TEST RESULTS OF INITIAL INSTALLATION OF DATAS/TCAS MONITOR - DFW AIRPORT

Leo J. Wapelhorst
John Van Dongen

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16. Abstract

This document presents the results of initial tests with the Data Link Test and Analysis System (DATAS/Traffic Alert and Collision Avoidance System (TCAS) Monitor at the Dallas/Fort Worth (DFW) Airport. DATAS was modified to provide independent monitoring of TCAS Resolution Advisories, which occur frequently at airports with multiple parallel runways.

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The data presented in this report was acquired using the Data Link Test and Analysis System (DATAS). The DATAS was designed and modified to be a Traffic Alert and Collision Avoidance System (TCAS) monitor by the Mode Select (Mode S) ground Data Link Development Team.

Mr. Nicholas Talotta was the Data Link Program Manager responsible for the development of DATAS and its many applications.

Mr. Leo Wapelhorst was the lead hardware design engineer for the ground Data Link project, and was the design engineer for the digital, analog, and radio frequency (RF) circuitry on DATAS.

Mr. Thomas Pagano was the lead systems design engineer for the ground Data Link project, and was the lead system design engineer for the computer control and interface systems of DATAS.

Mr. John Van Dongen was a computer systems analyst for the ground Data Link project, and was the lead software analyst for the design of the TCAS monitor application software.

Mr. John Zvanya was an electronics engineer responsible for initial hardware and software testing.

Mr. William Mateer (UAL) was a computer systems analyst for various DATAS applications.

Mr. John Stanks, Mr. Van Mason, and Mr. Robert Johns were electronic technicians responsible for the fabrication and testing of DATAS for this and all applications.

The TCAS monitor application of DATAS required the support of TCAS project personnel including: Mr Carl Jezierski, TCAS Program Manager, Mr. Ed Glowacki electrical engineer, and Mr. Arthur Madge who was instrumental in coordinating the data collection effort with Dallas/Fort Worth engineers and Air Traffic personnel.

The deployment of the TCAS monitor at the Dallas/Fort Worth Metroplex would not have been possible without the excellent support received from local FAA field personnel including: Ms. Tracy Mitchell (electronics engineer), Mr. Greg Juro (DFW Tower air traffic), Mr. Charles Smith, Mr. Ronald Gunner, and Mr. Tracy Smith.

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EXECUTIVE SUMMARY

Since a significant amount of air carriers have recently been equipped with Traffic Alert and Collision Avoidance Systems (TCAS) there have been reports from various airport terminals of a higher than expected amount of TCAS Resolution Advisories (RA's). In some cases, the TCAS logic could project possible conflicts which give advisories which could be contradictory to clearances made by Air Traffic Control (ATC) personnel. These situations need to be examined to determine if there is a problem with the existing air traffic patterns or if the TCAS threat sensing logic needs to be modified for certain situations. One of the objectives of the TCAS transition plan is to collect and analyze TCAS data.

Federal Aviation Administration (FAA) Technical Center Data Link project personnel designed, developed, and deployed a system to record TCAS activity. Through coordinated efforts with TCAS project personnel, the Data Link project design team modified the existing Data Link Test and Analysis System (DATAS) to perform as the TCAS monitor. The TCAS monitor, as the new application of the DATAS was named, was designed to record TCAS RA messages as they occurred. Along with such messages, the system stored aircraft identification data, capability reports, and altitude histories. All data transactions are "time tagged" so that it can be correlated with independent surveillance data from systems such as the Automated Radar Terminal Systems (ARTS) III, ARTS II, or Airport Surveillance Radar (ASR)-9. Given such information, systems analysts could determine what types of advisories are occurring and with what frequency, the altitudes at which they occur, and whether or not the pilots are maneuvering in response to the advisories. This function was to be performed by ARINC in conjunction with The MITRE Corporation.

The TCAS monitor was deployed at the Dallas/Fort Worth (DFW) airport complex. Project personnel were briefed by DFW air traffic personnel on the locations where most of the advisories occur. Since the TCAS monitor only provides directional coverage, it was decided that it would be best to aim the antenna at the southeast "corner post" because it was the most frequently used approach.

The system was operational from April 18 to June 18, 1991. During that time, approximately 40,000 Mode S aircraft were acquired and 119 TCAS RA encounters were recorded. The RA's generally occurred with aircraft on three different flightpaths: DFW arrivals (59 percent), DFW departures (31 percent), and aircraft on approach to neighboring airports (10 percent). Because the TCAS monitor tracks only Mode S equipped aircraft, the threat aircraft is unknown in most recorded cases. However, in 11 recorded cases two TCAS equipped aircraft were involved in an RA. Each of these 11 RA's occurred between a DFW arrival and a DFW departure. This report contains altitude plots for both aircraft in all 11 cases. This data is the best available to examine the apparent conflicts, but the analysis process emphasized the fact that azimuth data are required in order to completely analyze the data.

The altitude data of all aircraft which had RA's was examined by both the local ACD-320 TCAS group as well as the DATA LINK group to determine the pilots response. The lack of azimuth data to accompany the DATAS data makes the decisions somewhat subjective, so the results of both groups analyses are presented. The TCAS group determined that 12 percent followed the RA's, 55 percent ignored them, and the RA had no effect on 32 percent. The DATA LINK group analyzed the RA's in three separate classes (ARRIVALS, DEPARTURES, and EN ROUTE TO OTHER AIRPORTS). They surmised that 20 percent responded, 22 percent were already complying prior to the RA, 48 percent ignored the RA, and 11 percent of the cases were inconclusive for arriving aircraft. For departures, 57 percent responded, 14 percent were already complying and 19 percent ignored the RA. For those aircraft en route to other airports, none responded to the RA, 18 percent were already complying, and 72 percent ignored the RA. The mean duration of the RA's from the DFW sample was approximately 8 seconds.

The TCAS capability, as reported by the Mode S transponder, is monitored as part of the surveillance function. With the current TCAS systems, the capability reported is either NO TCAS, TCAS WITH RESOLUTION CAPABILITY INHIBITED (Traffic Advisory (TA) only), or TCAS WITH VERTICAL RESOLUTION CAPABILITY. The data indicates that approximately 10 percent of the pilots switched their TCAS units to either TA ONLY or NO TCAS mode, in response to an RA. The TCAS units were switched after the advisory in some cases, and during the advisory in others. In 5 percent of the other cases, the transponders reported NO TCAS for only one surveillance scan. These could have either been momentary switches by the pilots, or glitches within the system. This information is derived from the 119 RA encounters recorded. The TCAS monitor software was modified during the data collection effort in order to try to determine how many TCAS equipped aircraft overall are operating with their TCAS units either OFF or in TA only mode. Obviously, the only way to determine if an aircraft is TCAS equipped with the TCAS unit OFF is to capture the transition from or to the OFF state. The data recorded indicates that approximately 6 percent of the TCAS equipped aircraft reported NO TCAS when they should have been operating at a TCAS sensitivity level of 5 or higher.

Figure E-1 shows a particularly interesting encounter which occurred between three aircraft at DFW. Aircraft No. 1 was an arrival which was level at 11,025 feet at a range of 11 miles when it received an RA to **"climb"** (1:47 into the flight coverage). Aircraft No. 3 was outbound at approximately 11 miles at 9,900 feet when it received the Resolution Advisory Complement (RAC) of "**don't climb**" apparently from aircraft No. 1 (since it also occurred at 1:47). The RA data are shown on figure E-1 which has been expanded to show the data more clearly. Aircraft No. 3 was climbing at a rate of approximately 2000 feet per minute and continued to do so until it reached 10,500 feet. The RAC, however, ended at approximately 10,200 feet (at 1:52 into the flight), probably because the range was diverging sufficiently to end the RA by aircraft No. 1. At approximately 2:00 minutes into the flight, aircraft No. 3 started to descend toward 10,000 feet (the normal flight level assigned to departures). It then received an RAC of "**don't climb**" at 2:07 from aircraft No. 2. Its own system also gave an RA of "**don't climb**" at the same time. At 2:16, the RA eased to "**don't climb > 1000 fpm,**" and the

RAC from aircraft No. 2 remained the same. The RA lasted until 2:36 when aircraft No. 3 had leveled off at 10,000 feet and was at a range of approximately 13 miles. This sequence clearly illustrates the requirement that azimuth data be available in order to do a complete analysis of a situation such as this one. A more thorough analysis of this encounter is included in the body of the report.

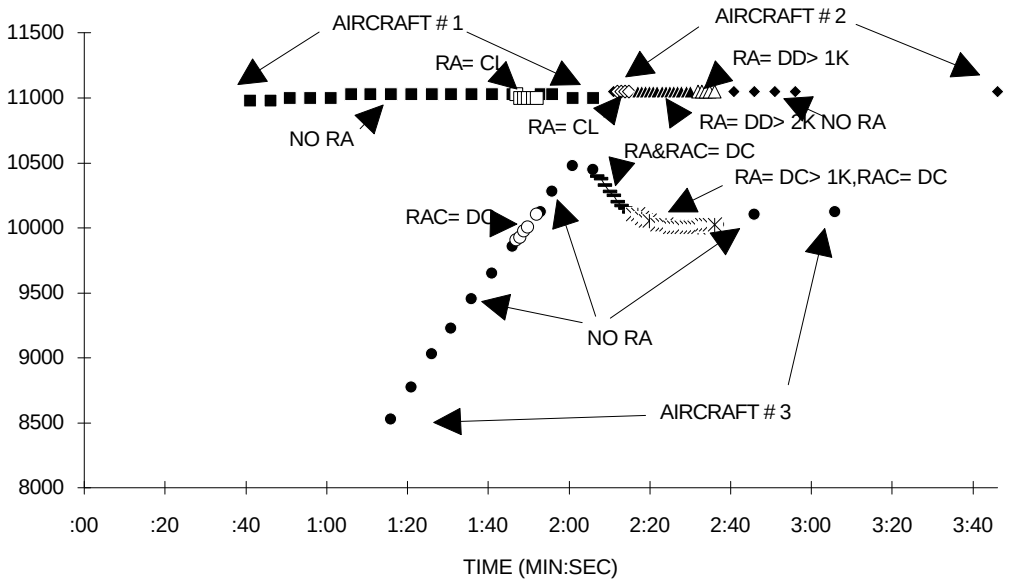

FIGURE E-1. TCAS ENCOUNTER NO. 11 BETWEEN THREE AIRCRAFT (EXPANDED)

INTRODUCTION

Implementation of Traffic Collision Avoidance System (TCAS) is now in progress as a result of legislation passed by congress. This legislation also mandates a joint Federal Aviation Administration (FAA)/airline industry operational evaluation of the system. The TCAS Transition Program (TTP) requires data recording systems in order to provide data for analysis during the early stages of TCAS implementation.

The primary objectives of the TTP are to evaluate the operational performance of a large number of TCAS installations and assist in the integration of these units into the National Airspace System (NAS). Government, airline industry, and equipment manufacturers represented on the TTP will investigate and resolve all noncertification related operational problems associated with TCAS implementation.

A limited number of TCAS equipped aircraft are being equipped with flight recorders in order to gather data on TCAS system operation. The Data Link Test Analysis System (DATAS), developed at the FAA Technical Center, was modified to provide a TCAS monitor function in addition to its existing functions. DATAS, as a TCAS monitor, operated independently of the TCAS systems to collect TCAS advisory data from the ground.

SYSTEM CONFIGURATION

Only a brief description of the system configuration will be provided. A more detailed description is included as appendix A . The user's guide for the TCAS monitor (report DOT/FAA/CT-TN90/62) also includes a more detailed description.

The DATAS (as used in the TCAS monitor application) is basically a programmable transmitter/receiver unit with radio frequency (RF) output capability in the frequency range of 950 to 1150 megahertz (MHz). The transmitter has two completely independent channels whose outputs are combined if the high power transmitter output is selected. Several RF outputs are available for different applications. The frequencies, pulse widths, and amplitudes of all RF outputs are programmable. However, on the high power transmitter output, the power output is fixed. This is a limitation of the modified APX-76 airborne interrogator which is normally used by the U. S. Air Force for Air Traffic Control Radar Beacon System (ATCRBS) interrogations. The output power of this unit was reduced to reduce the coverage area to approximately 30 miles. Further details are available in appendix A.

The receiver of DATAS is a single channel and is programmed to operate at a frequency of 1090 mhz when used as a TCAS monitor. The DATAS contains sophisticated pulse processing capability which is also programmable. Pulse characteristics such as RF frequency, amplitude, spacing, and pulse widths are stored for each reply pulse. The decoders which detect replies to DATAS interrogations are also programmable. In the TCAS monitor, the decoders were set up to detect the arrival of Mode S replies. The time of arrival of these replies is then saved (referenced to a moveable listening

"window" which is under program control) in order to provide the radar range of the reply. The Mode S reply code is also stored and sophisticated code correction capability is included in order to overcome interference from ATCRBS replies which may overlap the desired replies.

The TCAS monitor configuration of DATAS contains two processors. The first is a 68020 processor which performs the normal system functions of DATAS in its role as a limited Mode S sensor as well as control of the DATAS hardware. Any one of several ports (i.e., bench port, high power antenna port, diagnostic port, and medium power antenna port) can be selected for use by the RF receiver under program control. The second processor of DATAS is a personal computer (PC)/AT which communicates with the DATAS 68020 via the system VME bus. This processor is primarily for data analysis. Data collected via the 68020 can be transferred to the PC where it is manipulated and placed in a format compatible with standard commercial data base program packages. Data are retrievable via modem/phone line interface if desired.

This system provides coverage of approximately 35^{o} azimuth by 30 mile range. It monitors all Mode S equipped aircraft within this "wedge" while awaiting an active "TCAS Resolution Advisory" (RA). When an advisory occurs, data on all Mode S aircraft present within this azimuth are stored on disc for future analysis.

The azimuth wedge for coverage by the DATAS was selected after coordination with Dallas/Fort Worth (DFW) Air Traffic personnel. The basis for selection was their recollection of the airspace within which the highest number of TCAS RA's occurred. The standard air traffic pattern employed is a "corner post" operation. Arriving aircraft cross the feeder fix at or above 11,000 feet and departing traffic crosses the same fix at or below 10,000 feet. The primary direction of traffic flow was toward the south. Most aircraft were vectored in for landing from the "corner post" at approximately 45 miles southeast of the airport. Departing aircraft were using a parallel runway and taking off to the south at the same time. A coverage plot is included in appendix A.

The system was installed in a maintenance building located on the perimeter of the DFW Airport. After the initial installation, the equipment was operated as a completely unmanned facility for a period of approximately 2 months. Data were extracted via modem/phone line and analyzed at the FAA Technical Center.

STATISTICAL DATA DISCUSSION

During the data collection at DFW, approximately 40,000 Mode S equipped flights were monitored. The TCAS Monitor system evolved through several stages during the period of data collection. Changes were made which allowed more detailed statistical data to be collected on the population of Mode S equipped aircraft in the DFW terminal area. Only summary data of these statistics were stored unless an RA occurred. The full statistical package was only available on approximately the last 1,700 aircraft samples. These data indicated that approximately 78.5 percent of the Mode S aircraft were also equipped with TCAS.

Reply Information - Information regarding the TCAS Status was collected on all aircraft. Part of the "roll call" process consists of sending a "short special surveillance" (UF=0) interrogation to each aircraft within the coverage area. The response to this interrogation contains information regarding the status of the TCAS system of the aircraft. The raw data are shown in figure 1. These data show that aircraft which were equipped for TCAS reported "No TCAS" 26.2 percent of the time. They had their RA Capability Inhibited (operating in Traffic Advisory Only mode) 26.04 percent of the time and had their RA Capability fully enabled approximately 48 percent of the time. An aircraft was defined as being TCAS equipped if it reported TCAS capability at any time during the coverage period.

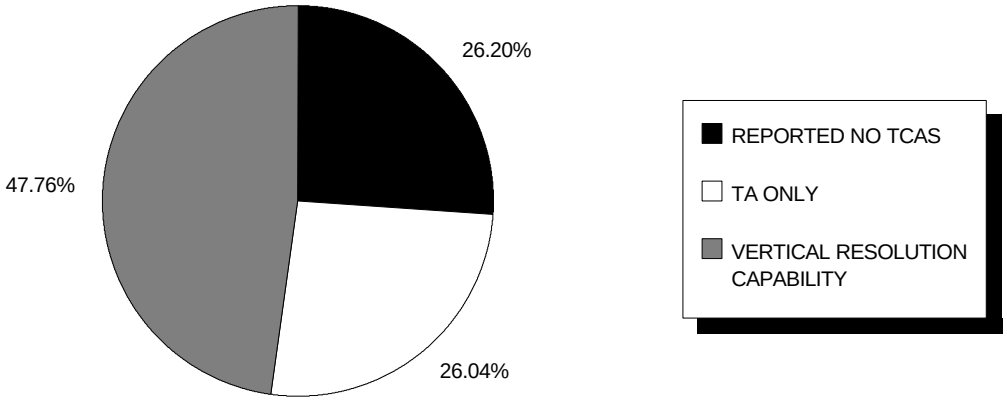

FIGURE 1. TCAS CAPABILITY REPORTED BY TCAS EQUIPPED AIRCRAFT

Data were collected on the TCAS switching activity as well as the TCAS status. Approximately 5 percent switched to each of the available options (OFF to anything, Anything to OFF, Inhibit to Vertical Only, and Vertical Only to Inhibit). The Sensitivity Level which was reported immediately before and after switching was also recorded.

The Sensitivity Levels are defined as indicated below:

Sensitivity Level 0	-	No TCAS
Sensitivity Level 1	-	Standby
Sensitivity Level 2	-	Traffic Advisory Only / below 500 feet
Sensitivity Level 3	-	Undefined
Sensitivity Level 4	-	500 feet to 2,500 feet
Sensitivity Level 5	-	2,500 feet to 10,000 feet
Sensitivity Level 6	-	Above 10,000 feet
Sensitivity Level 7	-	Undefined

The Sensitivity Level is determined by the automatic selection of the lowest of three different control inputs:

1. Ground Based Mode S selection (none at the present time)
2. Automatic selection related to barometric pressure or radar altimeter
3. Pilot manual selection

Figure 2 shows the sensitivity level reported immediately before and after switching the TCAS to "OFF."

