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A Field Study of Transponder Performance in General Aviation Aircraft

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16. Abstract

This report documents the results of a field study conducted to sample the technical health of transponders carried by General Aviation (GA) aircraft currently operating in the National Airspace System (NAS).

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EXECUTIVE SUMMARY

INTRODUCTION.

This report documents the results of a field study conducted to sample the technical health of General Aviation (GA) transponders currently operating in the National Airspace System (NAS). The primary goals of the study were (1) to identify the overall proportion of transponders that are operating outside of performance specifications, (2) to determine whether specific types/models of transponders display any characteristic problems, and (3) to examine the operational significance of existing transponder malfunctions. Additionally, data were collected in an effort to assess the effectiveness of current biennial testing requirements for maintaining acceptable transponder performance.

Data collection took place with the permission of aircraft pilot/owners during two Experimental Aircraft Association (EAA) fly-in events and at airports located in New Jersey and Maryland. Thirty-one performance parameters were tested on 548 transponders using the Data Link and Transponder Analysis System (DATAS) developed at the Federal Aviation Administration (FAA) William J. Hughes Technical Center.

KEY FINDINGS.

Only 4 percent of the sample transponders that were tested during this study were able to meet performance specifications on all 31 test parameters. Examination of the test parameters that were commonly failed, and the magnitude of the performance deviations on these parameters, indicated that many of the detected problems would not materially affect the transponder's ability to operate with existing secondary radar and Traffic Collision Avoidance System (TCAS) processors. However, an analysis of the operational implications of some of the failures showed that approximately 17 percent of the transponders would create functionally significant problems when interacting with ground Secondary Surveillance Radar (SSR) processors, TCAS, or both. These problems included 12 percent of the transponders that would not be detected by an interrogator or would experience intermittent detection failures.

Some of the detailed findings obtained in this study were unexpected and are particularly noteworthy. Results identified a second make/model of transponder that sometimes exhibits an operational flaw originally detected in Terra transponders. These transponders fail to reply consistently to interrogations used by the Mode Select (Mode S) radar system and by TCAS to acquire targets. This failure prevents the transponders from being detected by TCAS, and would be invisible to Mode S radar if the modification introduced to deal with the Terra transponders were removed from the Mode S processor.

A second notable finding was that a large number of transponders either exhibited significant altitude errors or failed to report an altitude during testing. The result indicates that the warmup time required for transponder/altitude encoders to achieve acceptable performance might be much longer than is commonly believed.

Thirty percent of the transponders failed at least one of the seven tests that must be performed as part of the biennial inspection required by FAR Part 43. The average transponder in the sample had received its last biennial inspection approximately 16 months prior to being tested in the study. However, the data indicate that there was no correlation between the time since last inspection and the number of biennial test failures.

Although acceptable performance was not predicted by how recently a transponder had received its biennial inspection, it was significantly associated with the pilot's use of air traffic control (ATC) radar services. Less than one-half as many transponders owned by pilots who had recently flown Instrument Flight Rules (IFR) or used Visual Flight Rules (VFR) flight following failed an operationally significant test than those owned by pilots who had not used radar services. This result suggests that pilots who use radar services may be using any feedback they receive from ATC as a basis for transponder maintenance decisions.

RECOMMENDATIONS.

The results of this study were the basis for recommending the pursuit of follow-on research initiatives aimed at: (1) the in-depth investigation of operationally significant transponder failures, (2) determining the technical health of transponders carried by commercial aircraft, and (3) identifying the level of transponder and altitude encoder performance that will be needed for safe operations in the future Free Flight environment.

A further recommendation is made to examine the need for improved methods and procedures to ensure the performance of transponders operating in the NAS. It is recommended that this be accomplished by forming a special committee composed of members drawn from government, industry, and GA user organizations. As a part of its charter, the committee should be tasked to: (1) examine current and future transponder performance requirements for safe NAS operations, (2) evaluate the effectiveness of biennial tests in meeting these requirements, and (3) make recommendations for methods and evaluation procedures that would support a consistently high level of transponder performance in the GA population, and (4) assess any system safety impact with either TCAS or SSR/NAS operations if determined to be a problem and suggest corrective action.

1. INTRODUCTION.

1.1 PURPOSE.

This report documents the results of a field study conducted to sample the technical health of General Aviation (GA) transponders operating in the National Airspace System (NAS). Pilots who had flown GA aircraft to two major fly-in events in 1997 were solicited for voluntary participation in the study. Additional data were collected at airports located in New Jersey and Maryland. Thirty-one performance parameters were tested on a total of 548 transponders using the Data Link and Transponder Analysis System (DATAS) developed at the Federal Aviation Administration (FAA) William J. Hughes Technical Center.

1.2 BACKGROUND.

1.2.1 The Role of Transponders in the NAS.

Current FAA regulations stipulate that GA aircraft must carry an operating Mode C transponder when flying in all Class A, B, and C airspace, when flying within 30 miles of primary Class B airspace airports, and anytime the aircraft is above 10,000 feet. This broad requirement reflects the importance of the aircraft transponder to the maintenance of flight safety in the NAS.

The NAS is built around a surveillance capability that permits air traffic controllers to monitor aircraft movements and ensure positive separation. Air traffic control (ATC) facilities use both primary and secondary radar to accomplish this task. Primary radar emits microwave pulses that are reflected off of an aircraft's skin. The reflected echo detected by the radar provides information about the targets azimuth and range, but provides no data on altitude, and cannot uniquely identify the aircraft that it is "seeing."

Because of this, secondary radars were developed to improve aircraft tracking and separation capabilities. These systems use aircraft transponder replies to positively identify an aircraft and monitor its 3-D position in space. Depending on the type of interrogation sent out by the radar, the transponder replies with an aircraft identification code (Mode A) or altitude information (Mode C). This additional information, as well as the superior reliability of transponder replies over "skin paint" radar returns, has made the secondary radar system ATC's principal surveillance tool.

Projecting beyond the current environment, the importance of properly functioning transponders in GA aircraft may grow in the future. Current proposals under consideration by the FAA call for the use of Automatic Dependent Surveillance-Broadcast (ADS-B) by commercial aircraft. Based on

the satellite Global Positioning System, ADS-B will provide precise position information that will be broadcast by aircraft and received by the ATC system. If ADS-B is adopted, the FAA is weighing the possibility of decommissioning large primary radars for en route coverage. Such a development would remove the backup function currently provided by primary radar and presumably increase the reliance on transponders for surveillance of GA aircraft.

In addition to the ATC surveillance function provided by transponders, recent innovations in collision avoidance technology are making properly functioning of transponders an even more essential priority. The Traffic Collision Avoidance System (TCAS) equipment installed on nearly all commercial passenger air carriers gives pilots an ability to see surrounding air traffic and provides collision avoidance maneuvering advisories when needed. While this system requires a specialized Mode Select (Mode S) transponder in the TCAS-equipped aircraft, its operation depends upon the transponder replies emitted by all aircraft. Consequently, if a transponder is not performing correctly in a non-TCAS-equipped aircraft, it may not be visible, or may be reporting inaccurate information, to airliner crews.

1.2.2 GA Transponder Performance Issues.

As implied by the discussion presented above, ensuring that all transponders flying within the NAS are functioning properly is of central importance to the maintenance of flight safety. However, recent incident reports and the nature of typical GA aircraft usage suggest that the transponders carried by these aircraft may deserve particular attention.

FAR Part 43 requires that GA aircraft transponders undergo a complete bench test inspection every 2 years. The requirement applies whether or not the aircraft is flown under Instrument Flight Rules (IFR). Despite this mandatory maintenance ruling, GA aircraft have been involved in several incidents over the past few years that suggest there may be some inoperative or malfunctioning transponders in service. These incidents have included erroneous TCAS alerts in which faulty GA transponders were implicated, and the case of a specific transponder model which fails to respond properly to certain Mode S interrogations either from TCAS-equipped aircraft or from ATC ground radar systems.

It is not known whether these are isolated cases or if they are indicative of a more widespread problem. The current mechanism for uncovering transponder problems is the reporting of "untracked" aircraft by FAA surveillance systems. Unfortunately, since GA aircraft often fly under Visual Flight Rules (VFR) without radar service, the opportunity to monitor the functioning of the transponder population by this means is extremely limited. In addition, there is

no system in place to gather and analyze the results of mandatory biennial GA transponder certification checks.

While it is difficult to estimate the number of GA aircraft that may be equipped with faulty transponders, it is possible to construct a profile of those aircraft whose pilots may fail to obtain regular operational checks of their transponders through contact with ATC. According to recent statistics (reference 1), there are approximately 140,000 fixed-wing, single piston engine aircraft operating in the NAS. Of these, 81 percent are equipped with transponders, and 68 percent of the owners list the aircraft's primary use as "personal/ recreational." As a group, these aircraft fly nearly 8 million hours each year without flight plans (47 percent of all hours). Seventy-two percent of their flights (nearly 17 million annually) are completed in the local area rather than involving cross-country trips.

These data suggest that a substantial number of private aircraft hours are flown each year under conditions that are not conducive to providing feedback to the pilot regarding the operational performance of the aircraft's transponder. In order to evaluate the magnitude of the risk that these aircraft may pose to system safety, research must be conducted to assess the health of the GA transponder population.

2. OBJECTIVE.

The overall objective of this study was to obtain an estimate of the status of the GA transponder population using *in situ* technical measurements of a relatively large sample of systems currently operating in the NAS. The primary goals of the study were to identify the overall proportion of transponders that are operating outside of specifications on one or more performance parameters, to determine whether specific types/models of transponders display characteristic problems, and to examine the operational significance of existing transponder malfunctions. Additionally, data were collected in an effort to assess the effectiveness of current biennial testing requirements for maintaining acceptable transponder performance.

