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Effect of Interference on the Performance of a Minimum TCAS II

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16. Abstract

Minimum TCAS II equipment is required to operate reliably in all aircraft densities up to the 0.3 transponder-equipped aircraft per square nautical mile anticipated in the Los Angeles Basin in the year 2000. Prototype TCAS equipment has been developed and shown to be capable of providing reliable surveillance in today's highest densities, which reach an average of about 0.1 aircraft per square nmi.

Since there are no existing environments that reach the density of asynchronous interference anticipated for the Los Angeles Basin in the year 2000, it is necessary to generate simulated interference to determine the performance of the TCAS II design in that environment. A series of bench tests were conducted at Lincoln Laboratory for this purpose. Special sources were used to generate asynchronous ATCRBS and Mode S reply signals (fruit) and TACAN/DME squitter and interrogation signals. Synchronous ATCRBS and Mode S reply sequences were also generated to simulate airborne encounters.

The performance was evaluated by observing how the interference signals either degraded the ability of a TCAS II unit to receive, process, and track the desired synchronous reply sequences, or caused the TCAS II unit to generate false tracks.

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Introduction

The Traffic Alert and Collision Avoidance System (TCAS) is a beacon-based airborne collision avoidance system that operates by providing air-to-air surveillance of all transponder-equipped aircraft.

The TCAS concept encompasses a range of capabilities. TCAS I is a low-cost version which provides traffic advisories only. Minimum TCAS II adds vertical resolution advisories and is intended to provide separation assurance in all current and predicted airspace environments through the end of this century. Enhanced TCAS II uses more accurate intruder bearing data to allow it to generate horizontal resolution advisories. All three forms of TCAS equipment track aircraft equipped with both the existing Air Traffic Control Radar Beacon System (ATCRBS) transponders and with the new Mode S transponders.

TCAS II Performance Requirements

Minimum TCAS II equipment is required by the RTCA Minimum Operational Performance Standards (MOPS) (Ref. 1) to operate reliably in all aircraft densities up to the 0.3 transponder-equipped aircraft per square nautical mile anticipated in the Los Angeles Basin in the year 2000.

Prototype TCAS equipment has been developed and shown (Ref. 2) to be capable of providing reliable surveillance in such densities. The expected performance was determined by extrapolation from performance measured in today's highest densities, which reach an average of about 0.1 aircraft per square nmi. Fruit rate measurements conducted in this aircraft environment indicate ATCRBS fruit rates on the order of 10K replies per second (Ref. 3).

Although such extrapolations provide a good assessment of the ability of TCAS to handle the synchronous interference and multipath that will occur in higher densities, they do not directly show the ability of TCAS II to handle the higher levels of asynchronous interference that might occur on the TCAS reply channel when the aircraft density is three times greater and when, in addition, the ground-based and airborne beacon interrogation rates and TACAN/DME transmission rates have also increased.

Since there are no existing environments that reach the density of asynchronous interference anticipated for the L.A. Basin in the year 2000, it is necessary to generate simulated interference to determine the performance of the TCAS II design in that environment. A series of bench tests were conducted at Lincoln Laboratory for this purpose.

Interference Simulation

The interference environment was simulated using equipment supplied by the FAA Technical Center. Special radio frequency (RF) sources were used to generate asynchronous ATCRBS and Mode S reply signals (fruit) at the TCAS reply frequency of 1090 MHz and to generate TACAN/DME squitter and interrogation signals operating on frequencies within and adjacent to the TCAS reply channel. Synchronous ATCRBS and Mode S reply sequences were also generated at RF to simulate airborne encounters. The performance was evaluated by observing how the interference signals either degraded the ability of a TCAS II unit to receive, process, and track the desired synchronous reply sequences, or caused the TCAS II unit to generate false tracks.

The anticipated density of 0.3 transponder-equipped aircraft per square nautical mile in the L.A. Basin in the year 2000 suggests an ATCRBS fruit rate three times the value measured today or approximately 30K fruit replies per second. This projected fruit rate assumes that the current ground interrogator population does not change. In order to account for an error in the projected aircraft density and number of future ground interrogators (and therefore fruit rate), the TCAS II performance was evaluated over a range of interference conditions in which the maximum fruit rate exceeds the current estimate by a factor of two. The maximum interference environment simulated for the tests consisted of ATCRBS fruit at 60,000 replies per second, Mode S fruit at 856 replies per second, TACAN/DME squitter signals at 7200 pulse pairs per second and TACAN/DME interrogations at 288 pulse pairs per second. Fruit rate is defined as that value observed above a TCAS II receiver threshold of -77 dBm referenced to the receiver input or -74 dBm referenced to the antenna terminal.

Traffic Simulation

Mode S and ATCRBS intruder aircraft were simulated by a device known as the Lincoln Laboratory Ground Test Facility (GTF). The GTF simulated replies from moving targets in response to TCAS interrogations. Target scenarios were designed to match the required TCAS II surveillance range in a high density environment.

Data Collection

The combination of intruder replies and interfering signals was fed to a Lincoln Laboratory TCAS Experimental Unit (TEU). The TEU front-end design meets the requirements of the TCAS MOPS except that it has no capability for angle-of-arrival estimation or for error correction. The fact that bearing estimation in the presence of interference is not evaluated in this study is not considered a serious deficiency. The critical minimum TCAS II functions affected by interference are surveillance and generation of resolution advisories, neither of which uses bearing information. The error correction function was simulated by estimating, based on previous reply performance studies, the fraction of the corrupted intruder replies that would be corrected by a TCAS II. That fraction of the replies was then included in the valid reply output of the TEU.

Data Analysis

Non-real-time versions of the TCAS II ATCRBS and Mode S surveillance functions were used to evaluate surveillance performance in the presence of interference. For the ATCRBS evaluation, the intruder reply data from the TEU was first re-formatted to resemble a reply stream resulting from the 83-level whisper-shout interrogation sequence specified by the TCAS II MOPS. The intruder replies and interference signals were then fed to the ATCRBS surveillance processor.

Mode S surveillance performance was handled differently because of the requirement for error correction. The Mode S reply data from the TEU was first processed to determine estimates of error-corrected reply probability verses reply amplitude for each interference environment tested. To reflect the effect of the simulated interference these reply statistics were then used to reduce the reply probabilities associated with real-world Mode S replies recorded during flight tests. The reduced reply streams were then fed to the Mode S surveillance processor.

ATCRBS Results

The results of the evaluation indicate that the TCAS II ATCRBS surveillance processor will be capable of functioning properly in an asychronous interference environment that is twice as severe as the worst case predicted for the Los Angeles basin in the year 2000. ATCRBS surveillance performance on an approaching intruder in this environment is illustrated in Table ES-1. In the range interval between 2.3 and 5.7 nmi the approaching intruder reply was subjected to synchronous interference from the reply of a second stationary target. Although the TCAS II reply performance for long range intruders and for intruders subject to synchronous garble was degraded appreciably, the ATCRBS surveillance processor was still able to acquire and maintain an acceptable track on the intruder. As shown in the table, ATCRBS surveillance performance in this environment achieved an overall track probability of 97% as compared to the MOPS requirement of 90% against intruders closing at 500 knots in a density of 0.3 aircraft per square nautical mile. The false track rate in the same environment was observed to be well below the 1% requirement of the MOPS.

Mode S Results

The performance of the TCAS II Mode S surveillance processor also exceeded the requirements specified in the TCAS II MOPS when subjected to an interference environment of the same magnitude as predicted for the L.A. Basin in the year 2000. Furthermore, this performance level was achieved under interference limiting conditions that simulated the presence of a very large number of other TCAS-equipped aircraft within the detection range of the TCAS unit under test. The effect of worst-case interference limiting on receiver sensitivity was simulated by reducing the probability of the recorded real-world replies to correspond to a 6 dB increase in receiver threshold.

TABLE ES-1.

TCAS II ATCRBS SURVEILLANCE PERFORMANCE

Intruder Range (nmi)	Interference Twice As Severe As Expected For Year 2000	
	Reply Prob.	Track Prob.
0.5-2.3	0.95	1.0
2.3-5.7	0.65	0.94
5.7-8	0.57	1.0
overall	0.70	0.97

Reply data from twelve separate Mode S flight test encounters were used to derive a cumulative performance estimate for the TCAS II surveillance processor in terms of the time of track establishment before the point of closest approach. Figure ES-1 illustrates the cumulative performance against the twelve encounters in an interference environment equivalent to that predicted for Los Angeles in the year 2000 and under conditions that reflect a severe density of TCAS-equipped aircraft. As seen in the figure, the TCAS II Mode S surveillance processor was able to establish a track on 98% of the intruders by the time that a resolution advisory would have had to be generated. This performance exceeds the MOPS requirement of 90% specified for the same conditions of traffic density and closing speed.

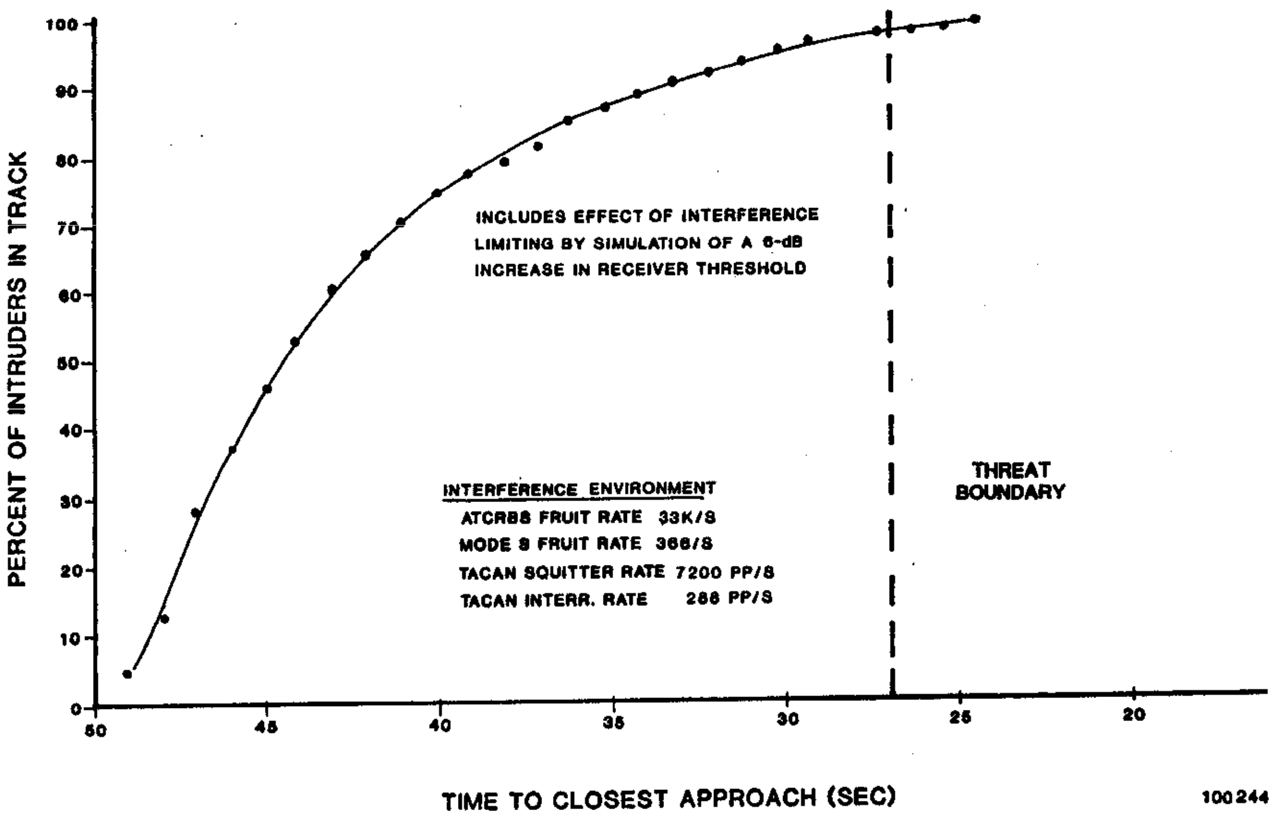

Figure ES-1. TCAS II Mode S surveillance performance for 500-knot encounters when interference limiting is in effect.

1.0 INTRODUCTION

The Traffic Alert and Collision Avoidance System (TCAS) is a beacon-based airborne collision avoidance system that operates by providing air-to-air surveillance of all transponder-equipped aircraft.

The TCAS concept encompasses a range of capabilities. TCAS I is a low-cost version which provides traffic advisories only. Minimum TCAS II adds vertical resolution advisories and is intended to provide separation assurance in all current and predicted airspace environments through the end of this century. Enhanced TCAS II uses more accurate intruder bearing data to allow it to generate horizontal resolution advisories. All three forms of TCAS equipment track aircraft equipped with both the existing Air Traffic Control Radar Beacon System (ATCRBS) transponders and with the new Mode S transponders.

TCAS equipment operates by interrogating once each second and measuring reply delay to determine the range of nearby aircraft. The replies to these interrogations contain the altitude of the aircraft if it is equipped with an encoding altimeter. Minimum TCAS II uses the range and range rate of the aircraft to determine if it is a collision threat. The relative altitude and altitude rate of the aircraft are used to determine the proper maneuver direction for collision avoidance. Thus minimum TCAS II equipment must reliably perform both range and altitude tracking on all aircraft that respond to its interrogation.

The TCAS tracking function must be accomplished in the presence of relatively high levels of radio frequency interference from other aircraft and ground equipment transmitting on the air traffic control beacon frequencies. This interference can be either sychronous or asynchronous. Synchronous interference can occur when two or more transponders reply to the interrogations transmitted from the TCAS equipment. Delayed replies from multipath reflectors also belong to the general class of synchronous interference, although multipath interference is usually treated as a separate subject. Asynchronous interference consists of transmissions from other equipment that are not triggered by interrogations from own TCAS. Both types of interference become more serious as the number of aircraft in a region increases.

Minimum TCAS II equipment is required by the RTCA Minimum Operational Performance Standards (MOPS) (Ref. 1) to operate reliably in all aircraft densities up to the 0.3 transponder-equipped aircraft per square nautical mile anticipated in the Los Angeles Basin in the year 2000.

Prototype TCAS equipment has been developed and shown (Ref. 2) to be capable of providing reliable surveillance in such densities. The expected performance was determined by extrapolation from performance measured in today's highest densities, which reach an average of about 0.1 aircraft per square nmi. Fruit rate measurements conducted in this aircraft environment indicate ATCRBS fruit rates on the order of 10K replies per second (Ref. 3).

Although such extrapolations provide a good assessment of the ability of TCAS to handle the synchronous interference and multipath that will occur in higher densities, they do not directly show the ability of TCAS II to handle the higher levels of asynchronous interference that might occur on the TCAS reply channel when the aircraft density is three times greater and when, in addition, the ground-based and airborne beacon interrogation rates and TACAN/DME transmission rates have also increased.

A series of bench tests were conducted at Lincoln Laboratory to evaluate TCAS II performance in the anticipated higher levels of interference. Special RF sources were used to generate a range of asynchronous ATCRBS and Mode S fruit reply rates and TACAN/DME squitter and interrogation rates that exceeded the levels predicted for the L.A. Basin in the year 2000. Synchronous RF replies from ATCRBS and Mode S intruder test targets were generated from test scenarios designed to simulate ATCRBS and Mode S encounters.

TCAS II reply performance on the intruder test targets in the presence of the simulated interference was evaluated using a Lincoln Laboratory TCAS Experimental Unit (TEU) to represent the receiving and reply processing functions of the MOPS TCAS II. Computer-based versions of the MOPS TCAS II surveillance processors for ATCRBS and Mode S were then used to process the TEU output reply data to determine TCAS II surveillance performance in the interference environment.

This report describes the equipment used for the tests, the generation of simulated test target scenarios and the test procedures. The report concludes with the results of the various tests and discusses the net impact of the tested interference environments on the performance of a TCAS II.

2.0 MEASUREMENT APPROACH

The evaluation of TCAS II performance in an interference environment was accomplished by conducting bench tests on a Lincoln Laboratory TCAS Experimental Unit (TEU) which is closely representative of a MOPS TCAS II design in terms of its receiving and reply processing functions. The evaluation consisted of generating replies from controlled simulated intruder aircraft and inputting these replies to the TEU simultaneously with a variety of interfering signals.

ATCRBS and Mode S intruder targets were simulated using the Lincoln Laboratory Ground Test Facility (GTF) which has the capability of generating replies from programmed target scenarios in response to TEU interrogations. Interfering ATCRBS and Mode S fruit replies and TACAN/DME squitter and interrogation signals were generated by FAA-supplied equipment and combined at RF with the GTF intruder replies. Different intruder target scenarios were used for the ATCRBS and Mode S surveillance tests. The ATCRBS test employed a scenario designed to simulate a realistic encounter during which the replies from the intruding aircraft were synchronously garbled by replies from a second stationary aircraft. The combined RF signals, consisting of the intruder replies and the interference, were processed by the TEU receiving and reply processing functions to generate a data tape containing reply reports on a scan-by-scan basis. A computer-based version of the TCAS II ATCRBS surveillance processor was then used to process the reply data to provide track outputs in a form suitable for determination of intruder reply detection and track probability and false track rate.

Mode S evaluation was performed somewhat differently than for the ATCRBS tests. Initially a GTF-based scenario consisting of a single fixed-range Mode S target was used to generate curves of Mode S reply detection probability as a function of received reply level. This was accomplished by recording at each of several target reply levels a statistically significant number of Mode S target replies along with interference. The reply probability curves were then used to modify reply statistics associated with live airborne data recorded during previous flight tests. The modified replies, which now reflect the effect of the generated interference, were input to an computer-based version of the TCAS II Mode S surveillance processor to determine Mode S track performance.

The remainder of this section discusses the relevance of assessing TCAS II performance in an interference environment based on TEU measurements and describes in greater detail the characteristics of the test equipment, the ATCRBS and Mode S target scenarios and the data collection process.

2.1 TEU Description

The tests were performed on Lincoln Laboratory TEU, Serial No. 3. The characteristics of the receiver and the ATCRBS and Mode S reply processors in TEU-3 are identical to the requirements specified in the Minimum TCAS II MOPS with the exception that TEU-3 is not implemented with an angle-of-arrival capability, Mode S error detection and correction, or Mode S confidence bit declaration.

Since the angle-of-arrival design that is incorporated into TEU-1 and TEU-2 is basically different from the scheme proposed by industry (the Lincoln Laboratory design is based on phase comparison as opposed to the amplitude comparison technique used by both Dalmo Victor and Bendix), an evaluation of TEU-derived angle estimate accuracies in the presence of interference was felt to be inappropriate. Furthermore, minimum TCAS II bearing estimates are not used for surveillance and are not used to generate resolution advisories. They are used only to provide a visual indication of intruder position on a traffic advisory display. The intruder bearing estimate in a minimum TCAS II is derived from intruder reply pulses that are determined to be ungarbled by other replies. If a pulse is garbled it is accompanied by a low confidence indication and the pulse is not used for bearing estimates. Therefore bearing estimates in a properly operating TCAS are not likely to be corrupted by interference. The ability of TCAS to recognize a garbled pulse condition, to declare such condition low confidence, and to inhibit bearing estimates on low confidence pulses are requirements that define a properly operating TCAS and are fully tested via the minimum TCAS II MOPS. The tests conducted on TEU-3 at Lincoln Laboratory will therefore not provide information on the effect of interference on an angle-of-arrival measurement.

The lack of error detection, correction and confidence bit declaration in TEU-3 is compensated by an approach that examines each recorded Mode S reply and determines whether an error condition associated with the reply is correctable such that it would have been corrected and accepted as a valid reply by a TCAS II. This scheme is described in more detail in 2.3.2.

