1030/1090 MEGAHERTZ SIGNAL ANALYSIS FRANKFURT, GERMANY

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Technical Note

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16. Abstract

The Data Link Test Analysis System (DATAS) was used in the Frankfurt, Germany to collect data in the frequency band used by Air Traffic Control Radar Beacon (ATCRBS), Mode Select (Mode S), and Traffic Alert and Collision Avoidance (TCAS). Data were collected and analyzed for both frequencies in order to assess compatibility of these users of this frequency

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

EXECUTIVE SUMMARY

The Data Link Test Analysis System (DATAS) was used in August 1995, to collect data from the environment surrounding the Frankfurt, Germany Airport. Signals of interest were those used by Mode Select (Mode S), Traffic Alert and Collision Avoidance System (TCAS), and existing Air Traffic Control Radar Beacon System (ATCRBS) (both military and civilian) systems. There were two separate phases of the data collection, "uplink" and "downlink," where "uplink" is defined as 1030 megahertz (MHz) and "downlink" is 1090 MHz. The DATAS was mounted aboard Federal Aviation Administration (FAA) aircraft "N40" for both phases, but for the downlink phase, the aircraft was parked on the ramp and the environment was monitored via the top omnidirectional antenna of the aircraft. Two round trips between Frankfurt and Munich were also flown while collecting uplink data.

The interrogations from at least 36 radars were seen while orbiting in the airspace around the Frankfurt airport at 10,000 feet. These interrogations are from a mixture of civilian and military radars.

In general, the beam widths of these radars are greater than those in the United States (30 to 40 hits is not uncommon for a terminal radar). There also appears to be a lot of side lobes from the interrogators. Both these characteristics help contribute to a very high ATCRBS fruit rate.

Transponder "availability" to respond to incoming interrogations averaged about 91 percent for the various tests conducted. A sudden drop in transponder "availability" to less than 85 percent was measured on two occasions on a test flight between Frankfurt and Munich. This was attributed to a single interrogation source, possibly a transponder test facility in the proximity of two general aviation airports.

Mode 4 interrogation activity was only a few interrogations per second except for a couple of short bursts (a few seconds) when more than 100 Mode 4 sequences occurred in a single second. The highest rate recorded was 420 Mode 4 sequences in a single second during a burst which lasted for 15 seconds. The transponder "availability" during this burst was 89.3 percent.

The average uplink Mode S rate was 114 interrogations per second for the 10,000-foot orbits of the Frankfurt airport. The number of TCAS aircraft present during this period varied from 8 to 19. The highest peak measured was 285 interrogations in a single second. The Mode S interrogation rate was a definite function of aircraft position with respect to the airport. It was also higher at 10,000 feet than at 15,000 feet. The highest rate occurred on landing.

The average unsuppressed ATCRBS Mode A rate was about 130 interrogations per second and was relatively independent of aircraft position. The rate, however, was higher at 15,000 feet than at 10,000 feet, an indication of greater coverage at higher altitudes. The corresponding ATCRBS Mode C rates were about 80 interrogations per second.

Downlink data were collected for approximately the same time period (04:00 to 19:30 coordinated universal time (UTC)) on two separate days. This data were collected via an omnidirectional antenna (top antenna of N40) with the aircraft parked on the ramp on the German Civilian side of the airport.

The highest ATCRBS rates occurred at approximately 06:00 and 08:00 (UTC) on August 24, 1995. In both cases, the rate was approximately 18,000 ATCRBS replies per second. The highest rate achieved on August 27 was about 17,000/second at approximately 18:00. In general, the rate remained fairly constant between 10,000 and 15,000 for the entire period after about 05:30. Mode S reply rates were generally between 150 and 200 per second. There were some peaks (one of 748 replies in a single second) which were attributed to an experimental Mode S sensor in the area.

Replies from a total of 958 aircraft were seen from 62 different countries. More than half the aircraft were from Germany, followed by the United Kingdom, and United States. The highest TCAS utilization was the aircraft from the United States (69 percent) while those from Germany had TCAS operational on 15 percent of the flights.

RADAR PRT and MODE 4 INTERROGATION ANALYSIS
FLIGHTS OF 8/23 and 8/25/95
FRANKFURT, GERMANY

INTRODUCTION

The Federal Aviation Administration (FAA) in conjunction with the airline industry has been conducting an operational evaluation of the newly implemented Traffic Alert and Collision Avoidance (TCAS) system. 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 data (such as Resolution Advisory (RA) as well as illegal addresses) from the ground. It was further modified to monitor both the 1030 megahertz (MHz) and 1090 MHz radio frequency (RF) signals which are used by Mode Select (Mode S) and Air Traffic Control Radar Beacon System (ATCRBS) as well as TCAS. This provided the ability to characterize the environment so that an assessment can be made of the impact on those systems on each other. This capability also allows investigation of the detailed operation of all the aforementioned systems when anomalies are encountered. The objectives of the data collection activities are to determine ATCRBS, TCAS, and Mode S signal activity and identify anomalies that may impact system performance and operation.

SYSTEM CONFIGURATION

The users guide for the TCAS monitor (DOT/FAA/CT-TN90/62) includes a more detailed description. The TCAS Monitor function is described in the report on testing at Dallas/Fort Worth (DFW) Airport (DOT/FAA/CT-TN91/56). Other system modifications which evolved during previous testing are described in the reports covering testing at Chicago O'Hare (DOT/FAA/CT-92-22) and John F. Kennedy (JFK) International Airport (DOT/FAA/CT-92-26). Extensive modifications were then performed in order to provide simultaneous operation in the 1030 and 1090 MHz modes.

There were two separate phases of the data collection, “uplink” and “downlink.” The DATAS was mounted aboard FAA aircraft “N40” for both phases, but for the downlink phase, the aircraft was parked on the ramp and the environment was monitored via the top omnidirectional antenna of the aircraft.

UPLINK CONFIGURATION

In this mode, only the activity on the 1030 MHz “uplink” is of interest. DATAS operated in a passive mode, “listening” on the 1030 MHz link while the aircraft conducted several types of maneuvers in the Frankfurt area. All interrogation data was stored on the DATAS “hard disk” for future “off-line” processing. The system characteristics as deployed during this phase of the effort are summarized below:

1. Standard transponder receiver was used as the “front end” for this data collection. The stronger signal received from either the top or bottom antenna was selected via “dual diversity” logic of the transponder. The transponder Minimum Triggering Level (MTL) was -75 decibels above 1 milliwatt (dBm).

2. This transponder was modified to eliminate its reply capability and “dead times” in order to see all interrogations even though a normal transponder would not be able to respond if already occupied by a previous interrogation.

3. Data collection was 100 percent duty cycle (100 nanoseconds (ns)) gap every 5 milliseconds (ms).

4. Each interrogation was ‘time tagged’ to within 100 ns.

5. All Mode S interrogation data were stored along with the time information.

6. Data were stored for the following interrogation types: Mode 4, Mode S, ATCRBS Mode 2, ATCRBS Mode A, ATCRBS Mode C, ATCRBS ONLY, and ATCRBS Suppressions.

DOWNLINK CONFIGURATION

In this mode, only the activity on the 1090 MHz “downlink” is of interest. DATAS operated in a passive mode, “listening” on the 1090 MHz link while the aircraft was parked on the ramp at the Frankfurt airport. The top omnidirectional antenna was used as input to the DATAS receiver, which was used at 1090 MHz. As in the “uplink” mode, all reply data were stored on the DATAS “hard disk” for future “off-line” processing. The receiver sensitivity was -76 dBm. The following data were stored:

1. All Mode S reply data were stored.

2. The count of ATCRBS and Mode S replies each interval were stored.

UPLINK DATA DISCUSSION

Mode 4 Interrogation Analysis
Frankfurt to Munich Trip

The uplink data collected at Frankfurt on August 23 to August 28 consisted of orbits around the Frankfurt airport and two round trips between Frankfurt and Munich, Germany. Orbits were flown around Frankfurt at a radius of 5 miles at 10,000 feet and 20 miles at 15,000 feet on three different occasions. Two of these were during the early morning traffic peak and the other was during the evening traffic peak period. The two round trips to Munich were approximately at midday.

The Mode 4 analysis must begin with a description of the equipment setup used during data collection and a brief description of the Mode 4 interrogations. Much valuable information was gained from an experiment conducted on the flight home over the Atlantic Ocean where Mode 4 interrogations were seen and almost no other aircraft were in the area. It was noticed that some Mode 4 interrogations were detected when there should have been no activity. It was suspected that these interrogations were being detected from the “onboard” TCAS interrogations. Experiments were conducted with the TCAS operating and not operating (for approximately 30 seconds) when we were isolated over the ocean. Analysis of this data enabled the development of techniques to eliminate Mode 4 (and other interrogation types) resulting from our own interrogations.

A Mode 4 interrogation consists of a group of 4 pulses spaced at 0, 2, 4, and 6 microseconds (μs) followed by up to 32 pulses which define the range requested by the transponder on its reply. The DATAS implementation of a Mode 4 decoder was not very sophisticated. DATAS merely checked for the presence of the groups of four pulses. It did not check for the 32 data pulses. Analysis showed that this technique was susceptible to false Mode 4's from Mode S interrogations. These interrogations are depicted in figure 1 below:

As indicated, the first two pulses are identical for both interrogation types, as well as ATCRBS suppressions and TCAS Whisper/Shouts. The leading edge of a Mode S data block is just at the edge of the tolerance to qualify for the third pulse of a Mode 4. The Mode S interrogation

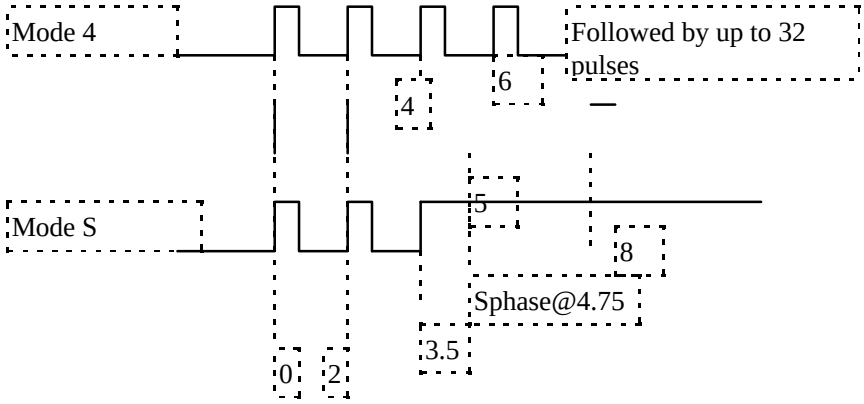

FIGURE 1. FALSE MODE 4'S FROM MODE S INTERROGATIONS

has phase transitions possible every 0.25 μs after sync phase. Many times, these transitions are accompanied by an amplitude change, so it is feasible that a Mode S could create a Mode 4 interrogation. It is also very feasible that the 32 data pulses of a Mode 4 interrogation could create several more Mode 4's from a single interrogation sequence. The analysis showed that a significant number of interrogations were declared during the Mode S data block. After this analysis, all interrogations declared within 30 μs of a Mode S interrogation were ignored in the later analysis such as radar pulse recurrence times (PRTs) or Mode 4.

The Mode 4 activity over the ocean was also used to further develop rules for processing the Mode 4 interrogation data. The interrogations of several files were examined in detail. The time between the first and last Mode 4 interrogations in any group separated by more than 100 μs was calculated as well as the number of interrogations detected within that time interval. Figure 2 shows the results of that exercise. Since this data was taken over the middle of the ocean and the Mode 4 counts rose almost instantaneously, this was taken as the actual Mode 4 profile. The data was easy to spot as there were bursts of Mode 4 decodes spaced closely together. The time difference between the first and last Mode 4 interrogation in a group is shown in figure 2. As indicated, most of the groups contained Mode 4's for 28 to 48 μs after the first Mode 4 was detected; i.e., 5.5 percent had a burst duration of 29 μs, .3 percent had a burst duration of 30 μs, 4 percent had a duration of 31 μs, etc.

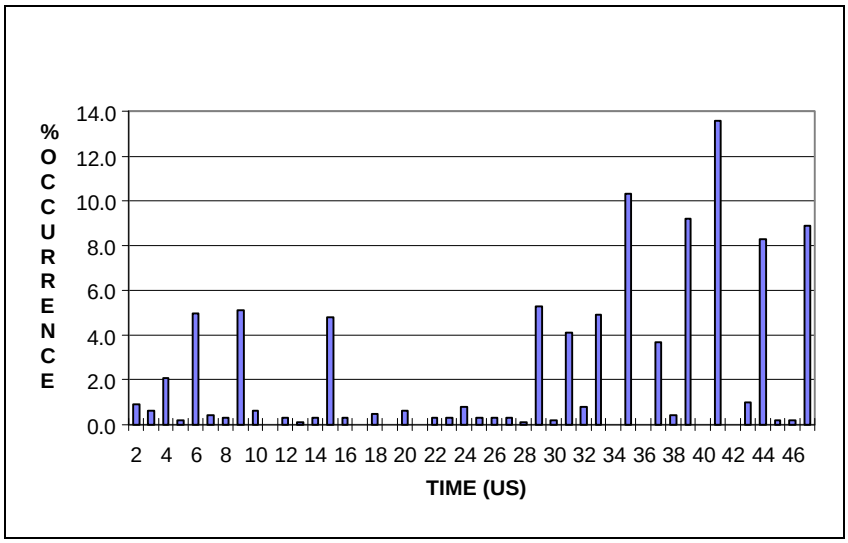

FIGURE 2. TIME DIFFERENCE - FIRST TO LAST MODE 4 INTERROGATIONS

When looking at the Mode 4 interrogation, this pattern starts to make sense. The Mode 4 interrogation details are shown in figure 3.

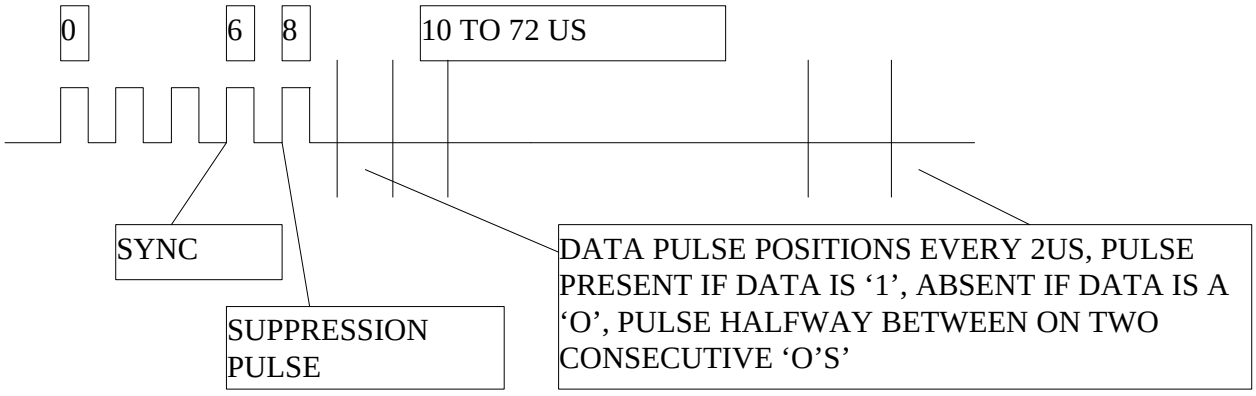

FIGURE 3. MODE 4 INTERROGATION DETAILS

Mode 4 interrogation counts were kept in two ways for the remainder of the Mode 4 processing. The first was the actual number of Mode 4 interrogations declared and the second was the number of Mode 4 sequences per second. The sequences are more meaningful as they are counts of single Mode 4 interrogations and not the pulse combinations of the pulses comprising the whole interrogation which create the extra Mode 4 decodes. These counts do not really matter as the important thing is what effect they have on the other transponders in the environment. These transponders will react to the suppression pair or mode pairs of the Mode 4 interrogations and act accordingly. This effect will be shown in transponder "availability" data to be presented later.

