THE EFFECT OF TCAS INTERROGATIONS ON THE

CHICAGO O'HARE ATCRBS SYSTEM

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16. Abstract

This report documents the Federal Aviation Administration (FAA) data collection and analysis effort to investigate Secondary Surveillance Radar (SSR) problems encountered at the Chicago O'Hare Terminal Approach Control (TRACON) facility. The FAA has mandated the implementation of Traffic Alert and Collision Avoidance System (TCAS) II to the entire air transport fleet by December 31, 1993. To provide for the smooth and orderly implementation of TCAS II, the TCAS Transition Program has been established to accomplish these objectives. The FAA Technical Center Research Directorate for Aviation Technology, ACD-320, conducted the investigation by developing the data collection system capability of the Data Link Test and Analysis System (DATAS). Two distinct capabilities were developed to monitor the uplink and downlink activity of the SSR system frequencies. The uplink data collection system is an airborne installation of DATAS on an FAA aircraft and test flights were conducted to obtain the uplink data. The downlink data collection system was installed at the ground radar facility to monitor the Air Traffic Control Radar Beacon System (ATCRBS) receiver signal for downlink analysis. Data results and analysis of both efforts are documented herein.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

EXECUTIVE SUMMARY

The Data Link Test and Analysis System (DATAS) was utilized to conduct flight tests at the Chicago O'Hare Terminal Radar Approach Control Facility (TRACON) area. The data collection activity was conducted to investigate coasting problems experienced by air traffic controllers at the Chicago TRACON. DATAS was initially utilized in the environmental analysis mode to measure interrogation rates received as a victim aircraft in the Chicago TRACON area. The flightpath selected for the 2-day data collection was a 10-mile orbit around the Chicago O'Hare Airport at 10,000 feet. Data were also collected in final approach when landing on the second day of flight. Measurements were taken to derive Air Traffic Control Radar Beacon System (ATCRBS) and Traffic Collision Avoidance System (TCAS) interrogation rates to analyze the uplink activity in the environment.

The TCAS system utilizes two distinct interrogation categories. The Whisper/Shout (W/S) and ATCRBS only interrogation types are utilized for existing ATCRBS transponders to solicit ATCRBS replies and inhibit Mode Select (Mode S) transponders from response. These interrogations vary slightly from the ATCRBS type interrogations from ground systems. The purpose is to accomplish selective suppression of ATCRBS transponders as a function of range and to prevent reply from Mode S transponders. Mode S interrogations are the second category of interrogation. These interrogations are generally directed to a single Mode S transponder. These interrogations contain a data stream as well as address parity that identifies the addressed transponder and verifies the data content. DATAS analyzed the content of Mode S interrogations to determine the number of TCAS equipped aircraft and Mode S aircraft to produce interrogation distributions. Interrogation rates as a function of the number of Mode S-equipped and TCAS-equipped aircraft were derived. The number of interrogations measured along with the impact of the interrogation rates on a victim ATCRBS and Mode S transponder were produced.

On the average, the number of TCAS interrogations measured over the 2-day flight data collection was 168 interrogations per second. The highest number of Mode S interrogations was nearly 600 per second which occurred during final approach. The TCAS system utilizes an interference limiting algorithm to reduce the number of interrogations produced in a high density traffic area. The mechanism operates to maintain interrogation rates at or below 280 per second. The data collected shows that, for the most part, the measured interrogation rates were at or below this except during landings. A significant percentage of the measured interrogation rates were due to the number of interrogations directed to aircraft on the ground.

The measurements from the data collection were analyzed to calculate transponder usage. The transponder usage represents the percentage time the victim transponder is utilized by the ATCRBS ground system or the TCAS system making it unavailable to the other

system. In today's system, only TCAS and ATCRBS ground interrogators compete for the transponder. In the future, Mode S sensors will compete for the transponder, which will reduce the usage required from ATCRBS interrogators as they are replaced by Mode S sensors. The transponder usage of a Mode S and an ATCRBS transponder are essentially identical with respect to ground ATCRBS interrogations. ATCRBS interrogations occupy Mode S and ATCRBS transponders approximately 4 percent of the time. This rate is essentially the same throughout the data collection interval due to the fixed repetitive nature of the ATCRBS ground interrogations. TCAS usage between ATCRBS and Mode S transponders varies due to the difference in the methodology utilized by the TCAS system to acquire and track ATCRBS and Mode S equipped aircraft. The Mode S transponder usage varies as a function of the number of Mode S aircraft. Mode S transponders are used by TCAS approximately 3 percent of the time on average. Peak interrogations result in a 6 percent usage. ATCRBS transponders are used by TCAS approximately 2 percent of the time on average.

The overall effect of TCAS on the existing ATCRBS system is a combination of both uplink and downlink effects of TCAS activity.

The overall system performance is a combination of effects of other ATCRBS sites, turning of aircraft, antenna pattern lobing, etc. At the present time the downlink effect of TCAS can be identified via Mode S fruit replies as TCAS is now the only source of Mode S replies.

A second data collection effort was conducted subsequent to the uplink flight tests to assess downlink activity. Data were collected on the downlink portion of the system to measure the number of Mode S replies received by the ground ATCRBS system at Chicago O'Hare. The measurements were made in July over a 4-day period at the output of the Air Traffic Control Beacon Interrogator (ATCBI)-5 receiver, the same video signal input to the ATCRBS processing system. This assures that the rates correspond to the actual rate experienced by the ground ATCRBS processor. At the time of data collection, the Airport Surveillance Radar (ASR)-9 beacon system was operational at Chicago O'Hare. The rates measured varied day to day as well as with the time of day. The peak rates occurred in approximately 1.5-hour intervals. A peak rate of 300 Mode S replies per second was encountered over a 7-minute average. At the measured peak rates, Mode S replies will overlap one or more replies of approximately 100 aircraft out of 144 on an average, if the nominal 18 replies per aircraft is assumed with normal time distribution of the Mode S replies. The effect to the ATCRBS processor is a function of run lengths and reply probabilities of the target environment. As target reply probabilities are reduced due to the collective effects of siting, lobing ATCRBS, and TCAS transponder usage and downlink fruit, weaker targets become more vulnerable to loss of detection, azimuth splits, and degraded code detection and validation.

DATAS SYSTEM CONFIGURATION

The Data Link Test 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. The system has four basic functions:

1. Monitoring of Data Link System Interfaces
2. Emulation of those Interfaces
3. Parametric Testing of Data Link System Components
4. Protocol Testing of Data Link System Interfaces

The TCAS monitoring capability is inherent in the DATAS as a subset of the monitoring of Data Link interfaces.

OVERALL SYSTEM.

The DATAS is a "state of the art" Versa Module Extended (VME) based system which presently contains a 68020 processor and personal computer (PC) which share the VME bus. Multiple processors can be added if required. It contains a fixed media "hard disk" with 1.2 gegabyte (gb) storage capacity. It also contains a 1.2 gb digital audio tape storage capability which was added for collection of large amounts of environmental data.

The system outputs are suitable for importation into standard commercial data base packages such as DBASE or EXCEL. The graphic outputs are handled by the PC which makes them compatible with commercially available graphic software packages and Laser Jet printers, etc.

The system is remotely controllable via modem and contains diagnostics for each system unit (including the radio frequency (RF) unit). The system was operated remotely at the Dallas/Fort Worth (DFW) Airport (using the Traffic Alert and Collision Avoidance System (TCAS) monitor option) for more than 2 months. Data retrieval was via modem.

ENVIRONMENTAL ANALYSIS OPTIONS.

The DATAS monitor function used for this effort is the Environmental Analysis (ENV) option. This capability provides a valuable tool which can be used to analyze system problems in either the uplink or downlink of Data Link, TCAS, or Air Traffic Control Radar Beacon Systems (ATCRBS). When using this function, the DATAS merely "listens" on 1030 megahertz (MHz) (the interrogation frequency of ATCRBS and Mode S) or 1090 MHz (the reply frequency of ATCRBS and Mode S). The system is readily configurable to collect either uplink or downlink data. The uplink (1030 MHz) was monitored in the first phase of the data collection effort. DATAS recorded the arrival time of all interrogations that would be seen by an ATCRBS or Mode S transponder. It also recorded the actual data content of Mode S interrogations (including TCAS broadcast interrogations). In this way, i.e., the actual number of TCAS equipped aircraft in operation at the time of data collection is known. On line statistics for decode counts of each type and a list of the active Mode S address are handled by the DATAS PC. A block diagram of the DATAS ENV option is shown on figure 1.

In order to avoid ambiguities caused by differences in receiver bandwidths, sensitivity, etc., a Mode S transponder was modified to be used as the front end processor in lieu of the normal DATAS receiver. DATAS was then configured to use "external" decodes from this modified transponder. The Mode S data were also transferred to DATAS for storage along with the Time of Arrival (TOA) data for the decodes. The DATAS transmitter was not used at all in this effort except to generate diagnostic signals to the transponder to verify proper operation of the system.

The second phase of data collection recorded downlink ATCRBS and Mode S reply counts. The data were collected at the ground radar site at the output of the ATCRBS receiver. Mode S replies were detected by configuring DATAS decoders to the preamble pulse timing tolerances. ATCRBS replies were detected by simply programming the DATAS decoder to the bracket framing pulse timing tolerance. The operation of the system was similar to the uplink function except that the downlink data is input at video level.

The DATAS ENV uplink and downlink options allow continuous storage of data by alternating storage control via the two transmit channels (although not transmitting). While the data from one channel is being transferred to temporary buffers while awaiting transfer to the disc, the live data are being stored in the other channel. In this manner, 100 percent duty cycle monitoring can be achieved.

<u>APPROACH</u>.

Coasting of beacon tracks at Chicago O'Hare was reported by air traffic controllers at the Terminal Radar Approach Control Facility (TRACON). Since the coasting steadily increased during the time of TCAS installations on airline aircraft, the TCAS transition team was alerted of the problem. One problem encountered involved certain aircraft which would coast for long durations, some for over 10 miles. These cases were determined to be associated to a particular manufacturer's transponder which effectively shutdown when Mode S interrogation rates reached the interrogation interference limit of 280 per second. This was the manufacturer's method of protecting the transmitter by limiting the reply rate. At the time of this report, the manufacturer was in the process of correcting these transponders, which were installed in aircraft of several major airlines.

FIGURE 1. BLOCK DIAGRAM OF DATAS ENVIRONMENTAL ANALYSIS OPTION

Due to the high interrogation rates claimed to be experienced by transponders in the Chicago O'Hare terminal area, the FAA deemed it necessary to quickly measure the activity of TCAS on the secondary surveillance radar (SSR) frequency and determine its effect on the SSR. DATAS, with its 1030 and 1090 MHz RF and data collection capability, was scheduled to collect uplink data to assess TCAS activity. These data and the DATAS capability developed to collect the data are described in the remainder of this report.

The data collected from the uplink environment analysis measures interrogation rates from the operation of TCAS in the Chicago TRACON area. The data provides the ability to assess the utilization of transponders by TCAS. The impact of TCAS on ground ATCRBS processors is clearly a function of TCAS usage of a transponder since the interrogations that are seen by aircraft within the vicinity of transmitting TCAS aircraft reduces its availability to the ATCRBS ground interrogator. This phenomena causes reduction in the number of replies received by the ground interrogator for the aircraft. The ATCRBS processing system on a sweep to sweep basis, attempts to detect a target by reception of a number of replies within a number of opportunities to reply. There are many factors which determine the number of replies received for aircraft on any given scan. If the minimum required for target detection is not received by the ATCRBS processor, the target is not declared for that antenna scan resulting in a potential coast of the track on the air traffic controller's display.

As uplink interrogation activity by TCAS reduces the reply opportunity for aircraft the ground system is also more prone to replies that are generated by the aircraft in response to the TCAS interrogation types. ATCRBS transponders responding to the TCAS ATCRBS interrogations will generate replies that appear as asynchronous replies with respect to the ground interrogator. Other ground ATCRBS interrogators which elicit replies from aircraft within the victim interrogation coverage produce the same fruit replies. The asynchronous replies can generally be eliminated by the ground ATCRBS processor since the sweep to sweep correlation process would detect these as noncorrelating replies and ignore them. If the asynchronous reply simultaneously arrived during the reply of a valid reply, the code or altitude, depending on the mode of the interrogation, may become garbled causing the wrong code or altitude to be detected. A Mode S reply consists of a longer pulse stream than an ATCRBS reply. The Mode S reply can be 64 or 120 microseconds long, depending upon the interrogation content which directs the transponder to respond with a short or long reply. The TCAS system, for the most part, utilizes short Mode S replies. The ATCRBS processors that are used in the ATC system today generally detect many ATCRBS replies from a single Mode S reply. The ATCRBS system detects a reply from two pulses spaced 20.3 microseconds apart. The Mode S reply consists of a series of 0.5 and 1.0 microsecond pulses spaced every 0.5 or 1 microsecond apart. The average number of ATCRBS replies detected from a short Mode S reply is 6 or 7. The effect that a Mode S reply on the ATCRBS processor is essentially the same as ATCRBS fruit except for the magnitude. A Mode S reply is longer in duration and results in the detection of multiple ATCRBS replies. The simultaneous reception of a Mode S reply and a valid ATCRBS reply will cause garbling or possible elimination of the detection of the valid reply if the lead edge positions of the bracket pulses are distorted by the overlap.

