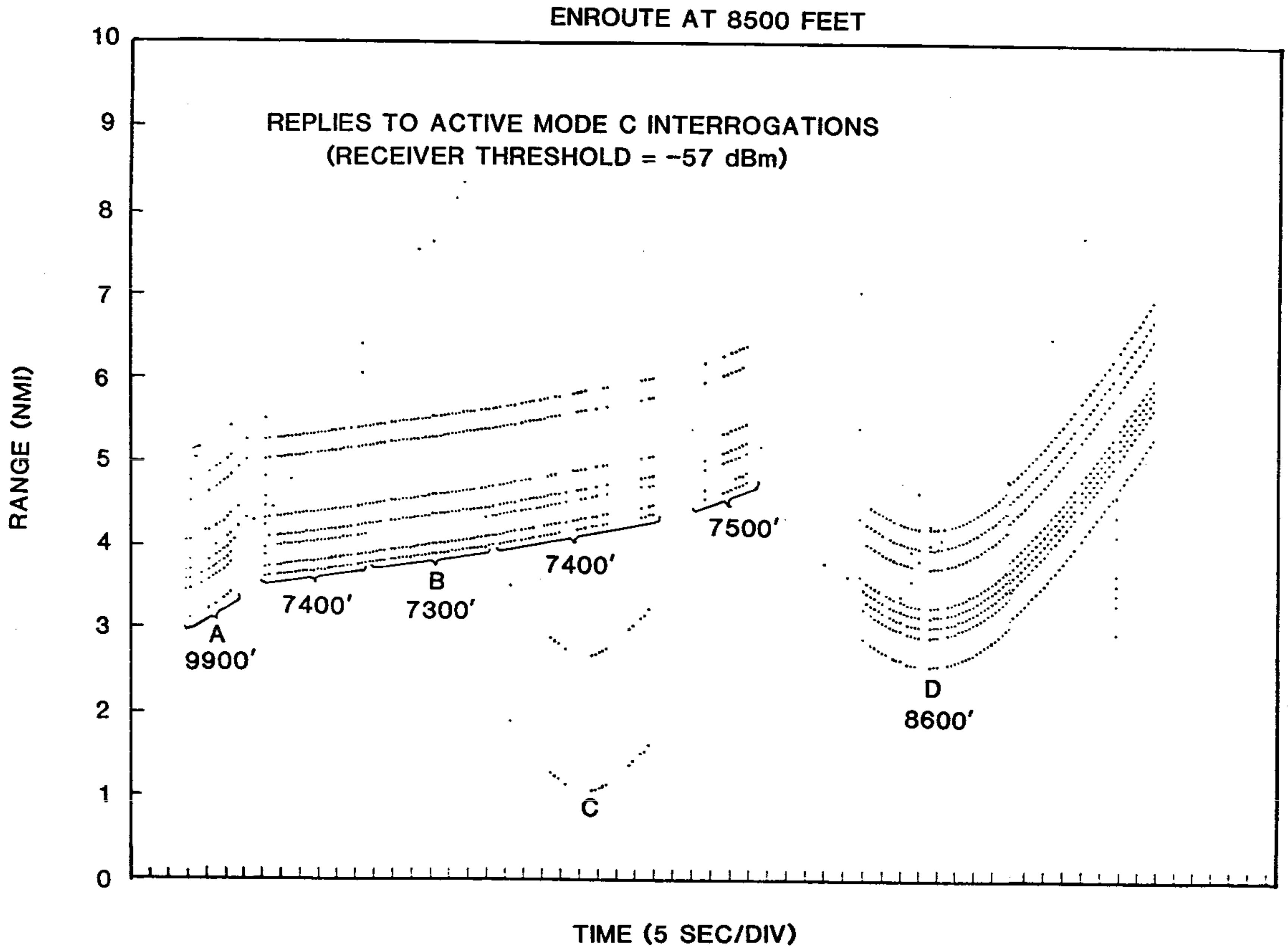


Fig. 6-3. Example of traffic environment for passive measurements.

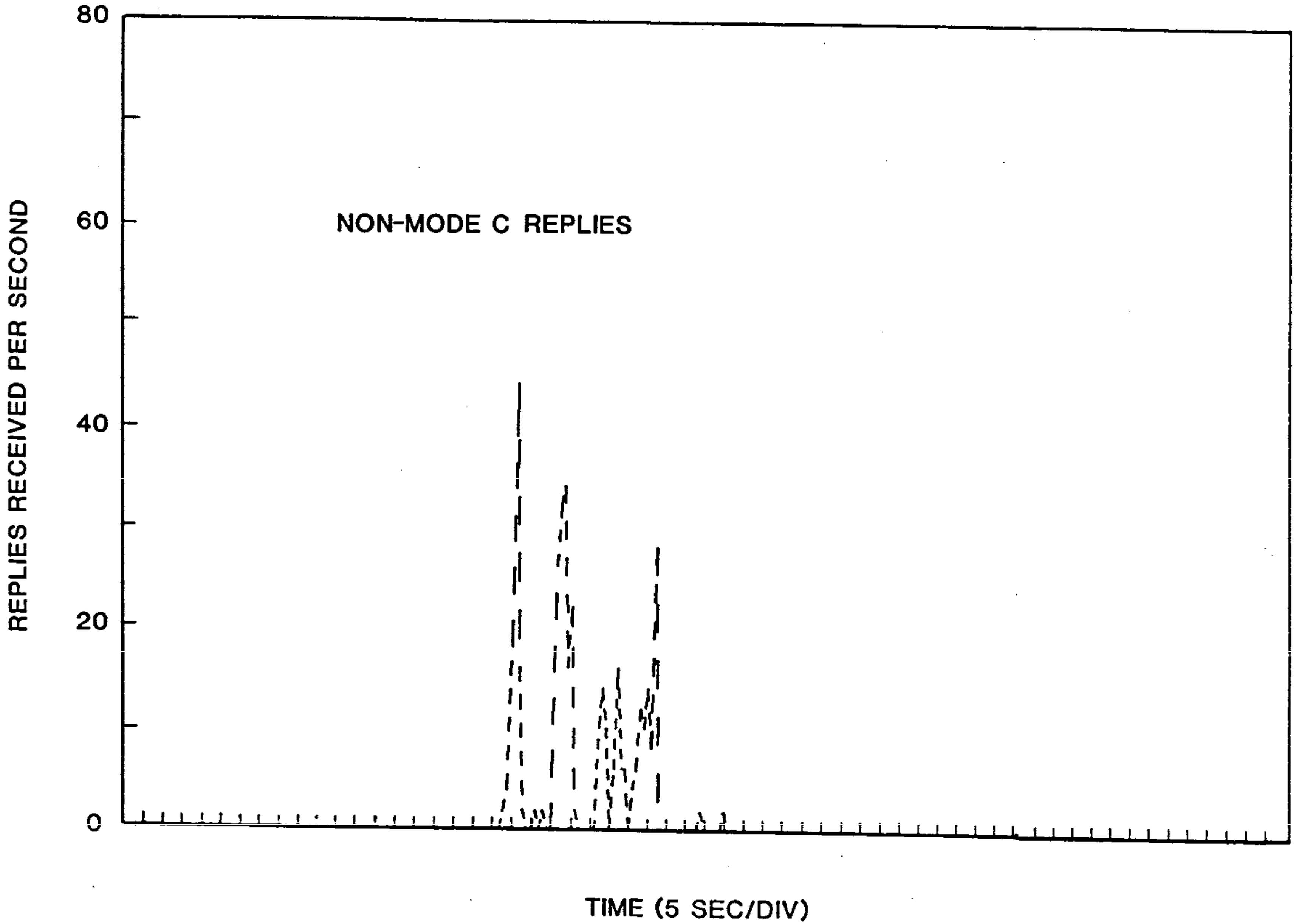


Fig. 6-4. Passive non-Mode C replies for traffic of Fig. 6-3.

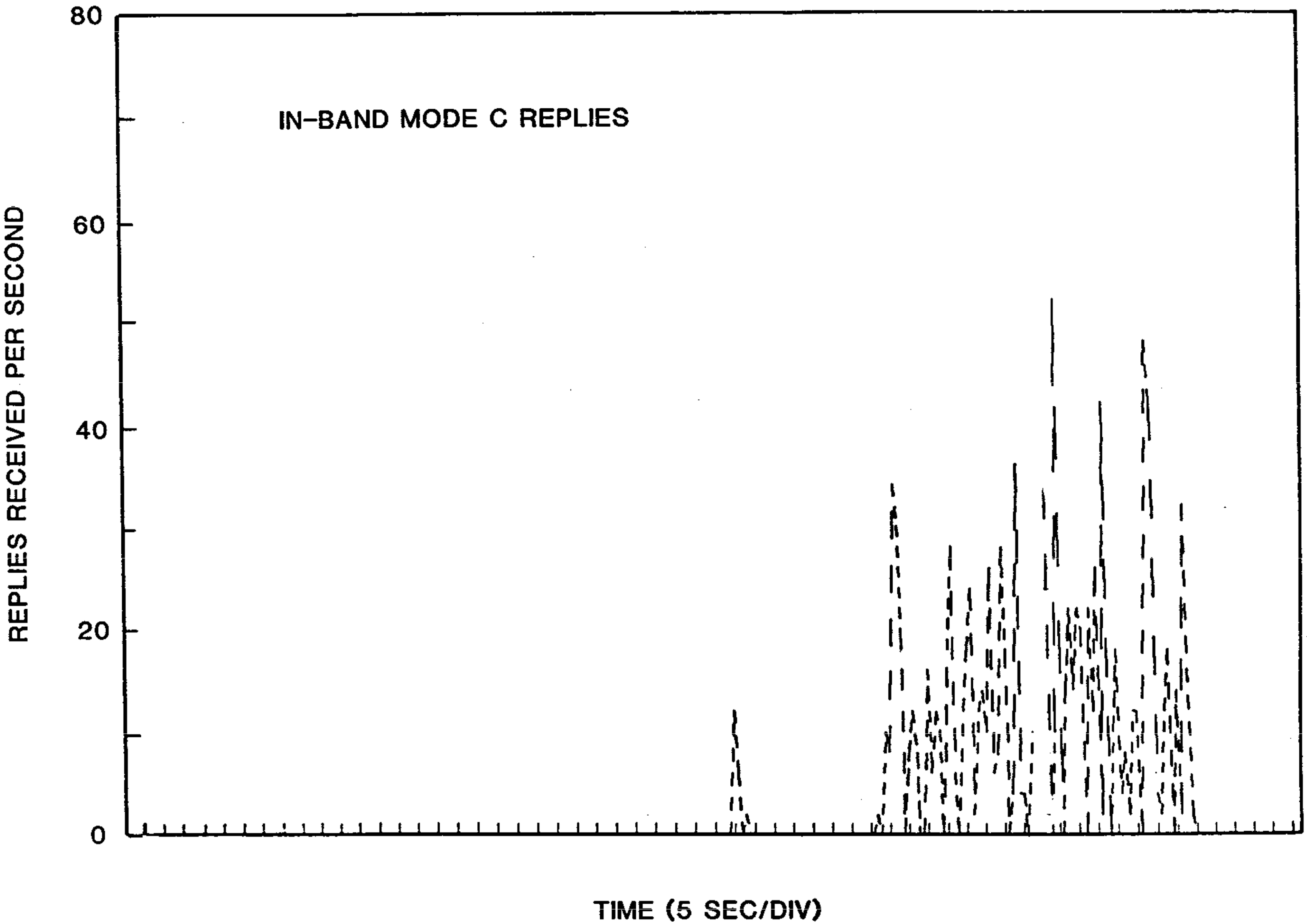


Fig. 6-5. Passive in-band Mode C replies for traffic of Fig. 6-3.