A sample of the Mode 4 activity over the ocean is shown in figure 4. The interrogations occurred in groups spaced at approximately 35 seconds. The inset shows an expanded view of the interrogations at 11:13:02 and 11:13:03.

For the remainder of this discussion, the Mode 4 Interrogations counts (actually Mode 4 preambles) will not be used. The Mode 4 activity will be characterized by using the number of Mode 4 sequences which occur, because they are probably a more accurate count of Mode 4 interrogations.

All the activity at 11:13:02 is in 2 seconds. The Mode 4 activity is insignificant (1 or 2 sequences per second or less) between the bursts of Mode 4 activity. At 11:13:02, when the rate goes to about 1,100 interrogations (250 sequences), there are really 300 consecutive sequences, but our arbitrary boundaries for seconds caused the data to be straddled across 3 seconds (253, 42, and 5 in the separate bins). The same thing occurred at the other times, split almost equally between the 2 seconds involved (e.g., 170 in 1 second and 130 in the other). Mode 4 interrogations separated by more than 72 μs (the maximum length of a single interrogation) were counted as separate sequences.

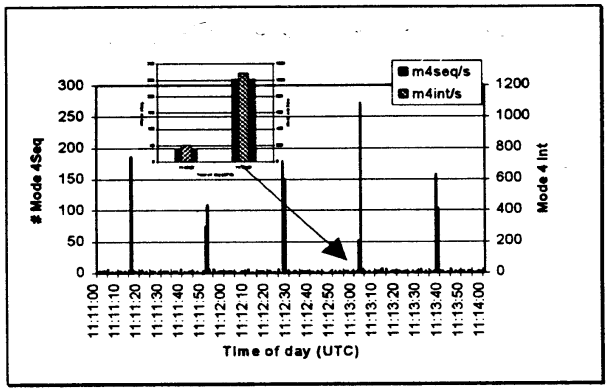

FIGURE 4. MODE 4 SEQUENCES OVER THE OCEAN

Mode 4 interrogations can also be caused by the combination of Whisper Shout and other interrogations. Figure 5 shows the ways of creating a false Mode 4 by combination with a suppression: Mode 4's caused by these combinations were also eliminated.

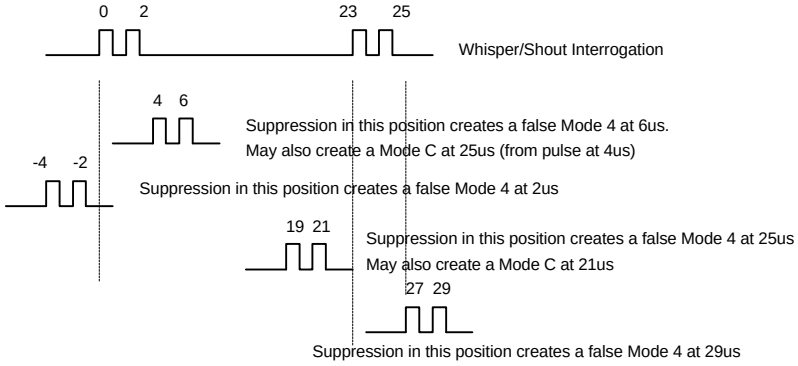

FIGURE 5. CREATION OF FALSE MODE 4 BY COMBINING WITH SUPPRESSION

Round Trip to Munich

The DATAS aircraft flew two round trips between Frankfurt and Munich. The first orbit was flown at an altitude of 10,000 feet and the second at 17,000 feet. Figure 6 shows the Global Positioning System (GPS) data for the first round trip. The time of day is superimposed on the position data at approximately 5-minute intervals.

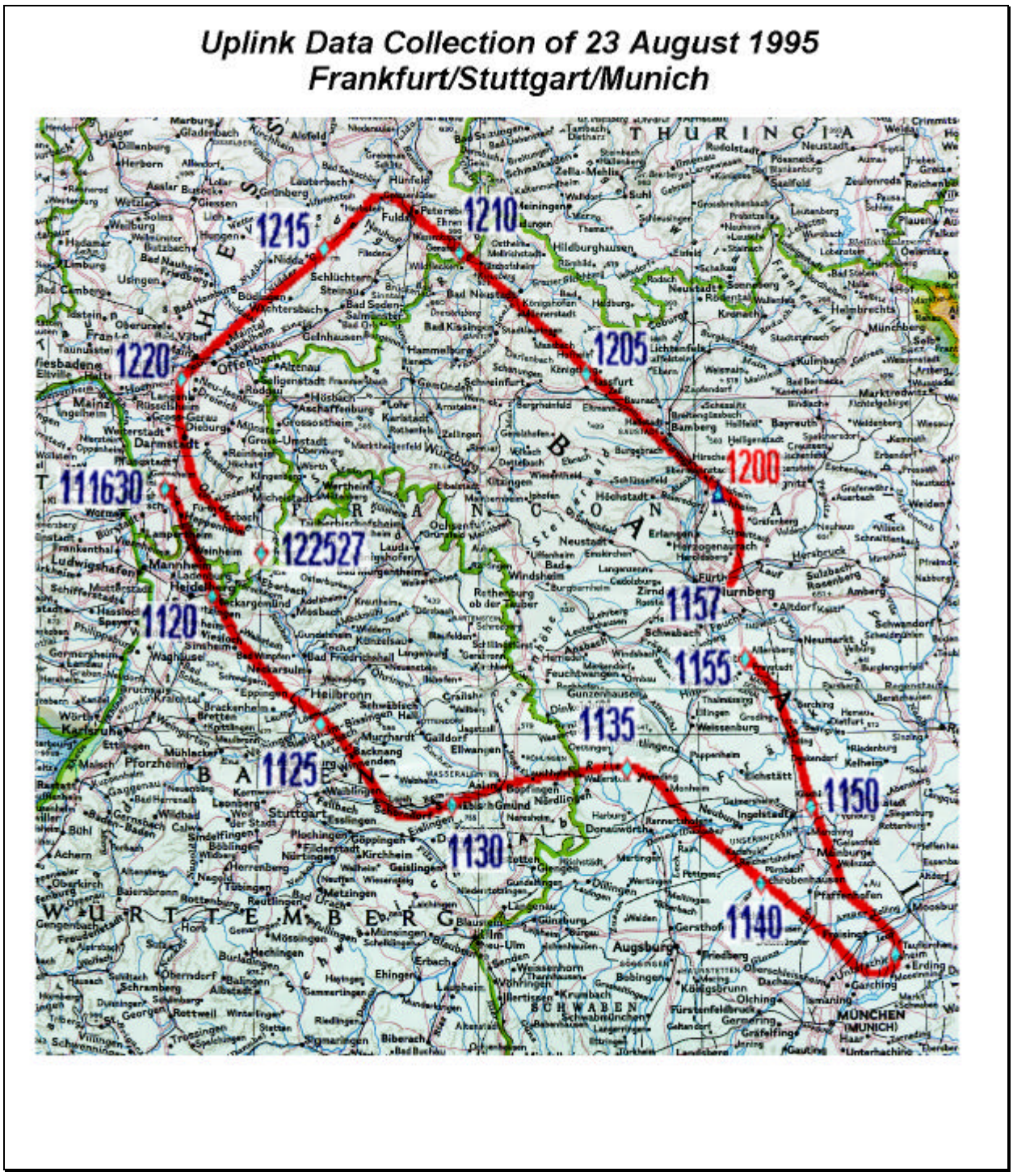

FIGURE 6. PATH OF FIRST ROUND TRIP TO MUNICH

Figure 7 shows the GPS data for the second round trip. The aircraft began climbing toward 17,000 feet at approximately 12:16. The aircraft was level at 17,000 feet at 12:19. The time of day is again superimposed on the position data at approximately 5-minute intervals.

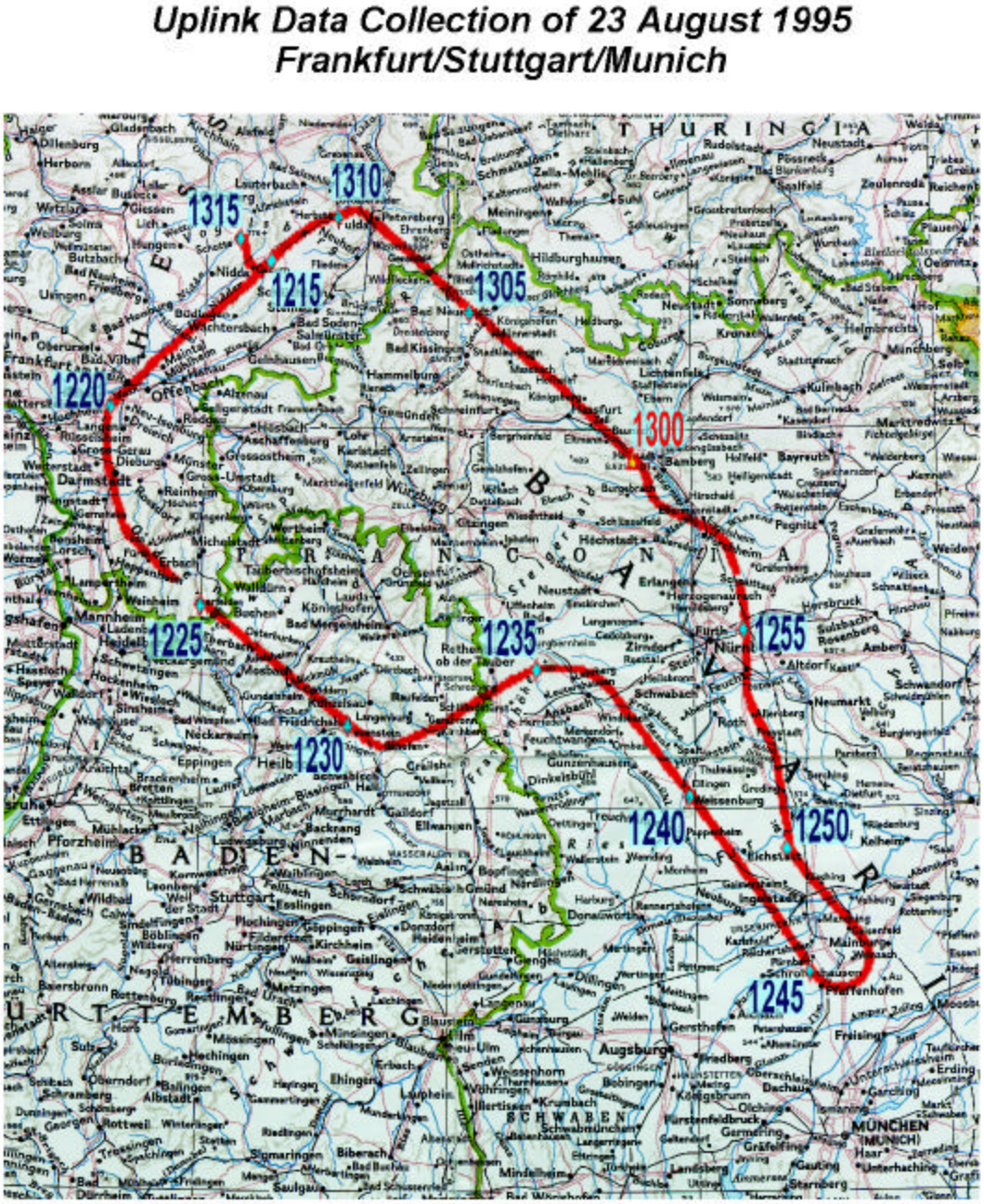

FIGURE 7. PATH OF SECOND ROUND TRIP TO MUNICH

The Mode 4 data from the first lap is shown in figure 8. The maximum number of Mode 4 interrogations was at 11:19:15 when 499 interrogations were detected which comprised 22 Mode 4 sequences. There were several seconds in this area with high counts. This is in the vicinity of Mannheim. The second highest rate occurred at about 11:58 when the aircraft was near Heroldsberg (see figure 6). Except for the peaks, however, the normal Mode 4 sequence count appears to be two or three per second.

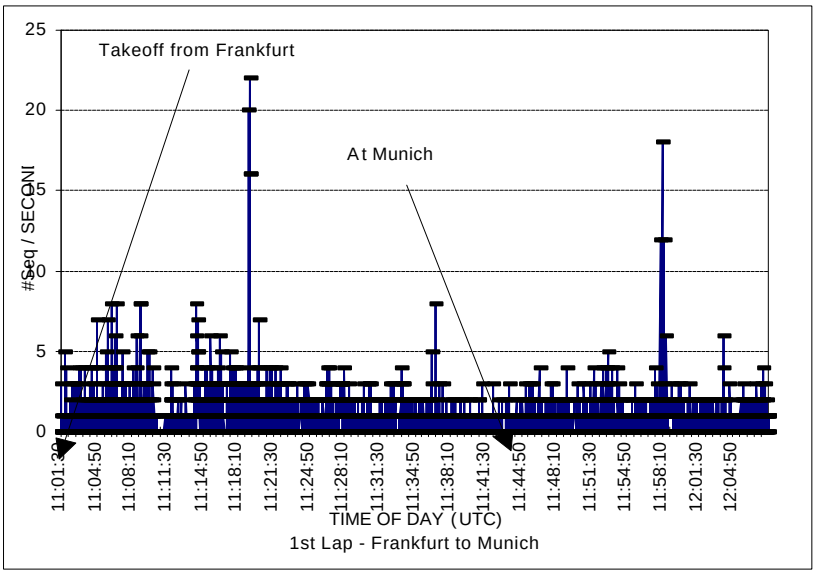

FIGURE 8. MODE 4 INTERROGATIONS

The Mode 4 data from the second leg of the flight between Frankfurt and Munich is shown in figure 9. Note that the Mode 4 rates never exceed 20 Mode 4 sequences/second. The peak was seen at about 12:52 when we were in the vicinity of Freystadt (see figure 7).

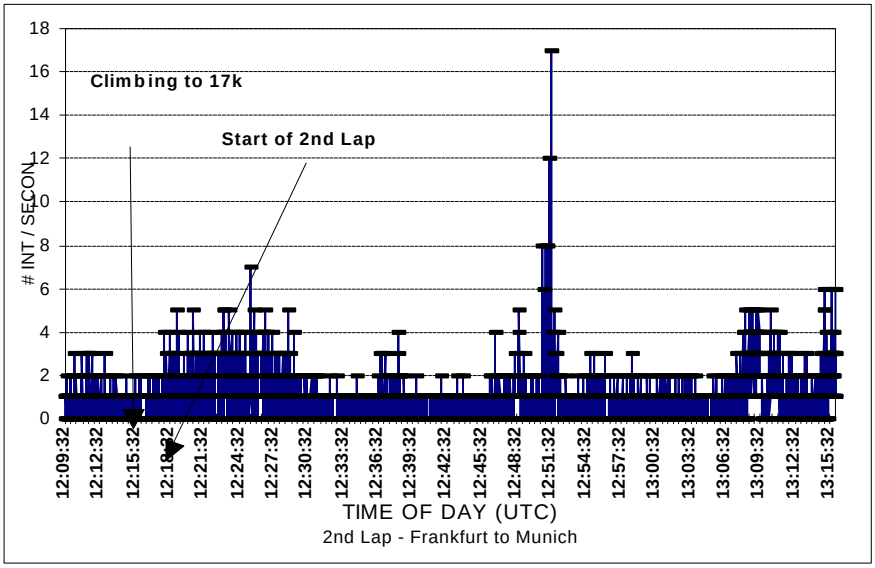

FIGURE 9. MODE 4 INTERROGATIONS

Counts of this magnitude certainly appear to be no problem, but the main concern is transponder "availability," so that will be investigated next. The effect of the peak of 499 Mode 4 interrogations will depend on the timing relationship between them as a normal transponder will react to the suppression pair which comprises the first part of a Mode 4. For example, if a second suppression (Mode 4) occurs while the transponder is suppressed, it merely extends the suppression time for another suppression period (typically 35 μs). Thus, the typical Mode 4 sequence which was comprised of about 20 Mode 4 interrogations would result in a total suppression time of only about 100 μs. The transponder "availability" software reacts just as a normal transponder would when seeing the sequence of interrogations which occurred. The interrogation data and "availability" data will be presented on the next few plots.