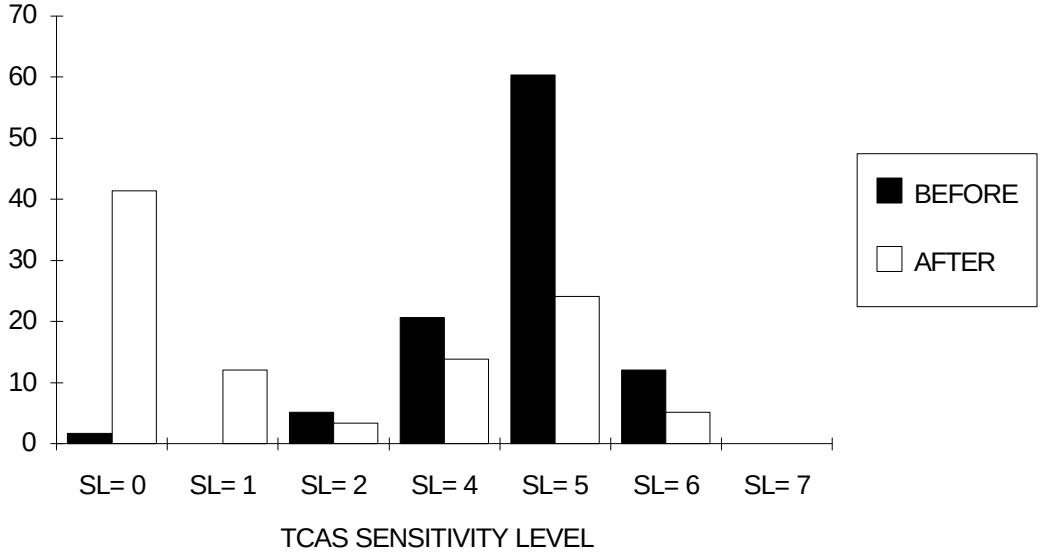

FIGURE 2. SENSITIVITY LEVELS REPORTED BY UNITS SWITCHED TO "OFF"

Since these sensitivity levels reported are essentially a function of aircraft altitude, we can conclude when the TCAS units are being switched off. The sensitivity level reported when TCAS is OFF does not seem to be consistent. Some aircraft continue to report the same sensitivity level as before the switch and others go to sensitivity levels 0 or 1. These data show that **of those which switched TCAS off, 59 percent of them did so at sensitivity level of 5 (2,500 to 10,000 feet) or greater.**

Figure 3 shows the sensitivity levels immediately before and after switching from "OFF to ON." These data shows that those units which were switched "ON" during our coverage, were activated primarily at 2,500 to 10,000 feet (63.6 percent). The same inconsistency of reported sensitivity level with TCAS OFF exists in this data (some units report sensitvity level of 0 or 1 and others appear to report the sensitivity related to aircraft altitude).

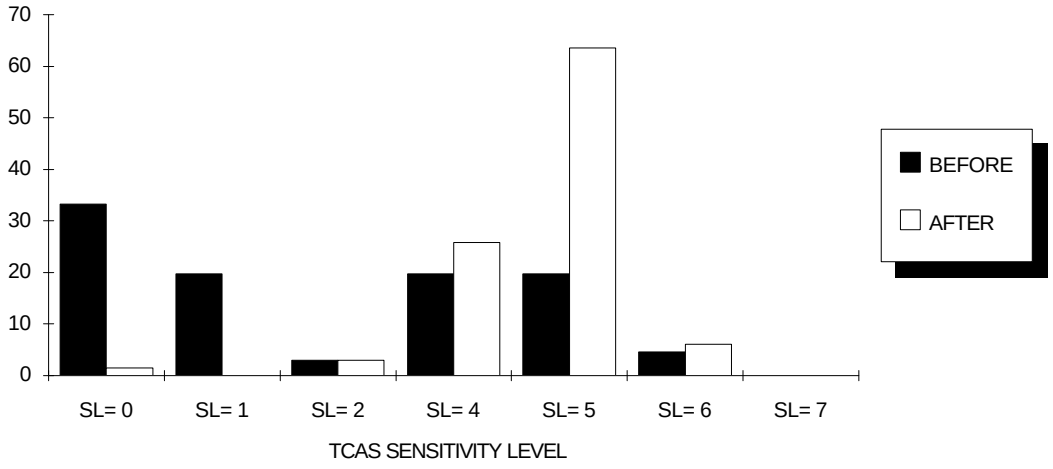

FIGURE 3. SENSITIVITY LEVELS REPORTED BY UNITS SWITCHED TO "ON"

RESOLUTION ADVISORY DATA DISCUSSION

There were 203 RA messages recorded by the TCAS monitor during it's operation at the DFW Airport. This number includes changes in the RA content during a TCAS encounter. A change in content can be a change in the Active Resolution Advisory (ARA) field, a change in the Resolution Advisory Complement (RAC) field, a change in both, or simply the addition of a RAC value to an existing ARA.

The 203 resolution advisory messages were generated from 119 TCAS encounters. There are more messages than encounters due to changes in message content during an encounter. Out of the 203 messages, 185 contained data in the ARA field other than zero. Figure 4 shows the distribution of the various types of advisories from the sample of 185 ARA messages.

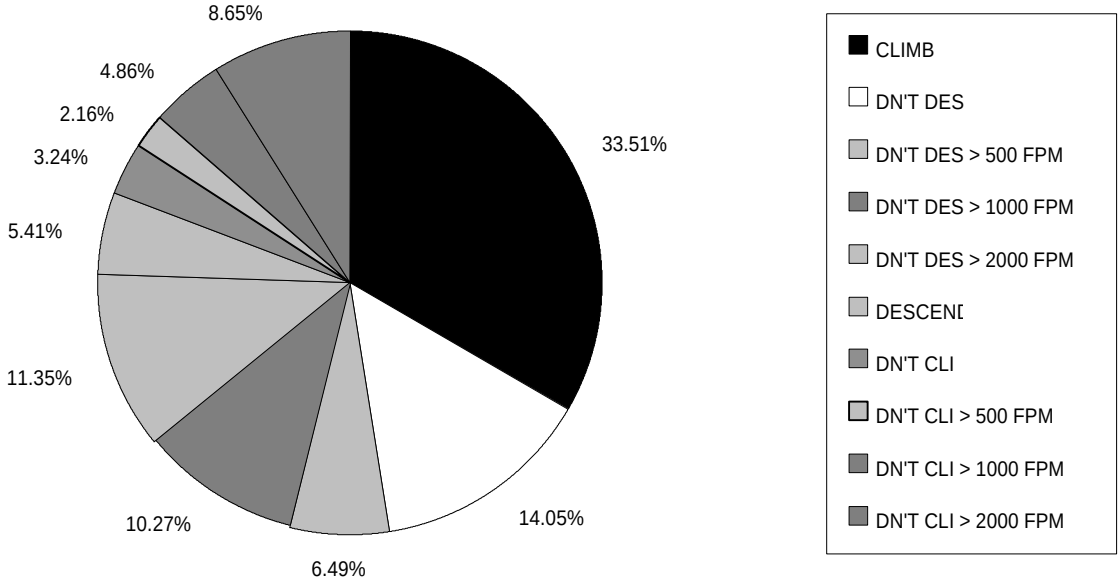

FIGURE 4. DISTRIBUTION OF RA TYPES

The TCAS Minimum Operational Performance Standards (MOPS) defines three categories for the advisories (Positive, Negative, and Vertical Speed Limit (VSL)). A positive advisory is a directive to an aircraft to change its vertical course (CLIMB and DESCEND). A negative advisory is a directive to an aircraft to not alter its present course into the direction of a threat aircraft (DON'T CLIMB and DON'T DESCEND). A VSL advisory warns the pilot not to exceed a vertical rate in the direction of a threat aircraft. These include advisories such as DON'T DESCEND FASTER THAN 500 FEET PER MINUTE and DON'T CLIMB FASTER THAN 2,000 FEET PER MINUTE, etc. Figure 5 shows the percentages of each of the three categories recorded at DFW. As indicated, the largest proportion (43.78 percent) were VSL advisories, followed by 38.92 percent POSITIVE advisories.

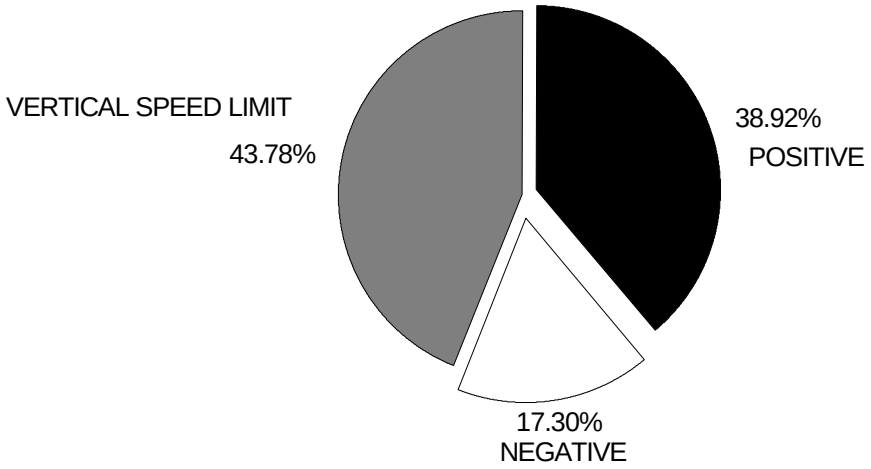

FIGURE 5. DISTRIBUTION OF RA CATEGORIES

The altitude and range data were correlated and examined and it was determined that the aircraft which posted RA's were going in three general directions: Departing DFW, Arriving at DFW, and Arriving at a nearby airport. Aircraft that were increasing in range and climbing were categorized as departing DFW. Aircraft that were decreasing in range and descending were categorized as arrivals to DFW. Other aircraft were increasing in range and descending. These aircraft may have been on approach to either Dallas Love Field or Dallas Hensley Field. As can be expected, most descending aircraft were advised of threats below them, and most climbing aircraft were advised of threats above them.

The 119 encounters consisted of 34 DFW departures and 66 DFW arrivals. Of the 34 departures, 32 were climbing when their RA occurred. Of the 66 DFW arrivals, 48 were descending when they received the RA. Eleven aircraft were on an approach to another airport within the DFW airspace. The remaining 8 RA's occurred during a period of data collection which resulted in the storage of "everything" which resulted in extremely large files. We could not feasibly download these files via modem (and they would have required manual insertion into the data base), so they were not included in the data base.

Figure 6 shows the altitude distribution where the RA's occurred. The x-axis is divided into increments where each division represents a range of 1,000 feet and is labeled with the low altitude value. For example, the division labeled 2,000 shows the number of RA's that occurred on or between 2,000 and 2,999 feet. The altitudes represented on this graph are those recorded at the start of the RA. The TCAS monitor was located north of the parallel runways at DFW with the antenna aimed to the southeast. The categories include DFW departures and arrivals and "other" which were aircraft on approach to neighboring airports.

As indicated on figure 6, the RA's occurred primarily at two altitude groups, low altitudes which are mostly arrivals, and between 9,000 and 11,000 feet (nearly an even distribution of departures and arrivals). As indicated, most RA's occurred between 9,000 and 10,000 feet for departures and between 10,000 and 12,000 feet for arrivals. At altitudes below 5,000 feet, the RA's occurred primarily for aircraft destined for other airports and some arrivals to DFW.

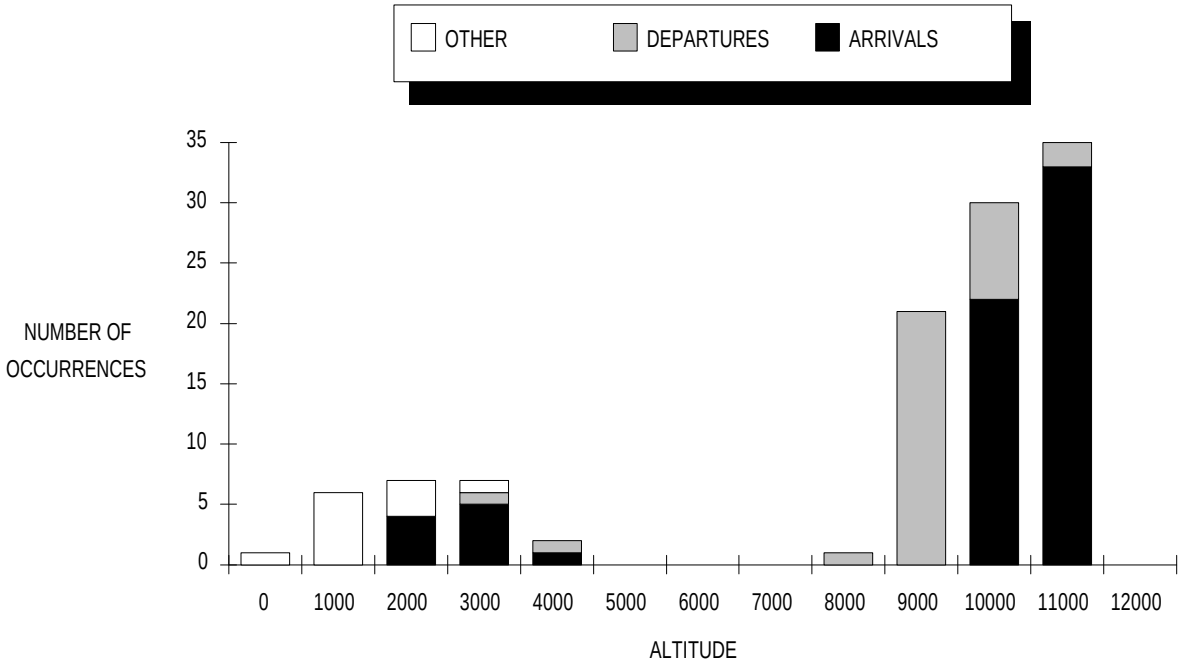

FIGURE 6. RA ALTITUDE DISTRIBUTION AS A FUNCTION OF FLIGHTPATH

Figure 7 shows where the TCAS aircraft sensed their threats. The aircraft are represented in three groups: arrivals, departures, and other. The determination for these categories is the same as described in the altitude distribution section. This graph shows the percentage of threat location for each category. The black area shows the percentage of threats detected below the TCAS aircraft. These data come from CLIMB, DON'T DESCEND, and vertical speed limits for descending. As expected, nearly all RA's occurring for arrival (descending) aircraft sensed the threat below them. The same is true for aircraft in the OTHER category since these aircraft were descending as well. The striped area represents the percentages of RA's where the threat was sensed above the TCAS aircraft. These data are from DESCEND, DON'T CLIMB, and vertical speed limits for climbing. As expected the

highest percentage of these occurred with departing (climbing) aircraft. A third category was added to this chart, and that is "RAC ONLY" THREAT ABOVE. This gray category was added because there were a significant amount of "RAC only" RA's. It is interesting to note that in all cases of "RAC only" aircraft the threat was above (RAC=DON'T CLIMB) and, as the chart shows, a large percentage of the RA's that occurred for departures were "RAC only." The sense direction was determined from the initial RA message. The threat sense was constant in all but three RA's where a sense reversal occurred.

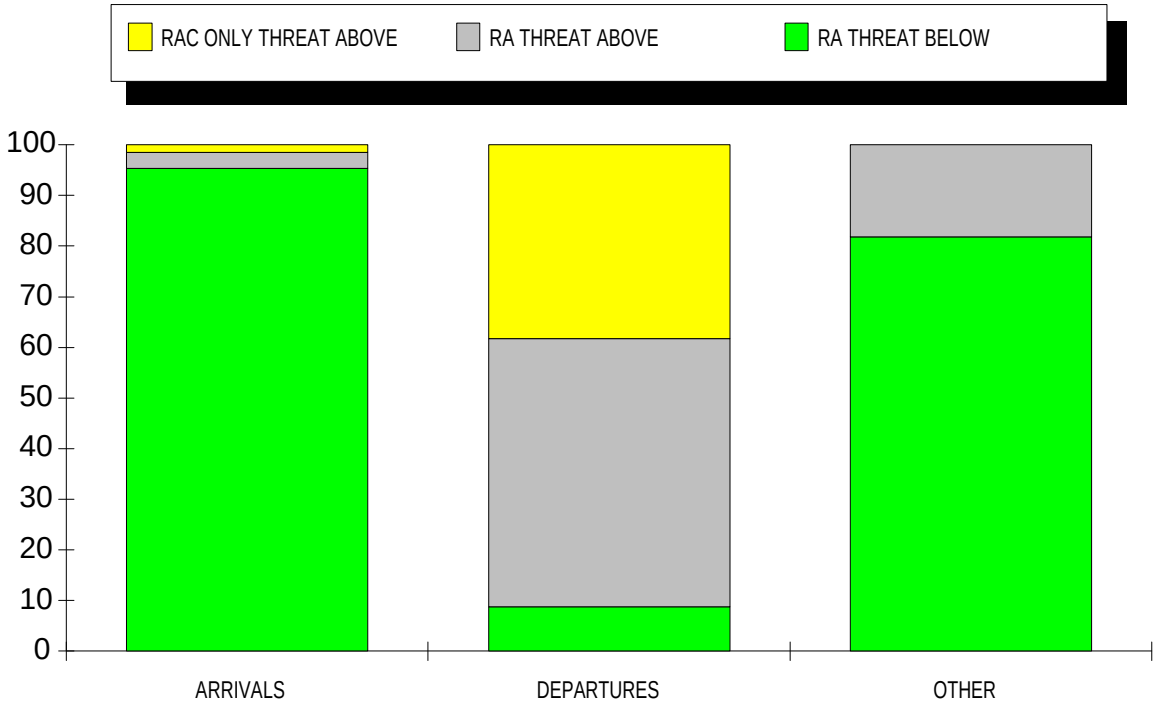

FIGURE 7. THREAT SENSE DISTRIBUTION

The 203 RA messages were generated from 119 TCAS encounters. There are more messages than encounters due to changes in message content during an encounter. Figure 8 shows the proportion of ARA and RAC field occurrences. The chart shows that in most cases (80.67 percent) only the ARA field contained data. The ARA and RAC fields both contained data in only 8.4 percent of cases (this percentage indicates the number of RA's occurring between two aircraft with TCAS enabled).

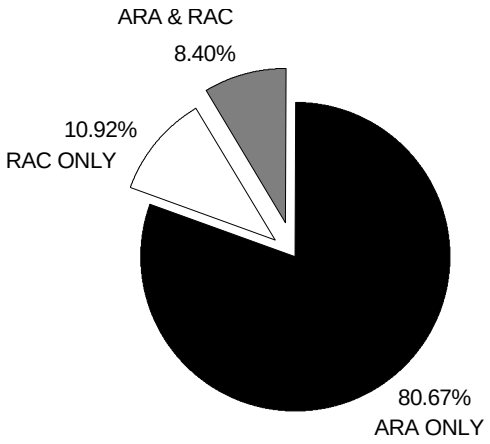

FIGURE 8. RESOLUTION ADVISORY REPORT DISTRIBUTION

Of the 119 TCAS encounters, 58 contained a single message advisory, and 61 were composed of multiple messages. A single message advisory means that the advisory remained constant throughout the encounter. In nearly all cases, surveillance data was recorded before, during, and after an active RA message.

The azimuth wedge for coverage by the DATAS was selected after coordination with DFW Air Traffic personnel. The basis for selection was their recollection of the airspace within which the highest number of TCAS RA's occurred. The primary direction of traffic flow was toward the south. Most aircraft were vectored in for landing from a "corner post" at approximately 45 miles southeast of the airport. Departing aircraft were using a parallel runway and taking off to the south at the same time. Since the TCAS monitor antenna was pointed directly at the "corner post" which was the suspect location of the advisories, these data seems to confirm the azimuth selection.

Figure 9 shows the proportion of single and multiple advisories. The chart also divides the multiple message advisories into four categories: RA softened, RA hardened, RA soft-hardened, and sense reversals. An RA is said to have softened if the RA switches to one with less severity such as a transition from CLIMB to DON'T DESCEND FASTER THAN 500 FEET PER MINUTE. Conversely, an RA is said to have hardened if the RA switches to one that is more severe such as a transition from DON'T CLIMB FASTER THAN 500 FEET PER MINUTE to DON'T CLIMB. The RA soft-hardened category covers cases where the RA first softened then hardened. A sense reversal is where apparently the threat aircraft switches its vertical position with respect to the aircraft. An example of a sense reversal might be CLIMB, then DESCEND, then DON'T CLIMB FASTER THAN 2000 FEET PER MINUTE. The chart shows that in most cases with multiple RA's, the RA softened.