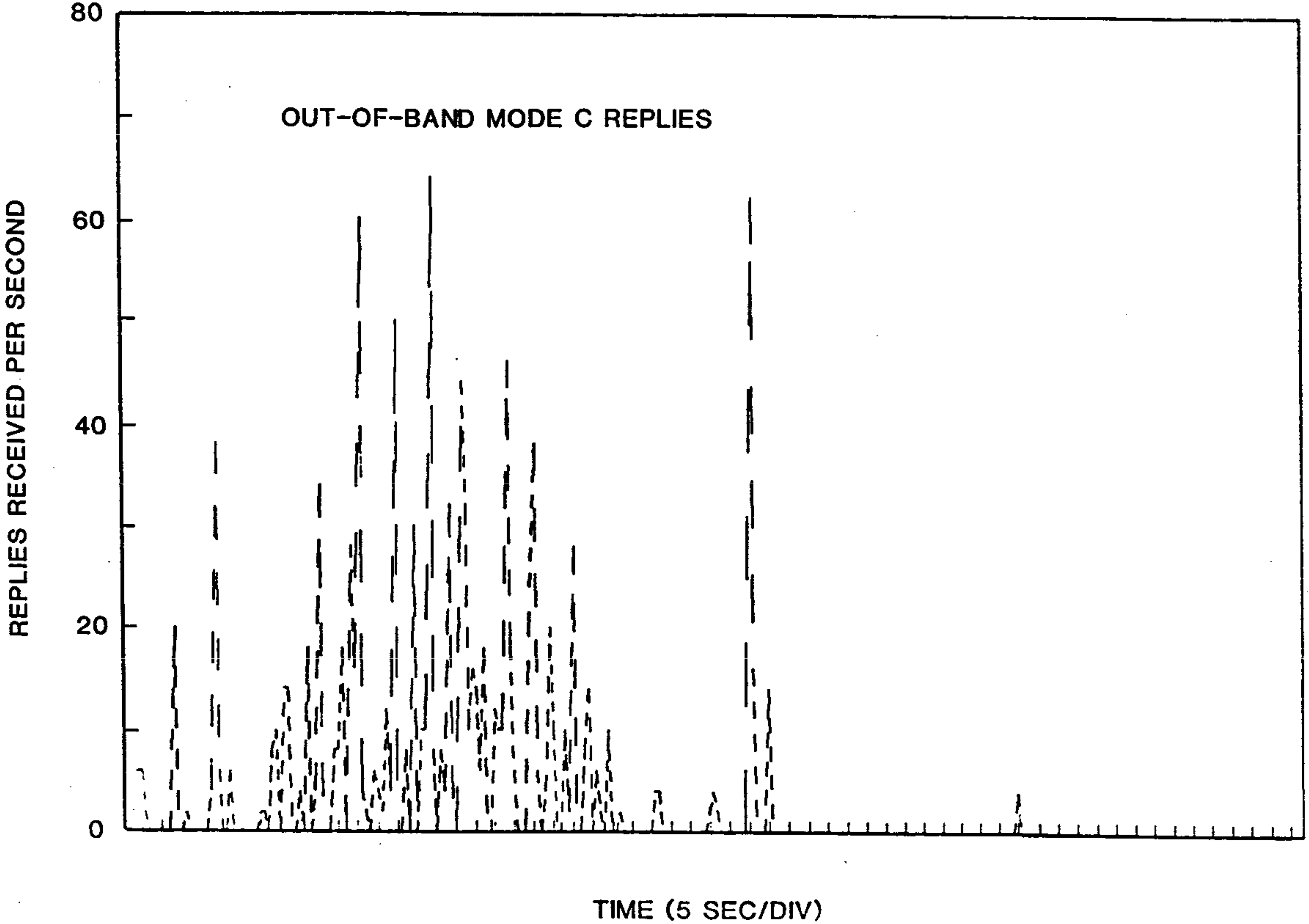


Fig. 6-6. Passive out-of-band Mode C replies for the traffic of Fig. 6-3.

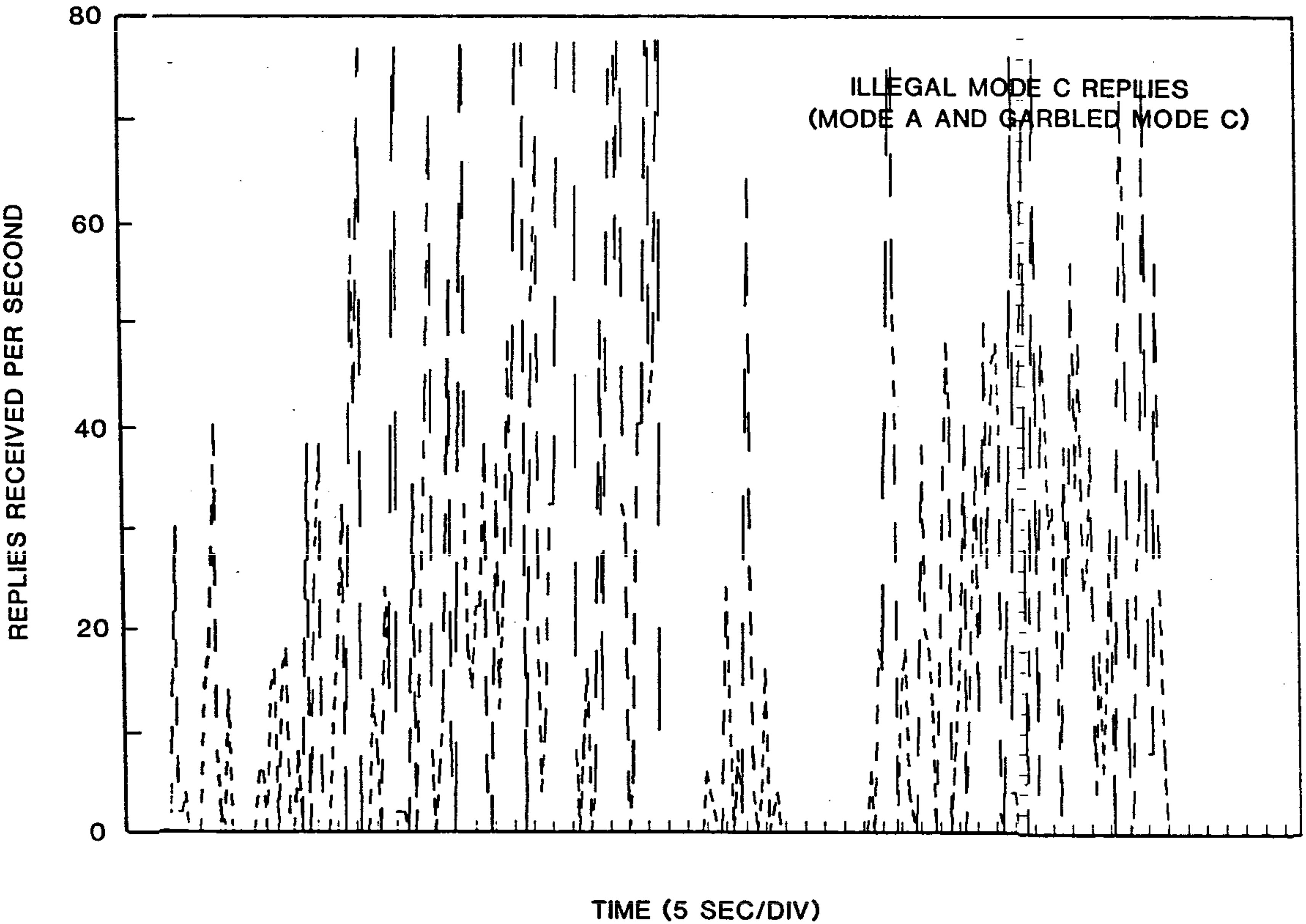


Fig. 6-7. Passive illegal Mode C replies for the traffic of Fig. 6-3.

Acquisition Range - The range at which the passive reply count initially exceeded four replies/second was determined for each of the 35 acquired aircraft. The results are plotted as an acquisition range histogram in Fig. 6-8. While the number of data points is not sufficient to completely validate the -57 dBm threshold, the range of acquisition is consistent with the calculated performance. Only two of the aircraft in the sample were non-Mode C equipped and are presumably general aviation aircraft. Note that these two aircraft were detected at close range (as predicted by the link calculations).

Warning Time - The time from initial acquisition until the time of closest approach was noted for the 10 aircraft in the sample whose minimum range was 3 nmi or less, since this would be the subset of most immediate interest to the pilot of the TCAS I aircraft. The results are presented in Table 6-1. Half of the aircraft were detected with very short warning times.

Probability of Surveillance False Alarm - Alerts due to Mode C detections were very reliable. Only 5% of the alert time could not be correlated with active traffic measurements. A much higher false alarm rate was noted for non-Mode C alerts. With a threshold of 4 replies/second, 53% of the alert time caused by non-Mode C detections could not be correlated with traffic detected by active measurement. Examination of the data indicated that a higher threshold could be used due to the high interrogation rates in the Boston area. The non-Mode C data were reprocessed using a detection threshold of 8 replies per second. This reduced the false alarm probability to 21% at a loss of only 4% of true alarm alert time as shown in Table 6-2. This demonstrates the utility of the adaptive threshold in controlling non-Mode C false alarms. It is likely that similar results would have been obtained with phantom elimination.

