4. MEASURED RESULTS

4.1 INTRODUCTION

The ADS-B tests in Frankfurt yielded a large amount of recorded data. The recordings have been analyzed in a number of ways, with the goal of bringing to light the most useful results.

4.2 OVERVIEW

The results are organized as follows:

Environment. These measurements consist of fruit rate, interrogation rate, and number of aircraft. Aircraft counts are presented in several ways, showing the total number of aircraft in the airspace during the test periods, and showing the distribution in range and the distribution in altitude.

Air-to-Air Performance. These results cover the performance of the LDPU receiving system (MASPS Class A3) in providing air-to-air surveillance. After that, the subject is the L-3 Communications (formerly Honeywell) TCAS receiving system and its air-to-air surveillance performance. This receiving system is an enhanced TCAS system, intended for ranges in MASPS class A2. Its receiver sensitivity is midway between that of a standard TCAS and the enhanced sensitivity of a full-range class A3 system.

Air-to-Ground. These results address air-to-ground reception. Results are shown for tracks of the ADS-B equipped aircraft, and also using the "spaghetti plot" technique, which gives results for all of the Mode S aircraft flying at that time. Results are presented separately for the three receivers that were used for the air-ground measurements; the LDPU, the ANS-MAGS, and the ERA Receivers.

Ground-to-Air Measurements. The performance of transmissions of Extended Squitter messages from the ground stations, as received by the LDPU on N40 are presented to quantify the performance as a function range.

Benchmark performance. "Benchmark performance" is presented, which is intended to show the best achievable performance in this high-interference environment, that is, using a well-calibrated receiver implementing the optimum enhanced reception techniques for Extended Squitter signals. The benchmark performance results were obtained by processing the data recorded by the 1090 MHz Test Bed and the RMF.

Techniques have been developed to improve the reception of Extended Squitters in high ATCRBS fruit environments (Ref.16, Appendix I). The optimum configuration of these techniques has been implemented as a non-real time processor (known as the "gold standard"). Sampled live recordings from the Frankfurt measurements run on the gold standard will produce the best performance results that are currently achievable. The optimum performance as determined from this processing is presented in 4.7. It can be used as a benchmark to evaluate the performance of the realtime systems that participated in the test program.

Note that gaps in plotted data represent periods when no data was being recorded.

4.3 MEASUREMENTS OF THE INTERFERENCE ENVIRONMENT

A major objective of this test program was to make measurements of the interference environment in the Frankfurt airspace. It had been anticipated that the density of signal transmissions in the 1090 MHz band would be found to be quite high, possibly the highest in the world. The test plans called for measurements of reply, squitter, and fruit rates in the 1090 MHz band, and simultaneous measurements of interrogation rates in the 1030 MHz band. These environmental measurements were made at the same time as the performance measurements, in order to be able to correlate changes in performance, if any, to changes in the environment.

The sections that follow present the resulting signal reception rates, first for 1090 MHz (4.3.1), followed by receptions in the 1030 MHz band (4.3.2), and finally measurements of the density of aircraft that were airborne at the time of the measurements (4.3.3).

In many of the tests, N40 was placed in an oval flight path in the Frankfurt area, as shown in Figure 4.3.1-1. This was done in order to stay in the Frankfurt airspace, which was anticipated to be the area of maximum interference. As shown in the figure, north-south ovals were flown about half the time, and east-west ovals were flown otherwise.

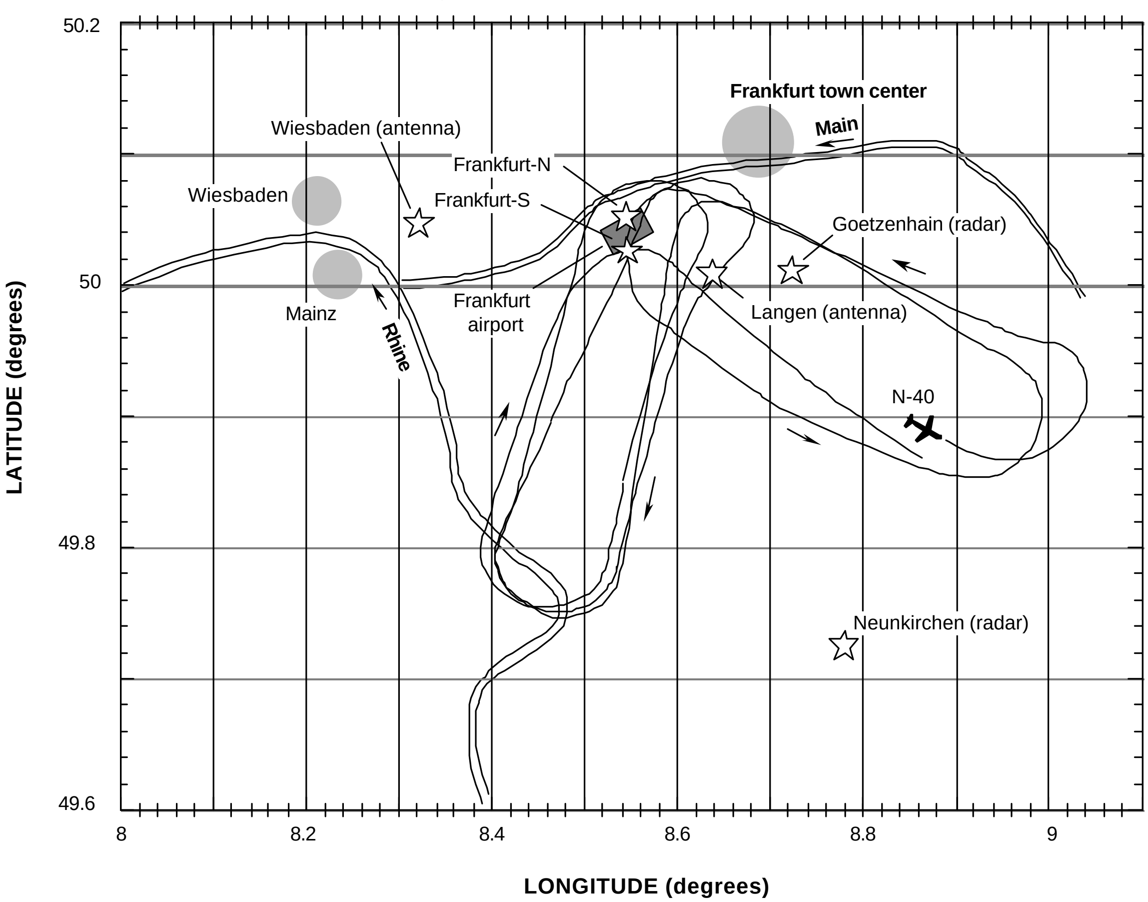


Figure 4.3.1-1. Oval Flight Path of N40, Staying in the Frankfurt High Density Area

4.3.1 Fruit Measurements

A large amount of data was recorded during the test series, including testing on five days and for several airborne hours on each day. In order to proceed systematically through the recorded data, and to coordinate the separate analyses being done by the different organizations, it was decided to focus initially on the 24 May data. This date was chosen because it was a test day with all 3 participating aircraft in the air and a requested shutdown of all military radars for the period 1100 to 1110 UTC.

The fruit rate results that follow are organized chronologically. After presenting the RMF fruit measurements for all five test days, corresponding AMF measurements are presented, followed by comparisons among the three instrumentation systems. The comparisons generally indicate good agreement, and support a conclusion that the fruit rate measurements in Germany were successful.

4.3.1.1 Detailed Fruit Rate Analysis

4.3.1.1.1 ATCRBS Fruit Results

4.3.1.1.1.1 RMF Measurements

The RMF was installed aboard the FAA aircraft (N40) and recorded 1090 MHz signals from top and bottom antennas simultaneously throughout all flights. All ATCRBS fruit rates based on RMF recordings are calculated as the average for a "two minute" segment selected for detailed analysis. Rates are presented as the total number of replies whose received power is greater than or equal to a designated threshold. Cumulative rates are calculated for threshold levels of -84dbm, -79dbm and -74dbm (referred to the antenna). A cumulative amplitude distribution is also presented so that the number of replies above any arbitrary level can be ascertained. The rates measured represent the rates after the elimination of "phantom" replies. Phantom replies are false replies created by combining pulses from overlapping ATCRBS replies from different aircraft that fall within the timing tolerance of the bracket detection logic.

4.3.1.1.1.1.1 19 May Measurements

Figure 4.3.1.1.1.1-1 shows the flight path for 19 May (Friday morning). The aircraft took off from Wiesbaden and made an orbit around the area at 12,000 ft as indicated. The aircraft then climbed to 22,000 ft (22k) for orbits near Frankfurt. Orbits were made in EW and NS directions at 22k before descending to 15k and 10k where orbits were also made in both directions. There was also a significant amount of time spent at 7k and 3k while waiting to land.

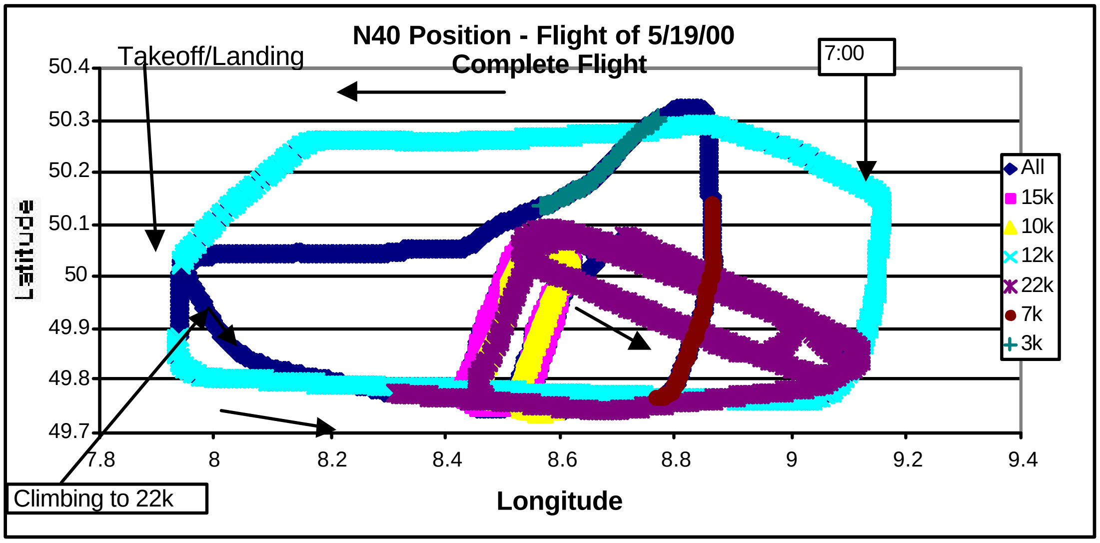


Figure 4.3.1.1.1.1-1. Flight Path of N40 on 19 May

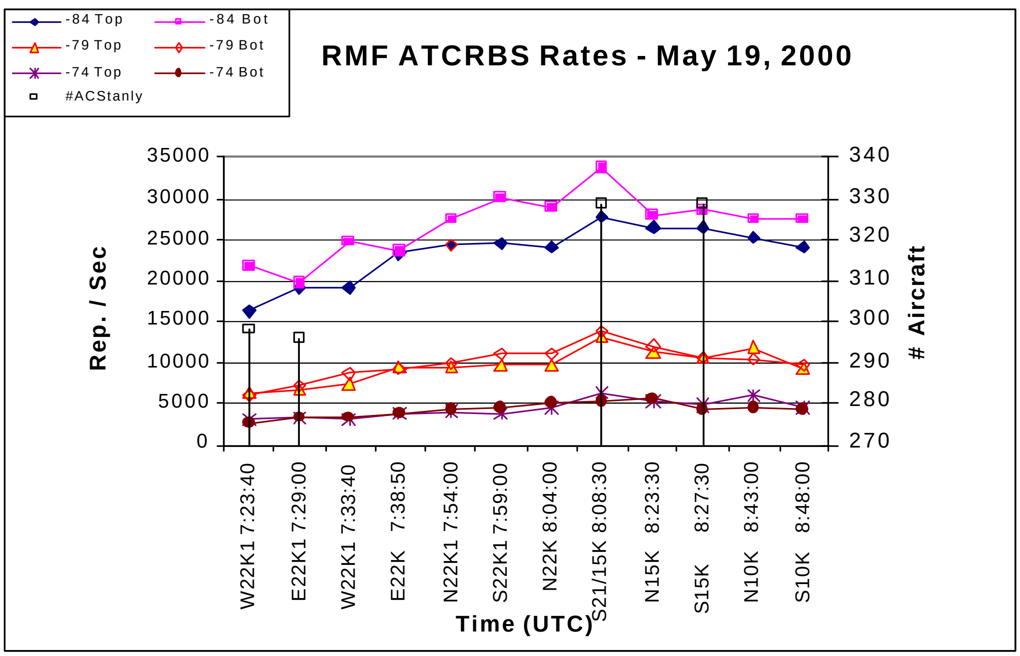


Figure 4.3.1.1.1.1-2. ATCRBS Fruit Rates on 19 May

Figure 4.3.1.1.1.1-2 shows the ATCRBS fruit rates at the levels of -84dbm, -79dbm and -74dbm as a function of "time" for the flight of 19 May. The fruit rates at -84dbm are always higher on the bottom antenna than the top. The highest rate was measured (33,700 replies/sec.) during the sample at 8:08:30 when the aircraft was in transition between 22k and 15k. The rates at the lower altitudes were relatively constant at approximately 28k on the bottom antenna and dropped slightly from 26k to 24k at lower altitudes on the top antenna.

The rates at -79dbm and -74dbm were nearly the same on both antennas. The lowest rate was measured during the first sample (7:23:40 to 7:25:40) at both levels. The rate was 6.1k at -79dbm and 2.8k at -74dbm. The maximum was also measured at the transition sample at these two levels. The rates at this time were 13.9k at -79dbm and 6.3k at -74dbm. The rates decreased to about the same level as that of the last sample at 22,000 ft (10k to 12k) when at the lower altitudes. The general trend of the rates, however, indicates that the rate was probably climbing throughout the test.

The number of aircraft seen by the ground radars increased from 298 at 7:23 to 330 at 8:30.

Figure 4.3.1.1.1.1-3 shows the amplitude distribution of ATCRBS replies for the top antenna of N40. The fruit rate at any amplitude may be obtained from this figure. The figure shows the minimum and maximum values measured during the data collection period of 19 May. The maximum value on the top antenna occurred during the transition from 22k to 15k during the sample at 8:08:30. The minimum rate occurred during the sample at 7:33:40. The maximum rate at -85dbm was 31.8k and the minimum was 22.7k. At -80dbm, the maximum was 15.4k and the minimum was 9.4k.

Figure 4.3.1.1.1.1-4 shows the amplitude distribution of ATCRBS replies for the bottom antenna of N40. The maximum rate at -85dbm was 36.1k and the minimum was 24.8k. At -80dbm, the maximum was 13.8k and the minimum was 8.7k.

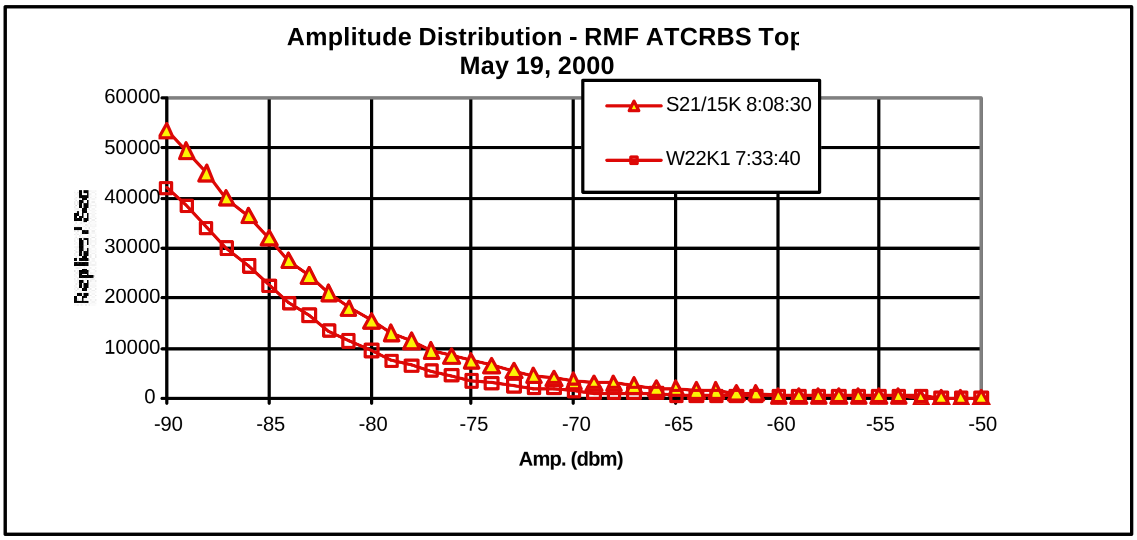


Figure 4.3.1.1.1.1-3. Top Antenna ATCRBS Fruit Amplitude Distribution on 19 May

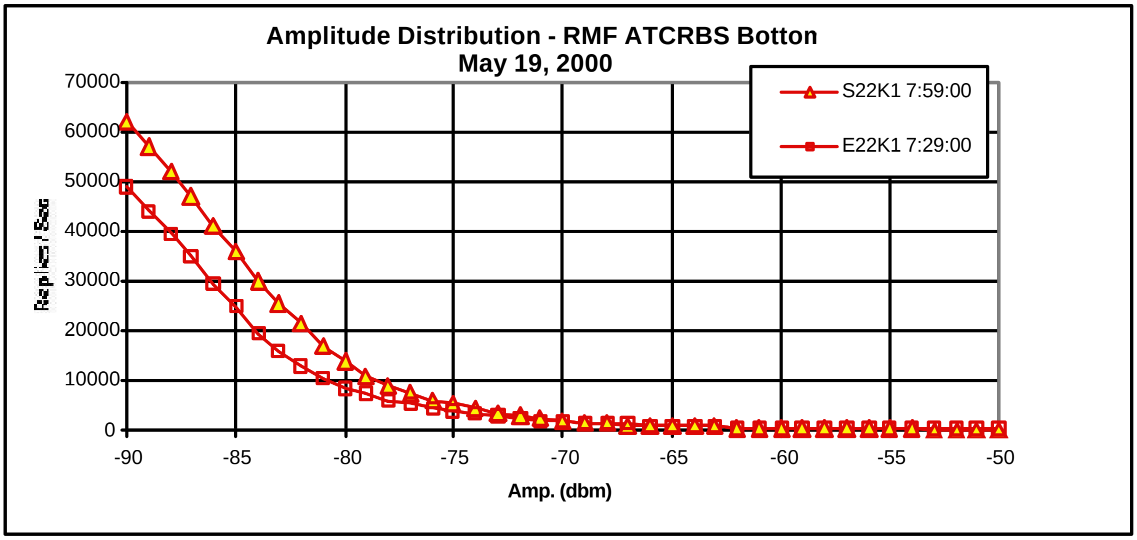


Figure 4.3.1.1.1.1-4. Bottom Antenna ATCRBS Fruit Amplitude Distribution on 19 May

4.3.1.1.1.1.2 20 May Measurements

Figure 4.3.1.1.1.2-1 shows the flight path for 20 May (Saturday afternoon). The aircraft again made orbits at (22k) near Frankfurt. Orbits were made in EW and NS directions.

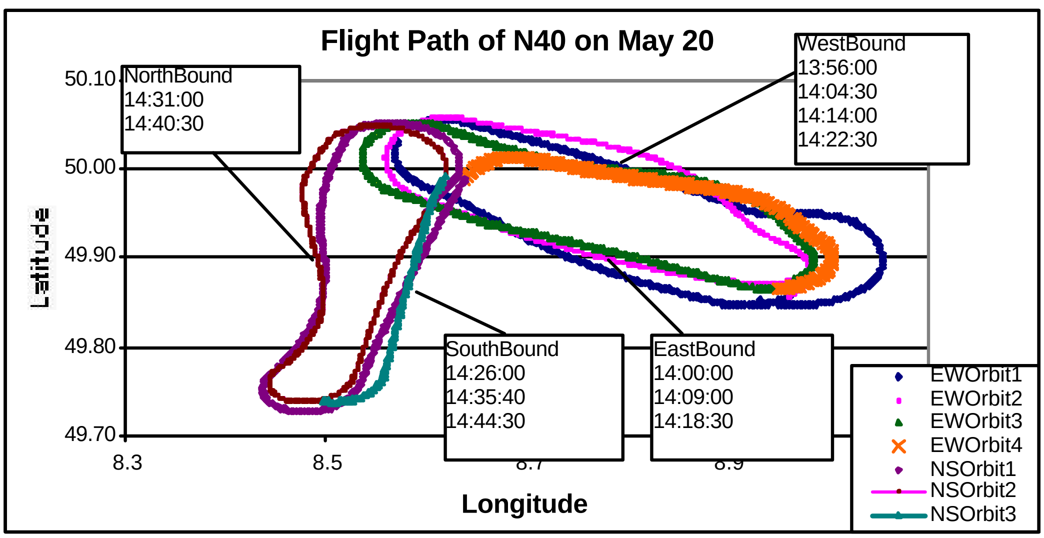


Figure 4.3.1.1.1.2-1. Flight Path of N40 on 20 May

Figure 4.3.1.1.1.2-2 shows the ATCRBS fruit rates at -84dbm, -79dbm and -74dbm as a function of time for the flight of 20 May. The ATCRBS fruit rates were significantly lower than on 19 May. They were also fairly constant throughout the test. The rate at a level of -84dbm or stronger varied from 14.1k to 18k. (Note that 19 May was a Friday and 20 May was a Saturday). They were also fairly constant throughout the test. The number of replies whose received power was -84dbm or stronger varied from 14.1k to 18k.

The cumulative rates at -79 and -74dbm were 7k and 3.5k respectively. The difference in rate when traveling a different direction does not seem to be the same as it was on 19 May. This data was taken on a Saturday afternoon, however, and that of 19 May was on a Friday morning.

Figure 4.3.1.1.1.2-3 shows the amplitude distribution of ATCRBS replies for the top antenna of N40 on 20 May. The variation between minimum and maximum is almost negligible except at very weak levels (< -85dbm). The rate at -85dbm was 18.1k while at -80dbm, it is 7.6k. There seems to be a concentration of targets at levels of approximately -75dbm.

Figure 4.3.1.1.1.2-4 shows the amplitude distribution of ATCRBS replies for the bottom antenna. The variation on this antenna is also negligible. The rate at -85dbm is 17.3k and at -80dbm it is 7.5k.

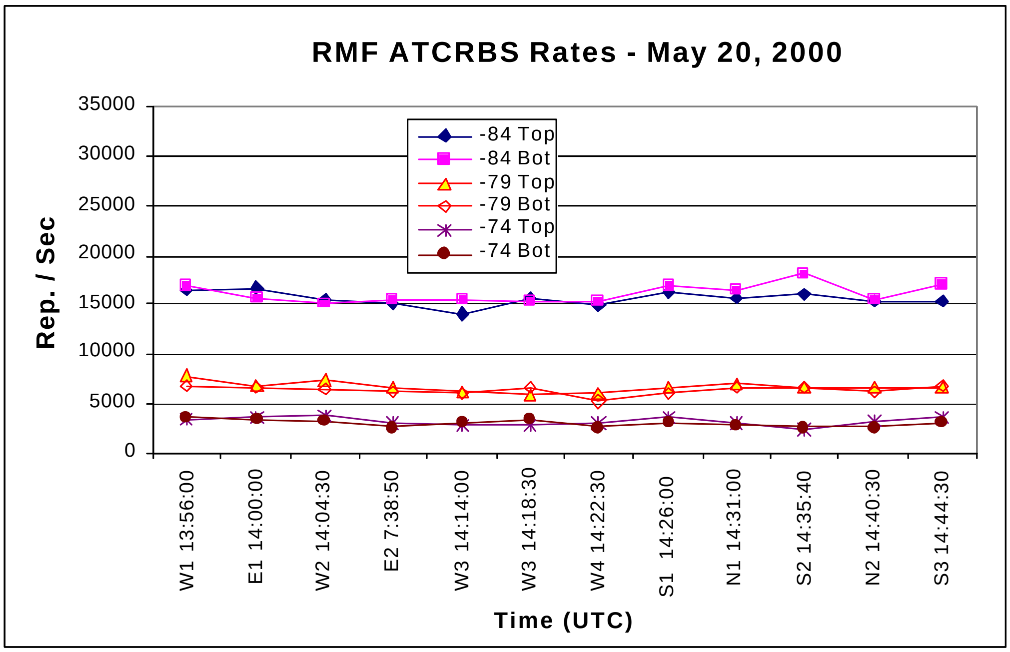


Figure 4.3.1.1.1.2-2. ATCRBS Fruit Rates on 20 May

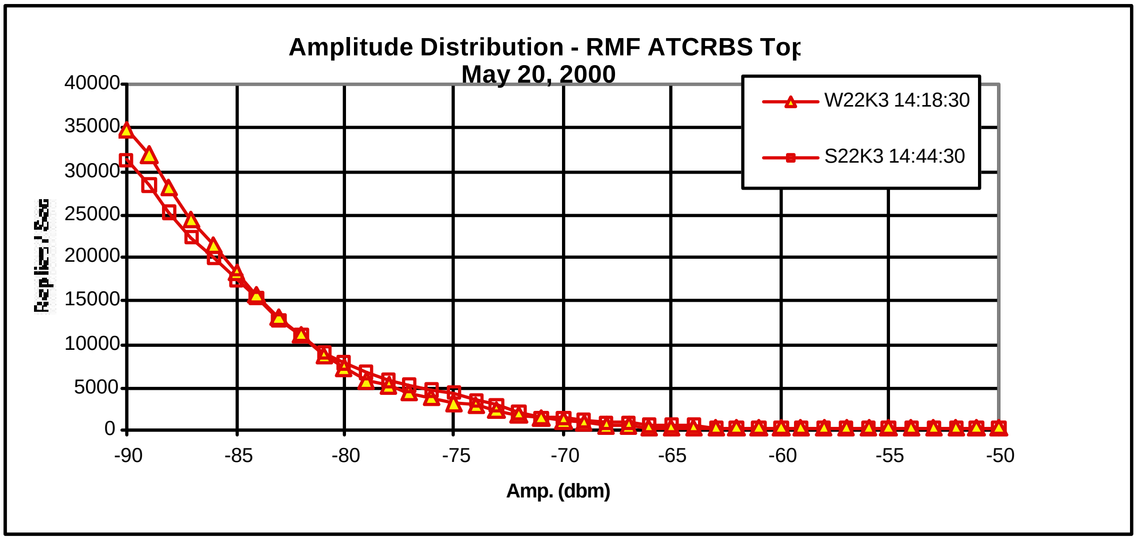


Figure 4.3.1.1.1.2-3. Top Antenna ATCRBS Fruit Amplitude Distribution on 20 May

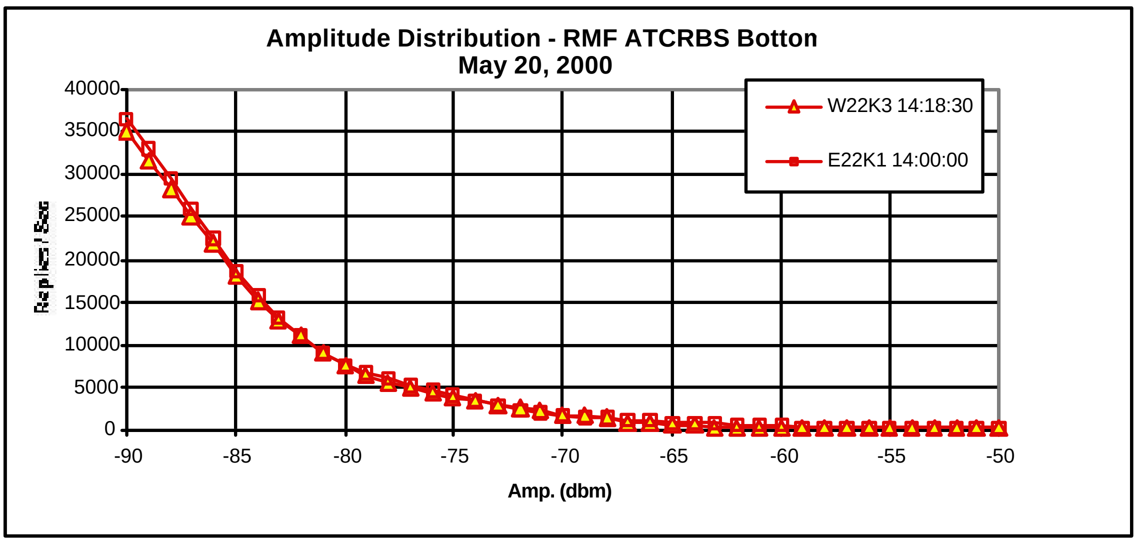


Figure 4.3.1.1.1.2-4. Bottom Antenna ATCRBS Fruit Amplitude Distribution on 20 May

4.3.1.1.1.1.3 22 May Measurements

Figure 4.3.1.1.1.3-1 shows the flight path for 22 May (Monday). N40 made a trip from Wiesbaden to Munich and back. There were no orbits as in the previous two days. The position of the aircraft during the data samples shown on the fruit rate plots is indicated by the blanks in the flight path.

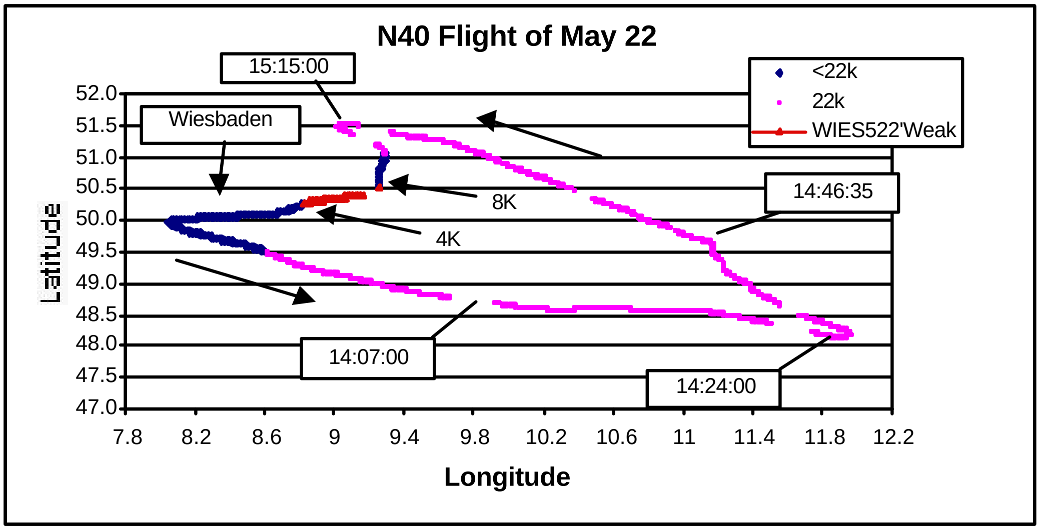


Figure 4.3.1.1.1.3-1. Flight Path of N40 on 22 May

Figure 4.3.1.1.1.3-2 shows the ATCRBS fruit rates at -84dbm, -79dbm and -74dbm as a function of time for the flight of 22 May. The highest fruit rate was measured during the sample at 14:07:00 when the aircraft was eastbound toward Munich. The rate was 20k on the top antenna and 17k on the bottom at -84dbm. The fruit rate at -84 on the top antenna is higher than the bottom when the aircraft is traveling eastbound. It is lower when traveling westbound. The lowest rate at -84 was measured at 14:21:00 on the bottom (11.5k) and at 14:30:00 on the top (12k). The aircraft was traveling in opposite directions for these two samples. The fruit rate at -79dbm varied from approximately 8k at 14:07:00 to 4.5k near Munich and then back up to about 7k when nearing Frankfurt on the return trip. The rates at a level of -74dbm or higher, show the same pattern (3.5k to 2k back to 3k).