The other interrogation rates for the first lap are shown in figures 10 through 14:

Mode S interrogation rate: Figure 10 shows the Mode S interrogation rates have the common characteristic of being the highest at takeoff when they reached slightly more than 100 interrogations per second. The second peak, 142 interrogations per second, occurred at 11:17:55 and is probably when the aircraft again comes into potential threat area of other aircraft when they take off. This can be verified by the GPS data. The rate averaged only 32 interrogations per second for the flight.

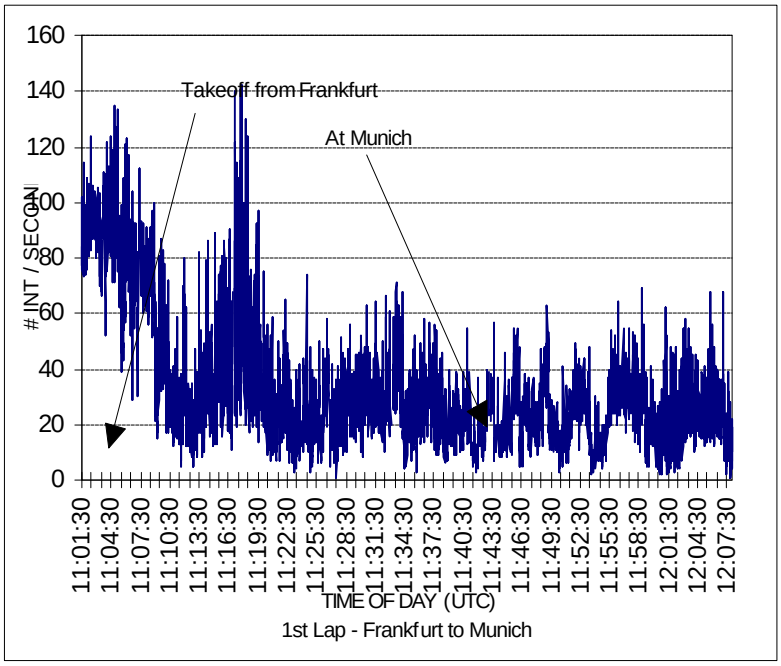

FIGURE 10. MODE S INTERROGATIONS

Unsuppressed ATCRBS Mode A and Mode C Interrogation Rate: Figures 11 and 12 show the unsuppressed Mode A and Mode C characteristics. The Mode C rate is 50 to 60 per second except for the peak at 11:19:30. The Mode A rate is slightly over 100 except for the same period. These peaks will be addressed below. Note the difference in the rates before 11:16. The aircraft was still on the ground at 11:01 and had reached 10,000 feet at 11:17.

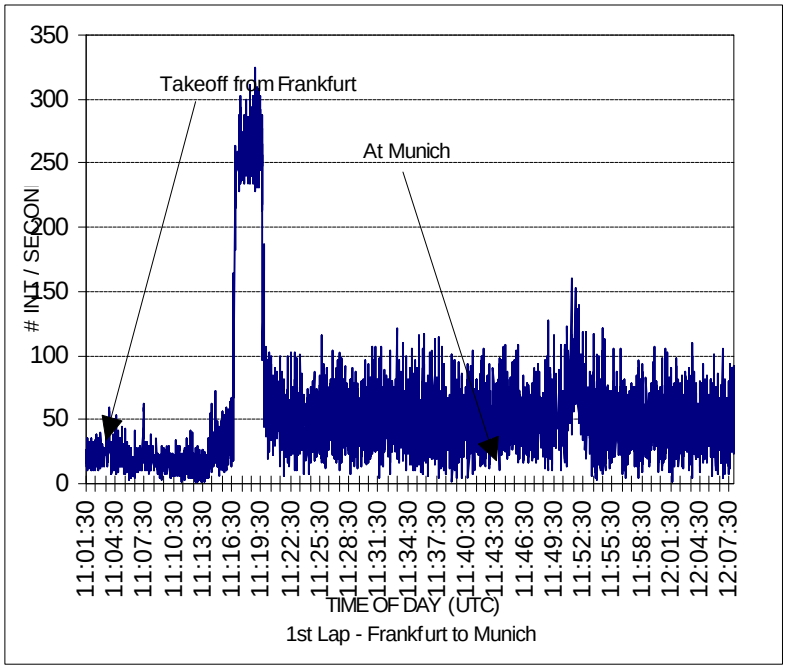

FIGURE 11. MODE C INTERROGATIONS

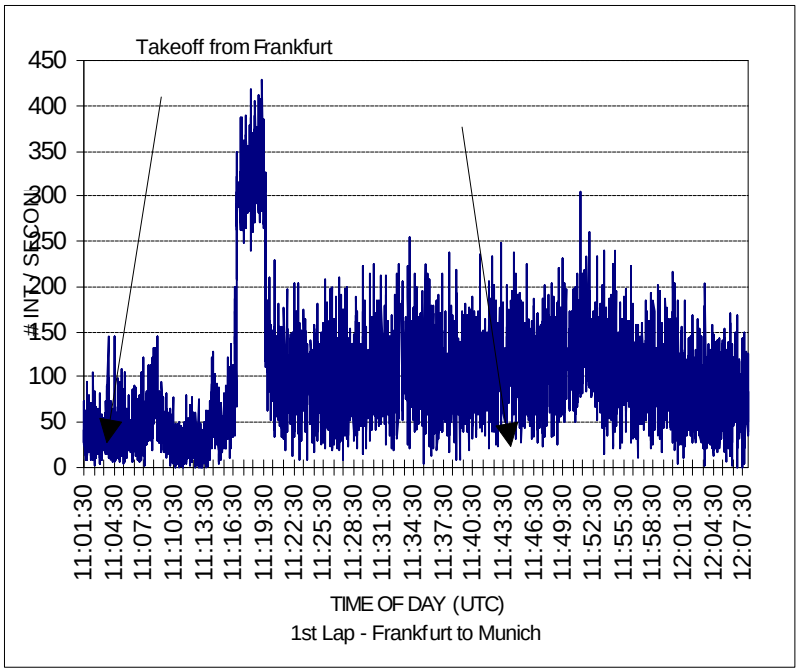

FIGURE 12. MODE A INTERROGATIONS

Figure 13 shows the Mode 2 interrogations for the first lap. They show a similar characteristic to the Mode A and C interrogations, but the pattern seems to have many more spikes. At least part of these are probably caused by our inability to eliminate false Mode 2's caused by other types such as Mode S and Mode 4.

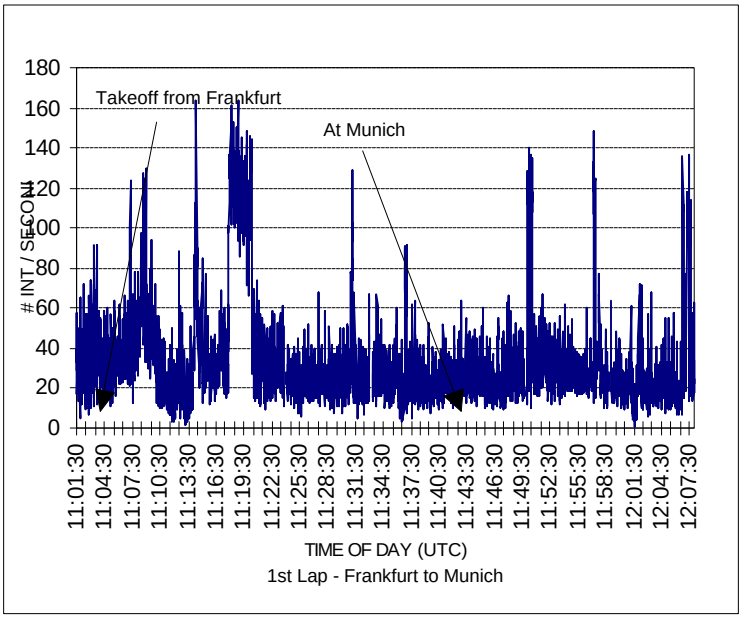

FIGURE 13. MODE 2 INTERROGATIONS

Transponder Availability: Figure 14 shows that the transponder availability for the period is approximately 95 percent except for the dip to about 85 percent at 11:19:16.

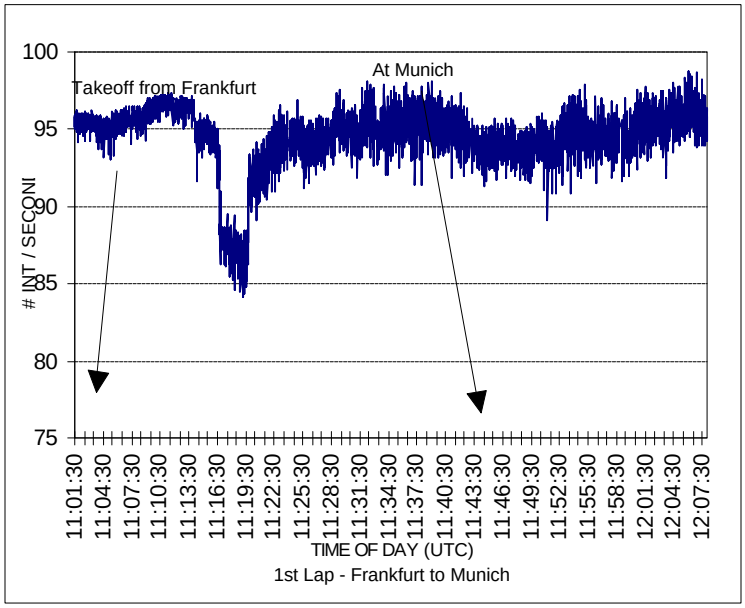

FIGURE 14. TRANSPONDER AVAILABILITY

Table 1 shows the interrogation rate summary of lap 1 on August 23: It shows average rates of 33, 53, and 96 interrogations/second for Modes 2, C, and A, respectively. These are all slightly skewed because of the one period of time of approximately 6 minutes when the rates were several times the normal rate. The source of these interrogations will be discussed later. The table also gives the time which each peak occurred for all interrogation types. The table shows that the lowest transponder availability occurred at 11:19:15. This time period is when

the Mode 4 peak as well as the Mode A and C interrogations are near their peaks. The calculations show that the availability reduction is due primarily to the Mode A and C interrogations. The source of these interrogations will be investigated below.

TABLE 1. INTERROGATION SUMMARY, LAP 1

Parameter	m4int/s	un ms/sec	un m2/sec	un mc/sec	un ma/sec	un sp/sec	% avail
Average	0.8	33	33	53	96	763	94.6
Peak	22	142	164	325	428	1747	84.1
Time_Pk	11:19:14	11:17:54	11:14:24	11:18:55	11:19:25	11:19:14	11:19:15

The interrogation rates for the second lap are shown on figures 15 through 19.

The performance on this lap is very similar to that of the other lap. The transponder availability is 90 to 95 percent (average is 92.82 percent) except for the time at about 12:25 where it dips to less than 85 percent. Note that the peak Mode A and Mode C rates also occurred in this area (495 unsuppressed Mode A's at 12:25:11 and 361 Mode C's at 12:25:06). This is far removed from the Mode 4 peaks at 12:51:29.