Alert Rate - Figure 6-9 shows the alert rate performance for the 80 minute flight in terms of the percent of time the alert was "on" for each of 10, 8-minute intervals. Results are shown with and without altitude code filtering and demonstrate the effectiveness of code filtering in reducing alerts in environments with high Mode C equipage.

6.4 Passive Only Measurements

Passive data on targets-of-opportunity were conducted on two flights from Boston to Washington. The TEU was configured to have the same characteristics as the candidate passive detector, except that: (1) a Mode C acceptance band of ± 1500 feet was used, and (2) the antenna was bottom-mounted.

Results for the two flights are shown in Figs. 6-10 and 6-11. Note the variablity of the alert rate over New York and the consistently high alert rate observed as descent was made into Washington National Airport.

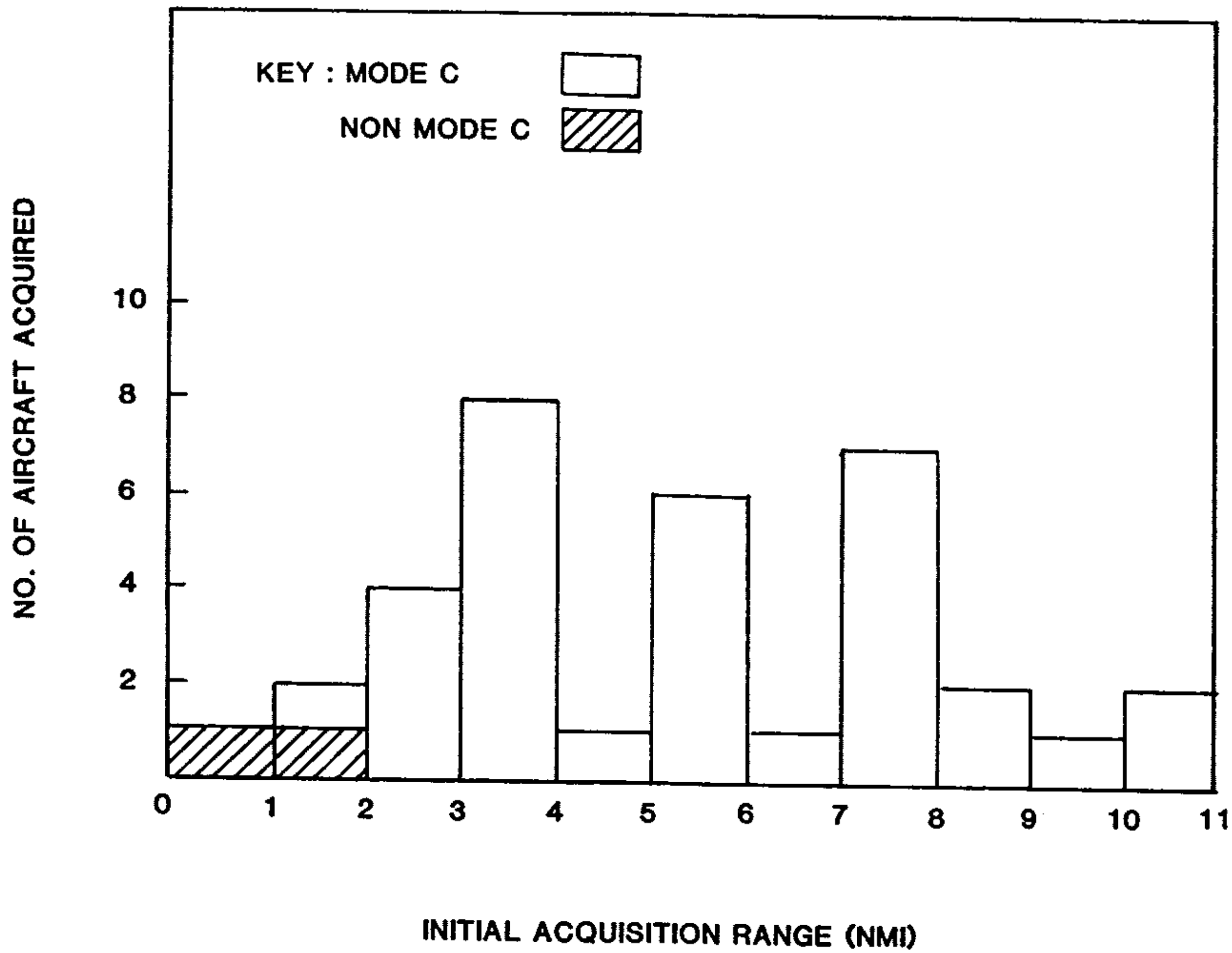


Fig. 6-8. Power thresholding acquisition performance.

TABLE 6-1.

PASSIVE DETECTION WARNING TIME.

(TARGET WITH MINIMUM RANGE ≤ 3 NMI)

ACQUISITION RANGE (NMI)	MINIMUM RANGE (NMI)	WARNING TIME * (SEC)
5.5	1.5	30
2.7	2.5	5
3.0	3.0	0
2.8	2.8	0
3.2	3.0	5
7.5	0.7	125
0.5	0.5	0
2.0	1.6	20
1.8	1.1	20
2.8	2.6	20

* Time of Alert Prior to Time of Closest Approach

TABLE 6-2.

NON-MODE C FALSE ALARM PERFORMANCE

	ALERTS WITH FIXED THRESHOLD (4 REPLIES/SEC)		ALERTS WITH ADAPTIVE THRESHOLD (8 REPLIES/SEC)	
PERIOD	TOTAL (SEC)*	TRUE (SEC)**	TOTAL (SEC)*	TRUE (SEC)**
1	5	0	0	0
2	5	0	0	0
3	0	0	0	0
4	0	0	0	0
5	55	0	22	0
6	25	0	10	0
7	20	0	0	0
8	100	93	91	88
9	75	40	40	40
10	0	0	0	0
TOTAL	285	133	163	128
FALSE	53%		21%	

* Duration of Non MODE C Alert

** Number of seconds Non MODE C aircraft was actually within 3 nmi as indicated by active measurements.

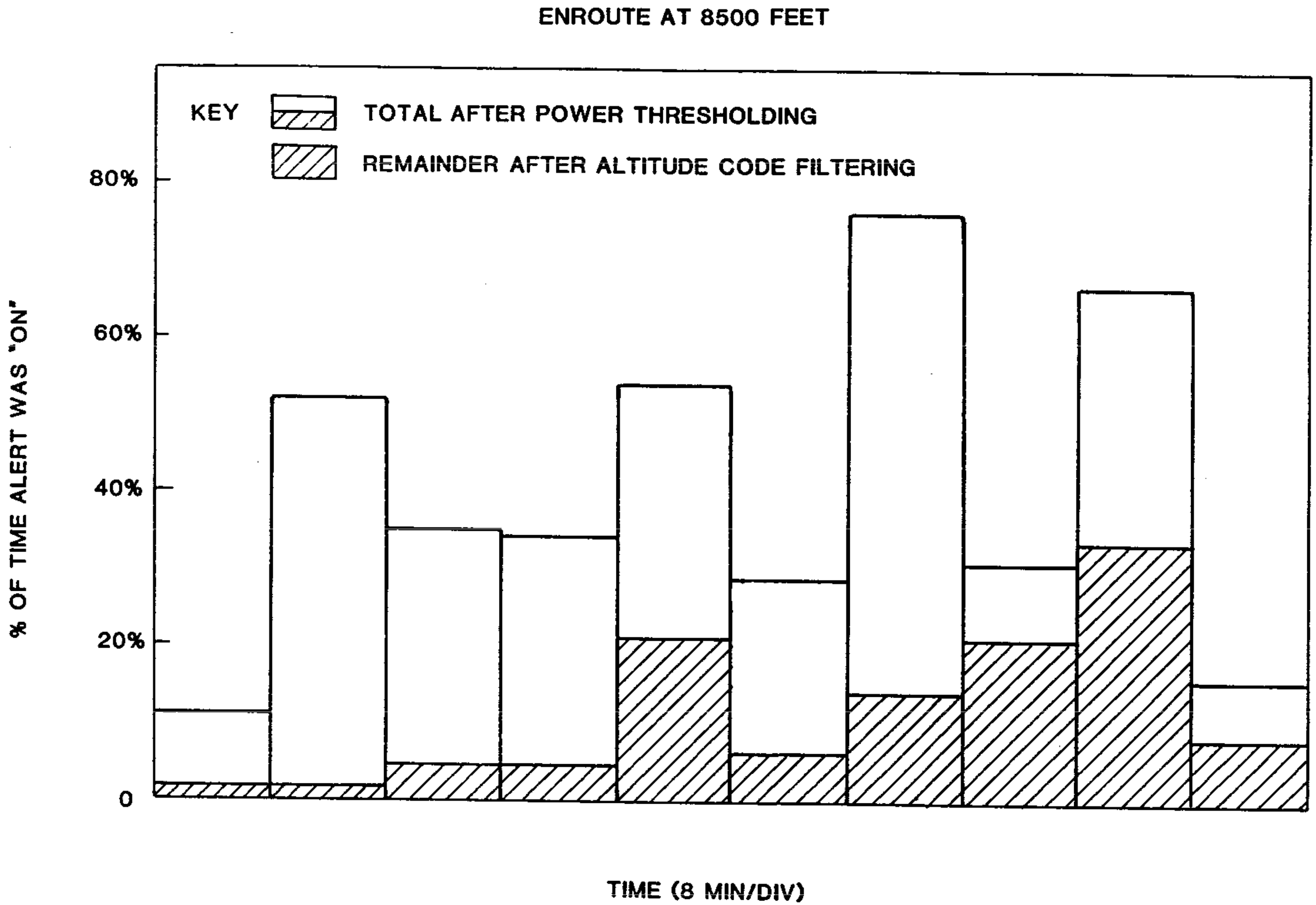


Fig. 6-9. Altitude code filtering performance - Boston area.