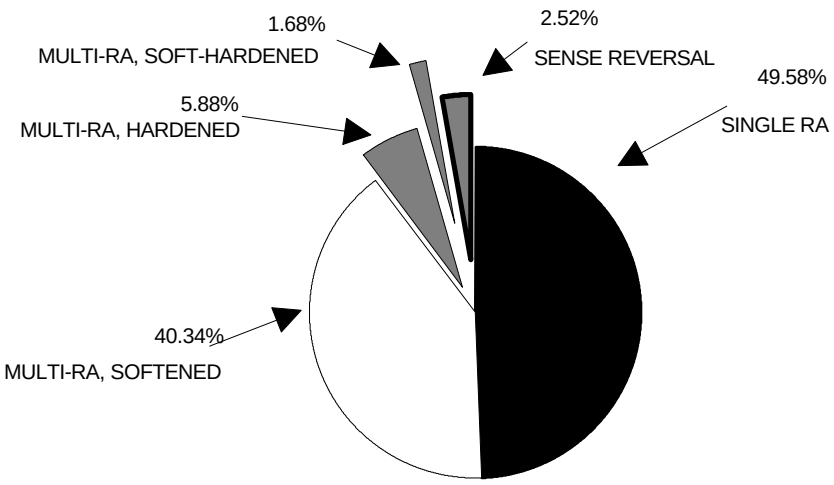

FIGURE 9. SINGLE/MULTIPLE ADVISORY DISTRIBUTION

Figure 10 shows that the largest percentage (55.46 percent) of RA's for the 119 encounters occurred on DFW arrivals. DFW departures accounted for another 28.57 percent. As stated previously, OTHER ARRIVALS are aircraft whose range (with respect to the TCAS monitor) is increasing while its altitude is decreasing.

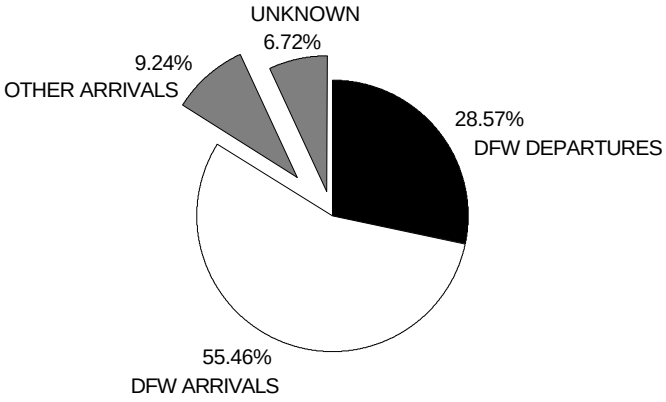

FIGURE 10. RA'S AS A FUNCTION OF FLIGHTPATH

Figure 11 shows the duration of the RA's. The RA's lasted for a period of 1 to 26 seconds. The mean RA time duration interval was approximately 8 seconds. The data may be somewhat skewed to the low end because of the way the aircraft were acquired as a result of our directional antenna system and effective scan pulse rate frequency (PRF) (5 seconds). If the RA was already in progress when the aircraft was initially acquired, the system obtained only the tail end of the RA message. It would then be shown as a duration which was less than the complete RA. This would also occur if the RA was still in progress when the aircraft left our coverage area. More significant are the cases where the duration of an RA segment was only 1 or 2 seconds while in transition between RA severities. Examples of this are shown on pages 25 and 26. Each of the changes would result in an aural alarm in the cockpit and because of the "nuisance factor," may lead to the pilot disabling the RA function (the minimum duration at any one level is supposed to be 5 seconds).

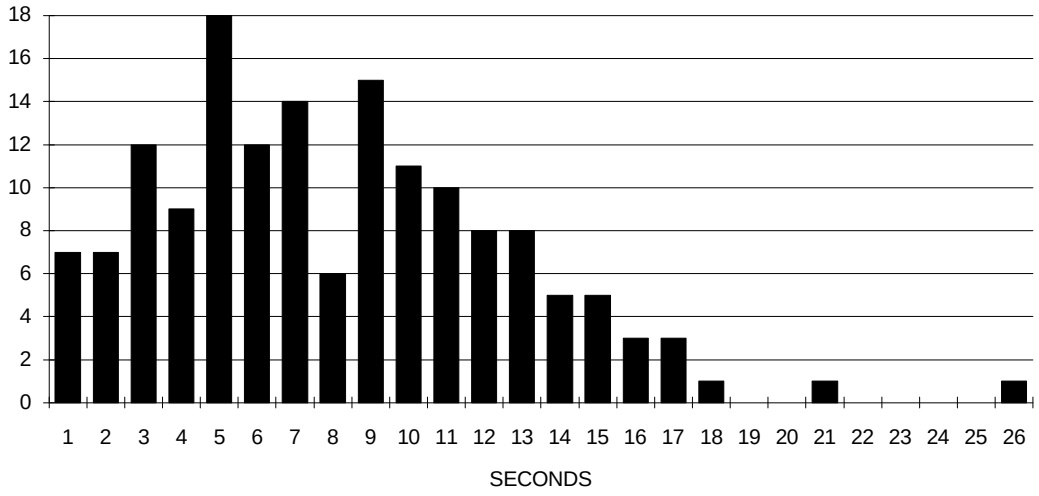

FIGURE 11. RA'S AS A FUNCTION OF DURATION

PILOT RESPONSE TO RA'S

There were a total of 97 TCAS RA encounters included in the data base for the analysis of pilot response. This number is the original 119 less those from the extremely large data files and those which were "RAC only" (which gives no indication to the pilot). The altitude data and RA data were "time correlated" and examined to determine an aircraft's response. The accuracy of placement in a category is somewhat questionable since it is partly based on speculation of what the pilot was doing. In order for the data to be as meaningful as possible, the rules to determine each category is carefully explained. The four categories were determined as follows:

1. **RESPONDED** - The aircraft appeared to have changed altitudes or changed vertical speed in response to the RA. The aircraft showed some kind of positive reaction to the RA. These include following a positive advisory, changing vertical rate for a VSL, a positive response to a negative advisory, or in some cases, reacting positively shortly after the advisory. The error rate is in favor of including aircraft in this category because in many cases a departure was leveling off at around 10,000 feet and was receiving an RA sense from above. Since it is impossible to distinguish these maneuvers from true responses, they were grouped into this category as well since the end result is that the pilot responded positively. There was no minimum vertical response required, if a pilot responded at all, it was included.

2. **ALREADY COMPLYING** - An RA was issued to an aircraft whose vertical direction agreed with a positive or negative advisory, or whose vertical speed was already within the limits of the VSL advisory.

3. **IGNORED** - The aircraft appeared to ignore a positive or negative advisory, or exceeded the VSL set by an advisory. The RA must be 5 seconds or longer to count. In some cases an aircraft received a positive or negative advisory, but simply changed its vertical rate. This is counted as a violation.

4. **UNSURE** - Insufficient altitude data, or the RA occurred at the beginning or end of the altitude data so prior or resulting altitude direction is not available.

The RA's were then separated into Arrivals and Departures. Pilot response for those two categories is shown on figures 12 and 13. These data indicate that 47.69 percent of the RA's which occurred on arrival flights were ignored. The pilot made a response which concurred with the RA in 20 percent of the cases. In 21.54 percent of the cases, the pilot was already complying with the RA which was issued by TCAS. The response of the remaining cases was inconclusive.

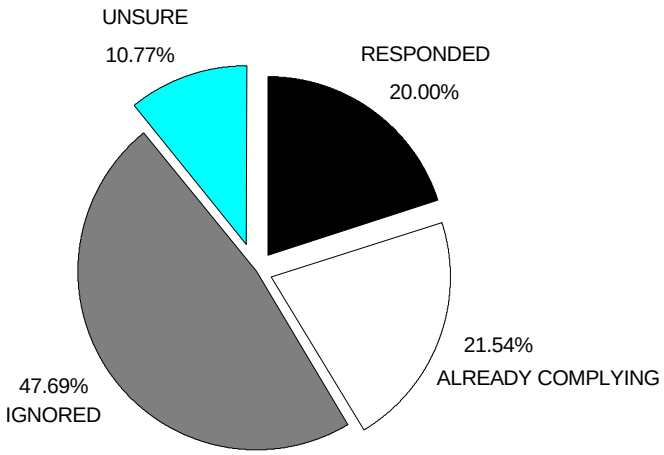

FIGURE 12. PILOT RESPONSE TO RESOLUTION ADVISORIES (ARRIVALS)

The pilot responses to RA's which occurred on departures was significantly better. More than 57 percent of the pilots responded in compliance with the RA, while 19.05 percent ignored them. Over 14 percent were already complying with the directive from the RA when it occurred. It is possible, however, that the pilots would have followed a flightpath in compliance with the RA even if it had not occurred. The normal path is to climb to 10,000 feet and level off prior to departing the area. The majority of the RA's would have been issued to avoid the aircraft which were level at 11,000 because of the "corner post" operation.

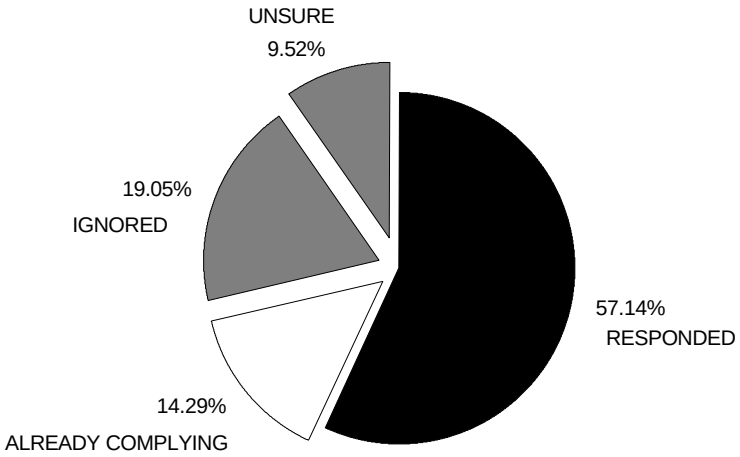

FIGURE 13. PILOT RESPONSE TO RESOLUTION ADVISORIES (DEPARTURES)

The positive response to RA's, however, was worst for those aircraft which were apparently destined for other airports. Of these cases, no one responded positively to an RA. Over 72 percent of the pilots ignored them completely and approximately 18 percent were already complying with the RA, see figure 14.

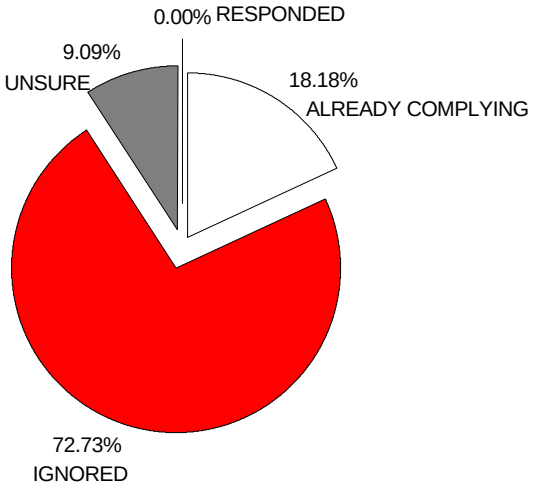

FIGURE 14. PILOT RESPONSE TO RESOLUTION ADVISORIES (OTHERS)

FAA Technical Center TCAS personnel conducted an independent analysis of the DATAS data and drew the following conclusions. Their interpretation of the pilot response to the resolution advisories is shown in figure 15. The main difference in the two analyses were the basic categories. They assumed that the RA had "no effect" if the aircraft was already following the instructions of the advisory and it was "ignored" if the first part of a multiple advisory was ignored. Using this definition of compliance, the percentage of compliance is considerably lower than the previously defined method.

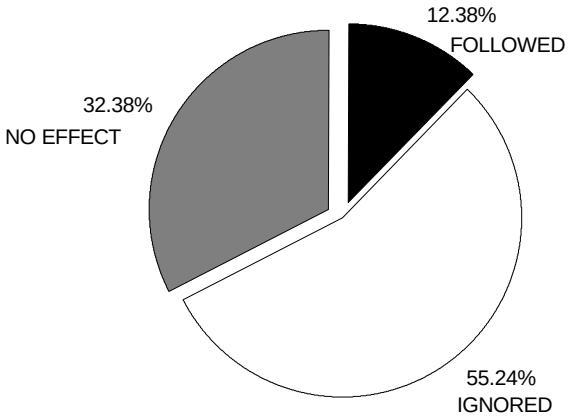

FIGURE 15. PILOT RESPONSE TO RESOLUTION ADVISORIES (TCAS ENGINEERS)

Perhaps a more disturbing statistic is the number of pilots that are apparently switching their TCAS units off in response to RA's. Out of this group of 97 encounters there were 15 cases where the TCAS units were switched to either off, or Traffic Advisory (TA) only for at least one scan (5 seconds). The evidence for this comes from the Reply Information (RI) field which is monitored during the surveillance scan. The RI field reports the TCAS capability of the aircraft as: 0-No TCAS, 2-TCAS with Vertical Resolution Inhibited (TA only), or 3-TCAS with Vertical Resolution Capability. Of these 15 cases, 5 were seen as reporting the RI field other than 3 for only one scan. When these replies were investigated they were determined as valid. A possible explanation is that the TCAS units were momentarily turned off or to TA only mode, and then returned to vertical resolution capability. In all of the remaining 10 cases, the RI field was switched to either 0 or 2 or a combination of each, and never returned to 3 for the duration of TCAS monitor coverage.

Figure 16 shows that over 15 percent of the aircraft reported decreased TCAS capability following an RA.

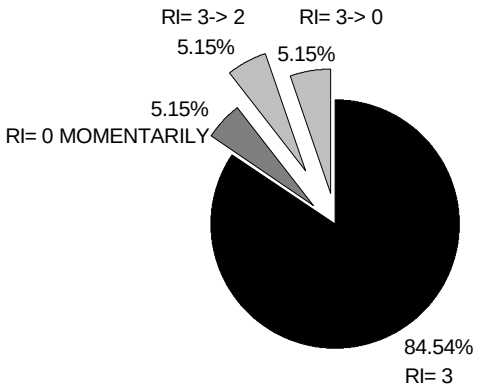

FIGURE 16. TCAS CAPABILITY AFTER RESOLUTION ADVISORY

Figure 17 shows the aircraft responses for the 15 aircraft that turned off their TCAS. The same criteria was used to determine these categories with the exception that the two types of violations were combined. The graph shows that nearly half of the pilots that turned off TCAS also ignored the advisory.

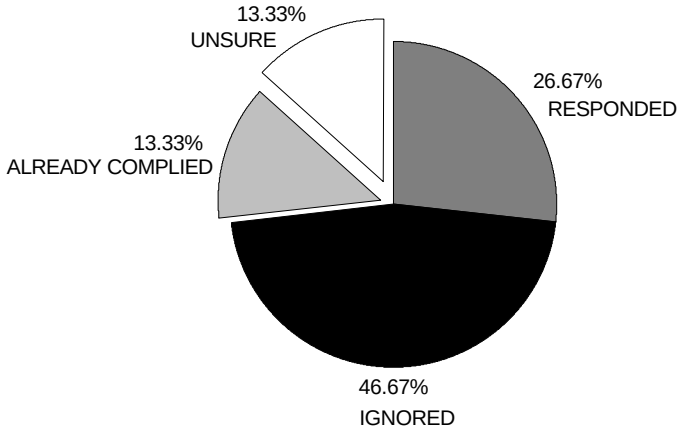

FIGURE 17. RESPONSE CATEGORIES FOR TCAS UNITS SWITCHED OFF

INDIVIDUAL DATA DISCUSSION

This section will display the altitudes of a sample of the aircraft that had RA's. The altitude information comes from the surveillance data recorded by the TCAS Monitor. The altitudes are time correlated with the RA information so the plots can show where the aircraft was located vertically during the RA. The altitude is acquired once per 5-second scan until an RA occurs, then it is acquired once per second along with the RA content. There are some gaps in the plots due to an insufficient response from the target aircraft at various time intervals. The example plots are categorized to illustrate the various types of pilot responses. The categories for the various responses are the same as described in the previous section.

EXAMPLES OF AIRCRAFT ALREADY COMPLYING.

This section shows altitude plots of those aircraft categorized as already complying with the RA message. Figure 18 shows a departure from DFW that was in a slight climb when it received an RA to CLIMB. The RA later softened to DON'T DESCEND.

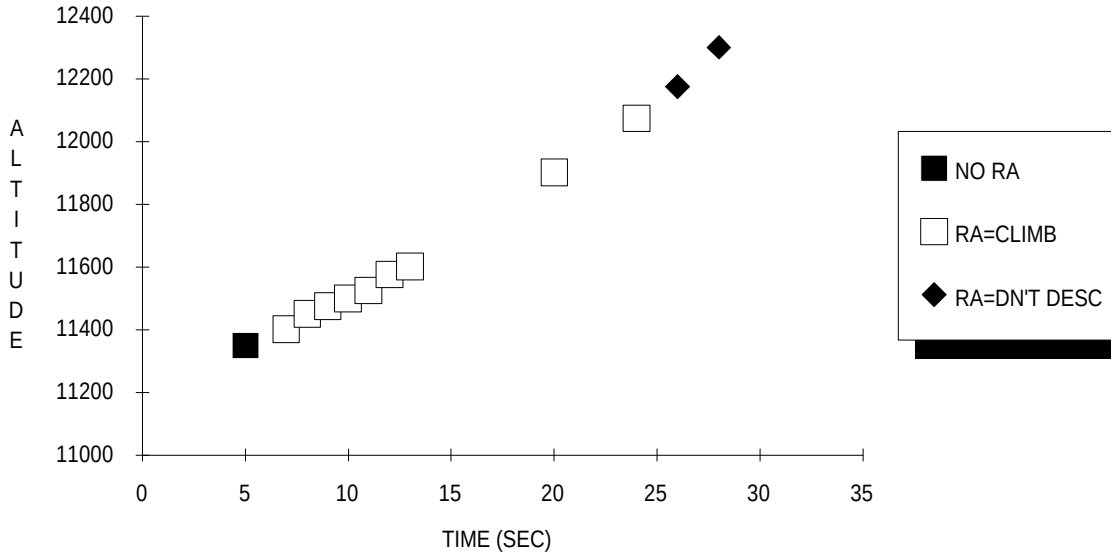

FIGURE 18. DFW DEPARTURE ALREADY COMPLYING WITH RA

Figure 19 shows an aircraft on approach to DFW that received an RA of DON'T DESCEND. The aircraft began its descent immediately after the RA, but since it was level prior to, and during the RA, it was categorized as already complying to the RA. There were 10 DFW arrival aircraft categorized as already complying to the RA, and 8 of those were DON'T DESCEND while the aircraft was level prior to descent.