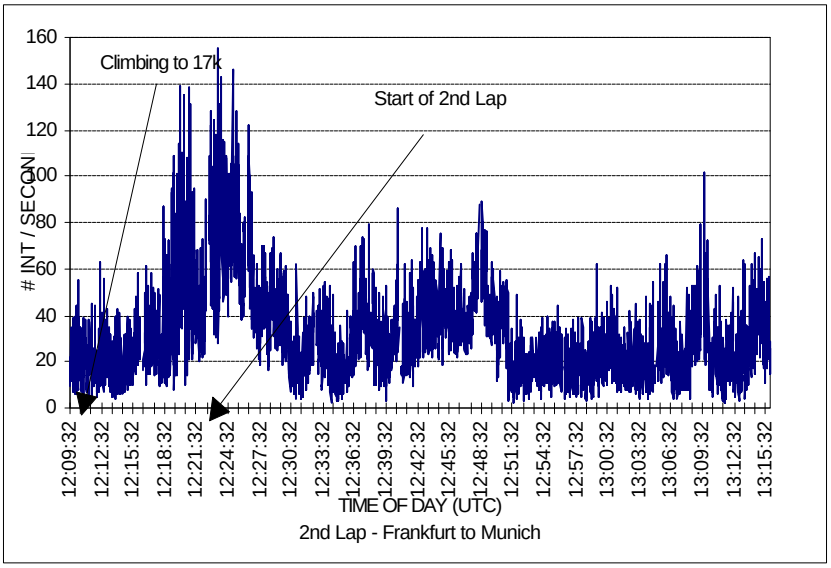

FIGURE 15. MODE S INTERROGATIONS

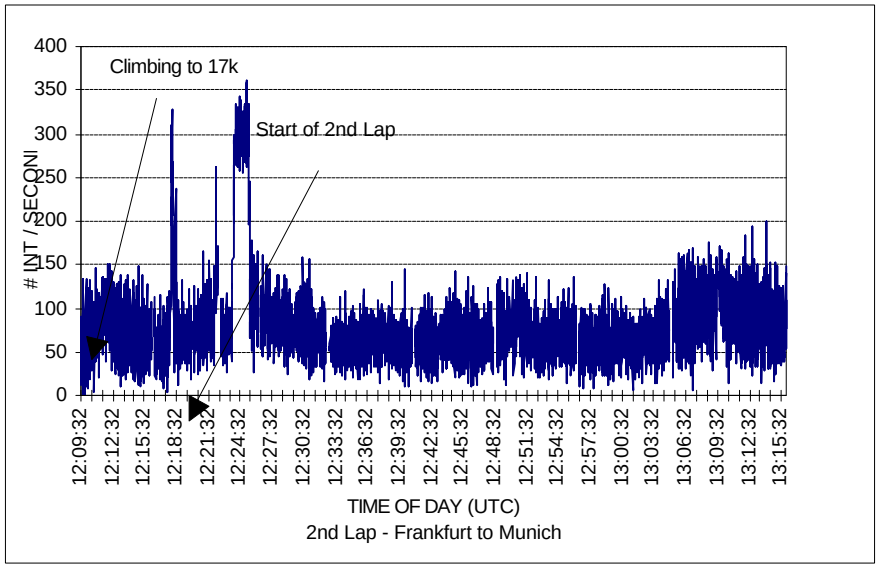

FIGURE 16. MODE C INTERROGATIONS

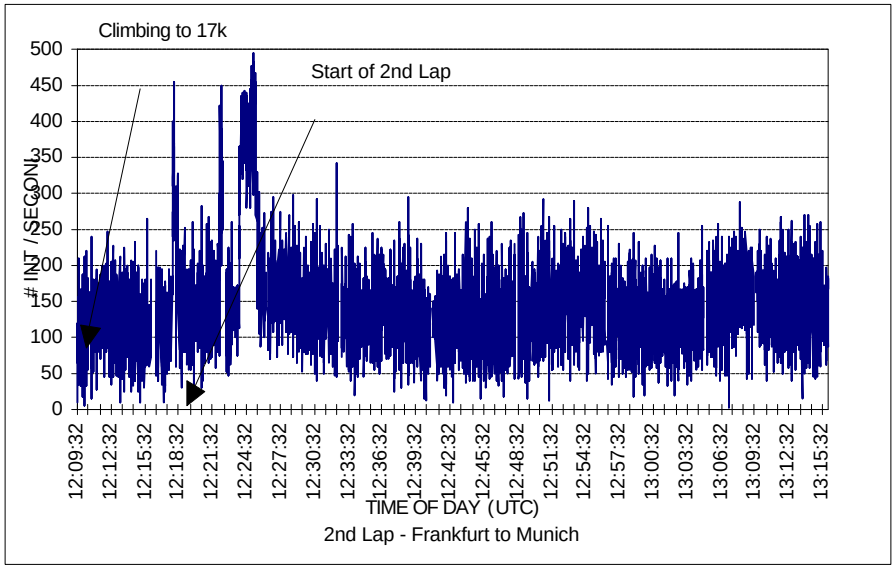

FIGURE 17. MODE A INTERROGATIONS

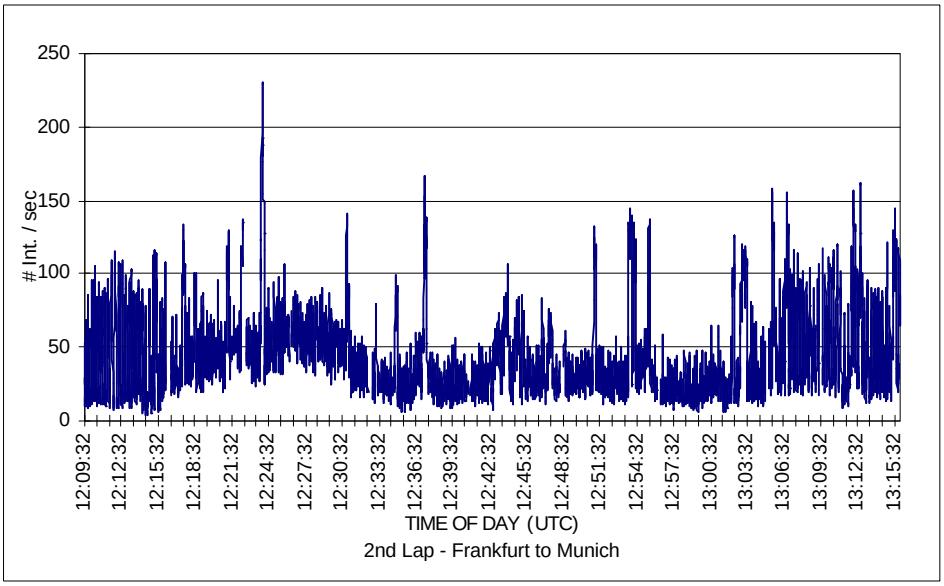

FIGURE 18. MODE 2 INTERROGATIONS

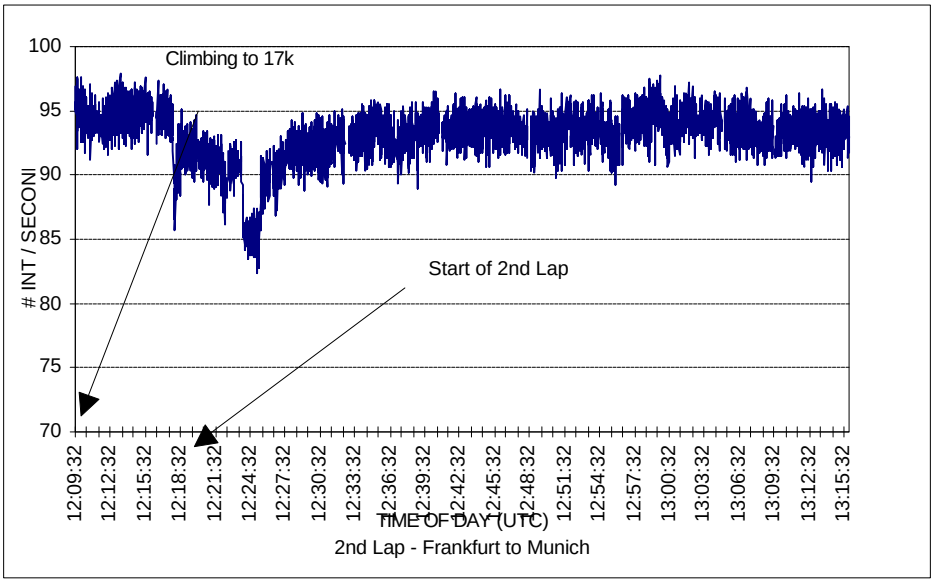

FIGURE 19. TRANSPONDER AVAILABILITY

Table 2 shows the overall statistics for the second lap. The interrogation rates are approximately 1.5 times what they were at 10,000 feet. Mode 4 interrogation rate was insignificant, at a peak of 17 in a single second.

The data from the two peaks will now be discussed.

TABLE 2. INTERROGATION SUMMARY, LAP 2

Parameter	m4int/s	μ ms/sec	μ m2/sec	μ mc/sec	μ ma/sec	μ sp/sec	%avail
Average	0.8	30	43	80	142	894	93.1
Peak	17	155	229	361	495	1898	82.4
Time_Pk	12:51:29	12:23:32	12:18:16	12:25:06	12:25:11	12:27:02	12:25:11

Data from the second lap starting at 12:25:00 is shown in figure 20. This radar was designated as Radar #36 in the PRT analysis. All the interrogations shown are at a fixed PRT of 21418 (2141.8 μs) and occur almost constantly. The X axis of this plot is the start time of the 12-second period which was processed. The interrogations were seen constantly for the entire period (with a few misses). The interlace pattern was always ACACAC.

Other parts of the same file were processed to search for this same radar. It was present only during the times indicated. It was present at a fixed PRF for approximately 6 minutes in both cases. The data from the Frankfurt orbits were also searched for this radar and it was not seen.

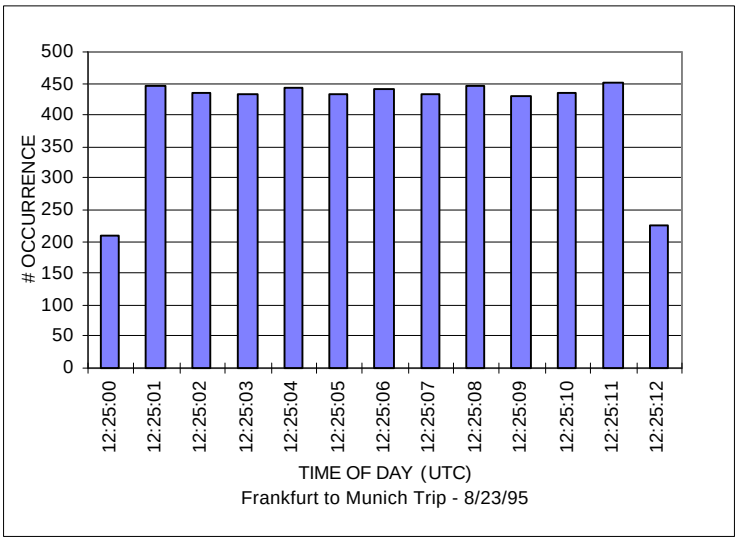

FIGURE 20. NUMBER OF INTERROGATIONS FROM RADAR #36

There was another characteristic of this radar significantly different than normal (see figure 21). There were a total of 4,030 Mode 2 interrogations during this 12-second period. A total of 2,524 (63 percent) were preceded by an interrogation from radar #36. Out of these Mode 2 interrogations, the plot shows that 72 percent were declared from 7.4 to 7.7 μs after the preceding interrogation (either a Mode A or Mode C). Another 12 percent were at 10.8 to 10.9 μs. This suggests some sort of "decoy" activity or combination of interrogations. The first interrogation (the Mode A or Mode C) is sent to keep other transponders occupied while those of interest respond to the succeeding interrogation (or the remainder of that interrogation sequence). There is little doubt, however, that the Mode A's Mode 2's and Mode C's are all associated with radar #36.

The important part of this interrogation sequence is what it does to "noncooperating" transponders. As evidenced by the preceding transponder "availability" plot this single radar occupied the transponder more than 5 percent of the time during a 2-minute period. This is approximately equal to the other 35 radars in the area.

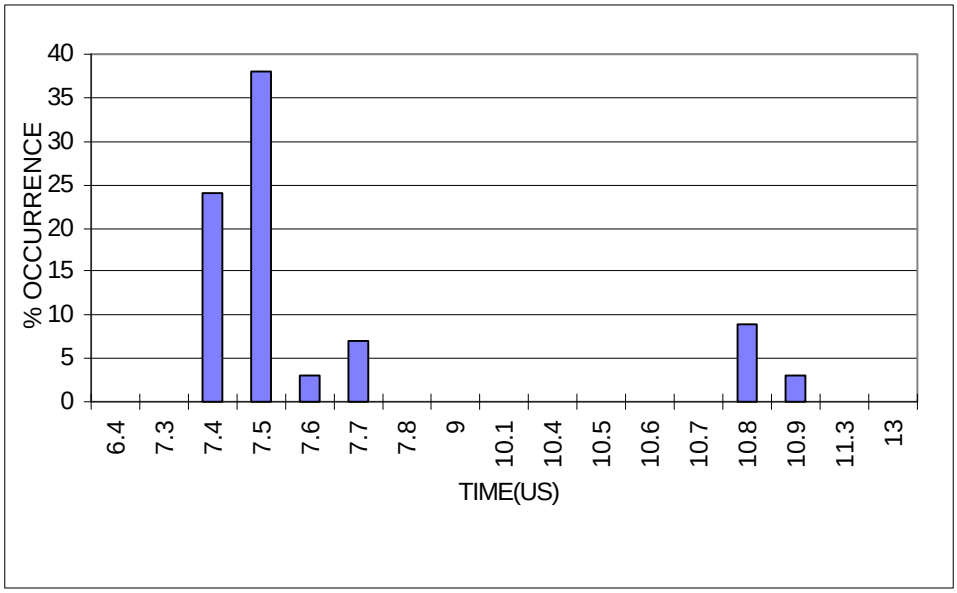

FIGURE 21. TIME DIFFERENCE OF MODE 2 AND PRECEDING INTERROGATIONS FROM RADAR #36

Figures 22 and 23 show the area which produced the high Mode A and C interrogation rates superimposed on the low altitude very high frequency (VHF) omnidirectional range (VOR) chart for the area. The high rates were both the same PRT (2141.8 μs). A few minutes before and after this high rate, the interrogator was not seen in the data. As indicated on figure 22 and 23, the high interrogation rates happened at exactly the same position on the two orbits. As indicated on this chart, there are two general aviation airports in this vicinity. This information presents another completely different possibility. This is almost the classic situation which has caused "phantom" targets for TCAS in the United States. That scenario is given below:

1. A maintenance group interrogates transponders with some sort of test set, usually at a general aviation airport.

2. The altimeter input is varied to assure compliance with altitude reporting.

3. These aircraft also respond to TCAS aircraft in the area with this same altitude.

4. The aircraft are not "seen" on other radars as they are usually below "line of sight" coverage of nearby radars as they are on the ground a few miles away.

5. If the altitude of the transponder under test is near that of TCAS aircraft, a "phantom" alert may be generated and the pilots and ground personnel see nothing.

Uplink Data Collection Frankfurt/Stuttgart/Munich
N-40 23 August 1995

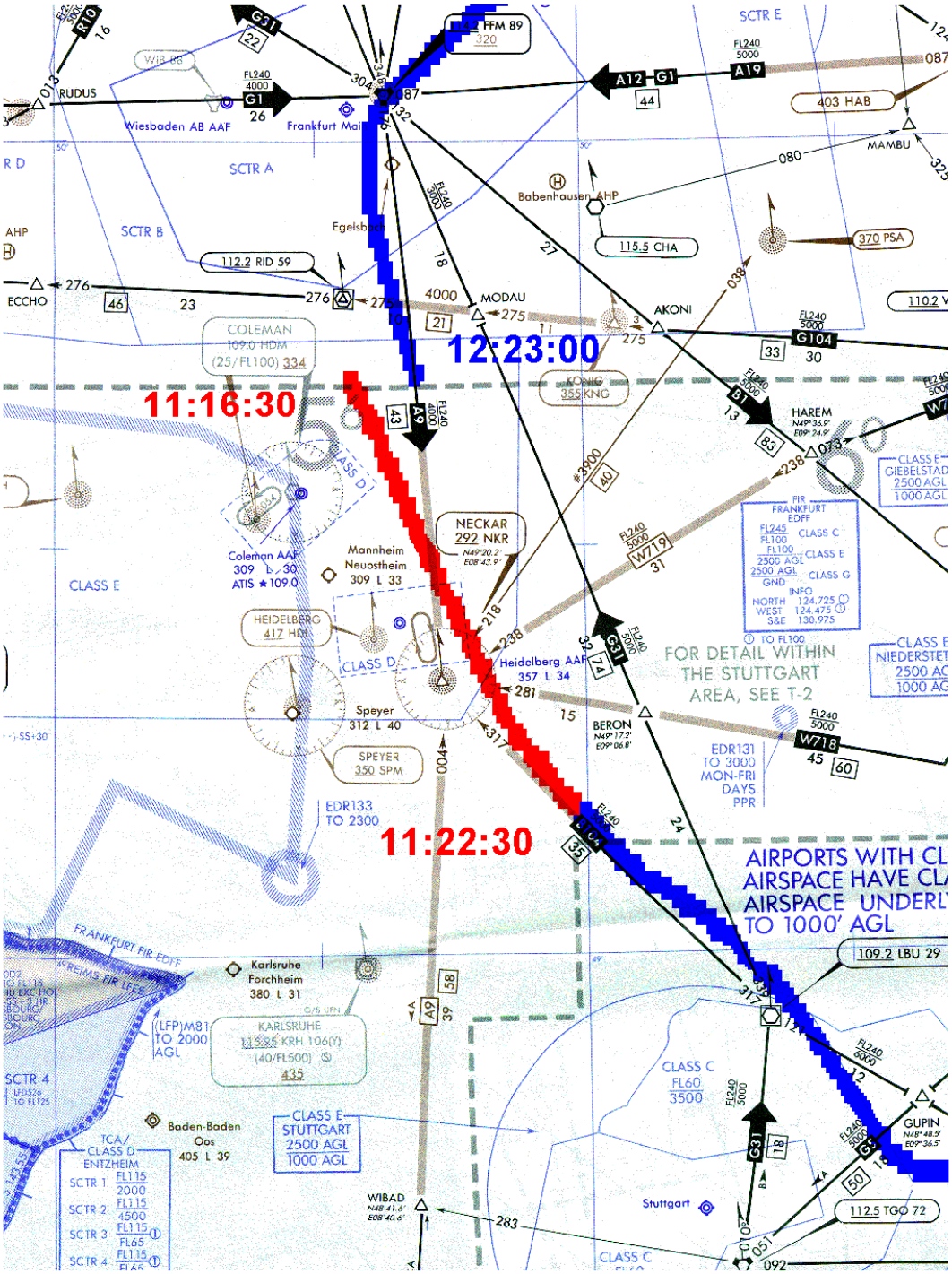

FIGURE 22 - OVERLAY OF LAP #1 HIGH MODE A/C RATES ON VOR CHART

FIGURE 23 - OVERLAY OF LAP #2 HIGH MODE A/C RATES ON VOR CHART

If this sort of testing is conducted in Germany, this is a good possibility for the source of these high interrogation rates. The effect on the environment is obvious from the transponder "availability" plots of figures 14 and 19. This source was tying up transponders more than 5 percent of the available time at two intervals more than an hour apart. As stated previously, this is about the same amount as the other 35 radars combined.

FRANKFURT ORBITS - MODE 4 ANALYSIS.

The orbits were flown at a 5-mile range at 10,000 feet and 20-mile range at 15,000 feet. The results of these two types of orbits will be discussed separately. Data from only one set of the flights will be presented. The data were similar for all three samples which were collected. Data were collected in the morning and evening of August 25 and on the morning of August 28. Data will be presented only from the flight of August 25 as it is very similar to that from August 28. The Mode 4 analysis and other interrogation analysis will all come from the same set of data.

Figure 24 shows the transponder availability and Mode 4 sequence data from all the 5-mile orbits at 10,000 feet. The availability is approximately 91 percent for the entire group of orbits with the lowest availability being 85.6 percent at 5:20:40.

The Mode 4 rates averaged 6.5/second for the period. The peak Mode 4 rate was 24 per second, at 6:07:00 near the end of the small orbits.