The original IF bandpass filter in TEU-3 provided an overall out-of-band rejection characteristic that was considerably narrower than the one specified in the Minimum TCAS II MOPS. A new IF bandpass filter was installed in TEU-3 that provides a rejection characteristic more nearly equal to the MOPS requirement. Figure 1 illustrates both the modified overall bandpass characteristic of TEU-3 and the bandpass characteristic specified in the TCAS II MOPS.

The TEUs are limited to the 26-level whisper-shout Mode C interrogation sequence that is specified in the MOPS for the baseline omni-directional TCAS. For the ATCRBS surveillance processor intereference tests, a full 83-level MOPS directional interrogation sequence was simulated by repeating the 26-level interrogation sequence four times for each setting of intruder range and reply level. The resultant ATCRBS reply data tape was then modified to resemble recorded replies received from an 83-level whisper-shout interrogation sequence by selecting the appropriate levels from each of the four 26-level sequences transmitted. This pre-processing function is described in greater detail in 2.3.1.

2.2 Test Equipment Description

Figure 2 is a block diagram showing the inter-connection between the TEU under test, the GTF target simulator and recording equipment, and the various interference generators.

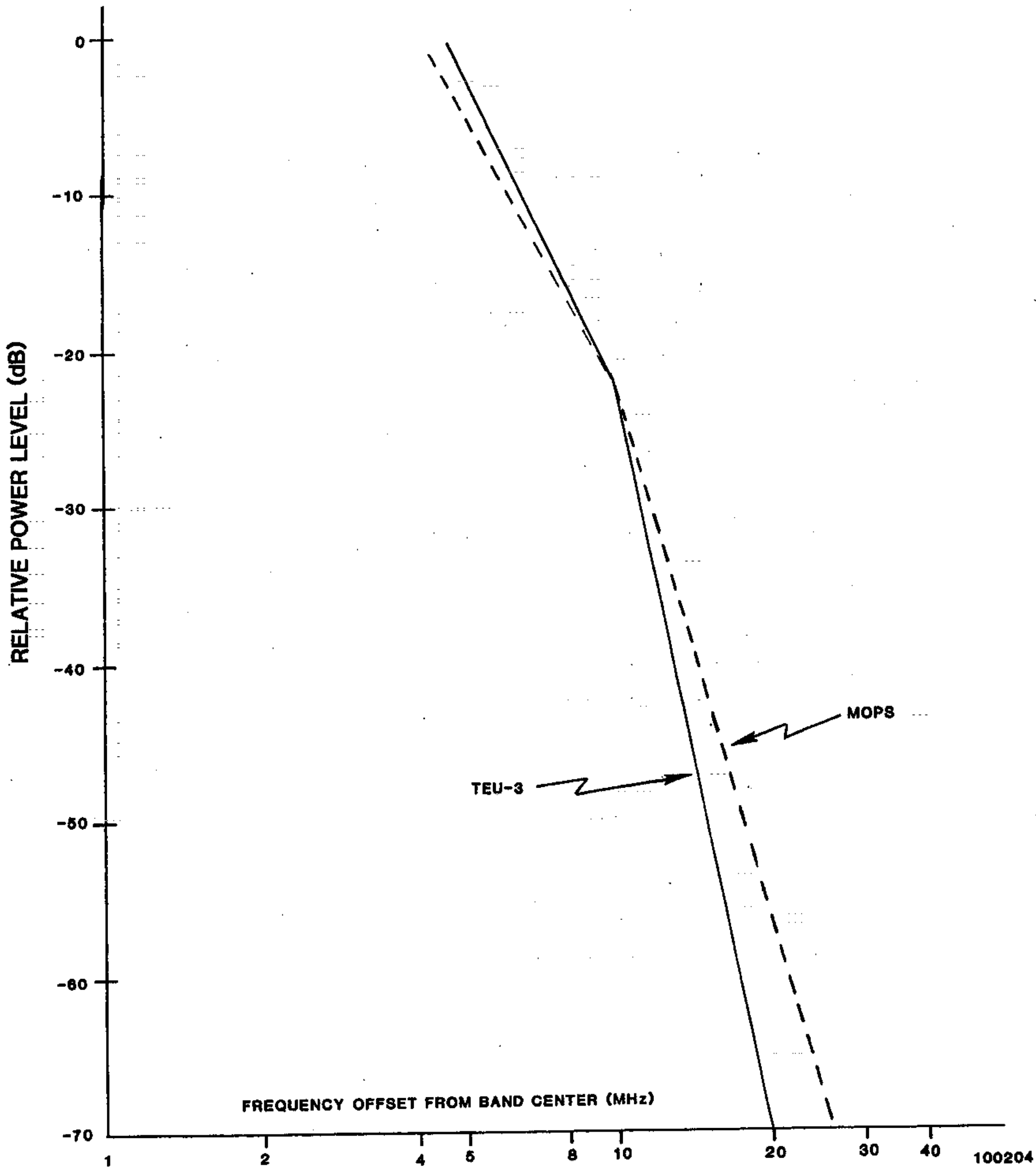

Figure 1. Frequency bandpass characteristics of TEU-3 receiver and MOPS specification.

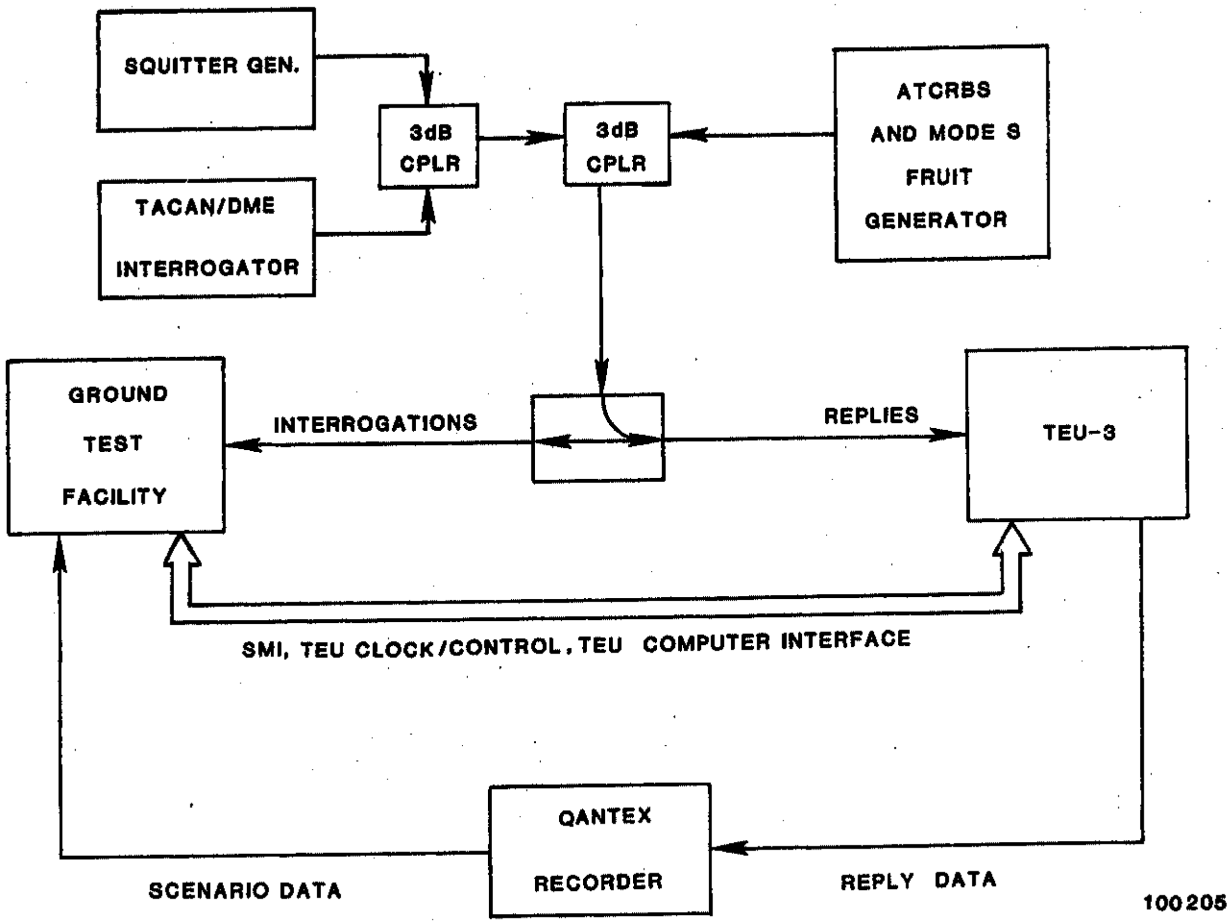

Figure 2. Interference test equipment configuration.

2.2.1 Ground Test Facility

The Lincoln Laboratory Ground Test Facility is designed to perform functional tests on TCAS Experimental Units. It is capable of generating ATCRBS and Mode S replies from simulated targets in response to interrogations from a TEU. The range and the reply amplitude associated with each simulated target are automatically controlled during a test according to programmed parameters entered in via a scenario data tape. The range of the target relative to the TEU under test can be programmed to vary between 0 nmi and 30 nmi in increments of either the 8.276 or 8.0 MHz internal TEU clock period (i.e., 120.83 nsec for ATCRBS targets and 125 nsec for Mode S targets). The amplitude of the target reply at the GTF output can be programmed to vary between -103 dBm and -40 dBm in 1 dB steps. A fixed altitude for the target is selected prior to the test and cannot be varied during the test.

A Qantex 2200 cartridge tape recorder was used to load in the TEU operational software and the test scenario parameters and to record the reply data outputs from the TEU.

2.2.2 Mode S and ATCRBS Fruit Generators

The Mode S and ATCRBS fruit generators were developed and fabricated by the FAA Technical Center to provide a simulated fruit environment for testing ATCRBS and Mode S processors. Figure 3 is a simplified block diagram of the Mode S and ATCRBS fruit generators.

Each of the four ATCRBS fruit generators is capable of generating nominal fruit rates up to 20,000 per second for a combined total of 80,000 fruit replies per second. A timing control provides a pseudo-random timing distribution about the nominal fruit rate. The nominal fruit rate is selectable in increments of 20 fruit replies per second via keyboard entry. The amplitude distribution of the fruit replies is designed to match previously measured aircraft densities throughout the U.S. (Ref. 3). The amplitude distribution of the generated fruit is controled by a PROM and cannot be readily modified without generating a new PROM with different parameters. The amplitude distribution is stored in 256 values in the PROM which is addressed by a pseudo-random number generator. The selected value for each fruit reply is then used to control an attenuator to establish the appropriate level for that reply. The total range of possible fruit reply amplitudes is designed to be 32 dB. The maximum amplitude is established by setting the output level of each of the 1090 MHz RF signal sources to the desired value.

Figure 4 illustrates the measured cumulative power distribution of the ATCRBS fruit generators for four nominal fruit rate settings of 80,000 40,000, 20,000 and 10,000 fruit replies per second. The output was adjusted to provide a maximum fruit reply power level of -45 dBm at the input to the TEU receiver. The curves were derived by counting ATCRBS fruit reply bracket detections in the TEU receiver for various settings of the TEU receiver threshold. The dynamic MTL function in the TEU was disabled during these measurements in order to prevent threshold capture by the larger amplitude fruit replies. The results indicate that the fruit generator power distribution approximates a uniform-in-range target distribution. The fruit rate specified for each of the interference tests is that rate observable by a TCAS receiver with a threshold setting of -77 dBm referenced to the receiver input.

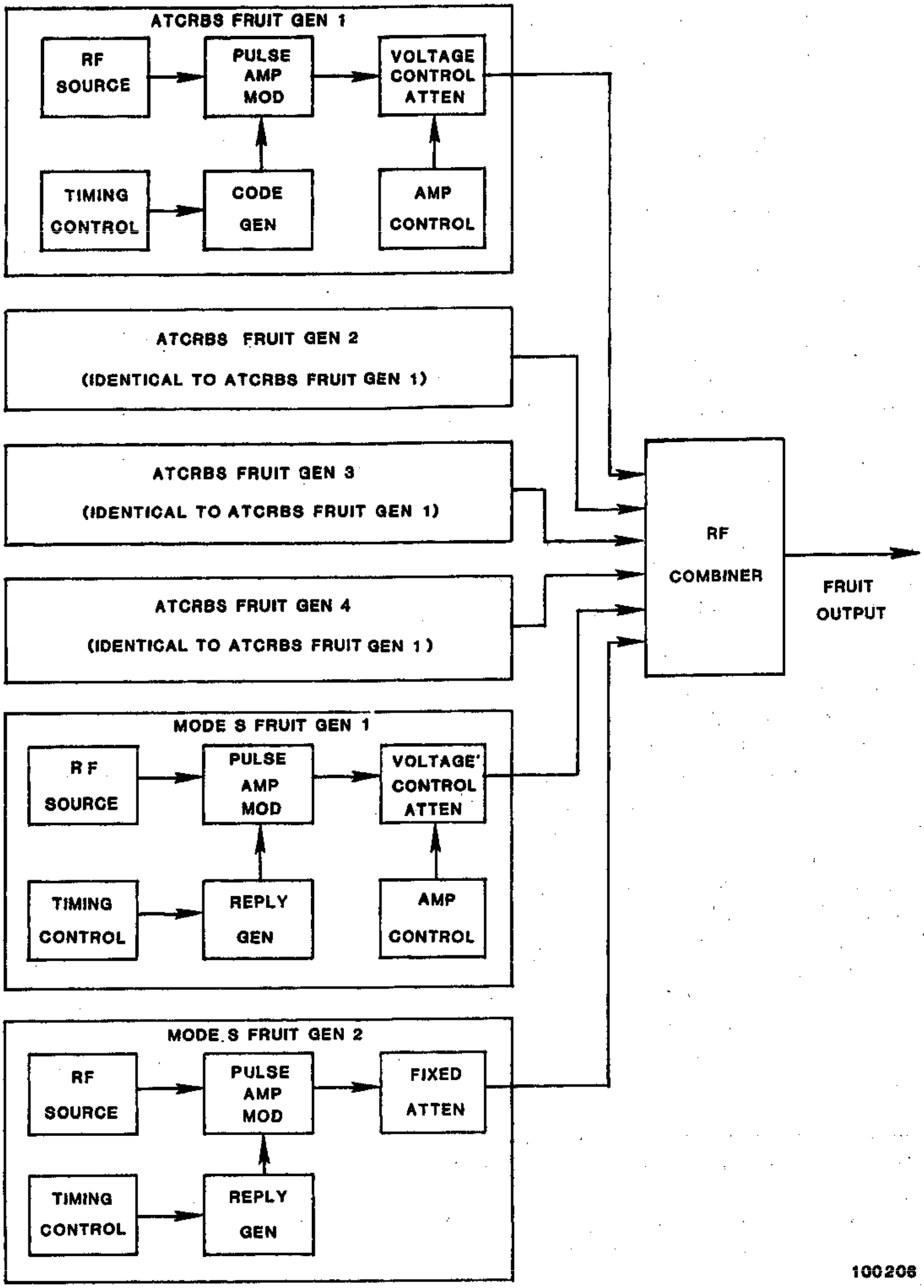

Figure 3. Simplified block diagram of ATCRBS and Mode S fruit generators.

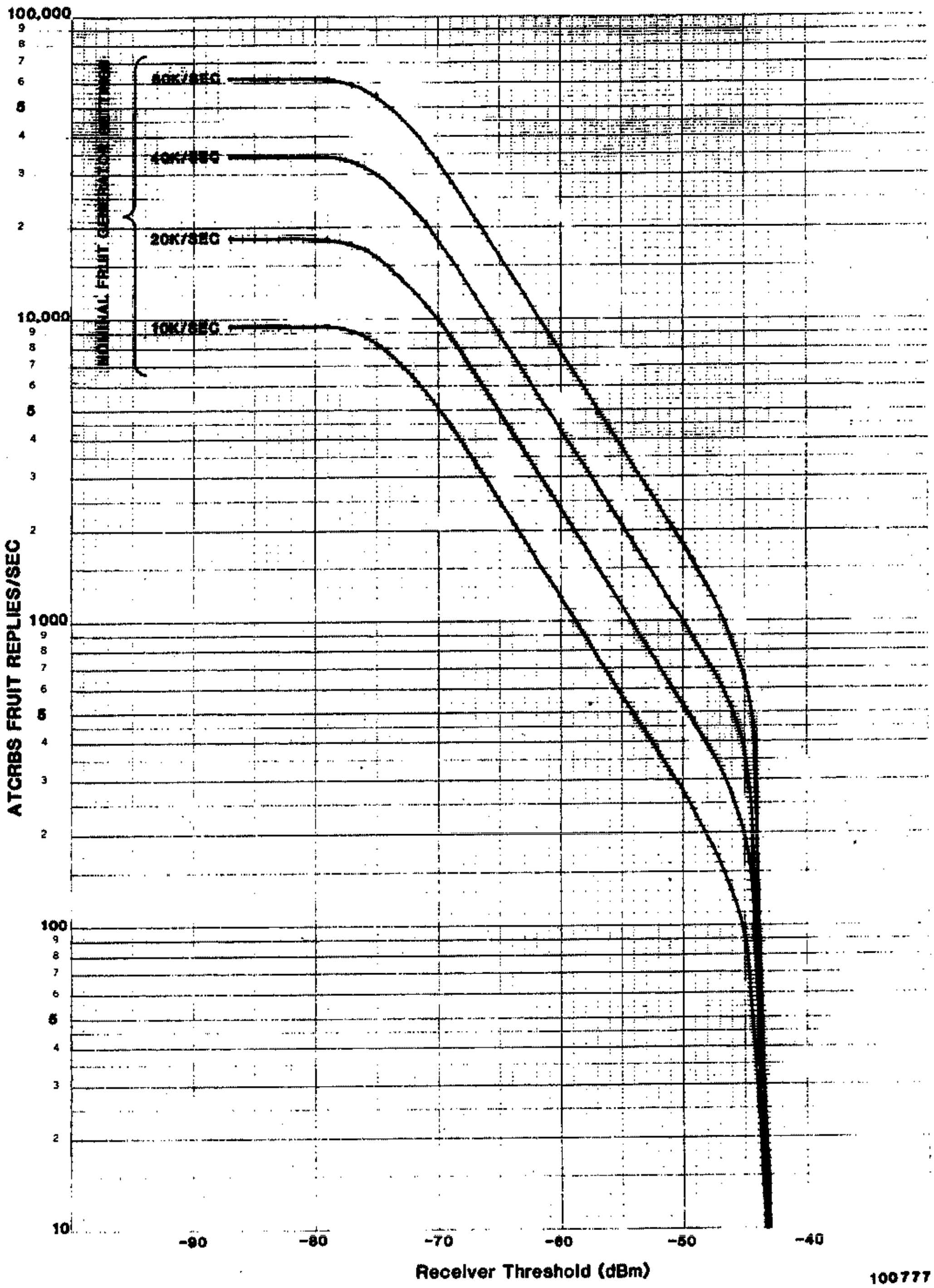

Figure 4. ATCRBS fruit generator cumulative power distribution.