In summary, in order to determine the overall effect of the operation of TCAS on the SSR, both uplink and downlink data collection was deemed necessary. The effect of TCAS on the ground ATCRBS processor is a result of reduced reply probability from uplink TCAS interrogation activity and interference on downlink from replies generated in response to the TCAS interrogations. To assess the effect of uplink TCAS activity, the amount of TCAS usage of the aircraft transponder is calculated.

To assess the effect of downlink interference on the ATCRBS processor due to TCAS, association of DATAS data with the target reply data of the ATCRBS processor is necessary. In this manner, the loss of a reply or the garbling of code or altitude can be associated with the Mode S reply. However, due to the length of time required to develop the downlink analysis software, it was decided that only ATCRBS and Mode S reply rates would be collected at Chicago O'Hare on the downlink. This would provide preliminary data to predict the potential impact of TCAS generated downlink activity on the ground ATCRBS system. This prediction was based on the percentage time the Mode S replies occupied on the downlink.

DATA COLLECTION CONFIGURATION.

UPLINK. The DATAS was installed aboard the FAA Technical Center Boeing 727 in order to collect the data described in this report. The omnidirectional antenna mounted on the bottom of the aircraft was used for data collection. The data (140 megabytes in all) were collected at Chicago's O'Hare Airport on May 5th and 6th during peak traffic periods. Most data runs were conducted while flying an orbit around O'Hare at an altitude of approximately 10,000 feet and a range of 10 miles. Data were also collected during a takeoff and landing of the aircraft. The total data collection time exceeded 3-1/2 hours over the 2-day period.

All interrogation data received was "time tagged" and stored. The "on line" PC provided statistics on the data while it was being collected. Data provided were:

1. Counts of the number of each interrogation type per second.
2. A count of the total number of active "Broadcast" interrogations.
3. A list of the Mode S address of the last 20 active "Broadcasts."

The data files were broken into segments of approximately 10-minute duration. The file size (compressed) was approximately 6 megabytes for this period. The total data collected was approximately 140 megabytes. The peak number of active "Broadcasts" achieved was 33.

DOWNLINK. The downlink data were collected at Chicago O'Hare over the 4-day period July 20 - 23, 1992. The system was setup at the radar site for connection to the Air Traffic Control Beacon Interrogator (ATCBI)-5 receiver output. In this manner, the counts of ATCRBS and Mode S replies directly reflects the amount seen by the ground ATCRBS processing system.

The data recorded included ATCRBS and Mode S decode counts along with their time of arrival. The DATAS PC maintained online statistics on the decode counts and peaks in

1-second averages. Data were recorded on the PC in data files in 7-minute intervals. No timing relationship analysis of Mode S replies and valid ATCRBS replies was done.

DATA ANALYSIS PROGRAMS.

Programs were developed to provide the tools necessary to investigate the causes of clustering of interrogation activity which were encountered many times during the course of data collection. The data were collected during the peak traffic periods of the morning and afternoon at O'Hare. The number of departing and arriving aircraft varies significantly as a function of time. This causes a corresponding fluctuation of the TCAS interrogation activity as a result. The programs provided the following:

1. Extracted output of each interrogation type and its time of arrival.

2. Extracted output of the Mode S interrogation data and time of arrival.

3. The Mode S parity operation was then performed on each received interrogation. This enabled the identification of the addressee of each interrogation. All addresses were also checked for validity (legal or illegal) and associated with a received "Broadcast" interrogation. Those interrogations addressed to a legal Mode S address which were not associated with a received "Broadcast" interrogation were assumed to be Mode S equipped aircraft without TCAS or with it disabled during data collection time.

4. Other programs provided the peak number of Mode S interrogations received within a 1-second period. The program also provided the peak number of Mode S interrogations to each aircraft within 1 second and marked the second in which the peak occurred.

5. Another program provided a list of "Broadcast" interrogations and the number received from each Mode S address. The time of arrival of each "Broadcast" was also provided.

6. Another program provided a sorted list of Mode S addresses along with the start and stop time for the period of coverage. The total number of interrogations to each Mode S address was also provided along with the peak number received within 1-second for that address.

7. Another program provided all the interrogations addressed to an individual Mode S address when the Mode S address was provided as a program input.

8. Another program provided all the interrogations received within any 10-second interval when the start time is entered.

9. Software was provided to calculate usage of a victim transponder due to TCAS interrogation activity and ATCRBS ground interrogator activity. The usage of the transponder is based on time analysis of the decode data. Overlapping due to more than one decode type is accounted for. Timing is based on worst case transponder performance levels.

The collected data were correlated with data collected via the Chicago O'Hare Automated Radar Terminal Systems (ARTS) III during the same time interval. Examples of this correlation are shown later in this document.

Data were also correlated with that collected by the "on board" TCAS system of the FAA Boeing 727 during the same time period.

UPLINK DATA COLLECTION

Data were collected for a total of approximately 3 hours on the afternoon of May 5th and the morning of May 6th. All data were collected while flying a 10-mile orbit centered at O'Hare International at an altitude of 10,000 feet. Data were also collected during landing and takeoff on May 6th. Only summaries of that data will be presented here along with a sample of detailed data. Data were collected on six different interrogation types. They are listed below along with the definition of each.

1. ATCRBS Suppression Pair. This interrogation type is used by the ATCRBS system to inhibit replies caused by the side lobes of the antenna system. This interrogation is a part of all Mode A or Mode C interrogations not within the azimuth of the main beam of the antenna and prevents a reply whenever it is seen by the transponder. Other interrogation types contain suppression pairs (Mode S, ATCRBS Only, TCAS Whisper/Shout (W/S)), but they were subtracted from the total ATCRBS Suppression count as they were really a subset of the other interrogation types.

2. ATCRBS Mode A Interrogations. This is the normal ATCRBS interrogation which elicits the identity of the aircraft (one of 4,096 codes). The data shown on the summary data contains the Mode A codes even though it may have been accompanied by a suppression pair. When calculating the "transponder unavailability," however, the interrogations with a suppression were treated as suppressions and not Mode A interrogations.

3. ATCRBS Mode C Interrogations. This ATCRBS interrogation which requests the altitude of the aircraft (one of 4,096 codes driven by the aircraft altimeter). As was the case with Mode A, the data shown on the summary data contains the Mode C codes even though it may have been accompanied by a suppression pair. When calculating the "transponder unavailability," however, the interrogations with a suppression were treated as suppressions and not Mode C interrogations.

4. TCAS W/S Interrogations. This interrogation sequence is used by TCAS to acquire and track non-Mode S aircraft. The interrogation is a standard "Mode C ATCRBS Only" interrogation with another pulse of variable amplitude preceding P1 (the first pulse of an ATCRBS only) by 2 microseconds, which makes it a suppression pair to a standard ATCRBS transponder. If the ATCRBS transponder sees this pulse, it suppresses for the duration of a normal suppression pair. If it does not see this pulse, it replies with its altitude. If a Mode S transponder sees this interrogation, it merely suppresses, as Mode S transponders do not reply to ATCRBS only interrogations. By increasing the amplitude of the first pulse, the TCAS system is able to suppress nearby aircraft and basically acquire ATCRBS aircraft in concentric rings for its tracking function.

5. ATCRBS Only Interrogations. This interrogation is described in paragraph 4 above. Whenever an ATCRBS aircraft is at a range which results in the loss of the initial pulse prior to P1 (because of the path loss of the interrogation), it responds with an ATCRBS reply when the W/S sequence is seen. The next interrogation in the sequence will contain an initial pulse which is larger than the present one, and will result in a suppression as the transponder sees this combination as an ATCRBS suppression pair. When the Mode S transponders see this interrogation, they do nothing. Normally, a transponder will reply to only one or two of the W/S interrogations of the complete sequence.

6. MODE S Interrogations. The data were also collected on Mode S interrogations. Each Mode S interrogation which was seen was "time tagged" and stored. The majority of the interrogations were uplink format (UF)=0 interrogations, which are used by TCAS to maintain the "tracking function" of Mode S equipped aircraft. The source of the interrogations were unknown, but the destination can be determined by the use of the Mode S parity algorithm. The TCAS Broadcast interrogations (UF=16), which contain the Mode S address of the interrogation source, were also stored. In this manner, the number of TCAS aircraft operating within approximately 30 miles of the DATAS aircraft can be determined at any particular time.

7. MODE S Intermode Interrogations. These interrogations are used by the Mode S sensor to acquire Mode S aircraft. Mode S aircraft respond with a Mode S "ALL CALL" reply which contains the Mode S address of the aircraft. ATCRBS transponders respond with an ATCRBS reply. There were none of these interrogations during the collection period at Chicago as there are no Mode S sensors in the Chicago area.

UPLINK DATA SUMMARY

The figures below show the various interrogation types as a function of time. The file start time listed on the x axis. Each point represents the average value for the file (approximately 10 minutes each). The first file on May 6th (starting at 16:57 in figure 2) indicates significantly lower values than the remainder of the files. The DATAS aircraft was still approaching O'Hare during this file and as a result, these data were collected in a different volume of airspace than the remainder of the files. This is also true of the last file on May 6th, as this file was collected during the landing of the aircraft.

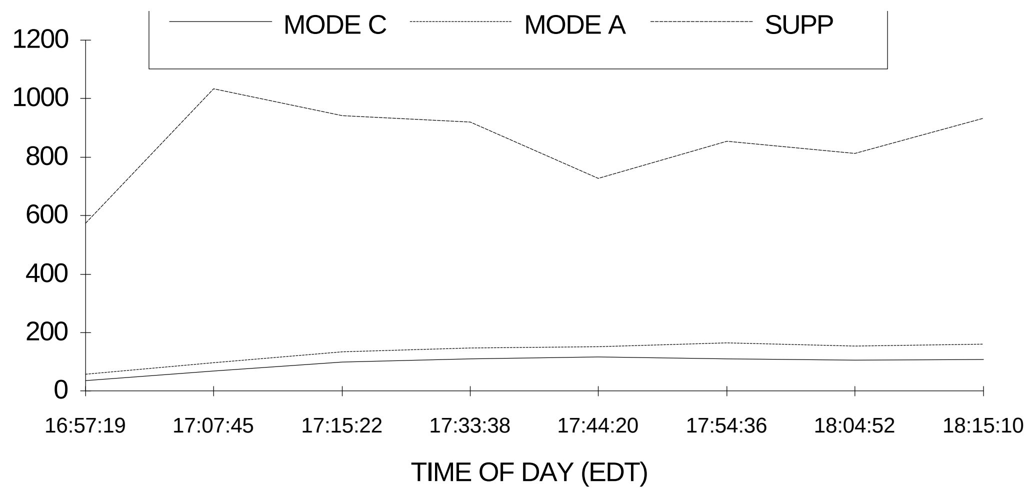

FIGURE 2. ATCRBS INTERROGATION SUMMARY FOR 5/5/92

Figure 3 shows the ATCRBS interrogation summary for the data collected on May 6, 1992. It shows approximately 1,000 ATCRBS suppressions per second, except for the last file when the DATAS aircraft was landing. The Mode C and Mode A interrogations averaged approximately 175 and 150 per second. These numbers are do not represent replies to those modes as many of the interrogations also contained a suppression pair. The data represented in these plots does not account for overlapped interrogation types. The data presented later in the report which depicts utilization of the transponder by the ATCRBS systems and the TCAS systems does take overlaps into account. Since the DATAS aircraft flew primarily orbits around the site, it was continuously within the side lobe area of two ATCRBS interrogators. At the edges of the beam on each antenna rotation, both suppression pairs and mode pairs were detected.

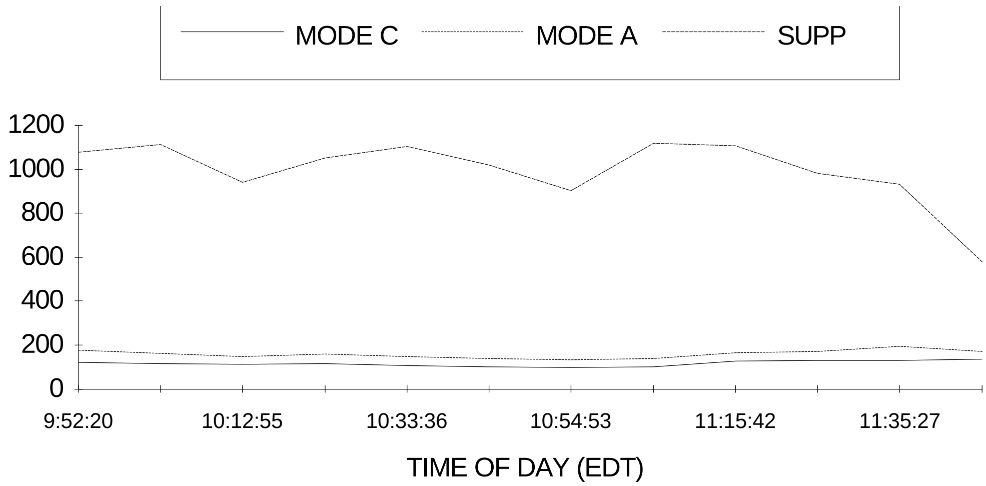

FIGURE 3. ATCRBS INTERROGATION SUMMARY FOR 5/6/92

The data presented on figures 4 and 5 represents the TCAS interrogation types observed during the data collection periods of May 5th and 6th. On May 5th, all interrogation types reached a peak at approximately 17:45 Eastern Daylight Time (EDT).