3. STUDY CONDUCT.

3.1 TEST PROCEDURES.

The GA aircraft of primary interest to this study were those that are privately owned and typically operated for personal business and recreational purposes. Aircraft in this category are based at numerous airports that are widely distributed throughout the United States. In order to resolve the problem of testing significant numbers of the transponders carried by such aircraft within a reasonable period of time, most data collection for this study (476 aircraft) was

conducted at airports hosting two of the annual Experimental Aircraft Association (EAA) fly-in events. An additional 72 aircraft were tested at three airports located in New Jersey and Maryland.

Data collection at the fly-ins occurred with the permission of the organizers at the Lakeland, FL Airport during Sun 'n Fun (April 1997), and at the Oshkosh, WI Airport during the EAA Annual Convention (July 1997). Both of these annual events attract large numbers of aviators from across the country who fly to the location and stay for several days to attend workshops, visit vendors, and view demonstrations. Many aircraft are parked in designated camping areas for the duration of the pilot's stay.

Test personnel approached pilots whose aircraft were located in the camping areas to secure participation in the study. Potential volunteers were informed that the results of the tests were unofficial, that no FAA actions against individuals would be taken based on the findings, and that the results would be reported anonymously.

Pilots who agreed to participate in the test were interviewed and asked to provide the following information:

a. Aircraft tail number,

b. Aircraft manufacturer and model,

c. Transponder manufacturer and model,

d. Approximate time since last biennial transponder check required under FAR Part 43,

e. Whether they had flown the aircraft IFR or had used VFR flight following within the past 3 months.

The fifth question listed above was asked in order to determine whether the pilot had recently received operational feedback regarding the performance of their transponder by requesting radar service from ATC.

The transponder tests were carried out using specialized equipment installed in a motorized FAA Technical Center van (see section 3.2) that was driven to each volunteer pilot's aircraft. To conduct a test, the owner was asked to dial "7777" as the transponder code and to place the transponder in the standby mode to allow for a limited warmup of the equipment while conserving aircraft battery power. A low gain, 1090 megahertz (MHz) horn antenna mounted on a dolly was wheeled to the aircraft and positioned below the transponder antenna,

which was typically located on the belly of the aircraft fuselage. When the antenna was in place, the pilot was instructed to turn the transponder from standby to the "ALT" mode. This setting enables altitude reporting and permits the transponder to respond to all types of interrogations sent by the secondary radar system and by TCAS-equipped aircraft.

The equipment then interrogated the transponder and recorded data on 31 performance variables. Normally, the test sequence was performed twice on each aircraft to insure reliability. In cases where suspected anomalies were observed, additional repetitions of the test sequence were conducted. The testing was ordinarily concluded within 3 to 4 minutes. Upon completion of the test, the pilots were informed of their results and reminded to set the transponder to the standard VFR code (1200).

3.2 TEST EQUIPMENT AND MEASURES.

3.2.1 DATAS Background.

Over the past decade, the Data Link Branch (ACT-350) of the William J. Hughes Technical Center has developed a unique capability to monitor and analyze the components of secondary surveillance radar (SSR) systems and their operational performance. The DATAS is a versatile and portable system which can test and emulate SSR systems such as the Air Traffic Control Radar Beacon System (ATCRBS) and the Mode S system. It is also capable of evaluating the performance of aircraft transponders, the Traffic Alert and Collision Avoidance System (TCAS), and Data Link systems which rely on secondary radar transmissions.

DATAS has been used in a variety of applications. The system was modified to monitor TCAS performance at the Dallas/Fort Worth Airport in order to investigate reports of greater than expected numbers of conflict resolution advisories in the area (reference 4). DATAS also was used to investigate radar track coasting problems observed by controllers at the Chicago O'Hare Terminal Radar Approach Control (TRACON) (reference 3). This flight test project focused on the rate of transponder interrogations in the area to determine whether TCAS was producing significant competition with the ATCRBS function of the radar for transponder utilization.

Pagano, Wapelhorst, and VanDongen (references 2 and 5) used DATAS to examine the ATCRBS environment at the John F. Kennedy Airport in New York and at the Los Angeles International Airport. The system was configured to store all interrogation and reply data for extended periods. DATAS detected a number of flights at both locations whose transponders had used illegal Mode S identification codes, as well as other anomalies that could interfere with proper

surveillance and/or TCAS performance. Recently, Wapelhorst and Pagano (reference 6) deployed DATAS to Frankfort, Germany, to perform similar tests of the mutual interaction of TCAS and ATCRBS functions and its potential impact.

3.2.2 Application of DATAS to GA Transponder Testing.

For the present study, rather than acting in a passive monitoring mode, DATAS was used to simulate the functions of an active SSR ground sensor. Interrogation signals from DATAS were varied from nominal values (center of range variation) in order to assess transponder acceptance/rejection characteristics. A schematic diagram of DATAS, as it was configured for close-coupled transponder testing, is presented in figure 1.

As shown in figure 1, DATAS is composed of a several computers, display terminals, and specialized hardware components linked by a standardized communications network. A Motorola 68060 computer system controlled the automated test sequence to interrogate the aircraft transponder through the radio frequency (RF) unit that drove the portable antenna. The computer also recorded the raw transponder replies. The system was tested and calibrated at regular intervals during data collection using a reference baseline transponder connected to the RF unit. A second Motorola 68060 system was used for off-line data analysis. Peripheral personal computers (PCs) were used to view the data and monitor the data collection process.

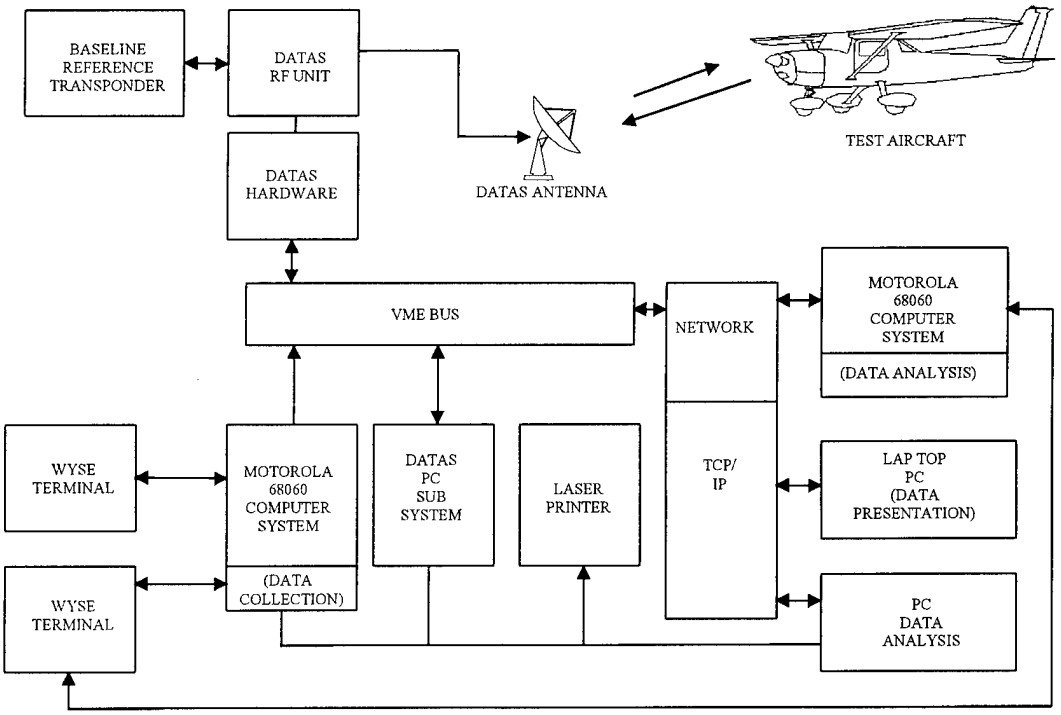

FIGURE 1. DATAS CONFIGURATION FOR GA TRANSPONDER TESTS

3.2.3 Test Parameters.

Analysis of the data recorded for each transponder yielded data on 31 performance parameters (see table 1). As noted in the table, seven of these parameters are evaluated during the biennial inspection required by FAR Part 43. Pass/fail criteria for all 31 parameters were derived from published specifications for ATCRBS transponders (ATCRBS/Mode S Minimum Operational Performance Standards - DO-181, Minimum Operational Characteristics for Airborne ATC Transponder Systems - DO-144, FAA Technical Standard Order - TSO-C74C, and Federal Aviation Regulations Part 43 – Appendix F). In cases where these documents specified different performance criteria for a parameter, the least stringent specification was adopted for the test. The test performance criteria that were applied for the parameters are summarized in appendix A of this report.