Figure 4.3.1.1.1.3-3 shows the amplitude distribution of ATCRBS replies for the top antenna of N40 on 22 May. The maximum rate at -85dbm was 23.1k and the minimum was 13.9k. At -80dbm, the values were 9.9k and 5.1k respectively.

Figure 4.3.1.1.1.3-4 shows the amplitude distribution of ATCRBS replies for the bottom antenna of N40 on 22 May. The maximum rate at -85dbm was 22.2k and the minimum was 13.7k. At -80dbm, the values were 6.7k and 5.7k respectively.

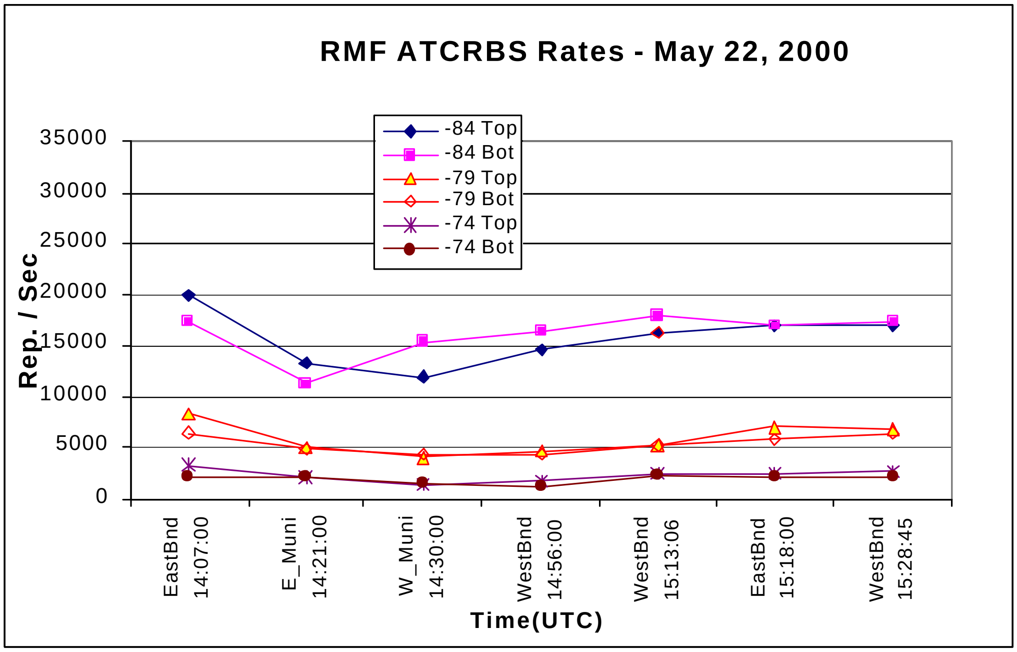


Figure 4.3.1.1.1.3-2. ATCRBS Fruit Rates on 22 May

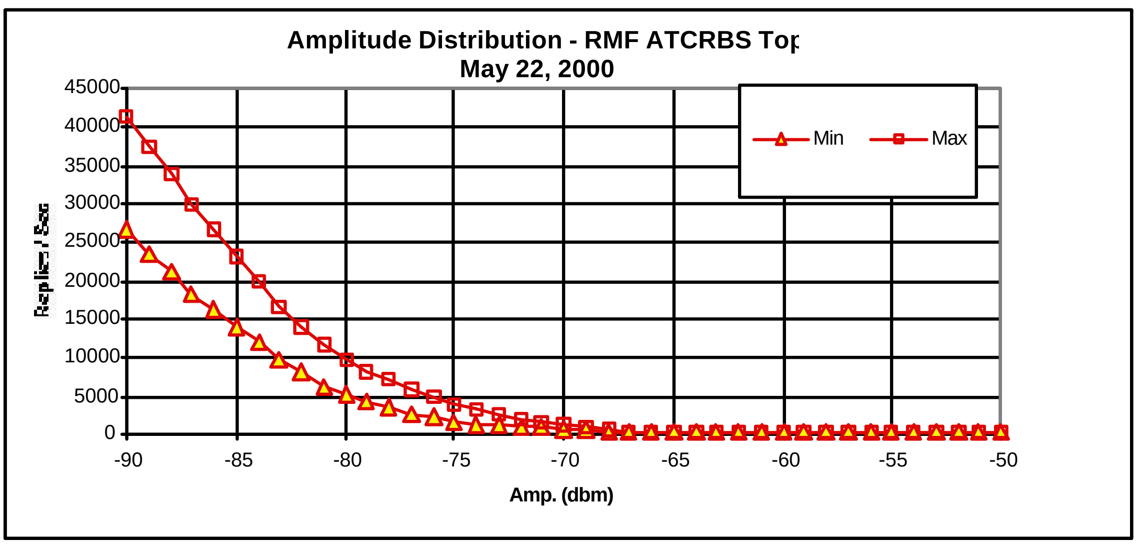


Figure 4.3.1.1.1.3-3. Top Antenna ATCRBS Fruit Amplitude Distribution on 22 May

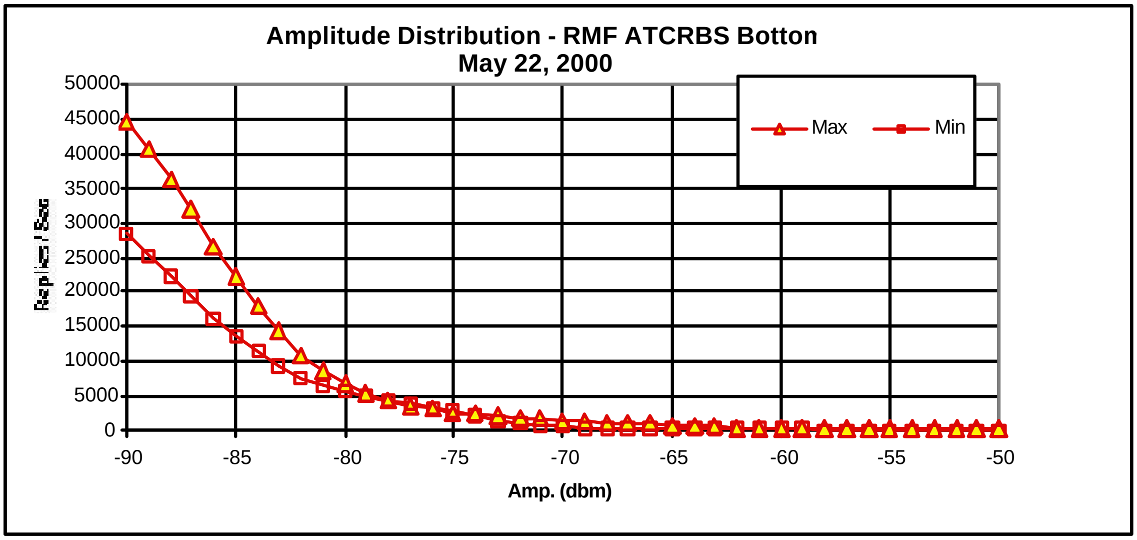


Figure 4.3.1.1.1.3-4. Bottom Antenna ATCRBS Fruit Amplitude Distribution on 22 May

4.3.1.1.1.1.4 24 May Measurements

Figure 4.3.1.1.1.4-1 shows the flight path for 24 May (Wednesday). Two sets of orbits in each direction (EW and NS) were completed during these tests with the Frankfurt airport near one end of the orbit. The data on the ATCRBS rate plots was taken only from non-maneuvering flight during the orbits.

The orbit sequence was EW, NS, EW, NS, and then EW (incomplete set). The aircraft was in the same location for the data of 1W at 10:46:00 and 4W at 11:43:00. Likewise, 1E corresponds to 4E etc.

Figure 4.3.1.1.1.4-2 shows a definite increase in fruit rate as a function of "time" for all cases. The increase seems to be from about 17k to 25k (at -84dbm) during the flight. The aircraft count from ground interrogator data is included on this figure. This data shows that the aircraft count increased from 300 at 10:47 to 328 at 12:42. The data was added to the nearest points of the RMF data. This is about a 10% increase in the number of aircraft. The fruit rate appears to increase more than that.

The fruit rate at -79dbm increases from approximately 7k to 10k during the flight. The rate at -74dbm increases from about 3k to 5k per second during the same period.

Figure 4.3.1.1.1.4-3 shows the amplitude distribution of ATCRBS replies for the top antenna of N40 on 24 May. The maximum rate at -85dbm was 29.2k and the minimum was 17.8k. At -80dbm, the values were 12.2k and 7.2k respectively.

Figure 4.3.1.1.1.4-4 shows the amplitude distribution of ATCRBS replies for the bottom antenna of N40 on 24 May. The maximum rate at -85dbm was 34.3k and the minimum was 19.1k. At -80dbm, the values were 12.9k and 7.8k respectively.

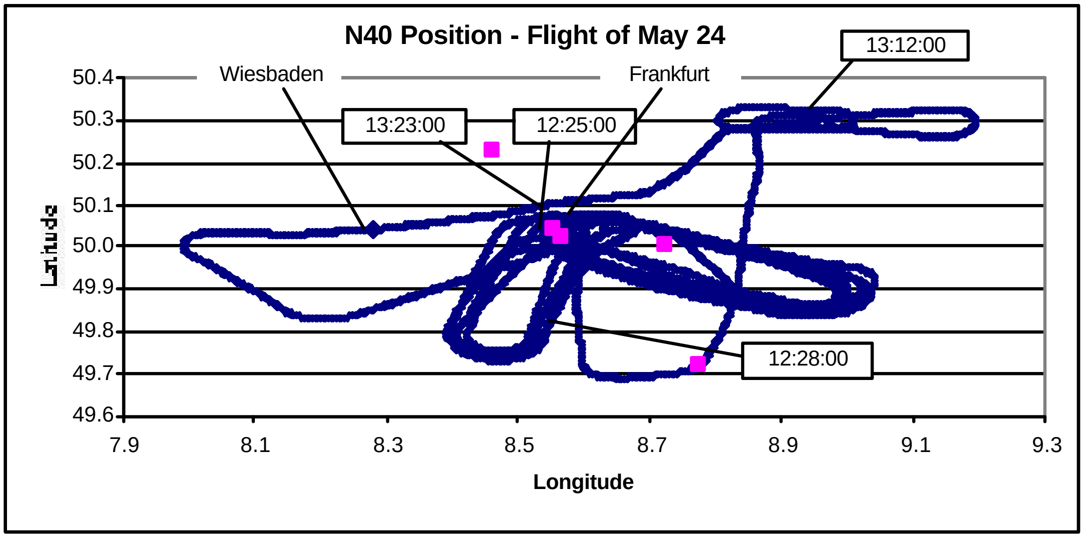


Figure 4.3.1.1.1.4-1. Flight Path of N40 on 24 May

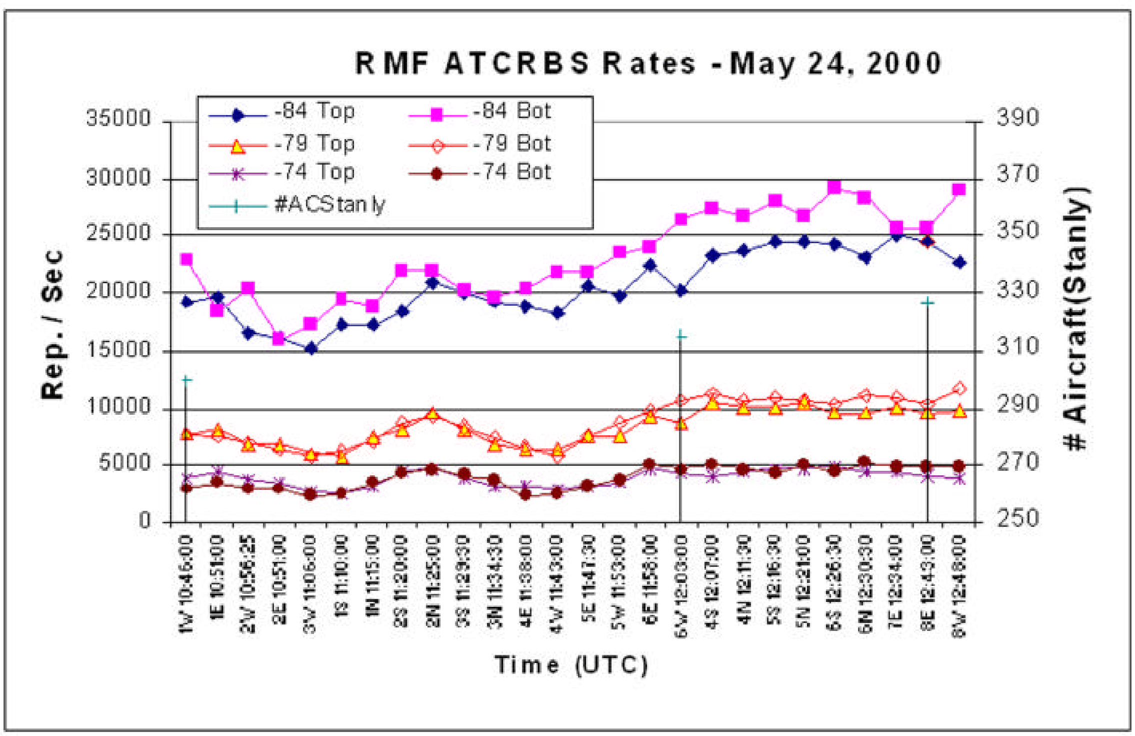


Figure 4.3.1.1.1.4-2. ATCRBS Fruit Rates on 24 May

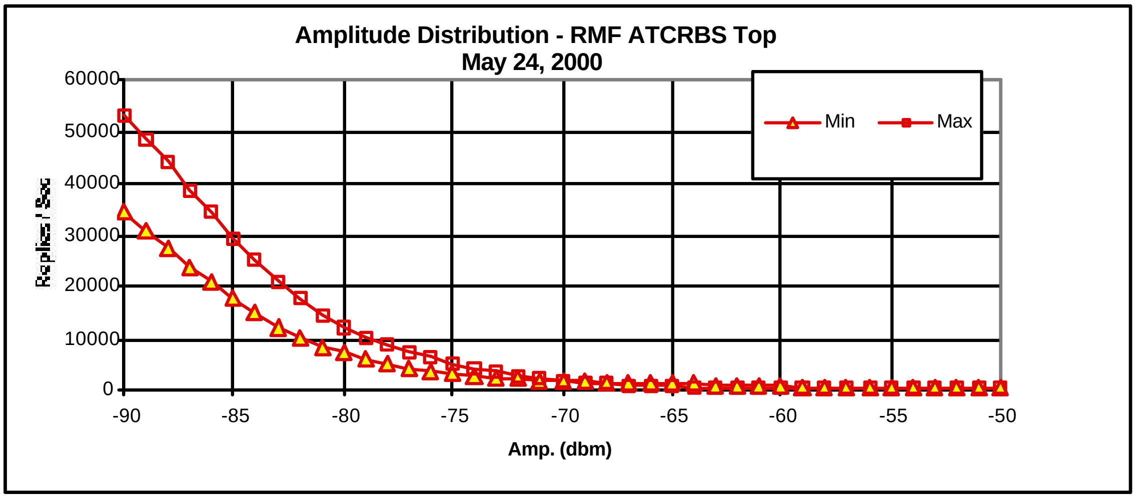


Figure 4.3.1.1.1.4-3 Top Antenna ATCRBS Fruit Amplitude Distribution, 24 May

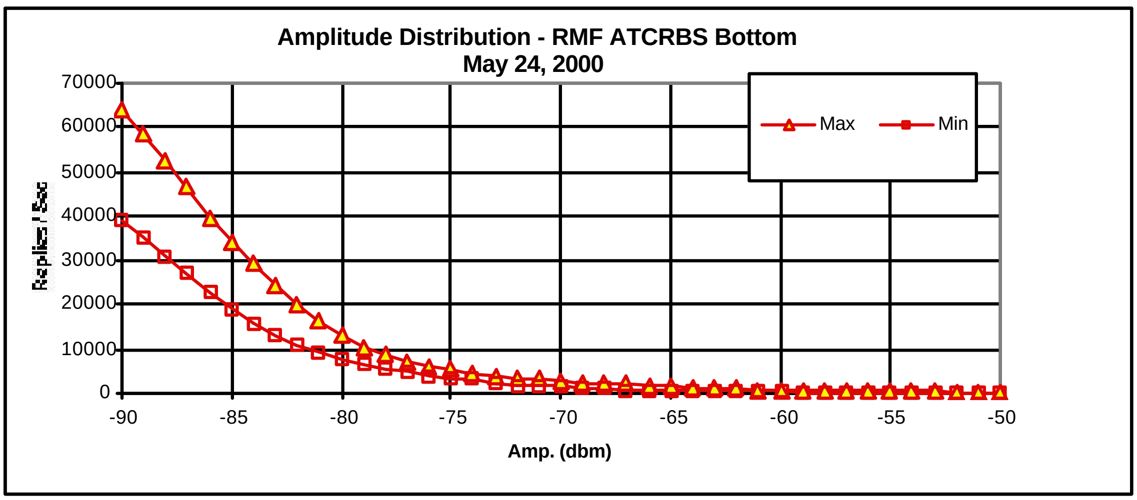


Figure 4.3.1.1.1.4-4. Bottom Antenna ATCRBS Fruit Amplitude Distribution, 24 May

4.3.1.1.1.1.5 25 May Measurements

Figure 4.3.1.1.1.5-1 shows the flight path for 25 May (Thursday). The first portion of the flight consisted of several orbits near Frankfurt. The gaps in the path represent the aircraft position during the data samples when away from the Frankfurt area.

The ATCRBS fruit rates are shown as a function of "time" on Figure 4.3.1.1.1.5-2. The ATCRBS rates are definitely higher on the westbound legs of the orbits near Frankfurt than the eastbound. They are also higher on the NS orbits than on the EW ones. The aircraft departed for Munich at 11:47. This corresponds with a significant drop in the ATCRBS fruit rates. The lowest rate measured was on the westbound leg from Munich at 12:14:00. The rate was 10k at a level of -84dbm, 3k at -79dbm and 1.5k at -74dbm.

Figure 4.3.1.1.1.5-3 shows the amplitude distribution of ATCRBS replies for the top antenna of N40 on 25 May. There are two distinct characteristics in this data. One set is when the aircraft is in the Frankfurt area doing the orbits. The other is when the aircraft is away from this area enroute to Munich. The maximum rate at -85dbm in the Frankfurt area, was 19.4k and the minimum was 17.8k. At -80dbm, the values were approximately 6.8k on both antennas. Away from the Frankfurt area, the maximum rate at -85dbm was 13.9k and the minimum was 9.6k. At -80dbm, it was 6.7k and 3.6k respectively.

Figure 4.3.1.1.1.5-4 shows the amplitude distribution of ATCRBS replies for the bottom antenna of N40 on 25 May. This data shows the same characteristics as the top antenna. The maximum rate at -85dbm in the Frankfurt area was 25.6k and the minimum was 20.6k. At -80dbm, the values were 9.8k and 7.1k respectively. Away from the Frankfurt area, the maximum rate at -85dbm was 17.4k and the minimum was 11.7k. At -80dbm, the values were 7.1k and 4.6k.

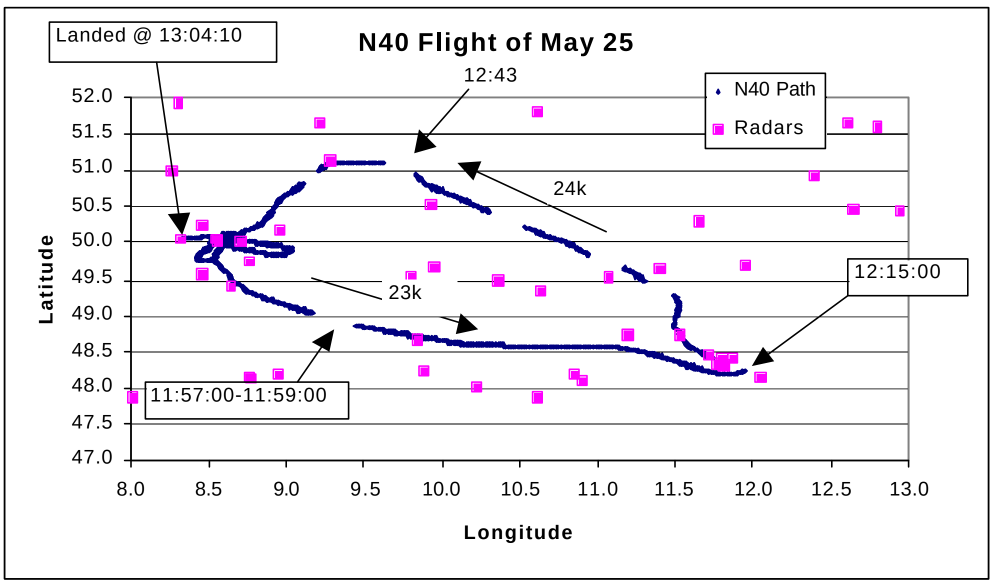


Figure 4.3.1.1.1.5-1. Flight Path of N40, 25 May

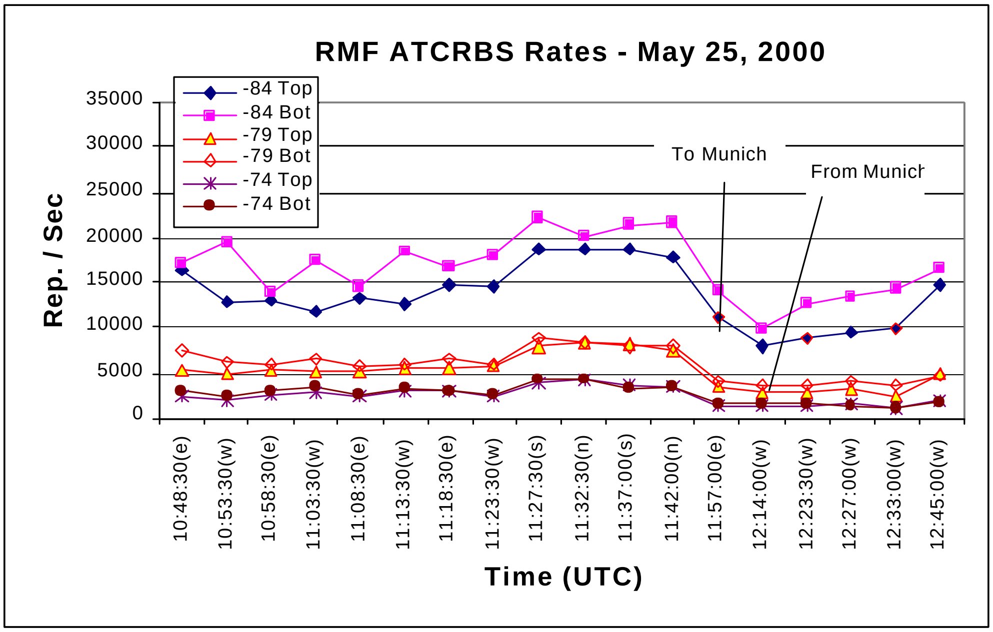


Figure 4.3.1.1.1.5-2. ATCRBS Fruit Rates on 25 May

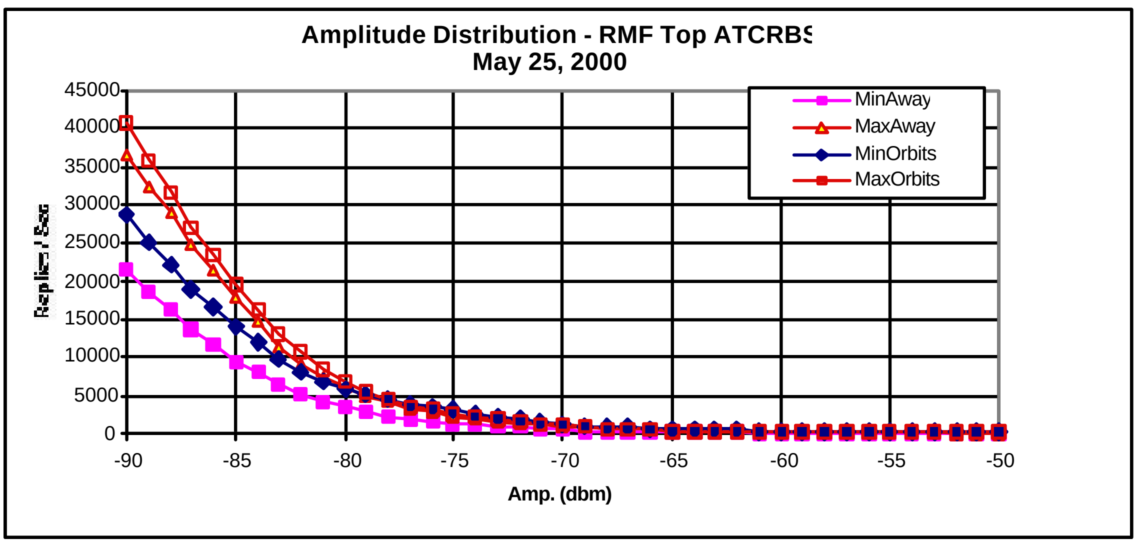


Figure 4.3.1.1.1.5-3. Top Antenna ATCRBS Fruit Amplitude Distribution, 25 May

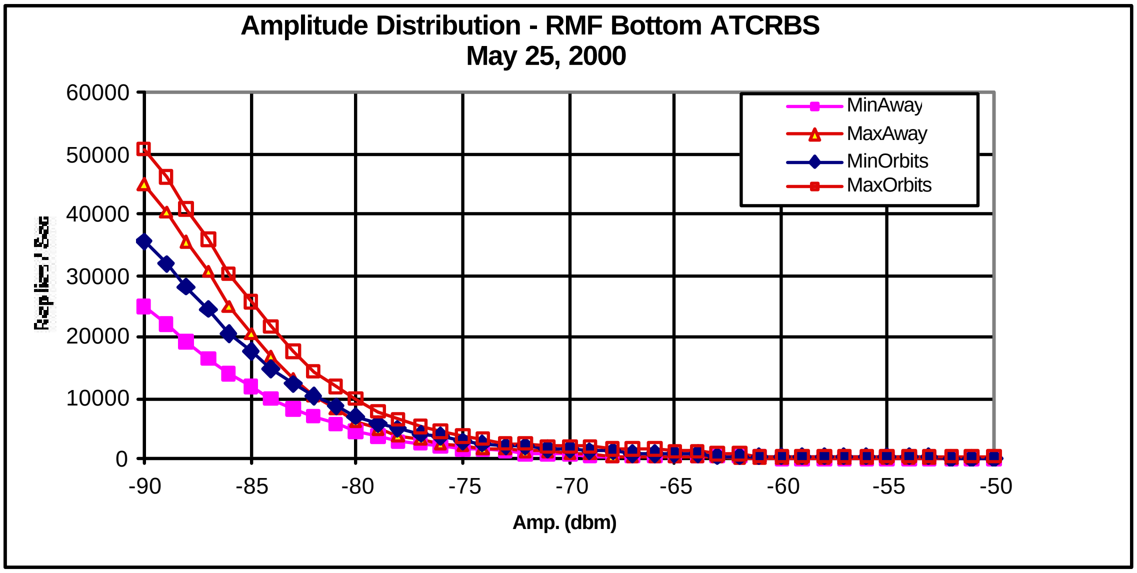


Figure 4.3.1.1.1.5-4. Bottom Antenna ATCRBS Fruit Amplitude Distribution, 25 May

4.3.1.1.1.2 AMF Measurements.

The AMF was also used to measure ATCRBS fruit received airborne on N40. Figure 4.3.1-3 shows the resulting fruit rates measured during the 24 May test. A threshold of -74 dBm referred to the antenna (as described in 2.2.1.10) was used for this data.

These results agree in a number of ways with the RMF measurements given above in Figure 4.3.1-1. Variations as a function of time are seen in both measurements: a dip in fruit rate occurred at about 11:10, and a gradual rise occurred between that time and 12:50. Also, both systems revealed a dramatic decrease in fruit rate from 12:50 to 13:10, which was when the aircraft was descending toward its landing. There is also agreement in the top-bottom difference. Both systems indicate that bottom-antenna fruit receptions were consistently higher than top-antenna receptions.

These agreements between the two systems add confidence to the results. The RMF and the AMF used different antennas, and also used different data processing techniques. As described in 2.2.1.5, the AMF fruit measurements made use of a gating technique, which required a compensating factor to be applied during post-mission data analysis. In spite of these differences, the results are seen to agree quite well.

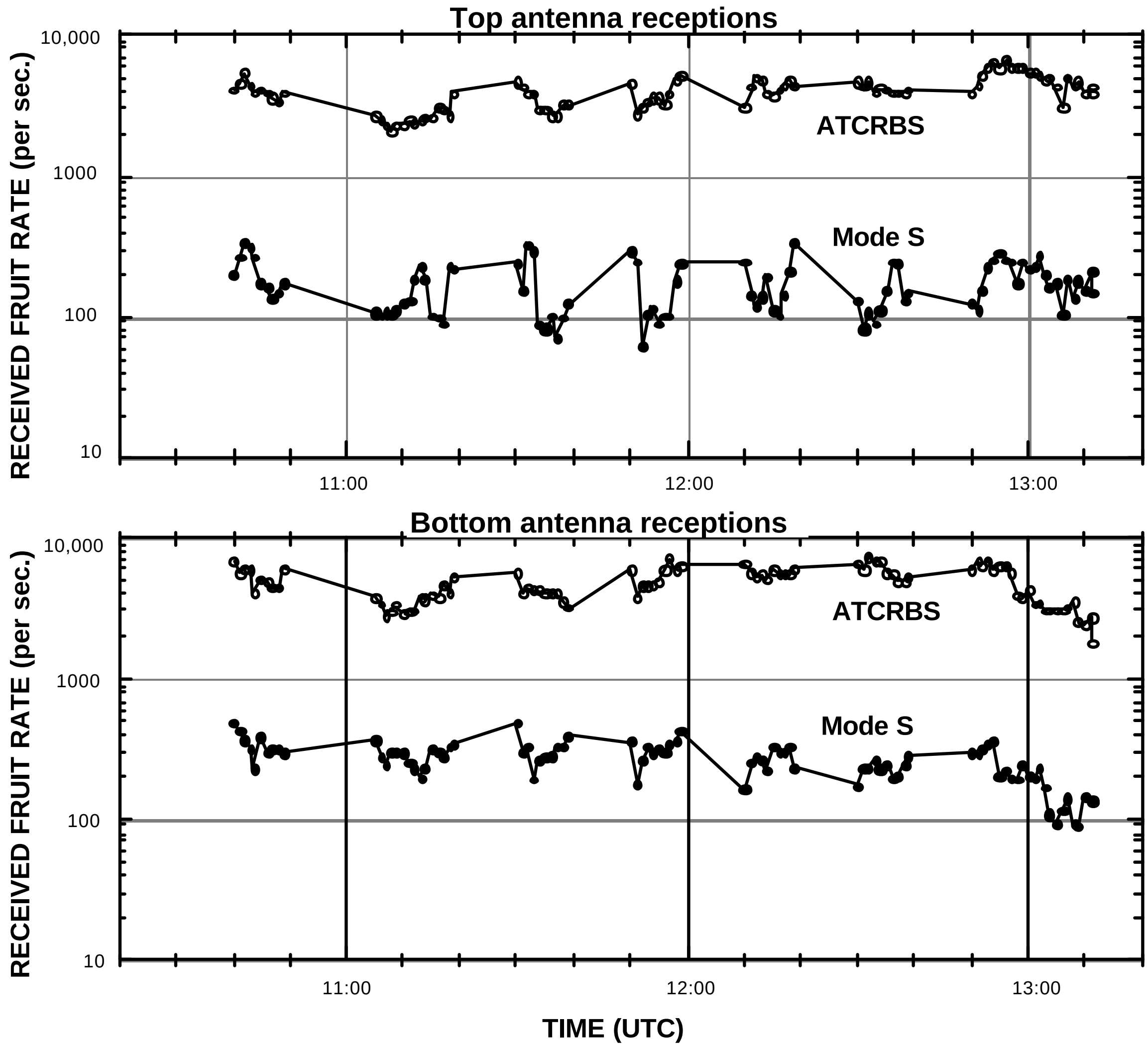


Figure 4.3.1-3. AMF ATCRBS Fruit Measurements, 24 May

(The gaps in fruit-rate data seen here were caused by the switching of AMF recording between 1090 MHz and 1030 MHz.)