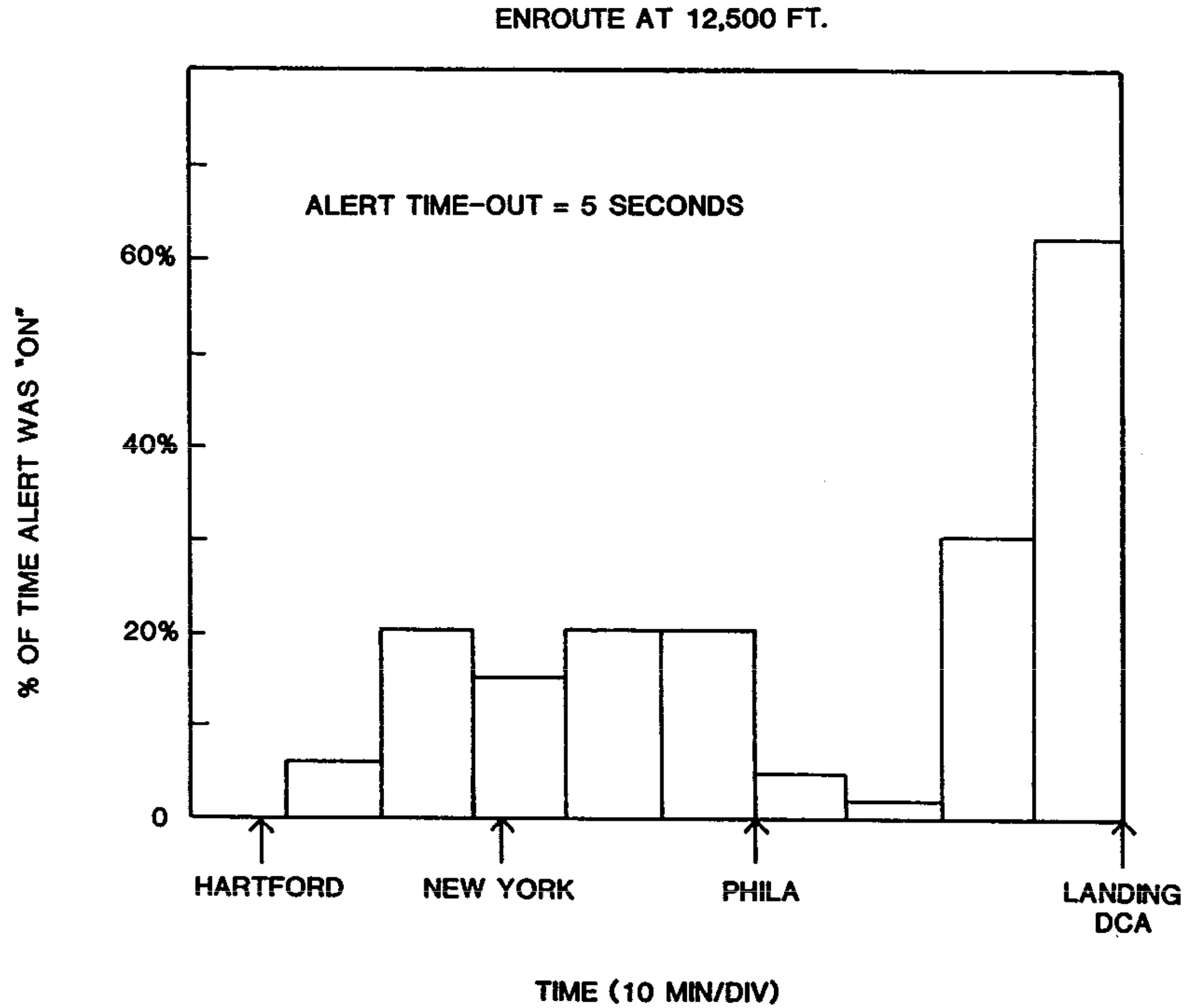


Fig. 6-10. Passive detector alert rate: Boston to Washington at 12,500 ft.

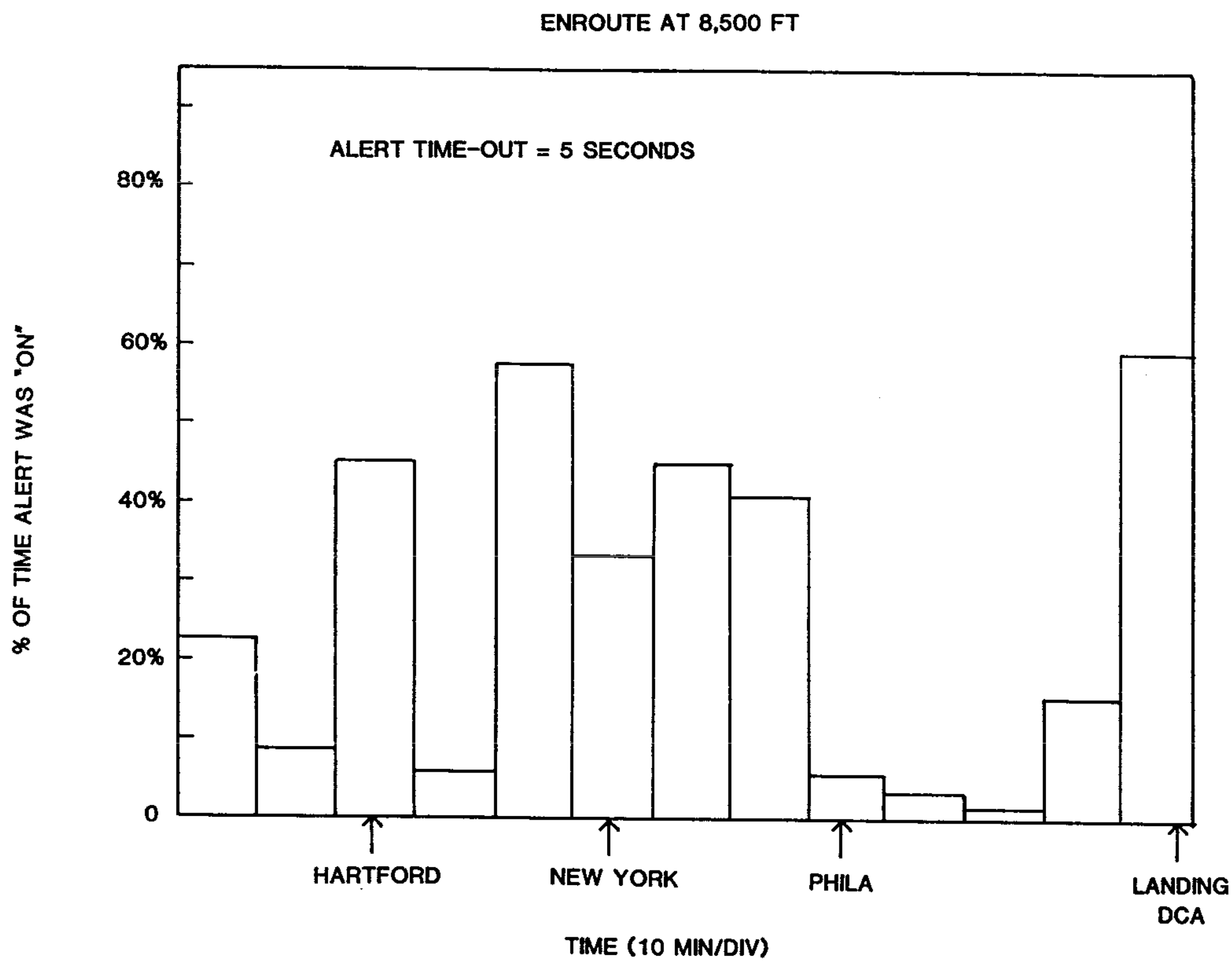


Fig. 6-11. Passive detector alert rate: Boston to Washington at 8,500 ft.

7.0 LOW POWER ACTIVE DETECTOR

An interference analysis was conducted to explore the possibility of using an active proximity detector for TCAS I. The purpose of the analysis was to determine the highest power that could be used by TCAS I aircraft in the highest density environments and still cause no significant effect on the interference environment. The calculation was based upon the Los Angeles high density model [Ref. 7], assumed that one-half of all aircraft were active TCAS I equipped, and allowed the total interference effect of TCAS I operation to be 10% of the interference caused by TCAS operation.

The results of the analysis (presented in Appendix C) indicate that an active TCAS I could use a time-power product equivalent to one 5-watt Mode C interrogation per second. Thus, a 10-watt Mode C interrogation could be used every two seconds, etc.

7.1 Calculated Performance

A link analysis was performed for a low power TCAS I interrogator in order to estimate the possible utility of this technique. This analysis, presented in Appendix D, also includes the performance of a 4-watt Mode C interrogation once per second. A power of 4-watts was included in the link analysis since measured data at that power level were already available. This in fact represents the transmitted power of the lowest level of the four-level whisper/shout sequence used in the original omni-directional TCAS design.

The calculated performance is shown in Table 7-1. Performance out to the range of principal interest for visual acquisition (about 2 nmi) is seen to be adequate. The table also shows the improved detection performance if a scan time (i.e., the time between interrogations) of 2 seconds (10 watts) or 4 seconds (20 watts) were used.

7.2 Measured Performance

AMF data for a flight from Boston to New York and return were analyzed in order to obtain measurements of performance of a low power active TCAS I in an actual in-flight environment. Attention was focused on the enroute portion of the flight, at 8000 feet southbound and 9000 feet northbound. A total of 70 minutes of flight was examined, which provided data on 16 aircraft targets-of-opportunity.

Four-level whisper/shout surveillance data from both top and bottom antennas were used to establish range/altitude truth. Replies from just the lowest level (4 watt) interrogation from the top antenna were examined to identify the portions of each flight path during which low power interrogations were successful. The top antenna was selected for this purpose since experience has shown that it is less affected by ground-bounce multipath than the bottom antenna. Figures 7-1 and 7-2 give results separately for each leg of the flight.

TABLE 7-1.