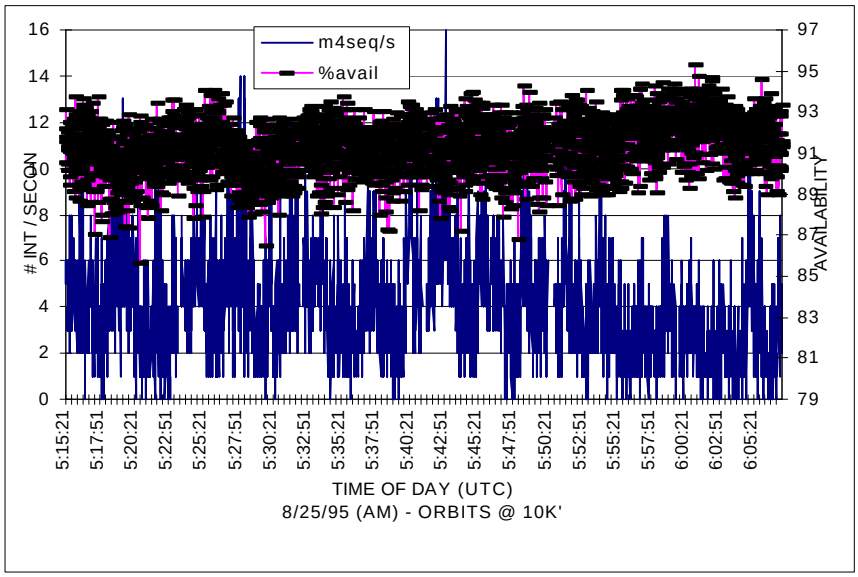

FIGURE 24. MODE 4 INTERROGATION SEQUENCES

The "availability" and Mode 4 sequence data for the first 20-mile orbit at 15,000 feet (see figure 25) shows the availability to be approximately 91 percent for the entire orbit. There were two significant bursts of Mode 4 interrogations during the orbit. The first group occurred at approximately 6:09 and lasted for about 30 seconds. There were several seconds with the rate of more than 100 sequences in that second. The second group, at 6:20 was significantly higher but did not last as long. This burst had a peak of 420 Mode 4 sequences in its highest second. The total burst lasted for about 15 seconds. The important fact, however, is that the transponder "availability" for this second (6:20:22 where the 420 Mode 4 sequences occurred)

was still 89.3 percent. Thus, the Mode 4 interrogations themselves are not enough to significantly affect the "availability."

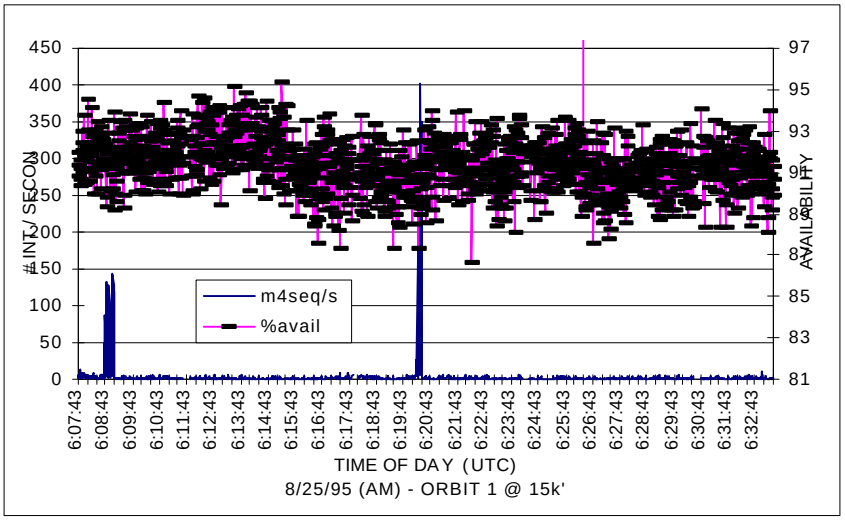

FIGURE 25. MODE 4 INTERROGATION SEQUENCES

Figure 26 shows the Mode 4 interrogations from the second 20-mile orbit at 15,000 feet on August 25. There are two significant bursts of Mode 4 activity. The first lasts for about 4 minutes and the second for a little more than 1 minute. The rates in both cases average less than 30 per second, with a maximum of 66 interrogations in a single second at approximately 7:01. The second orbit must have been slightly different than the first, because it lasted approximately 10 minutes longer. The GPS position data is available if this is considered important. The rates involved, however, appear to have no impact on availability as evidenced by the data of figures 25 and 26 when the bursts of Mode 4 activity occur.

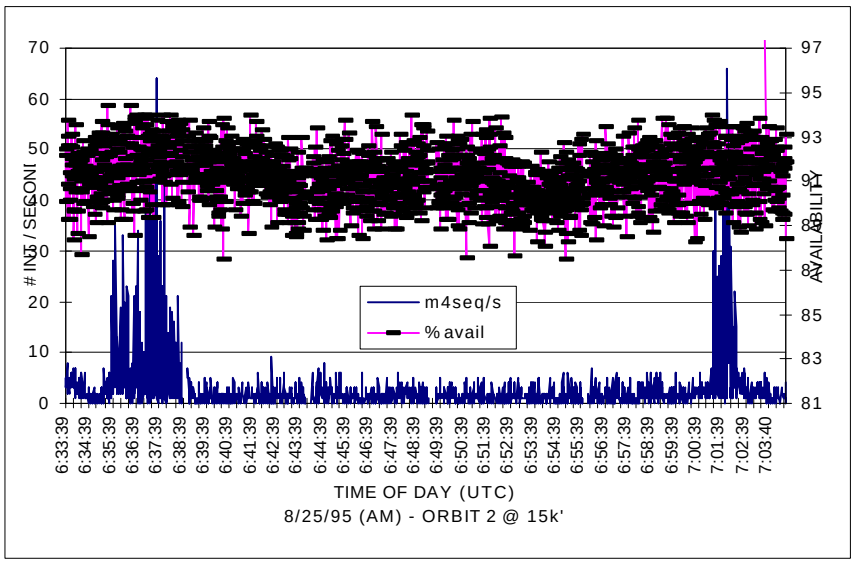

FIGURE 26. MODE 4 INTERROGATION SEQUENCES

FRANKFURT ORBITS - INTERROGATION ANALYSIS.

Figure 27 shows the normal characteristic for Mode S interrogation rates. The rate varies significantly dependent on position with respect to the surrounding traffic. When comparing this pattern to that of the "availability" of figure 25, it can be deduced that the effect of the decline in the Mode S rates from about 120 interrogations per second to 30 interrogations at 16:15:30 correlates with an increase in approximately 1 percent in transponder "availability."

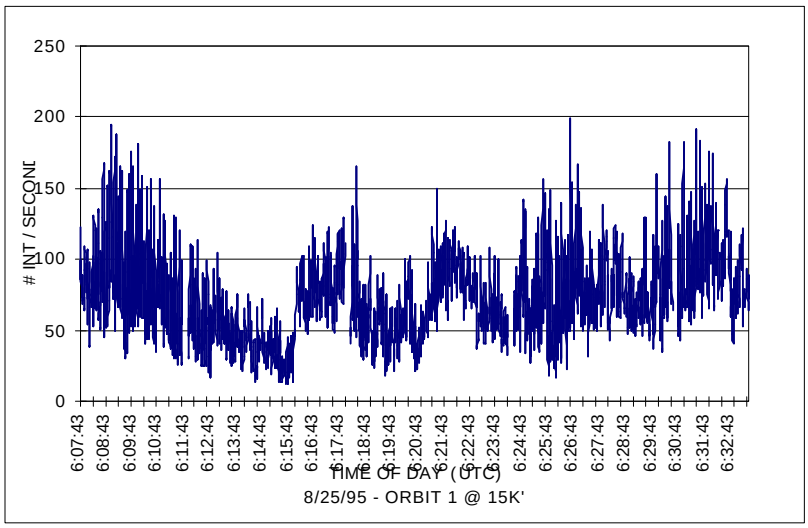

FIGURE 27. MODE S INTERROGATIONS

Figure 28 shows the Mode C interrogation rate for the time of the first 15,000-foot orbit. The average Mode C rate was relatively constant and averaged 87 interrogations per second. The peak number of interrogations seen in any single second was 195 at 6:18:46.

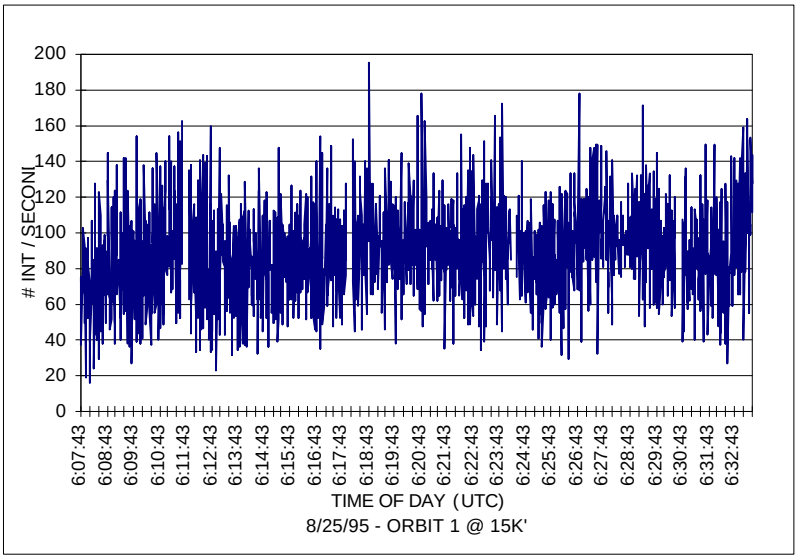

FIGURE 28. UNSUPPRESSED MODE C INTERROGATIONS

Figure 29 shows the Mode A interrogation rate for the first orbit. It is also relatively constant at 158 interrogations per second.

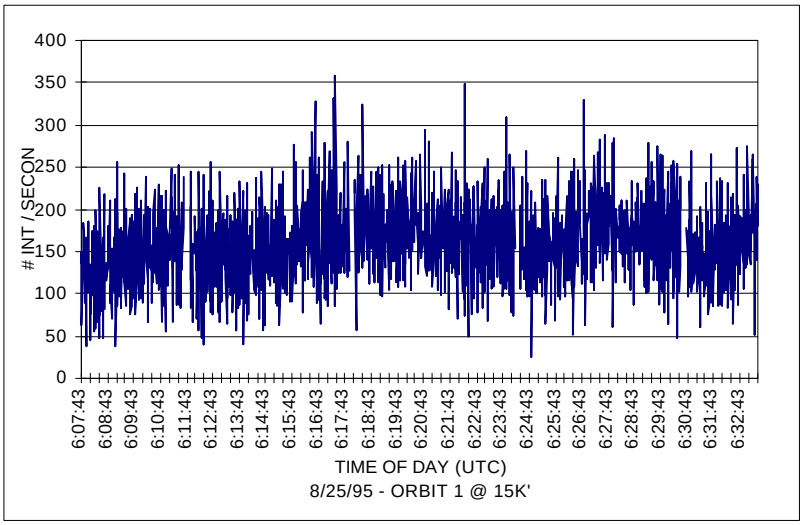

FIGURE 29. UNSUPPRESSED MODE A INTERROGATIONS

The gaps in the data in all figures are inter file gaps. New data files were started in order to keep the files to a manageable size for processing at a later date.

The Mode 2 interrogation rate for orbit 1 at 15,000 feet is shown in figure 30. It is relatively constant at about 50 per second except for the few short bursts at the beginning of the orbit.

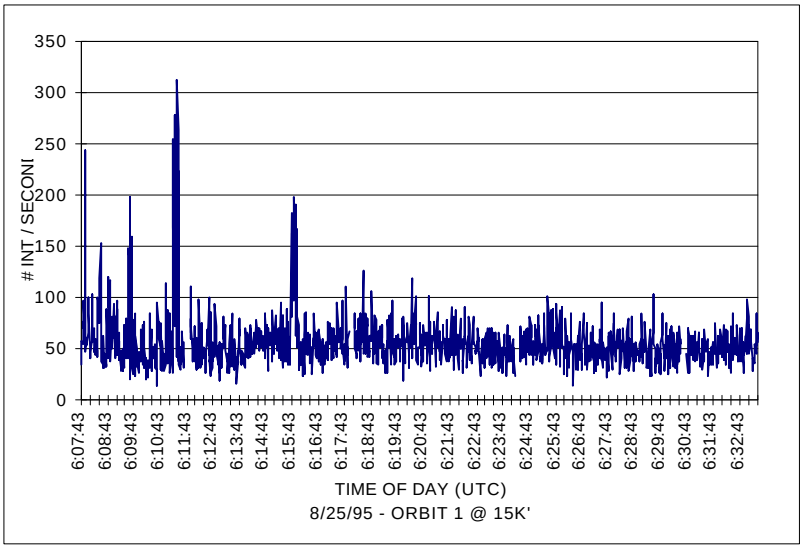

FIGURE 30. UNSUPPRESSED MODE 2 INTERROGATIONS

FIVE MILE ORBITS.

Figure 31 shows the Mode S data for six of the 5-mile orbits (orbits 2 through 7). Data from part of the first orbit was lost because of a power failure. There appears to be approximately 3 peaks in the Mode S interrogation rate per orbit. The average rate for the entire period was 114 Mode S interrogations per second. The peak second (5:32:50) contained 285 interrogations.

The number of TCAS aircraft present during this period varied from 8 to 19. The peak of 19 aircraft were seen at 5:32 and again at 5:36.

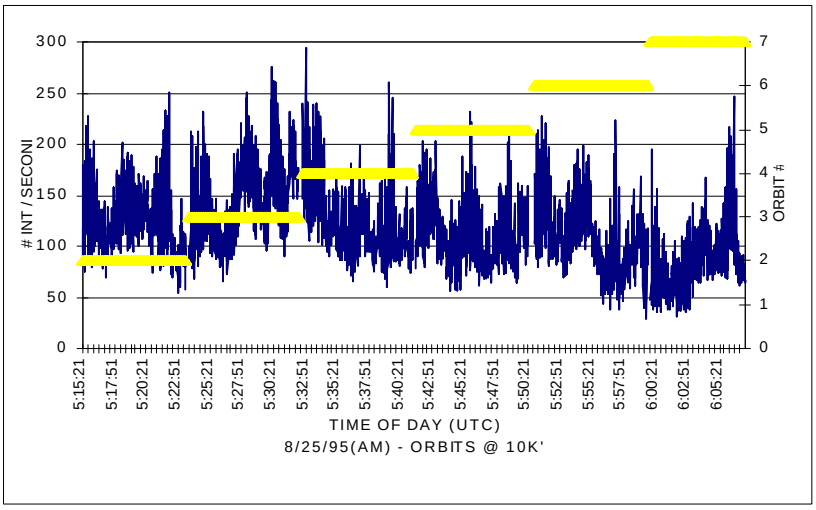

FIGURE 31. MODE S INTERROGATIONS

The Mode A interrogations for the 5-mile orbits are shown in figure 32. Note that, unlike the Mode S rate, the Mode A interrogation rate is relatively constant regardless of position around the airport. The average Mode A rate is 129 interrogations per second. The file gaps, which mark the beginning of a new orbit, are very evident in this data because it is so constant.

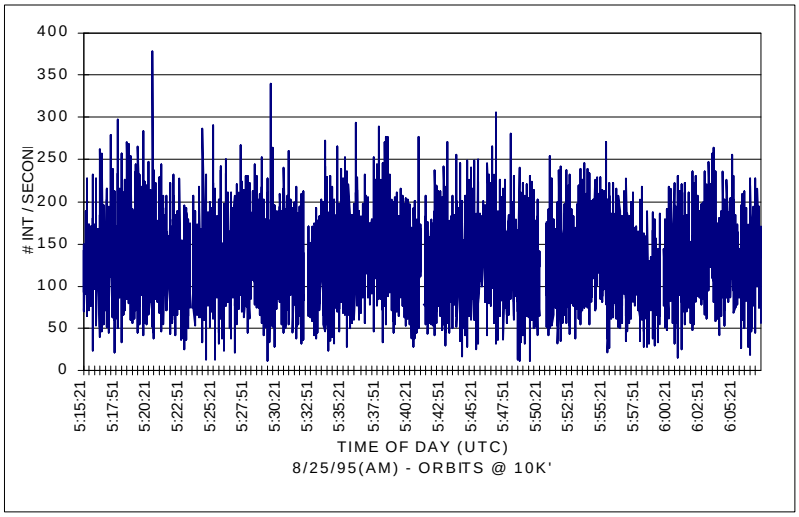

FIGURE 32. UNSUPPRESSED MODE A INTERROGATIONS

Figure 33 shows the Mode C interrogations for the 5-mile orbits. Like the Mode A's, they are very constant and average 80 interrogations per second.