4.3.1.1.1.3 Comparison among Instrumentation Systems

In making measurements of airborne ATCRBS fruit rate, it is important to accurately set the receiver threshold used in counting fruit. The need for this accuracy is seen in the steep variation of fruit rate as a function of threshold, which appears in Figure 4.3.1-2; if receiver threshold were uncertain to 3 dB, for example, the measured fruit rate would be uncertain to about 50%. The importance of accurate power calibration became clear in the previous program involving airborne measurements in the Los Angeles Basin (Ref. 10). At that time, many steps were taken to make calibration measurements on each instrumentation system, and later, to make comparisons among the measured values obtained. The same process was applied in the Frankfurt tests.

A specific time was chosen for comparison among the three instrumentation systems on the FAA aircraft. A time in which the 1090 MHz Test Bed was connected to the top antenna was used, and attention was limited to times in which all three systems were operating and recording data. Furthermore a time was selected in which the aircraft was flying straight and level. The comparison time was 11:16 UTC on 24 May.

Figure 4.3.1-4 shows the results of this comparison. Fruit rate measurements made by the RMF, and the AMF, and the 1090 MHz Test Bed are all plotted here in the form of the fruit power distribution. Similar measurements have been made in the form of fruit rate as a function of time. These indicate good agreement in the time-variation trends. For example, in the rate vs. time data in Figure 4.3.1-1, there is evidence of a consistent increase in fruit rates in the second hour as compared with the first hour. This trend appeared in all three systems.

The results in Figure 4.3.1-4 indicate fair agreement, although not perfect. Seeing that these measurements are not exactly the same, the authors have reviewed all of the steps involved in calibration. It is realized that some differences in fruit rate may be expected as a result of (1) the difference in antenna location (comparing the AMF with the other two systems), and (2) the differences in fruit sampling, especially the fact that the AMF measuring technique requires the receptions to be gated off 99 percent of the time, as described in 2.2.1.5. Furthermore there are other differences in fruit detection. Given that the absolute fruit rates in Frankfurt are quite high, the receptions contain many overlaps, which make it impossible to identify every individual signal. The algorithms used for fruit detection for RMF data and for 1090 MHz Test Bed data are not exactly the same. The results in this figure indicate that the fruit measurements are accurate to about 10 or 15 percent. Beyond that inaccuracy, the comparison provides confidence that all three systems are capable of making useful fruit measurements.

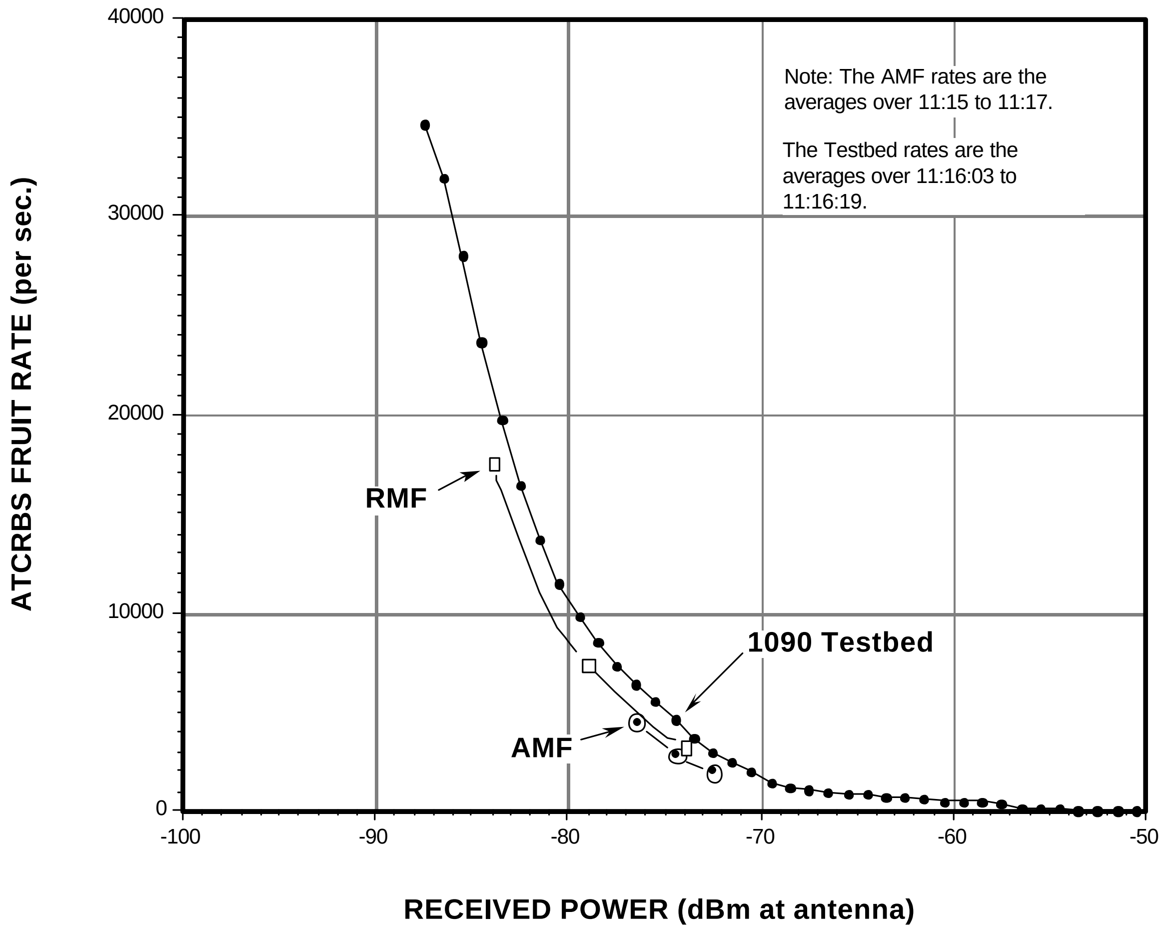


Figure 4.3.1-4. Comparison among Instrumentation Systems, 24 May

(Top Antenna Fruit Rate Measurements)

4.3.1.1.2 Mode S Fruit Results

4.3.1.1.2.1 RMF Fruit Rate Measurements

The RMF was installed aboard the FAA aircraft (N40) as described in 2.2.1.8. RMF measured Mode S fruit rates continuously for all flight test days. All 1090mhz signals from the top and bottom antennas were simultaneously recorded for the entire flight. All fruit rates given are the average for a "two minute" segment selected for detailed analysis. Rates are given at levels of -84dbm, -79dbm and -74dbm (referred to the antenna). An amplitude distribution is also presented so that the rate at any desired level can be ascertained. The counts in all cases consist of replies at and above the selected level.

4.3.1.1.2.1.1 19 May Measurements

Refer to Figure 4.3.1.1.1.1.1-1 for the flight path for 19 May (Friday morning). The aircraft took off from Wiesbaden and made an orbit around the area at 12,000 ft as indicated. The aircraft then climbed to 22,000 ft (22k) for orbits near Frankfurt. Orbits were made in EW and NS directions at 22k before descending to 15k and 10k where orbits were also made in both directions. There was also a significant amount of time spent at 7k and 3k while waiting to land.

Figure 4.3.1.1.2.1.1-1 shows the Mode S fruit rates at the levels of -84dbm, -79dbm and -74dbm as a function of "time" for the flight of 19 May. The fruit rates are always higher on the bottom antenna than the top until the lower altitude runs at the end of the test. At 10kft, the rates are almost the same on both antennas. The Mode S fruit rate varied from 750/sec to 1200/sec at a level of -84dbm or greater. At -79dbm or greater, the rate varied from 280/sec to 680/sec. At -74dbm or greater, the rate varied from 122/sec to 515/sec.

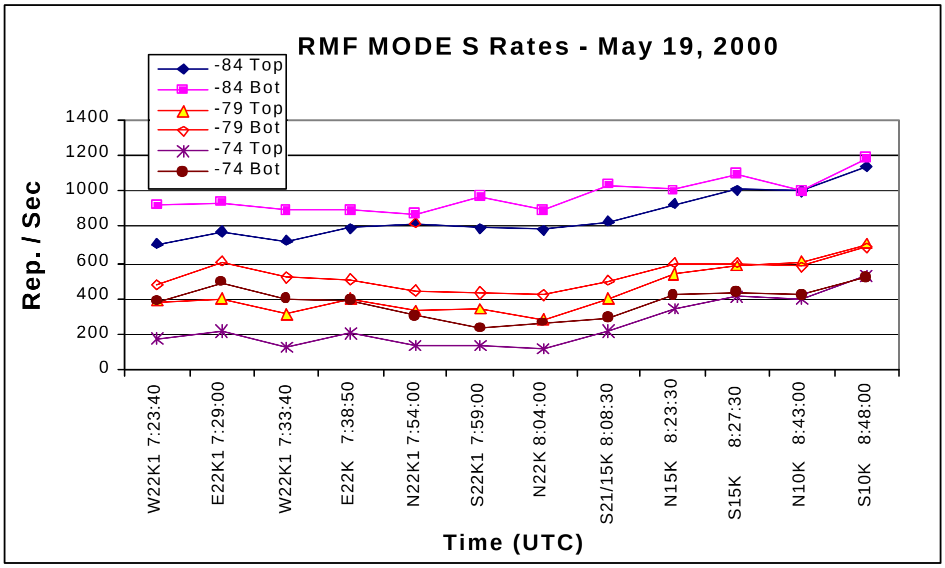


Figure 4.3.1.1.2.1.1-1. Mode S Fruit Rates, 19 May

The highest average rate for the samples at 22k, at -84dbm occurred on the bottom antenna. It was 910/sec. The average rate on the top antenna during these samples was 770 replies per second.

Figure 4.3.1.1.2.1.1-2 shows the amplitude distribution of Mode S replies for the top antenna of N40. This data clearly shows two different characteristics as a function of aircraft altitude. The series tagged "Min" and "Max" were selected for their values at -84dbm. The curve labeled Max22k actually shows a lower value at stronger signals than -80dbm than the one labeled "Min22kft. The values at 22kft are considerably less than at 10kft. The maximum rate at -85dbm (when the aircraft was at 22kft) was 937 replies/sec and the minimum was 794. At -80dbm, the maximum was 450 and the minimum was 408. The maximum rate at -85dbm (when the aircraft was at 10kft) was 1220 and the minimum was 1096. At -80dbm, the maximum was 763 and the minimum was 640.

The "hump" at -70dbm to -75dbm on the top antenna indicates a high percentage of targets of this amplitude that are above N40 when it descends to 10kft.

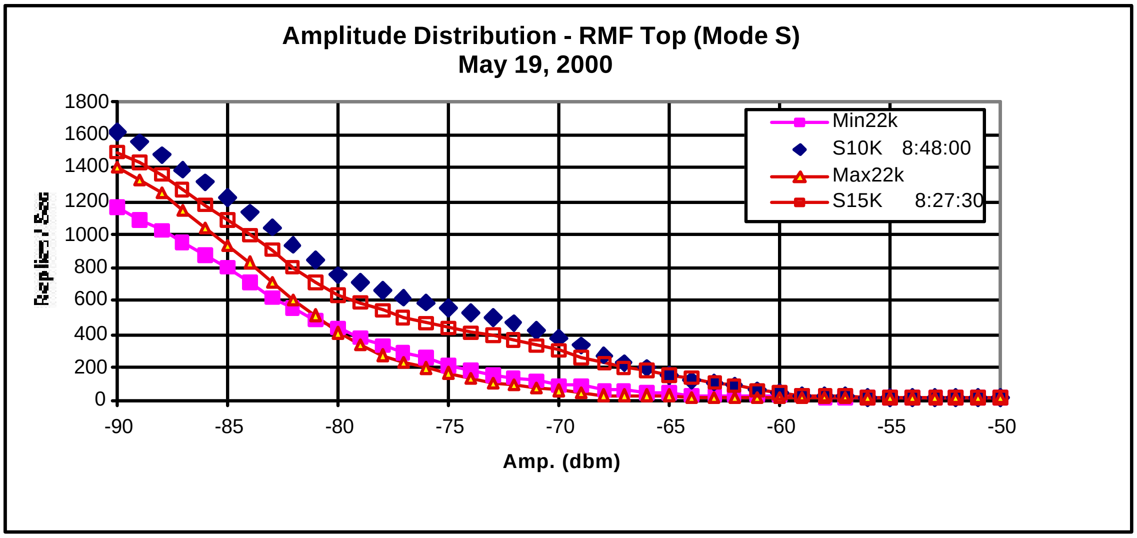


Figure 4.3.1.1.2.1.1-2. Top Antenna Mode S Fruit Amplitude Distribution, 19 May

Figure 4.3.1.1.2.1.1-3 shows the amplitude distribution of Mode S replies for the bottom antenna of N40. This data also shows two distinct sets of data. The maximum rate at -85dbm (when the aircraft was at 22kft) was 1169 replies/sec and the minimum was 1025. At -80dbm, the maximum was 622 and the minimum was 586. The maximum rate at -85dbm (when the aircraft was at 10kft) was 1358 and the minimum was 1257. The rates at -80dbm, were 840 (maximum) and 770 (minimum).

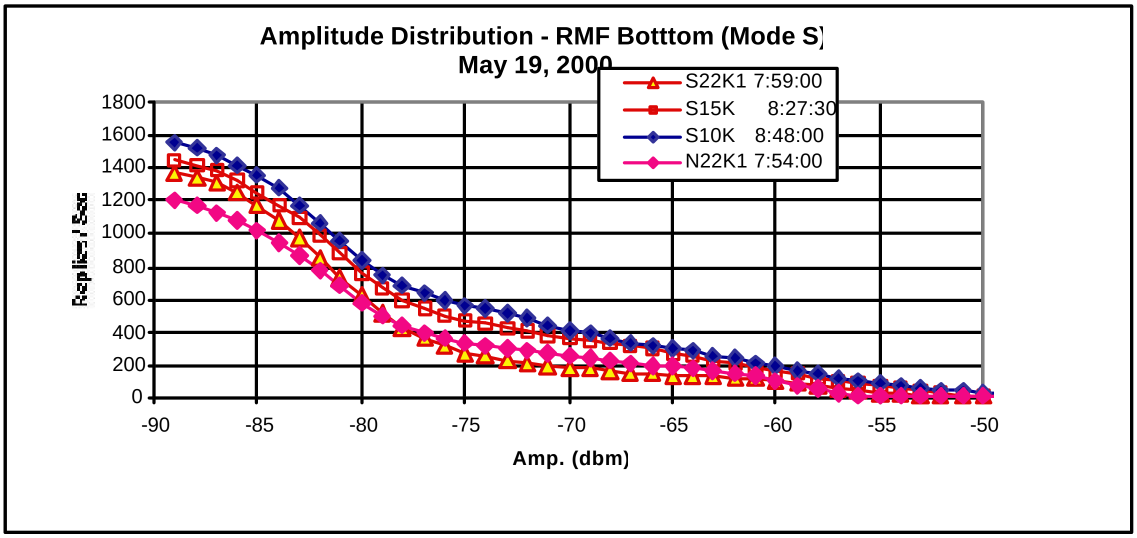


Figure 4.3.1.1.2.1.1-3. Bottom Antenna Mode S Fruit Amplitude Distribution, 19 May

4.3.1.1.2.1.2 20 May Measurements

Refer to Figure 4.3.1.1.1.1.2-1 for the flight path on 20 May (Saturday afternoon). The aircraft again made orbits at (22k) near Frankfurt. Orbits were made in EW and NS directions.

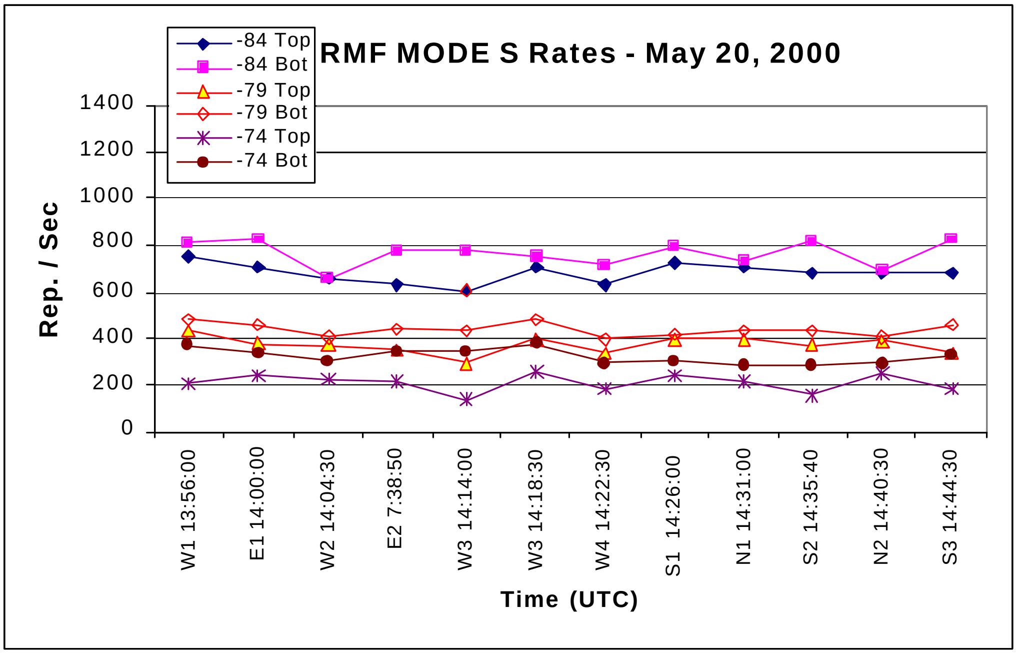


Figure 4.3.1.1.2.1.2-1. Mode S Fruit Rates, 20 May

Figure 4.3.1.1.2.1.2-1 shows the Mode S fruit rates at -84dbm, -79dbm and -74dbm as a function of "time" for the flight of 20 May. The data from 20 May seems more constant. All samples were taken at 22k. The highest average rate at -84dbm was on the bottom antenna (766/sec). The average rate on the top antenna was 682 replies per second. The average rates at -79dbm were 437 replies/second (bottom) and 371 replies/sec. (top). The average rates at -74dbm were 322 replies/second (bottom) and 208 replies/sec. (top).

Figure 4.3.1.1.2.1.2-2 shows the amplitude distribution of Mode S replies for the top antenna of N40 on 20 May. The variation between minimum and maximum is very small. The rate at -85dbm varied from 706 to 798. The rate at -80dbm varied between 387 and 435 replies/second.

Figure 4.3.1.1.2.1.2-3 shows the amplitude distribution of Mode S replies for the bottom antenna. The rate is higher than on the top and the variation on this antenna is also small. The rate at -85dbm varied from 803 to 1012. The rate at -80dbm varied from 482 to 552.

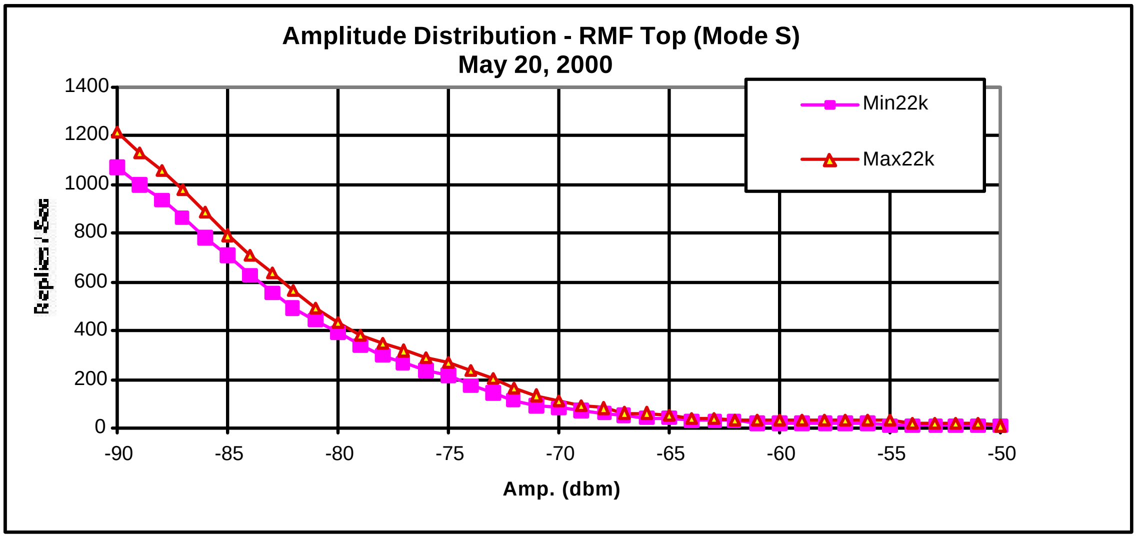


Figure 4.3.1.1.2.1.2-2. Top Antenna Mode S Fruit Amplitude Distribution on 20 May

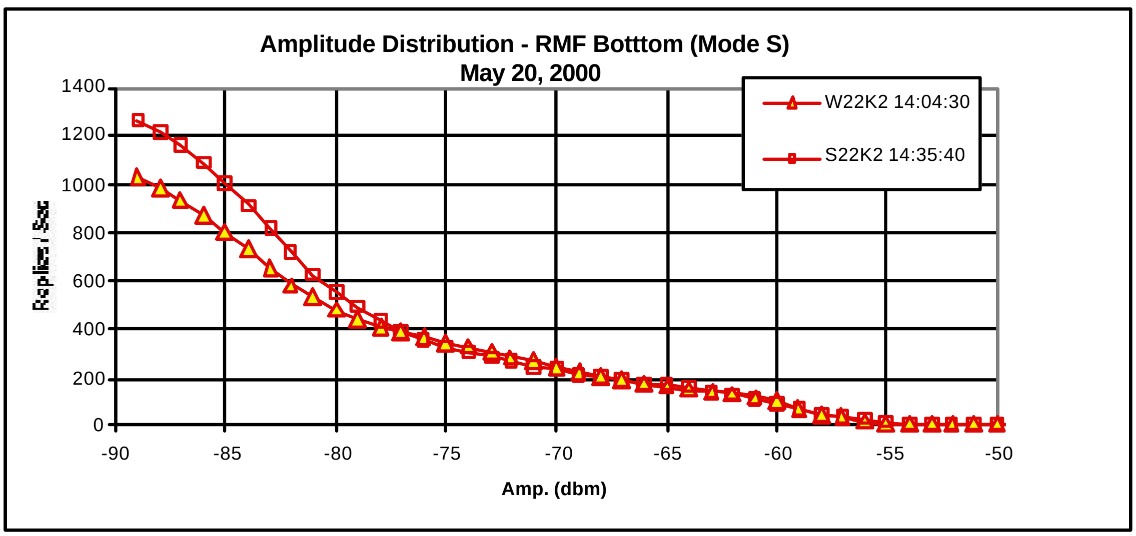


Figure 4.3.1.1.2.1.2-3. Bottom Antenna Mode S Fruit Amplitude Distribution, 20 May

4.3.1.1.2.1.3   22 May Measurements

Refer to Figure 4.3.1.1.1.1.3-1 for the flight path of N40 during the tests of 22 May. N40 made a trip from Wiesbaden to Munich and back. There were no orbits as in the previous two days. The position of the aircraft during the data samples shown on the fruit rate plots is indicated by the blanks in the flight path.

Figure 4.3.1.1.2.1.3-1 shows the Mode S fruit rates at -84dbm, -79dbm and -74dbm as a function of "time" for the flight of 22 May. The Mode S rates are higher on the top antenna when traveling east toward Munich. When traveling west, the rates are either the same or higher on the bottom antenna. The aircraft altitude when traveling east toward Munich was 23k. On the return trip (westbound), it was 24k. The average rates were 630 replies per second at -84dbm, 272 replies per second at -79dbm and 106 replies/second at -74dbm.

Figure 4.3.1.1.2.1.3-2 shows the amplitude distribution of Mode S replies for the top antenna of N40 on 22 May. The rate at -85dbm varied from 664 to 704 replies/sec. The rate at -80dbm varied from 330 to 360 replies/sec.

Figure 4.3.1.1.2.1.3-3 shows the amplitude distribution of Mode S replies for the bottom antenna of N40 on 22 May. The rate at -85dbm varied from 522 to 899 replies/sec. The rate at -80dbm varied from 328 to 393 replies/sec. This plot also shows a concentration of targets larger than -75dbm.

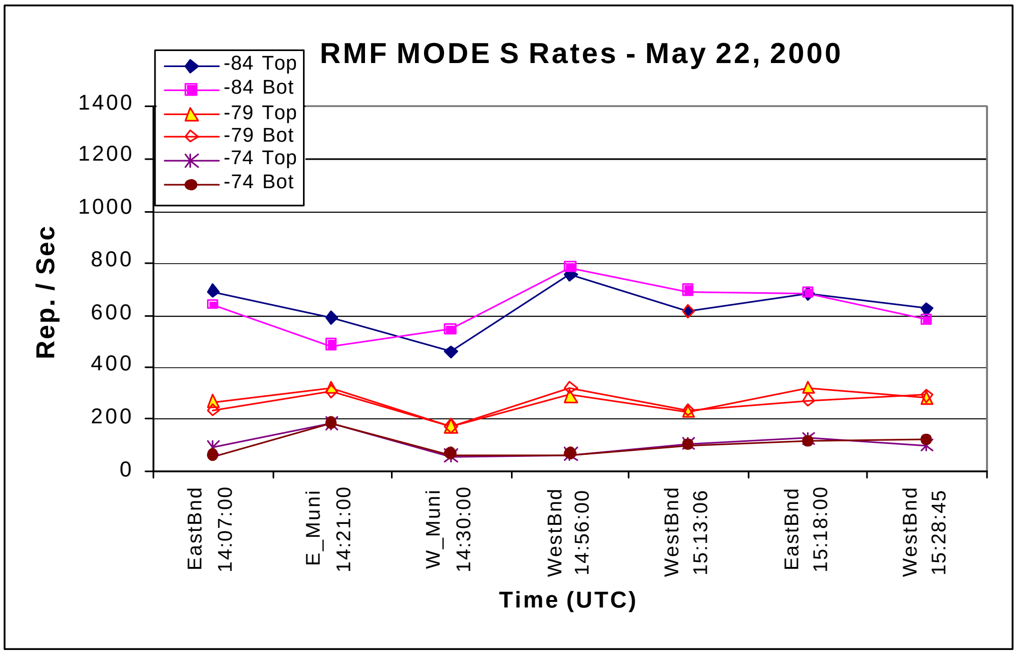


Figure 4.3.1.1.2.1.3-1. Mode S Fruit Rates, 22 May

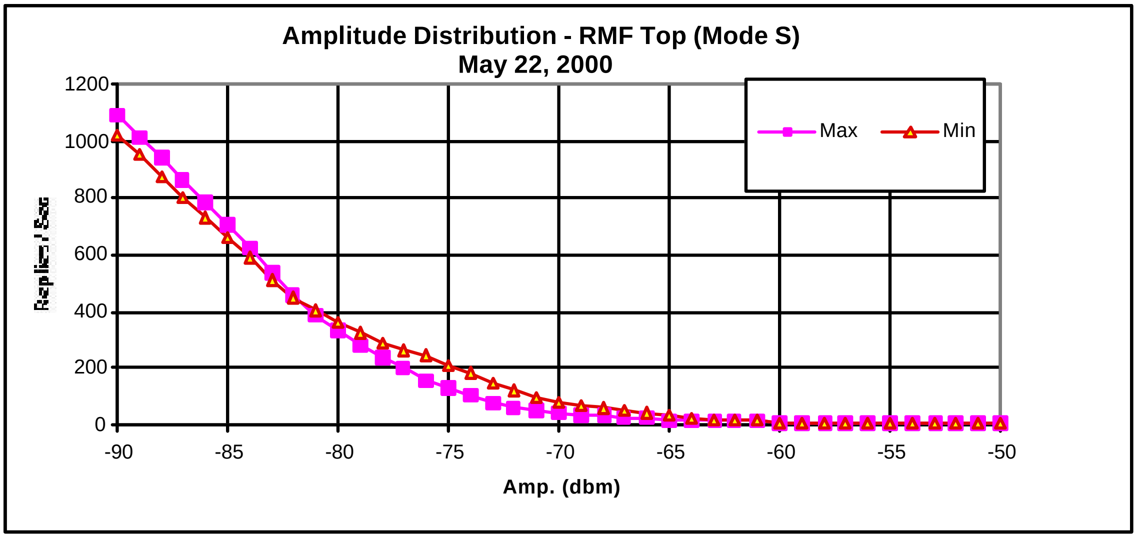


Figure 4.3.1.1.2.1.3-2. Top Antenna Mode S Fruit Amplitude Distribution on 22 May

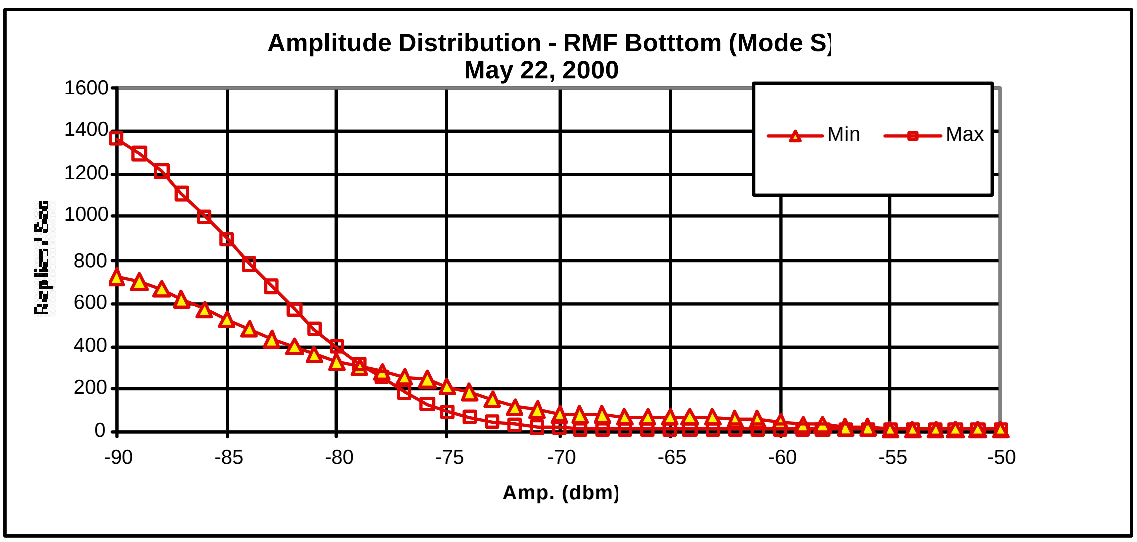


Figure 4.3.1.1.2.1.3-3. Bottom Antenna Mode S Fruit Amplitude Distribution, 22 May

4.3.1.1.2.1.4 24 May Measurements

Refer to Figure 4.3.1.1.1.1.4-1 for the flight path for 24 May. Two sets of orbits in each direction (EW and NS) were completed during these tests with the Frankfurt airport near one end of the orbit. The data on the fruit rate plots was taken only from the orbits.