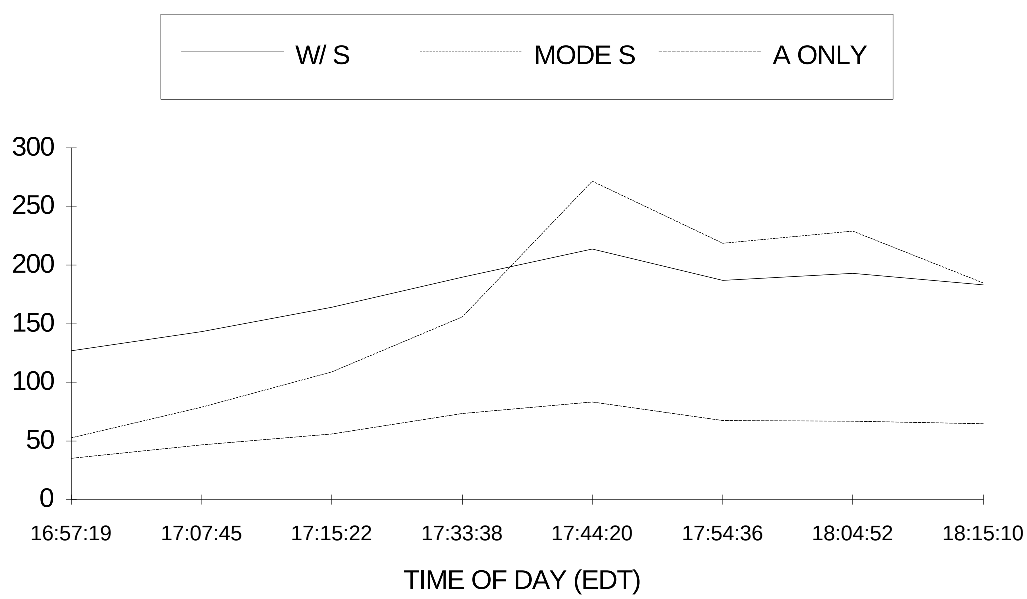

FIGURE 4. TCAS INTERROGATION SUMMARY FOR 5/5/92

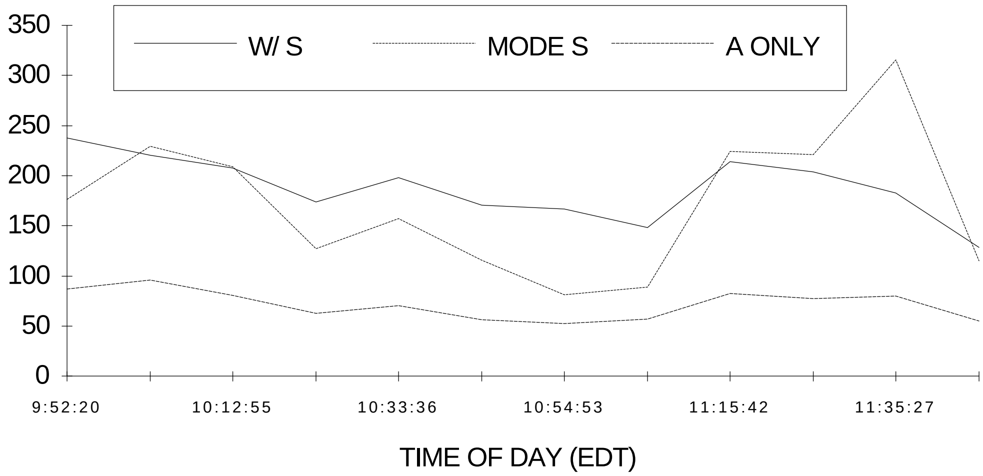

FIGURE 5. TCAS INTERROGATION SUMMARY FOR 5/6/92

The data collected on May 6th shows two distinct peaks in the interrogation numbers. The Mode S data peaked at approximately 10:00 (approximately 240 for a 10-minute average) and again at about 11:15 at approximately the same value. The peak observed at 11:35 (300 interrogations per second for a 10-minute average) occurred during the approach for the landing. The data were examined for the identity of the different Mode S aircraft. The number of different Mode S aircraft which received the interrogations is plotted in figure 6. As indicated, the number of different Mode S aircraft varied from approximately 30 to 50 for the data collection period of May 6th.

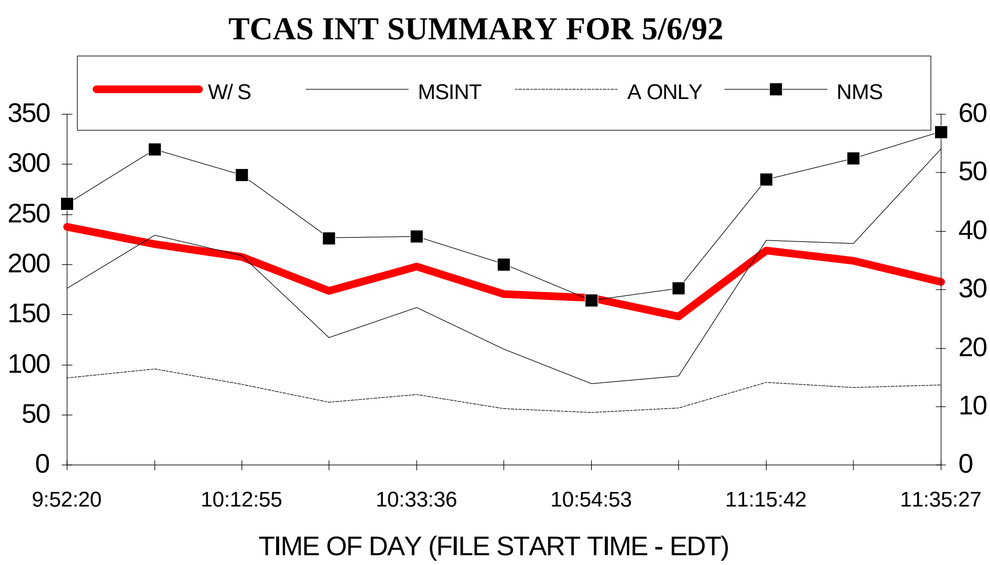

FIGURE 6. TCAS INTERROGATION SUMMARY FOR 5/6/92 (WITH MODE S AIRCRAFT)

Figure 7 shows the data from the landing on a 1-second basis. This file was started at 11:35 while the aircraft was in the process of getting into position for a landing. The number of Mode S interrogations per second as well as the number of different Mode S addresses receiving those interrogations are presented. The dip at approximately 11:36 was caused by the aircraft being in a "roll" position (see figure 8) which shielded the bottom antenna (DATAS used only the bottom antenna) from the majority of the other aircraft. The number of Mode S aircraft remained relatively constant at approximately 50 for the entire period. The onboard TCAS was tracking approximately 36 for most of this period. The number of Mode S interrogations steadily increased as we approached for the landing and reached a peak of approximately 600 per second at its highest point.

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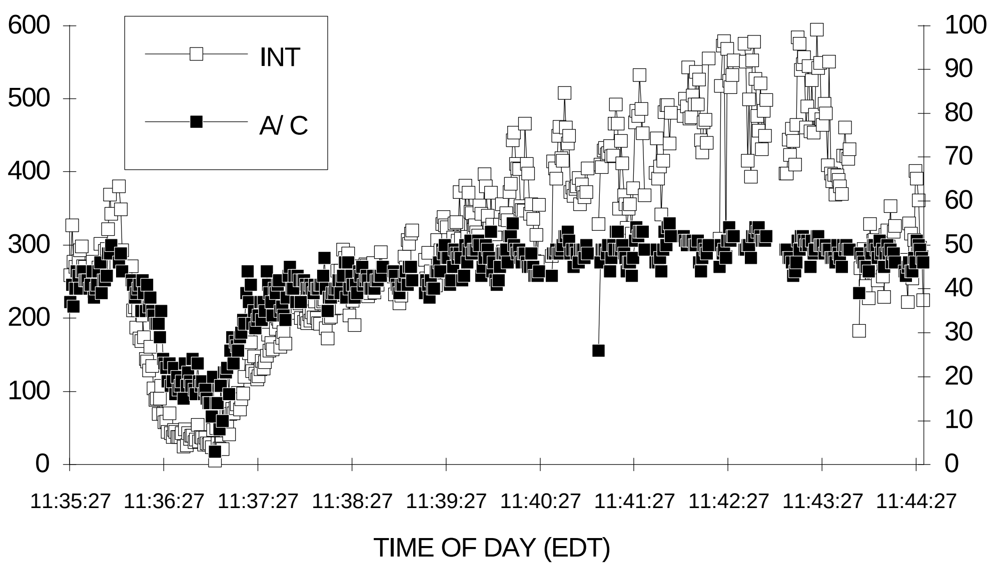

FIGURE 7. TCAS INTERROGATION SUMMARY FOR 5/6/92 (LANDING)

Figure 9 shows the range of the DATAS aircraft from the ground during the landing which occurred during the last file. Normally, the data from the ARTS III would be used to get this information, but data collection stopped approximately 7 minutes prior to landing. The information for range was obtained by first selecting an aircraft which was on the ground according to the TCAS data. The range from this aircraft, according to the onboard TCAS, was then plotted as the range of DATAS from the ground during the approach and landing. The onboard TCAS system was tracking several aircraft which were on the ground while we were on final approach. The start time of the plot was made on the same scale as the DATAS data for easier correlation. The range data were only available after the onboard TCAS began to track the "on ground" aircraft.

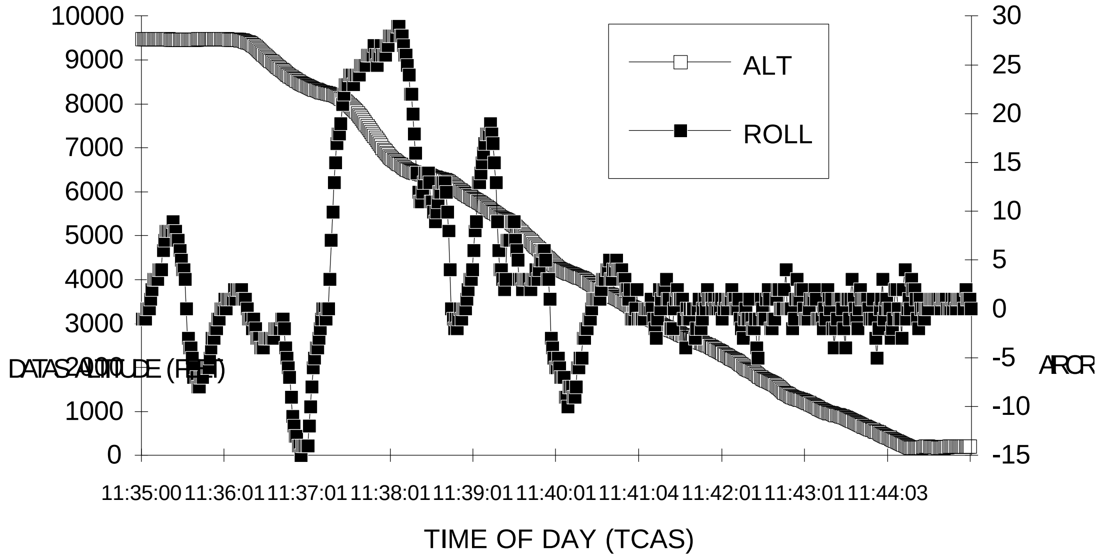

FIGURE 8. DATAS AIRCRAFT ALTITUDE AND ROLL

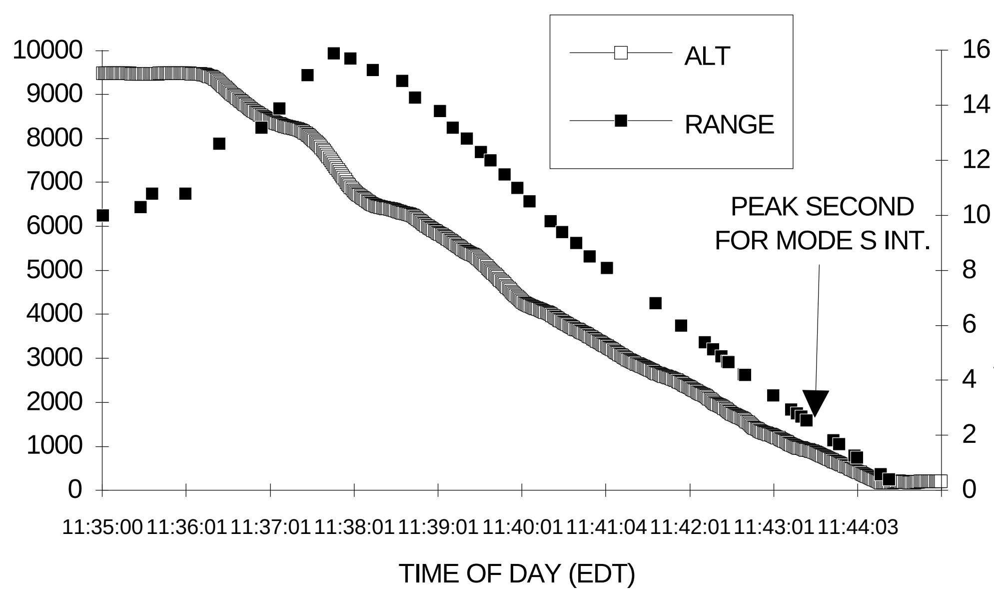

FIGURE 9. DATAS RANGE ON LANDING

Figure 10 shows an expanded view of DATAS data from the time period surrounding the second in which the peak value of Mode S interrogations were received. Each point is a 1-second sample. It also shows the number of different aircraft which received those interrogations. The interrogation rates varied from 400 to 600 per second while the number of different aircraft was relatively constant at about 50.