Four code generators were used to generate the total fruit output with each supplying one-fourth of the total. Three of the code generators can each produce 4 different altitude codes (the fourth code generator duplicates the altitude codes of one of the other generators) for a total of 12 different altitude values. The four sets of altitude code data for each generator are stored in PROMs and are selected sequentially when generating fruit. The limited number of ATCRBS fruit altitudes produced by the ATCRBS fruit generator tend to produce unrealistically high false track rates by the surveillance processor under test. To circumvent this problem, the recorded ATCRBS fruit replies were re-assigned a larger, more realistic set of altitudes prior to ATCRBS surveillance processing. This scheme, which is described in greater detail in 2.3.1, modified the distribution of ATCRBS fruit altitudes to resemble that which would be encountered in a high density environment (i.e., the LA basin).

The Mode S fruit generator is capable of generating Mode S fruit at rates up to 2000 per second with the rate selectable in increments of 4 fruit replies per second via keyboard entry. The fruit generator contains two independent fruit control and reply generator units, each of which contributes up to one-half of the total fruit output. The time distribution of generated fruit replies can be selectable, via switches, to simulate either the pseudo-random distribution or one in which the fruit occurs in bursts (i.e., a bunching effect). Each reply generator can produce up to 14 different 56-bit message fields and up to 6 different 112-bit message fields. The 20 messages are stored in a PROM with selection controlled by a combination of the random number generator and by switches. Four fixed percentages of long and short messages can be selected by switch controls to provide either 0.8%, 1.6%, 25% or 50% long Mode S messages. The selected percentage of short to long messages remains constant regardless of fruit rate. The amplitude of Mode S fruit from one of the two reply generators is controlled in a manner similar to that for ATCRBS fruit replies (i.e., the amplitude of a specific Mode S fruit reply is pseudo-randomly selected from one of 256 possibilities stored in a PROM). The amplitude of fruit replies generated by the second reply generator is fixed at a constant value. The interference measurement tests used only the single Mode S reply generator whose output amplitude is pseudo-randomly varied.

2.2.3 TACAN/DME Signal Generator

The TACAN/DME ground beacon squitter signals for the interference tests were generated by a Kustom Electronics Inc., Squawk/Naut-I test set. The Squawk/Naut-I can generate either X-Mode or Y-Mode squitter signals with gaussian-shaped pulse-pairs at rates of up to 10,000 pulse-pairs per second. The RF frequency of the squitter signals is selectable from 960 to 1215 MHz in 1 MHz increments and the output amplitude is continuously adjustable between -10 dBm and -110 dBm.

TACAN/DME interrogations from airborne interrogators were simulated using an RF generator whose output was pulse-modulated by a Hewlett Packard PIN modulator. The modulation signal consisted of either X-Mode- or Y-Mode pulse-pairs whose leading and trailing edges exhibited fast rise and fall times rather than a gaussian characteristic. Square pulse shapes for the interrogation signals were chosen to simulate the interrogation waveform characteristics of precision TACAN/DME interrogators and other TCAN/DME interrogators that are known to generate signals with fast rise and fall times.

2.3 Test Scenario and Data Collection Process

2.3.1 ATCRBS Surveillance

The test scenario used for evaluation of ATCRBS performance consisted of an approching intruder and a stationary target. The moving intruder began at a range of 8 nmi from the TEU and closed at constant altitude to within 0.5 nmi range of the TEU at a rate of 105.7 knots. The stationary intruder was positioned at 4 nmi range. The altitude of both the moving intruder and the TEU was 8000 ft. (altitude code 6620) and the altitude of the stationary target was 7000 ft. (altitude code 6020). The replies from the two targets resulted in a garble situation between the ranges of 5.7 and 2.3 nmi.

Since the TEU was configured to produce the MOPS omni-directional whisper-shout sequence of 26 levels, the bench test simulated the full Minimum TCAS II directional sequence (83 levels) by repeating the omni-directional sequence four times for a given set of conditions. Each 1-second scan interval therefore contained four successive 26-level interrogation sequences from the TEU with the moving intruder range re-adjusted every fourth interrogation sequence to simulate a closing rate of 105.7 knots. The amplitude of the moving intruder reply at the TEU input was adjusted throughout the scenario to coincide with nominal received levels (i.e. -65 dBm at 8 nmi to -40 dBm at 0.5 nmi). The amplitude of the stationary target was maintained at -59 dBm. The recorded reply data tape contained the two ATCRBS intruder replies and, when injected, interference in each of the 104 whisper-shout bins in the group of 4 successive 26-level sequences. In addition the data tape contained information to identify the four whisper-shout sequences in each group and a range value which indicated the true position of each intruder.

The ATCRBS reply tape was first processed to combine the four 26-level whisper-shout scans recorded for each setting of the target parameters into a single 1-second scan interval containing an 83-level whisper-shout sequence. This was accomplished by selecting the appropriate whisper-shout levels from each of the four omni-directional sequences and eliminating the rest. In addition, the recorded scenario target replies were identified on the basis of known range and retained in the three adjacent whisper-shout intervals of the 83-level sequence that are associated with the interrogation steps that would have elicited a response given nominal uplink parameters. Target replies occuring in the remaining bins were discarded. A target reply is retained in three adjacent bins since flight tests have shown that aircraft respond on average to three consecutive whisper-shout interrogations.

In order to overcome the problem of excessive false track rates due to the limited number of codes generated by the ATCRBS fruit generator, each of the ATCRBS fruit replies recorded during each test was distinguished from the scenario targets and re-assigned a new code randomly selected from a much larger set of codes. Each ATCRBS reply that occurred outside of a 0.05 nmi range window centered at the known target range was considered to be an ATCRBS fruit reply. The code set was developed based on measured aircraft distributions in the LA basin and represents a fruit model in which 27% of the replies are Mode A discretes, 41% are 1200 codes, 15% are Mode C altitude codes and 18% are empty brackets. The Mode C altitude codes in the set represent altitudes that have a gaussian distribution between 0 and 12,000 feet with a peak at 6,000 feet. The Mode A discrete codes were selected from 4096 possibilities with equal probability. The total number of code possibilities for a given test is equivalent to the number of aircraft that would have to be present in order to provide the selected ATCRBS fruit rate.

The reconfigured ATCRBS reply tapes for each test were then processed by a computer-based version of the MOPS TCAS II ATCRBS surveillance processor to provide plots of altitude and range tracks as a function of time. Since the track plot information for each scan was represented by a symbol that denoted the presence or absence of an updating valid reply, the plots could be examined to determine intruder reply and track probability for each test condition. The plots also indicated the extent to which false track reports were generated. Based on the plots, the performance of the ATCRBS surveillance processor under each of the interference conditions was evaluated relative to its performance in an interference-free environment.

2.3.2 Mode S Surveillance

Mode S surveillance performance in an interference environment was evaluated in a manner different than that for the ATCRBS processor. Figure 5 illustrates the procedures used to determine the effect of interference on Mode S performance. For the ATCRBS evaluation, the TEU reply data generated by the simulated intruder encounters was fed directly to the non-real-time ATCRBS surveillance processor. For Mode S evaluation, the TEU reply data was used to first generate Mode S reply detection probability curves for two of the severest environmental conditions tested. The data in these curves was then used to assign a probability of detection to each of the replies recorded during actual flight tests to reflect the presence of the simulated fruit and TACAN/DME interference. Based on these probabilities, the recorded reply stream was thinned-out to represent the output of a TCAS II reply processor in this environment. This thinned reply stream was then fed to a non-real-time Mode S surveillance processor. The advantage of this approach is that the Mode S performance evaluation in an interference environment also includes the effects of other link failure mechanisms (i.e., multipath etc.).

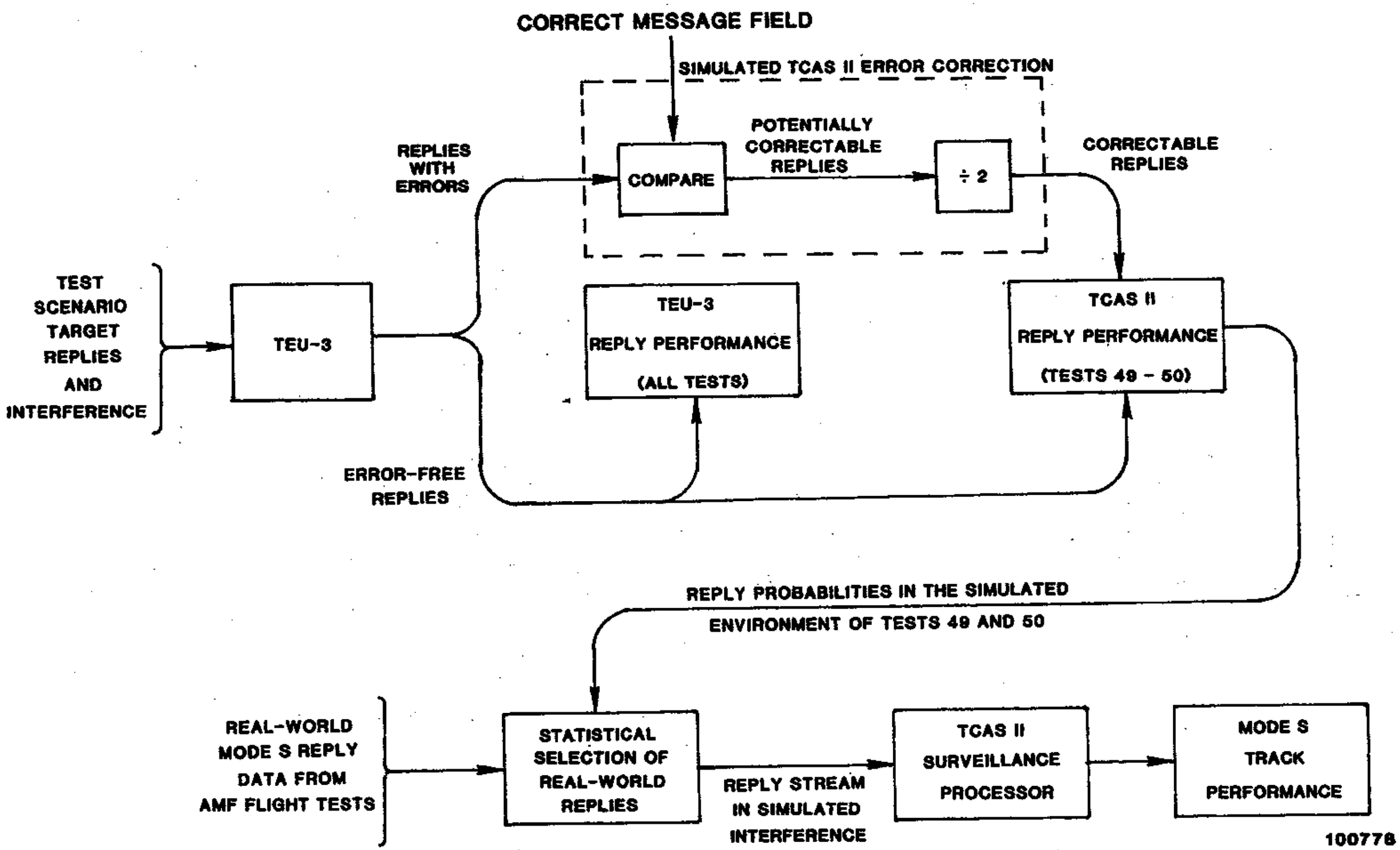

Figure 5. Procedure used to evaluate TCAS II Mode S performance in interference.

The scenario for the Mode S target consisted of a single intruder at a fixed range of 4 nmi and an altitude of 8000 ft. For each test, the intruder was interrogated 100 times at each of 24 settings of intruder reply level as measured at the TEU input. The 24 reply levels were varied from -79 dBm to -73 dBm in 1 dB steps and from -71 dBm to -41 dBm in 2 dB steps with the final step occuring at -40 dBm. The reply data was then processed to provide a probability of detection of a valid reply (i.e., a reply received with a correct or a correctable message field) as a function of reply level for both an interference-free environment and in the presence of various combinations of Mode C and Mode S fruit and TACAN/DME signals.

The TEU Mode S reply processor used for these tests did not provide error detection and correction or message bit confidence information as specified in the TCAS II MOPS. Therefore, a means was necessary to simulate the error correction process in order to provide realistic estimates of TCAS II reply performance.

The TCAS II error correction algorithm declares a corrupted message field to be correctable if; a) the number of low-confidence bit declarations in any 24 bit message field interval does not exceed 11, and b) the extent of decoded erroneous bits in the message field does not exceed 24 bits, and c) there are no high-confidence declarations associated with any of the erroneous bits. Although the absence of confidence information in the TEU reply data output prohibits an exact simulation of the reply correction process, an upper bound on TCAS II reply performance can be determined if the assumption is made that all of the TEU message bits in error, and no others, are of low-confidence.

The recorded replies generated by the Mode S scenario target were decoded and compared to the correct data field to determine the extent and number of any bit errors present in the received message. If the extent of the error burst did not exceed 24 bits and if the number of erroneous bits within a 24-bit span did not exceed 11, the errors were assumed to be low-confidence and the reply was considered, for the purpose of this evaluation, to be a potentially correctable reply.

The actual performance achievable by a TCAS II error correction scheme will be less than the upper bound value since decoded real world replies sometimes contain more than eleven low-confidence declarations and/or incorrect data bits that are declared high confidence. The results of a previous Mode S reply processor study (Ref. 4) were examined in an effort to determine the percentage of potentially correctable replies that would actually be corrected by a TCAS II. This study suggests that, for a constant level of performance, the use of error correction allows operation in twice the fruit environment as that with no correction. As will be evident from the discussion of Mode S performance results in 3.2.1, this implies that a TCAS II reply processor is effectively simulated if one-half of the potentially correctable replies are included in the valid reply output of the TEU.

The valid reply detection curves obtained from the TEU in the presence of interference were used to modify the detection probability of Mode S replies previously recorded by the Lincoln Laboratory Airborne Measurements Facility (AMF) (Ref. 5) during actual flight tests. Since the AMF equipment has the capability of recording the amplitude of received Mode S replies, the AMF reply data can be assigned a new statistical probability of occurence based on the information provided by the TEU reply detection curves. Valid replies recorded by the AMF occurred with a probability that was determined by the interference environment in which the AMF test was flown. In order to achieve a reply probability that reflected only the simulated interference environment, the measured values of reply detection from the TEU bench tests had to be normalized to the probabilities determined for the actual conditions of the flight test. For a given reply level, the resultant reply probability is the probability determined from the measurement in the simulated environment (e.g., from the reply detection curve) given that a valid reply was received in the actual environment. An AMF reply was then accepted as a valid reply if its resultant probability, as determined above, was equal to or greater than a value generated by a random number generator. The output of this process is a modified AMF reply stream which reflects the conditions of the simulated interference environment. The modified reply stream was then processed by a computer-based (non-real-time) version of the TCAS II Mode S surveillance processor to determine surveillance performance in the simulated environment.

2.4 Interference Environment and Test Summary

A total of 50 tests were conducted to determine ATCRBS and Mode S reply and track performance in the presence of interference (25 each for ATCRBS and Mode S). Tables 1 and 2 summarize the characteristics of the interference generated during each of the ATCRBS and Mode S tests. The power level indicated for the ATCRBS and Mode S fruit is the amplitude of the largest fruit reply generated. The remaining fruit reply amplitudes were distributed over a range of 0 to -32 dB with respect to the maximum value. The TACAN/DME squitter and interrogation levels were fixed at the values indicated.

Since the projected ATCRBS and TACAN/DME squitter environment in which TCAS II is expected to operate was not well defined at the time the tests were conducted, it was decided to evaluate TCAS II parametrically under a broad range of environments chosen such that the actual environment will never be likely to exceed the test maximums. Although TCAS II was evaluated in ATCRBS fruit rates of up to 60K replies per second, a preliminary estimate of the ATCRBS fruit rate in the L.A. Basin is more nearly 30K replies per second in the year 2000. This estimate is based on an ATCRBS fruit rate measurement of approximately 10K replies per second in the L.A. Basin when the aircraft density was 0.1 aircraft per square nautical mile (Ref. 3). The anticipated density of 0.3 transponder-equipped aircraft per square nautical mile in the L.A. Basin in the year 2000 suggests a threefold increase in the current ATCRBS fruit rate to approximately 30K replies per second assuming that the present ground interrogator population remains the same. More precise computer-simulated estimates of projected ATCRBS fruit rates in the L.A. Basin are currently being developed by the FAA. The Mode S fruits rates for the tests were selected to be approximately 1% of the ATCRBS fruit rates.

TABLE 1

ATCRBS SURVEILLANCE INTERFERENCE TESTS

Test No.	INTERFERENCE ENVIRONMENT: ATCRBS FRUIT Rate (/s)	Pwr (dBm)[1]	Freq (MHz)	MODE S FRUIT Rate (/s)	Pwr (dBm)[1]	Freq (MHz)	TACAN/DME SQUITTER Rate (/s)	Mode	Pwr (dBm)[1]	Freq (MHz)	TACAN/DME INTERROGATION Rate (pp/s)	Mode	Pwr (dBm)[1]	Freq (MHz)
1							No Interference							
2	9K	-45	1090	No Interference			No Interference				No Interference			
3	18K	"	"		"				"				"	
4	33K	"	"		"				"				"	
5	45K	"	"		"				"				"	
6	60K	"	"		"				"				"	
7	No Interference			93	-45	1090			"				"	
8		"		186	"	"			"				"	
9		"		366	"	"			"				"	
10		"		571	"	"			"				"	
11		"		856	"	"			"				"	
12	9K	-45	1090	93	"	"			"				"	
13	18K	"	"	186	"	"			"				"	
14	33K	"	"	366	"	"			"				"	
15	45K	"	"	571	"	"			"				"	
16	60K	"	"	856	"	"			"				"	
17	No Interference			No Interference			3600	Y	-58	1090			"	
18		"			"		7200	"	"	"			"	
19		"			"		No Interference				288	X	-58	1090
20		"			"				"		"	Y	"	"
21		"			"		7200	Y	-58	1090	"	"	"	"
22	45K	-45	1090	571	-45	1090	"	"	"	1090	"	"	"	"
23	60K	"	"	856	"	"	3600	"	"	"	"	"	"	"
24	"	"	"	"	"	"	7200	"	"	"	"	"	"	"
25	"	"	"	"	"	"	"	"	"	1082	"	"	"	

1. Measured at the TEU receiver input.

TABLE 2

MODE S SURVEILLANCE INTERFERENCE TESTS

Test No.	INTERFERENCE ENVIRONMENT														
	ATCRBS FRUIT			MODE S FRUIT			TACAN/DME SQUITTER				TACAN/DME INTERROGATION				
	Rate (/s)	Pwr (dBm)[1]	Freq (MHz)	Rate (/s)	Pwr (dBm)[1]	Freq (MHz)	Rate (/s)	Mode	Pwr (dBm)[1]	Freq (MHz)	Rate (pp/s)	Mode	Pwr (dBm)[1]	Freq (MHz)
26	No Interference													
27	9K	-45	1090	No Interference			No Interference				No Interference			
28	18K	"	"		"				"				"	
29	33K	"	"		"				"				"	
30	60K	"	"		"				"				"	
31	No Interference			93	-45	1090			"				"	
32		"		186	"	"			"				"	
33		"		366	"	"			"				"	
34		"		856	"	"			"				"	
35		"		No Interference			2700	Y	-58	1090			"	
36		"			"		3600	"	"	"			"	
37		"			"		7200	"	"	"			"	
38		"			"		3600	"	"	1086			"	
39		"			"		"	"	"	1084			"	
40		"			"		"	"	"	1082			"	
41		"			"		"	"	"	1080			"	
42		"			"		"	"	"	1078			"	
43		"			"		7200	"	-48	1090			"	
44		"			"		No Interference				288	X	58	1090
45		"			"		3600	Y	-58	1090	"	"	"	"
46		"			"		7200	"	"	"	"	Y	"	"
47	9K	-45	1090	93	-45	1090	"	"	"	"	"	"	"	"
48	18K	"	"	186	"	"	"	"	"	"	"	"	"	"
49	33K	"	"	366	"	"	"	"	"	"	"	"	"	"
50	60K	"	"	856	"	"	"	"	"	"	"	"	"	"

1. Measured at TEU receiver input.

The maximum TACAN/DME squitter rate was selected to be representative of a worst-case situation in which two military TACAN/DME ground beacons are located in the same place and operating at 1090 MHz. Lower squitter rates and offset RF frequencies were also tested and are more representative of possible FAA beacon channel assignments: two co-located beacons each operated at a rate of 2700 pulse pairs per second maximum and at frequencies of 1086 MHz and 1084 MHz respectively. The single TACAN/DME interrogation rate tested is representative of an airborne interrogator environment of 24 aircraft within 5 nmi of the TCAS aircraft with each transmitting 24 pulse pairs per second. The -58 dBm TACAN/DME signal level represents an average interrogator range of 2.5 nmi.