CALCULATED VALUES OF TRACKING PROBABILITY
FOR A LOW POWER TCAS I DETECTOR

Range	Interrogator Power (at antenna)			
(nmi)	4 watts	5 watts	10 watts	20 watts
1	0.90	0.93	0.97	0.99
2	0.67	0.72	0.84	0.93
3	0.47	0.53	0.69	0.83
4	0.33	0.38	0.56	0.72

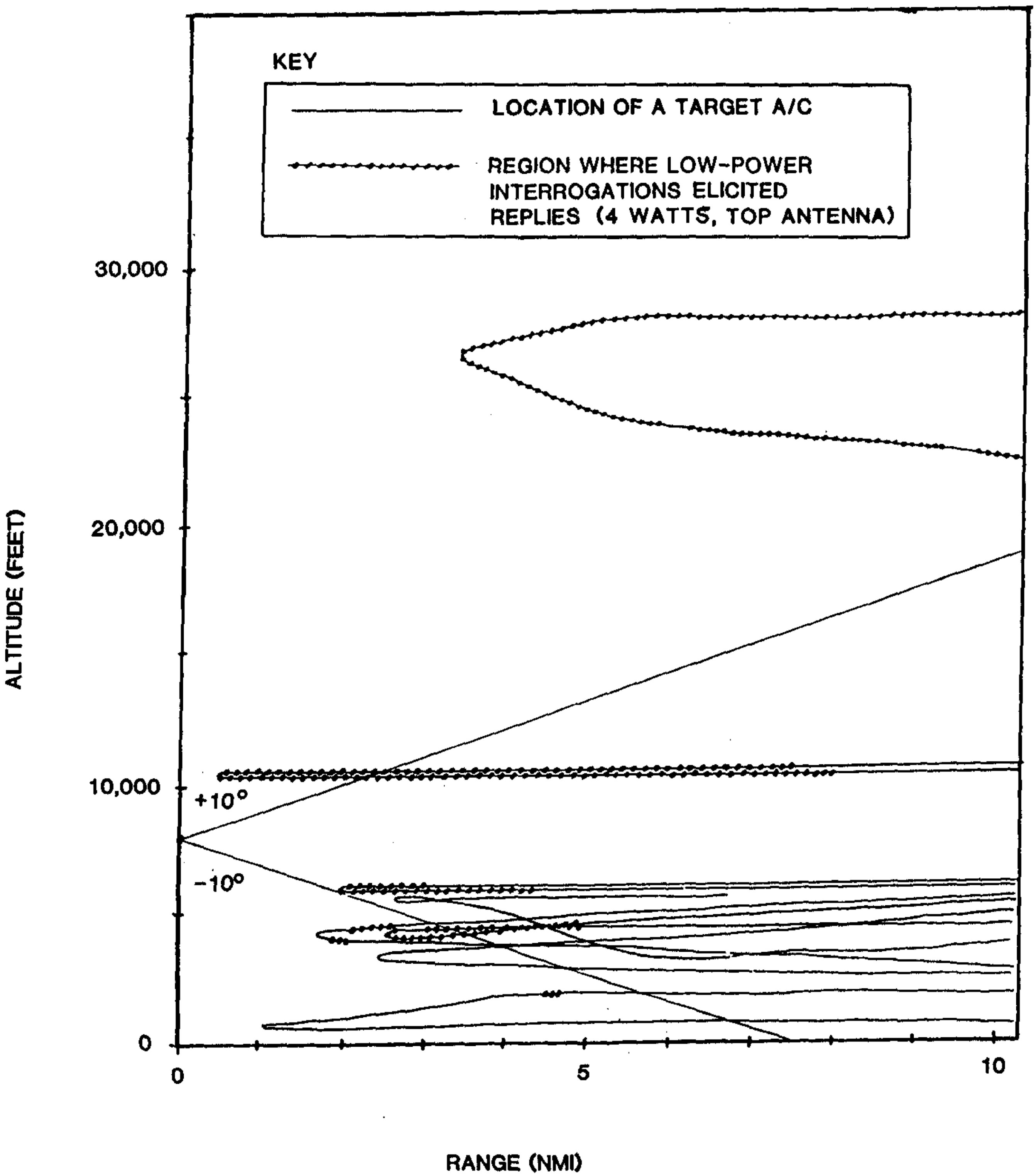


Fig. 7-1. Active TCAS I performance - Boston to New York.

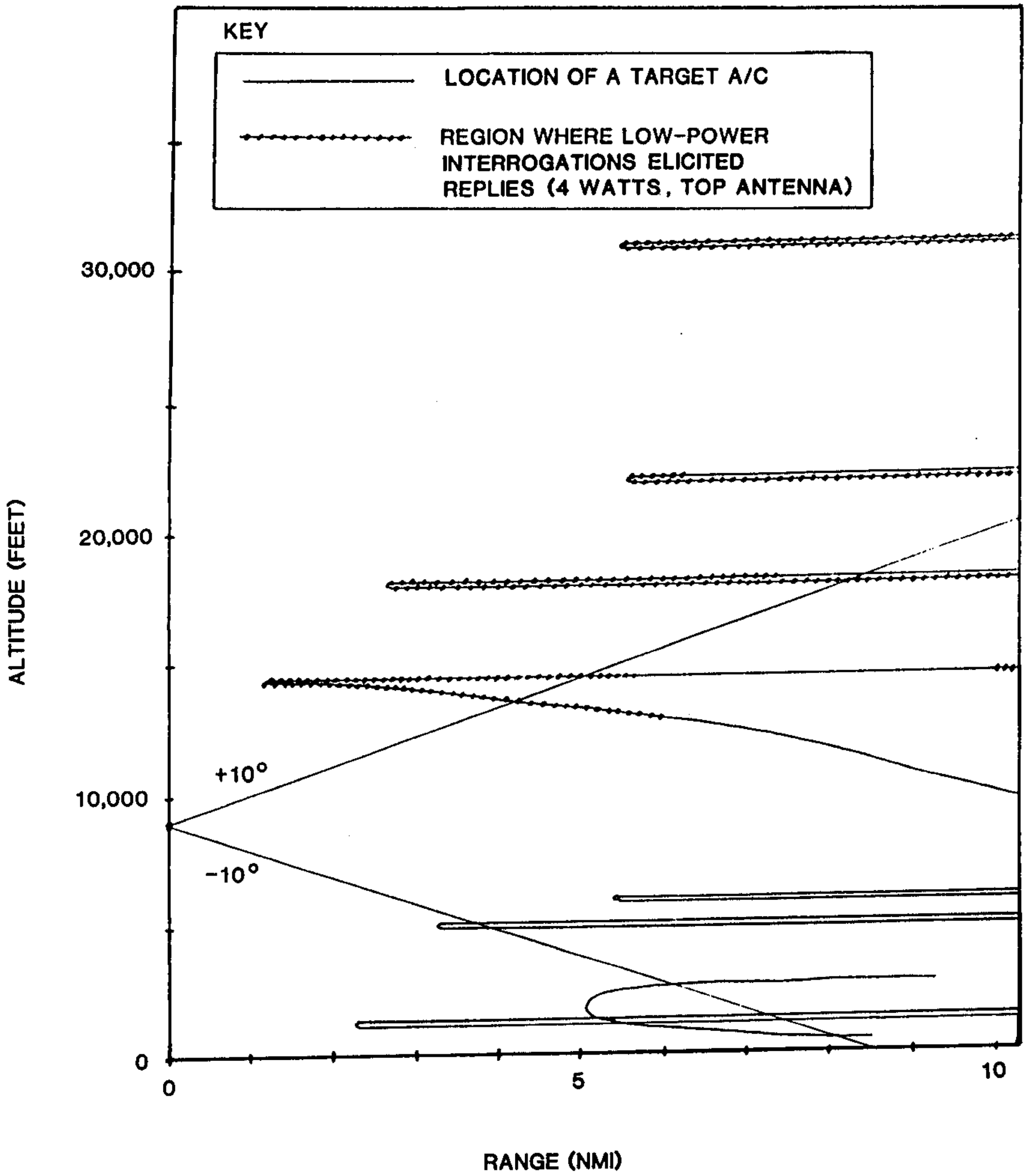


Fig. 7-2. Active TCAS I performance - New York to Boston.

In Table 7-2, the results for aircraft within the principal threat zone (± 10°) have been presented as a statistical summary. For each one-nmi range band, the actual traffic (expressed as aircraft-nmi) measured by the full whisper/shout sequence is compared to the performance observed for the low power interrogation only.

The results are also plotted in Fig. 7-3 along with the performance calculated in Appendix D. The match between airborne measurements and the calculated performance is good considering the number of tracks observed.

7.3 Active Detector Characteristics

A possible realization of a TCAS I active proximity detector is shown in Fig. 7-4. In addition to active surveillance, the detector shown includes altitude code filtering and a tracker used to perform Tau calculations. Direct calculation of Tau from active measurement will provide a very low rate of unwanted alarms.

TABLE 7-2.

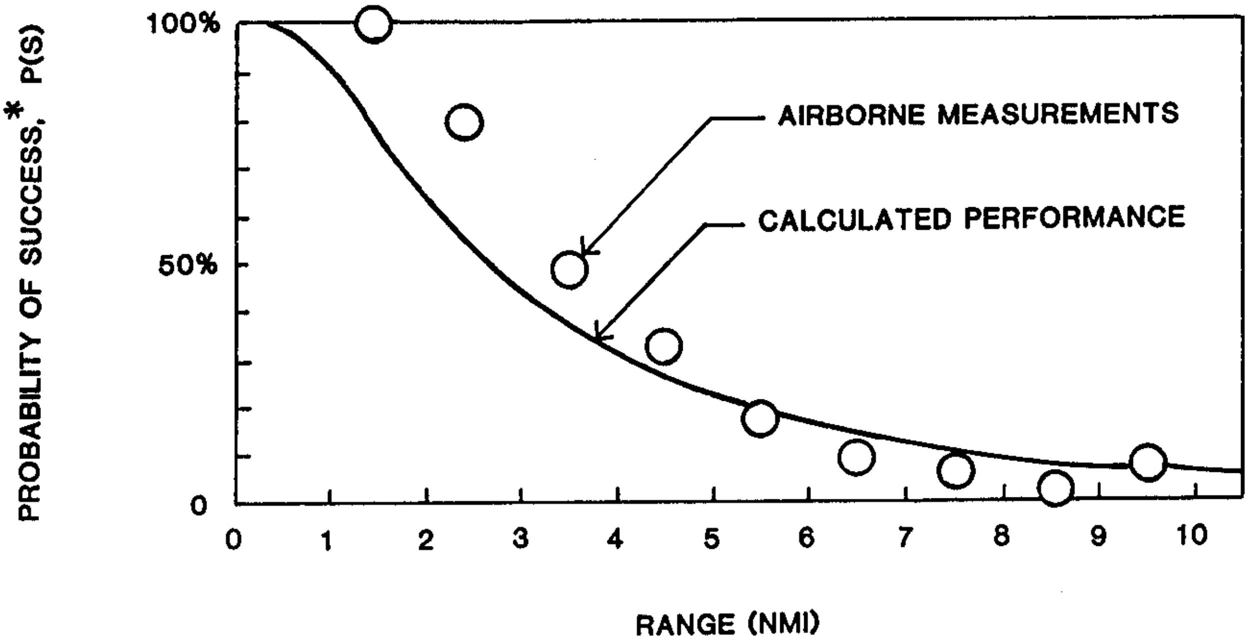
LOW POWER INTERROGATION, STATISTICAL SUMMARY