TABLE 1. DATAS GA TRANSPONDER TEST PARAMETERS

INTERROGATION PARAMETERS	REPLY PARAMETERS
Receiver Sensitivity * Mode A * Mode C * Mode A-C Sensitivity Difference	* Reply Frequency
Suppression Duration Mode A Mode C	* Reply Power
Suppression Reinitiation Mode A Mode C	* Altitude Report Error
Simultaneous Mode A and C Response	Pulse Error referenced to F1
ATCRBS/Mode S All-Call Protocol (Terra Characteristic Test)	Pulse Error referenced to all Others
SLS Suppression Position Acceptance Rejection	Bracket Spacing
* SLS Suppression Ratio Acceptance Rejection	Reply Pulse Width
Pulse Position – Accept Mode A Mode C	Reply Delay Mode A Mode C Mode A-C Delay Difference
Pulse Position – Reject Mode A Mode C	
Pulse Width – Accept Mode A Mode C	
Pulse Width – Reject Mode A Mode C	

• Parameter is included as a part of mandatory biennial transponder test

4. RESULTS.

4.1 AIRCRAFT AND TRANSPONDER SAMPLE CHARACTERISTICS.

The aircraft carrying the 548 transponders tested in this study were broadly representative of the population of fixed-wing GA aircraft currently operated in the NAS for recreational and private business purposes. Over 95 percent of the aircraft were "modern" production models, with the remainder of the sample comprising a mixture of experimental/homebuilt, classic/antique, and war bird types. Seventy-four percent of the aircraft were manufactured by Cessna, Piper or Beech. The most common aircraft models in the sample were the Piper PA-28 (16 percent) and the Cessna 172 (12 percent). The oldest aircraft in the sample was a Curtis Wright Robin built in 1929. The newest was an Aviat A-1 built in 1996. The median aircraft age was 28 years. Seventy-five percent were built between 1961 and 1979, while 17 percent were built prior to 1961, and 8 percent were built after 1979.

The transponder sample was composed of 34 different models commercially distributed under 12 different brand names. However, King Radio (45 percent) and Narco (34 percent) manufactured a majority of the transponders. Figure 2 presents a breakdown of the transponder sample by manufacturer and model. As shown in the figure, the most popular transponder was the King KT76A which comprised 28 percent of the units that were tested. The Narco AT150 model was the second most common unit (18 percent), and the Narco AT50 was third with 12 percent. The only other transponder that made up at least 10 percent of the sample was the King KT76. None of the 24 models categorized as "all others" in figure 2 constituted more than 1 percent of the sample.

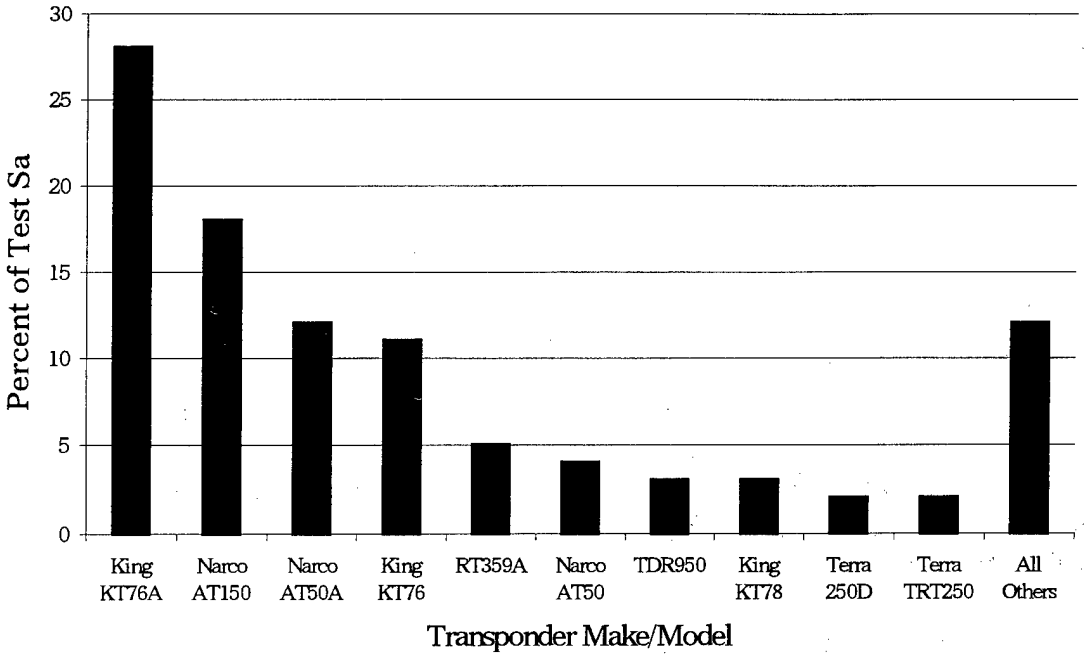

FIGURE 2. TRANSPONDER SAMPLE COMPOSITION

4.2 TRANSPONDER TEST PERFORMANCE.

This section presents the results of the transponder tests referenced to the technical performance criteria listed in appendix A. These criteria are based on FAA specifications for the performance of Mode C transponders. Section 4.3 presents an analysis of the operational significance of the test failures described here.

As noted earlier in this report, the 548 transponders were tested in three different groups during the spring and summer of 1997. Data collection on 72 transponders occurred at small airports in New Jersey and Maryland during March and early April, 246 were tested at a fly-in in Lakeland, FL, in late April and 230 were tested at the fly-in at Oshkosh, WI, during late July and early August. In order to determine whether the pattern of test performance differed among the testing sites and time periods, statistical comparisons of failure rates on each of the 31 test parameters were performed. Coefficients of correlation computed between the groups revealed a high degree of agreement among the test results (average r = .91). Because of this homogeneity among the findings, the data produced by the three groups were combined for detailed analysis.

4.2.1 Overall Sample Performance.

Figure 3 presents an overall picture of the number of tests that were failed by the combined transponder sample. As indicated by the figure, only 4 percent of the transponders succeeded in meeting the performance criteria on all of the 31 tests, while approximately 6 percent failed more than 10 of the tests. The average transponder failed just over three tests.

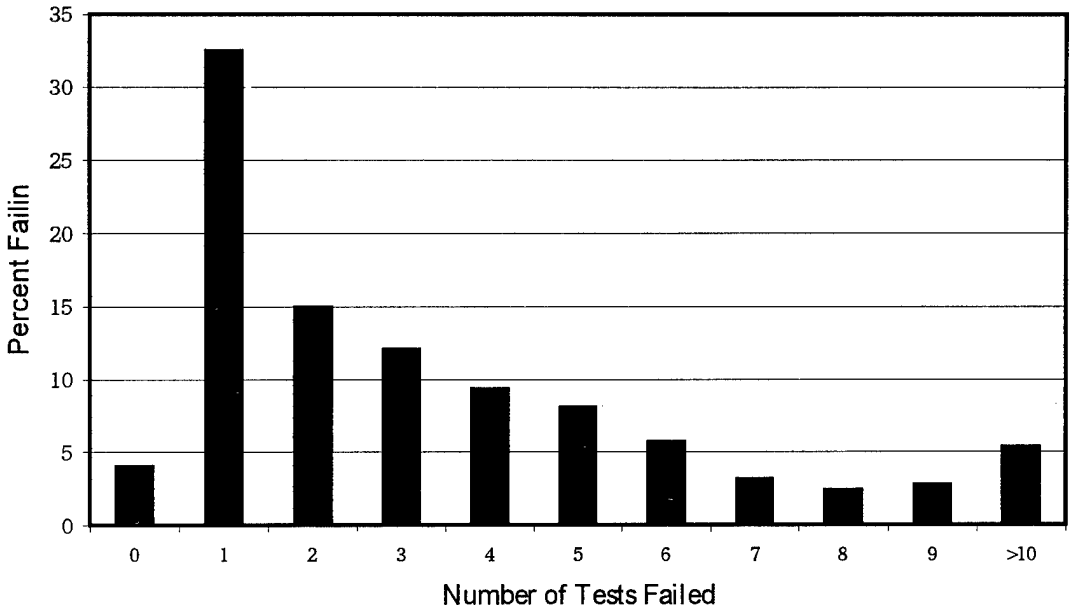

FIGURE 3. PERCENT OF TRANSPONDERS THAT FAILED TESTS

4.2.2 Failure Rates for Each Test.

Table 2 lists the transponder parameters along with the absolute number and percent of failures on each test in the combined sample of 548 units. The following paragraphs describe these findings in detail under the headings of individual and grouped tests.

Mode A and Mode C Sensitivity.

These tests are measures of the interrogation power required from an ATCRBS site to solicit a reply. Approximately 6 percent of the aircraft failed the tests. A failure in this parameter would result in occasional loss of the target when the signal is already weak as a result of some other effect such as an aircraft turn, weak coverage area, etc. Each 6-decibel (dB) reduction in sensitivity results in a reduction in the range of coverage by 50 percent.

TABLE 2. FAILURE RATES FOR 31 TRANSPONDER TESTS

Number of Aircraft Transponders	548	
TEST	Number of Failures	Percent Failures
Mode A Sensitivity	33	6.0
Mode C Sensitivity	32	5.8
A-C Sensitivity Difference	17	3.1
Reply Frequency	50	9.1
Reply Power	31	5.7
Altitude Error	21	3.8
Pulse Error–Ref F1	29	5.3
Pulse Error-Ref Others	10	1.8
Bracket Spacing	23	4.2
Reply Pulse Width	25	4.6
Reply Delay (Mode A)	9	1.6
Suppression Accept-Position	28	5.1
Suppression Rejection-Position	227	41.4
Suppression Accept-Ratio	18	3.3
Suppression Rejection-Ratio	33	6.0
Mode A Accept-Position	14	2.6
Mode A Reject-Position	14	2.6
Mode C Accept-Position	26	4.7
Mode C Reject-Position	28	5.1
Mode A Pulse Width-Accept	11	2.0
Mode A Pulse Width-Reject	147	26.8
Mode C Pulse Width-Accept	17	3.1
Mode C Pulse Width-Reject	144	26.3
ATCRBS All Call Test	17	3.1
Simultaneous A-C	221	40.3
Suppression Duration-Mode A	30	5.9
Suppression Duration-Mode C	48	9.4
Reply Delay (Mode C)	9	1.6
A–C Reply Delay Difference	23	4.2
Suppression Reinitiation-Mode A	24	4.4
Suppression Reinitiation-Mode C	38	6.9
Failed All Tests	12	2.2

Mode A-C Sensitivity Difference.