The orbit sequence was EW, NS, EW, NS, and then EW (incomplete set). The aircraft was in the same location for the data of 1W at 10:46:00 and 4W at 11:43:00. Likewise, 1E corresponds to 4E etc.

Figure 4.3.1.1.2.1.4-1 shows the Mode S fruit rates as a function of time for the orbits of 24 May. The rates were fairly constant throughout the time of data collection. The average rate for a level of -84dbm was 1036 replies/sec on the bottom and 862 on the top. The rates at -79dbm were 557 and 411. At -74dbm, they were 389 and 207. The rates are generally higher when the direction of flight was toward Frankfurt (north and west) legs of the orbits.

Figure 4.3.1.1.2.1.4-2 shows the amplitude distribution of Mode S replies for the top antenna of N40 on 24 May. The rate at -85dbm varied from 928 to 1097 replies per second. The rate at -80dbm varied from 365 to 621.

Figure 4.3.1.1.2.1.4-3 shows the amplitude distribution of Mode S replies for the bottom antenna of N40 on 24 May. The rate at -85dbm varied from 1009 to 1360 replies per second. The rate at -80dbm varied from 555 to 694 replies/sec. The distribution of replies from the bottom antenna shows a significant number of replies of about -65dbm.

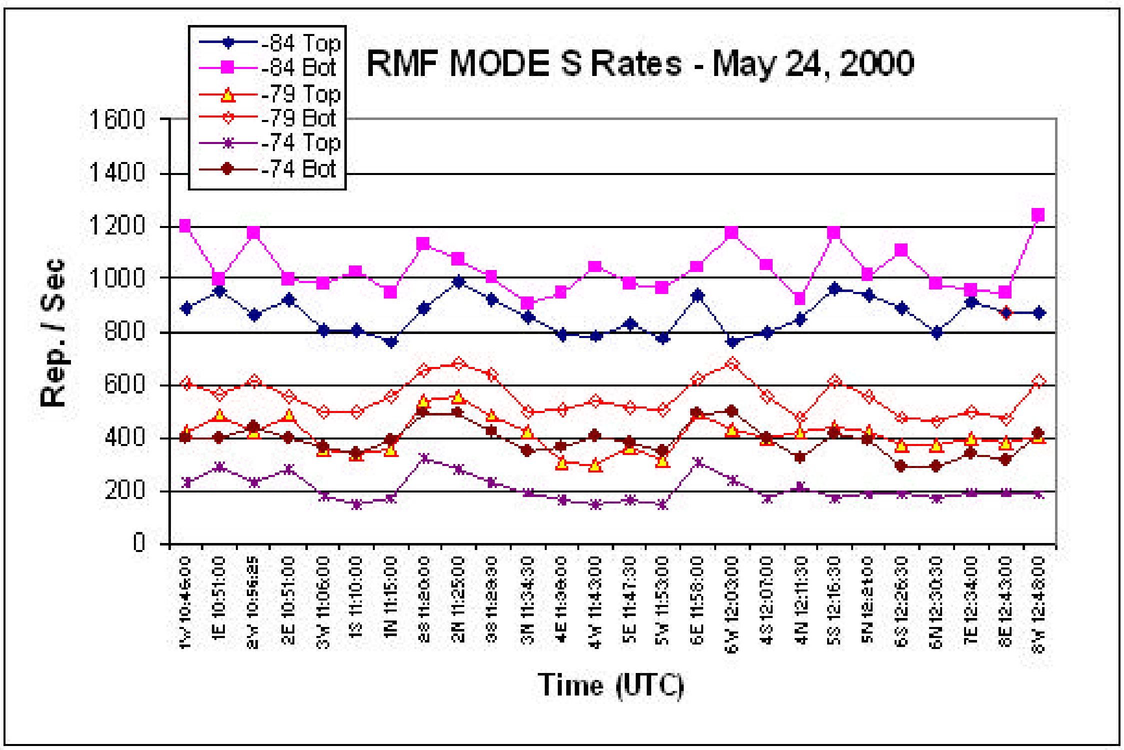


Figure 4.3.1.1.2.1.4-1. Mode S Fruit Rates, 24 May

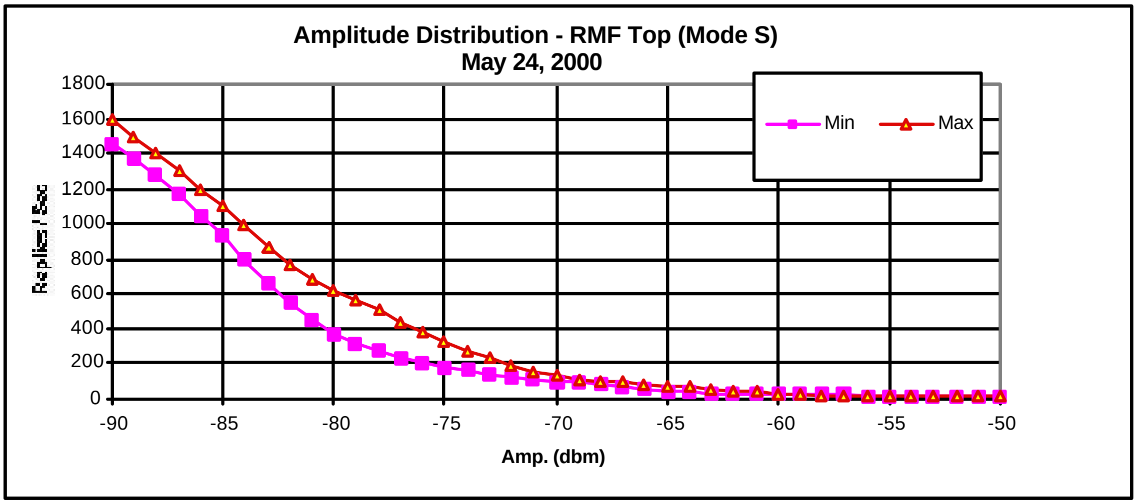


Figure 4.3.1.1.2.1.4-2. Top Antenna Mode S Fruit Amplitude Distribution, 24 May

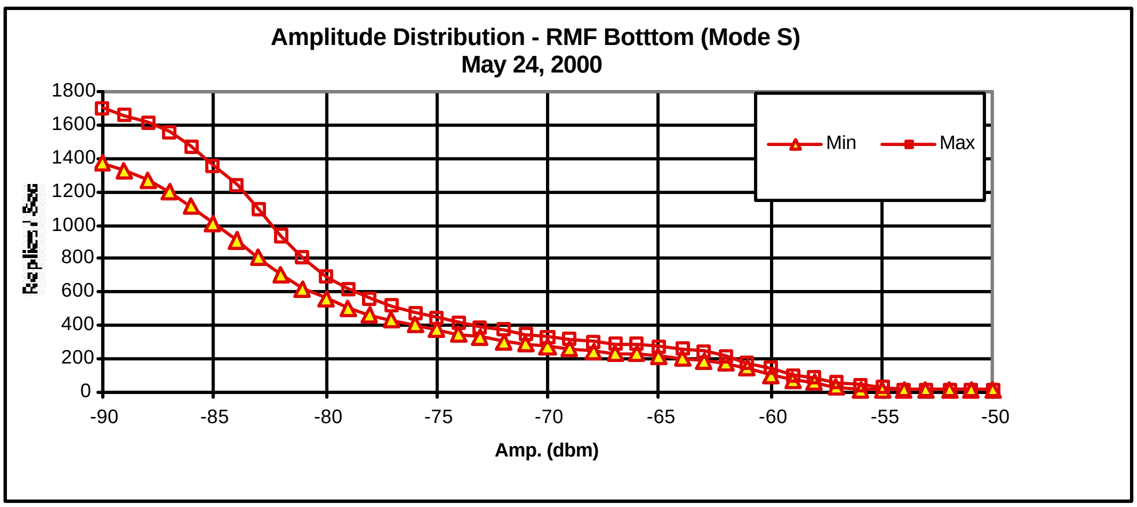


Figure 4.3.1.1.2.1.4-3. Bottom Antenna Mode S Fruit Amplitude Distribution, 24 May

4.3.1.1.2.1.5 25 May Measurements

Refer to Figure 4.3.1.1.1.1.5-1 for the flight path of N40 on 25 May (Thursday). The first portion of the flight consisted of several orbits near Frankfurt. The gaps in the path represent the aircraft position during the data samples when away from the Frankfurt area.

The Mode S fruit rates are shown as a function of "time" on Figure 4.3.1.1.2.1.5-1. Like the ATCRBS, the data is definitely different in the Frankfurt area while making orbits than when enroute to Munich. The Mode S data at a level of -84dbm on the bottom antenna shows a difference in rates in the EW direction. Rates are higher when traveling westbound toward Frankfurt. The rates on the top antenna do not show this characteristic. The rates are higher during the NS orbits for all levels. They drop sharply when leaving the Frankfurt area for the round trip to Munich.

The average rates for the Frankfurt orbits were 635 and 833 replies/second for the top and bottom antennas respectively at -84dbm. At -79dbm, the rates were 312 and 457 for top and bottom. At -74dbm, the rates were 156 and 314.

The rates drop to about 350 replies/sec at -84dbm in the Munich area and gradually increase on the return trip. At -79dbm the rates drop to less than 200 replies per second and increase slightly on the return trip. The rates at -74dbm, however, do not increase during the return trip. The rate is less than 50 replies per second.

Figure 4.3.1.1.2.1.5-2 shows the amplitude distribution of Mode S replies for the top antenna of N40 on 25 May. There are also two distinct characteristics in this data. One set is when the aircraft is in the Frankfurt area doing the orbits. The other is when the aircraft is away from this area enroute to Munich. The maximum rate at -85dbm in the Frankfurt area, was 902 and the minimum was 579. At -80dbm, the rates varied between 286 and 490. Away from the Frankfurt area, the maximum rate at -85dbm was 600 and the minimum was 351. At -80dbm, it was 186 and 140 respectively.

Figure 4.3.1.1.2.1.5-3 shows the amplitude distribution of Mode S replies for the bottom antenna of N40 on 25 May. This data shows the same characteristics as the top antenna. The maximum rate at -85dbm in the Frankfurt area was 1083 and the minimum was 785. At -80dbm, the values were 586 and 467 respectively. Away from the Frankfurt area, the rate at -85dbm varied between 400 and 760 replies/sec. At -80dbm, the rate was approximately 110 on both antennas.

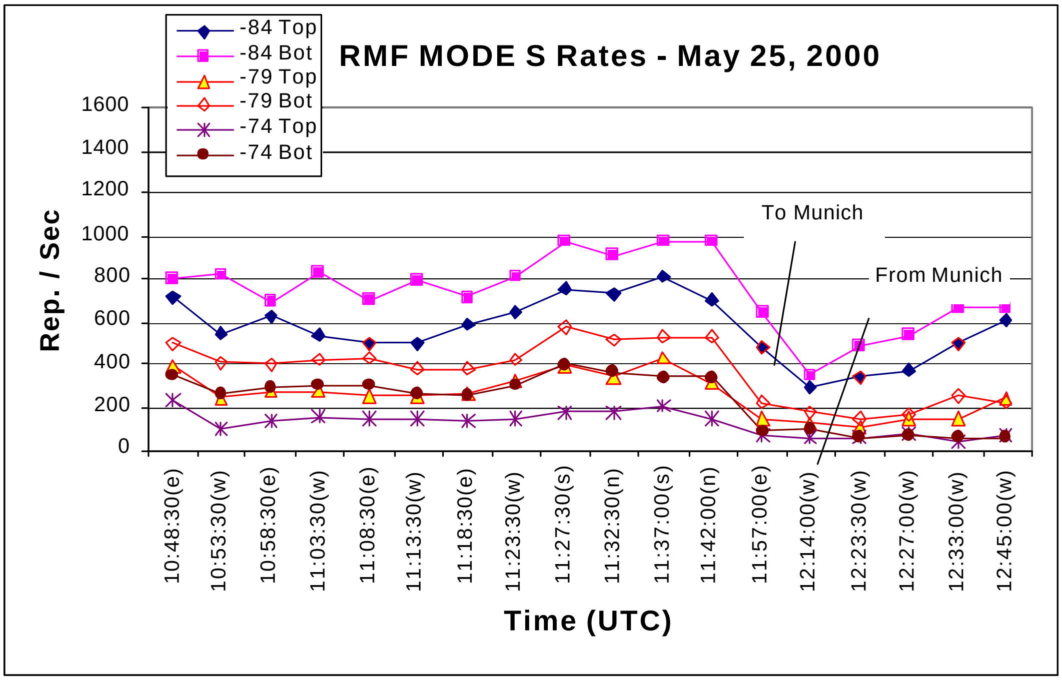


Figure 4.3.1.1.2.1.5-1. Mode S Fruit Rates, 25 May

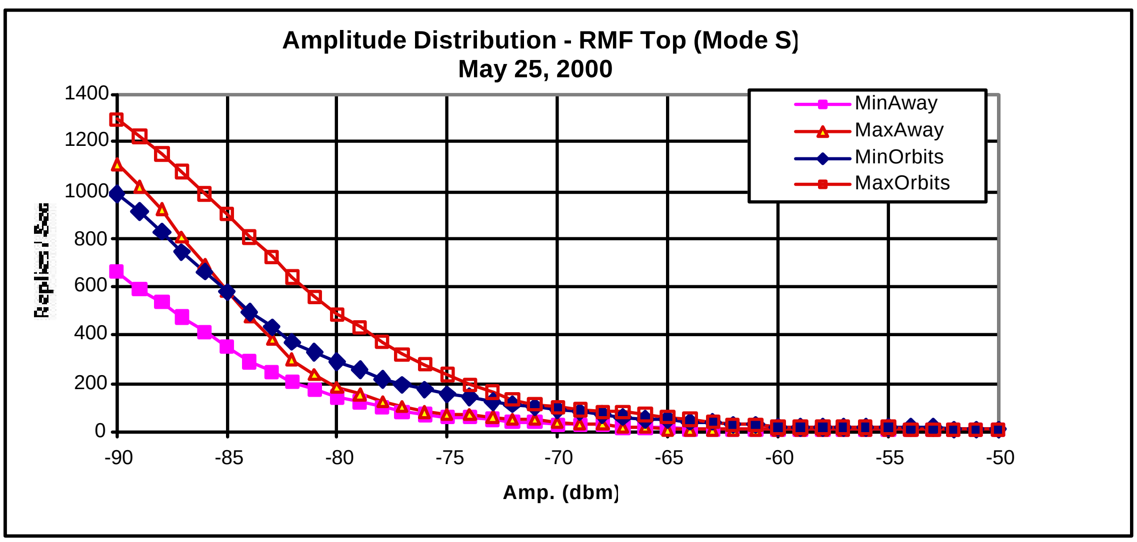


Figure 4.3.1.1.2.1.5-2. Top Antenna Mode S Fruit Amplitude Distribution, 24 May

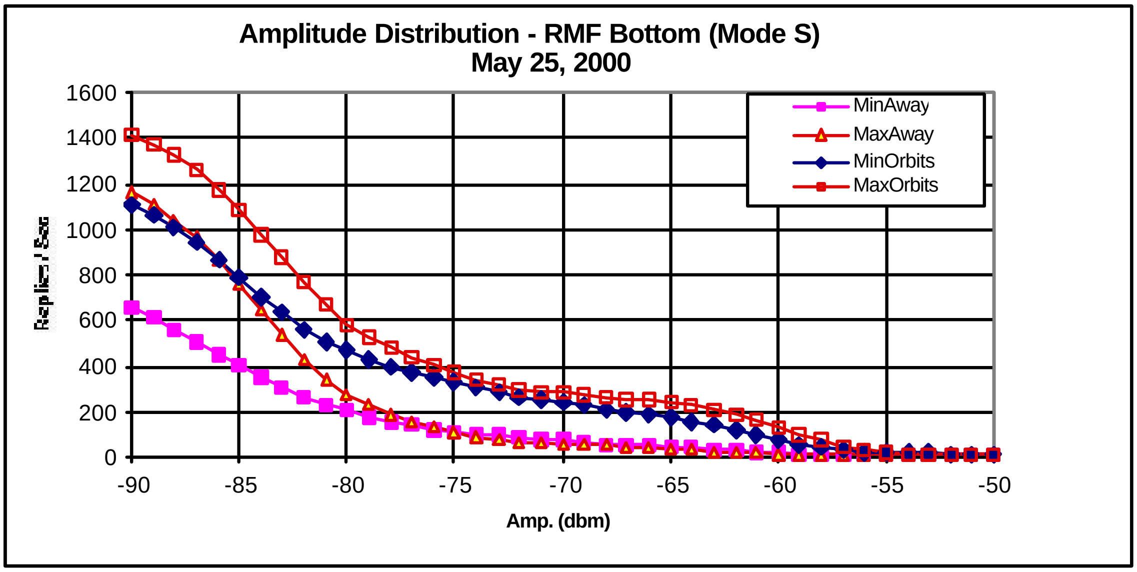


Figure 4.3.1.1.2.1.5-3. Bottom Antenna Mode S Fruit Amplitude Distribution, 25 May

4.3.1.1.2.2 Mode S DF Code Distribution

Figure 4.3.1.1.2.2-1 shows the distribution of DF values from the Mode S airborne data collected on 24 May using RMF. The DF value appears in the first 5 bits of a Mode S reply or squitter. There are 32 possible DF values, only a few of which are currently used. DF = 0 is the format used for replies to TCAS. DF = 4 and DF = 5 are used for surveillance replies to a Mode S ground based radar. DF = 11 is used for short squitters, which are transmitted spontaneously at a standard rate of one per second by each Mode S transponder. Some additional DF = 11 signals are replies to all-call interrogations from a Mode S radar.

The results on Figure 4.3.1.1.2.2-1 indicate that DF = 0 was by far the most common reception. This seems reasonable in view of the fact that only one Mode S radar (at Goetzenhain) was operating in this area. More Mode S radars would be expected to generate more DF =4 and DF = 5 replies. The second most common reception was DF = 11. The figure is marked to show short squitters separately from other DF = 11 receptions. Short squitters are seen to be much more common than all-call replies.

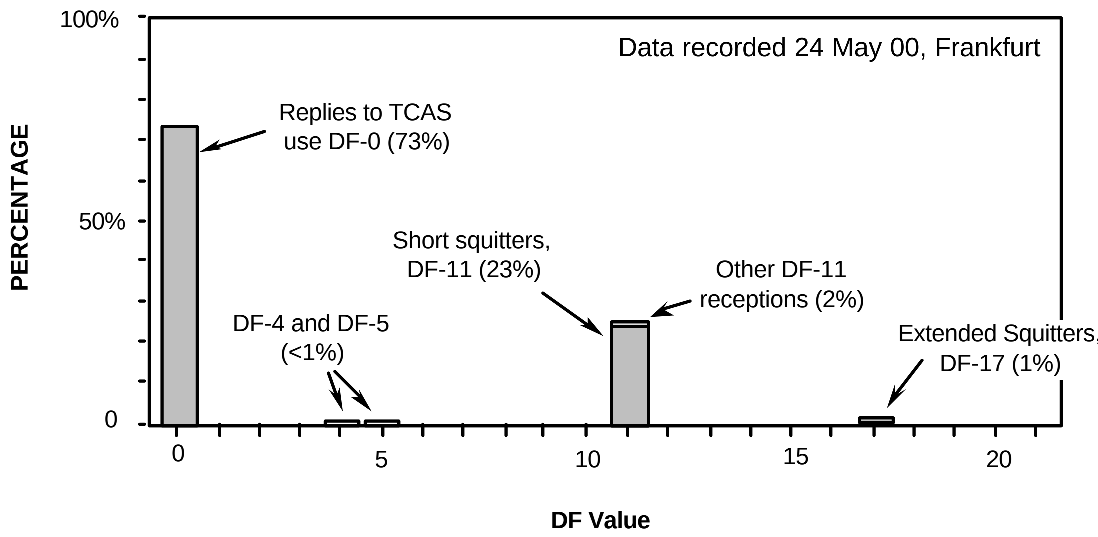


Figure 4.3.1.1.2.2-1. Observed DF Values

4.3.1.1.3 Example Extended Squitter Message Receptions

The 1090 MHz environment in the Frankfurt area represents one of the most challenging for Extended Squitter reception in the world. This is validated by the ATCRBS reply rates depicted in the fruit rate measurement and analysis sections of this report. Depicting representative messages from the environment can show some of the challenges overlapping interfering signals create for an Extended Squitter decoder. The RMF system continuously quantizes the incoming video signals, both top and bottom antenna ports, from the 1090 MHz receiving system. This data is utilized to plot complete Extended Squitter message receptions and to depict amplitude distortions due to overlapping signals. Appendix A contains example Extended Squitter messages received and recorded by RMF.

4.3.1.2 Day-to-day Differences in Fruit Rate

4.3.1.2.1 Summary

After initially focusing on the fruit-rate measurements on Wednesday, 24 May, the other day's measurements were then processed for comparison. Figure 4.3.1-8 gives a summary of the day-to-day results. For each day, the maximum value and the average value are plotted. This is AMF data using a threshold of -74 dBm referred to the antenna. This data represents airborne fruit measurements, and does not include times when the aircraft was on the ground, just after takeoff, or just before landing. Note that AMF data was only recorded on every other orbit (see Figure 4.3.1-3).

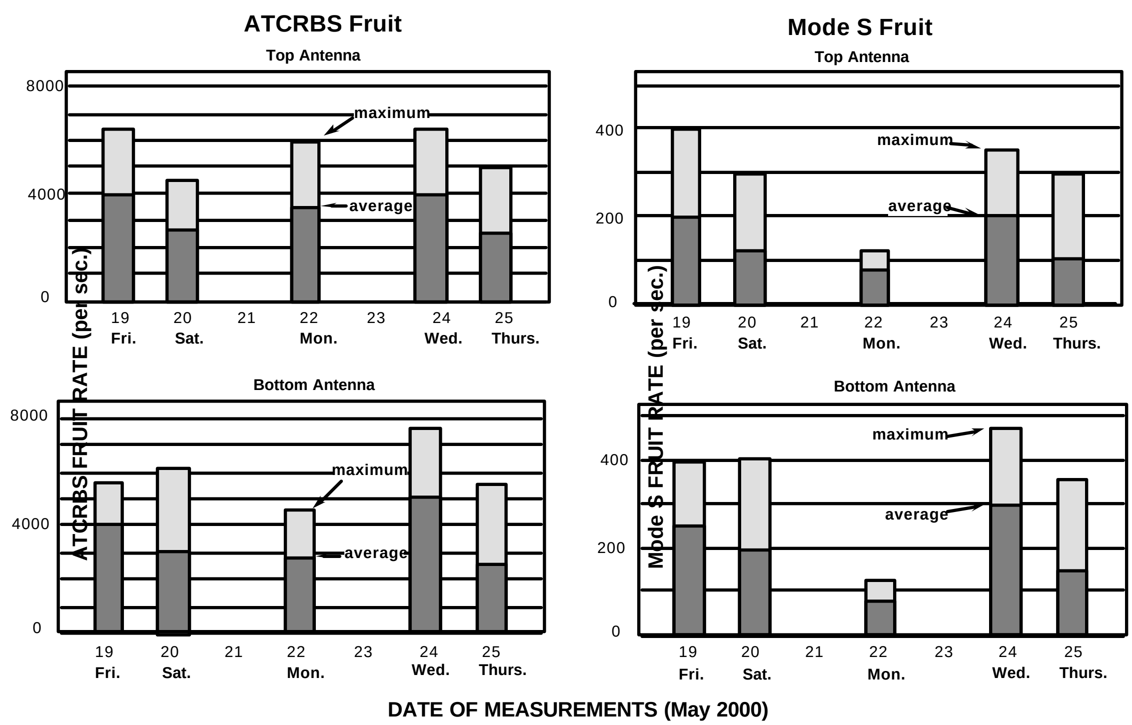


Figure 4.3.1-8. Day-to-day Variations in Fruit Rate

The results indicate that Wednesday 24 May and Friday 19 May were approximately the same and were the maximum conditions experienced in the five days of testing. Monday 22 May is seen to be substantially lower than the other days, which is probably a reflection of the fact that this was the only day when the aircraft (N40) did not fly in ovals staying in the Frankfurt airspace. On Monday, N40 flew to Munich and back, where fruit rate is evidently lower than in Frankfurt.

The results also indicate that Thursday 25 May was uniformly lower in fruit rate relative to Wednesday for both ATCRBS and Mode S fruit. Similarly, Saturday, 20 May was lower in ATCRBS fruit, while being about the same in Mode S fruit relative to 24 May.

4.3.1.2.2 ATCRBS Fruit

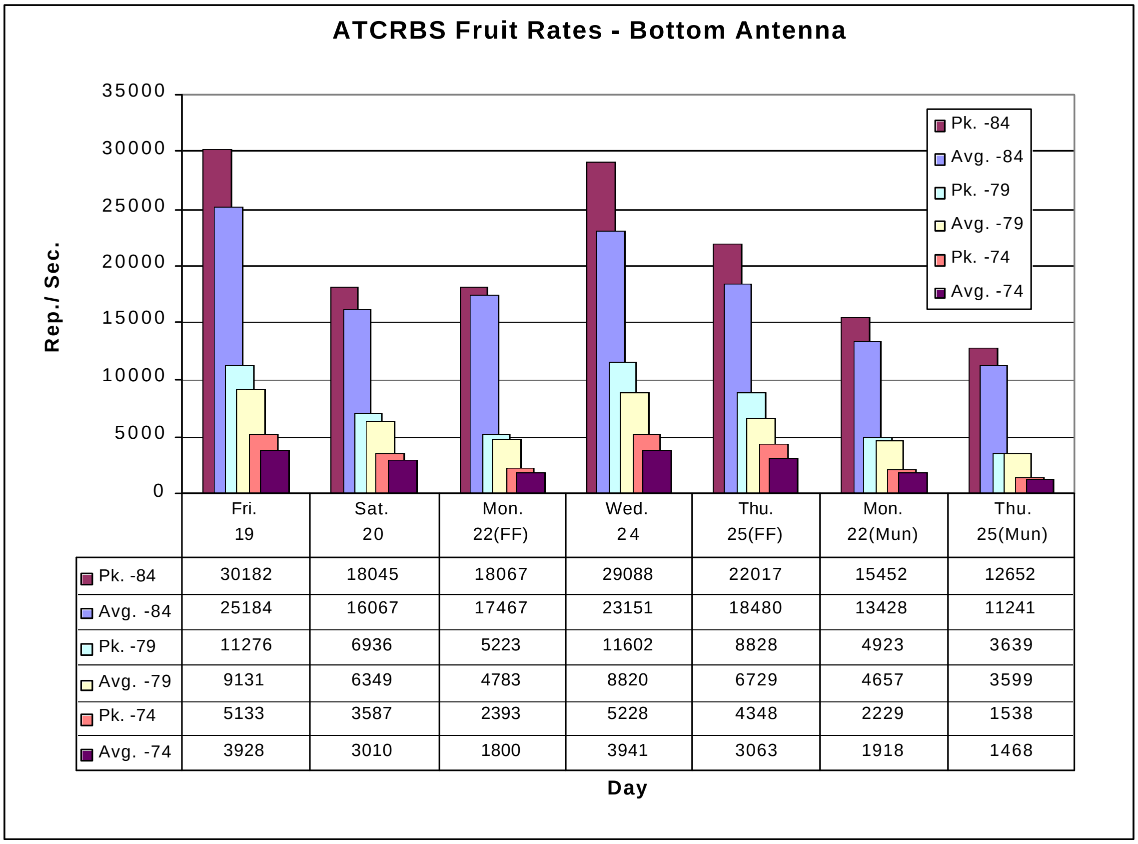
4.3.1.2.2.1 ATCRBS Fruit - Bottom Antenna

The fruit rates measured each day were analyzed for similarities and differences in rates. Figure 4.3.1.2.1.1-1 shows the rates for each day at the three levels presented in the "Fruit Rates as a function of Time" data presented in 4.3.1.1. All rates represent an average of the samples for the particular day. All samples were selected for time periods when the aircraft was on a straight leg of an orbit and level flight. This data includes only the samples when the aircraft was above 20,000 ft (usually 22,000). The trips to Munich were at 23,000 ft and 24,000 ft depending on the direction of travel. The fruit rate for the Frankfurt area was separated from that collected when the aircraft was enroute to Munich.

Orbits were done on May 19, May 20, May 24 and May 25. The time of the day, however, was not the same each day. The highest average fruit rate at -84dbm was measured on May 19, Friday at 25.1k. The next highest was May 24, Wednesday at 23.1k. The samples from the orbits of May 25, Thursday, produced 18.5k. The orbits of May 20, Saturday, produced the lowest fruit rate at 16k. The sample from May 22, Monday, was not from an orbit like the others. It was taken when the aircraft was enroute to Munich. The sample was taken when the aircraft was directly south of Frankfurt. The fruit rate was 17.5k.

The samples of data taken on May 22 (Monday) and May 25 (Thursday) when the aircraft was enroute to Munich produced fruit rates of 13.4k and 11.2k respectively at a level of -84dbm or greater.

The rates at the other levels as indicated in Figure 4.3.1.2.1.1-1. The fruit rate at a level of -74dbm is almost the same (at 3.9k) on May 19 and May 24 on the bottom antenna. It is the lowest on May 20, at 3.0k.