	Range									
	0 to 1 nmi		1 to 2 nmi		2 to 3 nmi		3 to 4 nmi		4 to 5 nmi	
	a/c	T	a/c	T	a/c	T	a/c	T	a/c	T
Southbound	0	0	0.2	0.2	4	3.2	8.3	4.2	11.3	3.9
Northbound	0	0	0	0	0	0	0.6	0	2.7	0.7
Total	0	0	0.2	0.2	4	3.2	8.9	4.2	14	4.6
Percentage				100%		80%		47%		33%

	Range									
	5 to 6 nmi		6 to 7 nmi		7 to 8 nmi		8 to 9 nmi		9 to 10 nmi	
	a/c	T	a/c	T	a/c	T	a/c	T	a/c	T
Southbound	12.3	2	13	2	13	1.3	13	0	13	0
Northbound	4.9	1.3	7	0	8.5	0	10.2	0.7	10.3	2
Total	17.2	3.3	20	2	21.5	1.3	23.2	0.7	23.3	2
Percentage		19%		10%		6%		3%		9%

a/c denotes the number of aircraft within ± 10° (in multiples of 1 aircraft-nmi) observed by the full whisper/shout sequence.

T denotes the subset of a/c reached by low power top interrogations.



* PERCENT OF AIRCRAFT FROM WHICH REPLIES ARE ELICITED BY A 4-WATT INTERROGATION, FOR AIRCRAFT WITHIN ± 10° IN ELEVATION ANGLE

Fig. 7-3. Active TCAS performance as a function of range.

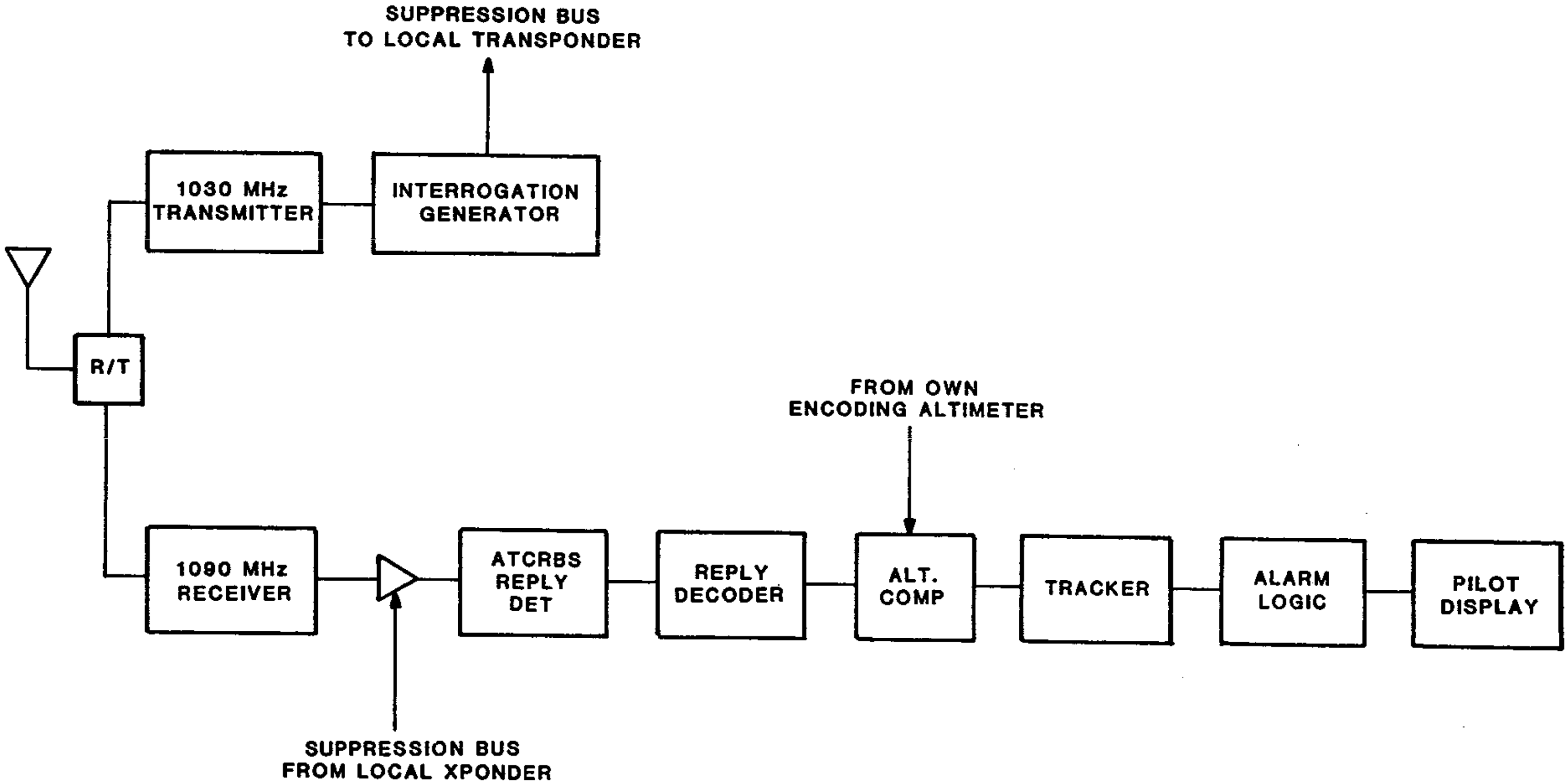


Fig. 7-4. TCAS I active detector possible realization.

8.0 SUMMARY

8.1 Passive Detection

Several simple techniques for passive filtering were evaluated. Those that were found to be useful were combined in a candidate passive detector that was evaluated with flight test data. The results show that initial acquisition ranges can vary from one to eleven miles and demonstrate the difficulty of the passive detection technique to effectively discriminate aircraft range. Altitude code filtering is an effective technique for reducing the alert rate in environments of high Mode C equipage.

Some improvement in passive detection performance can be expected with Mode S replies since power thresholding, altitude tracking and perhaps time-after-interrogation filtering can also be used.

8.2 Active Detection

It appears feasible to use a low power interrogator to greatly improve air-to-air surveillance performance. A time-power product equivalent to one 5-watt Mode C interrogation every second is low enough in power and rate that all interference effects resulting from these interrogations are acceptably small.

A limited set of data evaluated for a low-power active interrogator agreed with calculated link performance and showed adequate performance out to about 2 nmi for a 4-watt interrogator. Performance at 2 nmi and beyond could be enhanced by increasing the power and decreasing the interrogation rate. One 20-watt interrogation every four seconds would seem to be a suitable design.

The false alarm rate of the active detector should be low, due to the use of range gating and a top-mounted antenna. If Tau calculations are performed, the false alarm performance of the active TCAS I should approach that of the TCAS II.

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APPENDIX A

Link Analysis for Received Power Thresholding

This appendix gives an air-to-air link power budget for a passive reply detector that discriminates between close and distant aircraft by using received power thresholding. Also included is an analysis for the purpose of calculating detection reliability as a function of range R. The receiving aircraft uses either a single bottom mounted antenna or a single top mounted antenna.

Air-to-Air Link Power Budget

The air-to-air link power budget is given in Table A-1. The main output of this budget is the nominal margin. As an example, at a range of 2 nmi and for a receiver Minimum Triggering Level (MTL) of -57 dBm, the nominal margin is 3.5 dB.

Link Reliability Analysis

This analysis is aimed at calculating the probability of "success", P(S), where success means reception at a power level greater than or equal to MTL (Minimum Triggering Level).

To calculate P(S), let ΔI denote power deviation in the air-to-air link, and let:

$$\Delta I = \Delta 1 + \Delta 2 + \Delta 3$$

$\Delta 1$ = deviation associated with transmitter power
$\Delta 2$ = deviation associated with antenna gain at transmitter
$\Delta 3$ = deviation associated with antenna gain at receiver

Assign means and standard deviations as follows:

$$\text{mean}(\Delta 1) = \begin{cases} -0.5\text{ dB, for general aviation} \\ +5.9\text{ dB, for air carriers} \end{cases}$$

$$\sigma(\Delta 1) = \begin{cases} 3.1\text{ dB, for general aviation} \\ 2.2\text{ dB, for air carriers} \end{cases}$$

$$\text{mean}(\Delta 2) = \text{mean}(\Delta 3) = 0\text{ dB}$$

$$\sigma(\Delta 2) = \sigma(\Delta 3) = 2.3\text{ dB}$$

These assignments for transponder power, $\Delta 1$, make use of a database of transponder characteristics based on field measurements made in 1971 [Ref. 2, pages 40-41]. The assignments for antenna gain, $\Delta 2$ and $\Delta 3$, make use of a database of aircraft antenna patterns based on measurements of model aircraft [Ref. 8, page 18].

TABLE A-1.

REPLY LINK AIR-TO-AIR POWER BUDGET

	Item	Units	Value
1.	Transmitter power (at antenna)	dBm	54
2.	Transmitting antenna gain	dB	0
3.	Free space path loss	dB	104.5
4.	Receiving antenna gain	dB	0
5.	Receiving cabling loss	dB	3
6.	Received power (at the unit)	dBm	-53.5
7.	MTL (at the unit)	dBm	-57
8.	Nominal margin	dB	3.5

Notes

The values listed are for an example at a range of 2 nmi and for a receiver MTL (Minimum Triggering Level) of -57 dBm. Otherwise nominal values are entered into the budget, and the result is the nominal margin.

Item 3, free space path loss, = 20 log $(4\pi R/\lambda)$ where R = range and λ = wavelength.

Item 6, received power, is the sum of items 1, 2 and 4, minus the sum of items 3 and 5.

Item 8, nominal margin, equals item 6 minus item 7.