Appendix A provides a detailed description of each of the tests.

3.0 MEASUREMENT RESULTS

3.1 ATCRBS Surveillance

As noted in 2.3.1, the evaluation of a TCAS II ATCRBS surveillance processor in an interference environment was conducted by entering the recorded ATCRBS reply output of the TEU reply processor to a computer-based version of the TCAS II surveillance processor. The surveillance processor provided an output plot of range and altitude track reports on a scan-by-scan basis. This plot could than be examined for ATCRBS intruder track performance and false track generation. Figure 6, which is a portion of the track plot for test 24, illustrates the type of output used to evaluate ATCRBS surveillance performance. Each scan is represented by a symbol which denotes the condition of a target track for that scan. A plus sign indicates that an established track was updated by a correlating reply. A minus sign indicates that an established track was coasted because no correlating reply was received. A dot indicates an acquisition period in which track is not yet established and the absence of a symbol indicates a dropped track following a coast period with no updating reply.

3.1.1 Reply and Track Performance

The ability of the surveillance processor to establish and maintain track on an intruder in the presence of interference was determined by tabulating from the output track plot the number of scans associated with each of the track conditions (i.e., established track, no track and coasted track). Tables 3 and 4 summarize these results for the moving and stationary targets respectively for each of the interference environments tested. Performance values were derived for each of three separate range intervals associated with the moving target as well as for the entire 8 nmi to 0.5 nmi range interval. The three range intervals correspond to regions in which the moving and stationary target replies are non-garbling (8 to 5.7 nmi and 2.3 to 0.5 nmi) and garbling (5.7 to 2.3 nmi). The 5.7 to 2.3 nmi region provides a measure of the degarbling capability of TCAS II in an interference environment. The performance values in Tables 3 and 4 are presented in terms of reply and track probability. Reply probability for a target over any given measurement interval was computed as the ratio of the number of scans for which a correlating reply was received to the total number of scans within that interval. It should be noted that reply probability as determined here is on a per scan basis and not the probability of receiving a single correlating reply because replies from a target are generated in response to three consecutive whisper-shout interrogations each scan. Track probability for a target over any given measurement interval was computed as the ratio of the number of scans for which an established track existed to the total number of scans within that interval.

According to the track probabilities listed in Tables 3 and 4, the ATCRBS surveillance processor was able to acquire and maintain track on an intruder exceedingly well in all environments. The time of acquisition and the track

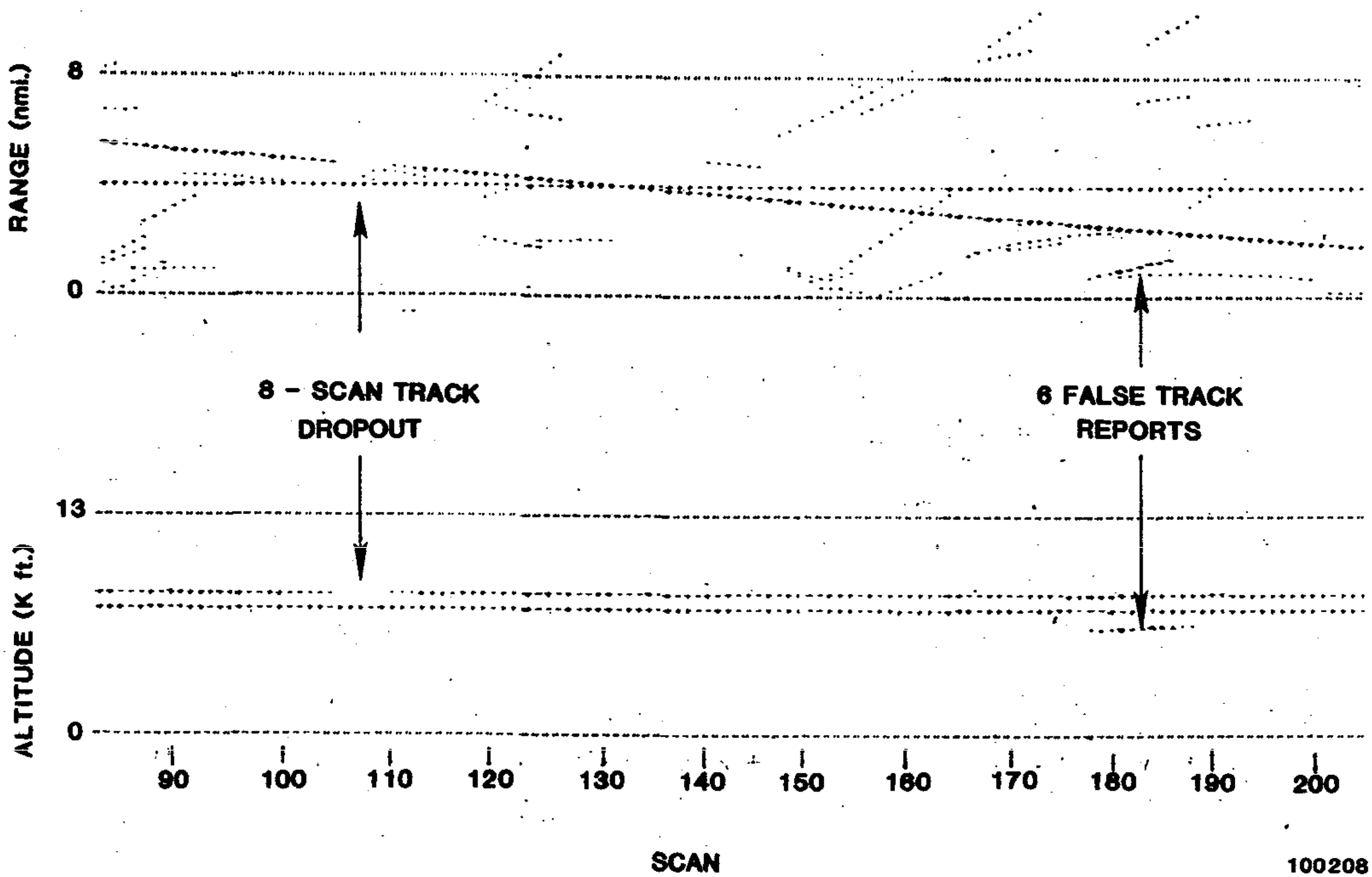

Figure 6. Partial track plot for test 24.

TABLE 3

ATCRBS SURVEILLANCE PERFORMANCE - MOVING TARGET

TEST	Interference/sec				8-5.7 nmi		5.7-2.3 nmi		2.3-0.5 nmi		8-0.5 nmi	
	ATCRBS Fruits/s	Mode S Fruits/s	TACAN/DME Squitter/s	TACAN/DME Inter's/s	Reply Prob.	Track Prob.	Reply Prob.	Track Prob.	Reply Prob.	Track Prob.	Reply Prob.	Track Prob.
1	0	0	0	0	1.0	1.0	0.84	1.0	1.0	1.0	0.92	1.0
2	9K	0	0	0	1.0	1.0	0.85	1.0	1.0	1.0	0.92	1.0
3	18K	0	0	0	1.0	1.0	0.83	1.0	1.0	1.0	0.92	1.0
4	33K	0	0	0	0.96	1.0	0.82	1.0	1.0	1.0	0.90	1.0
5	45K	0	0	0	0.90	1.0	0.80	1.0	1.0	1.0	0.87	1.0
6	60K	0	0	0	0.87	1.0	0.81	1.0	1.0	1.0	0.87	1.0
7	0	93	0	0	1.0	1.0	0.84	1.0	0.98	1.0	0.92	1.0
8	0	186	0	0	1.0	1.0	0.83	1.0	1.0	1.0	0.92	1.0
9	0	366	0	0	1.0	1.0	0.84	1.0	1.0	1.0	0.92	1.0
10	0	571	0	0	1.0	1.0	0.85	1.0	1.0	1.0	0.92	1.0
11	0	856	0	0	1.0	1.0	0.84	1.0	1.0	1.0	0.92	1.0
12	9K	93	0	0	0.97	1.0	0.84	1.0	0.98	1.0	0.91	1.0
13	18K	186	0	0	0.97	1.0	0.84	1.0	1.0	1.0	0.91	1.0
14	33K	366	0	0	0.99	1.0	0.82	1.0	0.98	1.0	0.90	1.0
15	45K	571	0	0	0.94	1.0	0.80	1.0	1.0	1.0	0.88	1.0
16	60K	856	0	0	0.88	0.97	0.83	1.0	0.91	1.0	0.86	0.99
17	0	0	3600Y	0	0.99	1.0	0.83	1.0	0.98	1.0	0.90	1.0
18	0	0	7200Y	0	0.94	0.99	0.82	1.0	0.98	1.0	0.89	1.0
19	0	0	0	288X	1.0	1.0	0.83	1.0	1.0	1.0	0.92	1.0
20	0	0	0	288Y	1.0	1.0	0.83	1.0	1.0	1.0	0.92	1.0
21	0	0	7200Y	288Y	0.94	0.99	0.77	1.0	0.98	1.0	0.86	1.0
22	45K	571	7200Y	288Y	0.67	1.0	0.71	1.0	0.93	1.0	0.75	1.0
23	60K	856	3600Y	288Y	0.88	1.0	0.75	1.0	0.93	1.0	0.82	1.0
24	60K	856	7200Y	288Y	0.57	1.0	0.65	0.94	0.95	1.0	0.70	0.97
25	60K	856	7200Y	288Y	0.79	1.0	0.76	1.0	0.88	1.0	0.80	1.0

TABLE 4

ATCRBS SURVEILLANCE PERFORMANCE - STATIONARY TARGET

TEST	Interference/sec				8-5.7 nmi		5.7-2.3 nmi		2.3-0.5 nmi		8-0.5 nmi	
	ATCRBS Fruit/s	Mode S Fruit/s	TACAN/DME Squitter/s	TACAN/DME Inter's/s	Reply Prob.	Track Prob.	Reply Prob.	Track Prob.	Reply Prob.	Track Prob.	Reply Prob.	Track Prob.
1	0	0	0	0	1.0	1.0	0.80	1.0	1.0	1.0	0.90	1.0
2	9K	0	0	0	1.0	1.0	0.79	1.0	1.0	1.0	0.90	1.0
3	18K	0	0	0	1.0	1.0	0.79	1.0	1.0	1.0	0.90	1.0
4	33K	0	0	0	1.0	1.0	0.79	1.0	1.0	1.0	0.90	1.0
5	45K	0	0	0	1.0	1.0	0.77	1.0	1.0	1.0	0.88	1.0
6	60K	0	0	0	0.94	1.0	0.75	1.0	0.96	1.0	0.85	1.0
7	0	93	0	0	1.0	1.0	0.79	1.0	1.0	1.0	0.90	1.0
8	0	186	0	0	1.0	1.0	0.80	1.0	1.0	1.0	0.90	1.0
9	0	366	0	0	1.0	1.0	0.79	1.0	1.0	1.0	0.90	1.0
10	0	571	0	0	1.0	1.0	0.80	1.0	1.0	1.0	0.90	1.0
11	0	856	0	0	1.0	1.0	0.80	1.0	1.0	1.0	0.90	1.0
12	9K	93	0	0	1.0	1.0	0.80	1.0	1.0	1.0	0.90	1.0
13	18K	186	0	0	1.0	1.0	0.79	1.0	1.0	1.0	0.89	1.0
14	33K	366	0	0	0.97	1.0	0.80	1.0	0.96	1.0	0.88	1.0
15	45K	571	0	0	0.99	1.0	0.79	1.0	0.96	1.0	0.89	1.0
16	60K	856	0	0	0.99	1.0	0.75	1.0	1.0	1.0	0.87	1.0
17	0	0	3600Y	0	1.0	1.0	0.81	1.0	1.0	1.0	0.90	1.0
18	0	0	7200Y	0	0.97	1.0	0.76	1.0	1.0	1.0	0.87	1.0
19	0	0	0	288X	1.0	1.0	0.81	1.0	1.0	1.0	0.90	1.0
20	0	0	0	288Y	1.0	1.0	0.79	1.0	1.0	1.0	0.90	1.0
21	0	0	7200Y	288Y	0.97	1.0	0.77	1.0	0.98	1.0	0.87	1.0
22	45K	571	7200Y	288Y	0.90	1.0	0.73	1.0	0.86	1.0	0.80	1.0
23	60K	856	3600Y	288Y	0.79	0.97	0.73	1.0	0.93	1.0	0.79	0.99
24	60K	856	7200Y	288Y	0.93	1.0	0.67	1.0	0.82	1.0	0.77	1.0
25	60K	856	7200Y	288Y	0.91	1.0	0.75	1.0	0.91	1.0	0.83	1.0

probability in all of the environments tested with the exception of tests 16, 18, 21, 23 and 24 matched the baseline performance exhibited in the non-interference environment of Test 1. The slightly degraded tracking performance measured in the 8-5.7 nmi region for tests 16, 18, 21 and 23 is a result of a delay in acquisition relative to the time of acquisition observed in Test 1. This is not particularly significant considering that the lowest value of 0.97 in test 16 (moving target) and test 23 (stationary target) corresponds to an acquisition delay of only two scans. The only loss of track following acquisition occured in test 24 when the target was within the garbling region of 5.7 to 2.3 nmi. The 0.94 track probability for this range interval corresponds to a loss of track for eight consecutive scans. This dropout is evident in Fig. 6 in the vicinity of scan 110.

Reply probability on a per-scan basis is also not appreciably affected by the presence of interference. The poorest reply performance observed relative to the baseline measurement occured in an environment consisting of both high ATCRBS fruit rates and high TACAN/DME squitter rates. With the exception of the 8-scan track loss in test 24, the duration of reply failures in the severest environments tested was not extensive enough to cause a track drop.

3.1.2 False Track Rate

The degree to which interference caused the ATCRBS surveillance processor to generate false tracks was evaluated by observing the total number of track reports in each test that did not associate with either of the simulated targets. Table 5 lists those tests for which false target reports were observed. To be meaningful, the number of false target reports should be compared to the number of real target reports. Traditionally, the false track performance of a TCAS has been assessed in terms of the ratio of the number of false target reports generated in a particular interference environment to the total number of real target reports generated by an aircraft population comparable to the interference environment. Since the measurements reported here were performed using a 2-aircraft population, a realistic evaluation of false track rate requires than an estimate be made of the number of aircraft that would have been present and in track for each of the interference environments tested.

For example, in Test 6 the surveillance processor generated 66 false track reports within an 8 nmi range as a result of an ATCRBS fruit environment of 60K replies per second. Assuming that each aircraft generated 200 ATCRBS fruit replies per second, the 60K replies per second total fruit rate implies that there were 300 aircraft present within detection range (30 nmi) of the TEU. The percentage of these aircraft within the 8 nmi measurement range of the TEU is determined using the high density aircraft distribution formula described in the TCAS II MOPS (i.e., a uniform-in-area distribution to 5 nmi and a uniform-in-range distribution beyond 5 nmi). This results in 80 aircraft within 8 nmi of the TEU. These aircraft are further assumed to be tracked with the same probability as measured for the two simulated targets. The false track rate in Test 6 was then computed as the ratio of measured false track reports (66) to the total of real track reports attributed to the assumed aircraft population (80 targets x 250 scans x 1.0 track probability = 20,000).

TABLE 5

ATCRBS FALSE TRACK PERFORMANCE

Test	Interference				No. of False Track Reports	Assumed No. of A/C within 8 nmi	False Track Prob. %
	ATCRBS Fruit/s	Mode S Fruit/s	TACAN/DME Squitter/s	TACAN/DME Inter's/s			
4	33K	0	0	0	6	44	0.05
6	60K	0	0	0	66	80	0.33
14	33K	366	0	0	6	44	0.05
16	60K	856	0	0	17	80	0.08
22	45K	571	7200Y	288Y	7	60	0.05
23	60K	856	3600Y	288Y	41	80	0.21
24	60K	856	7200Y	288Y	12	80	0.06
25	60K	856	7200Y	288Y	45	80	0.23

Table 5 lists for each test in which false target reports were observed, the number of aircraft assumed to be within 8 nmi of the TEU given the ATCRBS fruit rate and the MOPS aircraft distribution, and the resultant false track rate in percent. As observed in the table, the false track rates are all well within the 1% value specified in the TCAS II MOPS.

In the process of evaluating false track performance, a problem was discovered that indicated a deficiency in the non-altitude-reporting target processing function suggested by the TCAS II MOPS. The MOPS describes a technique for tracking transponder-equipped aircraft without encoding altimeters in which all replies that exhibit illegal C-bits are used. During the initial evaluation of false track performance, the ATCRBS surveillance processor, which employed the tracker for non-altitude-reporting aircraft suggested in the MOPS, generated an extremely large number of false target reports in the presence of high ATCRBS fruit rates. It was determined that the problem was due to a high degree of reply-to-reply correlation resulting from the large number of Mode A fruit replies (discrete and 1200 code) in the modeled environment. The non-altitude-reporting tracking function was then modified to accept only empty brackets, with the result that the number of false target reports diminished dramatically. For example the false target reports measured in Test 6 were reduced from 3500 to 66.

3.2 Mode S Surveillance

As noted in 2.3.2, evaluation of the Mode S surveillance processor in an interference environment was conducted in two separate stages. In the first stage the simulated GTF target scenario was used to measure Mode S reply probability as a function of reply level for each of the interference environments tested. The reply detection probabilities measured in the two most severe interference environments (Tests 49 and 50) were then used in the second stage to adjust the probability of replies recorded during an AMF flight test against an actual Mode S intruder to reflect the presence of the simulated interference. The modified AMF reply data was then processed by a computer-based version of the TCAS II Mode S surveillance processor to determine surveillance performance in each of the two worst-case environments.

3.2.1 Reply Performance

The measured curves of single reply detection probability vs. reply amplitude for each of the interference tests are presented in Figs. 7 through 11. The curves were derived using only those Mode S replies that occured within 0.05 nmi of the expected target range and whose decoded message fields matched exactly the field programmed into the target scenario. The resulting probability curves represent Mode S reply performance without error correction and therefore provide a lower bound on TCAS II reply performance in an interference environment.