This parameter is the difference between the measured Mode A and Mode C sensitivities for a transponder. Mode A provides the identity of the aircraft and

Mode C, the altitude. The range of variation for this parameter is very narrowly defined by the specification (+/- 1 dB). Three percent of the transponders failed to meet the specified limits. However, this group deviated from the specification by only 1 dB. Because of the tolerances of current ATCRBS systems, this degree of variation should not affect operational performance.

Reply Frequency.

This parameter was failed by 9 percent of the aircraft. The allowable reply frequency deviation is +/- 3 MHz. The largest deviation measured for a transponder was approximately 7 MHz. With large deviations, the replies from the transponder begin to split into two narrow pulses where only one should be. This phenomenon would not occur until the frequency deviated from the nominal value by more than the 7 MHz that was measured. However, the 7 MHz frequency deviation would result in reply amplitudes that are lower than normal. This could create a secondary effect if it occurred in conjunction with another factor that weakened the reply signal strength.

Reply Power.

This parameter, which describes the strength of the reply from the transponder, was failed by 5.7 percent of the transponders. The effect of low reply power is similar to a failure of the Mode A and Mode C sensitivity parameters, in that it would result in an occasional loss of the target when the signal is already weak.

Altitude Error.

The altitude measurement recorded for a transponder was the most accurate altitude reported during the test. Many transponders reported erroneous altitudes during initial phases of testing shortly after starting to reply with altitude data. If the aircraft eventually replied with the correct altitude, it received a passing score on the test.

The transponders that failed this test were those that reported altitudes that deviated by more than 200 feet from the correct altitude. Overall, 3.8 percent of the aircraft failed the test. Three of the 21 failures were 500, 600, and 11,600 feet from the correct altitude. Such errors are of particular importance to TCAS systems, which may initiate evasive maneuvers on the basis of erroneous altitude data.

Twenty-one percent of the transponders did not provide an altitude response during testing. This result is most likely to have occurred because the transponders and altitude encoders had insufficient time to warmup during the

tests. The finding is nonetheless significant since most of these transponders were tested repeatedly over a period of at least 10 minutes in an attempt to record an altitude reading. The results suggest that extended warmup times in many transponders could lead to the absence of altitude information in transponder replies to both ATCRBS and TCAS during a significant portion of the early phases of flight following departure.

Pulse Error with respect to F1, Pulse Error with respect to other pulses, and Bracket Spacing.

These three parameters are closely related and result in similar effects when out of tolerance. The ATCRBS reply consists of 14 pulse slots ("1" is pulse present and "0" is pulse absent). The first reply pulse is designated as "F1" and the last is "F2." These pulses are nominally spaced at 20.3 microsecond (μs) (bracket spacing). The tolerance on this parameter is +/- 100 nanosecond (ns). Most ATCRBS sites accept brackets spaced from 20.1 to 20.5 μs. Pulse errors with respect to any pulse affect the proper decoding of the transponder replies. If errors exist, the reply may be improperly decoded even though the bracket is declared. Most of the failures in these three parameters (F1- 5.3 percent, Other - 1.8 percent, Bracket – 4.2 percent) were marginal and barely missed the specification. A small number of these failures could result in intermittent decoding at some ATCRBS sites. This intermittency would produce a loss of tracking or incorrect altitude data.

Reply Pulse Width.

Reply pulses that are either too wide or too narrow result in a failure on this parameter. ATCRBS processors may reject pulses that are too narrow. None of the failures were pulses narrow enough to be rejected by the ATCRBS processors. Pulses that were too wide caused most of the 4.6 percent pulse width failures. ATCRBS processors have "pseudo lead edge" logic to insert extra pulses when wide pulses occur. This gives the processor the ability to resolve ambiguities caused by overlapping replies from different transponders with normal width pulses. An extra "lead edge" is inserted where a nominal one would have occurred (i.e., 600 ns prior to the "trail edge" of the pulse) were it not for the energy from the interfering reply source.

The "pseudo lead edge" logic is not intended to compensate for transponders that produce wide pulses because they are out of specification. None of the wide pulse failures measured were large enough to activate the "pseudo lead edge" logic. However, when added to other effects that increase pulse width (i.e., very near reflections), they may result in some extra "pseudo lead edge" insertions. If this occurs, the replies will normally be merged into a single target

because of code matches. If the codes do not match, the phenomenon could result in a "range split" (appearing as two separate targets when only one exists).

Mode A and C Reply Delay.

Less than 2 percent of the transponders failed these parameters. The permissible tolerance is +/- 500 ns. This translates to a "range error" of approximately 250 feet. All the failures of this parameter were just outside the allowable limit and would have no impact on the existing ATCRBS systems.

Mode A – C Reply Delay Difference.

Approximately 4 percent of the transponders failed this parameter. When the difference in the reply delays is too great, the transponder can create a "range split" where the aircraft appears on the controller's screen as two targets (one Mode A and one Mode C) slightly separated in range.

Suppression Acceptance/Rejection Criteria.

There are four separate parameters in this group concerned with the control of the transponder suppression logic. Two of the parameters are concerned with the relative position of the suppression interrogation pulses, while the other two are concerned with the relative amplitude of the suppression interrogation pulses. Two limits are checked by the tests: (1) the extremes at which the transponder must reply (reject the suppression and reply with the appropriate Mode), and (2) the extremes at which the transponder must not reply (accept the interrogation and suppress).

Suppression Acceptance – Position.

The transponder must suppress if the suppression pulses are spaced from 1.85 to 2.15 μs and meet the acceptance ratio criteria. The amplitudes of the two pulses used in the test protocol were equal. Approximately 5 percent of the transponders failed this test. These transponders all failed to suppress when the spacing was very near the nominal value. They would cause a phenomena called "ring around," which makes a target appear as a ring around the center of the controller's display at the range of the target. This phenomenon would occur at ranges less than a few miles and is not only a nuisance, but may result in an inability of ATCRBS (or TCAS) to determine the actual azimuth of the target.

Suppression Rejection – Position.

The specification requires that transponders reject as a suppression pair any pulses spaced at less than 1.3 μs or greater than 2.7 μs. Over 41 percent of the

transponders failed this test. All the failures at the lower limit (1.3 μs) were Narco or ARC transponders. Many of them still suppressed 100 percent of the time when interrogated with pulse pairs spaced at 1.2 μs. Most of the failures at 2.7 μs were King transponders. A majority of these replied approximately 50 percent of the time at the 2.7 μs spacing.

Neither of these two types of failure is expected to create significant operational problems. There are no ATCRBS systems that use interrogation pulse spacings at the extremes of the specification (all current systems use a nominal spacing of 2 μs and the tolerance on these spacings is usually 100 ns).

Suppression Acceptance – Ratio.

Transponders must suppress when the amplitude of the second pulse of the suppression pair is equal to the first and the spacing meets the acceptance criterion described above. Approximately 3 percent failed this specification.

Suppression Rejection – Ratio.

Transponders must reply when the amplitude of the second pulse of the suppression pair is at least 9 dB less than the first and the spacing meets the acceptance criterion described above. Six percent failed this specification.

Mode A and Mode C Pulse Position Acceptance/Rejection Criteria.

These tests are similar to the suppression interrogation specifications. However, the Mode A and Mode C interrogations are used.

Mode A or Mode C Acceptance – Position.

The transponder must reply when the mode interrogation pulses are 7.8 to 8.2 μs for Mode A and 20.8 to 21.2 μs for Mode C. Only 2.6 percent of the transponders failed to meet these criteria in Mode A and 4.7 percent in Mode C. One transponder, however, did not respond at nominal spacing in Mode A. This aircraft would be intermittent on ATCRBS systems because Mode A is used for tracking. Since TCAS uses Mode C, this aircraft would be seen by TCAS equipped aircraft.

Mode A or Mode C Rejection – Position.

The transponder must not respond when the Mode A interrogation pulses are spaced less than 7 μs or more than 9 μs apart. In Mode C, the corresponding spacings are less than 20 μs and more than 22 μs. As in the acceptance test, 2.6

percent of the transponders failed to meet these criteria in Mode A, while 5.1 percent failed in Mode C.

These parameters are adjustable on many models of transponder. It is more serious to fail the acceptance portion of the test because this will result in the target not being seen by ground and TCAS interrogators. Failure of the rejection portion of the test results in increased interference produced by transponders that should not be replying to interrogations it may see with these spacings. No systems are using pulse spacings in the rejection region. Consequently, this would occur only under rare circumstances where combinations of other interrogations produced such spacings.

Mode A and Mode C Pulse Width Acceptance/Rejection Criteria.

The specifications call for transponders to reply only to a fixed range of pulse widths in both Mode A and Mode C. They are to respond at least 90 percent of the time to interrogations with pulse widths from 0.7 to 0.9 μs and respond less than 10 percent of the time to interrogations with pulse widths narrower than 0.3 μs or wider than 1.0 μs.

The narrow and wide pulses are specified at two different power levels. Performance at pulse widths less than 0.3 μs is specified at levels between minimum triggering level (MTL) and MTL +6 dB in TSO-C74C and the ATCRBS National Standard. It is specified between MTL and –45 decibels above 1 milliwatt (dBm) (approximately MTL + 30 dB) in the Mode S National Standard. Performance, when subjected to wide pulses, is specified at MTL +50 dB in all documents. All tests were conducted at MTL +50 dB. Consequently, the failures at the narrow end may be overestimated in the data.