Since the total power deviation ΔI is the sum of these contributions, its mean and standard deviation can be obtained by adding the means and root-sum-squaring the individual standard deviations.

$$\text{mean}(\Delta I) = \begin{cases} -0.5 \text{ dB, for general aviation} \\ +5.9 \text{ dB, for air carriers} \end{cases}$$

$$\sigma(\Delta I) = \begin{cases} 4.5 \text{ dB, for general aviation} \\ 3.9 \text{ dB, for air carriers} \end{cases}$$

Using the central limit theorem and the fact that each of the contributions to ΔI has a bell shaped distribution, ΔI may be approximated as Gaussian, and

$$P(S) = 1 - Q\left(\frac{NM + \text{mean}(\Delta I)}{\sigma(\Delta I)}\right)$$

where NM is the nominal margin from Table A-1, and

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx$$

For example, for MTL = -57 dBm at the unit, and at R=2 nmi

NM = 3.5 dB

$$P(S) = \begin{cases} 0.75 \text{ for general aviation} \\ 0.99 \text{ for air carrier} \end{cases}$$

Values of P(S) calculated for other ranges are listed in Table A-2.

TABLE A-2.

CALCULATED LINK RELIABILITY, RECEIVED POWER THRESHOLDING

Range	Probability of Success	
(nmi)	Gen Aviation	Air Carrier
1	0.98	0.99
2	0.75	0.99
3	0.45	0.93
4	0.25	0.81
5	0.13	0.64
6	0.07	0.49
7	0.04	0.35
8	0.02	0.25
9	0.01	0.18
10	0.01	0.12

APPENDIX B

Derivation of Tau Based on Power Tracking

Assume that the beacon antennas of two aircraft are perfectly omnidirectional. One aircraft listens to the replies of the other in order to estimate Tau. The formula for Tau estimation is derived as follows:

Let R_i = actual range of threat at time t_i

P_i = received power (in dBm) of reply at time t_i

Then $\Delta P = P_{i+1} - P_i$

$$\Delta P = (k - 20\text{Log}_{10} R_{i+1}) - (k - 20\text{Log}_{10} R_i)$$

$$\Delta P = 20 \text{ Log}_{10}\left(\frac{R_i}{R_{i+1}}\right)$$

Thus

$$\text{Log}_{10}\left(\frac{R_i}{R_{i+1}}\right) = \frac{\Delta P}{20}$$

and

$$\frac{R_i}{R_{i+1}} = 10^{(\Delta P/20)} \qquad [1]$$

$$\text{Tau} = -\frac{\text{Range}}{\text{Range Rate}}, \text{ by definition}$$

$$\text{Tau}_{i+1} = -\frac{R_{i+1}}{\frac{\Delta R}{\Delta t}}$$

$$\text{Tau}_{i+1} = -\frac{\Delta t}{\frac{\Delta R}{R_{i+1}}} = -\frac{\Delta t}{\frac{R_{i+1} - R_i}{R_{i+1}}}$$

$$Tau_{i+1} = -\frac{\Delta t}{1 - \frac{R_i}{R_{i+1}}}$$

$$Tau_{i+1} = -\frac{\Delta t}{1 - 10^{(\Delta P/20)}} \quad \text{from [1]}$$

APPENDIX C

Interference Analysis for Low Power Interrogators

This analysis of the interference environment resulting from low power interrogators is based on the following concept. Hypothesize two populations of airborne interrogators:

- TCAS II
- Low power TCAS I interrogators

The low power interrogators operate in the ATCRBS mode only; there may be any number of them, and each need not carry out interference limiting (that is, each can use fixed values of interrogation rate and power, regardless of where the aircraft is flown).

There are three interference mechanisms to be considered:

(1) air-to-air effects on transponder reply ratio of proximate aircraft

(2) mutual suppression effects on own transponder reply ratio

(3) ATCRBS fruit generated by proximate aircraft replies to TCAS I interrogations.

These correspond to the three interference limiting inequalities given in the TCAS II National Standard, which are:

$$(1) \quad \sum \frac{P(i)}{250 \text{ watts}} < \frac{280}{N+1}$$

$$(2) \quad \sum M(i) < 0.01 \text{ sec.}$$

$$(3) \quad \frac{1}{BS} \sum \frac{PA(k)}{250 \text{ watts}} < \frac{80}{N+1}$$

where:

P(i) = power of the ith interrogation
PA(k) = power of the kth ATCRBS interrogation
N = number of TCAS II interrogators within 30 nmi.
BS = beam sharpening factor
M(i) = duration of mutual suppression of own transponder associated with the ith interrogation

and, where the summations include all interrogations in 1 second. These are the constraints for the TCAS II population, proposed prior to consideration of low power interrogators for TCAS I.

For low power interrogators the third effect is dominant, so the analysis will begin with this effect and then return to the other two. Consider dividing the total fruit allocation, 80/(N+1), into two parts, allocating 90% for TCAS II and 10% for low power interrogators. That is:

$$\frac{1}{BS} \sum \frac{PA(k)}{250 \text{ watts}} < \frac{72}{N+1} \quad \text{for TCAS II}$$

$$\sum \frac{PA(k)}{250 \text{ watts}} < \frac{8}{NL+1} \quad \text{for low power interrogators}$$

where NL = number of low power interrogators within 30 nmi. Let DL denote the density of lower power interrogators,

$$NL = \pi \; (30 \text{ nmi})^2 \; DL$$

The limit for low power interrogators becomes

$$\sum PA(k) \leq \frac{2000 \text{ watts/sec}}{\pi 30^2 DL + 1}$$

If we can assume that $DL < 0.15$ aircraft/nmi^2, then the constraint becomes simply

$$\text{rate-power product} = \sum PA(k) < 5 \text{ watts/sec.}$$

Thus if each low power interrogator were to transmit at a rate and power whose product did not exceed 5 watts/sec., then in any density of these interrogators up to 0.15/nmi^2, the resulting ATCRBS fruit would not exceed 10% of the total amount allocated to all of TCAS.

Next, return consideration to the other two interference mechanisms. The air-to-air effects on transponder reply ratio for the two classes of interrogators would be

$$(N+1) \sum \frac{P(i)}{250 \text{ watts}} < 280, \text{ for TCAS II}$$

$$(NL+1) \sum \frac{P(i)}{250 \text{ watts}} < 8, \text{ for low power interrogators}$$

Evidently, the contribution from low power interrogators is smaller than the amount associated with TCAS II operation (itself quite small) by a factor of 35. The mutual suppression effect on the transponder accompanying a low power interrogator, for a typical design,

$$\text{interrogation rate} = 0.5/\text{sec}$$

$$M = 50\ \mu s$$

is just

$$\sum M(i) = 0.000025$$

which is negligible.

In summary, if a constraint on the rate-power product of 5 watts/sec. is adopted for each low power interrogator, then such units can be operated otherwise unconstrained in any density up to 0.15 low-power interrogators per nmi^2, without imposing any significant interference penalty on themselves or on other systems. It may be appropriate to follow this analysis with a more detailed simulation of interference effects similar to the TCAS simulation studies now in progress at the Electromagnetic Compatibility Analysis Center in Annapolis.

APPENDIX D

Link Analysis for a Low-Power Interrogator

This analysis predicts the liklihood of achieving successful air-to-air surveillance at range R when using low-power omnidirectional interrogations.

Step 1. For a Given Range and Power, Calculate the Nominal Margin

The nominal margin is calculated using the method of Table D-1. For example, at a range of 2 nmi, and for a 4-watt interrogator (at the antenna input):

Nominal margin = 6 dB

Step 2. Calculate the Probability of Success

"Success" occurs when the signal is received at a power level greater than or equal to the Minimum Triggering Level (MTL)*. To calculate probability of success, P(S), let ΔI denote power deviation in the interrogation link, and let:

$\Delta I = \Delta 1 + \Delta 2 + \Delta 3$
$\Delta 1$ = deviation associated with antenna gain at transmitter
$\Delta 2$ = deviation associated with antenna gain at receiver
$\Delta 3$ = deviation associated with MTL

Assign means and standard deviations as follows:

$$\text{mean}(\Delta 1) = \text{mean}(\Delta 2) = 0 \text{ dB}$$
$$\sigma(\Delta 1) = \sigma(\Delta 2) = 2.3 \text{ dB}$$

$$\text{mean}(\Delta 3) = -3 \text{ dB}$$
$$\sigma(\Delta 3) = 6.1 \text{ dB}$$

These assignments for $\Delta 1$ and $\Delta 2$ make use of a database of model aircraft antenna patterns based on model aircraft measurements [Ref. 6, page 18]. The assignments for $\Delta 3$ make use of a database of General Aviation transponder characteristics based on field measurements made in 1971 [Ref. 2, page 42]. The transponder statistics in Ref. 2 are given separately for General Aviation and Air Carriers. That data shows the General Aviation transponders, as a class, to be significantly inferior in MTL. Thus while the performance calculated here applies to General Aviation traffic, it is to be expected that performance in detecting Air Carrier traffic will be significantly better.

*Appendix E addresses an issue relating to the use of MTL (which is the point of 90% reply ratio) in this calculation.

TABLE D-1.

CALCULATION OF NOMINAL MARGIN

Item	Units	Value
1. Transmitter power (at antenna)	dBm	36
2. Transmitting antenna gain	dB	0
3. Free space path loss	dB	104
4. Receiving antenna gain	dB	0
5. Received power (at antenna)	dBm	-68
6. MTL (at antenna)	dBm	-74
7. Nominal margin	dB	6

Notes

The values listed are for an example in which interrogation power = 4 watts (at antenna) and range is 2 nmi.

Item 3, free space path loss, = 20 log $(4\pi R/\lambda)$ where R = range and λ = wavelength.

Item 5, received power, is the sum of items 1, 2 and 4 minus item 3.

Item 6, MTL, denotes Minimum Triggering Level.

Item 7, nominal margin, equals item 5 minus item 6.

Since the total power deviation, ΔI, is the sum of these contributions, its mean and standard deviation can be obtained by adding the means and root-sum-squaring the individual standard deviations.

$$\text{mean}(\Delta I) = -3.0 \text{ dB}$$
$$\sigma(\Delta I) = 6.9 \text{ dB}$$

Using the central limit theorem and the fact that each of the contributions to ΔI has a bell shaped distribution, ΔI may be approximated as Gaussian, and

$$P(S) = 1-Q\left(\frac{NM + \text{mean}(\Delta I)}{\sigma(\Delta I)}\right)$$

where NM is the nominal margin, and

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx$$

For example, for 4-watt interrogations, and at R = 2 nmi

$$NM = 6 \text{ dB}$$
$$P(S) = 0.67$$

Values of P(S) calculated for other values of range and power are listed in Table D-2 and plotted in Fig. D-1.