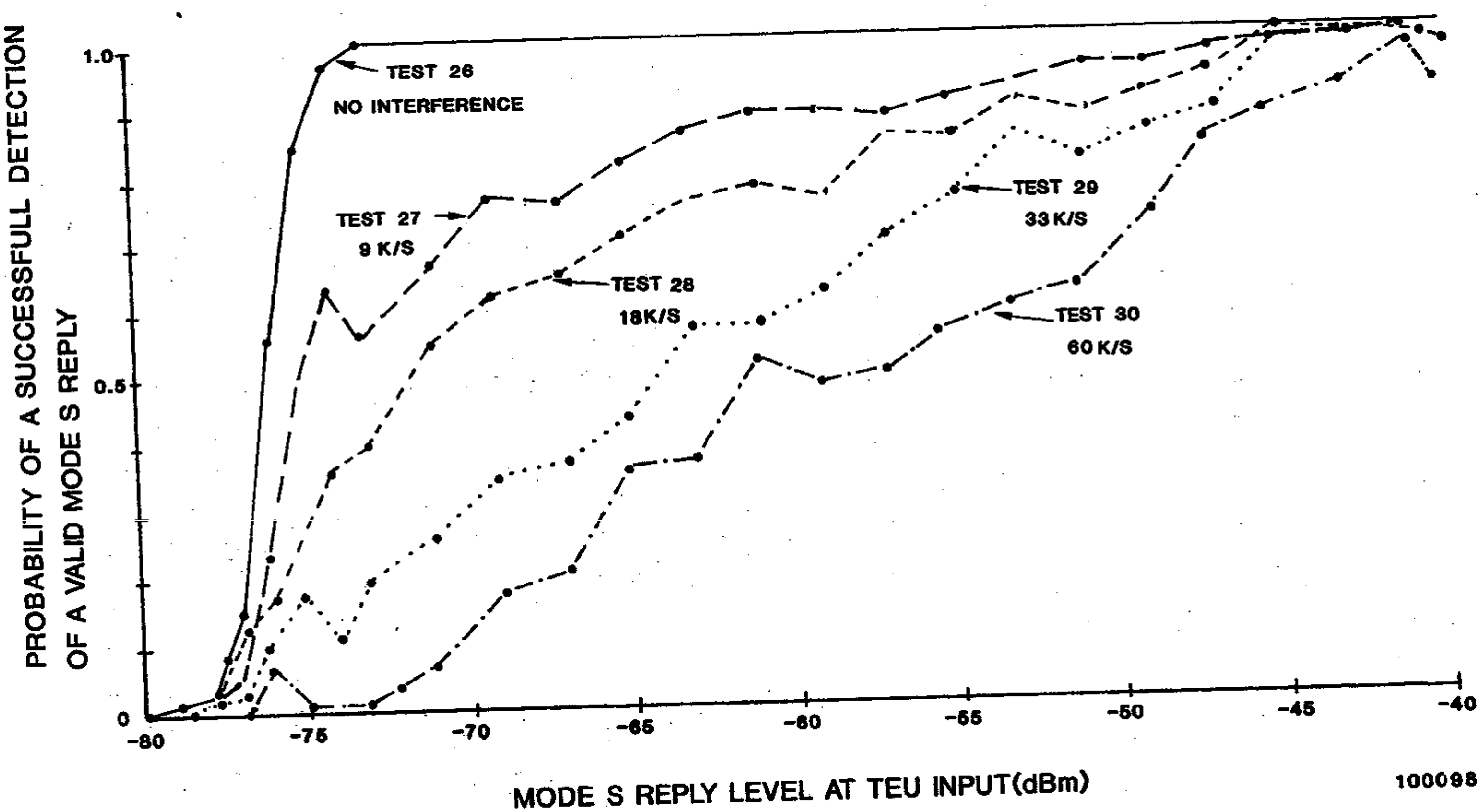

Figure 7. Mode S reply detection probability in the presence of ATCRBS fruit of various rates. (No error correction)

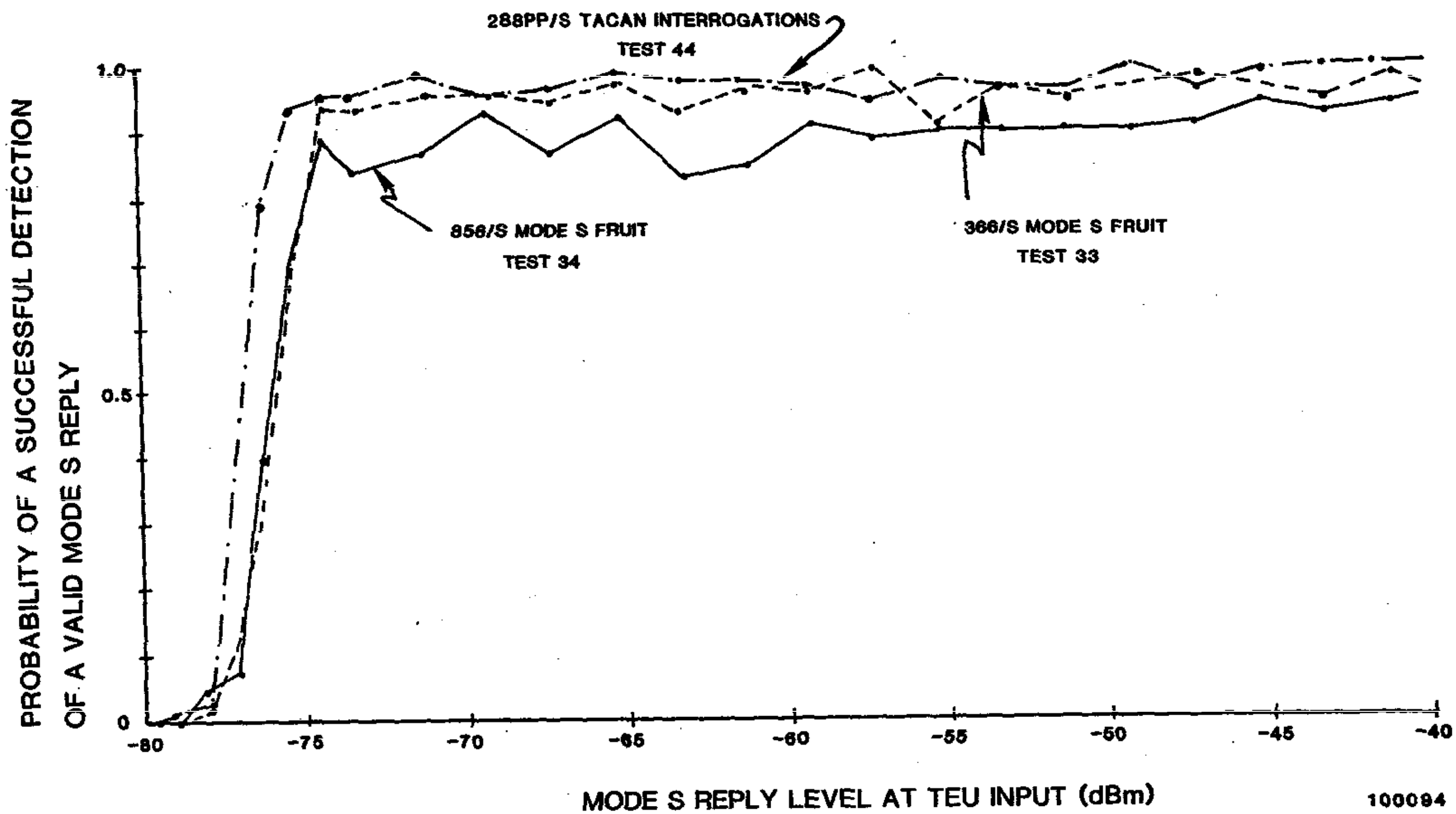

Figure 8. Mode S reply detection in the presence of Mode S fruit and TACAN/DME interrogations. (No error correction)

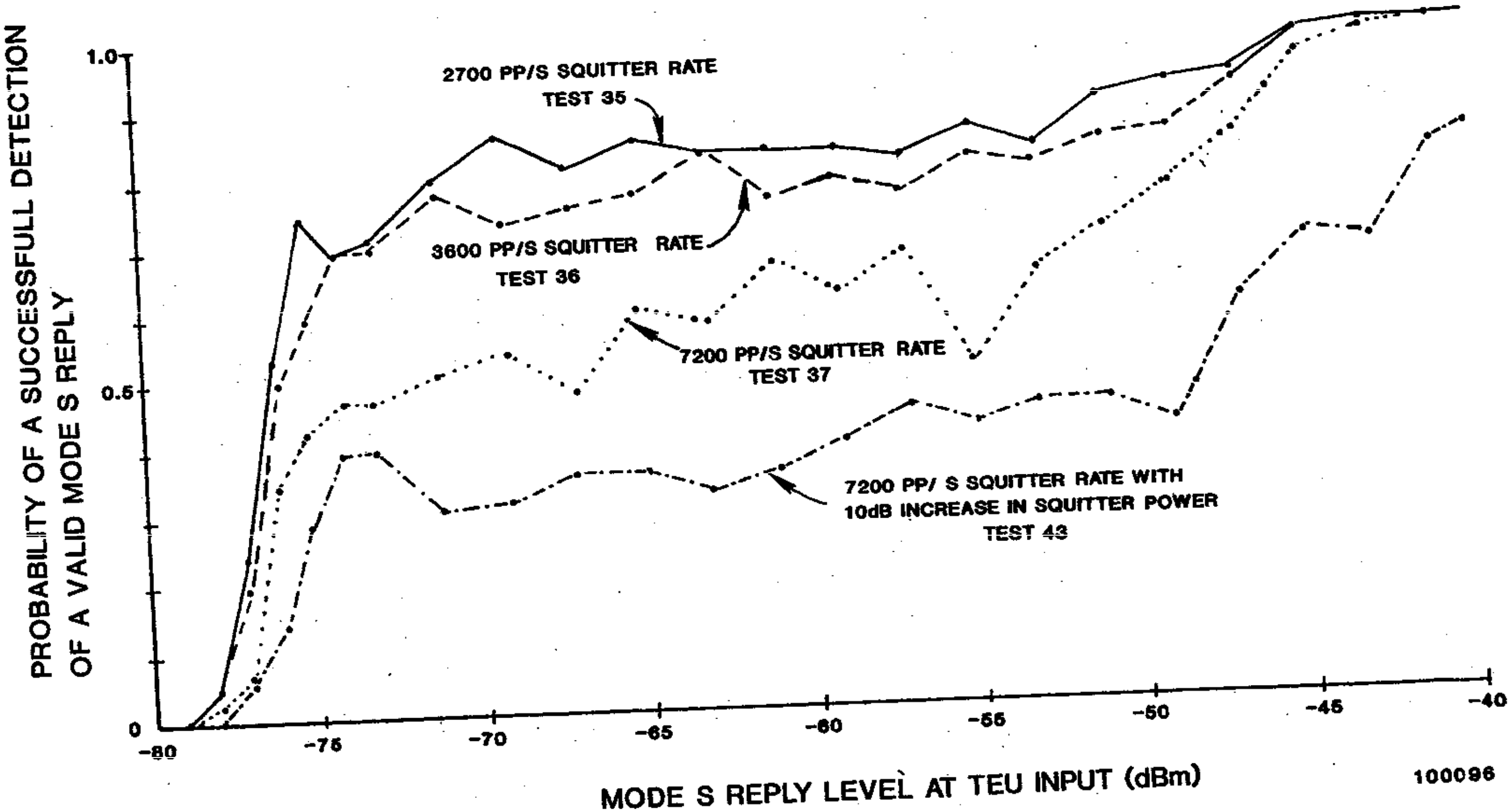

Figure 9. Mode S reply detection in the presence of TACAN/DME squitter of various rates. (No error correction).

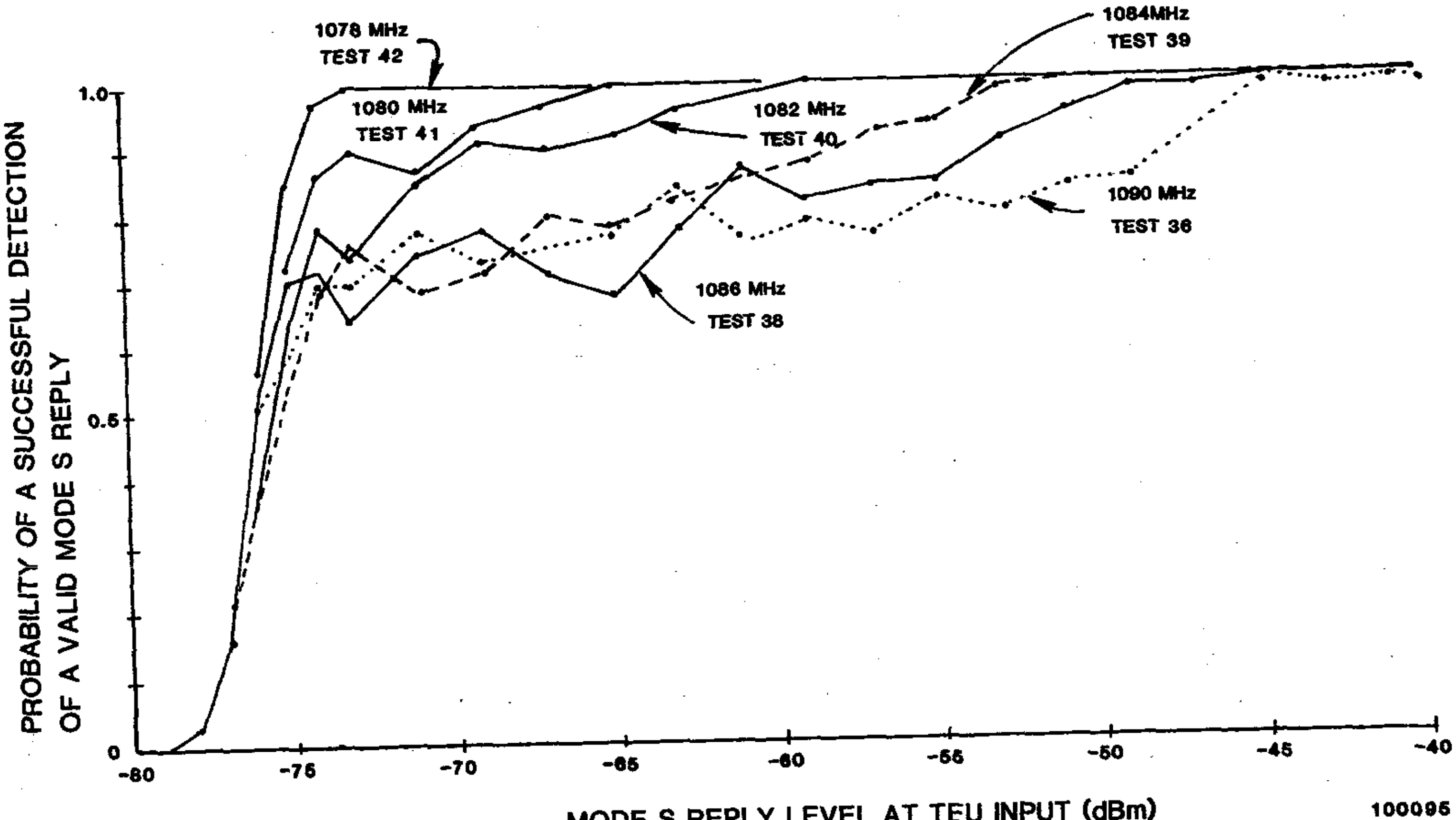

Figure 10. Mode S reply detection in the presence of TACAN/DME squitters at various RF frequencies. (No error correction)

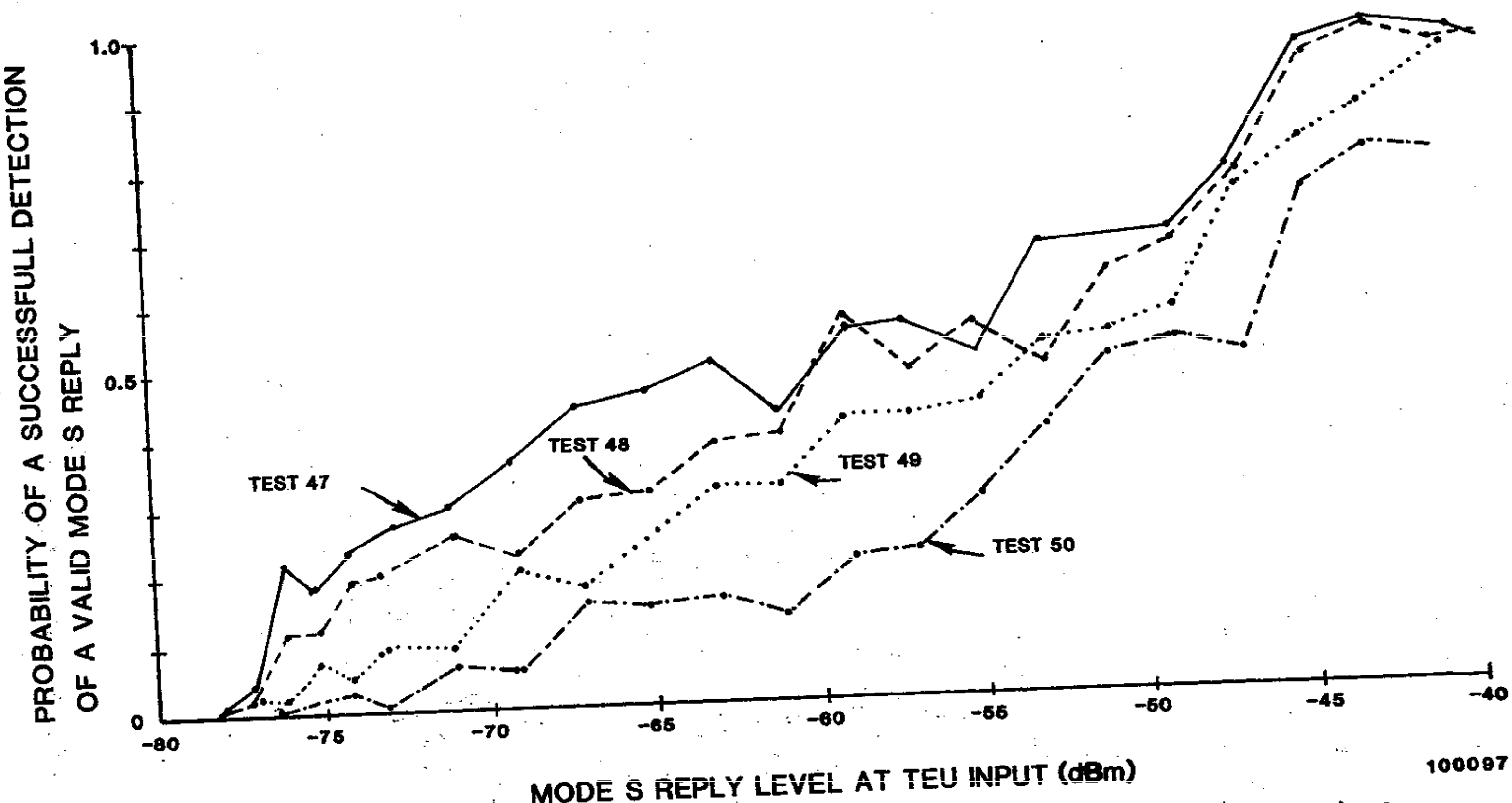

Figure 11. Mode S reply detection in the presence of combined fruit and TACAN/DME interference. (No error correction)

Figure 7 illustrates the effect of increasing levels of ATCRBS fruit on Mode S reply performance. A doubling of fruit rate within the range of 18K replies per second to 60K replies per second results in an approximate 6 dB decrease in the effective receiver threshold for a given reply performance. This is consistent with the approximate uniform-in-range amplitude distribution of the generated ATCRBS fruit. The tested low rates of Mode S fruit and TACAN/DME interrogation signals have predictably little or no effect on the Mode S reply performance as evident from Fig. 8. High rates of TACAN/DME squitter signals on the other hand degrade Mode S reply performance to an appreciable extent. Figure 9 presents Mode S reply probabilities when subjected to Y-mode squitter pulse pairs of -58 dBm amplitude at rates of 2700, 3600 and 7200 per second. The measured probabilites in Fig. 9 compare reasonably well with theoretical calculations based on the assumption that a reply would not be correctly decoded if either pulse of the squitter pulse pair overlaps any portion of the Mode S reply. For instance, the calculated probability of successful reception for squitter rates of 2700, 3600 and 7200 pulse pairs per second is 0.77, 0.7, and 0.5 respectively. Figure 10 illustrates the effect on Mode S reply performance when the RF frequency of squitter signals occuring at a 3600 pulse pairs per second rate is offset from 1090 MHz. There appears to be no appreciable improvement in performance until the squitter frequency is displaced by at least 8 MHz from the TCAS center frequency. According to Fig. 1, an 8 MHz offset results in a 15 dB reduction in squitter amplitude relative to the Mode S reply. Figure 11 presents the measured Mode S reply performance in a combined interference environment consisting of ATCRBS and Mode S fruit and TACAN/DME interrogation and squitter signals.