	Fri. 19	Sat. 20	Mon. 22(FF)	Wed. 24	Thu. 25(FF)	Mon. 22(Mun)	Thu. 25(Mun)
Pk. -84	30182	18045	18067	29088	22017	15452	12652
Avg. -84	25184	16067	17467	23151	18480	13428	11241
Pk. -79	11276	6936	5223	11602	8828	4923	3639
Avg. -79	9131	6349	4783	8820	6729	4657	3599
Pk. -74	5133	3587	2393	5228	4348	2229	1538
Avg. -74	3928	3010	1800	3941	3063	1918	1468

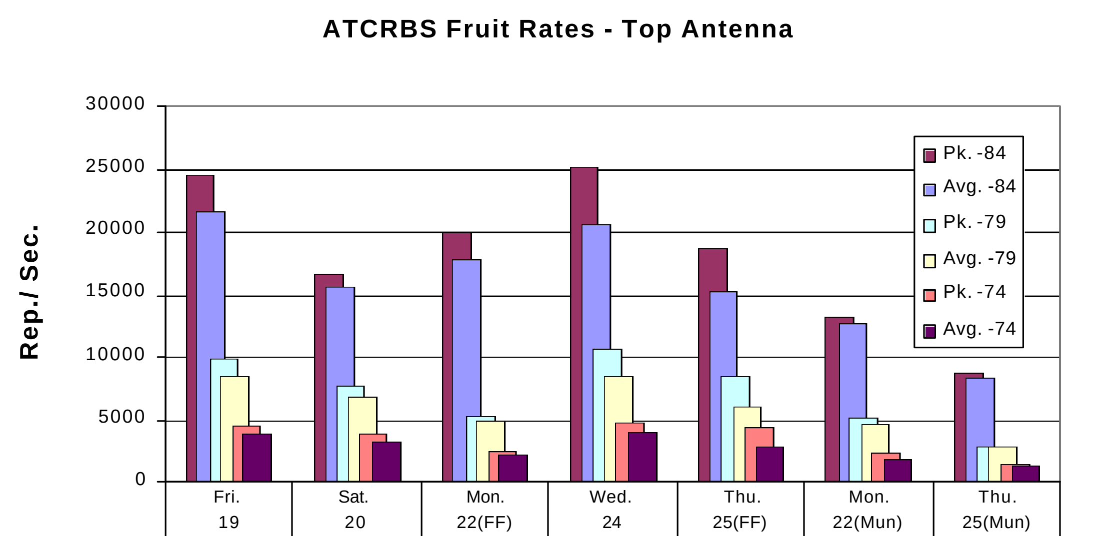
Figure 4.3.1.2.2.1-1. ATCRBS Fruit Rates at 22kft To 24kft - Bottom Antenna

4.3.1.2.2.2 ATCRBS Fruit - Top Antenna

The highest average fruit rate at -84dbm on the top antenna was also measured on May 19, Friday at 21.5k. The next highest was May 24, Wednesday at 20.6k. The samples from the orbits of May 25, Thursday, produced 15.3k. The orbits of May 20, Saturday, produced the lowest fruit rate at 15.6k. The sample from May 22, Monday, (taken when the aircraft was enroute to Munich) produced a fruit rate of 17.7k.

The samples of data taken on May 22 (Monday) and May 25 (Thursday) when the aircraft was enroute to Munich produced fruit rates of 12.6k and 8.4k respectively at a level of -84dbm or greater.

The rates at the other levels can be read from the figure directly. The fruit rate at a level of -74dbm is almost the same on May 19 (3.7k) and May 24 (3.9k) on the bottom antenna. It is the lowest on May 20,when the rate was 3.1k.



	Fri. 19	Sat. 20	Mon. 22(FF)	Wed. 24	Thu. 25(FF)	Mon. 22(Mun)	Thu. 25(Mun)
Pk. -84	24514	16619	20012	25171	18762	13288	8714
Avg. -84	21520	15596	17722	20621	15265	12609	8357
Pk. -79	9843	7800	5270	10568	8432	5062	2877
Avg. -79	8449	6703	4933	8389	6015	4587	2859
Pk. -74	4572	3737	2515	4784	4343	2217	1349
Avg. -74	3743	3181	2175	3916	2856	1822	1288

Figure 4.3.1.2.2.2-1. ATCRBS Fruit Rates at 22kft to 24kft - Top Antenna

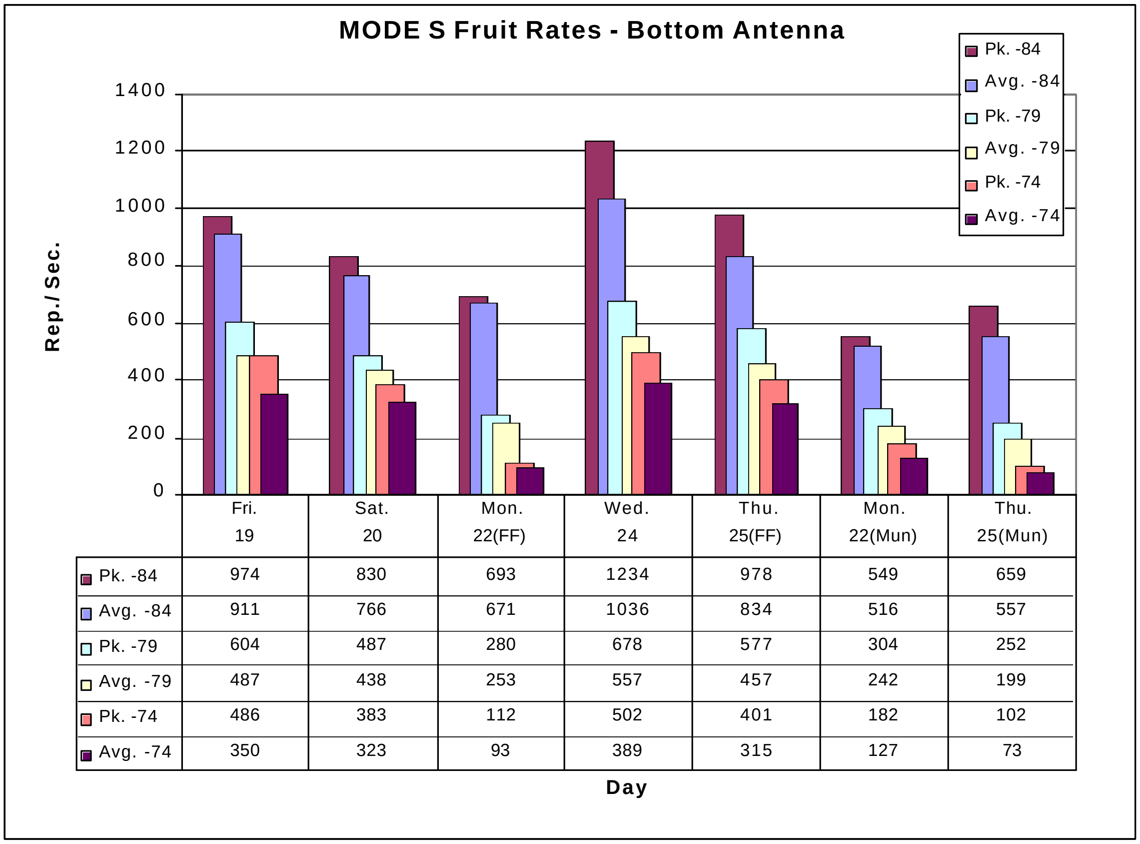
4.3.1.2.3 Mode S Fruit

4.3.1.2.3.1 Mode S Fruit - Bottom Antenna

Figure 4.3.1.2.3.1-1 shows the Mode S fruit rates for each day at the three levels presented in the "Fruit Rates as a function of Time" data presented in 4.3.1.2. All rates represent an average of the samples for the particular day (same as ATCRBS rates).

The highest average fruit rate at -84dbm was measured on May 24 (Wednesday), at 1036 replies/sec. Next highest was May 19 (Friday), at 911. The samples from the orbits of May 25 (Thursday), produced a rate of 834 replies/sec. The fruit rate on May 20 (Saturday), was 766 replies/sec. The orbits of May 22 (Monday), produced the lowest fruit rate at 671 replies/sec.

The Mode S fruit rate on May 22 (Monday) at -74dbm is significantly lower (93 replies/sec.) than the other days. It must be remembered that this flight path was not same as the other days. The other days, the aircraft was orbiting near Frankfurt. On this day, the aircraft was south of Frankfurt and headed away. This is also the only sample that has a higher fruit rate on the top antenna at -74dbm than on the bottom.



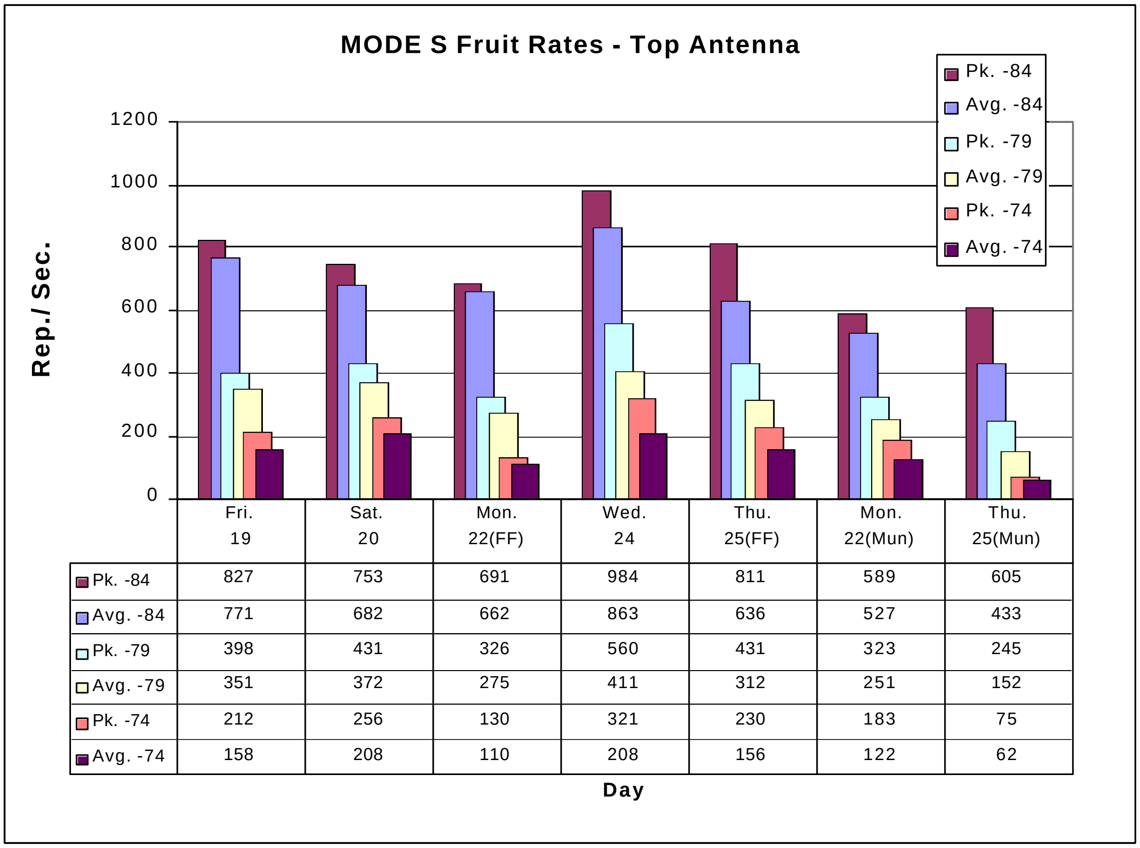
	Fri. 19	Sat. 20	Mon. 22(FF)	Wed. 24	Thu. 25(FF)	Mon. 22(Mun)	Thu. 25(Mun)
Pk. -84	974	830	693	1234	978	549	659
Avg. -84	911	766	671	1036	834	516	557
Pk. -79	604	487	280	678	577	304	252
Avg. -79	487	438	253	557	457	242	199
Pk. -74	486	383	112	502	401	182	102
Avg. -74	350	323	93	389	315	127	73

Figure 4.3.1.2.3.1-1. Mode S Fruit Rates at 22kft to 24kft - Bottom Antenna

4.3.1.2.3.2 Mode S Fruit - Top Antenna

Figure 4.3.1.2.3.2-1 shows the Mode S fruit rates for each day at the three levels for the top antenna. The highest rate at -84dbm was also produced on Wednesday, May 24, with a fruit rate of 863 replies/sec. The lowest occurred on Monday, May 22, at 662 replies/sec.

The Mode S fruit rates are highly dependent on where the aircraft is located. If the aircraft is near the airport (i.e., Frankfurt orbits), the fruit rate on the bottom antenna is much higher than on the top at the high signal levels (i.e. -74dbm). The ratio of bottom to top antenna fruit rate, for only the orbits, is 1.9 at -74dbm and 1.2 at -84dbm. The ratio of bottom to top antenna fruit rates for all the data is 1.5 at -74dbm and 1.16 at -84dbm.



	Fri. 19	Sat. 20	Mon. 22(FF)	Wed. 24	Thu. 25(FF)	Mon. 22(Mun)	Thu. 25(Mun)
Pk. -84	827	753	691	984	811	589	605
Avg. -84	771	682	662	863	636	527	433
Pk. -79	398	431	326	560	431	323	245
Avg. -79	351	372	275	411	312	251	152
Pk. -74	212	256	130	321	230	183	75
Avg. -74	158	208	110	208	156	122	62

Figure 4.3.1.2.3.2-1. Mode S Fruit Rates at 22kft to 24kft - Top Antenna

4.3.2 Interrogation Rates

To complement the 1090 MHz interference measurements, additional measurements were made of interrogation rates in the 1030 MHz band. The purpose of the 1030 MHz measurements was to assess the effects of interrogations on the observed reply rates. Suppression effects were of secondary interest, relative to received interrogations that would trigger replies. Similarly, received Mode S interrogations addressed to other aircraft were less of interest. Only interrogation rates received at the FAA aircraft, N40, were measured both by the AMF and DATAS.

The DATAS was installed aboard the FAA aircraft (N40) and used for interrogation rate measurements. All 1030 MHz signals received on the top and bottom antenna were recorded during all of the flights. When an interrogation was seen on both antennas simultaneously, the larger signal was selected for processing. In addition, special tests were conducted during some of the flights to determine the difference in rates when using only one of the two antennas. The results of those tests showed that the bottom-only interrogation rate was consistently higher than the top-only interrogation rate (which is evident also in the AMF data presented in the following sections). The results also showed that when using the combined top-bottom mode, the interrogation rate was 117 percent of the bottom-only rate.

Also, in the combined top-bottom mode, the interrogation rate was 140 percent of the top-only rate. These are typical values, whereas differences were observed as a function of aircraft location. In the DATAS measurements of interrogation rate that follow, the receiver threshold was -74 dBm (referred to the antenna), and rates were averaged over 5 second periods.

The AMF is capable of making measurements at either 1030 MHz or 1090 MHz, but not both simultaneously. Measurements in both frequency bands were made by switching between the two bands, dwelling for 10 minutes in each band. While N40 was flying in the oval pattern to stay near Frankfurt, the time to fly one full oval was nearly 10 minutes, and the AMF switching was synchronized to the oval. The recorded AMF data have been processed for presentation in the form of interrogation rate vs. time and reply rate vs. time. In the AMF measurements of interrogation rate that follow, the receiver threshold was -74 dBm (referred to the antenna), and rates were averaged over one minute periods.

4.3.2.1 Detailed Interrogation Rate Analysis for 24 May

4.3.2.1.1 ATCRBS Interrogation Rate

4.3.2.1.1.1 Interrogation Rate as a Function of Aircraft Location

For the testing on 24 May, N40 was flying in the oval pattern staying in the Frankfurt airspace, as described above and illustrated in Figure 4.3.1-1 and Figure 4.3.1.1.1.4-1. Two sets of orbits in each direction (east-west and north-south) were completed during these tests, as illustrated, with the Frankfurt airport near one end of the orbit. The orbit sequence was EW, NS, EW, NS, and then EW (an incomplete set). The aircraft was in the same location for the data of 1-west at 10:46:00 and 4-west at 11:43:00. Likewise location 1-east corresponds to 4-east.

Figure 4.3.2-1 shows the ATCRBS interrogation rates measured by DATAS on 24 May. The values plotted are the ATCRBS Mode A and Mode C unsuppressed rates, meaning that a reply from N40 is required for these. Interrogations from TCAS are not included in these rates.

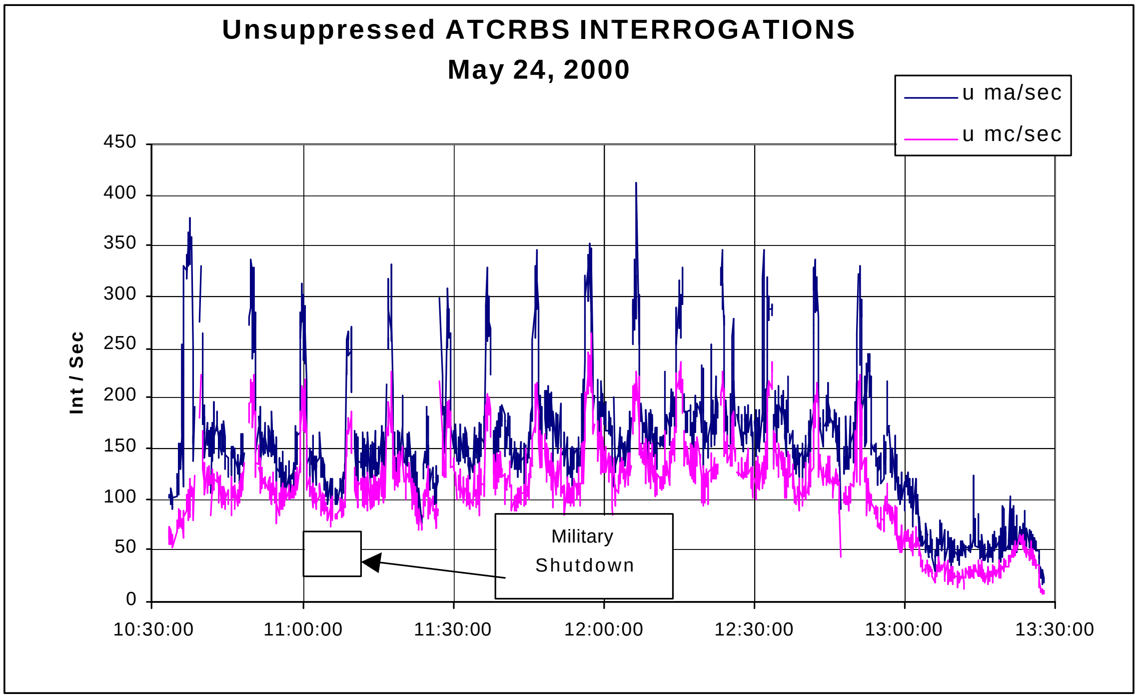


Figure 4.3.2-1. Top/Bottom Antenna DATAS Unsuppressed Ground ATCRBS Interrogation Rate Measurements, 24 May

Note. Interrogations from TCAS not included.

The rates shown in Figure 4.3.2-1 show significant variation depending on the location of the aircraft. Abrupt spikes are seen, with a repeating pattern that repeat about every 10 minutes. This agrees with the fact that the receiving aircraft, N40, was flying in an oval pattern, taking about 10 minutes for one complete oval. This peaking, and its relationship to the flight path, is described in more detail in 4.3.2.1.1.3 below.

Figure 4.3.2-1a shows the same data, except giving the combined Mode A and Mode C interrogation rate. Both figures are marked to show the 10 minute period when military radars were requested to be shut down. The effects of this shut down are discussed further in Chapter 5.

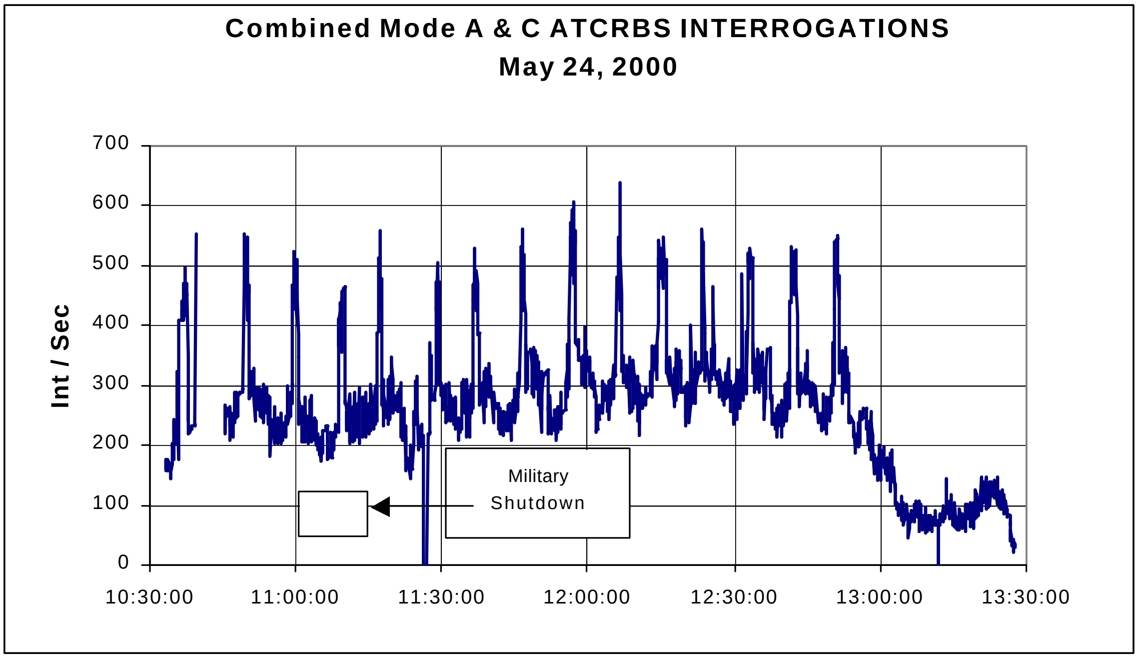


Figure 4.3.2-1a. DATAS Unsuppressed Mode A and C ATCRBS Interrogation Rate, 24 May

Note. *Interrogations from TCAS not included.*

Interrogation rate measurements by the AMF on the same aircraft are plotted in Figure 4.3.2-2. The DATAS measurements and the AMF measurements were made using somewhat different techniques. DATAS includes a transponder front end, which receives and detects interrogations. This is a top-bottom antenna diversity transponder, so the measured interrogation rates apply to the total as received via both antennas. The AMF, on the other hand, records all received pulses, which are analyzed after the tests for detection of interrogations. The data plotted in the AMF figure (4.3.2-2) was processed separately for the top antenna and the bottom antenna.

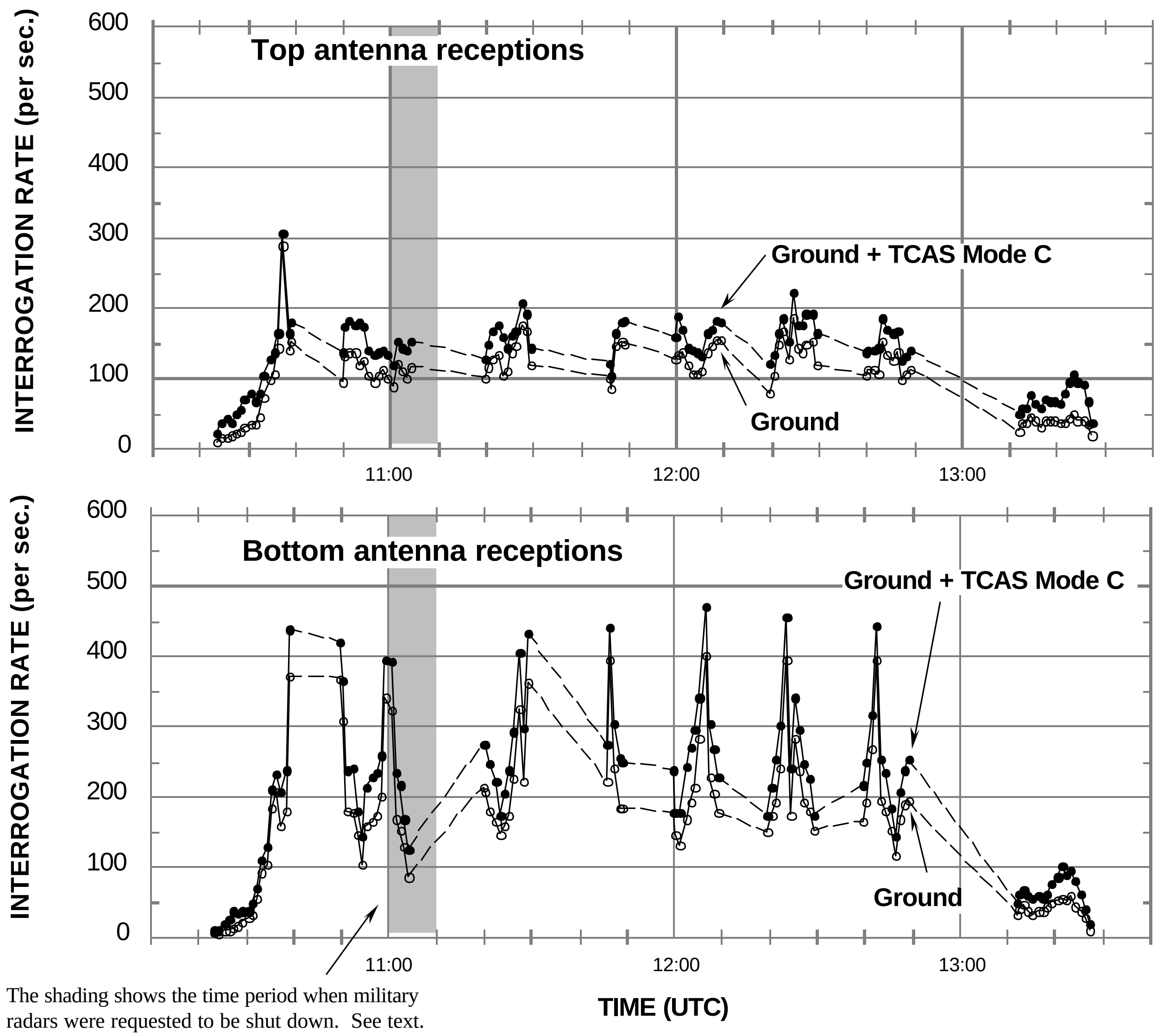


Figure 4.3.2-2. ATCRBS Interrogation Rate Measurements (AMF), 24 May

Note. *During these measurements, the AMF was switched between 1030 MHz and 1090 MHz, which accounts for the gaps in the data plotted here. Each point gives the average rate over a 1-minute period.*

The AMF processing also includes an analysis intended to distinguish between interrogations from the ground and those from TCAS. This is done by separating the Mode-C-only interrogations from the others. A Mode S transponder does not reply to Mode-C-only interrogations.

This AMF analysis technique allows the interrogations from TCAS to be counted separately from the interrogations transmitted from ground based radars, with one exception.

The exception is that a Mode S radar may also use the Mode-C-only interrogations, and in fact the radar at Goetzenhain was operating in this manner at the time of the tests. The magnitude of this exception can be estimated as follows. The Mode-C-only interrogation rate of the Goetzenhain radar is 64 interrogations per second, and the beamwidth is about one percent of 360 degrees. Therefore the average reception rate for interrogations from this one radar was about 0.64 interrogations per second. This is a small fraction of the received short-P4 reception, so the results plotted in Figure 4.3.2-2 give an accurate breakdown of the two classes of interrogations.

The format for presenting the data in Figure 4.3.2-2 was chosen so that two types of interrogations and the total can all be seen by inspection: the lower curve shows interrogations from the ground, the upper curve shows the total, and therefore the difference between the two curves is the contribution from TCAS.

The interrogation rates plotting in Figure 4.3.2-2 exhibit abrupt spikes, similar to those seen in the DATAS data in the two previous figures. One difference is that these spikes appear to be about 20 minutes apart rather than 10 minutes apart as they appear in the DATAS data. This difference can be attributed to the fact that the AMF was switched between 1030 MHz and 1090 MHz, dwelling on each for one cycle of the oval flight path (about 10 minutes). Closer study of the AMF data and the DATAS data indicate that the spikes observed by the two system agree in time. This peaking, and its relationship to the flight path, is examined in more detail in 4.3.2.1.1.3.

4.3.2.1.1.2 Altitude Dependence.

The interrogation rate measurements were examined to see if they are a function of aircraft altitude. Some indication that interrogation rate increases as altitude increases appears in the above figures. Plots of interrogation rate vs. time show increasing interrogation rate in the early part of the test when the aircraft was climbing, and decreasing rate at the end of the test when the aircraft was descending. This behavior is shown in more detail in Figure 4.3.2-3, which is an expanded plot of interrogation rate vs. time together with a plot of altitude vs. time. The increase of interrogation rate as altitude increased is clearly evident in this figure.

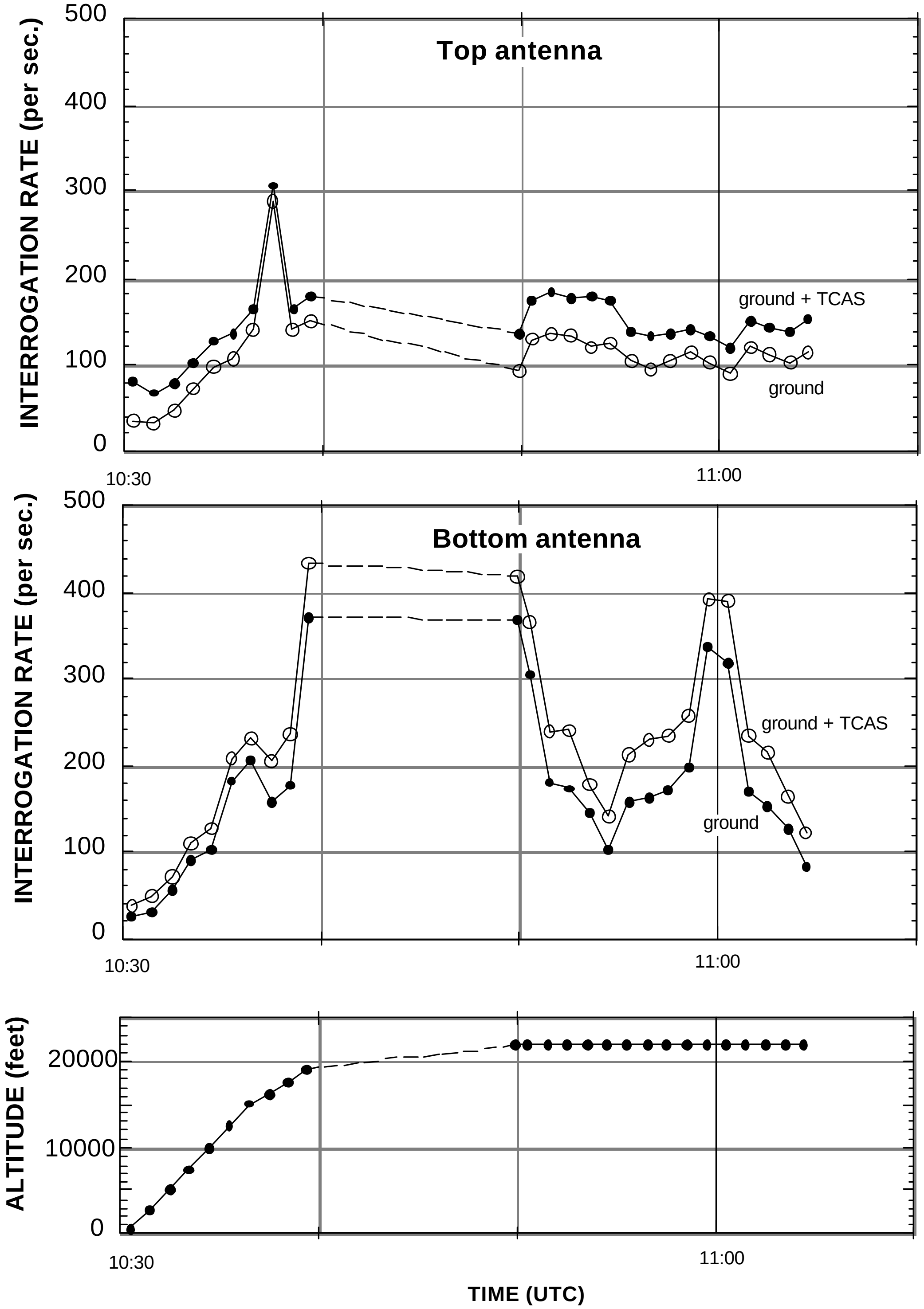


Figure 4.3.2-3. Altitude Effect on Interrogation Rates (AMF Data), 24 May

Note: Each point gives the average rate over a 1-minute period.