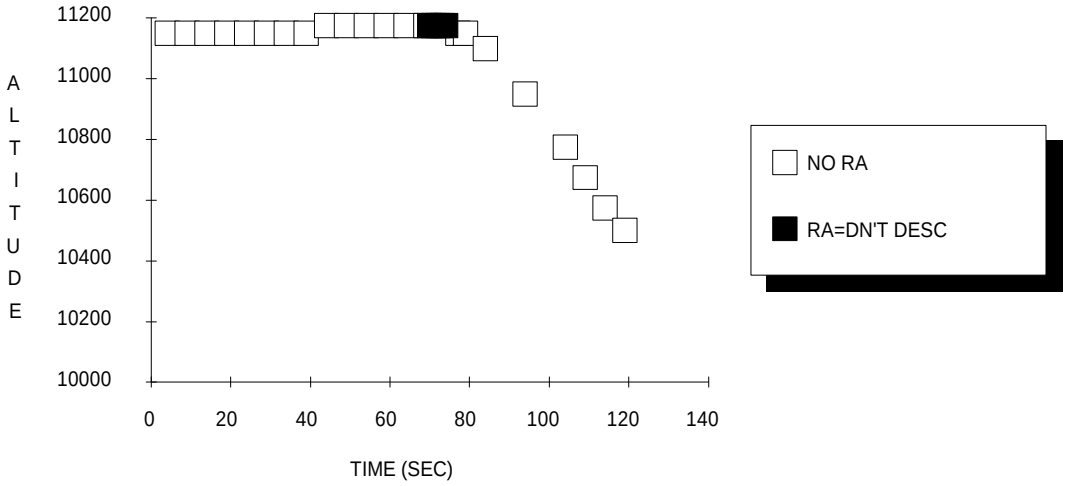

FIGURE 19. DFW ARRIVAL ALREADY COMPLYING WITH RA

Figure 20 shows an aircraft determined to be on approach to a different airport since, as it was descending, its range was increasing. This aircraft received an RA to DESCEND followed by DON'T CLIMB FASTER THAN 500 FEET PER MINUTE when it was in its descent.

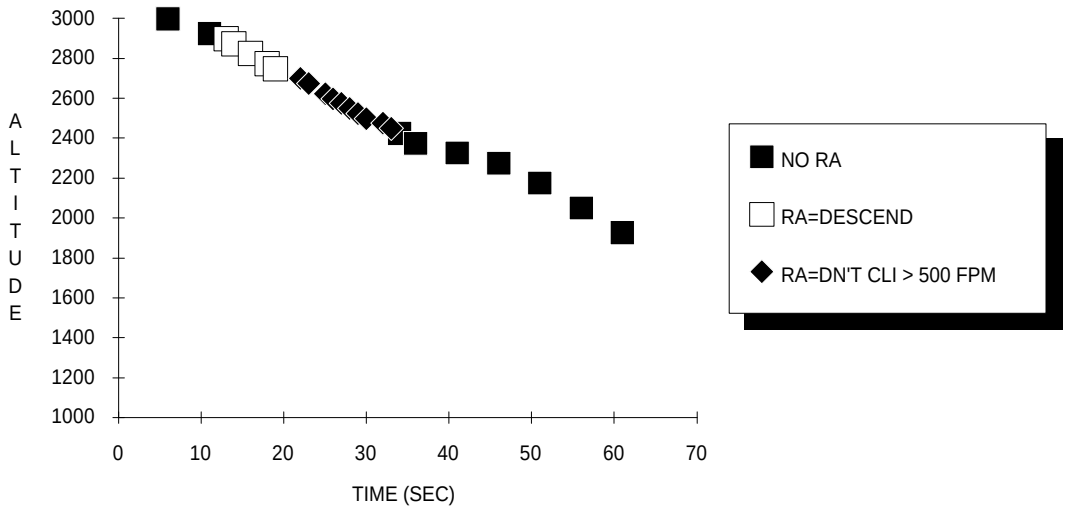

FIGURE 20. ARRIVAL TO OTHER AIRPORT ALREADY COMPLYING WITH RA

Figure 21 shows a more dramatic example of a pilot that was apparently already complying to an RA. This aircraft was also a departure from DFW that first received a RAC of DON'T CLIMB, then an RA of DON'T CLIMB, and later an RA of DON'T CLIMB FASTER THAN 1,000 FEET PER MINUTE. As the plot shows, the aircraft had already started its descent prior to the beginning of the RA. It appears as though the pilot may have overshot the normally assigned altitude of 10,000 feet for departures. This RA was one of three which happened simultaneously with three different aircraft. A more detailed analysis is presented in the section which discusses encounters with two or more TCAS equipped aircraft. The figure number for the entire encounter is E-1 in the Executive Summary.

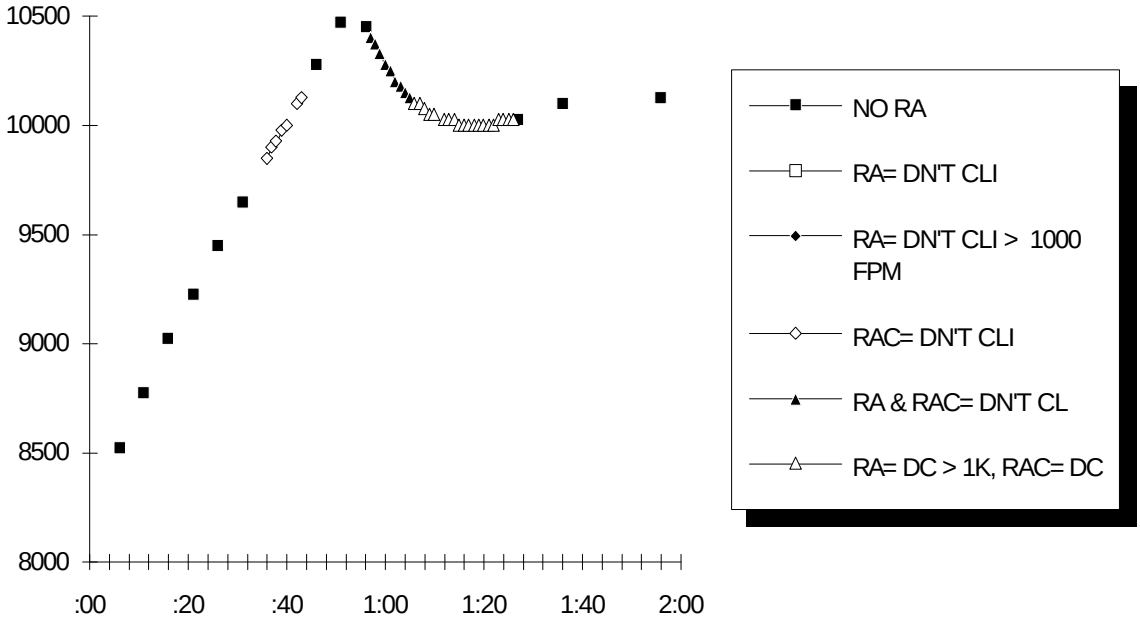

FIGURE 21. DFW DEPARTURE - ALREADY COMPLYING WITH RA

EXAMPLES OF AIRCRAFT WHICH RESPONDED.

This section shows altitude plots of aircraft that were categorized as responding to an RA. As discussed in previous sections, a response requires a pilot to show some reaction vertically with the aircraft, and the aircrafts vertical direction must comply with the RA. Figure 22 shows a climbing aircraft that received a VSL RA of DON'T CLIMB FASTER THAN 2000 FEET PER MINUTE. The altitude plot shows a slight reduction in the vertical rate of the aircraft just after the RA. This example illustrates how even such a subtle reaction was categorized as a response. The aircraft involved may not necessarily have reacted to the advisory at all. It may have been directed by air traffic personnel or merely intended to deviate from the projected flightpath prior to the issuance of the resolution advisory.

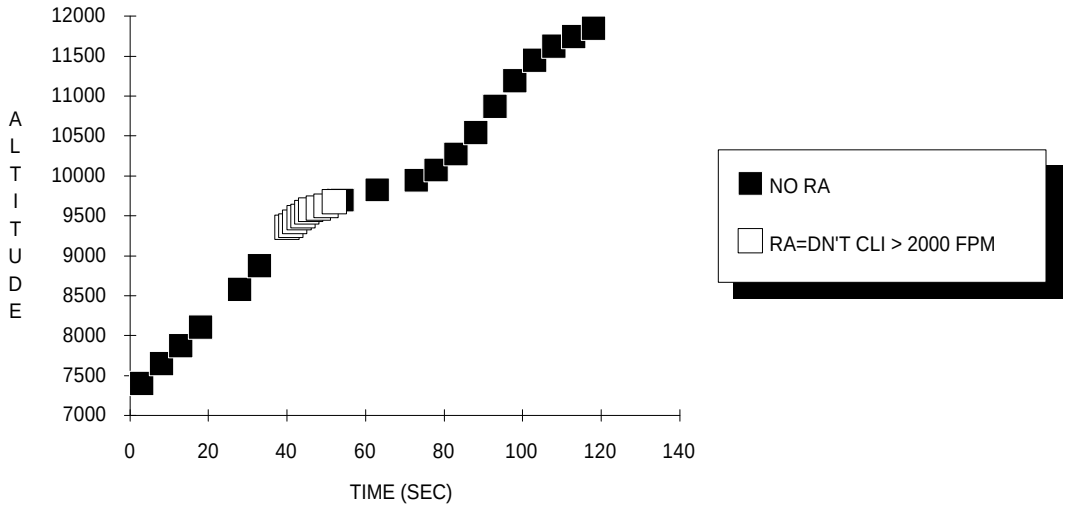

FIGURE 22. DFW DEPARTURE RESPONDED TO RA

Figure 23 shows an aircraft on approach to DFW that received an RA sense reversal. The RA switched from DESCEND, to CLIMB, then to DON'T DESCEND. This was categorized as a positive response because of the slight climb, followed by level flight of the aircraft at the end of the RA. Although the pilot did not react to the DESCEND message, it was categorized as a positive response because of the overall response and the short duration of the DESCEND message. This plot is probably a better example of a "sense reversal" than a response to an advisory.

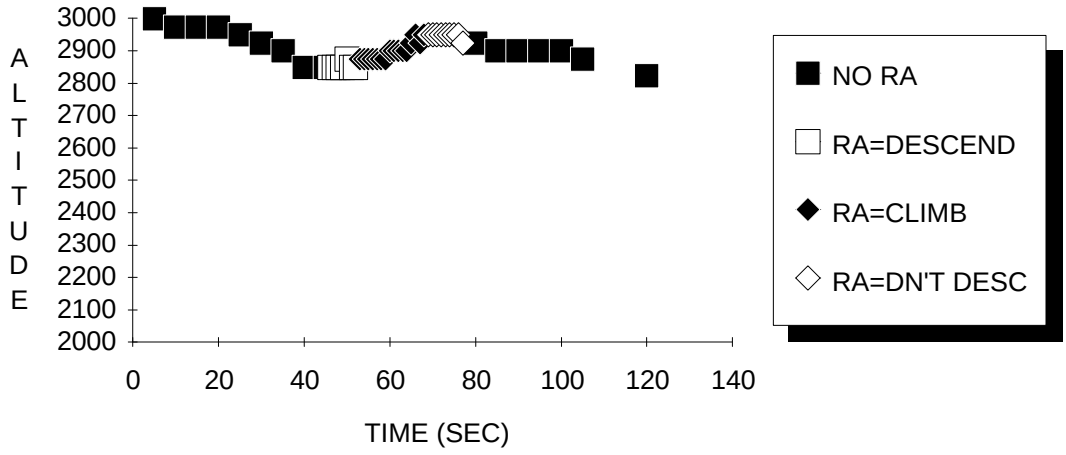

FIGURE 23. DFW ARRIVAL - SENSE REVERSAL

Figure 24 shows another positive response to an RA. The aircraft was descending on approach and leveled off for some time following a DON'T DESCEND RA. Figure 25 shows an expanded plot of the same aircraft.

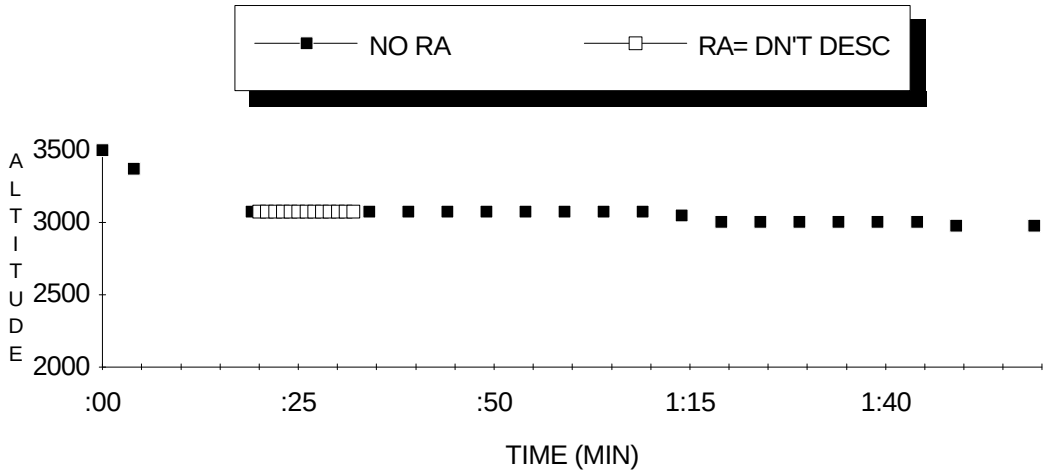

FIGURE 24. DFW ARRIVAL - MAY HAVE RESPONDED TO RA

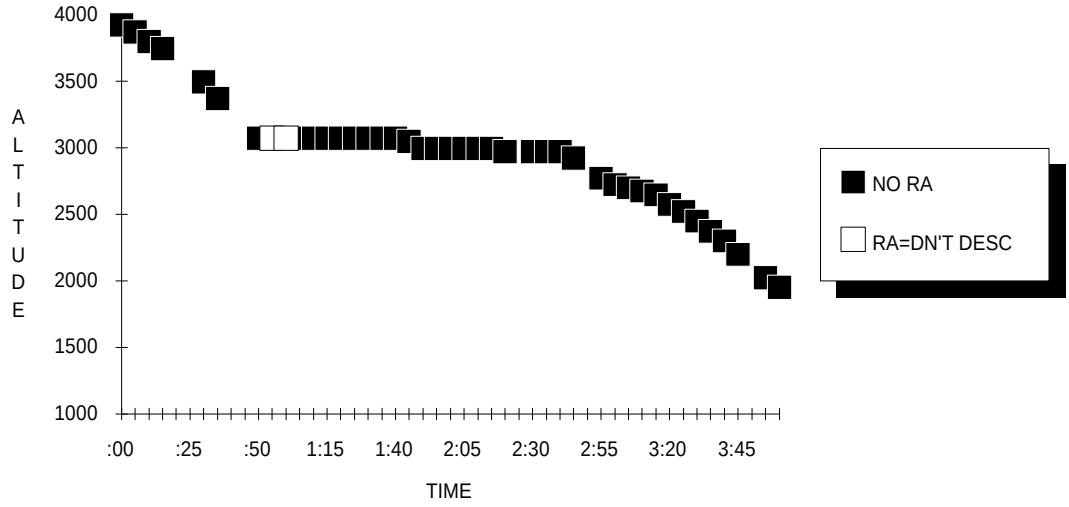

FIGURE 25. DFW ARRIVAL - FULL FLIGHTPATH OF FIGURE 24

Figure 26 shows another aircraft on approach to DFW. This aircraft climbed approximately 300 feet after receiving an RA of DON'T DESCEND. This plot shows a possible overreaction to an RA.

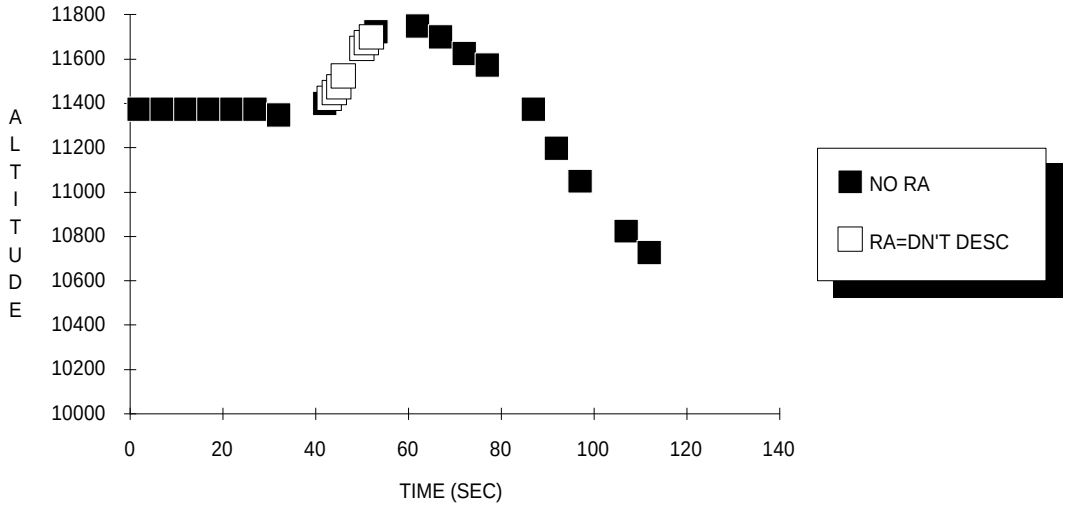

FIGURE 26. DFW ARRIVAL - POSITIVE RESPONSE TO NEGATIVE RA

Figure 27 shows another aircraft on approach to DFW that responded to an RA. This RA hardened from DON'T DESCEND to CLIMB. The pilot had apparently just begun his descent, and then climbed back up to 11,000 feet and then later began his descent.

None of the 11 aircraft that were determined to be on approach to the other airport showed a positive response to an RA.

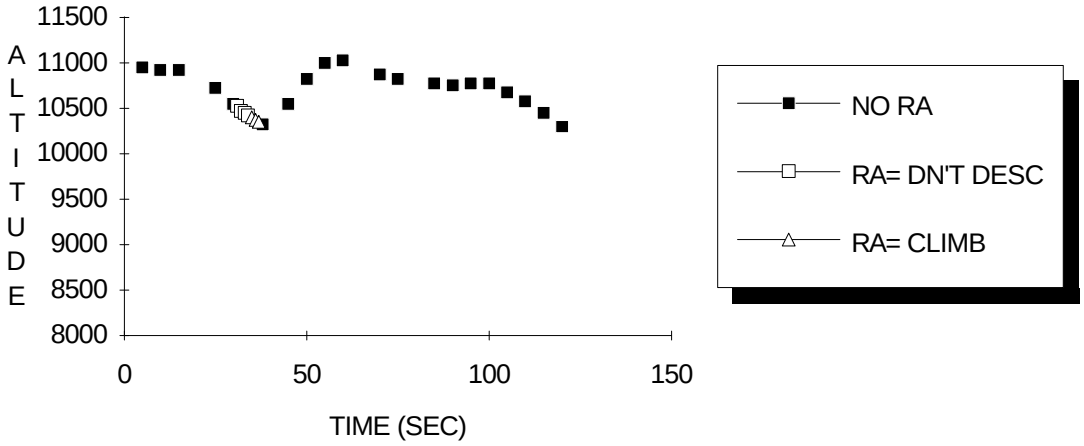

FIGURE 27. DFW ARRIVAL - RA HARDENED, PILOT RESPONDED

EXAMPLES OF AIRCRAFT WHICH IGNORED THE RA.

This section shows examples of aircraft that were categorized as ignoring the RA messages. Figure 28 shows a DFW departure that was categorized as ignoring the initial RA. The pilot continued to climb during the RA to DESCEND. It was a violation of only the initial RA since the aircraft leveled off following the RA. Since the normally assigned altitude for departures was 10,000 feet, the pilot was probably leveling off at his assigned altitude and ignored the whole RA.