TABLE D-2.

CALCULATED VALUES OF SUCCESS PROBABILITY, P(S)

Range	Interrogator Power (at antenna)				
(nmi)	2.5 watts	4 watts	5 watts	10 watts	20 watts
1	0.84	0.90	0.93	0.97	0.99
2	0.56	0.67	0.72	0.84	0.93
3	0.36	0.47	0.53	0.69	0.83
4	0.23	0.33	0.38	0.56	0.72
5	0.16	0.24	0.28	0.44	0.62
6	0.11	0.17	0.21	0.36	0.53
7	0.08	0.13	0.16	0.29	0.45
8	0.05	0.10	0.12	0.23	0.38
9	0.04	0.07	0.09	0.19	0.33
10	0.03	0.06	0.07	0.16	0.28

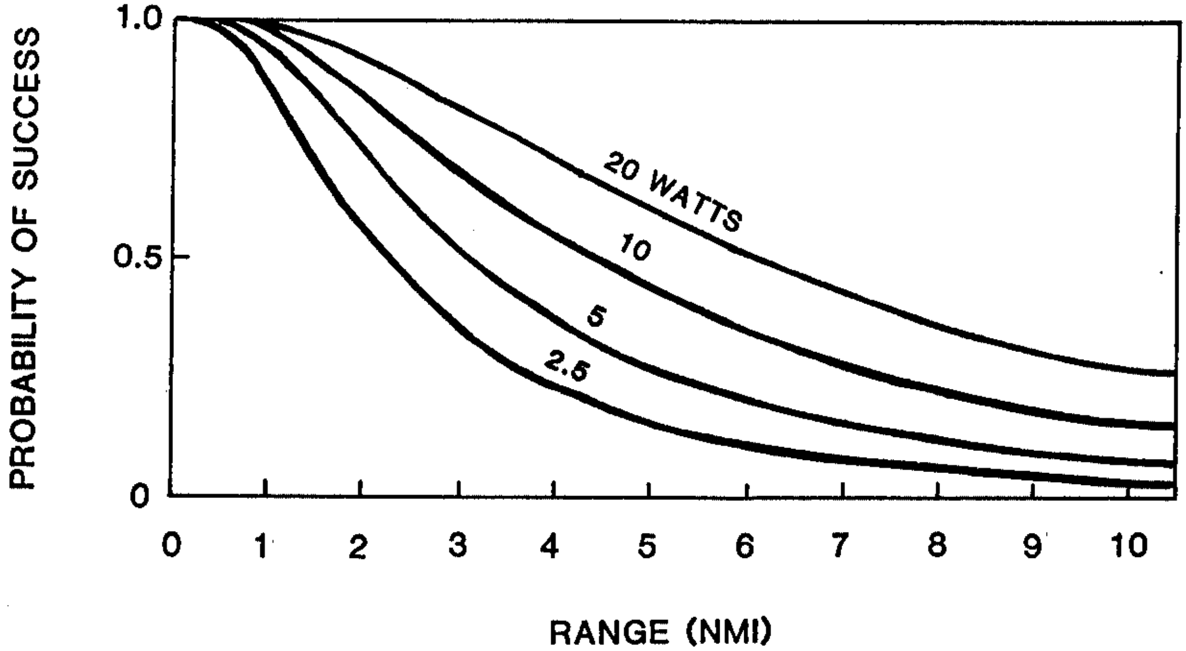

Fig. D-1. Calculated performance, low-power interrogation.

APPENDIX E

Interrogations Received Near MTL

Appendix D formulates a calculation of the fraction of aircraft that can be tracked using low-power interrogations. That calculation is based on the idealization that the fraction of aircraft in track equals the fraction of aircraft that receive the interrogations at or above MTL (Minimum Triggering Level). This appendix addresses the question of whether MTL, which is the point of 90% reply ratio, should be used here rather than some other point tied to a different percentage. Conceivably it would be more accurate to use the 50% detection point, which falls about 1 dB lower in power. This would be reasonable if it could be argued that

fraction of a/c in track	=	fraction of a/c whose reply prob. > 0.50

More detailed study shows that this is not really appropriate. Consider, for example, a design using a particular interrogation rate and power,

rate = 0.8/sec

power = 6 watts

that can successfully track aircraft of reply probability 0.50. Then better performance could be achieved, using the same rate-power product, by increasing the power and decreasing the rate. For example, a change (by 2 dB) to

rate = 0.5/sec

power = 10 watts

would achieve a higher reply rate from this same transponder, and would thus successfully track other less sensitive transponders that could not have been tracked by the original design.

Figure E-1 illustrates this point in more detail. The objective is to maximize, by choice of interrogation rate and power, the fraction of aircraft at a given range that can be tracked. The upper part of the figure is for a set of 5 transponders, denoted A,B,C,D and E, all at this range, but each having a different value of effective MTL, spaced 1 dB apart. The concept of "effective MTL" includes deviations in antenna gains and cabling losses along with the actual MTL values of the transponders. Suppose, without loss of generality, that for transponder D, a 10 watt (40 dBm) interrogation causes receiver power level at this range to be right at MTL. The reply rate under these conditions is

reply rate = IR x RR = 0.45 replies/sec

where

$$\text{interrogate rate, IR} = \frac{5 \text{ watts/sec}}{10 \text{ watts}} = 0.5/\text{sec}$$

reply ratio, RR = 0.90

which is the definition of MTL. Similarly, reply rate for each transponder is plotted in the lower part of Fig. E-1 as a function of interrogation power.

The minimum reply rate that will support reliable tracking is probably near this value, 0.45/sec., although to identify the precise minimum value would require a detailed tracking study. For present purposes, assume that the minimum required rate is simply 0.45/sec., and examine the results in Fig. E-1 for the 5 transponders. It is evident that under these conditions, the optimum interrogation power is 10 watts, in the sense that this value maximizes the number of aircraft (here 4 out of 5) that reply at or above the acceptable rate. The more general result, which is independent of the precise value of the required reply rate, is that

$$\text{fraction of aircraft in track} \approx \text{fraction of aircraft whose reply ratio} > 90\%$$

Thus the 90% point, or simply MTL as conventionally defined, should be used in the calculation in Appendix D.

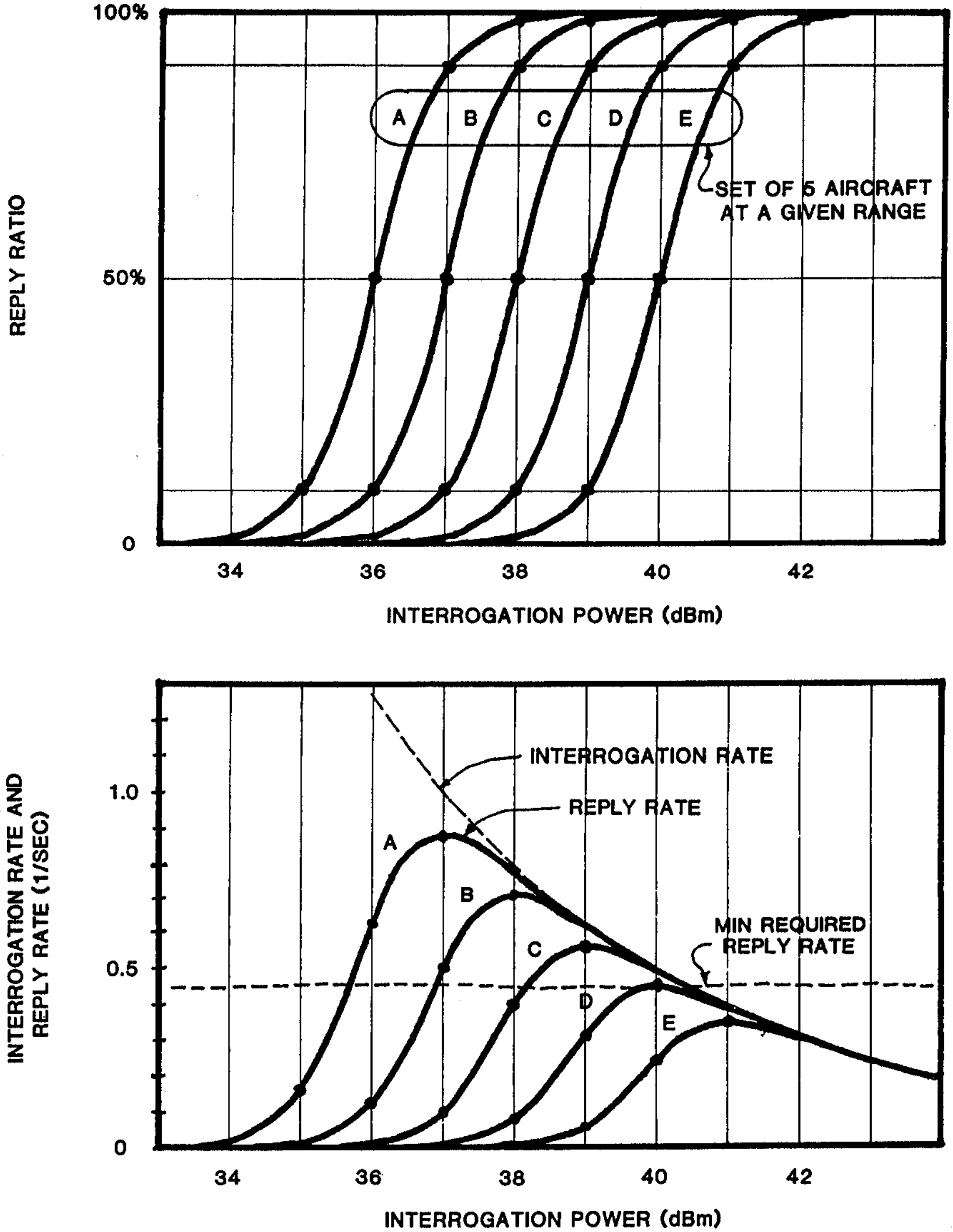

Fig. E-1. Relationships among rate, power, and MTL.