Two percent of the transponders failed the acceptance portion of this test in Mode A and 3.1 percent failed in Mode C. These units missed the specified reply rate by a small margin, and are likely to present no problems for the system. The rejection portion of the test was the third most frequently failed test in the study. This result was probably at least partially due to the high signal level used during the test. Over 26 percent of the transponders failed the test in both modes. Many transponders do not have minimum pulse width logic and continue to respond to very narrow pulses. Operationally, these failures should not cause a significant problem, but will contribute to noise in the system as they generate replies to narrow pulses when they should not do so.

ATCRBS/Mode S and ATCRBS Only All Call Test (Terra Test).

This test sequence assessed the transponder's response to the range of interrogations sent by ground systems and TCAS to acquire aircraft targets. The

test used all combinations of ATCRBS Only All Call and ATCRBS/Mode S All Call interrogations in both Modes A and C.

The test is referred to as the "Terra Test" because a design characteristic of certain Terra transponders prevent them from responding consistently to the ATCRBS/Mode S All Call or the ATCRBS Only ALL Call interrogations. This failure resulted in an inability of Mode S sensors and TCAS to detect aircraft equipped with the Terra unit. Mode S sensors were modified to accommodate the Terra transponder by following each Mode S Only All call with an ATCRBS interrogation. The modification to en route and terminal Mode S sensors is slightly different. The original modification to both required "double tracking" (a Mode S track and an ATCRBS track for each Mode S aircraft). This severely impacts the system capacity and as a result, the ATCRBS interrogation in en route systems was moved to a selectable time after the Mode S Only All Call (either 48 μs or 64 μs). In this way, Mode S transponders would not respond to the ATCRBS interrogation and the need for double tracking of Mode S targets was eliminated. An ATCRBS transponder would see the Mode S Only All Call and suppress for a nominal period of 35 μs. It would recover in time to see the following ATCRBS interrogation. Terminal Mode S sensors continue to utilize "double tracking" of Mode S aircraft. Regardless of the ground system modification, transponders displaying the "Terra characteristic" are not seen by TCAS, which uses the ATCRBS Only All Call to acquire targets. A factory modification was made available to Terra owners to correct the problem.

Seventeen transponders (3.1 percent) failed the test. Three of these were Terra transponders that had not received the factory modification. Two were transponders that had exhibited mode acceptance and sensitivity problems and could not be tested for the Terra characteristic. However, the remaining 12 that failed were Narco AT150 transponders. Some of these transponders replied to a few of the Mode C All Call interrogations, but none replied to any of the Mode A All Call interrogations. Prior to this study, no reports have been published to suggest that the "Terra like characteristic" had been observed in other transponder models.

All 17 failures would be invisible to Mode S sensors if the present "double tracking" modification were removed. They would also be invisible to TCAS aircraft, although some may present an intermittent track because they occasionally replied to the Mode C All Calls.

Simultaneous Mode A - C Interrogation.

This test parameter was first published in the Mode S specifications. It states that a transponder is to reply with Mode C if it receives a simultaneous Mode A

and Mode C interrogation (interrogation pulse $P1_c$ at 0, $P1_A$ at13 and P3 of both at 21 μs).

Approximately 40 percent of the transponders tested failed to meet this criterion. However, the specification cannot be enforced because it did not exist when many of the transponders in the sample were designed.

The inability of these transponders to reply appropriately is not a serious problem because it means that a stray pulse from some other source would have to be present 8 μs prior to P3 of the Mode C interrogation in order to create the simultaneous decode. If the stray pulse were actually the pulse at 21 μs prior to P3 (the real interrogation is the pulse pair spaced at 8 μs), the Mode C reply would be incorrect.

Suppression Duration – Mode A and C.

This test measures the duration of the suppression when the transponder is commanded to suppress via a pulse pair spaced at 2 μs. The test is conducted by sending a suppression pair, followed by a Mode A or C interrogation at a variable spacing from the suppression. The interrogation is moved closer to the suppression pair on each sequence. When the transponder no longer replies, the value of the spacing is saved as the suppression duration.

Approximately 6 percent (Mode A) and 9 percent (Mode C) of the transponders failed this specification. Three aircraft failed because they did not suppress at all. The remaining aircraft usually suppressed longer than the allowable 45 μs. The average duration was about 36 μs, while the maximum was 60 μs. The specification range is 25 to 45 μs.

Suppression Reinitiation – Mode A and C.

This test insures that "suppression" can be reinitiated within 2 μs after timing out from a previous suppression. Approximately 4 percent failed to meet this specification in Mode A and 7 percent in Mode C.

4.2.3 Failures as a Function of Transponder Manufacturer and Model.

Specific failure analyses were performed on the transponders produced by the two manufacturers that were most strongly represented in the test sample. King Radio units constituted 254 (46 percent) of the 548 tested transponders, while Narco units totaled 186 (34 percent). Figures 4 and 5 represent the failure findings of these analyses.

Figure 4 is a histogram of the number of test failures accumulated by three model groups of King transponders. The data show that the average KT76A model tended to have fewer test failures than the earlier KT76 design (typically from one to four). Almost one-half of the KT76A units had only one failure. This single failure typically occurred on the Suppression Rejection parameter that is probably attributable to a design characteristic of the KT76A.

The KT76 model normally failed from two to eight parameter tests. The transponder group labeled "other" was composed of a small group of newer King models and tended to have fewer failures than the KT76A.

Figure 5 summarizes the failure data for the Narco transponders. The sample group was primarily composed of three models: the AT 150 (97), the AT 50A (64), and the AT 50 (43). The pattern of test performance for the Narco models was similar to the King models with newer designs failing fewer tests. The AT 150 units appeared to fail the smallest number of tests (0 to 4). The AT 50A typically failed from two to eight tests. The AT 50 normally failed more than five tests. There were only two AT 150A models. One of these failed two and the other four tests.

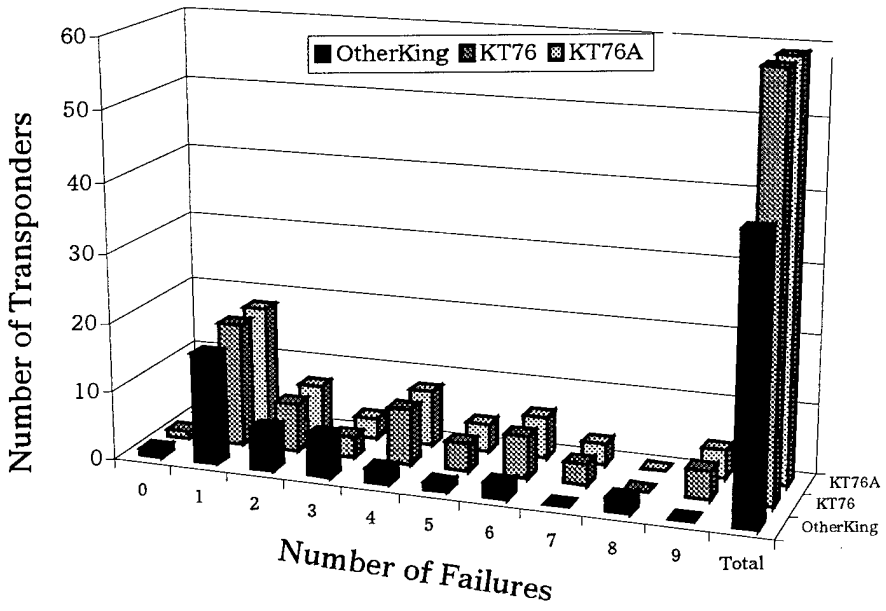

FIGURE 4. KING TRANSPONDER FAILURES

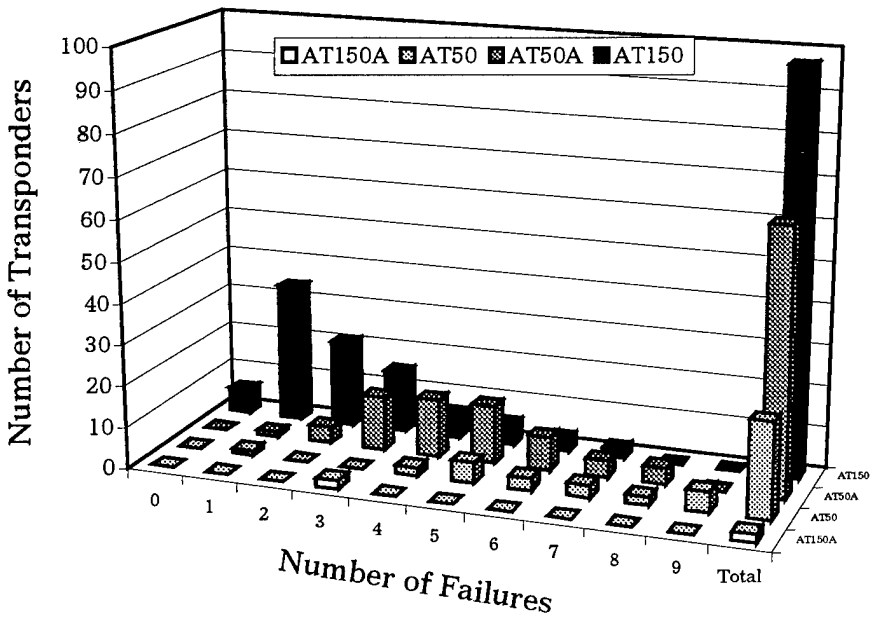

FIGURE 5. NARCO TRANSPONDER FAILURES

4.3 OPERATIONAL SIGNIFICANCE OF TEST FAILURES.

The results discussed in section 4.2 of this report describe the performance of the transponder sample referenced to the FAA and industry specifications for each of the 31 tested parameters. This section presents an interpretation of these results in terms of their implications for the functional performance of the transponders when operating in conjunction with existing ATCRBS ground processors and airborne TCAS processors.