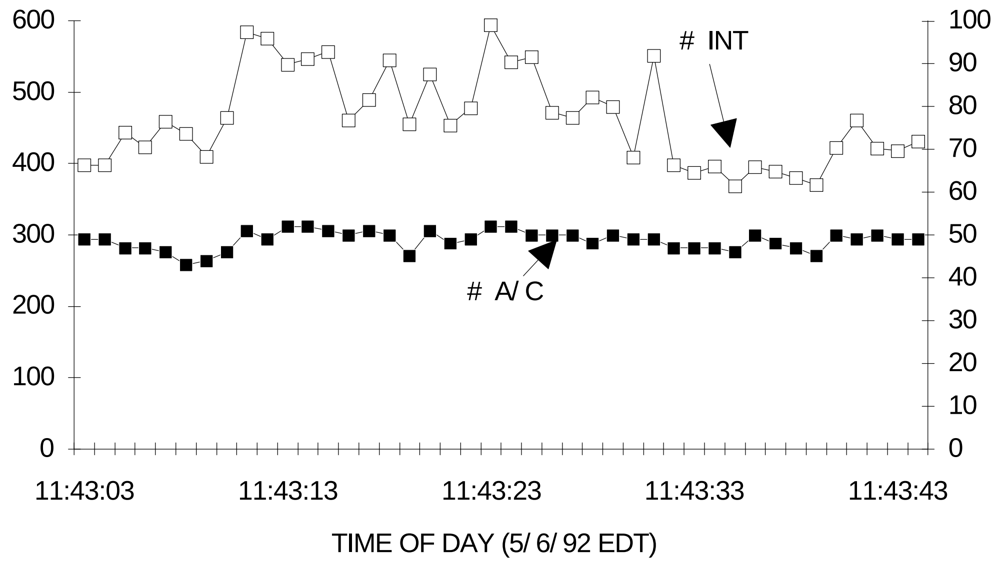

FIGURE 10. TCAS INTERROGATION FOR 5/6/92 (PEAK SECOND)

Further analysis of the data during the peak time interval shows that a significant number of the aircraft receiving interrogations were already on the ground. Figure 11 shows the different Mode S aircraft which received interrogations during this interval. Each point represents a different Mode S address (i.e., aircraft #57 received an average of approximately 17 interrogations per second and received a maximum of 27 in 1 second). The aircraft which were on the ground during the entire sample interval are indicated by the columns on the plot. These aircraft received approximately 1/3 of the total interrogations. The "interference limiting" mechanism of the TCAS system regulates the number of Mode S interrogations to approximately 280 per second. The mechanism used to achieve this regulation, however, is the elimination of Mode S targets which are far out in range. In this case, 1/3 of the interrogations were to aircraft on the ground, so the mechanism was not able to achieve the value because of the density of aircraft at the airport on the ground.

Of the 14 aircraft on the ground which received interrogations during the peak second, 7 were equipped with TCAS. All 7 issued broadcast interrogations during this period, so it is assumed that they were operational during this time interval.

The aircraft which took off during this period was investigated thoroughly. Its transponder was switched on approximately 1 hour and 20 minutes prior to takeoff. The TCAS was switched on for approximately 6 minutes and then turned off until 18 minutes prior to departure. Interrogations addressed to this aircraft were seen for the entire 1 hour and 20 minute period prior to departure.

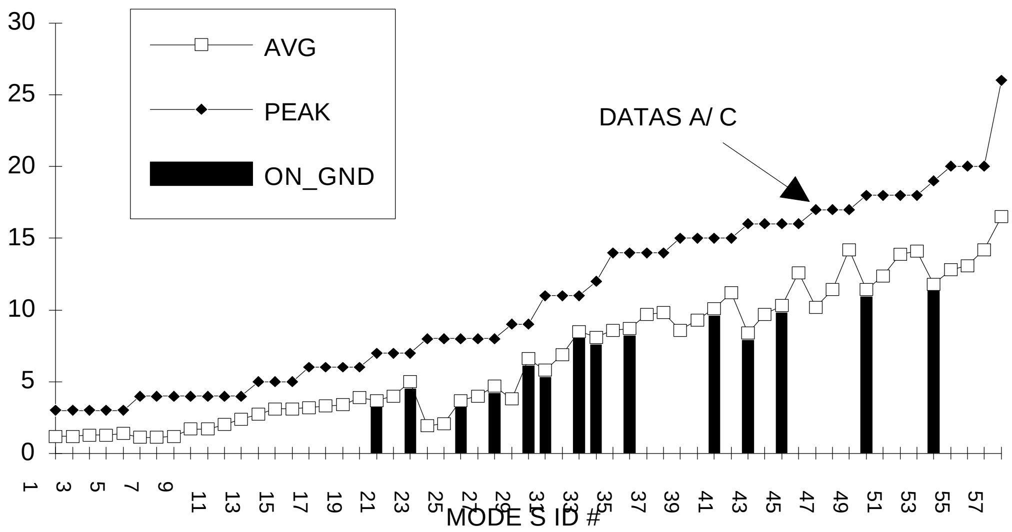

FIGURE 11. MODE S INTERROGATION TO INDIVIDUAL AIRCRAFT (PEAK SECOND)

Figure 12 shows the range and altitude of aircraft receiving interrogations during the peak interval. The aircraft are numbered the same as in figure 11. Aircraft #57 was 10 miles from the DATAS aircraft at an altitude of 4,100 feet. The bearing of aircraft #57 with respect to DATAS was 270 degrees (these data were not shown here). The position of DATAS during this peak interval was approximately 5 miles from the airport at an altitude of approximately 2,000 feet. The range indicated to all the aircraft which are on the ground (altitude = 200 feet) is not always 5 miles. The onboard TCAS did not always have a reply from all the aircraft on the ground, so the range of the reply nearest to the peak second was used as the range for this plot.

During the data analysis phase of the program, it was noticed that a large percentage of the interrogations were addressed to aircraft which were already on the ground. Figure 13 shows the percentage of interrogations from two perspectives: (1) those addressed to aircraft on the ground from our own "on-board" TCAS, and (2) all interrogations seen by DATAS from all aircraft within the Chicago terminal area. During the interval shown in the figure, about 30 percent of the interrogations were normally addressed to aircraft on the ground. At approximately 11:20, there was a significant decrease in the number of interrogations addressed to aircraft on the ground. This was true for the total environment as well as our own TCAS. An apparent correlation exists between the landing and takeoff cycles of the operations. The data relative to takeoff and landing operations was superimposed on the interrogation data. If an aircraft took off within the

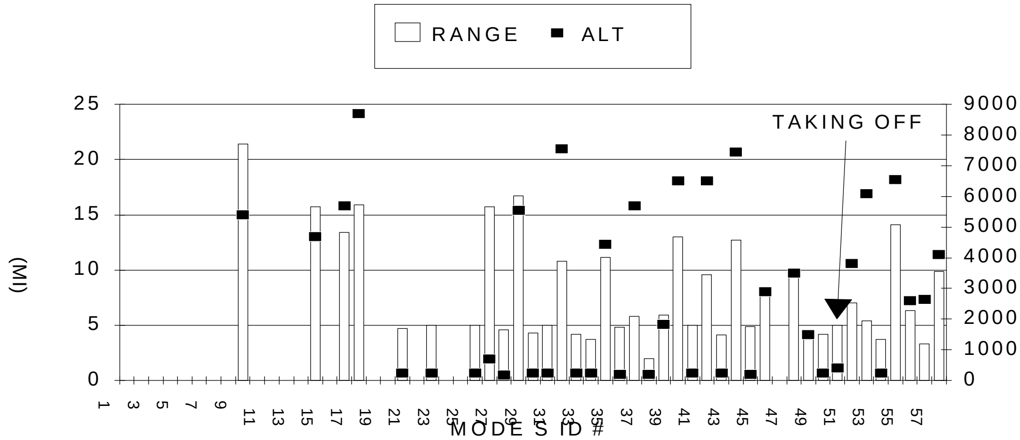

FIGURE 12. RANGE/ALTITUDE OF AIRCRAFT RECEIVING INTERROGATION (PEAK SECOND)

30-second interval (the granularity of this sample), a value of "2" was entered. If an aircraft landed, a value of “5” was entered. Examination of these data in figure 13 shows that to 11:20, the number of takeoffs significantly outnumbered the landings. After this time, the operations were primarily landings. At the crossover point and slightly thereafter, the percentage of interrogations to aircraft on the ground showed a significant decrease.

The number of interrogations to aircraft on the ground from our own TCAS was approximately 50 percent during the data collection landing phase (the landing leg began at about 11:35). The peak number of interrogations observed for the entire trip also occurred during this leg at approximately 11:43. During this interval, about 40 percent of all interrogations were addressed to aircraft on the ground. The number of interrogations to aircraft on the ground will also be increased because of poor link reliability to aircraft on the ground.

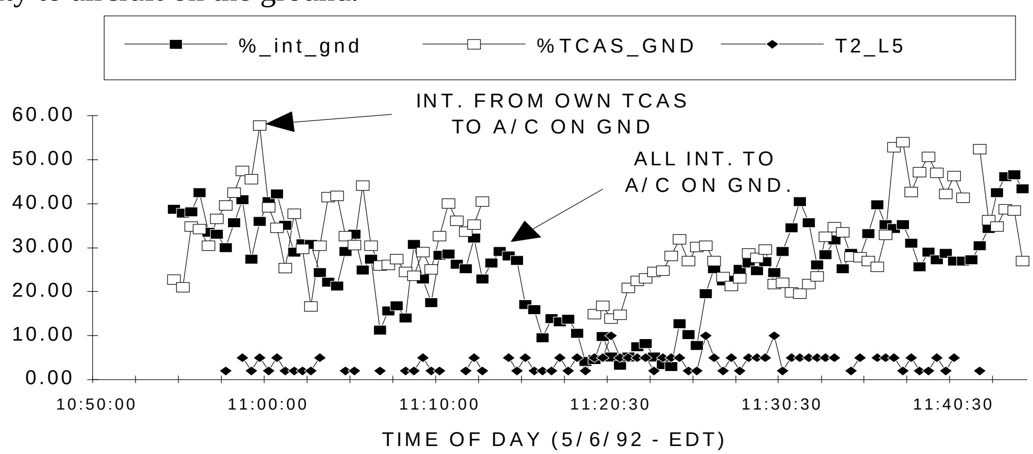

FIGURE 13. PERCENTAGE OF INTERROGATIONS TO AIRCRAFT ON GROUND

TRANSPONDER USAGE ANALYSIS

One of the primary interests is the amount of time each system type (i.e., ATCRBS, TCAS, MODE S, etc.) uses the transponder. When responding to one user, the transponder is unavailable for the other systems to use. The data from the different interrogation types enabled an analysis to be performed to estimate the usage of the various systems. In order to eliminate some of the ambiguities, DATAS used a receiver with the characteristics of a transponder and an omnidirectional antenna. All decodes were passed on to the DATAS processor for time tagging and storage. The front end was designed to pass **all** decodes. A normal transponder would block further decodes until the present task, i.e., reply/suppression, completed. Thus, decodes which arrived during the time which a transponder would be "busy" could be identified.

ATCRBS and Mode S transponders respond differently to some interrogations. Thus, the effect on usage is necessarily different. The following analysis was performed separately on both ATCRBS for Mode S transponders. The interrogations addressed to the "onboard" TCAS were counted for the duration of the data collection. It was learned that approximately 3 percent of all the Mode S interrogations seen at the position of DATAS were addressed to the "onboard" TCAS. This number was used during the processing for the Mode S transponder usage. It was assumed that a Mode S transponder would reply to 3 percent of the Mode S interrogations received and ignore the rest.

The incoming interrogations were processed serially with application of the following rules:

In all cases, a timer was started when the interrogation type was identified. All subsequent interrogations, which were received prior to the end of the timer, were blocked out. Total usage time was then calculated at the end of the file for each interrogation type. <u>The timer values are defined as follows when considering the effect on Mode S transponders:</u>

ATCRBS SUPPRESSION	35 μs
ATCRBS MODE A or C	149 μs (3 μs delay, 20.3 μs reply, 125 μs dead time)
TCAS W/S	35 μs
ATCRBS Only	35 μs
MODE S (reply required)	317 μs (128 μs delay, 64 μs reply, 125 μs dead time)
MODE S (no reply)	128 μ s

There is a discrepancy between the Mode S Minimum Operational Performance Standards (MOPS) and the Mode S National Standard on the requirement for recovery time of the transponder if no reply is required. The prototype models of several Mode S transponders were checked at the Technical Center during the development cycle of these transponders. Table 1 gives a summary of those test results.

TABLE 1. TRANSPONDER RECOVERY CHARACTERISTICS

	Reply Req'd (s)	No Reply Req'd (s)
Model 1	320	75
Model 2	225	70
Model 3	220	65
Model 4	> 300	> 125
Model 5	< 200	< 20
Model 6	240	125
Model 7	240	70

These transponders represented models for use in general aviation aircraft as well as commercial aircraft. The specified value of the Mode S MOPS (128 s when no reply is required) was used for the calculations in this report. The Mode S National Standard specified 35 s as this requirement.