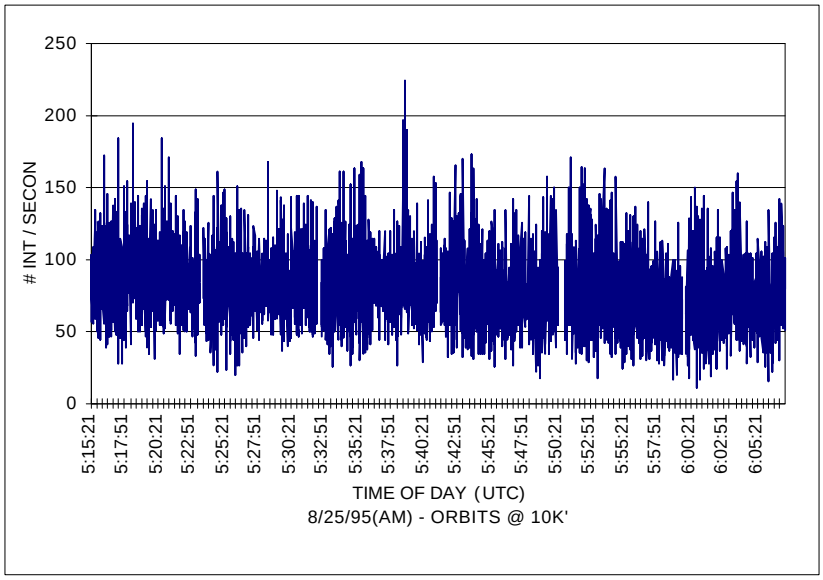

FIGURE 33. UNSUPPRESSED MODE C INTERROGATIONS

Figure 34 shows the Mode 2 interrogations for the six orbits at 10,000 feet as a function of time. It appears that there is a peak in Mode 2 interrogations in each orbit. Figure 35 shows the data from each orbit normalized to the start of that orbit. There is a slight error because all orbits were not the same duration (they varied from 8:08 to 8:51). The increase in Mode 2 activity definitely increases at about the same time in each orbit.

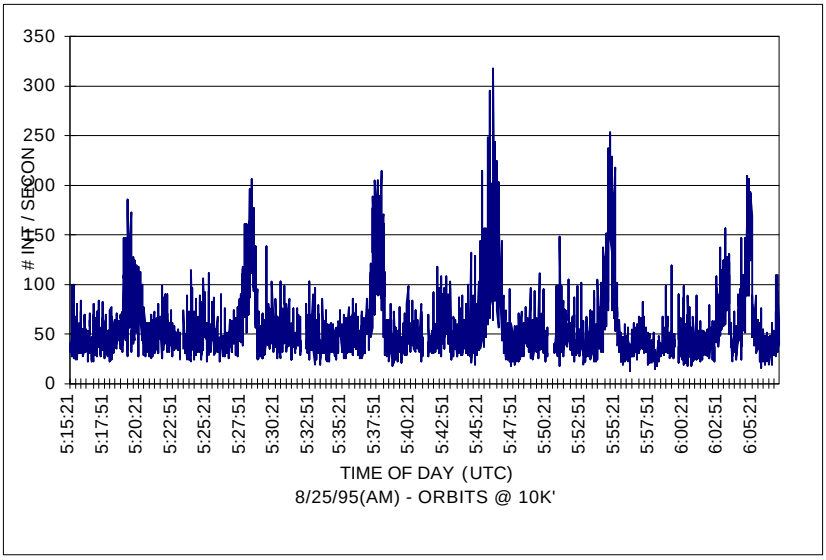

FIGURE 34. UNSUPPRESSED MODE 2 INTERROGATIONS

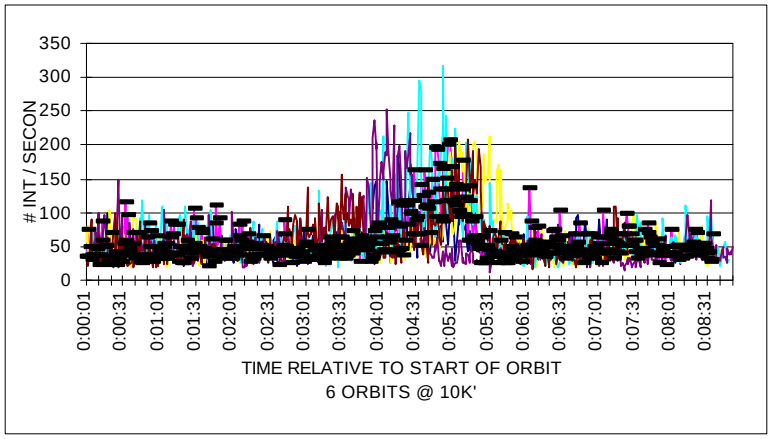

FIGURE 35. UNSUPRESSED MODE 2 INTERROGATIONS

This data was searched for a PRT pattern without success. There appeared to be a significant number of Mode 2 interrogations with a pseudo-random pattern spaced at about 2.1 ms. It did not appear to be from a "scanning" radar as they were present throughout the period which was checked.

Table 3 shows the relative interrogation rates as a function of the flight profile. Note that Mode A and Mode C interrogations increase as a function of altitude and Mode S interrogations decrease. Close inspection of figures 28 and 29 show the increase at the beginning of the file. This was the transition from 10,000 to 15,000 feet prior to the orbit. The Mode 2 interrogations appear to be fairly constant throughout all the orbits with a slight increase on landing. Mode A and C's decrease significantly when landing.

TABLE 3. OVERALL INTERROGATION SUMMARY (ORBITS)

InterType	10kOrbits	15korbit1	15korbit2	Holding	Landing
Mode4Seq	6.5	8.4	5.6	5	2.8
Mode S	114	66	77	61	141
Mode A	129	158	169	154	70
Mode C	80	87	91	84	38
Mode 2	57	55	53	50	69
Supp	1116	1093	1099	898	929
Availability	91.3	91.6	91.3	92.6	93.3

The transponder availability goes up slightly when landing in spite of the increase of Mode S interrogations to 141/second from 61/second while holding. This is a result of the Mode A and Mode C interrogations decreasing to 70 (from 154) and 38 (from 84) per second, respectively. It is also important to note that this "availability" time is for a normal Mode S transponder, which ignores Mode 2 interrogations. Military transponders would have a significantly different availability as they would respond to the Mode 2 interrogations which are fairly constant at 50 to 70 per second.

RADAR PRT ANALYSIS.

One of the main problems with the radar PRT analysis is the size of the files. The interrogation decode files, which contain only the "time of arrival" (TOA) and interrogation type, are 1 to 2 megabyte (Mb) per minute of data collection time. The analysis process (EXCEL was used for most of the PRT processing) produced files of 15 to 20 Mb for only a few seconds of data. In order to get meaningful results, it was felt that at least 30 seconds worth of time was required so that we have several scans of each radar producing the interrogations which were stored. The results presented here consist mainly of two orbits of Frankfurt. They were selected at random from the data of August 25. The orbits selected were the sixth orbit of the morning flight and the fourth orbit of the evening flight. Both were at 5 miles at 10,000 feet.

The interrogation files were first processed by macros in EXCEL to associate various interrogations which comprise other interrogations set by using their relative TOA information. Examples of these relationships are given below:

1. A Mode S interrogation consists of a suppression pair (the Mode S preamble) followed by the Mode S interrogation approximately 4.5 μs later.

2. An ATCRBS Mode A or Mode C interrogation contains a suppression pair where P1 of the suppression pair coincides with P1 of the Mode pair if the interrogation is within the side lobes of the interrogating antenna.

3. An ATCRBS Only interrogation consists of a Mode C interrogation followed by a suppression where P3 of the Mode C is used as P1 of the suppression.

4. A TCAS whisper/shout sequence consists of a suppression, a Mode C interrogation and an ATCRBS Only interrogation if the first suppression is seen. If it is not seen, the interrogation is seen as an ATCRBS Only.

The next step in this process was to eliminate all but the "unsuppressed" ATCRBS interrogations in order to reduce the size of the file. Theoretically, this will leave only the main beams of all the radars. In practice, it is not nearly this clean. Interrogations are produced by combinations of other interrogation types (which are not really produced by any interrogators) so additional processing was required to identify these. This was especially true for Mode 4 and Mode 2 interrogations, as will be discussed later.

Interrogations were associated with a particular radar by searching for certain sequences which repeated at regular intervals. The identification process to define a particular radar was largely a manual effort with the assistance of some EXCEL macros which looked for timing patterns for each interrogation in relation to the surrounding group of interrogations. It is important to note that none of the radars were known to the required detail prior to the investigation. Each radar PRT was identified (to 100 ns resolution) from the data which was collected.

Once the radars were identified, other macros searched the entire data sample looking for the occurrences of these sequences. These macros "flagged" each interrogation with the identity of the radar which was selected as a match (i.e., Radar #1, PRT#5, etc.). Another output of these macros was the radar beam characteristics for each radar. The number of hits for each

beam width, scan rate, and mode interlace sequence were tabulated for each radar. A total of 36 different radars were identified along with their characteristics. A total of 39 radars are listed in the table, but two were created to investigate variations of others, and one was the radar with no side lode suppression (SLS) discussed previously in the Frankfurt to Munich trip. This radar was not present during any of the orbits around Frankfurt. Performance was checked at two different points of each orbit on opposite sides of the Frankfurt Airport. As expected, some of the radar characteristics were different at the two points (or not present at all) as will be discussed later.

Table 4 shows the characteristics of the 39 radars identified in this sample.

TABLE 4. FRANKFURT RADAR

	NPRT	INTERLACE	HITS	BWID	SCANT	COMMENTS
RADAR-1	5	CAACAA	32	0.088	4.73	SIDE LOBES DURING SOME
RADAR-2	5	CAACAA	30	0.091	4.70	SIDE LOBES DURING SOME
RADAR-3	5	CAACAA	28	0.093	4.71	SIDE LOBES DURING SOME
RADAR-4	5	ACACAC	23	0.084	4.81	
RADAR-5	5	CAACAA	45	0.061	11.65	HOLES DURING A
RADAR-6	5	CAACAA	51	0.129	5.83	VERY CONSTANT
RADAR-7	5	CAACAA	43	0.131	5.47	HOLES DURING SOME
RADAR-8	5	CAACAA	40	0.079	5.45	
RADAR-9	4	AAAAAA	30	0.089	4.31	SEVERE SIDE LOBE PROBLEMS ON MORNING
RADAR-10	1	??????	39	0.088	9.30	SEE DISCUSSION
RADAR-11	3	2AC2AC	22	0.145	10.00	SIDE LOBES DURING SOME
RADAR-12	5	ACACAC	39	0.050	11.65	
RADAR-13	1	??????	20	0.103	10.04	SEE DISCUSSION
RADAR-14	3	A2CA2C	40	0.096	9.33	SEE DISCUSSION
RADAR-15	3	2CA2CA	21	0.094		EITHER DIRECTIONAL OR SEVERE SIDE LOBE
RADAR-16	5	CAACAA	33	0.119	4.74	VERY CONSTANT
RADAR-17	5	CAACAA	47	0.175	11.65	VERY WEAK AT SOME SPOTS
RADAR-18	3	2AC2AC	27	0.120	11.89	MILD SIDE LOBE
RADAR-19	4	AAAAAA	28	0.117	4.30	NOT THERE ON EVENING
RADAR-20	4	AAAAAA	28	0.090	4.16	NOT THERE ON EVENING
RADAR-21	3	2AC2AC	34	0.150	11.90	
RADAR-22	3	2AC2AC	25	0.108	10.05	
RADAR-23	1	ACACAC	18	0.060	4.41	SIDE LOBE PROBLEMS
RADAR-24	3	ACACAC	8	0.050	7.50	VERY LOW PRF OR MISSING
RADAR-25	5	CAACAA	30	0.095	4.73	SEVERE SIDELOBE PROBLEMS DURING SOME
RADAR-26	3	CAACAA	10	0.060	9.90	SIDE LOBE PROBLEMS DURING SOME
RADAR-27	1	ACACAC	16	0.052	4.41	
RADAR-28	3	2CA2CA	21	0.100	10.03	LOTS OF HOLES
RADAR-29	3	2CA2CA	16	0.070	12.03	NOT VERY MANY HITS FOR A LONG RANGE RADAR
RADAR-30	2	ACACAC	31	0.200	9.30	SEE DISCUSSION - SAME RADAR AS #10
RADAR-31	2	ACACAC	21	0.119	10.03	SEE DISCUSSION - SAME RADAR AS 13
RADAR-32	5	AACAAC	43	0.150	11.58	
RADAR-33	5	AACAAC	27	0.090	4.72	NO HITS IN SOME
RADAR-34	5	ACACAC	17	0.088	7.82	ONLY PRESENT DURING FILE
RADAR-35	8	MSALLCALL	8	0.130	9.93	MODE S SENSOR ALL CALLS
RADAR-36	1	ACACAC	5000	300.000	Omni	NO SLS - ONLY PRESENT ON FRANKFURT/MUNICH
RADAR-37	2	AAAAAA	9	0.096	4.73	
RADAR-38	3	CCCCCC	31	0.086	4.77	
RADAR-39	10	AACAAC	14	0.04	3.77	

Column definitions:

1. NPRT - This is the number of different PRTs in the stagger pattern for that particular radar. These vary from fixed (1 PRT) to 5 PRTs for the various radars.
2. INTERLACE - The mode Interlace as detected by the PRT macros.

3. HITS - The average number of hits per beam width. GPS data is available as a function of time if desired.
4. BWID - The average beam width in milliseconds.
5. SCANT - Radar scan time in seconds for that radar.
6. COMMENTS - any salient characteristics or other information.

Table 5 gives the PRTS associated with each of the radars identified during the Frankfurt orbits. The times are in “clocks” (100 ns): i.e., 28878 is 2.8878 ms, 28761 is 2.8761 ms. The PRTS were searched in the sequence shown in the table. The PRTs varied from 1 (non-staggered PRF) to 10 (sequence repeated after 10 different PRTs). Radar #39 is listed in the table as 2 sets of 5 because it is the only radar with more than 8 PRTs and it was felt unnecessary to make all PRT sets 10 columns wide in order to accommodate this. The PRT sequence for this radar is 27354, 28181, 27515, 27550, 26725, 27233, 28304, 27392, 27672, 26604 and then repeats.