This analysis of the operational significance of the results was performed by taking into consideration the tolerance of the various processors. For example, most processors accept replies with nominal bracket spacing of +/- 200 ns even though the specification calls for +/- 100 ns. Each of the 31 parameters was assigned a revised criterion value using the tolerance of the processing systems as a guide. A functional assessment of each of the sample transponders was then conducted to examine how it would fare with each processor type.

Figure 6 summarizes the results of the analysis. The graph presents the percentage of sample aircraft that would create significant operational problems for the ATCRBS processor and TCAS. The problems are divided into the seven failure categories described below.

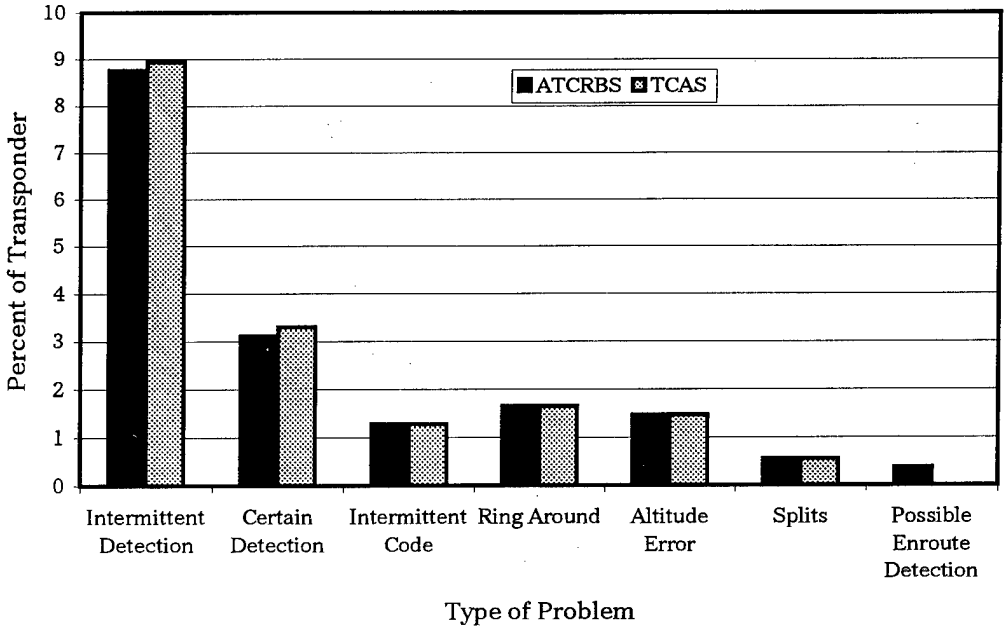

FIGURE 6. OPERATIONALLY SIGNIFICANT TRANSPONDER FAILURES

4.3.1 Intermittent Detection Problems.

The data indicate that approximately 9 percent of the aircraft in the study sample would probably have intermittent detection problems on some existing ATCRBS systems. It is important to note that this means that detection of an aircraft may be intermittent on some systems and not others, in some areas and not others, etc. The parameter failures that caused an aircraft to be included in the intermittent detection category were normally sensitivity, code acceptance window, or reply pulse characteristics. In some cases (i.e., if the transponder's problem was low sensitivity or reply frequency deviation), the performance may be degraded only in marginal coverage areas of the ATCRBS sites or when the aircraft is turning and thereby producing an even weaker signal from the transponder. In other cases (i.e., the bracket spacing is 20.1 μs), the reply may be occasionally dropped because this is the limit of acceptance for the processor.

The percentage of intermittent detection failures was slightly different for TCAS systems because some of the problems occurred only on Mode A and others only on Mode C (TCAS uses Mode C).

4.3.2 Certain Detection Problems.

Approximately 3 percent of the aircraft deviated sufficiently on the same parameters as those which would cause intermittent detection problems. This

will certainly create detection failures on both system types. The TCAS failure rate in this category includes the sample transponders that exhibited the "Terra characteristic."

4.3.3 Intermittent Code Problems.

The 1.3 percent of aircraft that will have intermittent code problems were a result of large reply pulse spacing or pulse width failures. These transponder replies contain pulses sufficiently far from nominal to be missed by some processors and would create incorrect decoding. When this decoding error occurs in Mode C, it will result in an erroneous altitude report. In Mode A, there would be an identity error.

4.3.4 Ring Around.

Of the total sample, 1.6 percent of the transponders failed the suppression decode specification by a wide enough margin that they did not suppress when requested. These transponders reply whether they are in the side lobes or not. Consequently, the target will seem to be at all azimuths simultaneously.

The transponders with this problem may not answer valid interrogations from ATCRBS and TCAS. In addition, ATCRBS will experience increased interference from these units and, when in close proximity to the radar site, the aircraft will appear as a ring around the center of the controller's display. With TCAS systems, units that do not suppress properly may "garble" replies from other transponders and inhibit the normal acquisition process of other aircraft within approximately 2 miles of the aircraft carrying the faulty transponder.

4.3.5 Altitude Error.

Altitude reporting errors greater than 400 feet were classified as operationally significant for this analysis. This criterion was exceeded by 1.5 percent of the transponders. It is possible that some of these errors would decrease after long periods of "warmup". However, as discussed in section 4.2, extended warmup time may result in an aircraft reporting no altitude, or erroneous altitudes, during significant portions of the early phases of a flight following departure. It should be noted that all testing for this study was performed at ambient temperatures greater than 70° Fahrenheit. Consequently, it is probable that an even larger proportion of the sample would display extended warmup problems under colder conditions.

4.3.6 Splits.

"Range splits" are caused by reply pulses that are too wide or those with a time delay difference between Mode A and Mode C replies larger than normal. The processors therefore create two targets slightly apart in range (i.e., range splits). Three transponders in the sample (.5 percent) would produce range splits. Because most systems accommodate range splits fairly well, this is largely a nuisance phenomenon.

4.3.7 Possible En Route Detection Problem.

This problem was created by the modification that was made to permit Mode S sites to detect the Terra transponders. Part of the Terra modification transmits a Mode S Only All Call followed at 48 μs or 64 μs (selectable) by an ATCRBS interrogation. Two transponders in the sample (.4 percent) had "suppression times" in response to the Mode S All Call greater than 60 μs. As a result, they may not detect the ATCRBS interrogation and therefore would not be tracked on the en route Mode S system.

4.4 RESULTS RELEVANT TO BIENNIAL TESTING.

A secondary objective of this study was to determine the implications of the results for mandatory periodic transponder inspection requirements. Currently, FAR Part 43 requires that all transponders be tested every 2 years to insure that they are within specifications on 7 of the 31 performance parameters assessed during the study (see table 1). Figure 7 presents the percentage of transponders that failed from zero to all seven of the biennial tests. These data show that 69 percent of the total transponder sample passed all of the required tests. Approximately 19 percent failed one of the tests. The transponders that failed all seven tests were those that did not work at all.

4.4.1 Time Since Last Biennial Inspection – All Transponders.

During a pretest interview, the aircraft pilots were asked to estimate the number of months that had elapsed since their transponder had received its last biennial inspection. Figure 8 is a plot of the mean time since the last inspection as a function of the number of failures recorded on the subset of biennial tests. In some cases, the pilots indicated that they felt it had "been a long time" since the last test, but could not estimate the elapsed period. These responses were assigned a value of 60 months for purposes of this analysis. The average