ATCRBS SUPPRESSIONS are defined as ONLY those suppressions which are not a part of another interrogation such as a W/S, ATCRBS Only, or Mode S.

For an ATCRBS transponder, the following differences were applied:

TCAS W/S	35 μs	(same as Mode S)
ATCRBS Only	149 μs	(the ATCRBS transponder will reply)
MODE S (reply required)	35 μs	(suppression from the Mode S preamble)
MODE S (no reply)	35 μs	(suppression from the Mode S preamble)

The following plots show the average usage over approximately 10-minute intervals (the length of each data file). Figure 14 shows the data from the runs of May 5th. It shows a fairly constant total usage of between 5 and 6 percent after the DATAS achieved its orbit (approximately 17:05). The ATCRBS system used about 4 percent. The TCAS usage varied from about 1 percent to 2.7 percent, with the peak occurring at about 17:45 (as shown previously on the TCAS interrogations summaries).

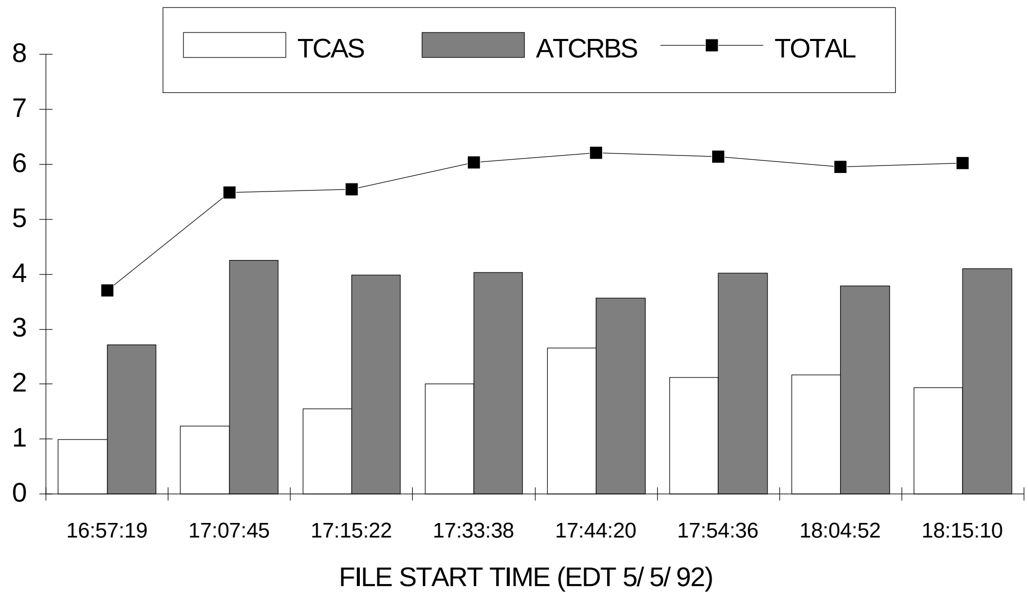

FIGURE 14. ATCRBS TRANSPONDER USAGE - TCAS/ATCRBS (5/5/92)

The data from May 6th for ATCRBS transponders is shown in figure 15. The total usage is slightly higher than on May 5th. The ATCRBS percentage remains at approximately 4 percent. The TCAS percentage reflects the two peaks shown in the interrogation data and varies from approximately 1.5 to 2.5 percent.

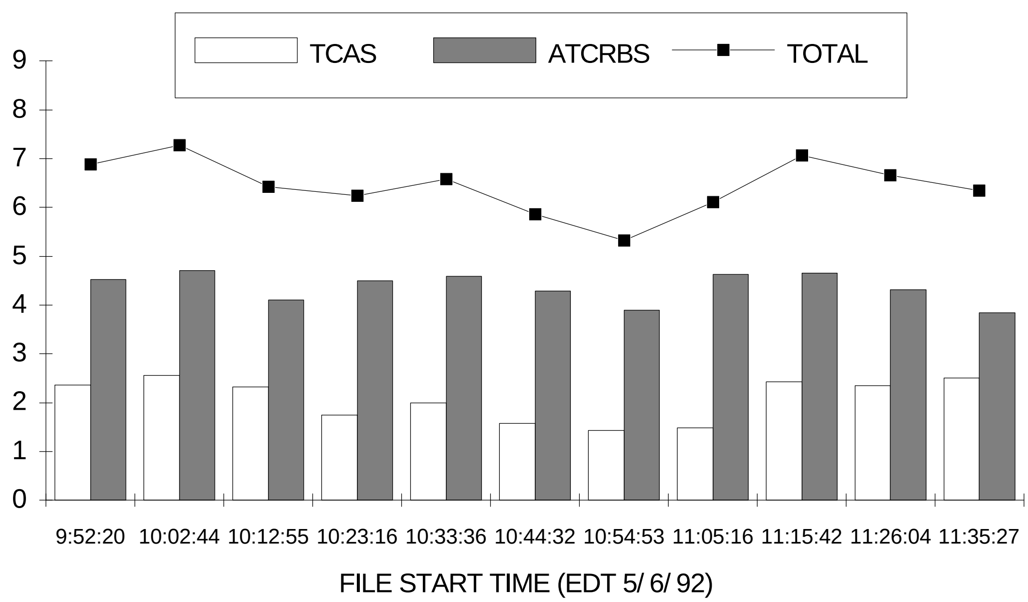

FIGURE 15. ATCRBS TRANSPONDER USAGE - TCAS/ATCRBS (5/6/92)

Figure 16 shows the transponder usage for Mode S transponders on May 5th. The the transponder usage varies from about 6 to 8 percent (ignoring the first leg in the flightpath). This usage basically reflects the Mode S interrogation rate, since the Mode S transponders are allowed 128   s to recover from a Mode S interrogation that requires no reply.

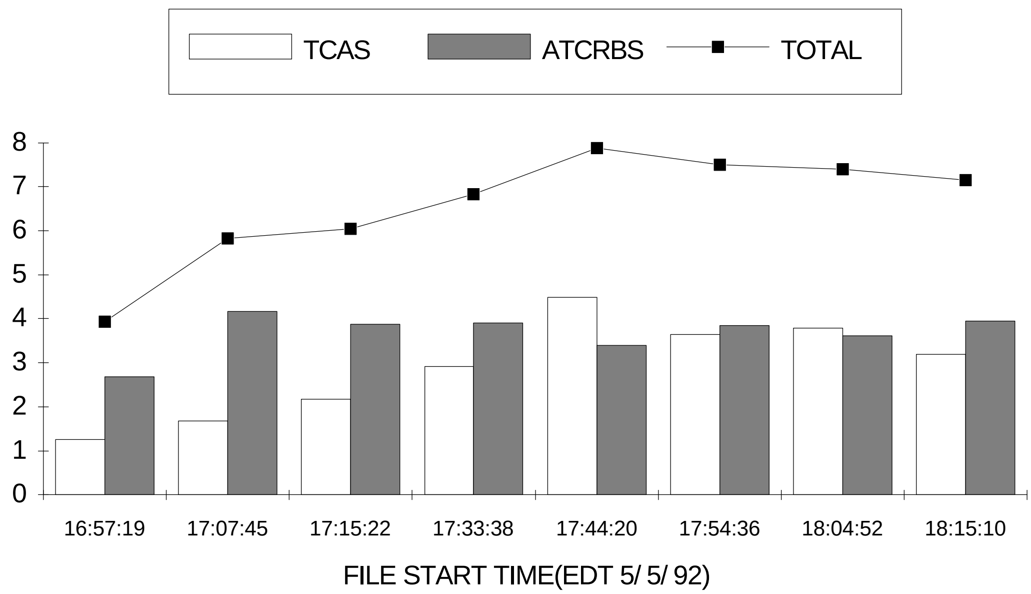

FIGURE 16. MODE S TRANSPONDER USAGE - TCAS/ATCRBS (5/5/92)

Figure 17 shows the usage of a Mode S transponder for the interrogations received on May 6th. The ATCRBS remains constant at approximately 4 to 4.5 percent. The TCAS usage varies much more, however, from approximately 2 percent at 10:50 to 4.8 percent at 11:35. This 11:35 point contains the landing of the DATAS aircraft when the peak number of Mode S interrogations were observed. This resulted from an average number of 300   Mode S interrogations per second averaged over the 10-minute interval. Peak rates were significantly higher (refer to figure 7).

The average transponder usage in the Chicago environment of May 5th and 6th is given below. It is listed separately for ATCRBS and Mode S transponders.

Transponder Type	TCAS Use	ATCRBS Use	Total Use
MODE S	3.0%	4.1%	7.1%
ATCRBS	2.0%	4.1%	6.1%

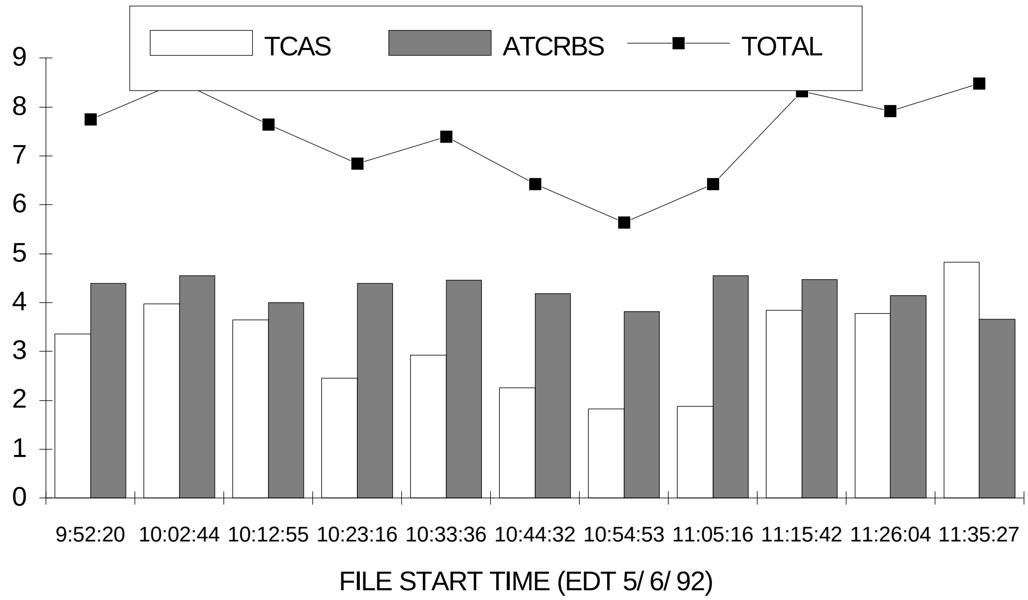

FIGURE 17. MODE S TRANSPONDER USAGE - TCAS/ATCRBS (5/6/92)

UPLINK SUMMARY

The uplink effect of the operation of TCAS on SSR is determined by calculating the usage of an ATCRBS and Mode S transponder when subjected to an environment measured during the uplink tests using DATAS. The effect on a Mode S transponder was greater than that on an ATCRBS transponder because of the time required to properly handle Mode S interrogations (ATCRBS transponders merely suppress). When using specified limits, a transponder in a point in space where DATAS collected the data would have been used approximately 4 percent of the time for ATCRBS interrogations. This percentage was independent of the number of aircraft and time of day (only peak periods were flown). The TCAS usage, however, was a function of the number of Mode S aircraft and/or time of day. The usage to handle TCAS interrogations varied from approximately 1 to 5 percent (during the landing when the average rate was 300 Mode S interrogations/second). If the transponder must handle the peak 500 Mode S interrogations which were measured during landing, the transponder is tied up for approximately 7 percent of the time for only the Mode S interrogations. This peak rate was measured for only a few seconds during the DATAS tests. This usage results in a lowering of the reply probability to an ATCRBS interrogation.

DOWNLINK DATA COLLECTION

The DATAS monitor function was configured to detect and record downlink reply data. DATAS was setup at the ASR-9 radar site and connected to the output of the ATCBI-5 beacon receiver. This video signal is the input to the beacon processing system. In this manner, DATAS received exactly the same video signal provided to the ATCRBS processing system. As of the time that the downlink data were collected at Chicago, July 20 - July 23, the ASR-9 processor was installed and operational. DATAS simply detected ATCRBS and Mode S replies and calculated their rates for the 4-day data collection period. The main data were collected for the full 2-day period July 21 - July 22. Data recorded included ATCRBS reply decodes and Mode S reply decodes. The data were stored on the DATAS PC in 7-minute intervals. The decode/second averages were collected only during the actual "listening interval" of the ATCBI-5 (only "on" approximately 1/3 of the total time).

DOWNLINK DATA SUMMARY

The following figures depict the downlink data from the Chicago O'Hare data collection. Figures 18 and 19 summarize the Mode S reply counts per second for the 2 days, July 21 and July 22. Both days of data collection encompass the peak afternoon traffic count. Data were not collected between 0400 and 1030 a.m., July 21, because of a channel change resulting from a system failure. The data from the 2 days are very similar. The average number of Mode S replies decoded on the second day is generally higher than the first day. The first day average rate was approximately 65 replies per second between 1030 and 2230. The highest peak rate was 230 replies per second for a 7-minute period at approximately 2100. On July 22, the averages were approximately 100 replies per second for the same period and the peak was 303 replies per second for the highest peak (7-minute interval). The pattern was very cyclical and appeared to repeat at approximately 1.5-hour intervals. The peak value, however, was not the same on the various days. This pattern can easily be seen in figure 20, which is the composite of all data collected over the 4 day period. The data were not collected for the entire day on the first and last day. Between the hours of 2400 to 0600, the rates were negligible on both complete days.