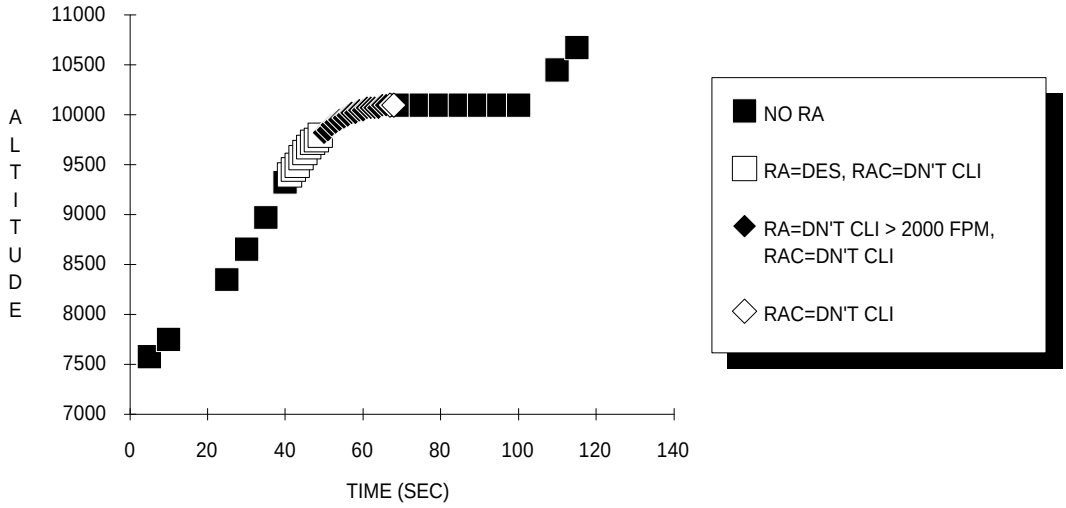

FIGURE 28. DFW DEPARTURE - IGNORED RA INITIALLY

Figure 29 shows an arrival to another airport that ignored the RA even as it hardened. Figure 30 shows another example of an aircraft on approach to another airport where the RA hardened and the pilot ignored it. There were a total of seven cases where a multiple RA message was recorded that hardened, and four of them were from the 11 aircraft on approach to the other airport.

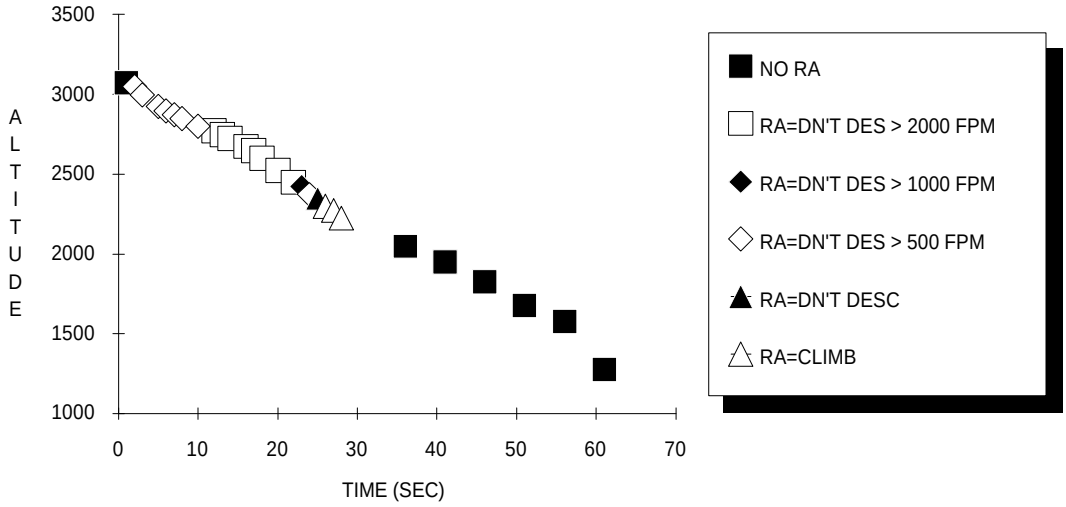

FIGURE 29. ARRIVAL AT OTHER AIRPORT - IGNORED RA

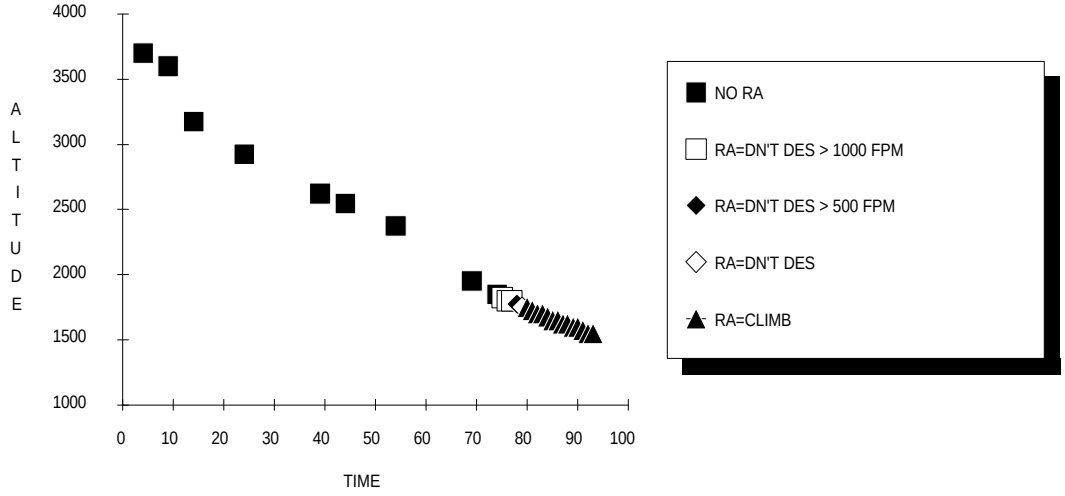

FIGURE 30. ARRIVAL NO. 2 AT OTHER AIRPORT - IGNORED RA

There were 24 DFW arrivals categorized as ignoring the RA, and all but one of them occurred during the level flight prior to descent. Most of these RA's were multiple RA's that softened. Figure 31 shows such a case. Figure 32 is an expanded view of the same RA in order to illustrate the location of the RA with respect to its descent. Note that the area of the plot designated as "RA Active" includes the total time for which the aircraft received three different advisories during the same encounter.

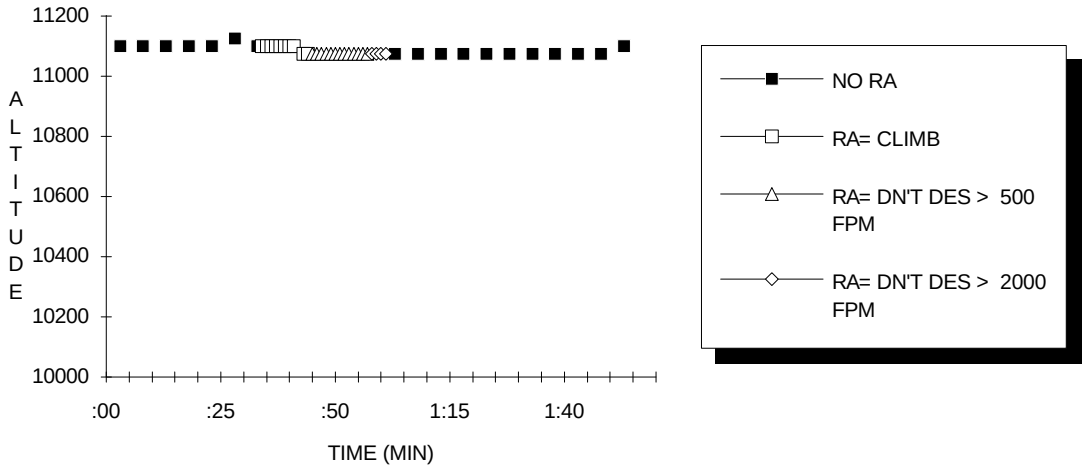

FIGURE 31. DFW ARRIVAL NO. 2 - IGNORED RA

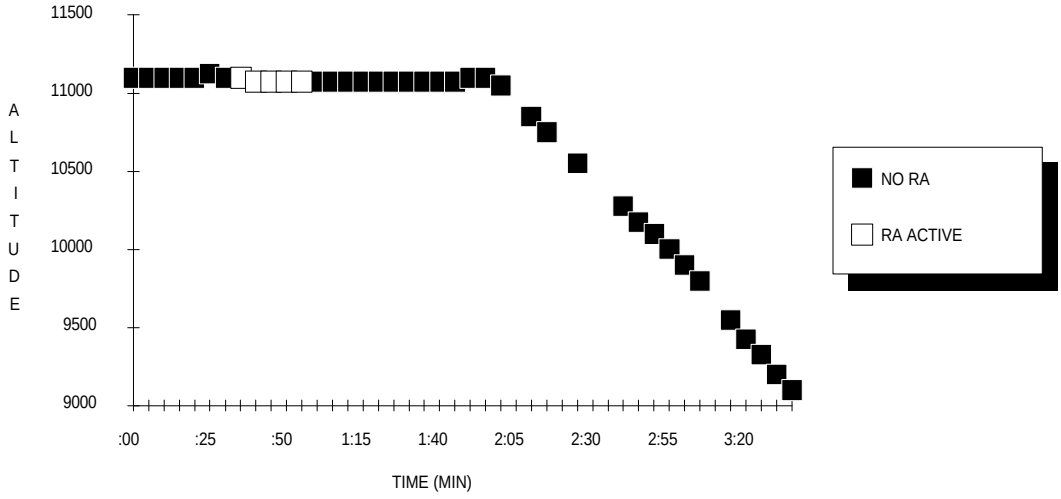

FIGURE 32. DFW ARRIVAL NO. 2 - IGNORED RA (FULL FLIGHT)

EXAMPLES OF PILOTS DISABLING TCAS.

The following figures are altitude plots of aircraft that had RA's, and, apparently in response, the pilot switched the TCAS unit to OFF or to TA only mode. These are plots of the aircraft altitude reports from the surveillance data with various symbols used to indicate RA messages and TCAS capability. The TCAS capability comes from the surveillance data. Each 5-second surveillance scan the aircraft are interrogated with a UF=0 (a short Mode S interrogation reserved for TCAS coordination) in order to request TCAS capability and other related information. This capability is reported in the RI field. The RI field reported contains one of the following values: 0=NO TCAS, 2=TCAS WITH VERTICAL CAPABILITY INHIBITED (TA ONLY), or 3=TCAS WITH VERTICAL RESOLUTION CAPABILITY. The legend in each plot has a symbol labeled TCAS ON - NO RA. This symbol identifies surveillance replies where the RI field reported was 3-TCAS WITH VERTICAL RESOLUTION CAPABILITY and there was no active RA for that aircraft. Other symbols are used to identify replies that contained an active RA message. The TCAS capability during these replies, although not labeled, is also RI=3. These plots are extended to show the aircraft replies for the entire time the aircraft was on surveillance by the TCAS monitor. Because of the variation in the amount of time each target was on surveillance, the time period of the x-axis varies. Figure 33 shows a departure from DFW where the RA was apparently ended when the TCAS unit was switched OFF. In some of the cases such as this one, the change in TCAS capability apparently ended the RA. In other words, the TCAS unit was switched during the RA. In other cases, the TCAS capability is switched soon after an RA has ended, perhaps to avoid future RA's.

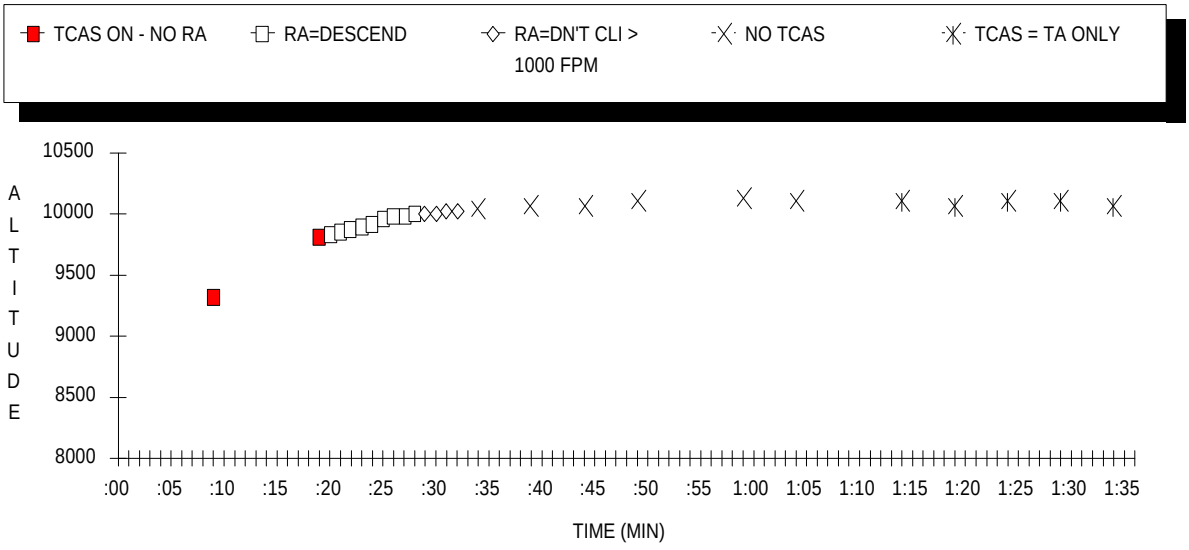

FIGURE 33. DEPARTURE WITH TCAS RESOLUTION CAPABILITY INHIBITED

Figure 34 shows an aircraft that apparently switched the TCAS unit OFF just after an RA. One scan occurred after the RA where the TCAS capability was RI=3. From that point on the aircraft reported RI=0. In this case the RA was apparently not ended by the

switch. The pilot may have switched off the TCAS unit because he was apparently on final approach.

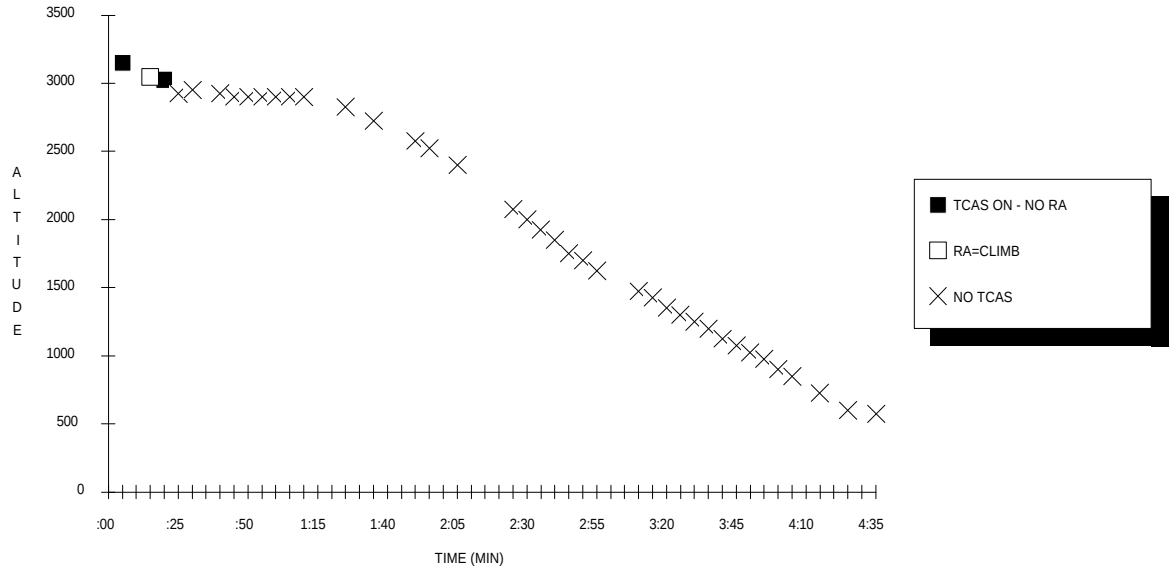

FIGURE 34. ARRIVAL WITH TCAS RESOLUTION CAPABILITY INHIBITED

Figure 35 shows another plot where the TCAS unit was switched to TA ONLY mode (RI=2) during the RA. This RA only lasted for 3 seconds, as seen by the TCAS monitor, before being cut off. The aircraft altitude was over 11,000 feet and level. The range data indicated the aircraft was on approach.

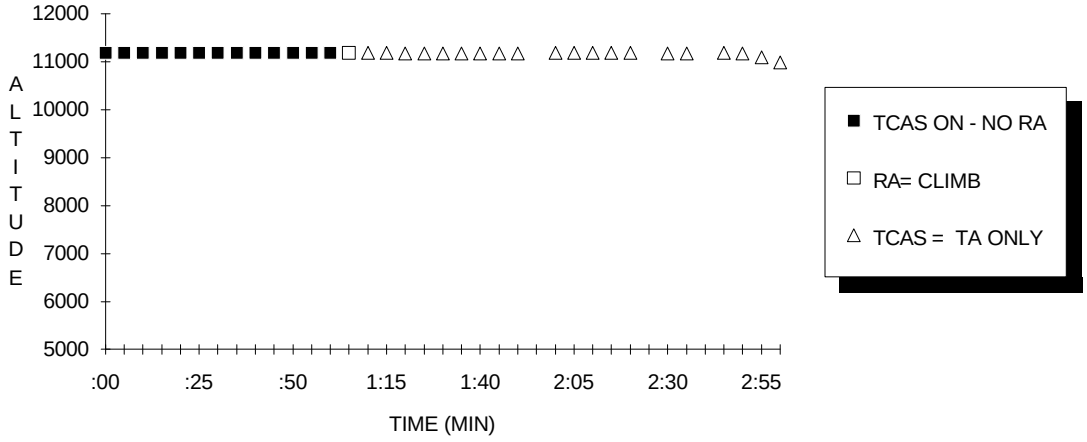

FIGURE 35. TCAS SWITCHED TO TA ONLY DURING RA

Figure 36 shows a similar case. Again, the TCAS unit was switched to TA ONLY but in this instance it was switched after the RA had ended. The pilot apparently switched the TCAS unit prior to descent from 11,000 feet.

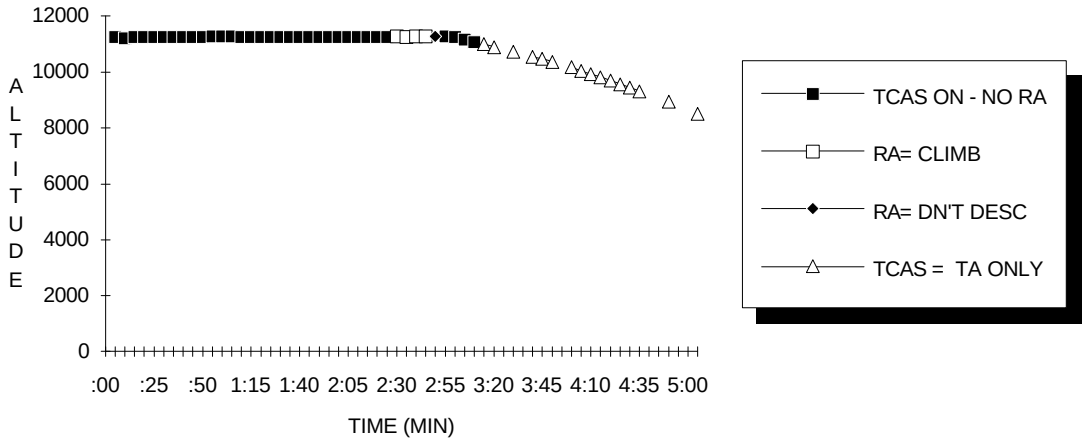

FIGURE 36. TCAS SWITCHED TO TA ONLY AFTER RA

Figure 37 shows another case where the TCAS unit was switched some time after the RA. Again, the unit was switched just prior to descending from 11,000 feet. In this case, however, TCAS was switched to OFF.