The observed behavior in which interrogation rate increases as a function of altitude seems reasonable, given the fact that as altitude increases an aircraft is in view of a larger number of ground based interrogators. The measurements on Friday 19 May provide a more straightforward opportunity to asses the altitude dependence. On that day, N40 was held at several fixed altitudes while flying in an oval pattern to stay in the same geographical area. The results (which confirm the trend seen here) are given in 4.3.2.2.1.1.

4.3.2.1.1.3 Analysis of Rate Peaks

Several of the interrogation rate peaks were examined in detail in order to determine if they occurred when the aircraft was at a particular location. Figure.4.3.2-4 shows the flight path of N40 during the data collection on 24 May. The duration of data plotted includes five of the prominent peaks that are evident in the interrogation rate measurements (Figure 4.3.2-1a). This plot covers the time period of 10:53 to 11:40. The portions of the aircraft path when interrogation peaking occurred is darkened so that one can judge whether these events consistently occurred in some location. The locations of known radar stations are also plotted in the figure.

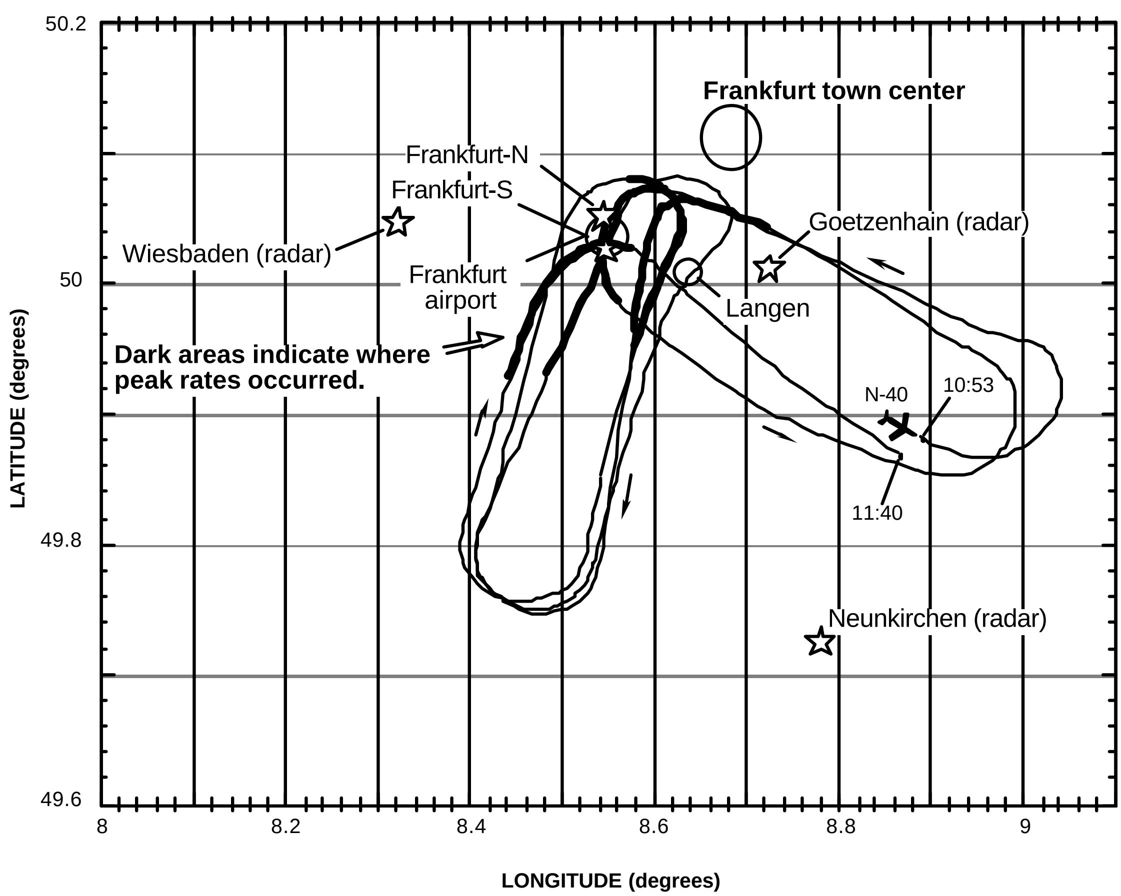


Figure 4.3.2-4. Peak Interrogation Rates ,24 May

The results indicate that the peak interrogation rates generally occurred when N40 was flying in a particular location. During the east-west ovals, the peaking occurred at the west end, and during the north-south ovals, the peaking occurred at the north end. Comparing this location with the radar locations leads to the suggestion that this peaking was in fact caused by one of the radars located at Frankfurt airport. Radar maintenance management, responsible for all civil radars in the Frankfurt area, agreed with this perception. It was known that the Frankfurt South radar, one of the oldest operated by DFS during the trials period, generated unsuppressed Mode A and Mode C interrogations at some higher elevation angles. This radar has been turned off since early 2001 and will be replaced by a Mode S interrogator in the near future.

4.3.2.1.2 Mode S and Mode 2 Interrogation Rates

Figure 4.3.2.5 shows the Mode S and Mode 2 interrogations for the flight of 24 May. The rates shown in this figure include receptions of Mode S interrogations addressed to other aircraft, to which own aircraft does not reply. Also included are TCAS broadcasts, which have the form of Mode S interrogations but do not elicit any replies. The data collected on 24 May was entirely from orbits of N40 near the Frankfurt airport.

The Mode S rate on 24 May varied from about 120 to 400 per second. As previously, the rate depended on the position of the aircraft in the orbit.

The Mode 2 rates, again, were about 20 to 25 per second. A shutdown of military radars was requested for a period of 10 minutes beginning at 11:00. There appears to be a slight "dip" in the Mode 2 rates during this period. A PRT analysis would be required to verify that this really occurred. The Mode S rate appears to drop during this period as well, but no correlation to the shutdown is likely.

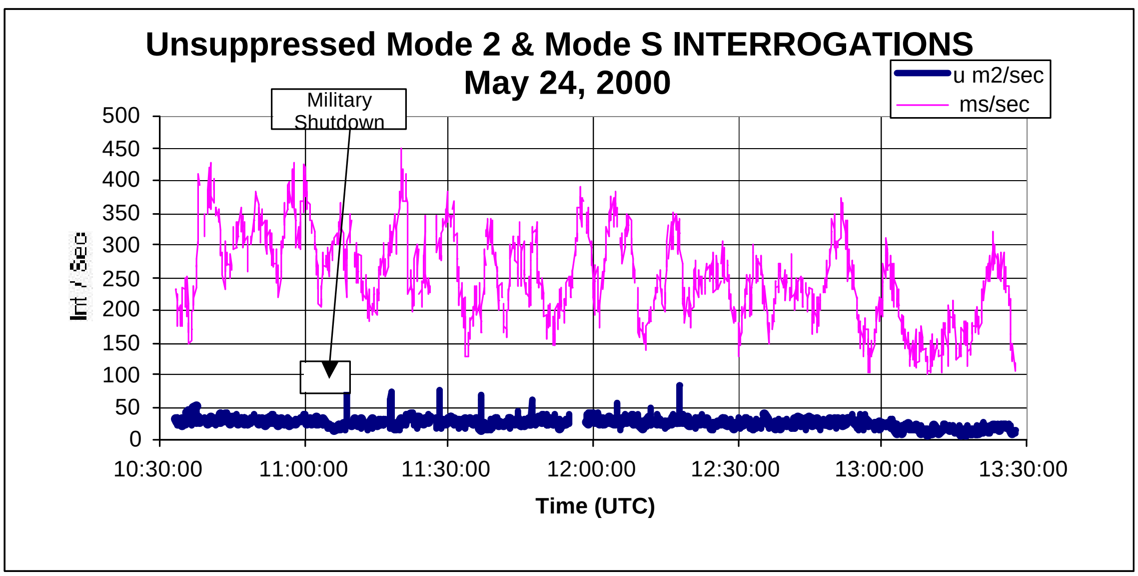


Figure 4.3.2-5. Mode S and Mode 2 Interrogations, 24 May

Note. *The rates shown in Figure 4.3.2-5 include receptions of Mode S interrogations addressed to other aircraft, to which own aircraft does not reply. Also included are TCAS broadcasts, which have the form of Mode S interrogations but do not elicit any replies.*

4.3.2.1.3 TCAS Interrogation Rate Measurements

Mode C interrogations were processed to separate those attributable to TCAS by presence of the P4 pulse. Interrogations with an associated S1 pulse were also identified. This produced the two types of TCAS interrogations analyzed below. The ATCRBS Only (Mode C) interrogations would elicit a reply from an ATCRBS transponder but would be ignored by a Mode S transponder. Those with an associated S1 (Whisper/Shout) would produce a suppression of all transponder types.

The number of TCAS aircraft was determined by examining the Mode S interrogation data for TCAS Broadcasts. A "moving average" was then produced for the number of different Mode S addresses reporting within the last 20 seconds. This is the number of TCAS aircraft in the following discussion.

Figure 4.3.2-6 presents the measurements of the TCAS interrogations as received by DATAS on N40 on 24 May. The number of TCAS aircraft is also plotted.

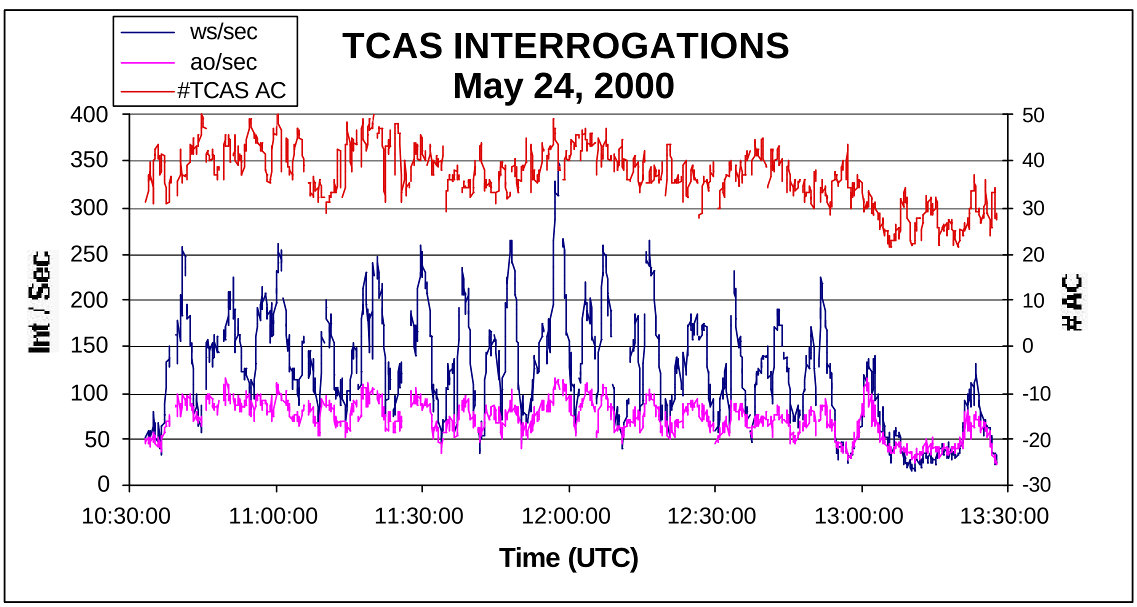


Figure 4.3.2-6. TCAS Interrogations, 24 May

4.3.2.1.4 ATCRBS Suppression Interrogation Rates

Suppression interrogations attributable to Mode S were removed from the overall counts of suppression interrogations. The remaining interrogations would be from any other interrogator source, mainly ground ATCRBS interrogators.

Figure 4.3.2-7 presents the measurements of suppression rate as received by DATAS on N40 on 24 May. The rate is fairly constant at 800 to 900 with fluctuations of plus and minus 200 to 300 depending on position of the aircraft in the orbit. Another increase in suppression rates is seen when coming in for a landing at the end of the flight.

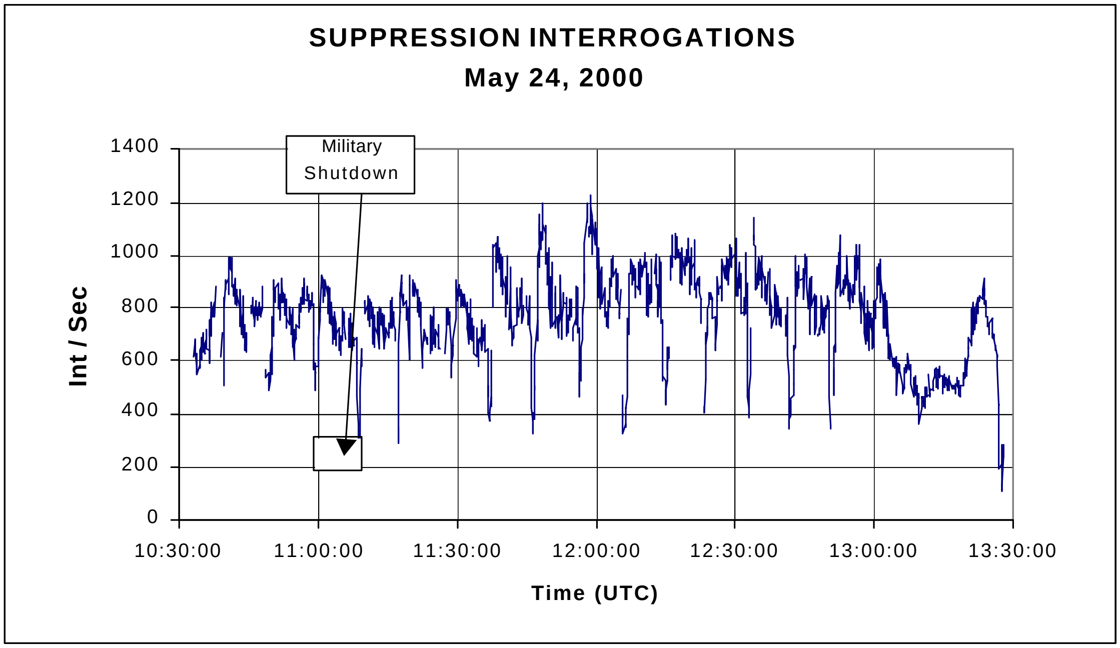


Figure 4.3.2-7. ATCRBS suppression Interrogations, 24 May

4.3.2.2 Day-to-Day Variations of Interrogation Rate

Following the detailed analysis for 24 May, the other four day's measurements were then processed for comparison. These results are presented in the following, first giving the measurements on individual days, and then giving comparisons between days.

4.3.2.2.1 Measurements on Individual Days

4.3.2.2.1.1 Individual Measurements on 19 May

Refer to Figure 4.3.1.1.1.1-1 for the flight path for 19 May (Friday morning). The aircraft took off from Wiesbaden and made an orbit around the area at 12,000 ft as indicated. The aircraft then climbed to 22,000 ft (22k) for orbits near Frankfurt. Orbits were made in EW and NS directions at 22k before descending to 15k and 10k where orbits were also made in both directions. There was also a significant amount of time spent at 7000 feet and 3000 feet while waiting to land.

Figure 4.3.2-8 shows the unsuppressed ATCRBS interrogation rates for the flight of 19 May. The altitude of the aircraft is superimposed on the interrogation data. These rates do not include TCAS Mode C interrogations, which are discussed separately.

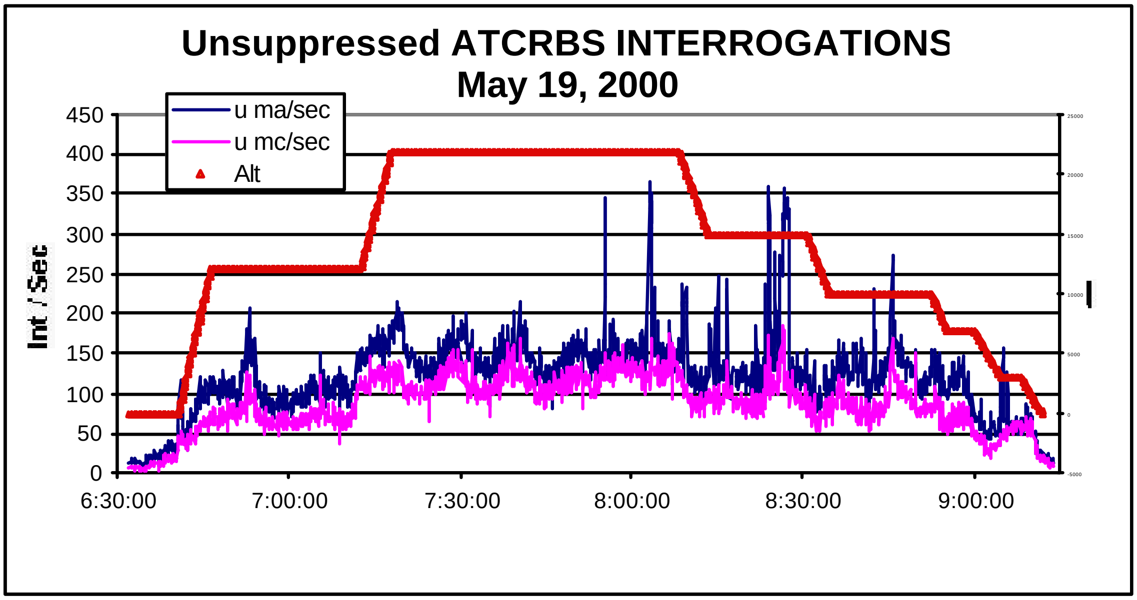


Figure 4.3.2-8. Unsuppressed ATCRBS Interrogation Rates, May 19

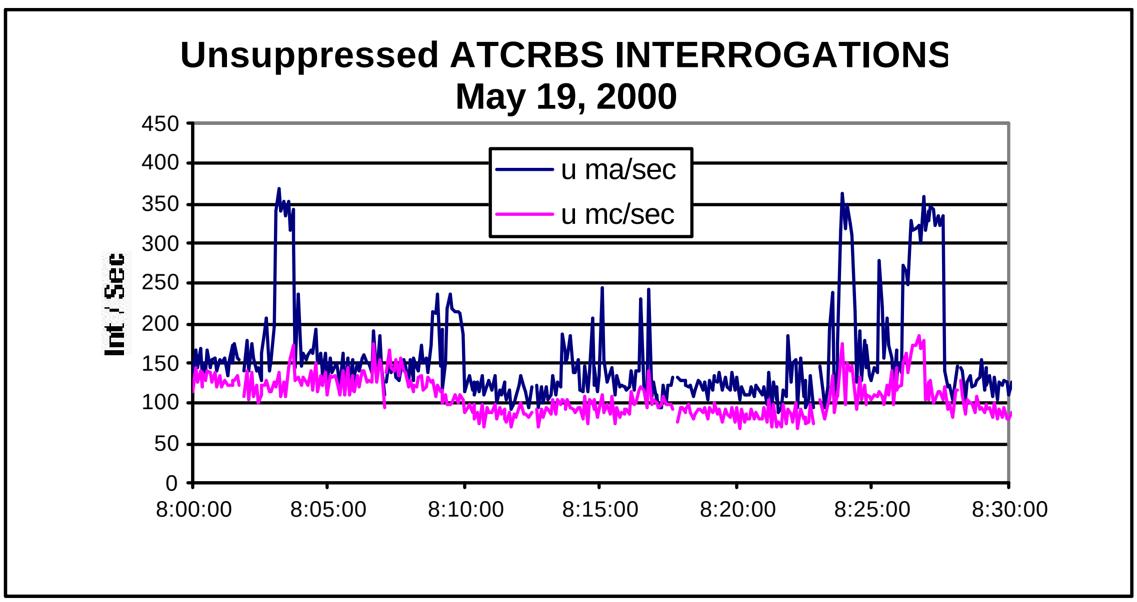


Figure 4.3.2-9. Unsuppressed ATCRBS Interrogations - 08:00 to 08:30, May 19

Several things are apparent from the interrogation data. There are large "spikes" in the Mode A data that are not really apparent in the Mode C data. Figure 4.3.2-9 is expanded to show the data from 8:00 to 8:30. It shows the Mode A rate to be greater than 300 interrogations per second, at times for more than a minute. It does not appear to be synchronous to the orbit of Frankfurt (which is approximately 10 minutes).

There is also a relationship between the altitude of the aircraft and the interrogation rates. This is most apparent on Figure 4.3.2-8 at the 12000 ft level. The aircraft was at 12,000 ft from 6:46 to 7:11. The Mode A and Mode C rates are approximately 100 and 70 interrogations/second respectively. When the aircraft climbs to 22000 ft, the rates increase to approximately 150 and 120 interrogations per second.

Figure 4.3.2-10 shows the rates as a function of altitude for the entire flight. This figure shows the rate to increase as a function of altitude, which confirms in a more direct manner the behavior seen on 24 May, as described above. The highest rate was measured at 22,000 and the lowest at 3000 ft.

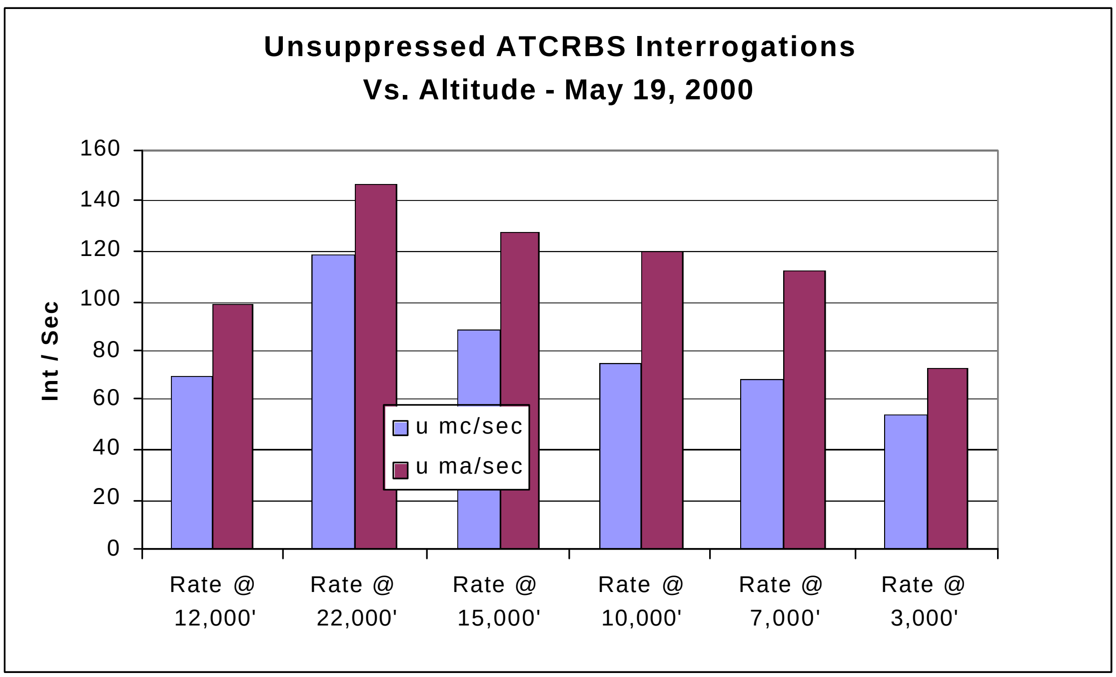


Figure 4.3.2-10. Unsuppressed ATCRBS Interrogations vs. Altitude, DATAS, May 19

The AMF measurements made on 19 May were also analyzed to observe the dependence of interrogation rate on altitude. The AMF data is summarized in Figure 4.3.2-10a, which is a plot of received interrogation rate as a function of altitude. These results confirm the trend suggested by the earlier figures. ATCRBS interrogation rate is seen to vary significantly with altitude, increasing in rate as altitude increases.

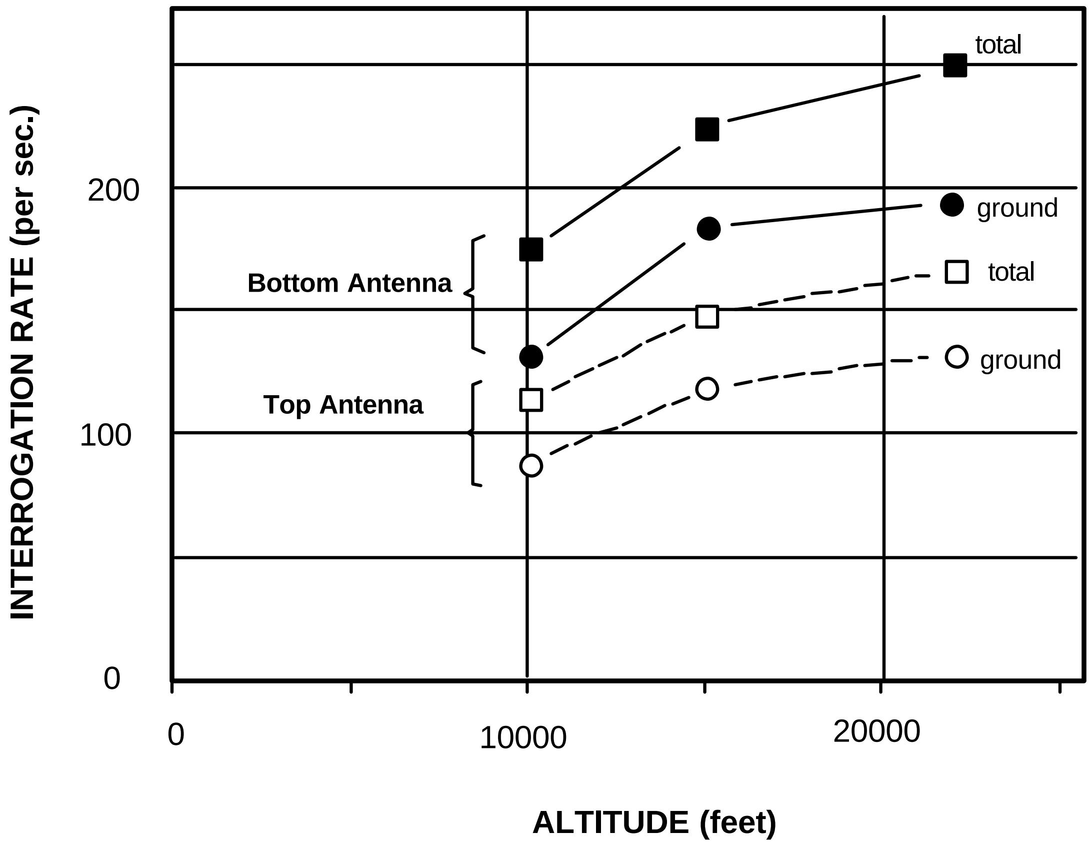


Figure 4.3.2-10a. Interrogation Rate as a Function of Altitude

(AMF measurements of Mode A and Mode C interrogations, threshold = -74 dBm at antenna)

Figure 4.3.2-11 shows the Mode S and Mode 2 interrogation rates for the flight of 19 May. The Mode S rates are seen to be a function of aircraft position when in an orbit near Frankfurt. The rate varied from approximately 100 on one end to as high as 500 on the other. The Mode 2 rate was fairly constant at about 20 per second. The highest rates were at the low altitude orbits (after 8:15).

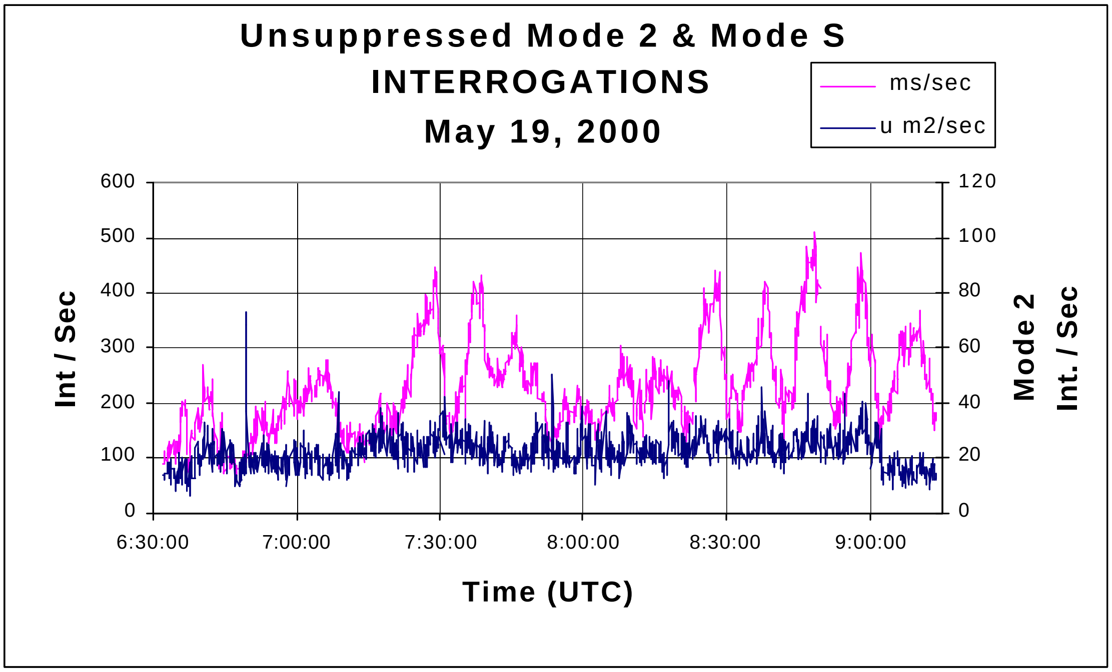


Figure 4.3.2-11 Mode S and Mode 2 Interrogations, 19 May

Figure 4.3.2-12 shows the TCAS interrogation rates for the flight of 19 May. The AO and WS rates both climbed to about 50 per second immediately after takeoff from Wiesbaden. The number then decreased to about 20 at approximately 6:48. The aircraft was eastbound at 12,000 ft south of Frankfurt (see Figure 4.3.1.1.1.1.1-1). This time also produced the fewest TCAS aircraft (17). The AO rate then increased to about 60/sec. from about 6:58 to 7:05. The aircraft was headed westbound north of Frankfurt at that time. The WS rate reached 100/sec. during this same period. After 7:05, the rate decreased again as the aircraft was west of Frankfurt and headed away from most of the TCAS traffic. Rates of less than 50 for both interrogation types were reached at 7:10 when the aircraft was near Wiesbaden (the takeoff point). During the transition from 12,000 ft to 22,000 ft, the WS rates reached as high as 350/sec. The number of TCAS aircraft remained approximately 30 during this change. The AO rate did not change either, and remained at approximately 75/sec. It remained at this value for all the orbits at 22,000 ft. The WS interrogation rate at 22,000 ft is highly dependent on the position within the orbit, the average change being from 50 to 200. The AO rate only varied from about 60 to 80 during the orbits.

The orbits after 8:15:00 were done at lower altitudes. At these altitudes, the AO rate also changes more as a function of position.