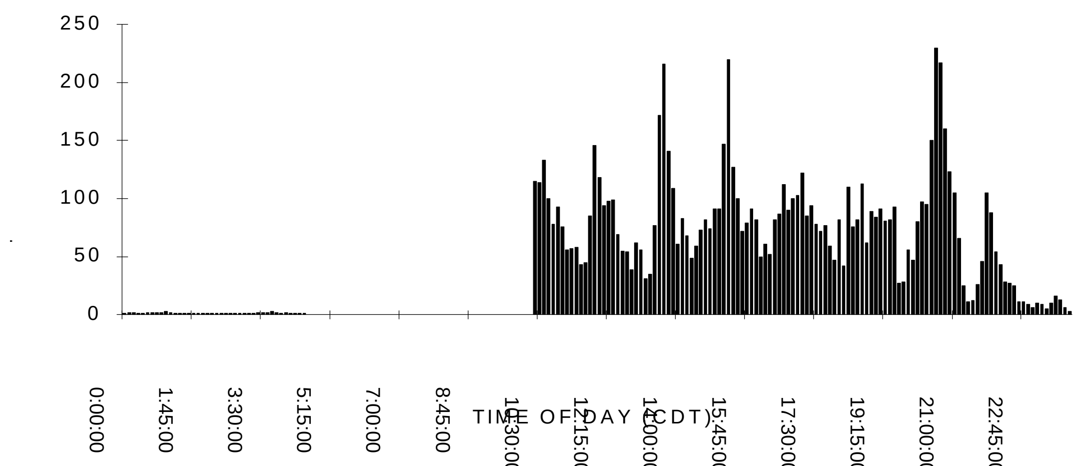

FIGURE 18. DOWNLINK MODE S DECODES (7/21/92)

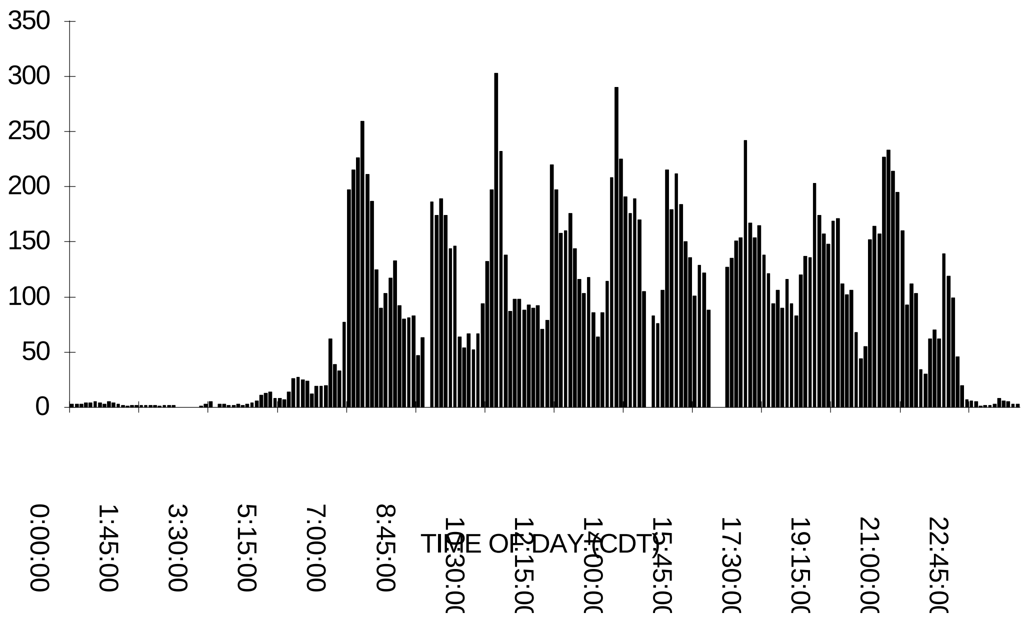

FIGURE 19. DOWNLINK MODE S DECODES (7/22/92)

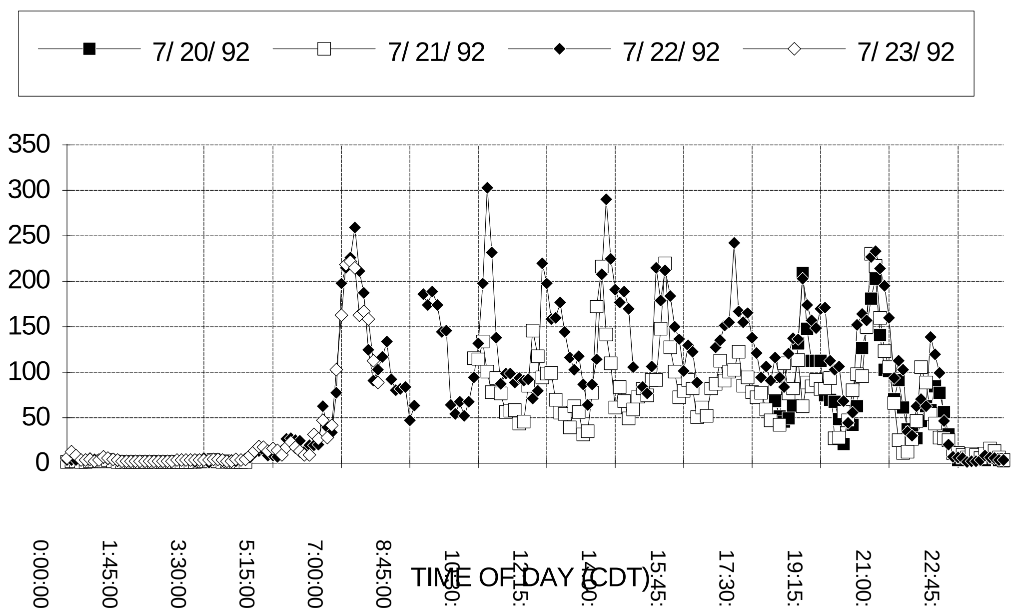

FIGURE 20. DOWNLINK DAY TO DAY COMPARISON

The Mode S reply data were then converted to a percentage of time which the input to the ATCRBS processor was occupied by these replies. The presence of these replies can distort the desired ATCRBS replies in two ways: (1) it can prevent the declaration of true ATCRBS replies, or (2) it can distort the code of the desired ATCRBS reply.

Figures 21 and 22 show the percentage time occupied by Mode S replies for the 2 days, July 21 and July 22. This percentage necessarily follows the pattern discussed previously. The highest percentage of occupancy approached 6 percent during the highest peak.

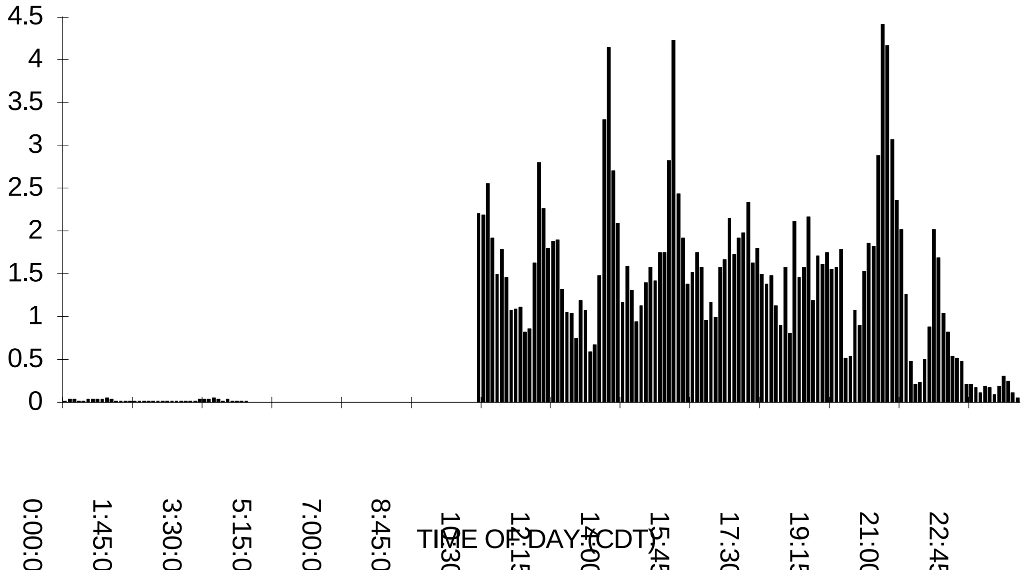

FIGURE 21. AVERAGE PERCENTAGE OF TIME OCCUPIED BY MODE S REPLIES (7/21/92)

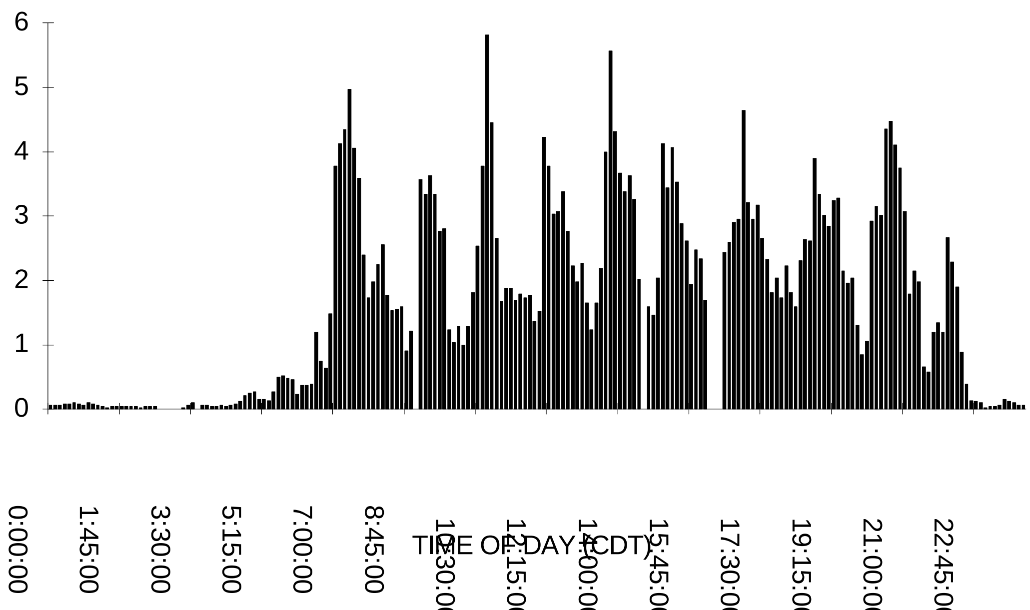

FIGURE 22. AVERAGE PERCENTAGE OF TIME OCCUPIED BY MODE S REPLIES (7/22/92)

An analysis of the frequency of overlap between Mode S replies and valid ATCRBS replies can be accomplished to evaluate the potential impact to an ATCRBS processor. The percentage time occupied by Mode S replies can be utilized to determine the probability of overlap of Mode S and ATCRBS replies and targets. The time occupation of a Mode S reply rate of 1,000 per second is 6.4 percent. Making the assumption that a nominal ATCRBS target consists of 18 replies, the probability of overlap of at least one reply is represented by the Bernoulli trial B_k (k events occur out of n events with a known probability). The resultant probability of overlap is given by:

$$P_r (B_k) = C_k^{18} \; p_c^k \; (1 - p_c)^{18-k} \qquad (1)$$

where C_k^{18} denotes a combination symbol and p_c is the probability of an ATCRBS reply overlapped by a Mode S reply. The result can be calculated by:

$$P_r \text{ (1 or more overlaps)} = 1 - (1 - p_c)^{18} = 70.3\%$$

The result shows that a single target has a 70.3 percent probability of having one or more of its replies overlapped by Mode S replies. The mean value and standard deviation of the Bernoulli trial B_k are:

$$E[B_k] = np_c = 18 \text{ x } 6.6\% = 1.19 \qquad (2)$$

$$\text{Standard Deviation} = \sqrt{n \, p_c \, (1 - p_c)} = 1.04$$

This shows that on an average there is one overlapped reply per target on a scan basis. the calculation shows that no overlaps or two replies overlapped are within the standard deviation. Using equation 1, the probability of two replies overlapped is 21 percent. The probability of one reply having an overlap is 37 percent and the probability of no overlaps is 29.7 percent. The remaining 12.3 percent is the probability of more than two replies overlapped. Figure 23 shows the probability as a function of the number of overlapped ATCRBS replies. This is shown at various Mode S reply rates. The Mode S reply rates are shown for comparison only and do not correspond to measured rates. The peak rate measured at Chicago corresponds to the 1,000 Mode S replies per second curve. At 500 Mode S replies per second, it is most likely to have no overlaps of a target's replies (56 percent probability of no overlaps). Inversely, the probability of one or more replies overlapped is 44 percent. Figure 24 depicts the probability of overlap as a function of Mode S fruit rate and target nominal reply length. The probability that at least one overlap will occur is still relatively high even for targets with reduced reply counts (greater than 50 percent with reply count of seven and Mode S reply rate of 1,000 per second). The probabilities of overlap at the reduced target reply counts is more critical since these are the targets most susceptible to tracking problems in the terminal ATC system. The previous calculations can be extended to determine the number of affected targets on an antenna scan basis. Assuming a scan contains 144 aircraft, a composite Bernoulli trial yields 100 aircraft which are overlapped by Mode S replies at 1,000 Mode S per second and the nominal 18 replies per target.