TABLE 5. FRANKFURT RADAR PRT'S

	PRT1	PRT2	PRT3	PRT4	PRT5	PRT6	PRT7	PRT8	AVPRT	AVPRF	RPM
RADAR-1	28878	28761	28918	28801	28837				28839.0	346.75	12.68
RADAR-2	29074	28951	28996	29032	28911				28992.8	344.91	12.77
RADAR-3	29192	29352	29235	29271	29314				29272.8	341.61	12.74
RADAR-4	22497	35374	36660	23778	23023				28266.4	353.78	12.47
RADAR-5	47190	47350	47230	47270	47310				47270.0	211.55	5.15
RADAR-6	24505	24549	24424	24587	24465				24506.0	408.06	10.29
RADAR-7	24291	24175	24328	24210	24253				24251.4	412.35	10.97
RADAR-8	24083	23967	24005	24046	23925				24005.2	416.58	11.01
RADAR-9	29460	28107	29700	27028					28573.8	349.97	13.92
RADAR-10	40015								40015.0	249.91	6.45
RADAR-11	39999	40022	39975						39998.7	250.01	6.00
RADAR-12	21671	21775	21634	21742	21703				21705.0	460.72	5.15
RADAR-13	39690								39690.0	251.95	5.98
RADAR-14	39991	40014	40040						40015.0	249.91	6.43
RADAR-15	40041	40195	39809						40015.0	249.91	
RADAR-16	29200	29078	29121	29158	29040				29119.4	343.41	12.66
RADAR-17	23372	23532	23416	23452	23496				23453.6	426.37	5.15
RADAR-18	33328	33352	33305						33328.3	300.05	5.05
RADAR-19	26996	29610	27957	29728					28572.8	349.98	13.95
RADAR-20	27057	29488	27989	29757					28572.8	349.98	14.42
RADAR-21	33300	33323	33272						33298.3	300.32	5.04
RADAR-22	40650	40675	40624						40649.7	246.00	5.97
RADAR-23	28838								28838.0	346.76	13.61
RADAR-24	71000	70900	71100						71100.0	140.65	8.00
RADAR-25	29024	29062	29104	28981	29143				29062.8	344.08	12.68
RADAR-26	38940	123234	40466						67546.7	148.05	6.06
RADAR-27	29090								29090.0	343.76	13.61
RADAR-28	39663	39692	39715						39690.0	251.95	5.98
RADAR-29	40996	41027	40971						40998.0	243.91	4.99
RADAR-30	40014	80030							60022.0	166.61	6.45
RADAR-31	39690	79380							59535.0	167.97	5.98
RADAR-32	47190	47350	47230	47270	47310				47270.0	211.55	5.18
RADAR-33	29358	29400	29438	29318	29481				29399.0	340.15	12.71
RADAR-34	45357	45458	45558	45658	45759				45558.0	219.50	7.67
RADAR-35	32219	127770	32298	127827	31911	128038	31938	127990	79998.9	125.00	6.04
RADAR-36	21418								21418.0	466.90	Omni
RADAR-37	38940	163704							101322.0	98.70	12.68
RADAR-38	26731	26083	27197						26670.3	374.95	12.58
RADAR-39(5)	27354	28181	27515	27550	26725				27453.0	364.26	15.92
RADAR-39(5)				27233	28304	27392	27672	26604			

DISCUSSION OF THE PRT DATA.

Analysis of the radar PRT data was extremely "time consuming" and could continue on much further than in this effort. This is because much of the work is manually searching for patterns in the data. The process of identifying the radars was to examine the interrogations not associated with any radars after the data was processed by the PRT search macro and determine if a pattern existed between those interrogations. With the number of interrogators in the Frankfurt, there were very few main beams which were not interleaved with interrogations from other radars. It is certain that several more radars could be found in the data if more time was spent on it. However, it was also felt that, without a specific reason to search further, the required time was not justified.

Of the radars identified, 18 were "terminal" (10 to 15 revolutions per minute (rpm)), 17 were en route (5 to 8 rpm), and the other was undetermined. The other may be directional (or a radar with severe side lobe problems) because beams consisted more than 100 hits. Radar #36 (discussed previously in the Mode 4 data discussion) was surely a directional radar as several thousand consecutive hits were seen and there were no hits found with suppression pulses present.

These 39 radars were identified from four orbits at 10,000 feet. The data from the transponder availability, discussed above, indicates that there are more unsuppressed Mode A's and C's at the 15,000-foot flight level, so it is probable that more radars could be identified from this data, but because of time constraints, this was not done.

The interlace pattern indicated in table 4 is the output of the PRT search macros. A total of six consecutive PRTs associated with the particular were required before using this data to identify the PRT. As indicated, two of the radars (radar #10 and #13) never met this criteria.

RADAR #13/31 DISCUSSION.

Radar #13 appeared in all files, had an average of almost 20 hits per beam width and a scan time of 10.04 seconds but it did not satisfy the criteria to identify the mode interlace. Radar #31 was defined in order to help analyze this situation. Note the similarities in the PRTs. Radar #13 is a single PRT of 39690 and radar #31 is a two pulse pattern of 39690 and 79380 (which is double the first PRT). Note that the PRT macros identified the interlace pattern of radar #31 as ACACAC indicating that the criteria of six consecutive hits were met. The main beams of both radars coincided in all cases so this is probably the same radar. It is more likely, however, that neither of these patterns is correct. DATAS stored only the detected interrogations, not the raw input data. Because of a limitation of eight different types, Mode 1 interrogations were not stored. It is probable that the radar is really operating at a fixed PRT of 39690 as indicated by radar #13, but the interlace is A1CA1C.

Table 6 shows the relative timing of the interrogations. All time is relative to the interrogation preceding it.

The following sequence defines radar #31: Mode A followed 79380 clocks later by Mode C, then 39690 clocks later another Mode A 79380 clocks later, etc.

The interrogations at 79380 clocks are probably a result of not decoding the other interrogation which occurred at 39690 clocks.

The real sequence is probably as shown in the right hand column. All interrogations spaced at 39690 with the interlace pattern AXCAXCAXC, where X is probably Mode 1.

TABLE 6. MISSING MODE TABLE

	RADAR31	REAL
MODE A	0	0
X	.	39690
MODE C	79380	39690
MODE A	39690	39690
X		39690
MODE C	79380	39690
MODE A	39690	39690
X		39690
MODE C	79380	39690
MODE A	39690	39690
X		39690
MODE C	79380	39690
MODE A	39690	39690

RADAR #10/30 DISCUSSION.

The same technique was tried on radar #10, using radar #30 with a stagger sequence of a single PRT plus a value equal to two PRTs. The mode interlace of this radar was also discovered to be ACACAC, which will probably make it A1CA1C as in radar #13. This is probably a radar with severe side lobe problems, because one file was processed from the opposite side of the airport on a 20-mile orbit and the characteristics were found to be that of an en route radar. The scan time was 6.45 seconds.

Radars #14 and #15 also appeared to be directional because of the large number of hits in some beam widths and no discernible scan pattern. These were also searched in the 20-mile orbit. Radar #14 also turned out to be an en route radar with a scan time of 6.43 seconds. Radar #15 still had no discernible scan time, but its similarity in PRTs to radar #14 suggests that it is probably a similar radar. Both radars have the same mode interlace pattern, A2CA2C.

OTHER RADAR PRT PATTERNS.

During the investigation, other patterns were apparent as ‘main beams’ of radars, but no discernible pattern was seen so that the occurrence of that pattern could be included in the search macros. An example of such a pattern is shown in table 7. Most of the beams were in the clear (not overlapped with another radar), so it was obvious they belonged to the same source. The PRT pattern appears to be some sort of pseudo random pattern of approximately 3 ms. There were several other sets, predominantly Mode 2, with a PRT of approximately 2.1 ms.

TABLE 7. STRAY PRT SAMPLE

SCANT		**4.669**	**4.835**	**4.867**	**4.828**	**4.85**	**4.8098**
	272.736	**277.405**	**282.24**	**287.107**	**291.935**	**296.785**	
1	30385	34413	29300	64907	30776	33099	
2	35090	34520	34701	33256	35765	30936	
3	35093	31191	36525	37163	30692	36044	
4	30128	35710		30971	35977	32193	
5	30126	34793	68204	33159	34913	32616	
6		31652	31239	34673	30063	34796	
7	63524		36563	30553	33696	31600	
8	36141		29560	34912	35564	34127	
9	30239	100965	35659	34408	32262	34664	
10	30241	38507		31464	32197	30873	
11			64235	33196	35134	32826	
12	71153		33489	35014	32223	35746	
13				32752	32057	30961	
14	59366		66613	34298	34363	35187	
15	30384		34219	33184	33463	34763	
16			34913	33123	32607	31622	
17			31132	33457	34813	33558	
18			34740	34192	32872		
19			34623		30648		
20			32960	65853			

The interrogations from at least 36 radars were seen while orbiting in the airspace around the Frankfurt Airport at 10,000 feet. These interrogations are from a mixture of civilian and military radars. Figure 36 shows the periods of time when the DATAS aircraft was illuminated by these radars during one of the orbits. Most of the radars have a very regular main beam pattern (i.e., radar #37 was seen at 3, 13, and 23 seconds during this sample). A couple of the radars (33 and 34) were not seen in this orbit. Radar #36 was the radar which was only seen in the vicinity of the general aviation airport during the Frankfurt/Munich trip.

Some of the radars (i.e., #10, 14, and 15) have many side lobes. The Mode S sensor, which is radar #35, also has several side lobes. The main beam of radar #35 is indicated by the arrowheads. This timing was ascertained by identifying the times when the DATAS aircraft received “roll call” interrogations from the sensor.

As figure 36 indicates, there are many times when the main beams of several radars are directed at the DATAS aircraft. In order to present a problem, however, the time of receipt of the interrogations must also be “near synchronous.” The differences in scan rate are evident from figure 36, but the PRTs are also considerably different, so interference from the same radar is greatly diminished.

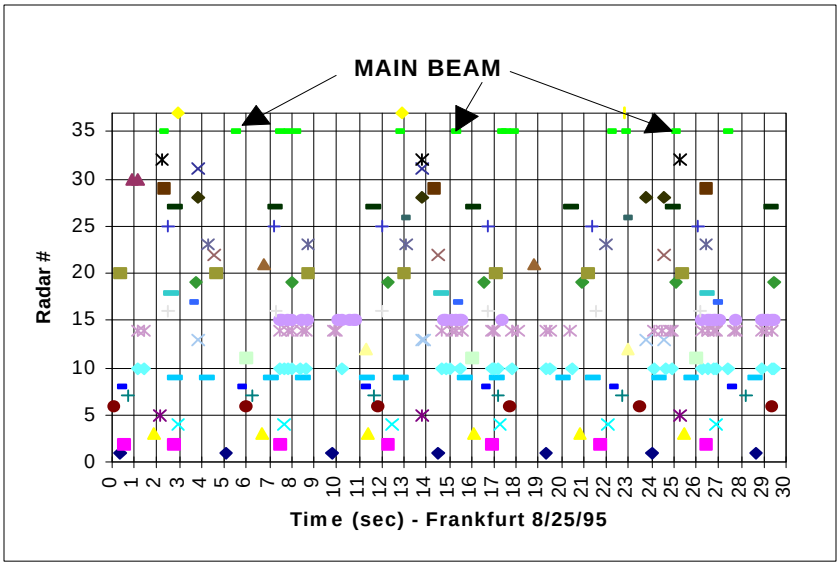

FIGURE 36. BEAMS OF FRANKFURT RADARS - ORBIT 6

UPLINK INTERROGATION SUMMARY.

In general, the beam widths of these radars are greater than those in the United States (30 to 40 hits is not uncommon for a terminal radar). There also appear to be a lot of side lobes from the interrogators. Both these characteristics help contribute to a very high ATCRBS fruit rate (see Downlink Summary).

Transponder “availability” to respond to incoming interrogations averaged about 91 percent for the various tests conducted. A sudden drop in transponder “availability” to less than 85 percent was measured on two occasions on a test flight between Frankfurt and Munich. This was attributed to a single interrogation source, possibly a transponder test facility in the proximity of two general aviation airports.

Mode 4 interrogation activity was only a few interrogations per second except for a couple of short bursts (a few seconds) when more than 100 Mode 4 sequences occurred in a single second. The highest rate recorded was 420 Mode 4 sequences in a single second during a burst which lasted for 15 seconds. The transponder “availability” during this burst was 89.3 percent.

The average uplink Mode S rate was 114 interrogations per second for the 10,000-foot orbits of the Frankfurt Airport. The number of TCAS aircraft present during this period varied from 8 to 19. The highest peak measured was 285 interrogations in a single second. The Mode S interrogation rate was a definite function of aircraft position with respect to the airport. It was also higher at 10,000 feet than at 15,000 feet. The highest rate occurred on landing.

The average unsuppressed ATCRBS Mode A rate was about 130 interrogations per second and was relatively independent of aircraft position. The rate, however, was higher at 15,000 feet than at 10,000 feet, an indication of greater coverage at higher altitudes. The corresponding ATCRBS Mode C rates were about 80 interrogations per second.

DOWNLINK DATA ANALYSIS.

Downlink data was collected for approximately the same time period on 2 separate days. The ATCRBS and Mode S reply rates for the 2 days is superimposed on the same graph. This data was collected via an omnidirectional antenna (top antenna of N40) with the aircraft parked on the ramp on the German civilian side of the airport.

The reply rate shown on the following figures is the average value for the 5-minute period ending at the indicated time. Data was not collected between the times of 11:30 and 12:20 on August 24 and 10:45 to 11:15 on August 27 (see figure 37) because this time was needed to transfer data from disk to tape because of insufficient disk space. Data points for these periods were filled in by interpolating using the end and start points of the adjacent periods. The maximum ATCRBS rates achieved were similar for the 2 days, but at completely different times of the day. This may partially be accounted for by the day of the week (August 24 was a Friday and August 27, a Sunday). The highest ATCRBS rates occurred at approximately 06:00 and 08:00 (UTC) on August 24. In both cases, the rate was approximately 18,000 ATCRBS replies per second. The highest rate achieved on August 27 was about 17,000/second at approximately 18:00. In general, the rate remained fairly constant between 10,000 and 15,000 for the entire period after about 05:30.

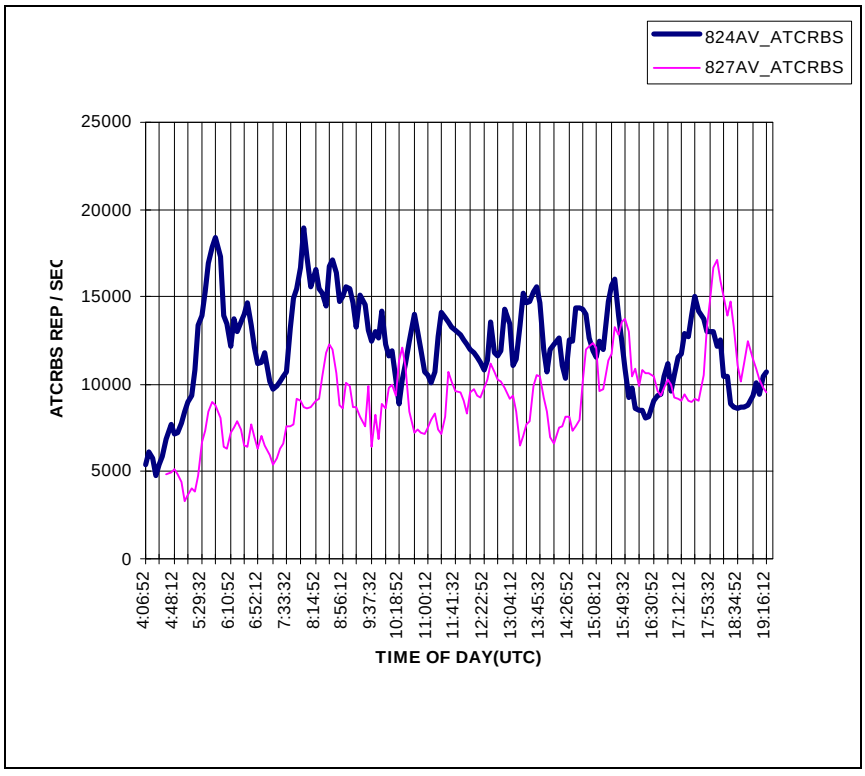

FIGURE 37. ATCRBS REPLY RATES - FRANKFURT, GERMANY

The peak ATCRBS rate achieved in any single second is shown on figure 38. This follows the average rates for the same period. The highest rate achieved during any single second was 27,000/sec, which occurred at about 05:50 on August 24.