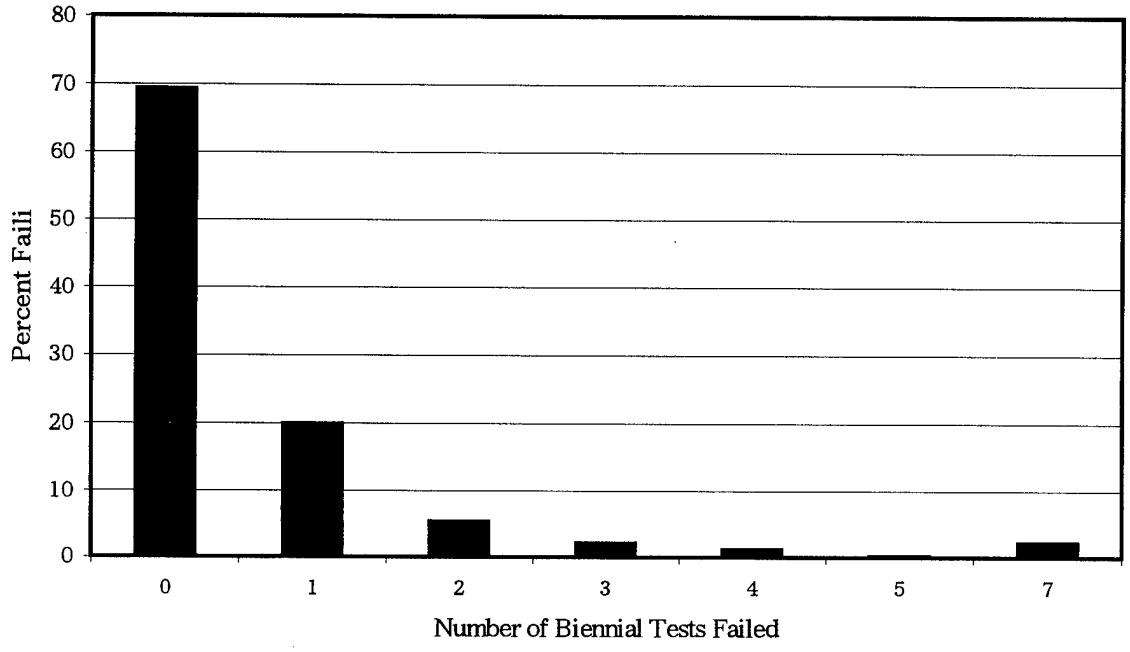

FIGURE 7. NUMBER OF FAILURES ON THE BIENNIAL INSPECTION TESTS

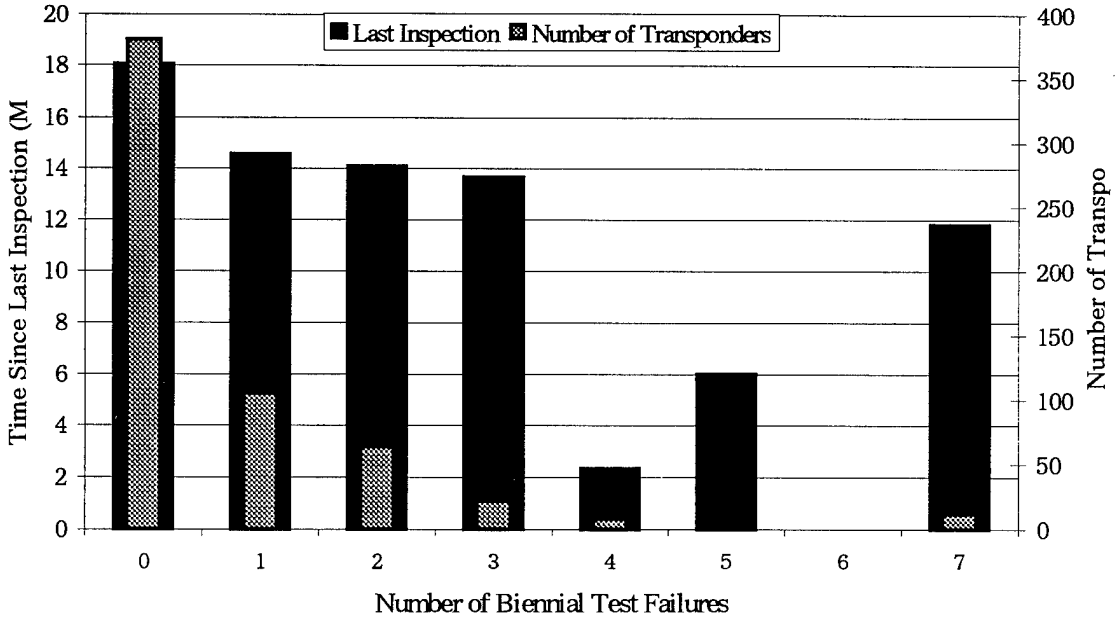

FIGURE 8. BIENNIAL TEST FAILURES AS A FUNCTION OF TIME SINCE LAST INSPECTION

transponder in the sample had received its last inspection 16 months prior to testing in this study. As shown in the figure, transponders with no failures averaged 18 months since the last inspection, while those failing all tests averaged 12 months.

The sample sizes for those failing four, five, and seven tests were small in comparison to those that failed from one to three tests. Nevertheless, the findings suggest that time, since the last inspection, is not a good predictor of the number of biennial tests that a transponder will fail. This apparent lack of association between the recency of biennial inspection and transponder performance was confirmed by statistical testing. A coefficient of correlation computed between inspection date and test failures for each of the transponders in the total sample yielded a Spearman's r value of -.04, indicating a complete lack of relationship between these two variables.

4.4.2 Time Since Last Inspection – Canadian Transponders.

Thirty of the transponders tested in this study were carried by aircraft registered in Canada. The performance of this group of transponders is of interest here because biennial inspections are not required in Canada. The average time since last inspection for this group was 34 months.

Figure 9 shows how the Canadian transponders fared on the biennial tests. More than half of these transponders failed none of the biennial tests.

However, it is noteworthy that of these 30 aircraft, eight had failures sufficient to cause problems with existing ATCRBS and TCAS systems. Of the eight failures, one transponder did not work at all, three will have intermittent detection problems with existing systems, two will have intermittent code problems, one will have an altitude error, and one will create "ring around."

Despite these failures, for those Canadian aircraft that reported an inspection date, there was no correlation between biennial test performance and time since last inspection ($r = .02$).

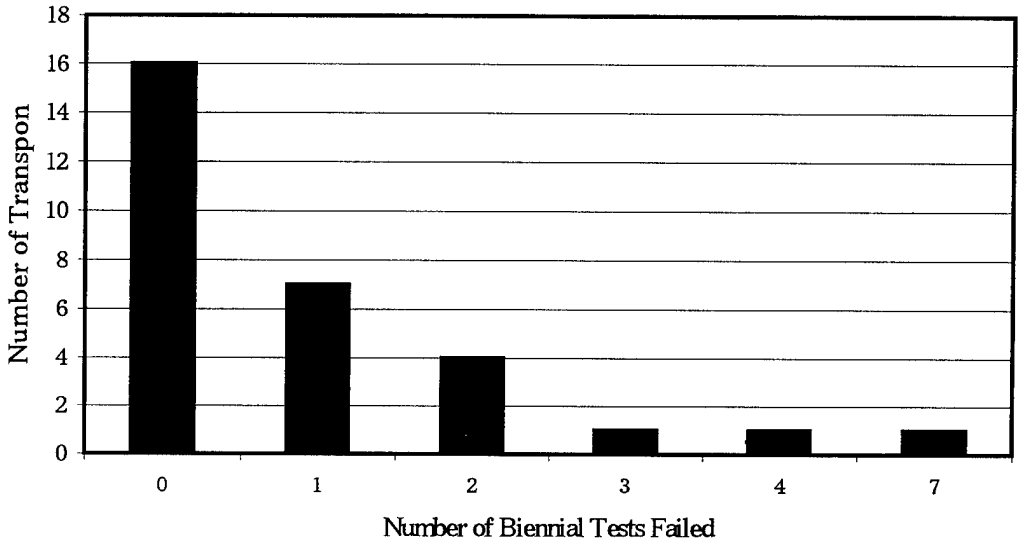

FIGURE 9. NUMBER OF BIENNIAL TEST FAILURES FOR 30 CANADIAN AIRCRAFT

4.4.3 Use of Radar Service and Transponder Performance.

As noted in the introduction to this report, one source of concern over the health of the GA transponder population stems from the fact that small GA aircraft fly many hours each year under VFR without radar service. This type of flying limits a pilot's opportunities to obtain regular operational feedback on the performance of a transponder.

During the pretest interview, the volunteer pilots were asked whether they had flown their aircraft under IFR, or had used VFR flight following services within the past 3 months. The purpose of this question was to determine whether use of radar services, and the use of any feedback from ATC, was associated with better transponder maintenance, and presumably a higher level of performance.

The results showed that 88 percent of the pilots had flown their aircraft IFR or used flight following. To examine the relationship between radar service usage and transponder performance, pilot responses to the interview item were cast into a 2 x 2 contingency table as a function of whether the aircraft's transponder had failed any of the operationally significant tests discussed in section 4.3 of this report. The data indicated that 13 percent of the transponders used by pilots who had recently received radar service failed an operationally significant test. In contrast, 27 percent of the transponders used by pilots who had not flown IFR or used flight following exhibited an operationally significant problem. A Chi-

squared test performed on the contingency table indicated that this difference is statistically significant ($X^2 = 6.87$, $p < .01$). Thus, the results lend support to the hypothesis that pilots who use radar service are more aware of their transponder's performance, and tend to use this knowledge as a basis for maintenance decisions.

5. CONCLUSIONS.

a. The data collection conducted for this study generated a comprehensive database on a large sample of general aviation (GA) transponders operating in the National Airspace system (NAS). This database contains technical data on 31 performance parameters for each transponder, identifies the transponder manufacturer and model designation, and includes information obtained from the pilot/owner regarding the recency of biennial inspection and the equipped aircraft's usage of ATC radar services. The findings of the study constitute the best available estimate of the technical health of the GA transponder population currently operating in the NAS.

b. A majority of the transponders that were tested during this study failed to meet all performance specifications. Although the least stringent criteria contained in the specifications documents were used in the evaluation, only 4 percent of the sample passed all 31 tests on the best of a minimum of two measurements that were taken.

c. Examination of the test parameters that were commonly failed, and the magnitude of the performance deviations on these parameters, indicated that many of the detected problems would not materially affect the transponder's ability to operate with existing secondary radar and Traffic Collision Avoidance System (TCAS) processors. In general, most of the transponder test failures can be classified as technical nuisances. Typically, the transponders that failed to meet specifications either generate noise in the system by replying when they should suppress, or have a small deviation that is accommodated by the tolerances of the interrogator's processor.

d. Although most test failures were inconsequential, an analysis of the operational implications of some of the failures showed that approximately 17 percent of the transponders would create functionally significant problems when interacting with ground secondary surveillance radar (SSR) processors, TCAS, or both. These problems included 12 percent of the transponders that would not be detected by an interrogator or would experience intermittent detection failures.

e. Some of the findings obtained in this study were unexpected and are particularly noteworthy. The results revealed a second make/model of

transponder that sometimes exhibits an operational flaw originally detected in Terra transponders. These transponders fail to respond consistently to the ATCRBS/Mode S All Call or the ATCRBS Only ALL Call interrogations. As a consequence, they cannot be detected by TCAS, and would be invisible to Mode S radar if the modification introduced to deal with the Terra transponders were removed from the Mode S processor.