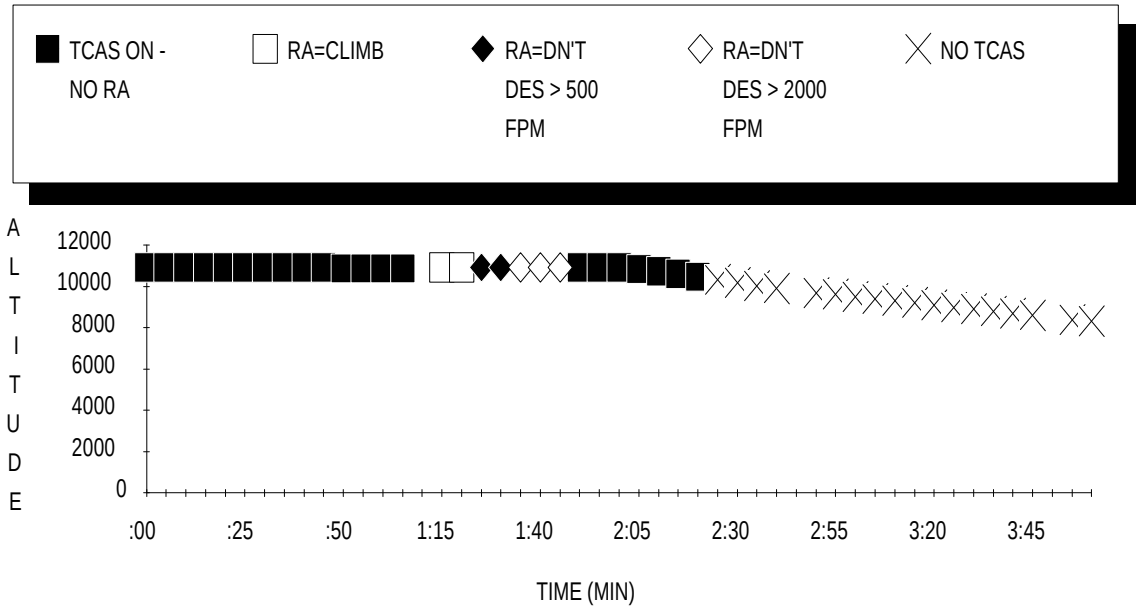

FIGURE 37. TCAS SWITCHED TO OFF AFTER RA

ENCOUNTERS WITH TWO OR MORE TCAS EQUIPPED AIRCRAFT

The TCAS monitor deployment in DFW recorded 13 instances where two or more TCAS equipped aircraft were apparently involved in the same RA. Although there were no azimuth data available, the aircraft altitudes, RA messages, and TCAS capability were time correlated and plotted together. This information provides some insight to the situations which caused the RA's. The lack of azimuth data is perhaps the greatest limitation of the existing TCAS monitor and justifies the need for enhancement by adding azimuth tracking. As stated previously, the TCAS monitor was located within the confines of the DFW Airport at the north end of the four parallel runways. The directional antenna was aimed towards the southeast. This direction was chosen to provide coverage of the southeast "corner post." This "corner post" was reported to be the most active location for RA's by air traffic personnel. As such, all of the encounters recorded occurred southeast of the airport. Range information provided is approximate with respect to the TCAS monitor location. The range data are intended to provide only a coarse estimate of the location of the aircraft. The aircraft are described as arrivals and departures. They were determined as such based solely on the altitude and limited range data provided by the data recorded. Most aircraft could be divided into three categories: arrivals, departures, and those on approach to another airport. Arrivals are those aircraft that were either level or descending and whose range was decreasing with respect to the system. Conversely, departures were those aircraft that were climbing or level and increasing in range. Other aircraft were seen as descending and increasing in range. Because these aircraft were at relatively low altitudes (approximately 3,000 feet and descending) they were assumed to be on approach to other nearby airports.

The altitude profiles of 11 dual encounters were plotted and are included in the following figures. The RA's all occurred within the range of 10 to 20 miles from the airport. The remaining two dual encounters were part of the large data files not included in the data base.

Figure 38 shows two aircraft apparently involved in the same RA. Aircraft No. 1 was an arrival aircraft flying level at 11,200 feet at a range of 12 miles at the first report of the CLIMB RA. Aircraft No. 2 was a departure climbing at 10,025 feet at a range of 11 miles at the time of first report of the RAC=DON'T CLIMB. Aircraft No. 1 had an ARA with no RAC and aircraft No. 2 had an RAC with no ARA.

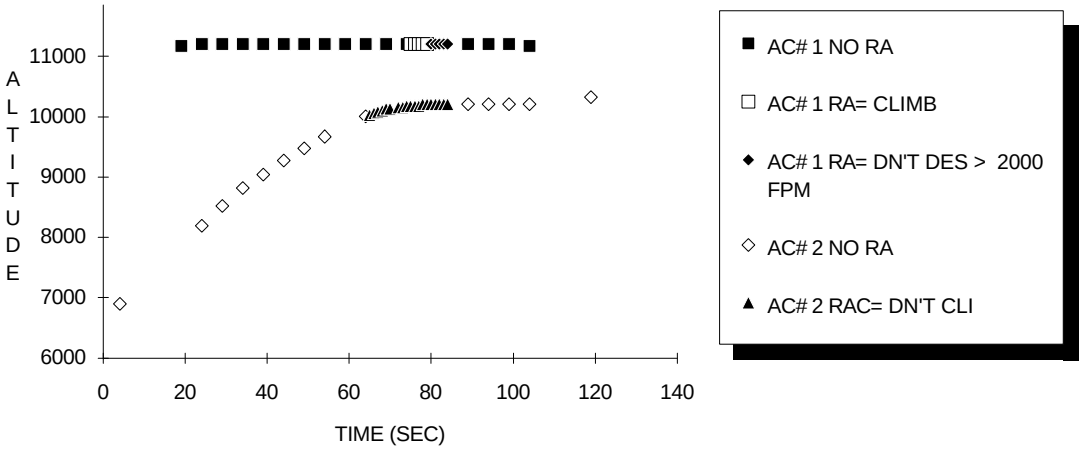

FIGURE 38. TCAS ENCOUNTER NO. 1 BETWEEN TWO AIRCRAFT

Figure 39 shows a similar scenario. Aircraft No. 1 was an arrival aircraft flying level at 11,000 feet at a range of 13 miles at the first report of the CLIMB RA. Aircraft No. 2 was a departure climbing at 9,975 feet at a range of 10 miles at the first report of the DON'T CLIMB FASTER THAN 1,000 FEET PER MINUTE RA. Aircraft No. 1 had an RAC of DON'T DESCEND and aircraft No. 2 had an RAC of DON'T CLIMB during the RA.

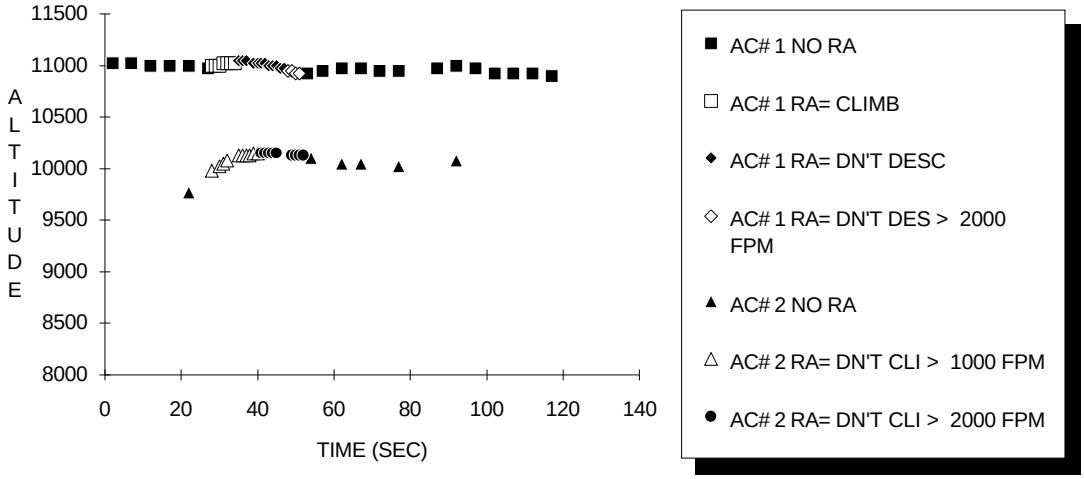

FIGURE 39. TCAS ENCOUNTER NO. 2 BETWEEN TWO AIRCRAFT

Figure 40 shows another case where only one aircraft had an RA. Aircraft No. 1 was an arrival (level at 10,875 feet) at a range of 13 miles at the start of the RA. This aircraft had an RA as it flew into the coverage of the TCAS monitor. Aircraft No. 2 was a departure climbing at 9,225 feet at a range of 10 miles at the start of the RAC. Although these aircraft appear to converge vertically, they apparently had sufficient horizontal separation to end the TCAS encounter.

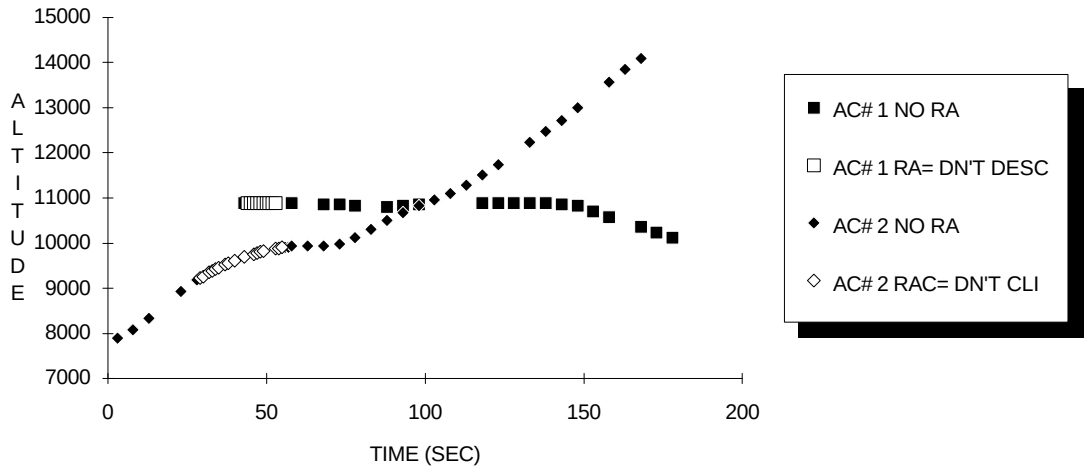

FIGURE 40. TCAS ENCOUNTER NO. 3 BETWEEN TWO AIRCRAFT

Figure 41 shows a similar scenario. Aircraft No. 1 was an arrival (level at 11,000 feet) at a range of 12 miles at the start of the RA. Aircraft No. 2 was a departure climbing at 9,900 feet at a range of 11 miles at the start of the RA.

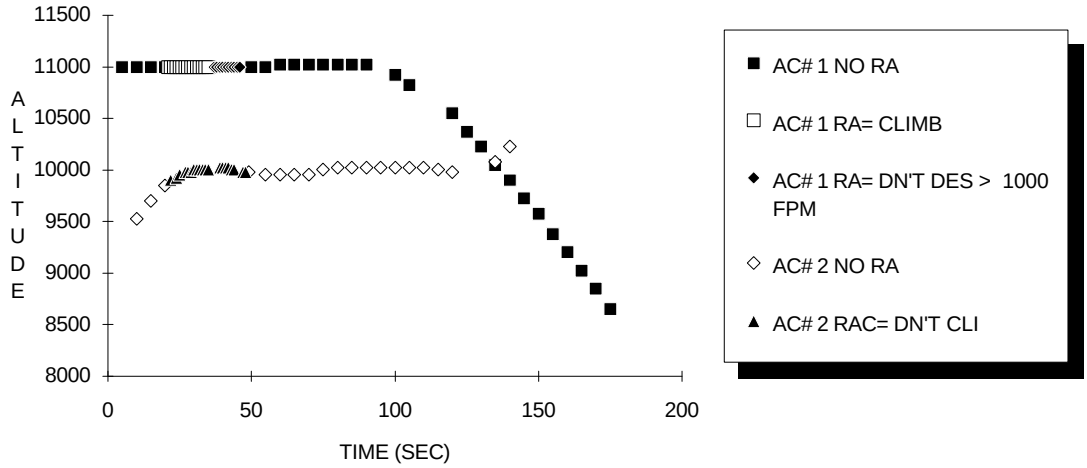

FIGURE 41. TCAS ENCOUNTER NO. 4 BETWEEN TWO AIRCRAFT

Figure 42 shows two aircraft involved in an RA where the TCAS unit in aircraft No. 1 was apparently switched to TA ONLY mode following the RA. Aircraft No. 1 was an arrival which was level at 10,975 feet at a range of 21 miles at the start of the RA. Aircraft No. 2 was a departure climbing at 10,025 feet at a range of 19 miles.

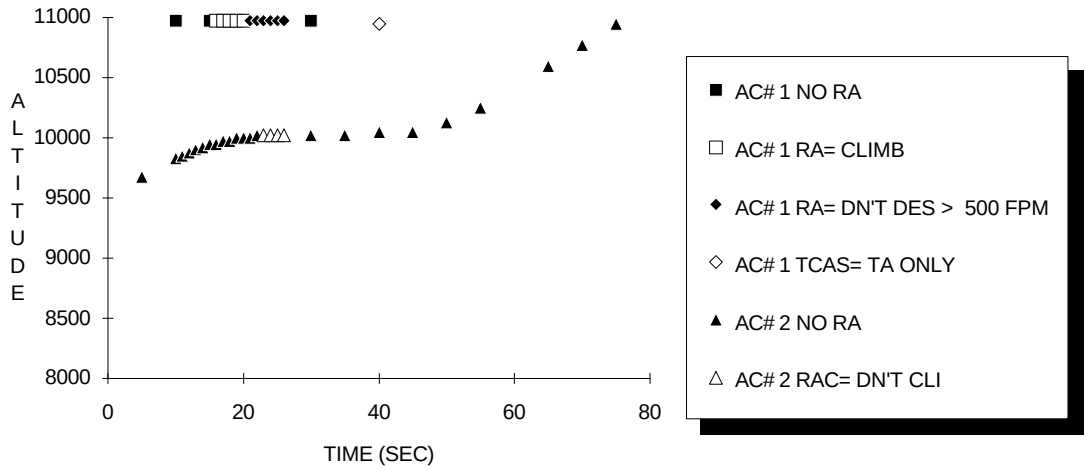

FIGURE 42. TCAS ENCOUNTER NO. 5 BETWEEN TWO AIRCRAFT

Figure 43 shows a typical scenario. Aircraft No. 1 is an arrival which was level at 11,025 feet at a range of 16 miles at the start of its RA. Aircraft No. 2 is a departure climbing at 9,900 feet at a range of 13 miles at the start of its RA.

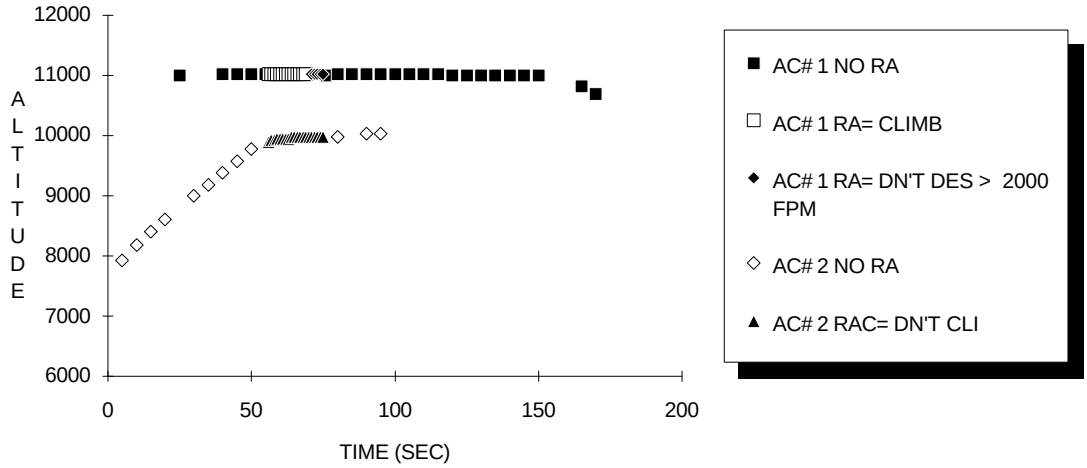

FIGURE 43. TCAS ENCOUNTER NO. 6 BETWEEN TWO AIRCRAFT

Figure 44 shows an RA where the arrival aircraft responded to the RA. Aircraft No. 1 was an arrival which was level at 11,125 at a range of 12 miles at the start of the RA. Aircraft No. 2 was climbing at 9,525 feet at a range of 11 miles.

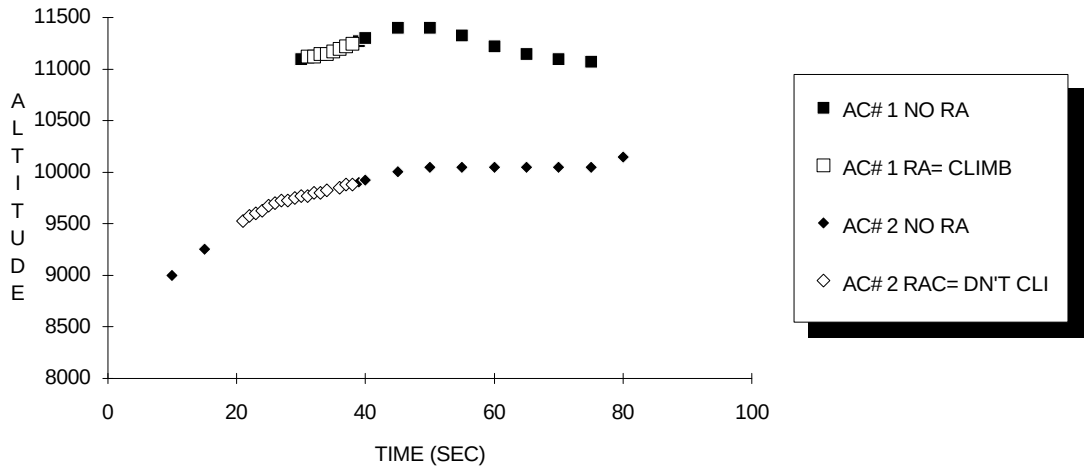

FIGURE 44. TCAS ENCOUNTER NO. 7 BETWEEN TWO AIRCRAFT

Figure 45 shows two aircraft involved in an RA where aircraft No. 2 reported that its TCAS unit had been switched OFF and then to TA ONLY. Aircraft No. 1 was an arrival which was level at 11,075 at a range of 13 miles at the start of the RA. Aircraft No. 2 was a departure climbing at 9,825 at a range of 13 miles at the start of the RA.