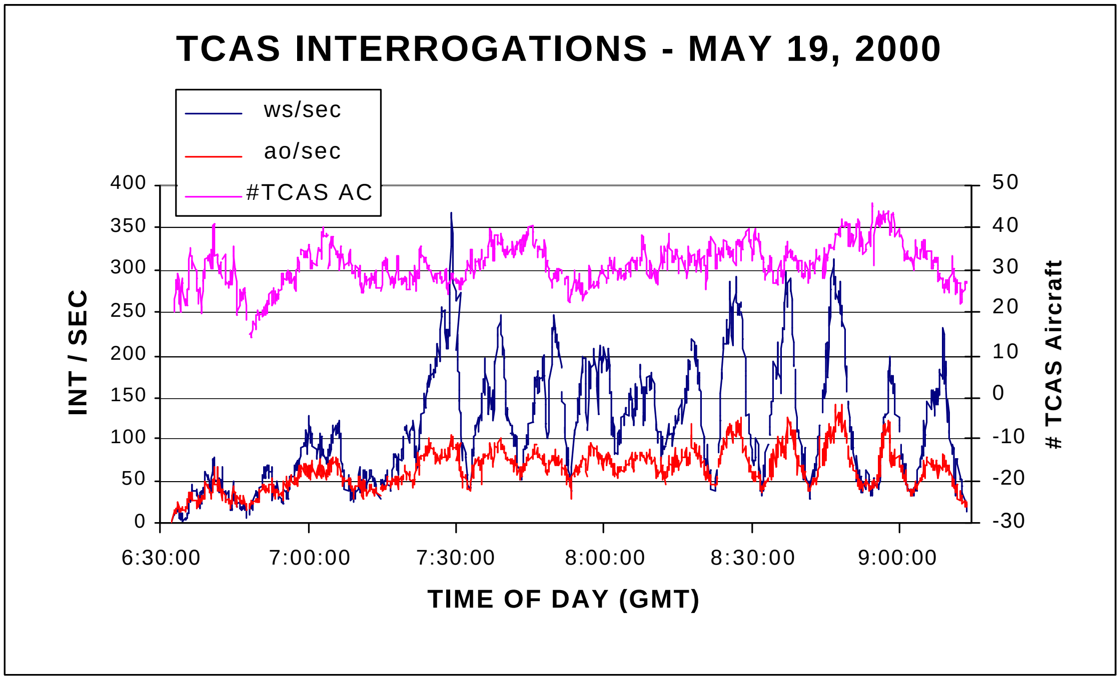


Figure 4.3.2.1.3.1-1. TCAS Interrogations, 19 May

Figure 4.3.2-13 shows the ATCRBS suppression interrogation rates for the flight of 19 May. There were several sudden increases in suppression rate during the flight. The increases at approximately 6:50 and 7:20 occurred when the aircraft was south-southeast of Frankfurt in about the same position. The first happened when the aircraft was making the orbit at 12,000 ft and the second when the aircraft was in the same position at 22,000 ft. This coincides with an increase in unsuppressed Mode A and Mode C interrogations as well. This is probably the result of a single radar site. The increase in suppression rates is approximately 350 interrogations per second. This is about the nominal PRF of many radars.

The other peaks are related to the position of the aircraft within the orbit. The highest peak of 1100 interrogations per second occurred at 8:48 when the aircraft was doing an orbit at 15,000 ft. A smaller peak occurred at 10,000 ft and another occurred when the aircraft was coming in for a landing at Wiesbaden.

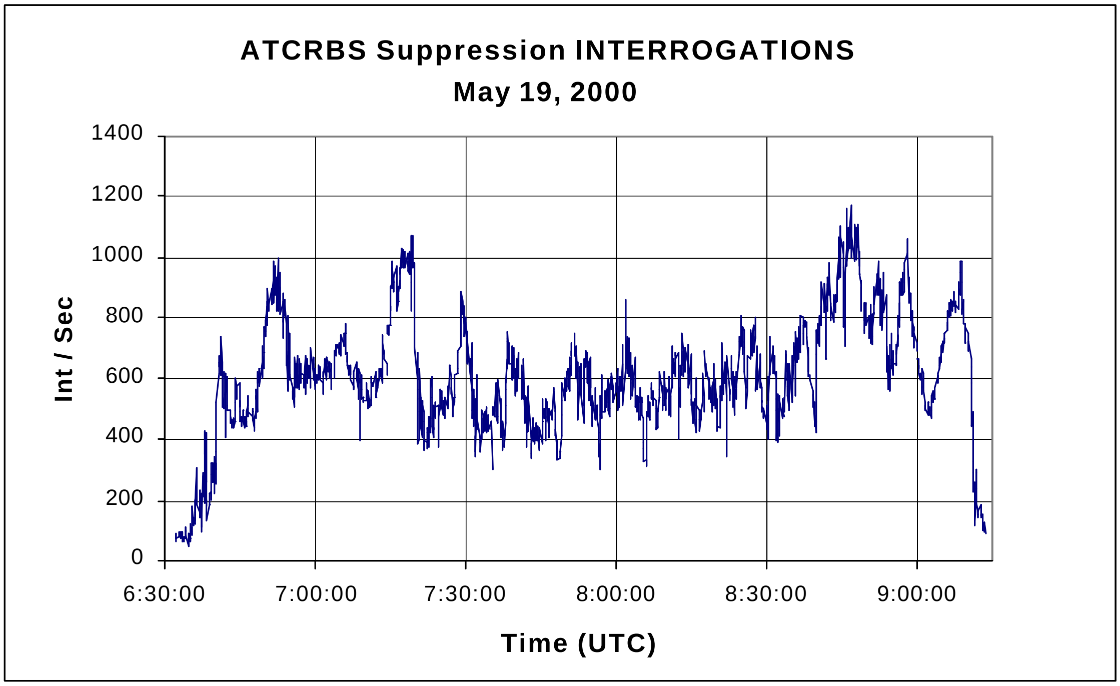


Figure 4.3.2-13. ATCRBS Suppression Interrogations, 19 May

4.3.2.2.1.2 Individual Measurements on 20 May

Refer to Figure 4.3.1.1.1.1.2-1 for the flight path on 20 May (Saturday afternoon). The aircraft again made orbits at (22k) near Frankfurt. Orbits were made in EW and NS directions.

Figure 4.3.2-14 shows the ATCRBS interrogation rates for the flight of 20 May. The most obvious characteristic is the peaks in interrogation rates. They are very periodic and correspond to the orbits made by the aircraft near Frankfurt. The peaks at 13:50, 13:59, 14:08 and 14:17 occurred when the aircraft was making orbits in the EW direction near Frankfurt. The absence of a peak at 14:26 is obvious. The aircraft was making the transition from EW to NS orbits at this time. The other, similar occurrence at 15:20, was probably the same thing, but loss of LDPU data (the source of aircraft position information) prevented the verification of this.

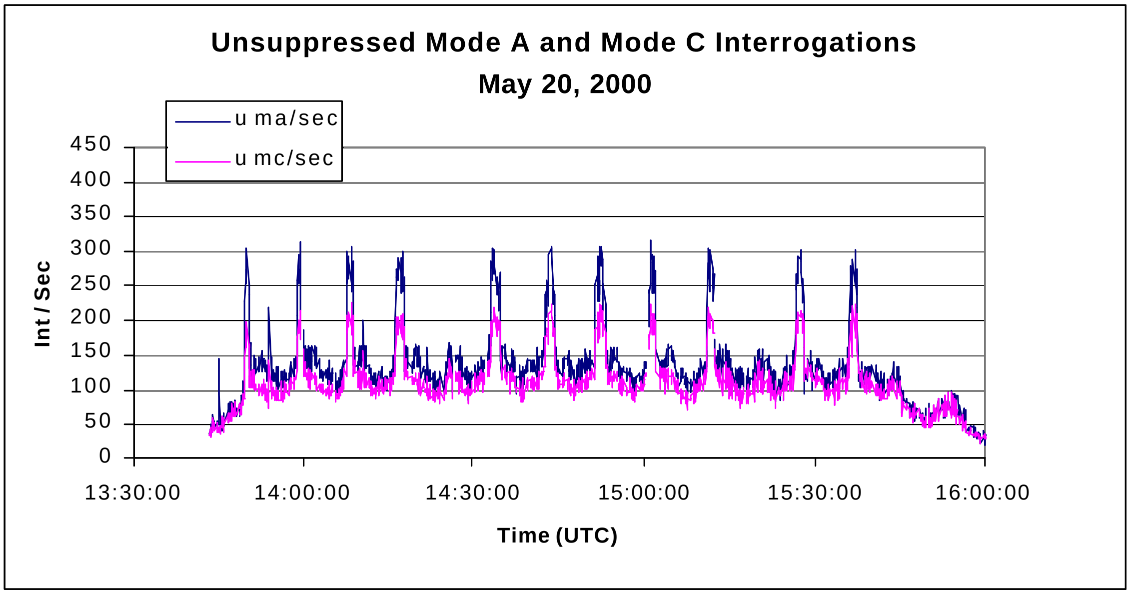


Figure 4.3.2-14. Unsuppressed ATCRBS Interrogations, 20 May

Figure 4.3.2-15 shows the Mode S and Mode 2 interrogation rates for the flight of 20 May. N40 took off at approximately 13:41 and climbed immediately to 22,000 ft. The Mode S rate on 20 May was much more constant than on 19 May. It varied around 200/sec for most of the flight.

Mode 2 looks the same as on 19 May, fairly constant at about 20 interrogations/sec.

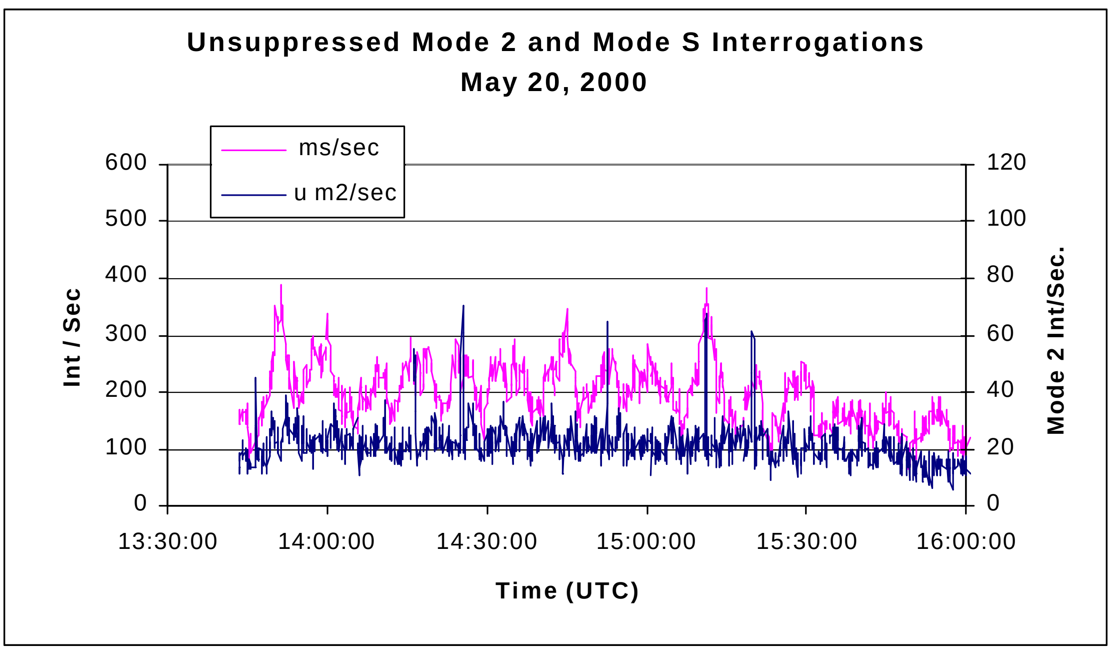


Figure 4.3.2-15. Mode S and Mode 2 Interrogations, 20 May

Figure 4.3.2-16 shows the TCAS interrogation rates for the flight of 20 May. N40 took off at approximately 13:41 and climbed immediately to 22,000 ft. The AO interrogations decrease slightly through the flight from about 75 at the beginning to about 50 per second at the end. The WS are a function of position in the orbit and vary from about 50 per second to more than 200 per second. The highest rate of more than 250 occurred during takeoff. The number of TCAS aircraft gradually decreased from about 35 at the beginning to about 20 at the end of the flight.

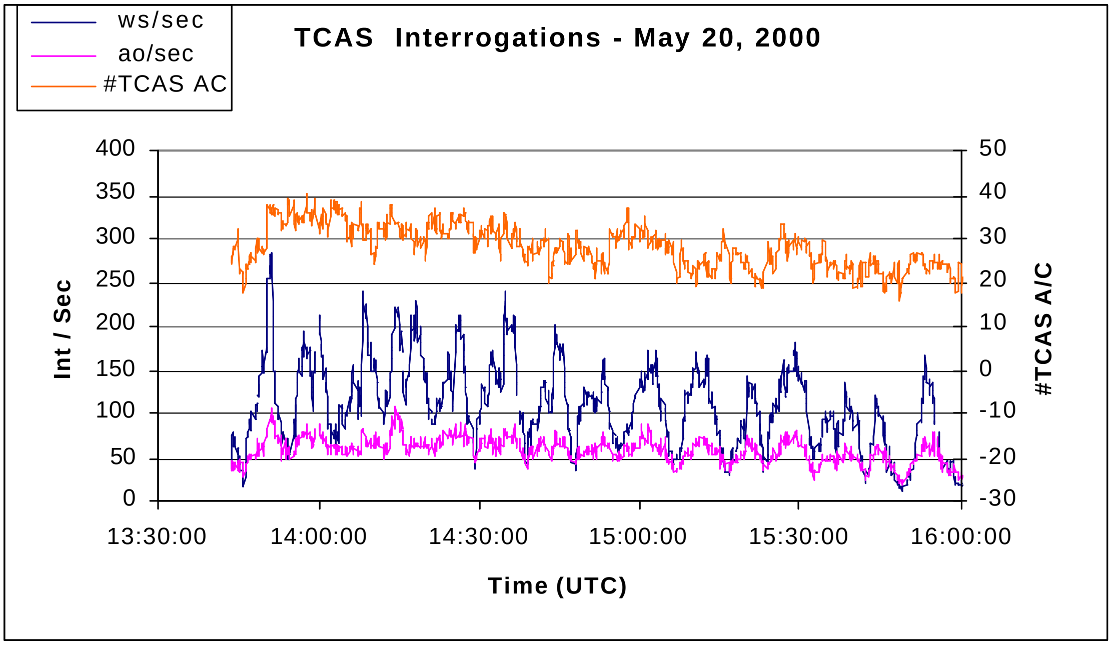


Figure 4.3.2-16. TCAS Interrogations, 20 May

Figure 4.3.2-17 shows the ATCRBS suppression interrogation rates for the flight of 20 May. N40 took off at approximately 13:41 and climbed immediately to 22,000 ft. The number of ATCRBS suppressions remained fairly constant throughout the flight. They fluctuated approximately plus or minus 200 to 300 from an average value of about 800 interrogations per second.

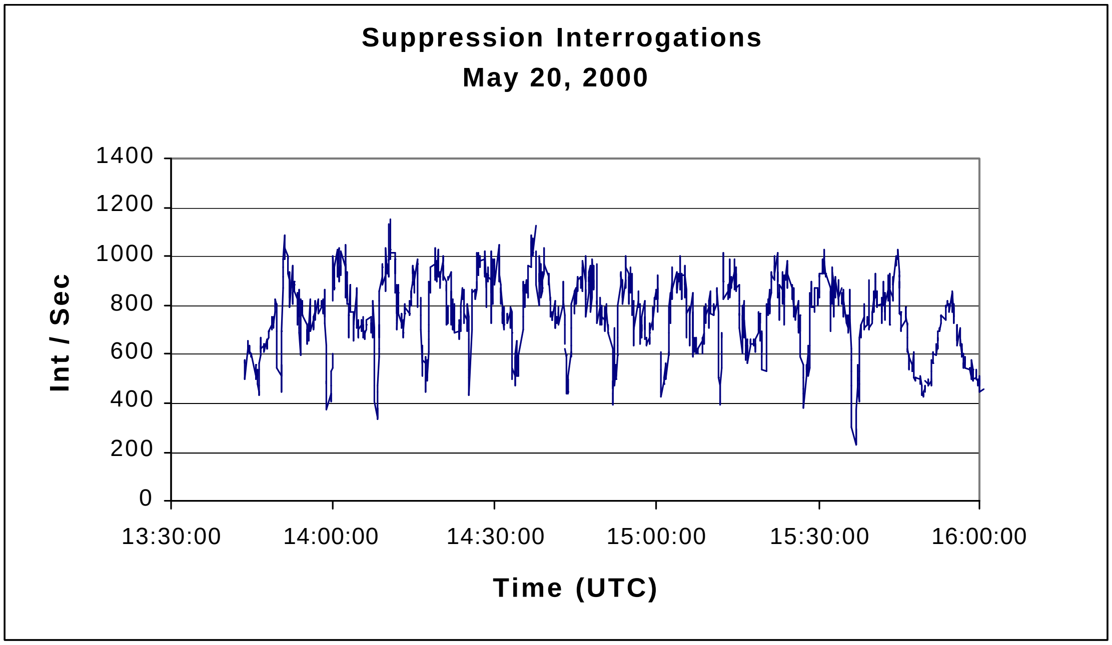


Figure 4.3.2-17. ATCRBS Suppression Interrogations, 20 May

4.3.2.2.1.3 Individual Measurements on 22 May

Refer to Figure 4.3.1.1.1.1.3-1 for the flight path of N40 during the tests of 22 May. N40 made a trip from Wiesbaden to Munich and back. There were no orbits as in the previous two days. The position of the aircraft during the data samples shown on the fruit rate plots is indicated by the blanks in the flight path.

Figure 4.3.2-18 shows the ATCRBS interrogations for the flight of 22 May. The "takeoff" was at 13:46:00. The rates prior to this time (less than 20 interrogations per second) were measured while N40 was on the ground in Wiesbaden. The rates increased dramatically after takeoff to a peak value of slightly more than 150 (Mode A) and 100 (Mode C) interrogations per second. The same high peaks in Mode A interrogations rate was seen (discussed previously on 19 May data).

The aircraft departed the Frankfurt area at approximately 14:00 and arrived in the Munich area at approximately 14:30. A slight increase in both Mode A and Mode C rates was seen in the immediate Munich area. The rates away from the Frankfurt area were 91 and 65 interrogations per second for Mode A and Mode C respectively.

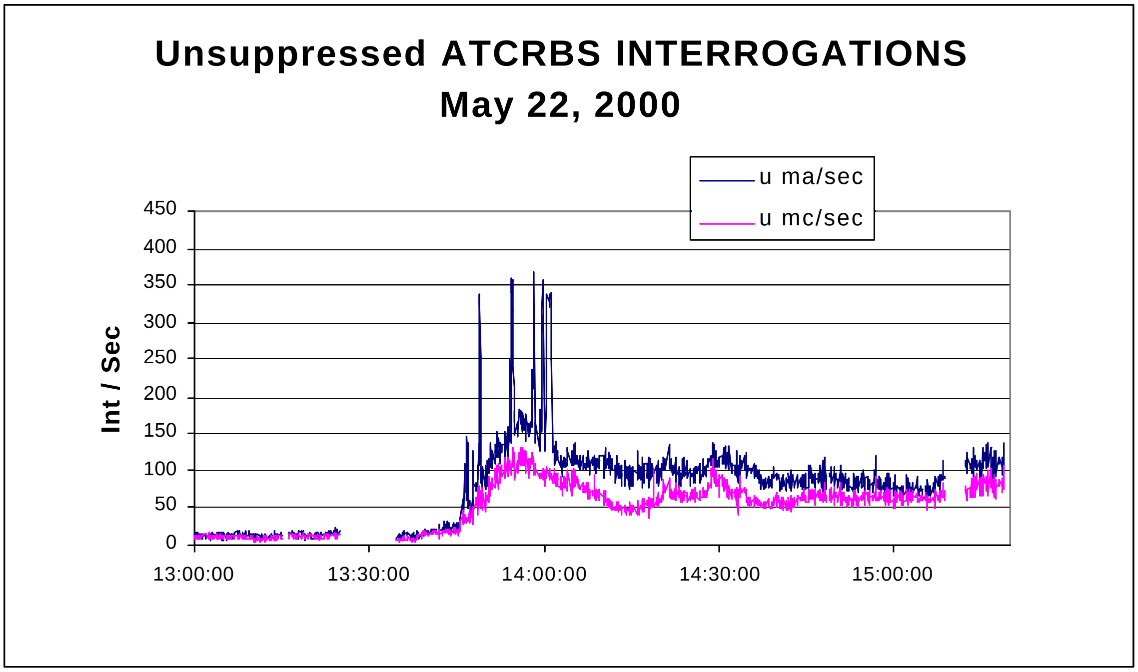


Figure 4.3.2-18. Unsuppressed ATCRBS Interrogations, 22 May

Figure 4.3.2-19 shows the Mode S and Mode 2 interrogations for the flight of 22 May. The "takeoff" was at 13:46:00. The highest Mode S interrogation rate (~200/sec) was measured while the aircraft was still on the ground. This data collection consisted of only a round trip flight to Munich (no orbits near Frankfurt). The aircraft was in the Munich area at approximately 14:30.

The Mode 2 interrogation rate was lower than measured near Frankfurt at less than 20 interrogations per second.

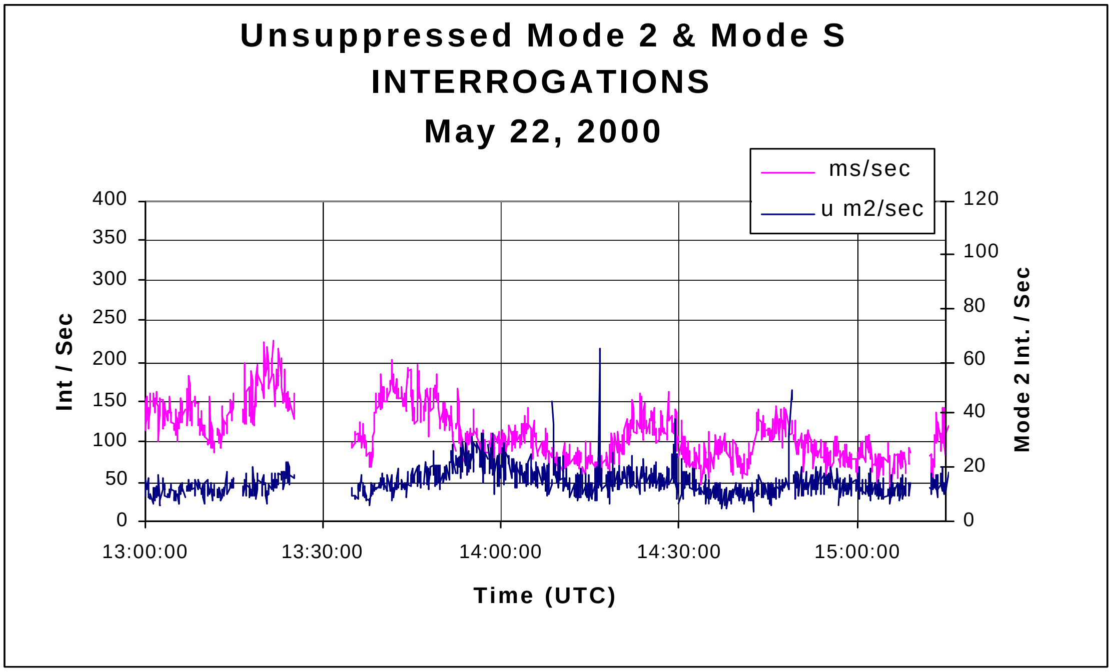


Figure 4.3.2-19. Mode S and Mode 2 Interrogations, 22 May

Figure 4.3.2-20 shows the TCAS interrogations for the flight of 22 May. The "takeoff" was at 13:46:00. The rates prior to this time (20 to 50 interrogations per second) were measured while N40 was on the ground in Wiesbaden. The number of TCAS aircraft seen while on the ground was about 25. The rates increased after takeoff to a peak value of about 70 interrogations per second. The number of TCAS aircraft reached as high as 40 during takeoff.

The peak at about 14:05 occurred when the aircraft was travelling toward Munich and almost directly south of Frankfurt. The number of TCAS aircraft decreased steadily to about 15 when midway between Frankfurt and Munich. The AO and WS rates at this time were both about 20 interrogations per second. The number of TCAS aircraft increased to about 28 when the aircraft was in the Munich area (14:20 to 14:35). The WS rate reached its peak during this period at 95 interrogations/sec. This occurred as the aircraft had turned back toward Frankfurt while in the Munich area. The number of TCAS aircraft reached as low as 10 when on the return trip from Munich.

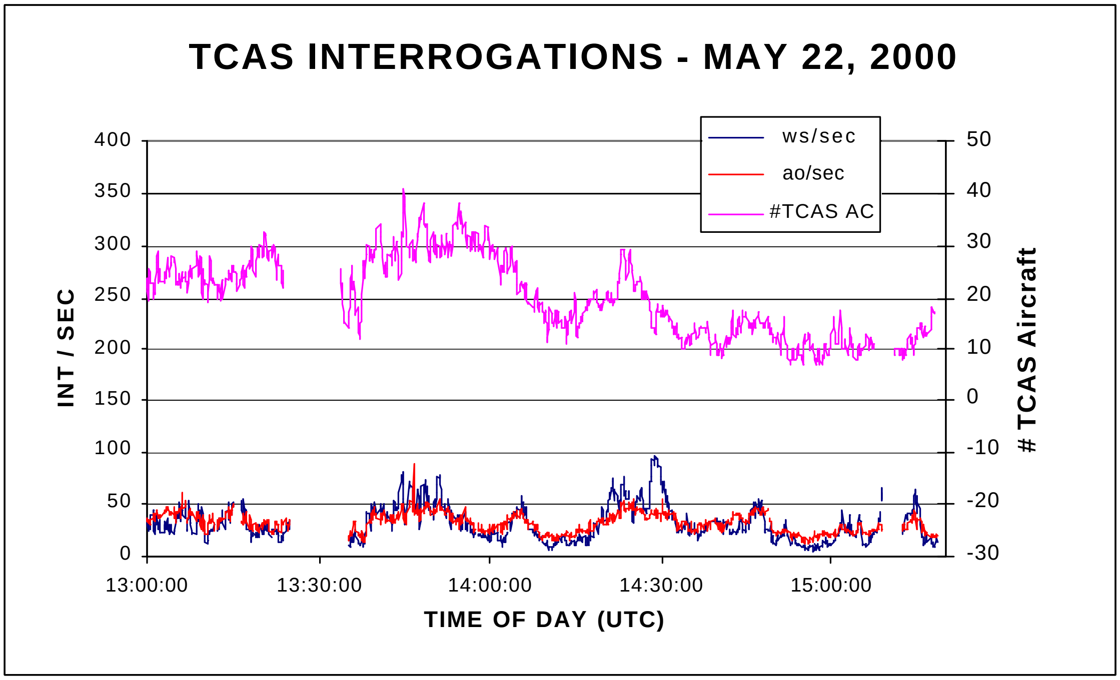


Figure 4.3.2-20. TCAS Interrogations, 22 May

Figure 4.3.2-21 shows the ATCRBS suppression interrogations for the flight of 22 May. The suppression rate while on the ground (prior to 13:46:00) was approximately 100 per second. The aircraft climbed immediately to 22,000 and departed for the round trip to Munich. The peak suppression interrogation rate was approximately 900/second while the aircraft was still in the Frankfurt area south of the airport. The rate dropped steadily to less than 100 interrogations per second at about 14:15. The aircraft was in the Munich area from about 14:20 to 14:35. The suppression rate in this area increased to slightly more than 300 interrogations per second. The rate then dropped again while enroute back to Frankfurt. It increased again when approaching the Frankfurt area.

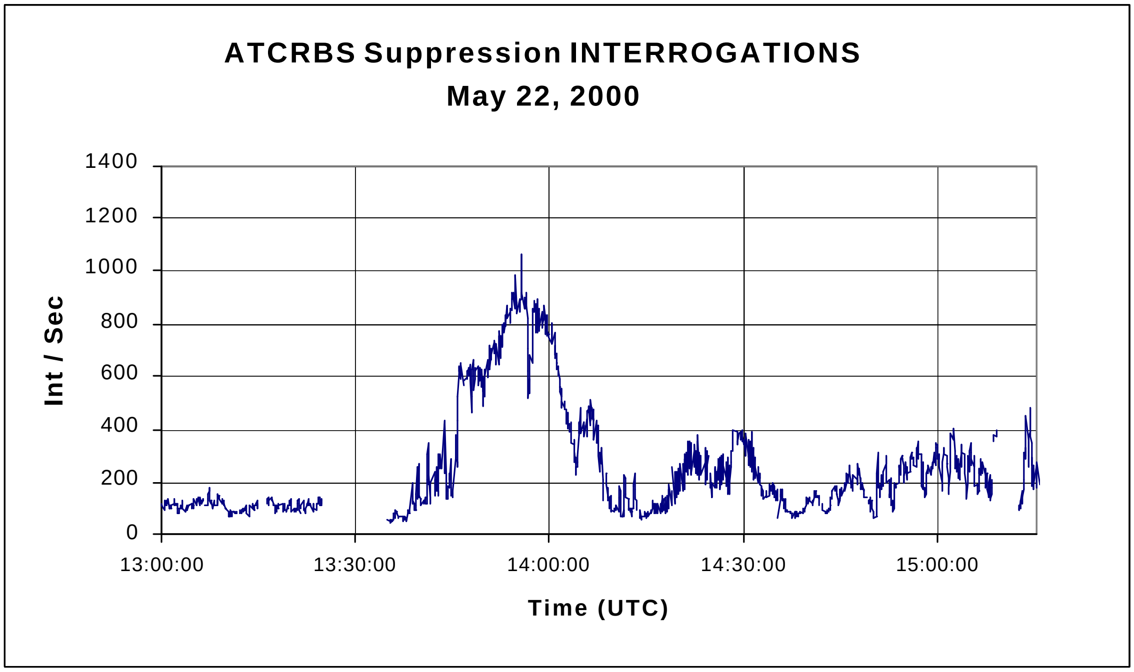


Figure 4.3.2-21. ATCRBS Suppression Interrogations, 22 May

4.3.2.2.1.4 Individual Measurements on 25 May

Refer to Figure 4.3.1.1.1.1.5-1 for the flight path of N40 on 25 May (Thursday). The first portion of the flight consisted of several orbits near Frankfurt and the second part was a round trip to Munich.

Figure 4.3.2-22 shows the ATCRBS interrogation rates for the entire trip. It shows characteristics seen in earlier flights. The aircraft took off from Wiesbaden at 10:38. During the takeoff, the high peaks of "all Mode A" interrogations occurred. During the orbits near Frankfurt, the Mode A and Mode C peaks of almost 300 interrogations per second occurred.

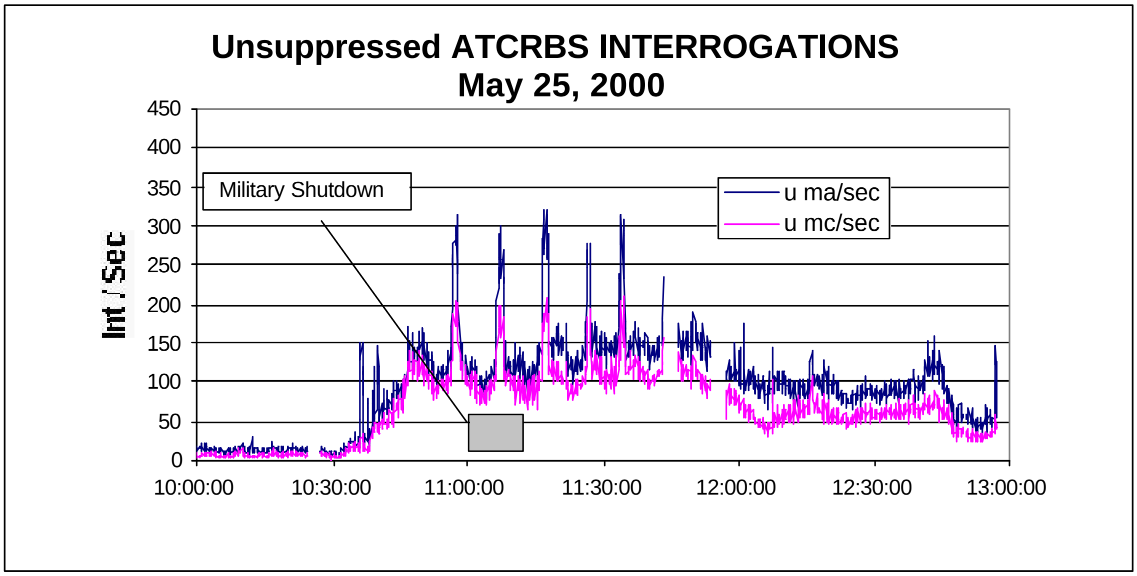


Figure 4.3.2-22. Unsuppressed ATCRBS Interrogations, 25 May

A shutdown of military radars was scheduled from 11:00 to 11:10. There appears to be a reduction in the Mode A and Mode C rates at this time. The start and stop times of the shutdown of individual radars were not synchronized, so it is difficult to ascertain the effect. A further analysis of radar interrogation repetition frequencies as would be necessary to identify the radars and determine the contribution to interrogation rates by the military, and the effect of the shutdown on interrogation rates is beyond the scope of this report.