A second notable result was the unanticipated number of transponders that either exhibited large altitude errors (3.8 percent) or failed to report an altitude (21 percent) during testing. These problems often persisted over periods of at least 10 minutes of testing during which the ambient temperature was never below 70° Fahrenheit. The result indicates that required transponder/altitude encoder warmup times may be much longer than commonly believed. This extended warmup requirement has significant implications for the ability of TCAS and secondary radar systems to accurately identify an aircraft's altitude during the early phases of flight.

f. The average transponder in the sample had received its last biennial inspection required by FAR Part 43 approximately 16 months prior to being tested in the study. Thirty percent of the transponders failed at least one of the seven tests that must be performed as part of the biennial inspection. However, the data indicate that there was no correlation between the time since the last inspection and the number of biennial test failures. In addition, over 50 percent of a sub-group of Canadian aircraft, whose transponders are not subject to biennial testing, passed all of the seven tests. The average time since the last inspection for this group was 34 months, and there was no statistical association between biennial test performance and time since last inspection.

In contrast to the recency of biennial testing, transponder acceptable performance was significantly associated with the pilot's use of ATC radar services. Less than one-half as many transponders owned by pilots who had recently flown IFR or used VFR flight following failed an operationally significant test than those owned by pilots who had not used radar services. This result suggests that pilots who use radar services may be using any feedback they receive from ATC as a basis for transponder maintenance decisions.

g. When projecting from the results of this study to the overall population of GA transponders operating in the NAS, it should be noted that most of the transponders in the sample were tested at Experimental Aircraft Association (EAA) fly-in events. As a group, it can be argued that the pilots who fly to these conventions are likely to use their aircraft more frequently, and fly more cross-country trips than does the average GA pilot. Nearly 90 percent reported that they had used ATC radar services within the last 3 months. It is also probable that many of these pilots are technically sophisticated, aware of the performance

of their avionics systems, and more knowledgeable about NAS operations. As a consequence, the case can be made that the sample tested in this study may have produced results that underestimate the incidence of operationally significant transponder problems in the overall GA population.

6. RECOMMENDATIONS.

a. Based on the results of this study, it is recommended that the following transponder performance issues are pursued in future research:

1. This study detected a group of transponders that exhibited extended suppression times (>60 μs) in response to the Mode S Only All Call. This characteristic may prevent the transponders from detecting the Air Traffic Control Radar Beacon System (ATCRBS) interrogation that currently follows the Mode S All Call interrogation in en route Mode S processors. Research is needed to determine the possible impact of extended ATCRBS transponder suppression duration under all types and sequences of Mode S interrogation.

2. A relatively large number of transponders tested in this study exhibited significant altitude errors or failed to report altitude. This finding indicates that research is needed on available transponders and altitude encoders in order to characterize their performance during "warmup" under various ambient temperature conditions.

3. The Federal Aviation Administration's (FAA's) Free Flight initiative will introduce a variety of new technologies and procedures that will make properly functioning transponders even more important to effective National Airspace System (NAS) operations than they are currently. Because of this, research is required to examine the implications of Free Flight for effective airborne surveillance, and to identify the level of transponder and altitude encoder performance that will be needed for safe operations in the future Free Flight environment.

4. This study produced a valuable database on the performance of transponders carried by General Aviation (GA) aircraft. It is recommended that this line of investigation be extended to create a similar database for transponders carried by commercially operated aircraft.

b. The results of this study indicate that most of the transponders carried by GA aircraft fail to meet all of the performance criteria specified in national standards documents, and that a number of these failures may be serious enough to significantly affect their performance with secondary surveillance radar systems and TCAS collision avoidance equipment. In addition, the data showed that performance failures on key transponder parameters were unrelated to the

time that had elapsed since a transponder had received its last biennial inspection.

Taken together, these findings suggest that an effort should be initiated to examine the need for improved methods and procedures to ensure the performance of transponders operating in the NAS. It is recommended that this be accomplished by forming a special committee composed of members drawn from the FAA, the avionics industry, and organizations representing the GA pilot community. As a part of its charter, the committee should be tasked to: (1) examine current and future transponder performance requirements for safe NAS operations, (2) evaluate the effectiveness of biennial tests in meeting these requirements, (3) make recommendations for methods and evaluation procedures that would support a high level of consistent transponder performance in the GA population, and (4) assess any system safety impact with either TCAS or Secondary Surveillance Radar (SSR)/NAS operations if determined to be a problem and suggest corrective action.

If the committee judges modifications to the current inspection approach necessary, it could consider a wide range of potential recommendations beyond the existing biennial test regulations to insure consistent performance. These could include, but would not be limited to:

1. Existing documents - Possible changes to existing transponder Technical Standard Orders (TSO's).

2. Educational Efforts - Programs instituted to increase pilot awareness of transponder performance requirements and the operational consequences of various transponder problems.

3. Procedural Approaches - As suggested by some of the results of this study, improved levels of transponder performance may also be achieved by requiring periodic "operational tests" of a transponder that the pilot would perform by making contact with ATC and documenting the results in a log book entry. Depending on the safety impact, TCAS procedures need to be assessed in light of the performance of transponders.

4. Automated Test Equipment - While costly, regular transponder performance verification could be performed by incorporating Built In Test Equipment (BITE) into the design of transponders, or by developing automatic test equipment for installation on airport ramps.

7. REFERENCES.

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3. Wapelhorst, L., Pagano, T. and VanDongen, J. *The Effect of TCAS Interrogations on the Chicago O'Hare ATCRBS System.* Final Report, DOT/FAA/CT-92/22, FAA Technical Center, November 1992.

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APPENDIX A

TRANSPONDER TEST CRITERIA

Receiver Sensitivity - Mode A: Sensitivity less than –66 dBm

Receiver Sensitivity - Mode C: Sensitivity less than –66 dBm

Mode A - C Sensitivity Difference: Sensitivity difference must be less than 1 dB

Suppression Duration - Mode A: Allowable time = 25 to 45 μs

Suppression Duration - Mode C: Allowable time = 25 to 45 μs

Suppression Reinitiation – Mode A: Must be capable of reinitiating within 2 μs of first suppression

Suppression Reinitiation – Mode C: Must be capable of reinitiating within 2 μs of first suppression

Simultaneous Mode A and C Response: No fewer than 90 percent of replies must be to Mode C interrogation

ATCRBS/Mode S All-Call Protocol (Terra Characteristic Test): ATCRBS transponders must reply at least 90 percent to ATCRBS short P4 (0.8 μs).

Suppression Position Acceptance: Must reply less than 10 percent to P2 throughout the acceptance range

Suppression Position Rejection: Must reply at least 90 percent with P2 in the rejection region

Single Side Lobe Suppression Ratio – Acceptance: Must reply at least 90 percent when P2=P3-9db.

Single Side Lobe Suppression Ratio – Rejection: Must reply less than 10 percent when P2=P3+0db.

Pulse Position Acceptance – Mode A: Must reply at least 90 percent with spacing in the acceptance region (7.8 μs < P1-P3 > 8.2 μs).

Pulse Position Acceptance – Mode C: Must reply at least 90 percent with spacing in the acceptance region (20.8 μs < P1-P3 > 21.2 μs).

Pulse Position Rejection – Mode A: Must reply less than 10 percent with spacing in the rejection region (7.0 μs $\geq$ P1-P3 $\geq$ 9.0 μs).

Pulse Position Rejection – Mode C: Must reply less than 10 percent with spacing in the rejection region (20.0 μs $\geq$ P1-P3 $\geq$ 22.0 μs).

Pulse Width Acceptance – Mode A: Must reply at least 90 percent when pulse width is in the acceptance region (.7 μs < P1-P3 > .9 μs).

Pulse Width Acceptance – Mode C: Must reply at least 90 percent when pulse width is in the acceptance region (.7 μs < P1-P3 > .9 μs).

Pulse Width Rejection – Mode A: Must reply less than 10 percent with spacing in the rejection region (P1,P3 < 0.3 μs).

Pulse Width Rejection – Mode C: Must reply less than 10 percent with spacing in the rejection region (P1,P3 < 0.3 μs).

Reply Frequency: Must be within range of 1087 to 1093 MHz

Reply Power: Must be greater than 47.5 dBm

Altitude Error: Report must not differ by more than 200 feet from calibrated reference altitude

Pulse Error referenced to F1: Position of pulse with respect to F1 must be less than 100 ns

Pulse Error referenced to all other pulses: Position of pulse with respect to all other pulse must be less than 100 ns

Bracket Spacing: Average spacing between first (F1) and fourteenth possible pulse position (F2) must be 20.2 to 20.4 μs.

Reply Pulse Width: Mean pulse width of all pulses from all replies must be from .35 to .55 μs

Reply Delay – Mode A: Time from leading edge of P3 to leading edge of F1 of the reply must be from 2.5 to 3.5 μs

Reply Delay – Mode C: Time from leading edge of P3 to leading edge of F1 of the reply must be from 2.5 to 3.5 μs

Mode A-C Reply Delay Difference: The reply delay difference must be no larger than .2 μs.

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