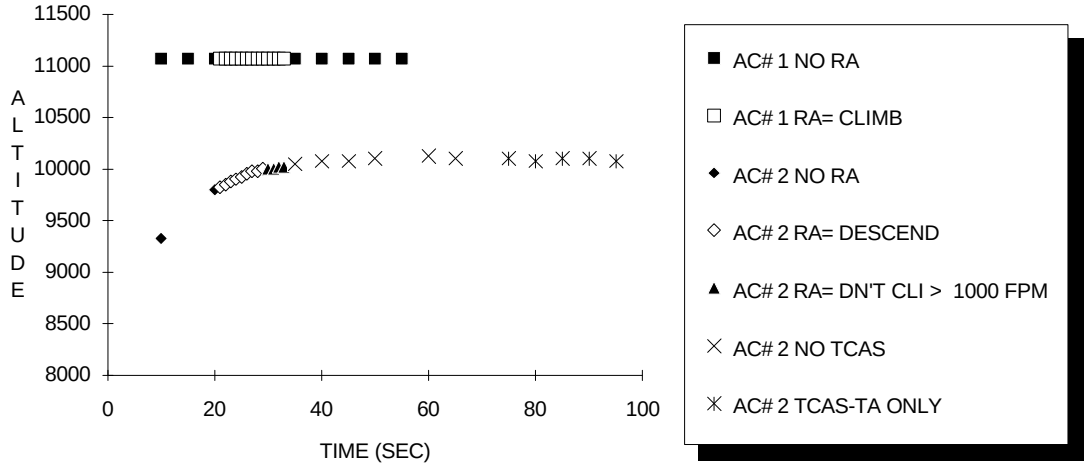

FIGURE 45. TCAS ENCOUNTER NO. 8 BETWEEN TWO AIRCRAFT

Figure 46 shows two aircraft with RA's which occurred very close in time, but they were not actually simultaneous. Aircraft No. 1 was an arrival which was level at 11,100 feet at a range of 12 miles at the start of the RA. Aircraft No. 2 was a departure climbing at 9,925 feet at a range of 11 miles. There was probably another aircraft involved in the RA's which was either not in our coverage wedge or was not Mode S equipped. This is another example of the requirement for azimuth data to adequately analyze situations such as this one.

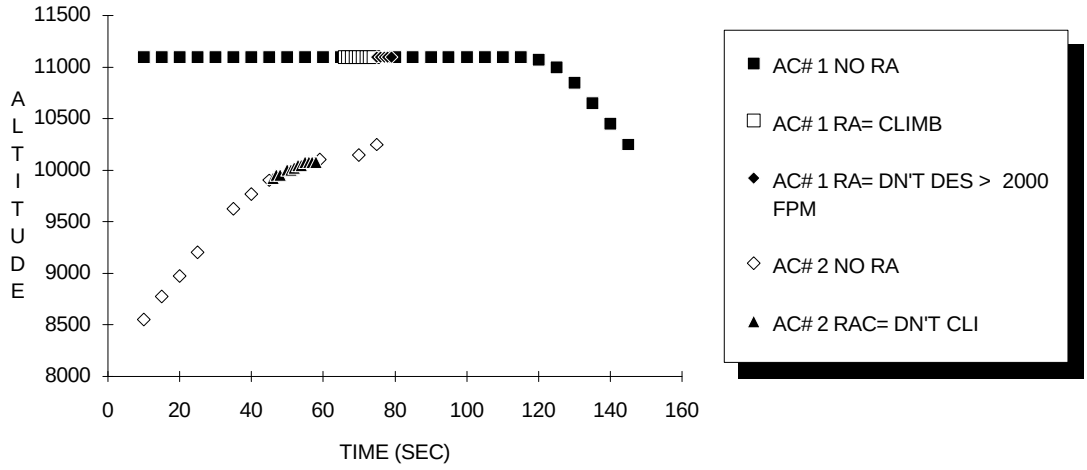

FIGURE 46. TCAS ENCOUNTER NO. 9 BETWEEN TWO AIRCRAFT

Figure 47 shows two aircraft involved in the same RA. Aircraft No. 1 is an arrival which was level at 11,000 feet at a range of 12 miles. Aircraft No. 2 is a departure climbing at 9,575 feet at a range of 11 miles.

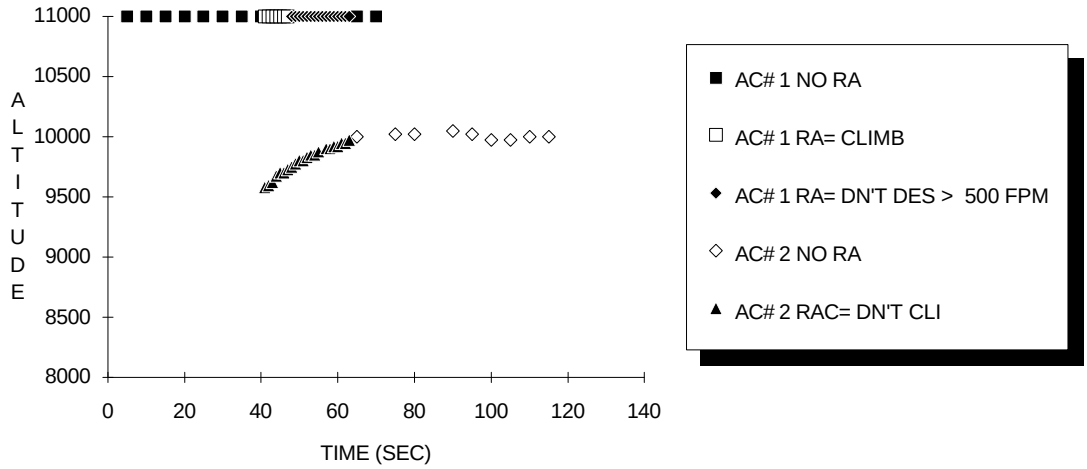

FIGURE 47. TCAS ENCOUNTER NO. 10 BETWEEN TWO AIRCRAFT

Figure 48 shows the altitude plot of three aircraft involved in RA's. There are actually four aircraft on "roll call" at the time, but aircraft No. 4 does not appear to be involved.

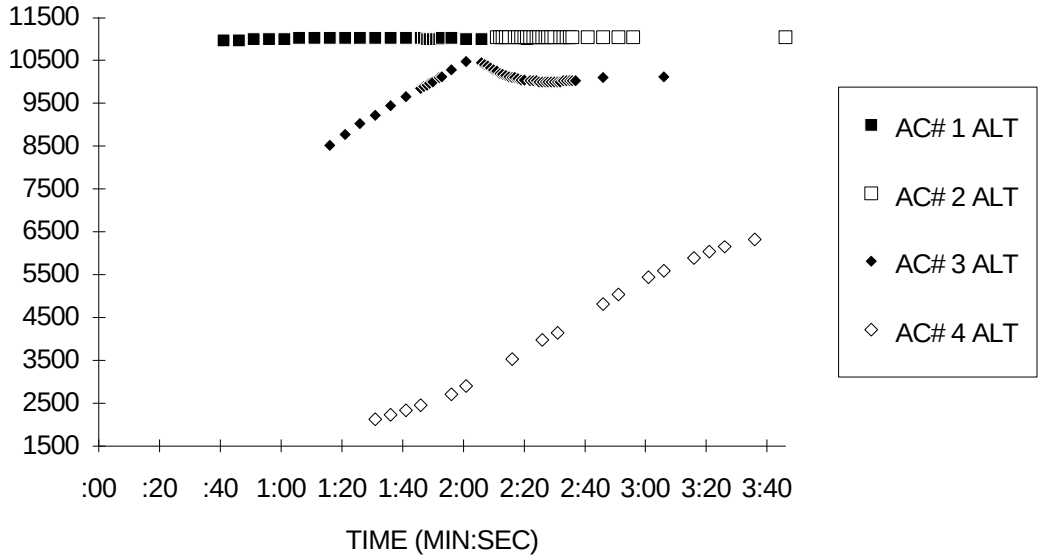

FIGURE 48. ALTITUDE - TCAS ENCOUNTER NO. 11 BETWEEN THREE AIRCRAFT

The range of the aircraft as a function of time is shown on figure 49. The dashed lines on this plot were manually inserted in the data to more clearly define the flightpaths of the different aircraft. In the mode of operation of the DATAS at DFW, the range data is only stored at the beginning or end of a track. Altitude data is stored on each scan (5 seconds for this data). All data are stored during an RA, so we have 1-second updates on range and altitude during the RA's.

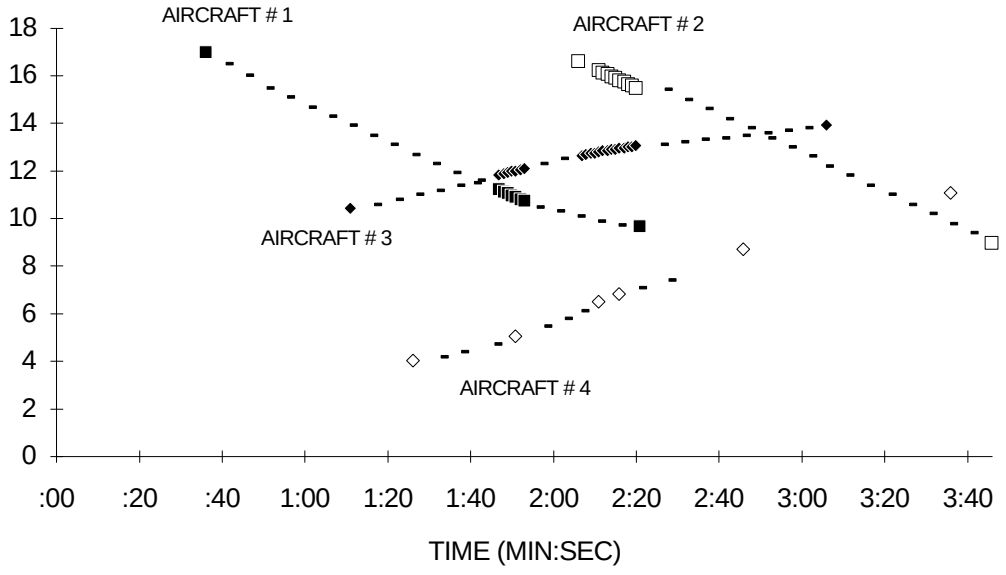

FIGURE 49. TCAS ENCOUNTER NO. 11 BETWEEN THREE AIRCRAFT - RANGE DATA

Aircraft No. 1 was an arrival which was level at 11,025 feet at a range of 11 miles when it received an RA to **"climb"** (1:47 into the flight coverage). Aircraft No. 3 was outbound at approximately 11 miles at 9,900 feet when it received the RAC of "**don't climb**" apparently from aircraft No. 1 (since it also occurred at 1:47). The RA data is shown in figure 50 which has been expanded to show the data more clearly. Aircraft No. 3 was climbing at a rate of approximately 2,000 feet per minute and continued to do so until it reached 10,500 feet. The RAC, however, ended at approximately 10,200 feet (at 1:52 into the flight). Examination of the range data shown In figure 50 shows that the range of the two aircraft is now diverging so that was probably the reason to end the RA by aircraft No. 1. At approximately 2:00 minutes into the flight, aircraft No. 3 started to descend toward 10,000 feet (the normal flight level assigned to departures). It then received an RAC of "**don't climb**" at 2:07 from aircraft No. 2. Its own system also gave an RA of "**don't climb**" at the same time. At 2:16, the RA eased to "**don't climb > 1,000 fpm,**" and the RAC from aircraft No. 2 remained the same. The RA lasted until 2:36 when aircraft No. 3 had leveled off at 10,000 feet and was at a range of approximately 13 miles. This sequence clearly illustrates the requirement that azimuth data be available in order to do a complete analysis of a situation such as this one.

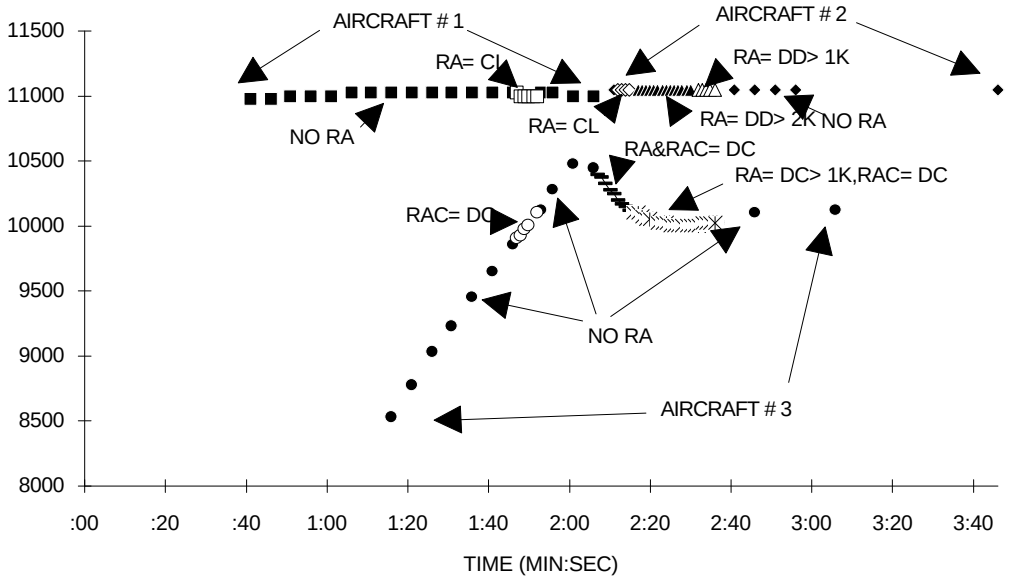

FIGURE 50. TCAS ENCOUNTER NO. 11 BETWEEN THREE AIRCRAFT (EXPANDED)

APPENDIX A

Data Link Test and Analysis System (DATAS) is a multi-purpose test system designed and fabricated at the Federal Aviation Administration (FAA) Technical Center to test the performance of Mode Select (Mode S) Data Link subsystems. It is capable of testing various components of Data Link including: Air Traffic Control Radar Beacon System (ATCRBS) and Mode S transponders, Data Link Processors (DLP), and Data Link subsystem interfaces. It also provides the capability of Mode S sensor emulation and radio frequency (RF) environment analysis within the frequency range of 950 to 1,200 megahertz (MHz).

The Traffic Alert and Collision Avoidance System (TCAS) monitor function uses a standard DATAS with the addition of a high power transmitter, a directional horn antenna, and application software. The TCAS monitor provides coverage in an approximate 35 degree arc to a range of 35 miles. In this application, DATAS is programmed to operate like a limited Mode S sensor. Any Mode S equipped aircraft that fly within range of the system will be acquired using Mode S surveillance protocol. When an aircraft is involved in a TCAS Resolution Advisory (RA), the content of the advisory and related information is stored. All such Mode S transactions are time tagged in the recorded data in order to allow correlation with other independent surveillance data from systems such as Automated Radar Terminal Systems (ARTS) III, ARTS II or Airport Surveillance Radar (ASR)-9. The system also counts aircraft, transponder capabilities, and TCAS information reported from every aircraft encountered in order to provide sample statistics.

The TCAS monitor was designed to operate as an unmanned system. After the system was installed in Dallas/Fort Worth (DFW), it was run remotely from the FAA Technical Center. Project personnel were able to check the system status and download data via a Personal Computer (PC). Analysis was then performed by using standard commercially available data base packages.

SYSTEM DESCRIPTION

The TCAS Monitor application of DATAS was designed to record TCAS activity in the air traffic environment. It performs a scaled down Mode S sensor function. Mode S equipped aircraft are acquired by sending periodic Mode S only all-call interrogations. Responding targets are put on roll-call for as long as they are within range of the antenna beam. Surveillance replies are checked for the presence of a TCAS RA message. When such messages occur, they are requested like an air- initiated comm-B. The system has also been programmed to store relevant information about Mode S targets encountered in order to provide statistics on TCAS equipped targets.

The DATAS was installed in a maintenance building on the DFW Airport perimeter road. The horn antenna system of DATAS provided coverage for the TCAS Monitor in an azimuth wedge of approximately 35 degrees. The DATAS interrogation power was reduced until the maximum range of target replies was approximately 35 miles. Without an azimuth indicator as an integral part of the system, a method was required which assured proper orientation of the antenna. Aircraft within the DFW approach airspace were also interrogated by the ATCRBS system of the DFW ASR-9. A method was developed to correlate simultaneous data from the ASR-9 with that of the DATAS to provide this assurance.

Software was developed to merge interrogation reply data from the TCAS monitor with ASR-9 beacon data collected from the Surveillance Communications Interface Processor (SCIP) using a software package developed by FAA personnel on another project. Targets were matched using time and ATCRBS code. The programs plot the common targets flightpaths on a model radar grid on a standard PC and highlight the tracks where Mode S responses from the TCAS monitor occurred.

The azimuth wedge for coverage by the DATAS was selected after coordination with DFW Air Traffic personnel. The basis for selection was their recollection of the airspace within which the highest number of TCAS RA's occurred. The standard air traffic pattern employed is a "corner post" operation. Arriving aircraft cross the feeder fix at or above 11,000 feet and departing traffic crosses the same fix at or below 10,000 feet. The primary direction of traffic flow was toward the south. Most aircraft were vectored in for landing from the "corner post" at approximately 45 miles southeast of the airport. Departing aircraft were using a parallel runway and taking off to the south at the same time. Figure A-1 shows the coverage achieved with this configuration at DFW.

FIGURE A-1. DALLAS COVERAGE PLOT

Figure A-1 shows the flightpath of all aircraft seen by the DATAS within a 22-minute period of data collection. The software correlates all aircraft seen by both systems and plots the data. When an aircraft is seen by the DATAS, the symbol is changed to a square or triangle (good reply or parity error). This cannot be readily seen in this plot, but shows up as broadened lines. The area within the broad outline is approximately the coverage selected by the DATAS during data collection.

TCAS MONITOR OPERATION SCENARIO.

This section will briefly discuss the operation of the TCAS Monitor data collection program. Emphasis is placed on parameters and procedures that are used in the scenario that can have an impact on the quantity and quality of the data collected. The data collection program reads a file from the systems hard disk which contains parameter values that control various important aspects of the system operation. A separate program exists which allows system engineers to set the parameters as they see fit.

Although the TCAS Monitor performs a more specific function, it was designed to emulate a Mode S sensor. Even though it has a fixed direction antenna, it uses an internal timer to periodically "scan" for targets. There are two scan rates defined: one for normal Mode S targets on surveillance roll-call, and another for targets that have active RA's. The two-scan rate values are from the parameter file, selectable in increments of 1 second. For the DFW operation, the scan rate was 5 seconds for surveillance targets, and 1 second for Active RA's.

The surveillance scan consists of roll-call interrogations to targets previously acquired by the system and all-call interrogations used to acquire new targets. The all-call interrogation is a Mode S only all-call with Uplink Field (UF) 11. The Probability of Reply (PR) field value, which is determined by the system parameters, was set to cause a 1/4 reply probability. The PR field is used lower the all-call reply probability in order to avoid overlapping replies from two or more aircraft. The reply probability value selected determines the number of all-calls sent per scan. The lower the reply probability, the greater the number of all-calls sent. There were two all-calls sent per scan for the Dallas project. Under normal conditions new targets would be acquired within two scans. Once acquired, during optimum conditions, each target is sent a UF 5 and a UF 0 for each surveillance scan. These interrogations allow the system to monitor TCAS information, ATCRBS code, and altitude. Nonselective lockout protocol is used to prevent acquired targets from responding again to all-call interrogations. Despite the use of lockout logic, the active target list is searched upon receipt of all-call responses to ensure that it is not a repeat target due to failure of the lockout mechanism.