As mentioned earlier, the measured probabilities presented in Figs. 7 through 11 are the result of reply processing without error correction. In order to provide a meaningful evaluation of TCAS II performance in interference, the measured probabilities had to be revised to match the probabilities that could be achieved with a TCAS II reply processor with error correction. An estimate of the performance of a reply processor using error detection and correction was accomplished by first examining the message field of all scenario test target replies received in error. If the error pattern in the received message field satisfied the MOPS criteria for a correctable message, excluding any requirement associated with confidence bit declarations, (see 2.3.2), the reply was considered for this evaluation to be potentially correctable by a TCAS II. Figure 12 illustrates the possible improvement in reply performance in a 60K replies per second ATCRBS fruit environment if all of the potentially correctable replies are actually declared valid replies. Since a high density of low confidence bits in a message field can inhibit error correction, the two solid curves in Fig. 12 depict the upper and lower bounds of performance achievable by a TCAS II reply processor. Actual performance with error correction will fall somewhere in between these two curves. As mentioned in 2.3.2, a previous Mode S reply performance study (Ref. 4) indicated that the level of performance in a given fruit environment with error correction is roughly equivalent to the level of performance achievable in one-half the fruit environment with no error correction. In Fig. 12 the dashed curve illustrates the measured reply performance without error correction in an ATCRBS fruit environment of 33K replies per second.

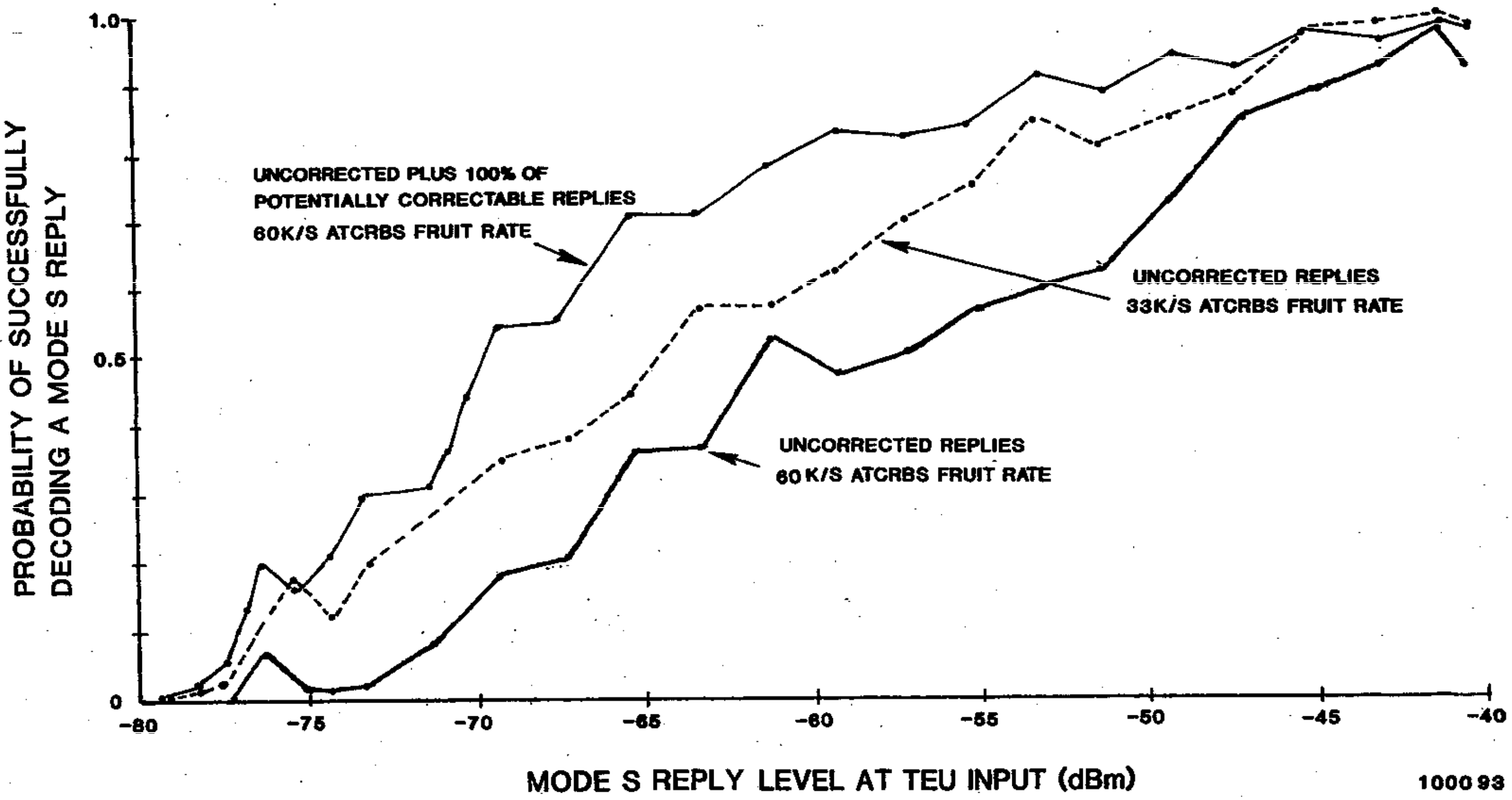

Figure 12. Mode S reply probability improvement with error correction.

According to the curves, a realistic estimate of reply performance with error correction is acheived for TCAS II evaluation if 50% of the potentially correctable replies resulting from ATCRBS fruit interference are accepted as valid replies.

TCAS II reply performance in a TACAN/DME squitter interference environment is not as readily evaluated since Mode S reply performance in real TACAN/DME interference has never been investigated. TACAN/DME squitter interference can be caused by either one or both of the pulses in a TACAN/DME pulse pair. If both pulses of a TACAN/DME pulse pair with 30 sec Y-mode spacing overlap a Mode S data field, the error span exceeds 24 data bits and the corrupted reply will not be considered a potentially correctable reply. If a single TACAN/DME squitter pulse of -58 dBm amplitude interferes with the Mode S data field, the maximum extent of the error will generally not exceed seven data bits since this is the approximate width of the gaussian-shaped pulse at a level equivalent to the MTL of the receiver. Also the span of low-confidence bits produced by the single pulse would not exceed seven data bits and because of the shape of the pulse there is little likelihood that high confidence would be associated with any of the erroneous bits. The result is that an error caused by a single TACAN/DME pulse has a high probability of being corrected by a TCAS II. In comparison, ATCRBS fruit interference can generate confidence bit patterns that would inhibit correction of what otherwise appears to be a potentially correctable Mode S reply. A conservative approach would be to assume that TCAS II reply correction performs at least as well against single-pulse TACAN/DME interference as it does against ATCRBS fruit interference. Consequently, this TCAS II evaluation considers 50% of the potentially correctable replies resulting from a TACAN/DME interference environment as valid replies.

3.2.2 Comparison of Mode S and ATCRBS Reply Performance

The recorded data allows a direct comparison of Mode S and ATCRBS single reply performance under the same conditions of signal level and interference. The Mode S reply probabilities depicted in Figs. 7 through 11 are already based on a single reply. The ATCRBS reply probabilities presented in Table 3 for the moving target are on a per scan basis and, as described in 3.1.1, is the probability of receiving a reply given three opportunities. The probability of receiving a single ATCRBS correlating reply is given as:

$$P_{single\ reply} = 1 - [1 - P_{per\ scan}]^{1/3}.$$

Four tests which employed the same interference conditions for both the ATCRBS and Mode S evaluations were selected for the comparison. In each of these tests the ATCRBS reply probability measured in the 8 to 5.7 nmi region, which is equivalent to a reply amplitude range of -65 to -62 dBm, was compared to the Mode S reply probability measured at a reply level of -63.5 dBm. Table 6 tabulates the results of the comparisons for the four different interference conditions. As seen in the table, the single Mode S reply

TABLE 6

COMPARISION OF ATCRBS AND MODE S REPLY PROBABILITIES

Test 4/29 (33K/s ATCRBS Fruit)	
Per-scan ATCRBS Reply Probability	0.96
Single ATCRBS Reply Probability	0.64
Single Mode S Reply Probability (error-free replies)	0.50
Single Mode S Reply Probability (simulated error correction)	0.65
Test 6/30 (60K/s ATCRBS Fruit)	
Per-scan ATCRBS Reply Probability	0.87
Single ATCRBS Reply Probability	0.49
Single Mode S Reply Probability (error-free replies)	0.37
Single Mode S Reply Probability (simulated error correction)	0.54
Test 18/37 (7200 pp/s TACAN/DME Squitters)	
Per-scan ATCRBS Reply Probability	0.94
Single ATCRBS Reply Probability	0.61
Single Mode S Reply Probability (error-free replies)	0.58
Single Mode S Reply Probability (simulated error correction)	0.75
Test 24/50 (Combined Worst-case Interference)	
Per-scan ATCRBS Reply Probability	0.57
Single ATCRBS Reply Probability	0.25
Single Mode S Reply Probability (error-free replies)	0.15
Single Mode S Reply Probability (simulated error correction)	0.27

probability for the case in which error correction is simulated by including 50% of the potentially correctable replies closely matches the single ATCRBS reply probability in all four interference environments. Since the ATCRBS surveillance processor performance was only slightly degraded in the worst environment tested, one would anticipate that, based on the comparison, the Mode S surveillance processor, with its ability to re-interrogate, would perform satisfactorily in the same enviroment.

3.2.3 Surveillance Performance

Evaluation of the TCAS II Mode S surveillance processor was accomplished using Mode S reply data recorded during selected AMF flight tests over land and involving head-on encounters against a single Mode S-equipped intruder. Each of the Mode S replies recorded during the flight test was first assigned an equivalent TCAS II reply probability based on the performance of the TEU reply processor measured in Tests 49 and 50. The assigned reply probabilities were used to modify the recorded flight data to resemble the output of a TCAS II reply processor operating in each of these two interference conditions. The modified reply stream was then fed to a computer-based version of the TCAS II surveillance processor for Mode S track evaluation.

Since the tested TEU did not include an error correction capability, some means was necessary to estimate the expected performance of a MOPS-configured TCAS II reply processor. In 3.2.1 it was argued that a reasonable estimate of TCAS II error-corrected reply performance is possible if 50% of the potentially correctable replies are considered as TCAS II valid replies and included with the measured error-free reply output of the TEU. The detection curves illustrated in Figs. 13 and 14 represent the estimated TCAS II reply performance and the measured TEU error-free reply performance for the environmental conditions of Tests 49 and 50 respectively. The estimated TCAS II probability curves were used to establish the probability values for each of the recorded AMF replies according to the procedure described in 2.3.2.

The expected output reply stream from a TCAS II reply processor was then simulated by comparing the new probability of detection value asigned to each received AMF reply against a value selected sequentially from a progression of random numbers. If the reply probability was equal to or greater than the random number the reply was considered to have been declared valid by a TCAS II reply processor and retained for surveillance processing.

The characteristic of the output reply stream resulting from the random number comparison was found to be dependent on the order of random numbers which in turn is dependent on the seed value used to initialize the number generator prior to each operation of the surveillance processor. The result is that, for a given set of flight and interference conditions, different seed values cause statistical variations in surveillance performance. It was determined that if a given encounter was processed repeatedly using a different seed value each time, the total cumulative track performance would stablize after about five or six trials. To ensure that the measured

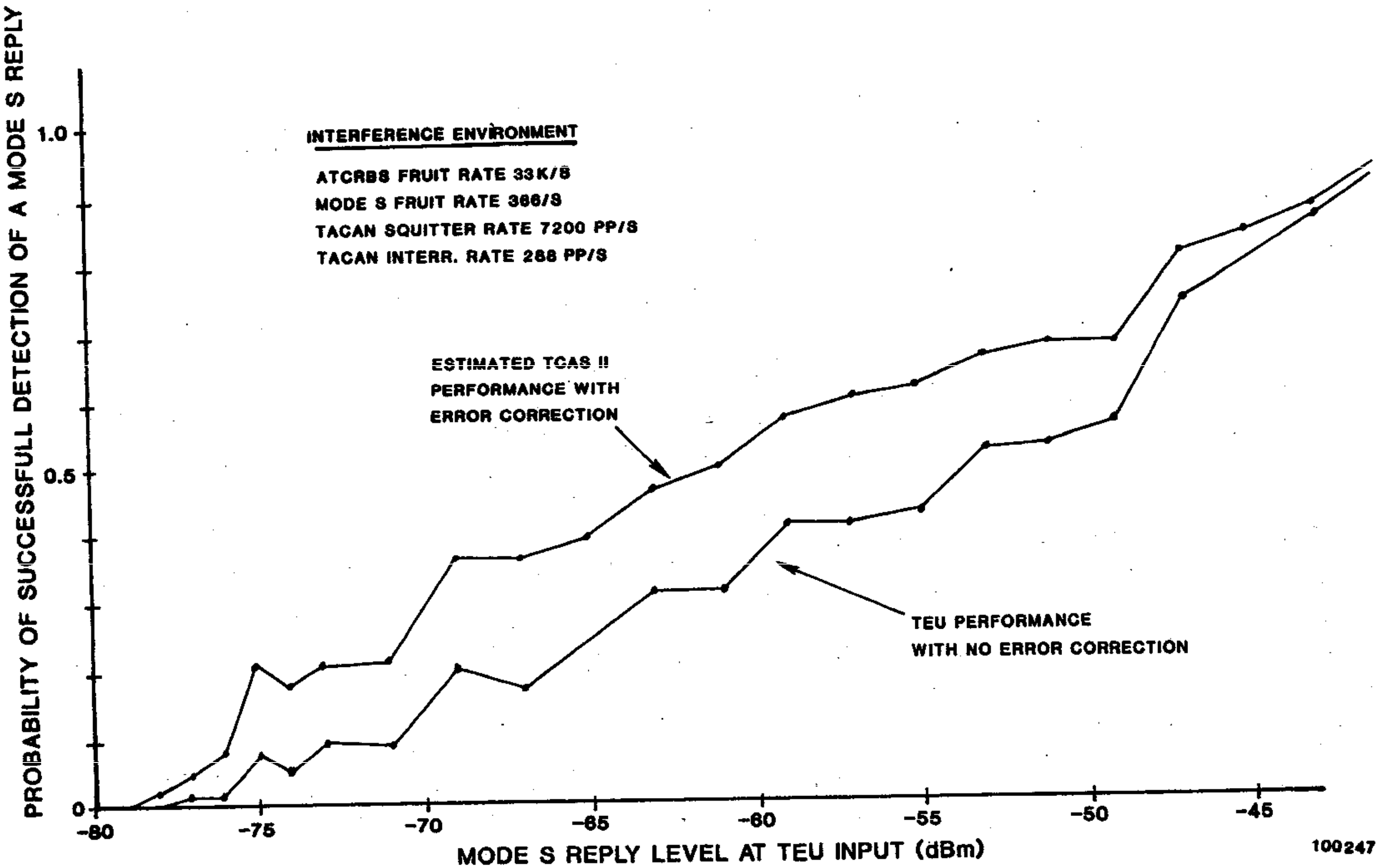

Figure 13. Mode S reply performance.

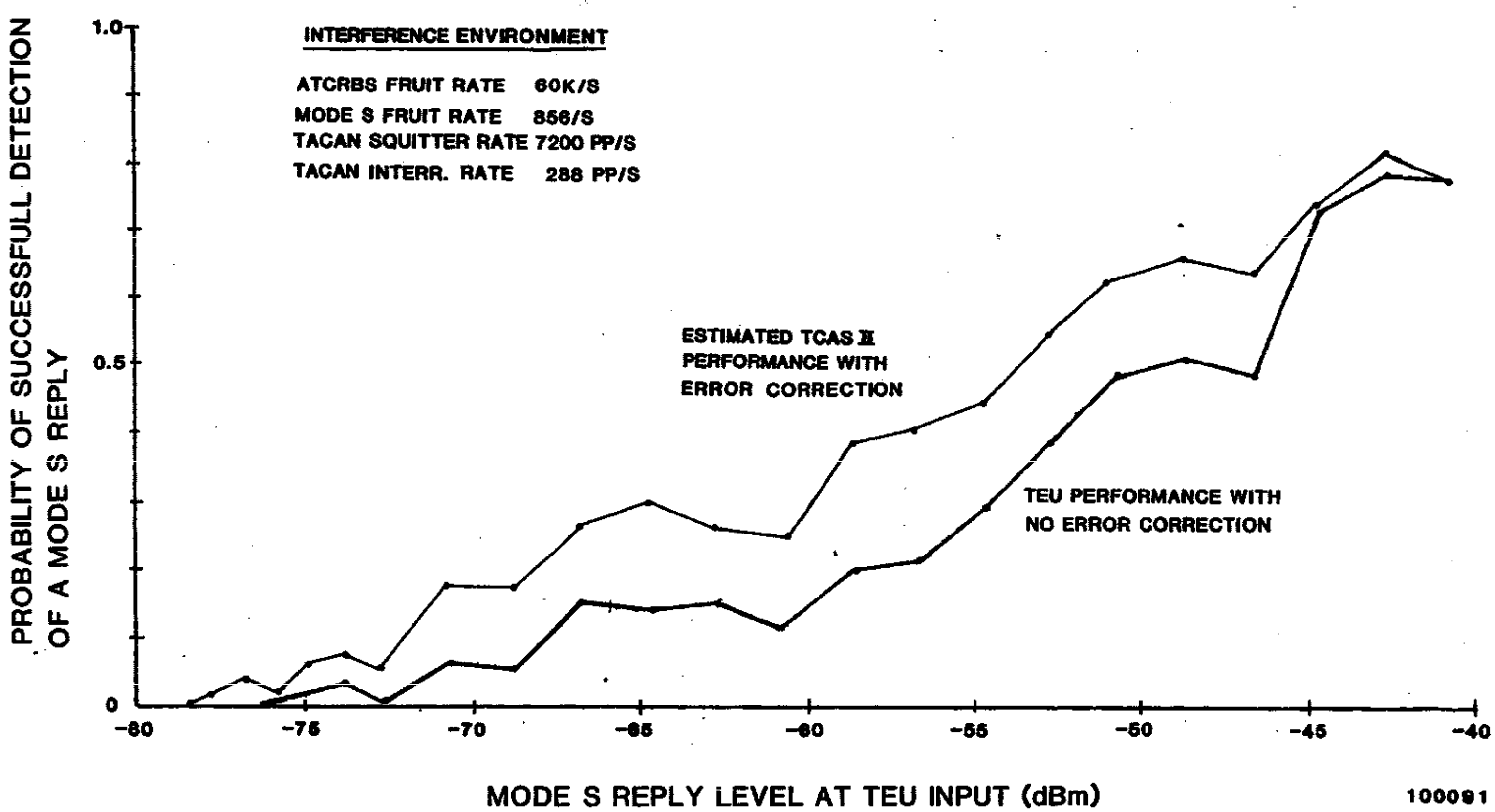

Figure 14. Mode S reply performance.

surveillance performance is independent of the initialization process, each encounter was repeated with ten different seed values.