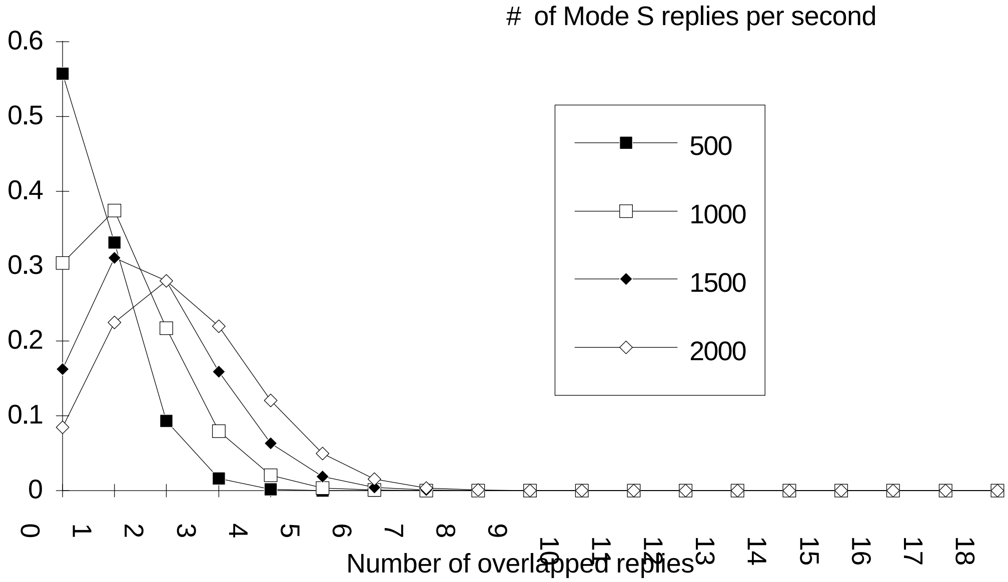

FIGURE 23. PROBABILITY OF OVERLAP OF MODE S AND ATCRBS REPLIES

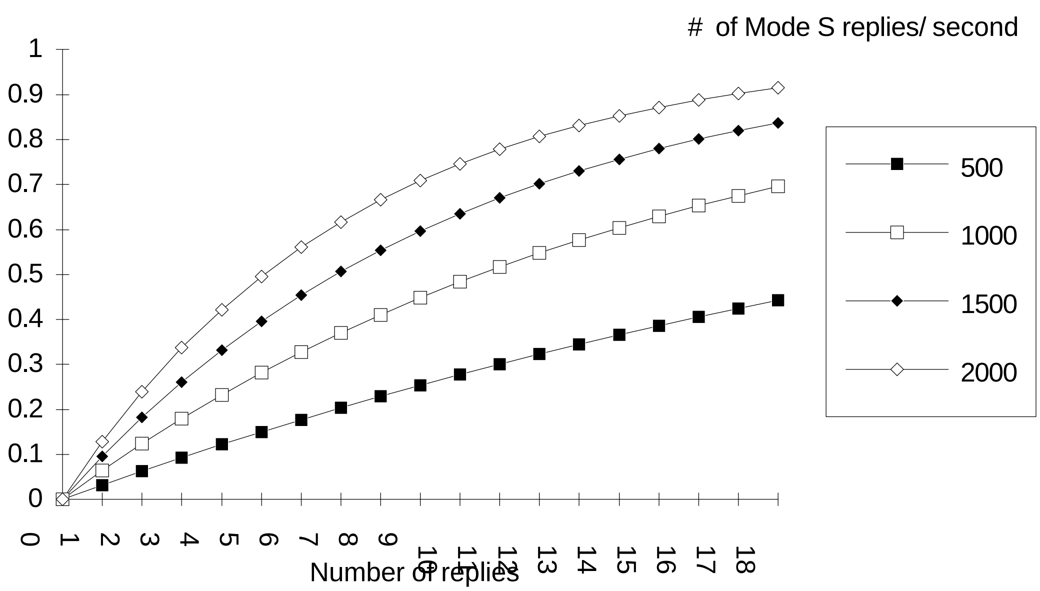

FIGURE 24. PROBABILITY OF OVERLAP VS. NUMBER OF TARGET REPLIES

The effect of the downlink Mode S replies on ATCRBS system operation is not easy to assess. The effect may be very different depending on the system (i.e., Sensor Receiver and Processor (SRAP), ASR-9, Common Digitizer, etc.) and the mode of operation of that system. A Mode S fruit reply is approximately 5 miles in length. All ATCRBS processors will normally declare multiple ATCRBS brackets when processing a Mode S reply. The mode of operation is of particular importance here. If a defruiter is not used with a SRAP, for example, the processor will inhibit processing at the extreme ranges because of the additional processing required for ATCRBS brackets caused by Mode S fruit. When the "preamble detector" was used to detect Mode S replies and blank the processor input (on the ASR-9 at Chicago), local personnel noticed a definite decrease in performance. If the Mode S replies are allowed to enter the processor, they will be used in some cases to correlate with ATCRBS targets which are in process as well as inhibit ATCRBS replies which occur for the duration of the Mode S reply. The range and azimuth accuracy, as well as code validation, will be degraded, but the targets will not be lost if the false bracket occurs at a range which can be correlated with the real target. In a place like Chicago, where the Mode interlace is A/A/C, the most susceptible parameter is the Mode C validation. Another product of the Mode S replies is target "splits" which are caused by "holes" in the azimuth pattern of a target.

All the above effects are a combination of both the uplink and downlink paths of the ATCRBS system. The overall system performance is a combination of the effects of other ATCRBS sites, turning of the aircraft, antenna pattern lobing, etc. Data collected during previous efforts on all the existing ATCRBS processors showed the following performance characteristics as a function of reply probability:

TABLE 2. ATCRBS PROCESSOR PERFORMANCE DATA

System	Reply Prob.	Percent Detection	Code Valid.	Split Per Scan	AZ ACC. (ACP's)
SRAP(DEFRUITED)	.90	99.2	98.2	.03	3.5
SRAP(DEFRUITED)	.70	93.5	88.2	.75	5.2
SRAP(PRE.DET)	.90	99.7	99.5	.02	1.5
SRAP(PRE.DET)	.70	99.1	98.5	.06	2.2
SRAP(UNDEFRUIT)	.90	99.7	99.5	.02	1.5
SRAP(UNDEFRUIT)	.70	99.1	98.5	.06	2.2
ARTS II	.90	99.6	98.1	.01	
ARTS II	.70	98.3	94.5	.05	
AN/TPX-42	.90	99.2	99.5	.05	
AN/TPX-42	.70	92.5	98.5	.35	
COM.DIGITIZER	.90	99.9	99.9	.01	
COM.DIGITIZER	.70	99.5	99.5	.01	

The data in table 2 were collected during an earlier project using targets with a run length distribution which matched the measured value of the environment for a terminal system in 1981. Data were also collected to determine the effect of Mode S fruit, but the fruit rates were lower than those measured during the uplink tests of DATAS.

The real effect of the TCAS on the existing system depends on the vulnerability of the existing system to factors. Generally, the run lengths (the number of replies between the lead and trail edges of a target in azimuth) and round reliabilities of aircraft replies detected by the ATCRBS ground processor provides the system immunity to individual sources of interference. However, the cumulative effects of coverage problems, interference, and reduced transponder availability acts to reduce its performance. If the targets have long run lengths, the effect is certainly negligible. If the targets are weak, however, because of lobing, turning, shielding, etc., the loss of one or two hits may cause the targets to be lost for that scan.

The targets in the system need to be categorized into two groups: (1) those interfered with by Mode S replies, and (2) those not interfered with by Mode S replies. The two groups can then be analyzed to determine what the population of targets is because of all other interference sources (except downlink Mode S fruit). This process will show how vulnerable the environment is to Mode S fruit. Targets of similar run lengths can then be compared to determine the effect of the loss of one or two replies in the run length of the target.

ATCRBS INTERROGATOR ANALYSIS

The data collected as a result of the uplink environmental analysis system provides a wealth of information to analyze 1030 MHz frequency activity.

The Chicago TRACON operates in an area within the operating coverage of other ATCRBS interrogators. As a point in space referenced from the DATAS aircraft, the detection of operating ATCRBS interrogators is possible. DATAS detects the Mode A and Mode C interrogations transmitted by the ATCRBS systems and time of arrival of the interrogations. Each of the operating ATCRBS interrogators within the Chicago O'Hare areas has its own unique characteristics that can be utilized to identify it within the DATAS collected data. The characteristics utilized consist of mode interlace pattern, pulse repetition timing (PRT), and antenna scan rate. Side lobe suppression pulses from the ATCRBS interrogator located at Chicago O'Hare were detected for the duration of the antenna scan due to the proximity of the aircraft to the ATCRBS interrogator. The ground interrogators are a combination of FAA and military short range and long range sites. The interrogator characteristics were utilized to search the collected data to identify interrogation patterns.

The software algorithm to detect and identify interrogations from a particular ATCRBS interrogator utilized the trademarks of the interrogator, i.e., PRT, scan rate, and Mode interlace, as input to the search software. The search algorithm associates individual decodes to an interrogator. These were distinguished subsequent to filtering Mode C decodes declared as a result of other TCAS decode types. The main beam of the interrogator site is identified by searching for the proper timing and interlace sequence that accompanies the interrogator. The DATAS aircraft would be illuminated by each ATCRBS interrogator once per antenna scan. The actual ATCRBS interrogators and the site locations were derived from a national data base. This data provided the interrogator characteristics required by the software algorithm. The Chicago O'Hare TRACON area is within the coverage of seven ATCRBS interrogators. One is a long range ATCRBS site which covers a range of 200 nautical miles (nmi). The remaining six are short range which provide coverage to 60 nmi. Although the coverages of both long range and short range systems are as specified, the transmitted power by ground systems allows reception beyond the processing range.

The results obtained from the analysis of the Chicago uplink data identified the interrogators with coverage in the Chicago terminal area. The two closest sites, the ASR-7 operating as the primary sensor at Chicago, and a naval equivalent to the ASR-8 operating at Glenview, are depicted in figures 25 to 27. The ATCRBS interrogator located at Glenview is approximately 7 miles from the Chicago airport. The site is a short range interrogator with a PRT of 2.926 milliseconds. The antenna scan rate is 4.678 seconds. The main beams over 35 scans is shown in figure 25. Figure 26 shows the Glenview main beam detected for a single scan (one antenna rotation). The mode interlace is 1:1 (alternating Mode A, Mode C). The main beam detection of the Chicago primary sensor is shown in figure 27. The antenna scan rate is 4.678 seconds. The detection of the interrogation pattern at Chicago required matching the staggered pulse repetition frequency (PRF) pattern of the ASR-7 radar. The stagger pattern consists of an 8 pulse repetition. Figure 28 shows a long range interrogator located in Joliet, 33 miles from the Chicago Airport. The detected main beams from this site are shown for a 3-minute interval. The antenna scan rate is 10.1 seconds, typical of long range radar rates. The PRT of 2.821 milliseconds is depicted by the expansion of a single main beam, as shown in figure 29. The mode interlace pattern of the interrogator is 1:1.