There is a system parameter that controls the time between interrogations during a scan. This value was 10 milliseconds for the Dallas project. The time between interrogations is varied by plus or minus 1-millisecond for each interrogation to help avoid possible synchronization with other interrogating sources.

The surveillance replies are examined for the presence of a TCAS RA message. When a target has posted an RA, it is interrogated at the once per second scan rate in order to store changing values in the message content.

Targets are kept on surveillance until they no longer respond. The two parameters that determine how long to retry nonresponding targets are miss limit and scan limit. Both the miss limit and the scan limit were set to two for the Dallas project. The miss limit of two means that a target can get up to two reinterrogations per scan, depending on the availability of interrogations. If a target does not respond during a scan, it is counted as a missed scan. With the scan limit set to two, if a target has two consecutive missed scans, it is dropped from the active target list and no longer interrogated.

The system counts and stores information regarding transponder capability and TCAS capability for gathering statistics, but it does not test these values before requesting further information from an aircraft. This is to avoid the possibility of losing valuable information from targets that might only be reporting their capability incorrectly.

INTERROGATION LIMITING.

The TCAS Monitor has built in protection against over interrogating in both software and hardware. These protection mechanisms serve to limit the amount of transmissions induced into the environment as well as to protect the RF amplification circuits from being overdriven. The hardware monitors the duty cycle of the transmitter (which is loaded from the 68020) and compares it to the maximum duty cycle allowed (also loaded from the 68020). If the duty cycle is exceeded, the transmitter is "shut down" and the 68020 is notified of this fact via an interrupt. It also provides feedback on a periodic basis of the duty cycle for that reporting period. This capability was primarily used for analysis of the operation of the transmitter output system.

The hardware protection circuits are initialized via software yet operate independently from the system to shut down the transmitter if the selected duty cycle limit is exceeded. The software considers the hardware duty cycle limit to calculate the maximum number of interrogations to send per scan to further insure that such costly shutdowns do not occur. This software protection uses a priority interrogation scheme to make the best use of available interrogation time during high traffic periods.

The system was limited to sending a maximum of 18 interrogations per scan for the Dallas project. This number would allow for up to eight aircraft to receive both surveillance and special surveillance interrogations plus the two all-call interrogations during the surveillance scan. When less than eight aircraft are on surveillance, the unused interrogations are available to use as reinterrogations when an aircraft does not reply. As the number of aircraft increases, the interrogation types are sent on a first come first serve basis. The surveillance interrogations have priority over special surveillance, and special surveillance have priority over reinterrogations. The prescribed number of all-calls remains constant. Some example interrogation distributions are as follows:

8 or less aircraft:

All aircraft are interrogated with both surveillance and special surveillance interrogation types. Reinterrogations are available.

Example with 6 aircraft:

2 Mode S all-calls
6 Surveillance (UF 4 or 5)
6 Special surveillance (UF 0)
4 Available for reinterrogations.

9 to 16 aircraft:

All aircraft are interrogated with the surveillance interrogation, special surveillance interrogations are sent on a first come first serve basis while they are available, and there are no reinterrogations available.

Example with 10 aircraft:

2 Mode S all-calls
10 Surveillance interrogations
6 Special surveillance interrogations
0 Available for reinterrogations.

Greater than 16 aircraft:

Aircraft are interrogated with surveillance interrogations on a first come first serve basis, there are no special surveillance or reinterrogations available.

The amount of traffic responding to the system in Dallas varied. The traffic rate was only observed closely during the 2 weeks required for system setup. The highest number of aircraft on "roll call" during one period was nine. A typical high traffic burst was six to eight aircraft.

Different rules for interrogation limiting exist during the RA scan. Only aircraft that have an RA are interrogated at this time. There is only one interrogation type sent to each aircraft. The interrogation used will acquire the RA data in a comm-B response. Preliminary field testing had shown that there is no need to have extensive interrogation limiting at this time due to their infrequent occurrence. Since these targets are of the highest priority, the miss limit has been extended by three for a total of five tries per aircraft to get a valid response. Also, each target is interrogated until a reply with good parity is received, not just a preamble decode. These targets were interrogated once per second in Dallas. During the normal surveillance scan active RA targets do not have priority over other aircraft, but the Reply Request (RR) field of the surveillance interrogation is set to request the RA message.

REPLY QUALIFICATIONS.

This section describes the criteria that DATAS uses to determine a valid Mode S reply.

After DATAS transmits a Mode S interrogation, it must enable its receiver to get the reply. The time period during which the receiver is enabled is called a reply window. The reply window following all-call interrogations is long enough to accommodate replies from anywhere within the range of the TCAS monitor. The reply window for roll-call interrogations is smaller to reduce the possibility of false decodes, but is positioned for the expected reply using the reply delay of the previous scan. The reply window is large enough for a long Mode S reply with enough time before and after the expected response to allow for 1 mile of movement by the aircraft.

In order to detect Mode S replies in the reply window, the DATAS has programmable decoders set up to detect a Mode S preamble. The decoder logic is activated when the first pulse is received, and is programmed to look for three more pulse lead edges following by 1.0 , 2.5, and 1.0 microseconds. These pulses must occur within a tolerance 100 nanoseconds of their expected times.

If a valid decode is detected, the hardware performs parity checks and error correction algorithms on the reply data. If parity is good or a parity error was successfully corrected, the reply is considered valid and its contents are appropriately examined.

DATA.

The system parameters allow selection of the extent of data collection to perform. The data collection selections for the Dallas project were set to store all information available on all active targets only when an RA occurred. Interrogation and reply data was stored only for the duration of the advisory. Summary data for each target present at the time of an advisory is maintained and stored for as long as the target is on surveillance even if the advisory has ended. A header file contains information about the data collection run as well as the statistical data. All files are updated each scan to minimize data lost due to power failures.

HEADER FILE. The header file is used by programs that access the data files. It defines the contents of the data files, contains the operation parameters values, and the statistics data. The header file contains the following information:

System start and stop, date and time
System parameters
Total interrogations, valid replies, corrected replies, and uncorrectable replies
Statistics data

INTERROGATION AND REPLY DATA. The data in the interrogation and reply file are used primarily as a backup for the summary data. This file contains more detailed information regarding each interrogation/reply transaction that may be used to reveal

actual target ranges, confidence of error correction, and system status during the transaction. The contents of each record is as follows:

Date and time of transaction
Mode S address
Interrogation and reply status
Interrogation data
Uncorrected reply data
Corrected reply data
Error correction confidence data
Reply delay (range)
Reply amplitude
System status

Figure A-2 is a sample of an interrogation/reply data file. Aircraft ID a10f67 on May 9 has an active RA and is being interrogated each second. At 09:30:23 and 09:30:24, valid replies with good parity were received. At 09:30:25, a decode with an uncorrectable parity error was received and the hardware flagged the decode as "invalid." At 09:30:26, no reply was received on the first interrogation and a valid interrogation with good parity was received on the second try. The RA was again listed as a "climb" (ARA=2000). A good reply was also received to the UF=0 interrogation at 09:30:26. At 09:30:27, another invalid decode was received. It showed a "climb" RA, and a "turn left" RAC, but was listed as "invalid" by the hardware as it was an uncorrectable parity error.

In all cases, the range is given (when a reply is received - old data when one is not received). The Mean Preamble Power is the average amplitude of the four pulses which make up the Mode S preamble. This number is a relative value (full scale is 256) and is used only as an indicator of received signal strength.

```
05/09/91 09:30:23 - SYS ST:00000001 INT ST:5960 REP ST:81a10f67
DECODE STATUS=0 - DECODE PRESENT
     INTER:219f0000a10f67
UNC. REPLY:a010073e3080000000000086b4d50000  REPLY DATA PRESENT
COR. REPLY:a010073e3080000000000086b4d50000  GOOD PARITY,  VALID DECODE
CONF. DATA:ffffffffffffffffffffffffffff0000  CORR. OK,  CONF. OK
DF=20 FS=0 DR=2 UM=0 AC=73e BDS1=3 BDS2=0 ARA=2000 RAC=0 CLI=0
RANGE: 18.48 nm    MEAN PREAMBLE POWER: 75

05/09/91 09:30:24 - SYS ST:00000001 INT ST:5960 REP ST:81a10f67
DECODE STATUS=0 - DECODE PRESENT
     INTER:219f0000a10f67
UNC. REPLY:a010073e3080000000000086b4d50000  REPLY DATA PRESENT
COR. REPLY:a010073e3080000000000086b4d50000  GOOD PARITY,  VALID DECODE
CONF. DATA:ffffffffffffffffffffffffffff0000  CORR. OK,  CONF. OK
DF=20 FS=0 DR=2 UM=0 AC=73e BDS1=3 BDS2=0 ARA=2000 RAC=0 CLI=0
RANGE: 18.40 nm    MEAN PREAMBLE POWER: 75

05/09/91 09:30:25 - SYS ST:00000001 INT ST:5960 REP ST:f1a10f67
DECODE STATUS=0 - DECODE PRESENT
     INTER:219f0000a10f67
UNC. REPLY:a010073e3080000401240086b4d50000  REPLY DATA PRESENT
COR. REPLY:a010073e3080000401240086b4d50000  PARITY ERROR,  INVALID DECODE
CONF. DATA:ffffffffffffffbfedbffffffff0000  CORR. FAIL,  CONF. OK
DF=20 FS=0 DR=2 UM=0 AC=73e BDS1=3 BDS2=0 ARA=2000 RAC=0 CLI=0
RANGE: 18.40 nm    MEAN PREAMBLE POWER: 75

05/09/91 09:30:26 - SYS ST:00000001 INT ST:5960 REP ST:01a10f67
DECODE STATUS=1 - NO DECODE
     INTER:299f0000a10f67
UNC. REPLY:a010073e3080000401240086b4d50000  NO REPLY DATA PRESENT
COR. REPLY:a010073e3080000401240086b4d50000  GOOD PARITY,  VALID DECODE
CONF. DATA:ffffffffffffffbfedbffffffff0000  CORR. OK,  CONF. OK
DF=20 FS=0 DR=2 UM=0 AC=73e BDS1=3 BDS2=0 ARA=2000 RAC=0 CLI=0
RANGE: 18.40 nm    MEAN PREAMBLE POWER: 75

05/09/91 09:30:26 - SYS ST:00000001 INT ST:5960 REP ST:81a10f67
DECODE STATUS=0 - DECODE PRESENT
     INTER:299f0000a10f67
UNC. REPLY:a810133c3080000000000056d6bf0000  REPLY DATA PRESENT
COR. REPLY:a810133c3080000000000056d6bf0000  GOOD PARITY,  VALID DECODE
CONF. DATA:ffffffffffffffffffffffffffff0000  CORR. OK,  CONF. OK
DF=21 FS=0 DR=2 UM=0 ID=4674 BDS1=3 BDS2=0 ARA=2000 RAC=0 CLI=0
RANGE: 18.24 nm    MEAN PREAMBLE POWER: 73

05/09/91 09:30:26 - SYS ST:00000001 INT ST:5960 REP ST:80a10f67
DECODE STATUS=0 - DECODE PRESENT
     INTER:00000000a10f67
UNC. REPLY:00c1873e1e62540000000056d6bf0000  REPLY DATA PRESENT
COR. REPLY:00c1873e1e62540000000056d6bf0000  GOOD PARITY,  VALID DECODE
CONF. DATA:ffffffffffffff00ffffffffffff0000  CORR. OK,  CONF. OK
DF= 0 VS=0 SL=6 RI=3 AC=73e
RANGE: 18.24 nm    MEAN PREAMBLE POWER: 74

05/09/91 09:30:27 - SYS ST:00000001 INT ST:5960 REP ST:f1a10f67
DECODE STATUS=0 - DECODE PRESENT
     INTER:219f0000a10f67
UNC. REPLY:a010073e3080009004100086b4d50000  REPLY DATA PRESENT
COR. REPLY:a010073e3080009004100086b4d50000  PARITY ERROR,  INVALID DECODE
CONF. DATA:ffffffffffffff6ffbeffffffff0000  CORR. FAIL,  CONF. OK
DF=20 FS=0 DR=2 UM=0 AC=73e BDS1=3 BDS2=0 ARA=2000 RAC=2 CLI=0
RANGE: 18.24 nm    MEAN PREAMBLE POWER: 74
```

FIGURE A-2. SAMPLE INTERROGATION/REPLY DATA FILE

SUMMARY DATA. The summary data file contains information about each target that was present during an RA. The information stored is anything that might be relevant when an RA occurs. Altitude is included in this information and the system can accommodate either gray code (100-foot increments) or 25-foot reporting. Information fields are checked at each scan and stored only when changes occur. The contents of this file are made available for transfer to data base programs. The contents of the summary file are as follows:

Mode S address
Time and date of all-call response
Time of last roll-call response
Range of first and last responses
Transponder capability
Extended capability

Resolution Advisories
Start time
End time
Content

Altitudes Reported
Start time
End time
Altitude

ATCRBS code
Start time
End time
Code

Special Surveillance data
Start time
End time
Content (includes vertical status, reply information, and sensitivity level)

Figure A-3 is a sample of summary data. An RA occurred on May 9 which had both sides of the coordination, where both aircraft had information in the RA and RAC fields. A24465 was inbound at 11k and A8163E was outbound at 10k (both were relatively level). The interrogation/reply data for the two were all high confidence data, so the encounter was probably textbook TCAS operation.

```
DATE:05-09-1991
Mode S ID:a24465   Surveillance time from: 20:23:46  to: 20:25:15
 Initial range: 19.417  Final range: 11.254 (nm)
 Transponder capability (CA): 1
 Extended Capability: BDS1: 1 BDS2: 0 CFS: 0 ACS:10000 BCS:0400 ECS:00

 2 resolution advisorie(s):
...MESSAGE.....................................FROM.......TO.......
BDS1: 3 BDS2: 0 ARA:2000 RAC:8 CLI:0            20:24:57   20:25:03
BDS1: 3 BDS2: 0 ARA:1000 RAC:8 CLI:0            20:25:04   20:25:15
 10 altitude(s) reported:
...MESSAGE.....................................FROM.......TO.......
 ALT= 10975                                    20:23:51   20:24:26
 ALT= 11025                                    20:24:31   20:24:36
 ALT= 11000                                    20:24:41   20:24:51
 ALT= 10975                                    20:24:56   20:24:56
 ALT= 11000    RA=CLIMB, RAC=DON'T DESCEND     20:24:57   20:24:59
 ALT= 11025        "          "      "         20:25:00   20:25:03
 ALT= 11050    RA=DON'T DESC,RAC=DON'T DESC    20:25:04   20:25:06
 ALT= 11025        "          "      "         20:25:08   20:25:11
 ALT= 11000        "          "                20:25:12   20:25:14
 ALT= 10975        "          "                20:25:15   20:25:15
 1 ATCRBS ID(s) reported:
...MESSAGE.....................................FROM.......TO.......
 ID=2216                                        20:23:56   20:25:11
 1 special surveillance report(s):
...MESSAGE.....................................FROM.......TO.......
 VS=0  SL=6  RI=3                              20:23:51   20:25:11
TARGET SUMMARY_____________________________________________________________
DATE:05-09-1991
Mode S ID:a8163e   Surveillance time from: 20:22:21  to: 20:25:31
 Initial range: 2.905  Final range: 11.626 (nm)
 Transponder capability (CA): 1
 Extended Capability: BDS1: 1 BDS2: 0 CFS: 0 ACS:10000 BCS:0400 ECS:00

 3 resolution advisorie(s):
...MESSAGE.....................................FROM.......TO.......
BDS1: 3 BDS2: 0 ARA:0020 RAC:4 CLI:0            20:24:57   20:25:09
BDS1: 3 BDS2: 0 ARA:0010 RAC:4 CLI:0            20:25:10   20:25:21
BDS1: 3 BDS2: 0 ARA:0000 RAC:0 CLI:0            20:25:23   20:25:23
 10 altitude(s) reported:
...MESSAGE.....................................FROM.......TO.......
 ALT=  9775                                    20:24:51   20:24:51
 ALT=  9975  RA=DON'T CL>1K/S, RAC=DON'T CL    20:24:57   20:24:57
 ALT= 10025        "                "          20:24:59   20:24:59
 ALT= 10050        "                "          20:25:00   20:25:00
 ALT= 10075        "                "          20:25:01   20:25:01
 ALT= 10125        "                "          20:25:04   20:25:07
 ALT= 10150  RA=DON'T CL/2K/S, RAC=DON'T CL    20:25:08   20:25:14
 ALT= 10125        "                "          20:25:18   20:25:21
 ALT= 10100                                    20:25:23   20:25:23
 ALT= 10050                                    20:25:31   20:25:31
 1 ATCRBS ID(s) reported:
...MESSAGE.....................................FROM.......TO.......
 ID=2324                                        20:24:51   20:25:31
 1 special surveillance report(s):
...MESSAGE.....................................FROM.......TO.......
 VS=0  SL=5  RI=3                              20:24:51   20:25:31
```

FIGURE A-3. SAMPLE SUMMARY DATA FILE

STATISTICAL DATA. Information relative to TCAS is collected from all aircraft encountered by the TCAS monitor. These data can be used to provide statistics on the TCAS units in the field. The collection of this type of information was not the primary goal of the original TCAS monitor, but there was much improvement made in this area during the Dallas project. The major limitation of the accuracy of the counts was multiple encounters with the same aircraft. There are no provisions made to avoid recounting such data. However, if a large enough sample is taken, the proportions of all numbers should correlate to the real world. This section describes the criteria used when counting the data in order to qualify its accuracy.

The data is extracted from valid Mode S replies, determined as such, as described in the previous section. The following is a summary of the data collected:

1. Capability (CA) field from Mode S all-call response reports the capability of the on-board Mode S transponder.

2. Reply Information (RI) from special surveillance reply (DF 0) reports the TCAS capability.

3. Sensitivity Level (SL) from the special surveillance reply reports the sensitivity level at which the TCAS unit is operating.

4. Vertical Status (VS) from the special surveillance reply reports whether the aircraft is airborne or on the ground.

The following counts are made (made separately for "on ground" and "in air"):

The number of aircraft that reported:
CA=0 - No communication capability
CA=1 - Comm A and B communication capability
CA=2 - Comm A, B, and C communication capability
CA=3 - Comm A, B, C, and D communication capability

The number of airborne aircraft that reported :
RI=0 - No TCAS
RI=2 - TCAS with Resolution Capability Inhibited
RI=3 - TCAS with vertical Resolution Capability
The number switched from 0 to either 2 or 3
The number switched from either 2 or 3 to 0
The number switched from 2 to 3
The number switched from 3 to 2

These Sensitivity Level (SL) counts are made separately for both airborne and on ground aircraft:

Each level reported when RI = 0

Each level reported when RI = 2
Each level reported when RI = 3

These SL counts are made from all aircraft encountered:

Each level reported when RI transitioned from 0 to either 2 or 3, both prior to and after the transition
Each level reported when RI transitioned from either 2 or 3 to 0, both prior to and after the transition

The number of aircraft that reported both Airborne and On ground status.

These counts are incremented when the first valid response that yields the information is received from a target, or when a subsequent response yields a changed value. Multiple encounters with the same aircraft, or aircraft that change values repeatedly could affect the statistics. Within these conditions, it should be viewed that the data represents the number of times the values occur rather than the number of aircraft that report these values.

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