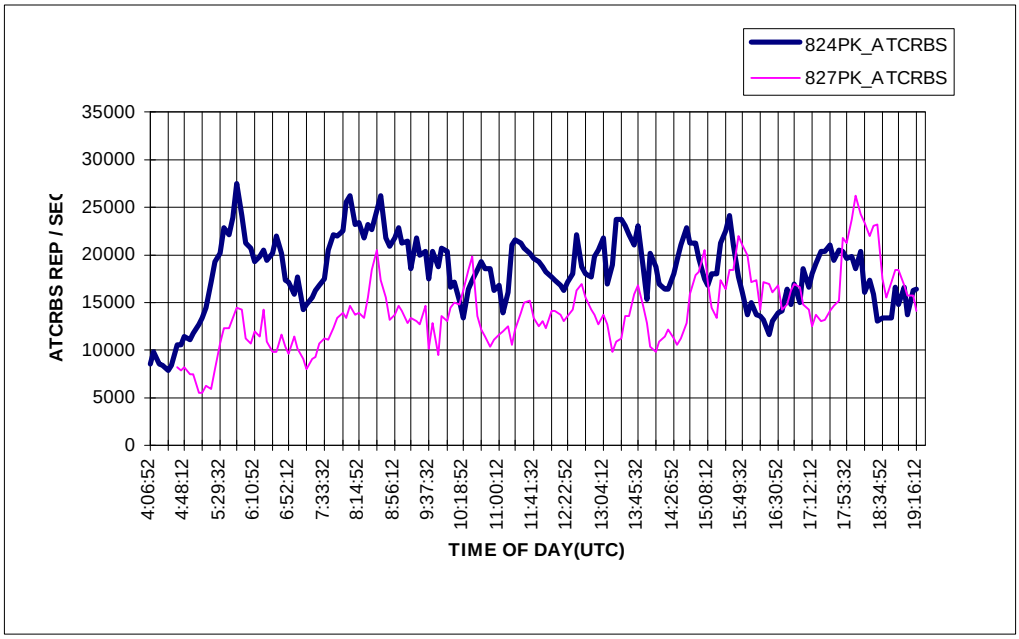

FIGURE 38. ATCRBS PEAK REPLY RATES - FRANKFURT, GERMANY

The Mode S reply rates for the corresponding periods of the 2 days is described on the next two plots. The average Mode S reply rate for any 5-minute period is shown on figure 39. There were three major peaks on August 24. The first two corresponded to the ATCRBS peaks at approximately 06:00 and 08:00. The main peak, however, was higher at 328 replies per second and occurred at approximately 15:30. See the discussion of the Mode S peaks below.

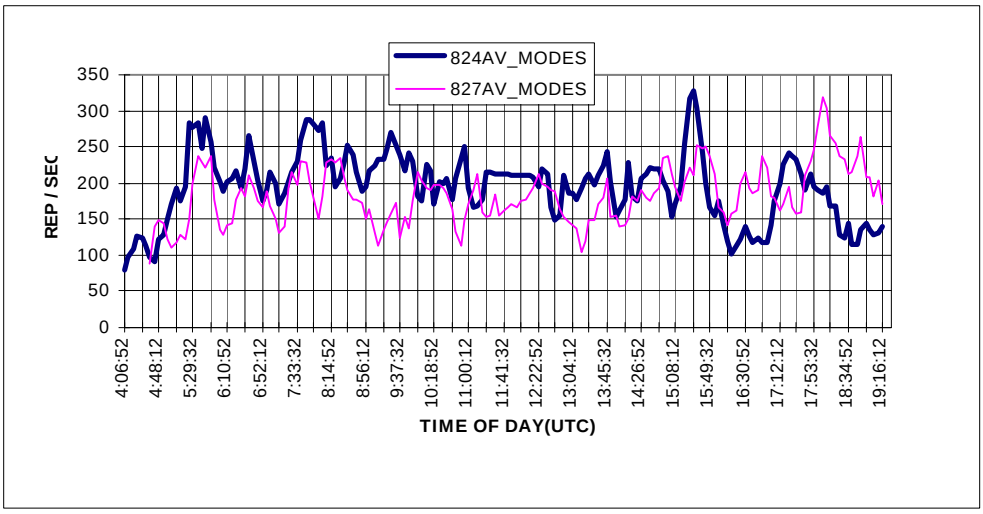

FIGURE 39. AVERAGE MODE S REPLY RATES - FRANKFURT, GERMANY

The highest peak Mode S rate for any one second was 748 per second at approximately 5:30 on Friday, August 24 (see figure 40). This was attributed to a Mode S sensor restart which occurred at that time. There were several more peaks which were far above the norm during the period (one at 15:30 on August 24 definitely is related to the high average for that period).

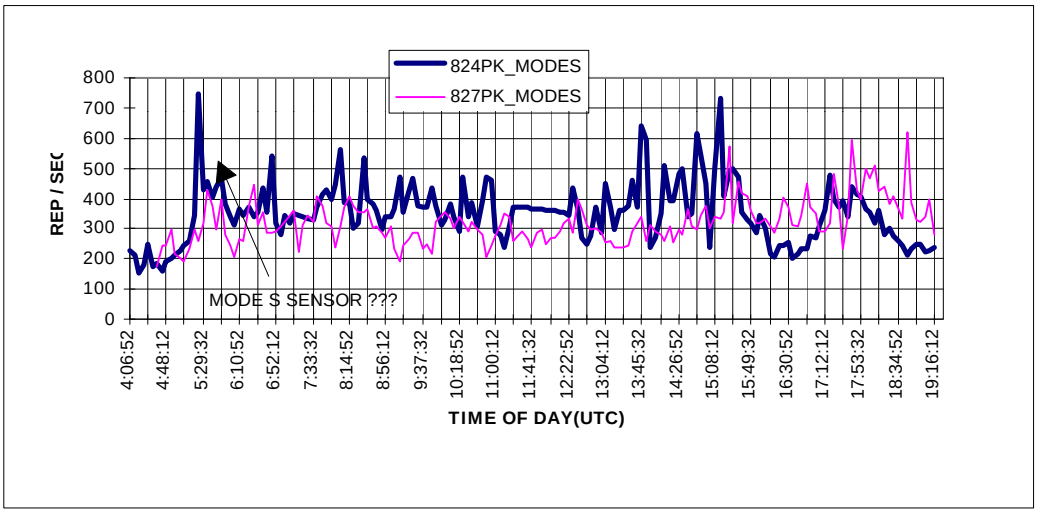

FIGURE 40. MODE S PEAK REPLY RATES - FRANKFURT, GERMANY

The Mode S reply data from the time period which contained the high peak at 05:30 on August 24 was examined. Figure 41 shows the replies to Mode S sensor (IIS=2) during this period. Note the absence of replies prior to 05:30. It should be noted that the x axis of this figure is not linear (each reply attributed to the sensor is displayed along with its associated time). There were several seconds shortly after 5:30 which contained more than 100 replies attributed to the Mode S sensor. There were undoubtedly more than that, because the replies represented here were only those which contained no parity errors. With the ATCRBS fruit rate at that time (approximately 13,000 average and 19,000 peak), there were a considerable number of overlapping replies. No “error correction” was used to correct replies which contained parity errors.

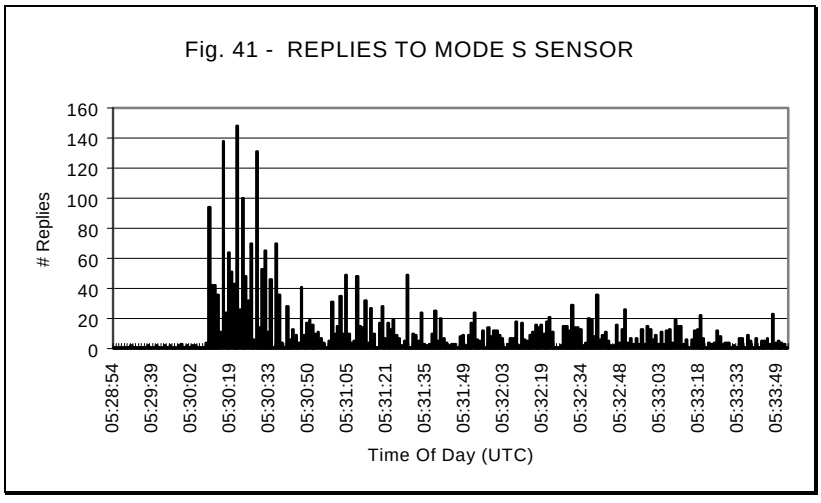

FIGURE 41. REPLIES TO MODE S SENSOR

A sample of replies from a single aircraft on sensor startup is shown in table 8. Aircraft “3C64E8” is responding with downlink format (DF)=11’s (the Mode S sensor All Calls) until

approximately 5:30:21 when there are three DF=4's indicating an attempt by the sensor to put the aircraft on "roll call." It continues to respond to the DF=11's for the next scan of the sensor (about 10 seconds). At 05:30:30, it responds with a DF=5 (ATCRBS Identity reply) and two more DF=4's (altitude reply). At 5:30:40 (the next scan), it responds with a DF=20, which contains the extended capability report of the aircraft, and three more DF=4's. After this time, there are from two to five DF=4's each scan, indicating that the sensor has locked the transponder out to "all calls" and has the aircraft on "roll call." The "all calls" which appear (at 5:30:41 and 5:31:02) are not at the main beam times of the radar, so may be the result of an interrogation meant for another aircraft instructing the aircraft to ignore the lockout and respond with a DF=11. This aircraft responded to 173 Mode S all calls before being placed on "roll call" by the sensor. This is probably a typical scenario when the sensor initially starts up and acquires all the aircraft in the area. This particular aircraft was descending from 9,000 feet during this acquisition.

The other peaks in Mode S reply rate were not investigated, but this one makes it very feasible to believe that they may also be a result of the Mode S sensor. This Mode S sensor was not operating in the normal mode as they were still in the process of experimenting with it when this data was collected.

TABLE 8. SENSOR ACQUISITION OF A SINGLE AIRCRAFT WHEN STARTING UP

TIMESEC	Total	DF=11	DF=4	DF=5	DF=20
05:30:11	10	10			
05:30:13	22	22			
05:30:18	30	30			
05:30:21	17	14	3		
05:30:23	48	48			
05:30:27	6	6			
05:30:28	40	40			
05:30:30	5	2	2	1	
05:30:40	4		3		1
05:30:41	1	1			
05:30:50	4		4		
05:31:00	2		2		
05:31:02	1	1			
05:31:10	4		4		
05:31:20	3		3		
05:31:30	3		3		
05:31:41	3		3		
05:31:51	3		3		
05:32:01	4		4		
05:32:11	2		2		
05:32:21	3		3		
05:32:30	3		3		
05:32:40	2		2		
05:32:49	1		1		
05:32:59	3		3		
05:33:18	2		2		
05:33:28	1		1		
05:33:47	3		3		
05:33:48	1	1			
Grand Total	231	175	54	1	1

MODE S REPLY ANALYSIS.

The Mode S reply data is incorporated into a valuable database which can be searched for a number of different characteristics. This data consists of all the Mode S equipped aircraft which were seen in the downlink data for the 2 days of collection (Friday, August 24, and Sunday, August 27). The following table is a summary of information gained thus far by using this database:

Number of Total Mode S flight segments	3073	
Number of different aircraft	958	
Number of departures from Frankfurt	573	18.6%
Number of arrivals to Frankfurt	590	19.2%
Number of "overflights" (above 25k')	1063	34.6%
Number of aircraft reporting 25' altitude resolution	2752	89.6%
Number of aircraft reporting 100' altitude resolution	88	2.9%
Number of aircraft reporting 100' and 25' at least twice	13	0.4%
Number of aircraft with TCAS 'ON'	875	28.5%
Number of aircraft reporting 'on-ground' while airborne	20	15 different aircraft
Number of aircraft always reporting 'airborne'	10	6 different aircraft
Number of illegal Mode S addresses = '000000'	4	Probably 1 aircraft
Number of illegal Mode S addresses = 'FFFFFF'	3	Probably 2 aircraft
Average 'turn on time' prior to departure (minutes)	10.0	Max. = 2 hr. 26 min
Average 'turnoff time' after arrival (minutes)	8.3	Max. = 2hr. 10 min

The "Illegal Mode S Addresses" were examined in more detail to produce the following results. "Illegal" is defined as per our program "MSCOUNTRY." It is possible that this program may not be up to date with latest assignments. The "all zero or all one" addresses are definitely illegal, however. Some of the others appear to be derivatives of these.

ILLEGAL ADDRESS	# FLIGHTS	# REPLIES
000000	4	8053
29CBB8	1	950
899011	1	325
9585A1	2	4494
9585A2	1	14350
9C4D84	1	8
B47F38	3	4502
F0000E	4	4435
F0000F	2	384
FDFFFF	3	3191
FFFFFF	3	4518

All these flights with the exception of "9C4D84" have sufficient replies to be sure that these aircraft were responding to these illegal addresses. The two which start with "958" are either a misinterpretation of the specifications or our program is obsolete. The derivatives of all ''1s" were all "over flights," but may be similar to the problem we have seen where transponders change their Mode S ID's while in flight.

There were Mode S aircraft from 64 different countries. The count of Mode S aircraft as a function of Country is shown in table 9.

Table 9 consists of the data from only Mode S equipped aircraft. It indicates that, for the 2-day collection period, there were 1,952 flights of aircraft registered in Germany. These flights were taken by 279 different aircraft. Of these, TCAS was operational for 296 flights (a total of 15 percent of the flights). The highest TCAS utilization (using only countries with more than 50 flights) was from aircraft from the United States. A total of 69 percent of the USA aircraft had their TCAS operational.

TABLE 9. TCAS IMPLEMENTATION AS PER DOWNLINK DATA

COUNTRY#	COUNTRY	#AIRCRAFT	TOTFLIGHTS	TOTCASFL	%TCASFL
1	GERMANY	279	1952	296	15
2	UNITED KINGDOM	129	339	82	24
3	UNITED STATES	93	242	168	69
4	FRANCE	52	120	12	10
5	TURKEY	25	103	12	11
6	NETHERLANDS	31	92	10	10
7	BELGIUM	22	75	3	4
8	SPAIN	25	70	6	8
9	ITALY	26	68	1	1
10	SWITZERLAND	31	62	15	24
11	AUSTRIA	13	47	26	55
12	ICELAND	13	39	16	41
13	CZECHOSLOVAKIA	7	28	1	3
14	GREECE	8	27	6	22
15	TUNISIA	8	23	0	0
16	POLAND	7	23	0	0
17	SWEDEN	9	22	1	4
18	SINGAPORE	9	20	15	75
19	EGYPT	6	18	2	11
20	NORWAY	6	18	0	0
21	CANADA	8	16	13	81
22	ROMANIA	6	16	2	12
23	CYPRUS	4	16	0	0
24	ISRAEL	6	15	9	60
25	PORTUGAL	4	13	2	15
26	AUSTRALIA	5	12	2	16
27	HUNGARY	4	12	4	33
28	ILLEGAL	4	12	0	0
29	DENMARK	3	12	0	0
30	YUGOSLOVIA	1	12	0	0
31	LUXEMBORG	10	11	1	9
32	MALAYSIA	7	11	3	27
33	BRAZIL	5	11	4	36
34	INDIA	5	9	8	88
35	USSR	5	9	2	22
36	BRUNCI DARUSSALAM	3	9	5	55
37	OMAN	6	8	4	50
38	PAKISTAN	5	8	6	75
39	JAPAN	4	8	5	62
40	FINLAND	3	8	0	0
41	SRI LANKA	3	7	4	57
42	THAILAND	2	7	7	100
43	CHINA	4	6	4	66
44	JORDAN	4	6	4	66
45	KUWAIT	4	6	5	83
46	BANGLADESH	2	6	1	16
47	SOUTH AFRICA	2	6	4	66
48	BARBADOS	1	6	3	50
49	INDONESIA	3	5	2	40
50	MALTA	4	4	0	0
51	ILLEGAL	3	4	3	75
52	REP. OF KOREA	3	4	4	100
53	PHILLIPINES	1	4	3	75
54	MEXICO	2	3	3	100
55	SAUDI ARABIA	2	3	2	66
56	UNITED ARAB EMIRATES	2	3	1	33
57	ARGENTINA	1	3	2	66
58	ILLEGAL	1	3	0	0
59	SAN MARINO	1	3	0	0
60	BULGARIA	1	2	0	0
61	ETHIOPIA	1	2	0	0
62	MAURITIUS	1	2	2	100
63	NIGERIA	1	2	2	100
64	ZAMBIA	1	2	2	100