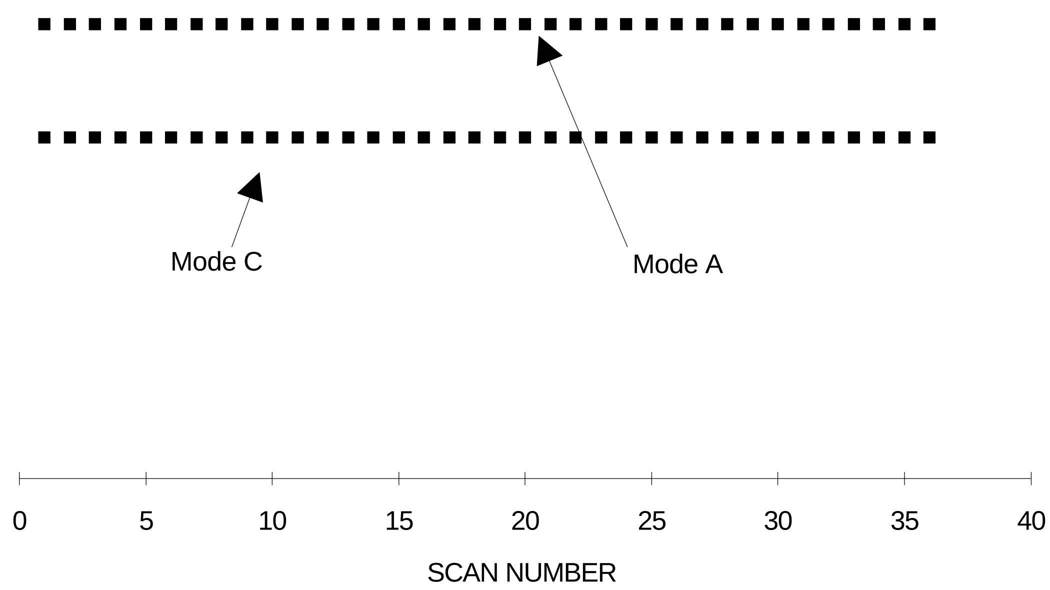

FIGURE 25. MAIN BEAM SUMMARY - 35 SCAN SAMPLE - GLENVIEW

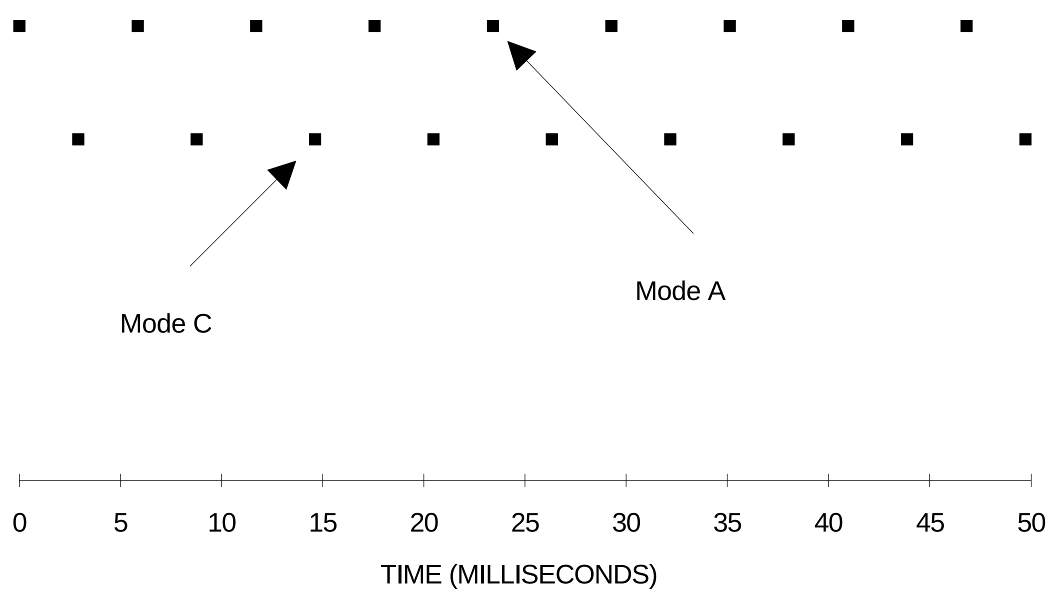

FIGURE 26. SINGLE MAIN BEAM INTERROGATIONS - GLENVIEW

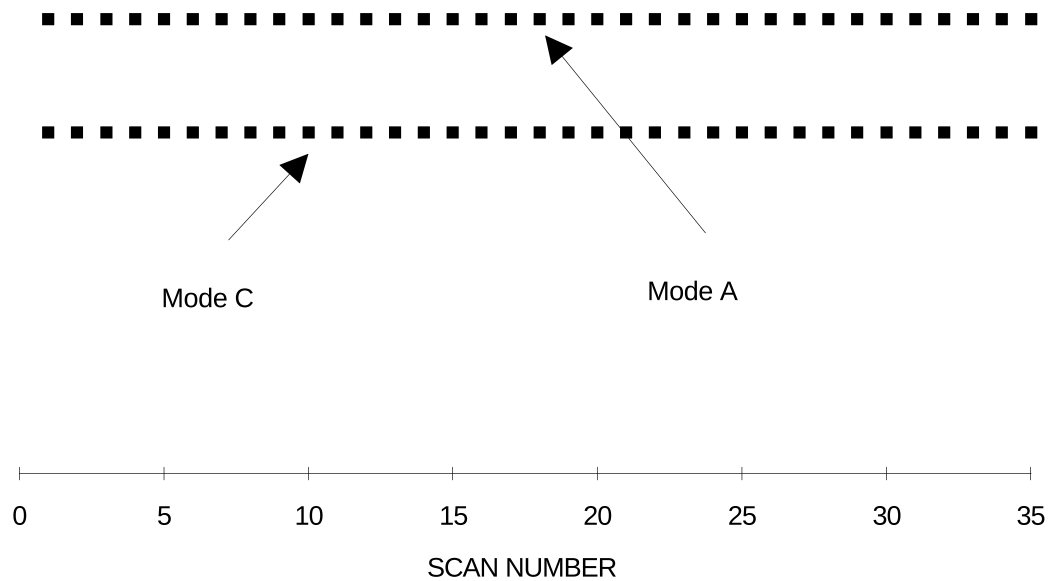

FIGURE 27. MAIN BEAM SUMMARY - 35 SCAN SAMPLE - CHICAGO

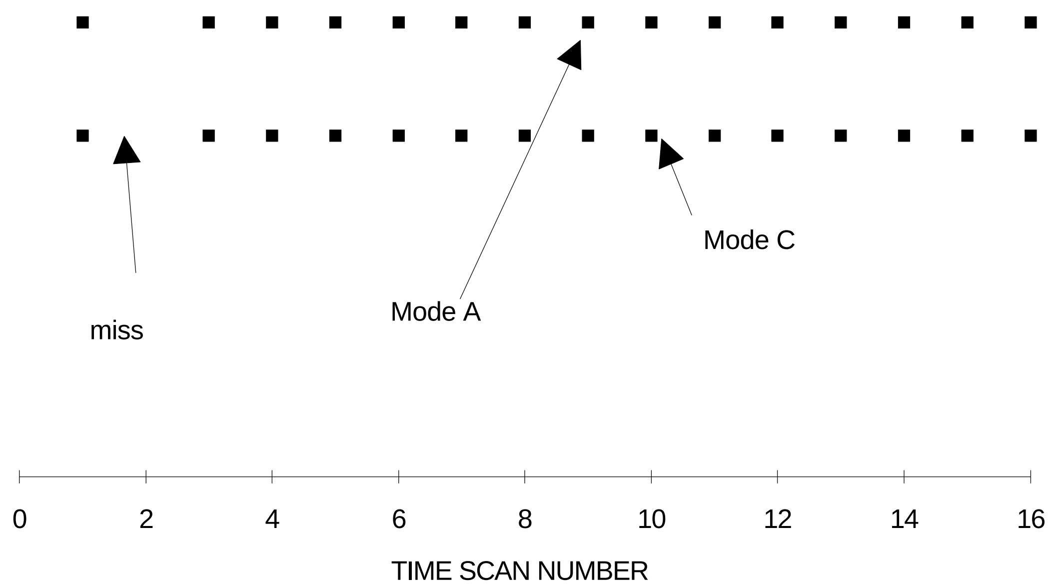

FIGURE 28. MAIN BEAM SUMMARY - 16 SCAN SAMPLE - JOLIET

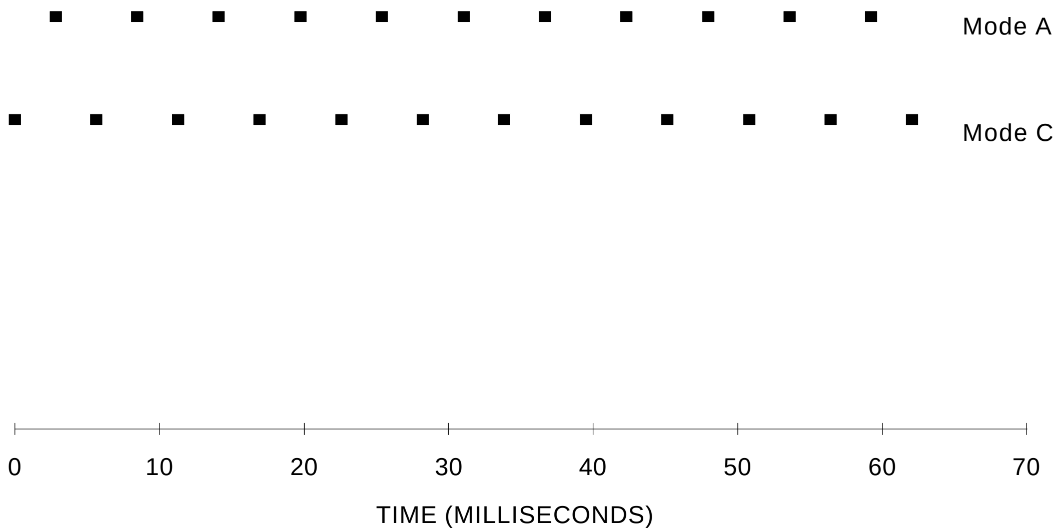

FIGURE 29. SINGLE MAIN BEAM INTERROGATIONS - JOLIET

One of the benefits of the DATAS uplink data collection capability is the ability to analyze operation of an interrogator. The coverage of a particular interrogator can be derived if the flightpath is correlated with the collected interrogations. The configuration of DATAS represents the coverage as seen by an actual transponder. Analysis of usage of the transponder for the subject interrogator by other ATCRBS interrogators or TCAS interrogations can be determined. A sample of the percentage of interrogations detected over a main beam over a number of antenna scans is shown in figure 30 for the Chicago sensor. The average number of interrogations over 35 main beams is 17.8. For the antenna dwell, PRT, and antenna scan rate of the Chicago sensor, the result agrees with the expected average.

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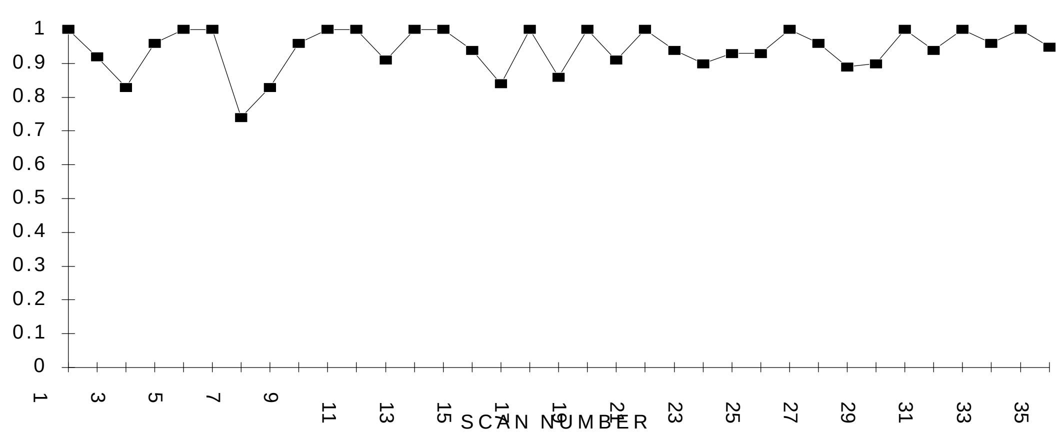

FIGURE 30. INTERROGATION DETECTION RATIO - CHICAGO

CONCLUSIONS

1. The amount of Traffic Collision Avoidance System (TCAS) usage of a Mode S transponder is mainly the result of Mode S interrogations.

2. The number of Mode S interrogations is proportional to the number of Mode S aircraft except during the final approach for landing.

3. On average, the number of TCAS interrogations measured over the 2-day flight data collection was 168 interrogations per second. The highest number of Mode S interrogations were observed during the final approach. The peak interrogation rate was nearly 600 interrogations per second.

4. Approximately one-third of the interrogations observed were addressed to aircraft already on the ground. The "on board" TCAS directed approximately one-half of its interrogations to aircraft on the ground while landing. Of the 14 aircraft on the ground which received interrogations during the peak second, 7 were equipped with TCAS. All 7 issued broadcast interrogations during this period, so it is assumed that they were operational during this time interval. Some aircraft received interrogations for more than an hour while on the ground.

5. An Air Traffic Control Radar Beacon System (ATCRBS) transponder is used by the TCAS system an average of 2 percent of the time.

6. Mode S transponder is used by TCAS approximately 3 percent of the time on the average. Peak interrogation rates resulted in nearly double the average.

7. The ATCRBS system occupies both transponder types approximately 4 percent of the time.

8. TCAS transponder usage fluctuates as a function of the number of Mode S aircraft.

9. The ATCRBS system usage of the transponder is independent of the number of aircraft.

10. The number of Mode S interrogations measured during the peak intervals exceeded the limit established by the interference limiting algorithm of TCAS.

11. The TCAS usage of the Mode S transponder reduces the reply probability with respect to an ATCRBS interrogator by an average of 3 percent. The total reduction of reply probability with respect to an ATCRBS interrogator as a result of TCAS is the combination of transponder usage and possible garbling of the replies to an ATCRBS interrogator on the downlink.

12. Downlink Mode S and ATCRBS replies are received by the ground ATCRBS interrogators as a result of TCAS interrogation activity. The downlink rates measured varied by day and time of day. The downlink Mode S reply rates are cyclic and repeat at approximately 1.5-hour intervals. One day average was less than 200 per second and another day's average was 300 per second.

13. The effect of the TCAS system on the existing ATCRBS system depends on the vulnerability of the existing system because of other factors. Generally, the run lengths (the number of replies between the lead and trail edges of a target in azimuth) and round reliabilities of aircraft replies detected by the ATCRBS ground processor provides the system immunity to individual sources of interference. However, the cumulative effects of coverage problems, interference, and reduced transponder availability acts to reduce its performance. If the targets have long run lengths, the effect is certainly negligible. If the targets are weak, however, because of lobing, turning, shielding, etc., the loss of one or two hits may cause the targets to be lost for that scan.