Twelve AMF flight test encounters were used to evaluate TCAS II Mode S surveillance performance. Five of the encounters involved a Mode S intruder equipped with a Mode S diversity antenna system. The remaining seven encounters involved a Mode S intruder with a bottom-only antenna. Since the actual closing rates for the twelve encounters ranged between 209 and 324 knots, the program cycle time associated with the Mode S surveillance processor was adjusted so that each encounter appeared to be closing at a rate of 500 knots. Surveillance performance for the twelve encounters was then examined in terms of the time-before-closest-approach at which a reliable intruder track was established.

The measured performance of the TCAS II Mode S surveillance processor is illustrated in Figs. 15 and 16 for the interference environments of Tests 49 and 50 respectively. The curves represent the cumulative performance in terms of time of track of the twelve 500 knot-encounters, each processed with ten different random number seeds. The accepted criteria for TCAS II performance against an approaching intruder is that a reliable track be established early enough to provide sufficient time to react to a resolution advisory. In a high density environment with maximum 500 knot closing speeds the required time for surveillance has been established by the collision avoidance logic as 25 seconds prior to the time at which the separation becomes 0.3 nmi. In the illustrations of performance this value is represented by the threat boundary line which, for a 500 knot closing rate encounter, occurs 27 seconds before closest approach. Figure 15 shows that for an interference environment consisting of ATCRBS fruit at a rate of 33K replies per second, Mode S fruit at a rate of 366 per second, TACAN/DME squitters at a rate of 7200 pulse pairs per second and TACAN/DME interrogations at a rate of 288 pulse pairs per second, a reliable track was established on the Mode S intruder by the required time in nearly 99% of the encounters. In Fig. 16, which represents the highest environment tested, it is seen that the required surveillance performance was achieved in 85% of the encounters.

Figures 15 and 16 represent Mode S surveillance performance in an environment that contains no TCAS-equipped intruders. The presence of other TCAS aircraft will cause the interference limiting algorithms of own TCAS to reduce its Mode S interrogation power to minimize interference effects. Because the TCAS receiver sensitivity during the squitter listening period is automatically tailored to match the Mode S interrogation power level (i.e., lower power results in lower sensitivity), the effect of interference limiting is to degrade the acquisition performance of TCAS II.

Since the flight tests did not involve TCAS-equipped intruders, some means was necessary to simulate the results of interference limiting on surveillance performance. According to previous simulation studies of Mode S surveillance performance (Ref. 2), a density of 30 other TCAS-equipped aircraft within a 30 nmi range of own TCAS will generally cause interference

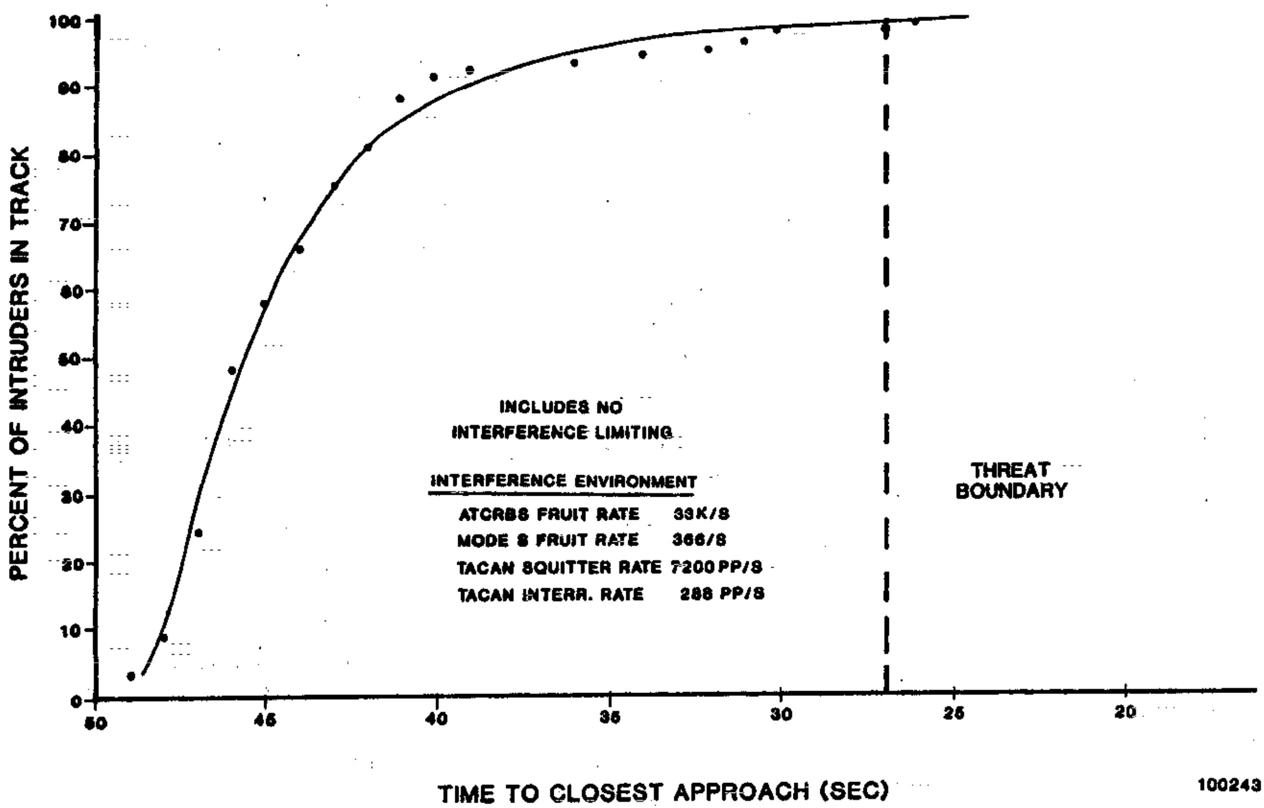

Figure 15. TCAS II Mode S surveillance performance for 500-knot encounters.

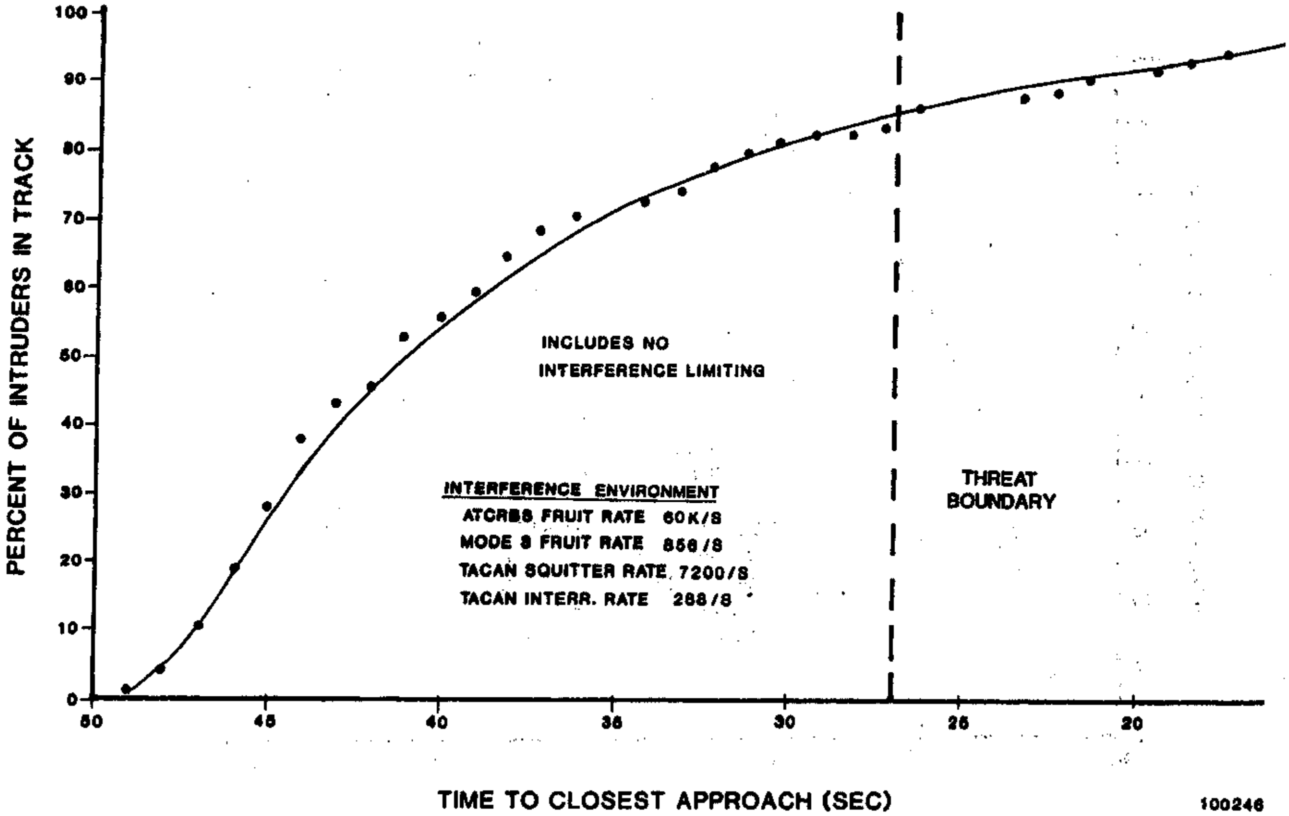

Figure 16. TCAS II Mode S surveillance performance for 500-knot encounters in the highest interference environment.

limiting to raise own TCAS receiver threshold by about 3-4 dB and certainly by no more than 6 dB. For this evaluation a 6 dB increase was selected to represent the result of an absolute worst-case TCAS environment.

A 6 dB increase in the AMF receiver threshold was simulated by reducing the reply probability associated with each recorded flight test reply by an appropriate amount. This was accomplished by first separating the effects of receiver noise and simulated interference on the overall reply probability curves of Figs. 13 and 14. The detection curve for noise alone was then raised by 6dB and recombined with the probability due to interference alone to produce a new joint probability curve. The new probability curves were then used to establish a reply stream to the surveillance processor to simulate the output of a TCAS II reply processor operating in the presence of 30 other TCAS aircraft.

The surveillance performance of TCAS II in the simulated TCAS aircraft environment was evaluated in the same manner as for the situation involving no other TCAS aircraft. Figures 17 and 18 represent the cumulative performance for the twelve encounters under the interference conditions of Tests 49 and 50 respectively and in an environment of 30 other TCAS aircraft. Figure 17 shows that the required Mode S surveillance performance was achieved by a TCAS II in 98% of the encounters when operating in an 0.3 aircraft per square nautical mile density in Los Angeles in the year 2000 and in the presence of 30 other TCAS aircraft. Figure 18 indicates that the required performance was acheived in approximately 80% of the encounters in an environment twice as severe and in the presence of 30 other TCAS.

The ability of TCAS II to provide reliable traffic advisory service in a high density environment was evaluated by examining TCAS II surveillance performance 40 seconds prior to closest approach. The 40-second value provides a 15-second search interval for visual acquisition before the occurrence of a resolution advisory. According to the performance curves presented in Figs. 15 through 18, TCAS II was able to provide adequate traffic advisories in 90% of the encounters closing at 500 knots when subjected to the environmental conditions of Test 49 and in the absence of other TCAS aircraft. In the most severe environment tested and when interference limiting was simulated, the ability to provide 40-second traffic advisories against 500 knot closing speed encounters fell short of the desired 90% performance level. Specifically, Fig. 17 indicates that TCAS II would have issued a traffic advisory no later than 33 seconds before closest approach in 90% of the encounters when operating in the anticipated Los Angeles basin environment in the year 2000 with 30 other TCAS. A 33-second traffic advisory provides a 6-second warning prior to the resolution advisory.

In 500-knot encounters against intruders with relatively low visual areas (i.e. single engine general aviation aircraft and military interceptors), the issuance of a traffic advisory 40 seconds before closest approach may not be useful to the pilot. Studies have shown (Ref. 6) that the probability of being able to visually acquire small aircraft at ranges beyond about 4 nmi is very low. This means that, in a 500-knot head-on encounter, the pilot cannot

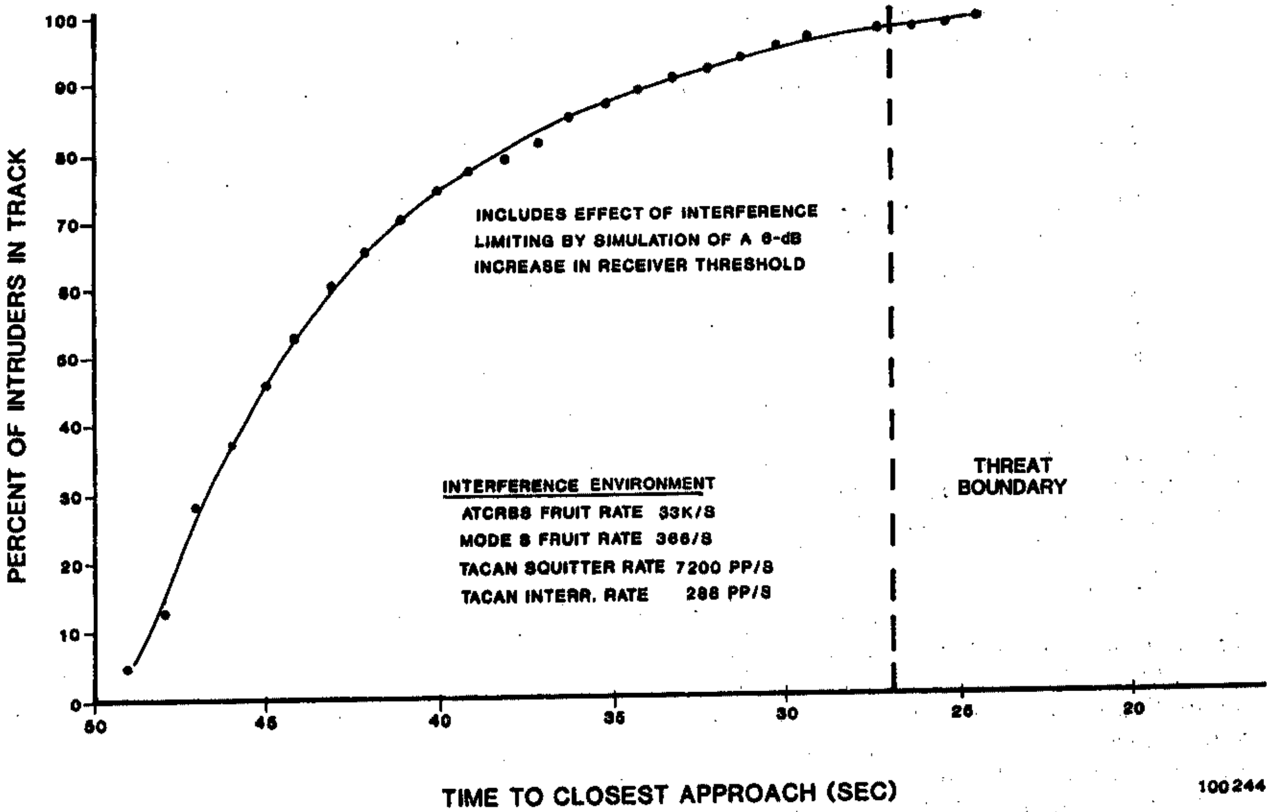

Figure 17. TCAS II Mode S surveillance performance for 500-knot encounters when interference limiting is in effect.

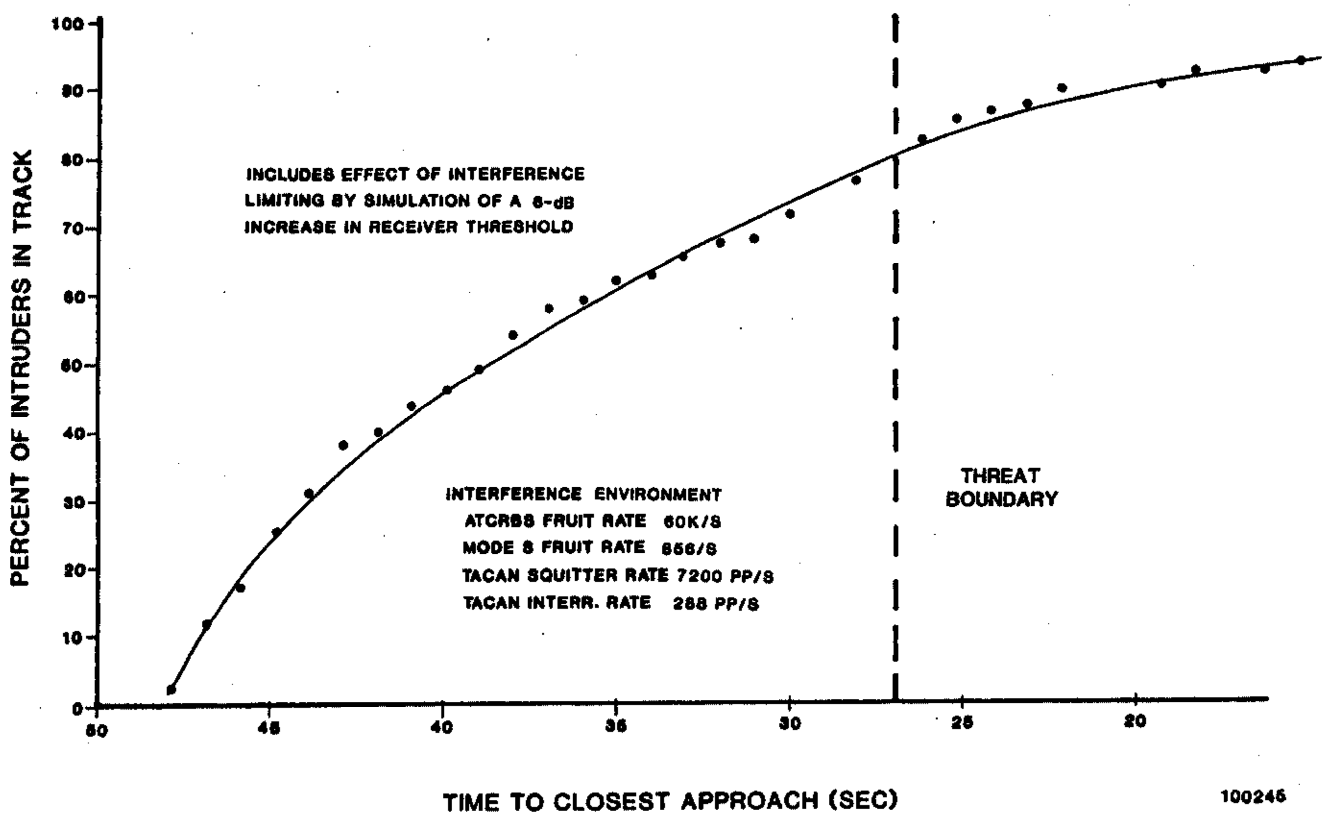

Figure 18. TCAS II Mode S surveillance performance for 500-knot encounters when interference limiting is in effect in the highest interference environment

expect to see these aircraft until they are about 30 seconds away. If it is assumed that a traffic advisory is useful only when the pilot can be expected to visually acquire the target, the measured TCAS II surveillance performance in the Los Angeles basin environment for the year 2000 and in the presence of 30 other TCAS is more than sufficient to support traffic advisory service against most general aviation and military interceptor intruders.

4.0 CONCLUSIONS

The results of the interference study indicate that the TCAS II ATCRBS surveillance processor exceeds the high density performance specified in the Minimum Operational Performance Standard For TCAS II when operating in an interference environment in which the ATCRBS and Mode S fruit rates were twice as severe as that predicted for the Los Angeles basin in the year 2000. This environment consisted of an ATCRBS fruit rate of 60K replies per second, a Mode S fruit rate of 856 replies per second, a TACAN/DME squitter rate of 7200 pulse pairs per second and a TACAN/DME interrogation rate of 288 pulse pairs per second. An ATCRBS fruit rate of 60K replies per second implies a uniform-in-area aircraft density within 5 nmi of the TCAS aircraft of 0.64 aircraft/nmi^2 if it is assumed that each aircraft generates 200 ATCRBS fruit replies per second.

Specifically, the ATCRBS processor achieved an overall track probability of 97% on an approaching intruder in this environment. The track probability was measured over an intruder range of 8 nmi to 0.5 nmi and included a 3.4 nmi region in which the intruder reply was subjected to synchronous garble from another reply. In comparison the TCAS MOPS requirement specifies that the probability of successful surveillance of an intruder in an aircraft density of 0.3 aircraft/nmi^2 shall be at least 90%. The highest false track rate measured for the ATCRBS surveillance processor within the 8 to 0.5 nmi surveillance region was 0.31%. This is well below the maximum 1.0% value specified in the MOPS.

According to the results of the study, the TCAS II Mode S surveillance processor also exceeded the high density performance level specified in the TCAS II MOPS when operating in an interference environment in which the ATCRBS and Mode S fruit rates were equivalent to that anticipated for the Los Angeles basin in the year 2000. This environment consisted of an ATCRBS fruit rate of 33K replies per second, a Mode S fruit rate of 366 replies per second, a TACAN/DME squitter rate of 7200 pulse pairs per second and a TACAN/DME interrogation rate of 288 pulse pairs per second. The ATCRBS fruit rate of 33K replies per second is equivalent to an aircraft density of approximately 0.35 aircraft/nmi^2. The performance was achieved under conditions that simulated the effect of 30 other TCAS-equipped aircraft on interference limiting and consequently on the surveillance performance of the TCAS II Mode S processor.

Specifically, the TCAS II Mode S surveillance processor, operating in this environment and in the presence of 30 other TCAS aircraft, achieved a successful track on approximately 98% of the tested 500-knot encounters early enough to be able to provide a resolution advisory at the required time. This measured performance exceeds the required 90% probability of successful Mode S surveillance specified in the TCAS MOPS. In the interference environment considered to be twice as severe as expected for Los Angeles and in the presence of 30 other TCAS, the Mode S surveillance processor established track on 80% of the tested encounters by the time a resolution advisory was required.

4.1. Recommended MOPS Changes

With one exception, a TCAS II design based on the minimum requirements described in the TCAS II MOPS will provide adequate performance in an interference environment that is equivalent to the levels projected for the year 2000. The one area of the MOPS which was found to be deficient deals with the technique suggested for tracking non-altitude-reporting targets.

The MOPS currently suggests that all replies exhibiting illegal C-bits be accepted for processing of non-altitude-reporting targets. It was discovered during the evaluation of false track performance, that this approach leads to an unnecessarily large number of false target reports. Performance is improved considerably if soley those replies containing empty brackets are used for surveillance of non-altitude-reporting targets. Therefore, it is suggested that the first sentence in the third paragraph of the note of 2.2.15.8 of the TCAS II MOPS, (Ref. 1) be modified to read as follows:

> "All replies with empty brackets are assigned a pseudo-altitude, such as 127,000 feet."

REFERENCES

1. Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System (TCAS) Airborne Equipment, RTCA/DO-185, (September 1983).

2. W.H. Harman, R.S. Kennedy, "TCAS II: Design and Validation of the High Traffic Density Surveillance Subsystem," Project Report ATC-126, Lincoln Laboratory, M.I.T., (7 June 1984), DOT/FAA/PM-84-5.

3. W.H. Harman, "Airborne Measurements of ATCRBS Fruit," Project Report ATC-84, Lincoln Laboratory, M.I.T., (3 October 1978), FAA-RD-77-149.

4. Development of a Discrete Address Beacon System, Quarterly Technical Summary, Lincoln Laboratory, M.I.T., (1 October 1976), pp. 29-32, FAA-RD-76-174.

5. G.V. Colby, "The Airborne Measurements Facility (AMF) System Description," Project Report ATC-60 Lincoln Laboratory, M.I.T., (25 March 1976), FAA-RD-75-233.

6. J.W. Andrews, "Air-to-Air Visual Aquisition Performance with TCAS II," Project Report ATC-130, Lincoln Laboratory, M.I.T., (7 November 1984), DOT/FAA/PM-84/17.

APPENDIX A

Measurement Test Procedures

Test 1 - ATCRBS Surveillance Performance Without Interference

This test is designed to establish a performance baseline for the TEU ATCRBS surveillance tracker in the absence of any interfering signals.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None
TACAN/DME Signals	= None
TEU Receiver Threshold	= -76 dBm referenced to TEU receiver input
Target Scenario	= ATCRBS

Test Procedure

Using the ATCRBS target scenario, record an ATCRBS reply tape.

Tests 2 through 6 - ATCRBS Surveillance Performance With ATCRBS Fruit Interference

These tests are designed to measure the performance of the TEU ATCRBS surveillance tracker in terms of reply detection, track probability and false track rate when subjected to various levels of ATCRBS fruit interference.

Test Parameters

ATCRBS Fruit	
Frequency	= 1090 MHz
Max Reply Amplitude	= -45 dBm at TEU input
Nominal Reply Rate	
Test 2	= 9K/sec
Test 3	= 18K/sec
Test 4	= 33K/sec
Test 5	= 45K/sec
Test 6	= 60K/sec
Mode S Fruit	= None
TACAN/DME Signals	= None
TEU Receiver Threshold	= -76 dBm referenced to TEU receiver input
Target scenario	= ATCRBS

Test Procedures

Using the ATCRBS target scenario and the ATCRBS fruit generator, record an ATCRBS reply tape for each of five ATCRBS fruit rates of 9K/sec, 18K/sec, 33K/sec, 45K/sec, and 60K/sec respectively.

Tests 7 through 11 - ATCRBS Surveillance Performance With Mode S Fruit Interference

These tests are designed to measure the performance of the TEU ATCRBS surveillance tracker in terms of reply detection, track probability and false track rate when subjected to various levels of Mode S fruit interference.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	
Frequency	= 1090 MHz
Max Reply Amplitude	= -45 dBm at TEU input
Ratio of Long to Short Replies	= 25%
Time Distribution	= Pseudo-Random
Reply Rate	
Test 7	= 93/sec
Test 8	= 186/sec
Test 9	= 366/sec
Test 10	= 571/sec
Test 11	= 856/sec
TACAN/DME Signals	= None
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= ATCRBS

Test Procedure

Using only the Mode S fruit generator whose output amplitude is varied pseudo-randomly from reply to reply and the ATCRBS target scenario, record an ATCRBS reply tape for each of five Mode S fruit rates of 93/sec, 186/sec, 366/sec, 571/sec, and 856/sec respectively.

Tests 12 through 16 - ATCRBS Surveillance Performance With Combined ATCRBS and Mode S Fruit Interference

These tests are designed to measure the performance of the TEU ATCRBS surveillance tracker when subjected to various levels of simultaneous ATCRBS and Mode S fruit interference.

Test Parameters

ATCRBS Fruit	= Same as for Tests 2 through 6
Mode S Fruit	= Same as for Tests 7 through 11
TACAN/DME Signals	= None
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= ATCRBS

Test Procedures

Using the ATCRBS target scenario and the ATCRBS and Mode S fruit generator, record an ATCRBS reply tape for each of the following five combinations of ATCRBS and Mode S fruit rates:

Test 12	ATCRBS fruit rate =	9K/sec
	Mode S fruit rate =	93/sec
Test 13	ATCRBS fruit rate =	18K/sec
	Mode S fruit rate =	186/sec
Test 14	ATCRBS fruit rate =	33K/sec
	Mode S fruit rate =	366/sec
Test 15	ATCRBS fruit rate =	45K/sec
	Mode S fruit rate =	571/sec
Test 16	ATCRBS fruit rate =	60K/sec
	Mode S fruit rate =	856/sec

Tests 17 and 18 - ATCRBS Surveillance Performance with TACAN/DME Squitter Interference

These tests are designed to measure the performance of the TEU ATCRBS surveillance tracker when subjected to interfering TACAN/DME squitters at rates of 3600 and 7200 pulse pairs per second respectively.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None
TACAN/DME Interrogations	= None
TACAN/DME Squitters	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Mode	= Y
Rate	
Test 17	= 3600 pulse pairs/sec
Test 18	= 7200 pulse pairs/sec
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= ATCRBS

Test Procedures

Using the ATCRBS scenario and the Squawk/Naut I test set, record an ATCRBS reply tape for each of two squitter rates of 3600 and 7200 pulse pairs per second.

Tests 19 and 20 - ATCRBS Surveillance Performance with TACAN/DME Interrogation Interference

These tests are designed to measure the performance of the TEU ATCRBS surveillance tracker when subjected to interfering TACAN/DME interrogations in X mode and Y mode respectively.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None

TACAN/DME Squitters	= None
TACAN/DME Interrogations	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Rate	= 288 pulse pairs/sec
Mode	
Test 19	= X
Test 20	= Y
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= ATCRBS

Test Procedures

Using the ATCRBS scenario and the TACAN/DME interrogation generator, record an ATCRBS reply tape for each of TACAN/DME interrogation modes X and Y.

Test 21 - ATCRBS Surveillance Performance with Combined TACAN/DME Squitter and Interrogation Interference

This test is designed to measure the performance of the TEU ATCRBS surveillance tracker when subjected to a combination of interfering signals consisting of TACAN/DME squitters and TACAN/DME interrogations.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None
TACAN/DME Squitters	
Frequency	= 1090 MHz
Amplitude	= -58 dBm
Rate	= 7200 pulse pairs/sec
Mode	= Y
TACAN/DME Interrogations	
Frequency	= 1090 MHz
Amplitude	= -58 dBm
Rate	= 288 pulse pairs/sec
Mode	Y
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= ATCRBS

Test Procedures

Using the ATCRBS scenario, the Squawk/Naut I test set and the TACAN/DME interrogation generator, record an ATCRBS reply tape.

Tests 22 through 25 - ATCRBS Surveillance Performance with Combined ATCRBS and Mode S Fruit and TACAN/DME Interference

These tests are designed to measure the TEU ATCRBS surveillance performance when subjected to various levels of interference consisting of a combination of ATCRBS and Mode S fruit and TACAN/DME squitter and interrogation signals.

Test Parameters

ATCRBS Fruit	
Frequency	= 1090 MHz
Max. Reply Amplitude	= -45 dBm at TEU input
Reply Rate	
Test 22	= 45K/sec
Tests 23-25	= 60K/sec
Mode S Fruit	
Frequency	= 1090 MHz
Max Reply Amplitude	= -45 dBm at TEU input
Ratio of Long to Short Replies	= 25%
Time Distribution	= Pseudo-Random
Reply Rate	
Test 22	= 571/sec
Tests 23-25	= 856/sec
TACAN/DME Squitters	
Frequency	
Tests 22-24	= 1090 MHz
Test 25	= 1082 MHz
Amplitude	= -58 dBm at TEU input
Mode	= Y
Rate	
Tests 23,24 and 25	= 7200 pulse pairs/sec
Test 23	= 3600 pulse pairs/sec
TACAN/DME Interrogations	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Rate	= 288 pulse pairs/sec
Mode	Y
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= ATCRBS

Test Procedures

Using the ATCRBS scenario, the ATCRBS and Mode S fruit generators, the Squawk/Naut I test set and the TACAN/DME interrogation generator, record an ATCRBS reply tape for each of the following four combinations of interference rates:

Test 22	ATCRBS Fruit Rate	= 45K/sec
	Mode S Fruit Rate	= 571/sec
	TACAN/DME Squitter Rate	= 7200 pp/sec
	TACAN/DME Interrogation Rate	= 288 pp/sec
Test 23	ATCRBS Fruit Rate	= 60K/sec
	Mode S Fruit Rate	= 856/sec
	TACAN/DME Squitter Rate	= 3600 pp/sec
	TACAN/DME Interrogation Rate	= 288 pp/sec

Test 24	ATCRBS Fruit Rate	=	60K/sec
	Mode S Fruit Rate	=	856/sec
	TACAN/DME Squitter Rate	=	7200 pp/sec
	TACAN/DME Interrogation Rate	=	288 pp/sec
Test 25	ATCRBS Fruit Rate	=	60K/sec
	Mode S Fruit Rate	=	856/sec
	TACAN/DME Squitter Rate	=	7200 pp/sec at 1082 MHz
	TACAN/DME Interrogation Rate	=	288 pp/sec

Test 26 - Mode S Surveillance Performance Without Interference

This test is designed to establish a performance baseline for the TEU Mode S surveillance tracker in the absence of any interfering signals.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None
TACAN/DME Signal	= None
TEU Receiver Threshold	= -76 dBm referenced to TEU receiver input
Target Scenario	= Mode S

Test Procedure

Using the Mode S target scenario, record a Mode S reply tape and determine the Mode S reply probability of detection for each of the 24 values of received reply level specified in the target scenario.

Test 27 through 30 - Mode S Surveillance Performance With ATCRBS Fruit Interference

These tests are designed to provide a measure of the Mode S reply detection probability as a function of received signal level when subjected to various levels of ATCRBS fruit interference.

Test Parameters

ATCRBS Fruit	
Frequency	= 1090 MHz
Max Reply Amplitude	= -45 dBm at TEU input
Nominal Reply Rate	
Test 27	= 9K/sec
Test 28	= 18K/sec
Test 29	= 33K/sec
Test 30	= 60K/sec
Mode S Fruit	= None
TACAN/DME Signal	= None
TEU Receiver Threshold	= -76 dBm referenced to TEU receiver input
Target Scenario	= Mode S

Test Procedures

Using the Mode S target scenario, record a Mode S reply tape and determine a Mode S reply detection probability for each of the 24 values of received reply level specified in the scenario when subjected to ATCRBS fruit rates of 9K/sec, 18K/sec, 33K/sec and 60K/sec respectively.

Tests 31 through 34 - Mode S Surveillance Performance with Mode S Fruit Interference

These tests are designed to provide a measure of the Mode S reply detection probability as a function of received signal level when subjected to various levels of Mode S fruit interference.

Test Parameters

ACTRBS Fruit	= None
Mode S Fruit	
Fequency	- 1090 MHz
Max Reply Amplitude	= -45 dBm at TEU input
Ratio of Long to Short Replies	= 25%
Time Distribution	= Pseudo-Random
Nominal Reply Rate	
Test 31	= 93/sec
Test 32	= 186/sec
Test 33	= 366/sec
Test 34	= 856/sec
TACAN/DME Signal	= None
TEU Receiver Threshold	= -76 dBm referenced to TEU receiver input
Target Scenario	= Mode S

Test Procedures

Using the Mode S target scenario, record a Mode S reply tape and determine a Mode S reply detection probability for each of the 24 values of received reply level specified in the scenario when subjected to Mode S fruit rates of 93/sec, 186/sec, 366/sec and 856/sec respectively.

Tests 35 through 43 - Mode S Surveillance Performance with TACAN/DME Squitter Interference

These tests are designed to provide a measure of the Mode S reply detection probability as a function of received signal level when subjected to various levels of TACAN/DME squitter interference.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None
TACAN/DME Interrogations	= None
TACAN/DME Squitters	

Frequency	
Tests 35,36,37 and 43	= 1090 MHz
Test 38	= 1086 MHz
Test 39	= 1084 MHz
Test 40	= 1082 MHz
Test 41	= 1080 MHz
Test 42	= 1078 MHz
Amplitude	
Tests 35-42	= -58 dBm at TEU input
Test 43	= -48 dBm at TEU input
Mode	= Y
Rate	
Test 35	= 2700 pp/sec
Tests 36,38	= 3600 pp/sec
Tests 37 and 39-43	= 7200 pp/sec
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= Mode S

Test Procedures

Using the Mode S target scenario, record a Mode S reply tape and determine the Mode S reply detection probability for each of the 24 received reply levels specified in the scenario when subjected to the TACAN/DME squitter signal characteristics listed in tests 35 through 43.

Test 44 - Mode S Surveillance Performance with TACAN/DME Interrogation Interference

This test is designed to provide a measure of the Mode S reply detection probability as a function of received signal level when subjected to TACAN/DME interrogation interference.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None
TACAN/DME Squitters	= None
TACAN/DME Interrogations	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Mode	= X
Rate	= 288 pp/sec
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= Mode S

Test Procedure

Using the Mode S target scenario, record a Mode S reply tape and determine the Mode S reply detection probability for each of the 24 received reply levels specified in the scenario when subjected to TACAN/DME interrogation interference.

Tests 45 and 46 - Mode S Surveillance Performance with TACAN/DME Squitter and Interrogation Interference

These tests are designed to provide a measure of the Mode S reply detection probability as a function of received signal level when subjected to various combinations of TACAN/DME squitter and interrogation interference.

Test Parameters

ATCRBS Fruit	= None
Mode S Fruit	= None
TACAN/DME Squitters	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Mode	= Y
Rate	
Test 45	= 3600 pp/sec
Test 46	= 7200 pp/sec
TACAN/DME Interrogations	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Rate	= 288pp/sec
Mode	
Test 45	= X
Test 46	= Y
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= Mode S

Test Procedures

Using the Mode S target scenario, record a Mode S reply tape and determine the Mode S reply detection probability for each of the 24 received reply levels specified in the scenario when subjected to the following two combinations of TACAN/DME squitter and interrogation rates:

Test 45	Squitter Rate	= 3600 pp/sec
	Interrogation Rate	= 288 pp/sec
Test 46	Squitter Rate	= 7200 pp/sec
	Interrogation Rate	= 288 pp/sec

Tests 47 through 50 - Mode S Surveillance Performance with Combined ATCRBS and Mode S Fruit and TACAN/DME Squitter and Interrogation Interference

Test Parameters

ATCRBS Fruit	
Frequency	= 1090 MHz
Max Amplitude	= -45 dBm at TEU input
Rate	

Test 47	= 9K/sec
Test 48	= 18K/sec
Test 49	= 33K/sec
Test 50	= 60K/sec
Mode S Fruit	
Frequency	= 1090 MHz
Max Amplitude	= -45 dBm at TEU input
Ratio of Long to Short Replies	= 25%
Time Distribution	= Pseudo-Random
Rate	
Test 47	= 93/sec
Test 48	= 186/sec
Test 49	= 366/sec
Test 50	= 856/sec
TACAN/DME Squitters	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Mode	= Y
Rate	= 7200 pp/sec
TACAN/DME Interrogations	
Frequency	= 1090 MHz
Amplitude	= -58 dBm at TEU input
Mode	= Y
Rate	= 288 pp/sec
TEU Receiver Threshold	= -76 dBm referenced to TEU input
Target Scenario	= Mode S

Test Procedures

Using the Mode S scenario, record a Mode S reply tape for each test and determine the Mode S reply detection probability for each of the 24 received reply levels specified in the scenario when subjected to the combination of interfering sources specified in tests 47 through 50.