The aircraft completed the orbits near Frankfurt and departed for Munich at 11:47. Note the steady decrease in Mode A and Mode C rates until 12:08, when the aircraft is approximately midway between Frankfurt and Munich. The aircraft was in the Munich area at approximately 12:15 when the slight peak in interrogation rate occurs. The aircraft then returned to the Frankfurt area and landed at Wiesbaden. Note the decrease between 12:15 and 12:30 (until midway on the return trip). The rates then increase when the aircraft approached the higher interrogation rate area around Frankfurt. The aircraft landed at 13:04.

Figure 4.3.2-23 shows the Mode S and Mode 2 interrogation rate as received by DATAS on N40 on 25 May. This flight consisted of two parts, the first being orbits near Frankfurt and the second a round trip to Munich (similar to the one on 22 May). The aircraft was on the ground prior to 10:30. The Mode S data from 25 May shows two distinct values. When orbiting near Frankfurt, the Mode S rate is between 200 and 250 with the peaks going as high as 350. The Mode S rate is below 100/sec when the aircraft was enroute to Munich. In the Munich area (at approximately 12:15), the rate climbed to about 150 per second.

The Mode 2 rate was about 20 per second in the Frankfurt area and about half that while enroute to Munich.

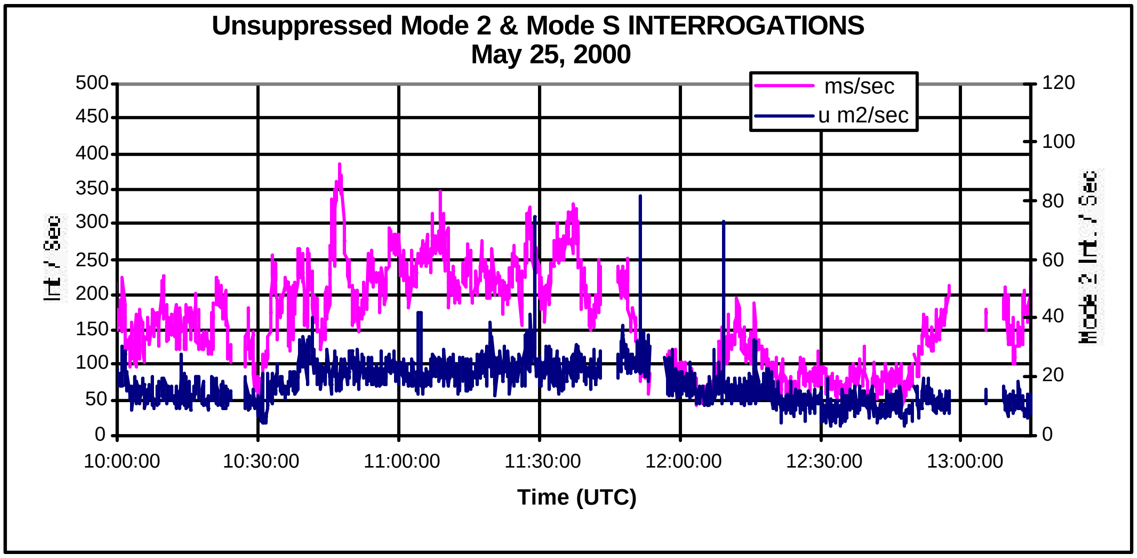


Figure 4.3.2-23. Mode S and Mode 2 Interrogations, 25 May

Figure 4.3.2-24 shows the TCAS interrogation rates for the entire trip. The aircraft is on the ground prior to 10:42. The number of TCAS aircraft increased to approximately 30 when orbiting near Frankfurt (prior to 11:47). The ATCRBS Only interrogation rate during this period was fairly constant at about 70/sec. The WS rates were a function of the position of the aircraft in the orbit. They reached more than 150/sec. on all orbits. The rates decreased sharply to about 20/sec. when enroute to Munich. The number of TCAS aircraft also decreased to about 10 when the aircraft was about midway to Munich. The aircraft was in the Munich area at approximately 12:15. This coincides with the peak in AO interrogations of about 50/sec and WS interrogations of about 120/sec. The rates decreased again on the return trip until approaching for the landing at 13:04.

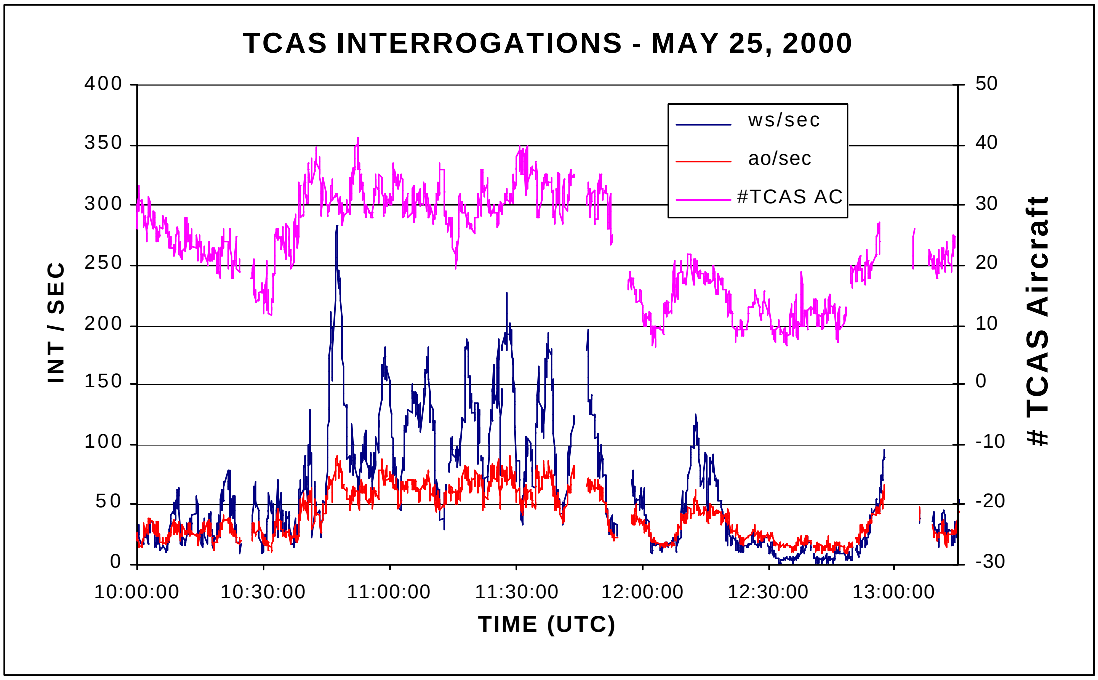


Figure 4.3.2-24. TCAS Interrogations, 25 May

Figure 4.3.2-25 shows the ATCRBS suppression interrogation rates for the entire trip. It shows characteristics seen in earlier flights. The aircraft took off from Wiesbaden at 10:38. The highest suppression rate was measured as the aircraft was starting the first orbit headed eastbound near Frankfurt. The rate was slightly more than 1000 interrogations per second. The orbits prior to 11:30 were in the east-west direction near Frankfurt. The average rate here appears to be about 700 interrogations per second with some points in the orbit where the rate drops to about 400. The north-south orbits (from 11:30 to 11:47) appear to have a higher average rate of about 900 interrogations per second. When the aircraft departs for Munich at 11:47, the rate drops significantly. It reaches the minimum of less than 100 interrogations/sec. at about 12:10 when the aircraft is about midway between Munich and Frankfurt. It increases to about 300 interrogations per second when the aircraft is near Munich (12:10 to 12:20). It then goes back down while enroute and increases back up when the aircraft nears Frankfurt.

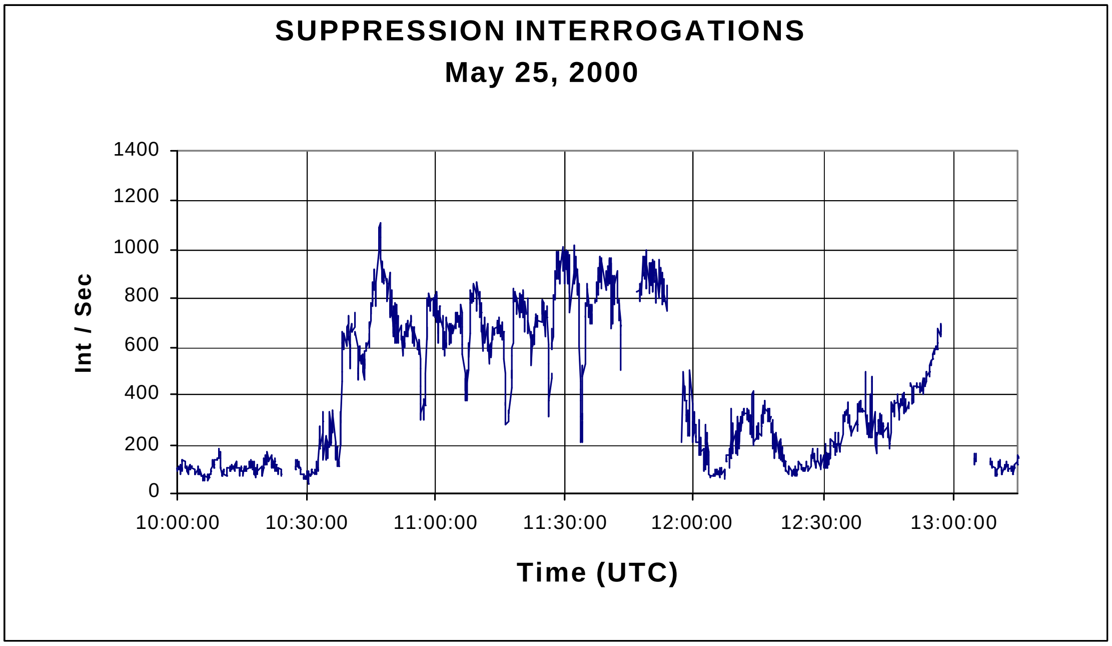


Figure 4.3.2-25. ATCRBS Suppression Interrogations, 25 May

4.3.2.2.2 Day-to-Day Comparisons

Unsuppressed ATCRBS Interrogations. The 1030 MHz signals ATCRBS interrogations from each day were analyzed to characterize and compare the rates. Figure 4.3.2-26 shows the average ATCRBS interrogation rates as a function of the day of the week. These average rates did not use data from areas where the interrogation rates increased dramatically as a function of position in the orbit. The purpose of giving the "average" rate is to enable the user to relate that information to all aircraft in the general vicinity so "localized" effects are eliminated which would severely skew the results.

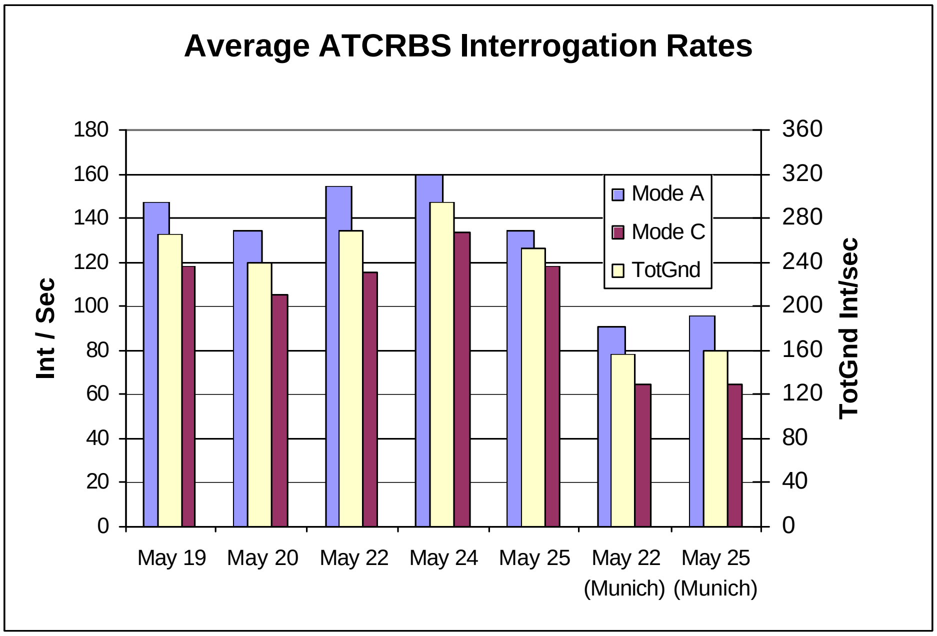


Figure 4.3.2-26. Average ATCRBS Interrogation Rates - Frankfurt Area (DATAS)

The average ATCRBS interrogation rate when in the Frankfurt area was 264 interrogations per second. The rate varied from the lowest of 240 interrogations per second on May 20 (Saturday) to 294 interrogations per second on May 24 (Wednesday).

The two trips to Munich produced interrogation rates of 156 and 160 interrogations per second. The ratio of Mode A to Mode C near Frankfurt was 1.24:1. On the round trip to Munich, the ratio was 1.43:1. This is probably the result of more "long range" radar sites on the Munich trip as many of those use 2:1 interlace.

Figure 4.3.2.2.1-2 shows the peak ATCRBS interrogation rates as a function of the day of the week. The total Mode A and Mode C peak interrogation rate was 673 interrogations per second on May 24 (Wednesday) when making the Frankfurt orbits. This was comprised of 412 Mode A interrogations and 262 Mode C. The peak rates on the Munich trip were much lower. The total peak rate in the Munich area was 253 on May 22 and 329 on May 25.

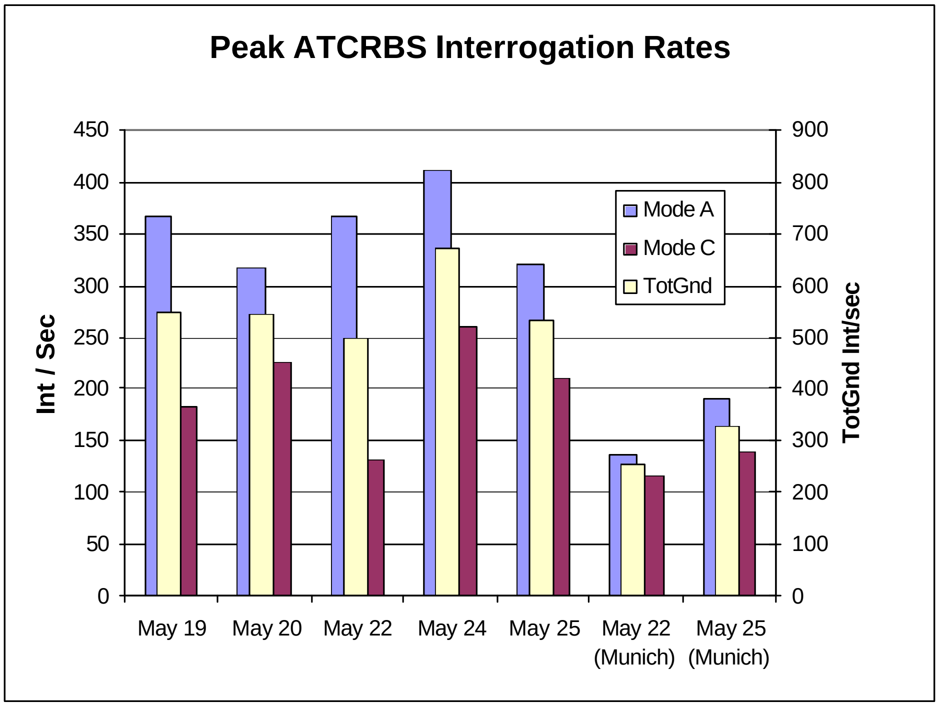


Figure 4.3.2-27. Peak ATCRBS Interrogation Rates - Frankfurt Area (DATAS)

The peak rates are the result of two different phenomena. One is apparently radar(s) with side lobe suppression (SLS) characteristics out of specified limits. This causes interrogations that should be suppressed to appear unsuppressed, thereby causing extra replies from transponders. The second cause of excessive peaks was seen only in Mode A. There are apparently interrogators with directional antenna capability that interrogate for several seconds at a rate of 300 to 350 interrogations per second. Thus a single radar with either characteristic can cause the peak rate to increase dramatically.

Mode S and Mode 2 Interrogations. The Mode S interrogation rate for the five days of orbits near Frankfurt averaged approximately 200 interrogations per second. The lowest was on May 22, but this day there were no orbits so a sample was taken when the aircraft was near Frankfurt. Next lowest was May 20, the Saturday afternoon. The Mode S rates near Munich were much lower, only about 100 interrogations per second.

Mode S interrogations were analyzed for several samples to determine the approximate reply rate for our aircraft. Approximately 1.5 to 2% of the Mode S interrogations were addressed to N40. This is somewhat lower than previous data taken several years ago. It makes sense, however, that as Mode S equipage increases, the percentage addressed to an individual aircraft would decrease.

The Mode 2 interrogation rate averaged 21 interrogations per second in the Frankfurt area and 14 on the Munich trip.

TCAS Interrogations. Figure 4.3.2-28 shows the TCAS interrogation rates as a function of the day of the week. The average number of TCAS aircraft, when in the Frankfurt area, was 29. The lowest number was seen on Saturday (May 20), when only 20 were present during the flight. The average number of ATCRBS Only interrogations was 55, or slightly less than 2 interrogations per aircraft. The average number of Whisper/Shout interrogations was 98 or slightly less than 4 interrogations per aircraft.

On the two trips to Munich, the average number of TCAS aircraft was 16. There were approximately 2 Whisper/Shout and 2 ATCRBS Only interrogations per aircraft.

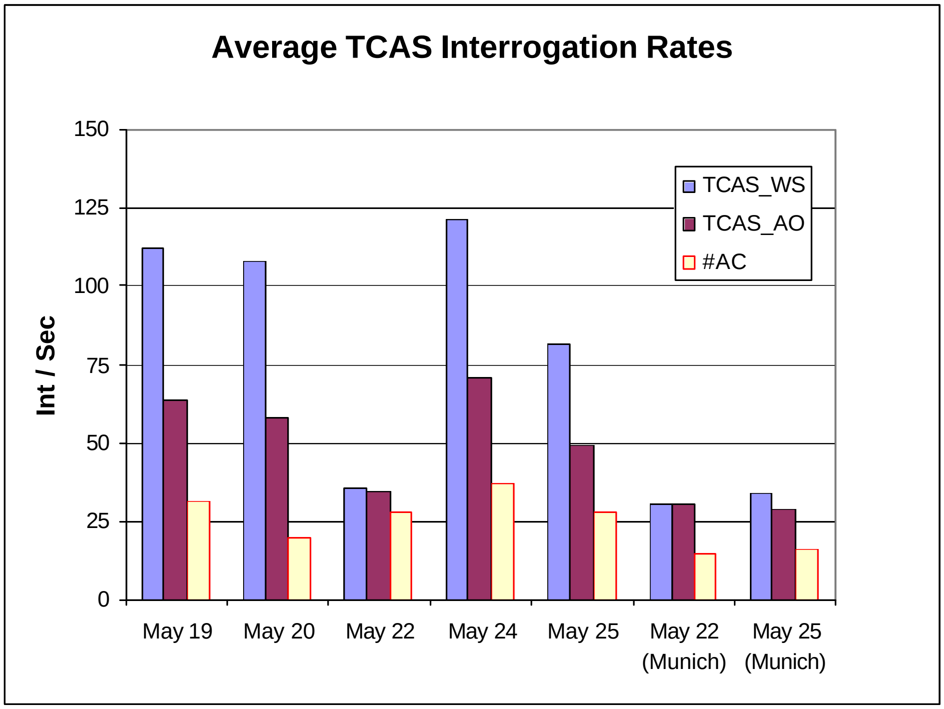


Figure 4.3.2-28. Average TCAS Interrogation Rates - Frankfurt Area (DATAS)

Figure 4.3.2-29 shows the peak TCAS interrogation rates as a function of day of the week. The number of aircraft is repeated (same as Figure 4.3.2.3.1). The peak number of ATCRBS Only interrogations (during the Frankfurt orbits) is approximately 4 per aircraft. The peak number of Whisper/Shout interrogations is between 9 and 10 per aircraft. This is highly dependent on the position of the aircraft in the orbits. The ratios are almost identical for the data while on the round trip to Munich. The peaks occurred when very near to the Munich airport.

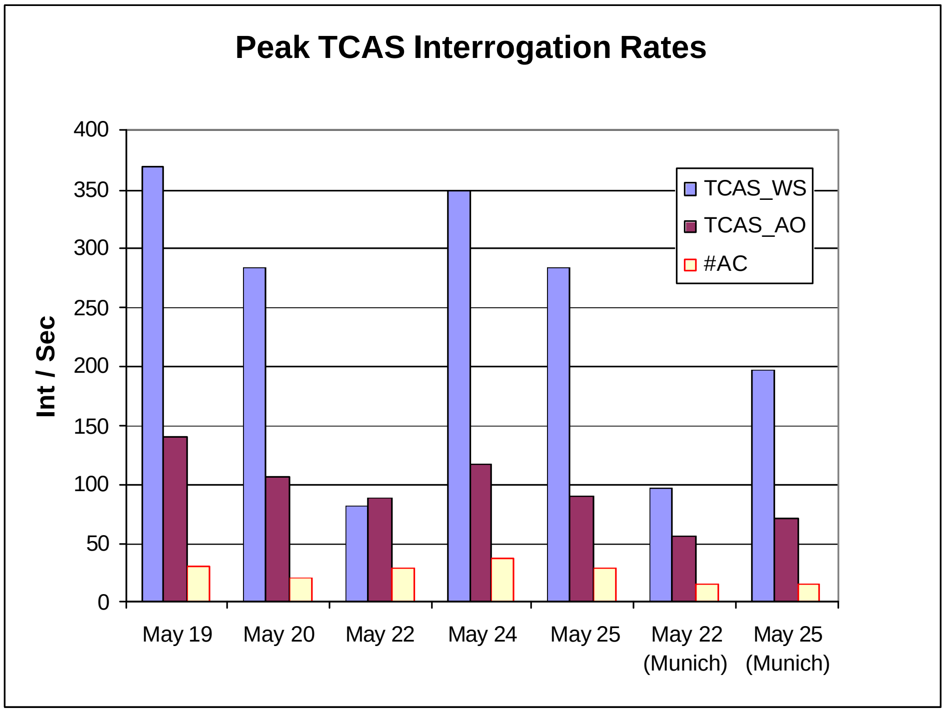


Figure 4.3.2-29. Peak TCAS Interrogation Rates - Frankfurt Area (DATAS)

Suppression Interrogations. Figure 4.3.2-30 shows the suppression interrogation rates for each day of data collection. The average suppression rate for the Frankfurt area is 707 interrogations per second. The first day, May 19, is the lowest at 600. Examination of the data from May 19 shows some areas where there are sudden increases in the suppression rate. This may have been a condition that gradually got worse and increased the rate for the rest of the week. The average rates only vary about 100 interrogations per second for the remainder of the week. The peaks vary by slightly more than that. The average suppression interrogation rate on the Munich trips is 249 interrogations per second. The maximum rate seen was 1000 in the Munich area.

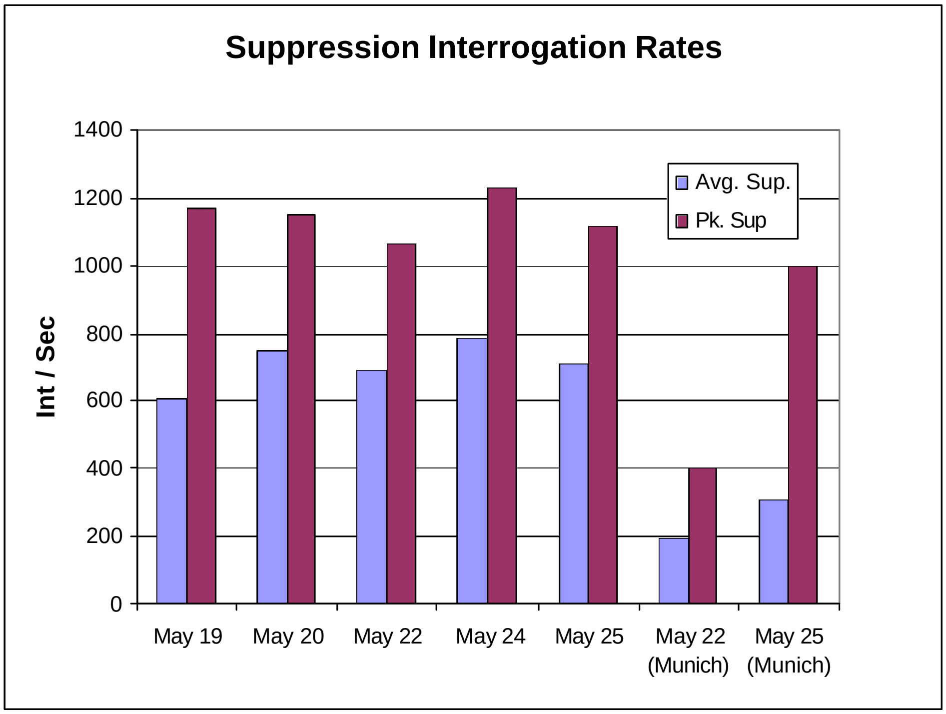


Figure 4.3.2-30. Suppression Interrogation Rates - Frankfurt Area (DATAS)

AMF Measurements. The AMF interrogation rate measurements also exhibited day-to-day differences that are consistent with the above results. The AMF results are summarized in Figure 4.3.2-31, which shows the maximum rate and average rate of received Mode A and C interrogations (for which a reply would be triggered). The sharp peaking of interrogation rate, seen in above figures (Section 4.3.2.1.1) were not included in this figure, nor were the periods when the aircraft (N40) was on the ground or at low altitude just after takeoff or just before landing.

The results indicate relatively little variation of interrogation rate from day-to-day. The minimum rates were observed on Monday, which this is when N40 did not fly in ovals staying in the Frankfurt airspace. Instead N40 flew to Munich and back, and the results tend to indicate that the interrogation rates are somewhat lower at locations away from Frankfurt.

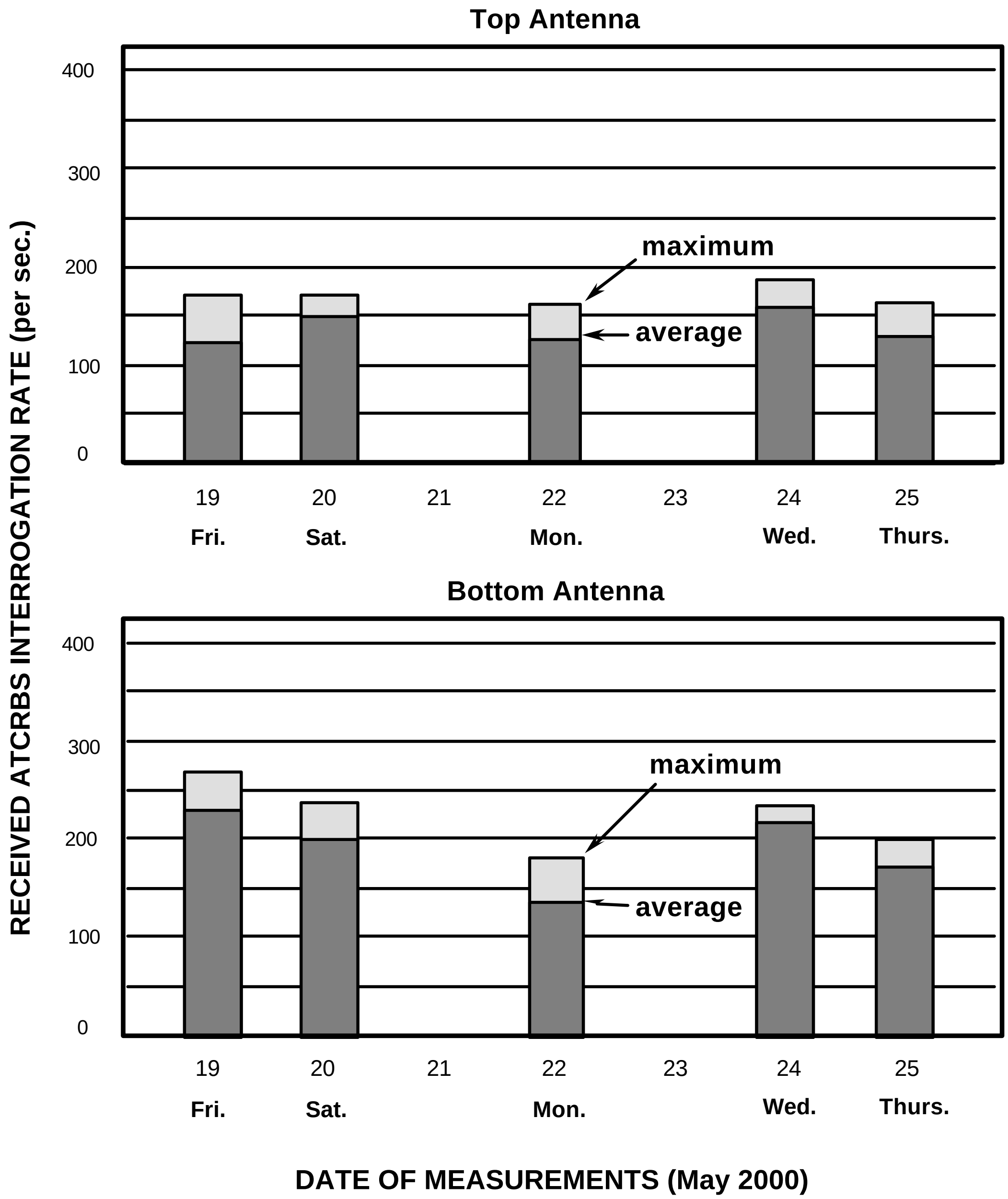


Figure 4.3.2-31. Day-to-Day Variations in Interrogation Rate (AMF measurements, Mode A plus Mode C interrogations)

4.3.3 Aircraft Density and Distribution

Radar data was recorded during the tests as a way of monitoring aircraft traffic at those times. The recordings were made of secondary surveillance radar (SSR) data; primary radar surveillance was not used. The experimental radar at Goetzenhain was used for surveillance in Mode S and a number of other radars were used for surveillance in Modes A and C.

4.3.3.1 Detailed Traffic Analysis for 24 May

4.3.3.1.1 Number and Distribution of Aircraft

4.3.3.1.1.1 Aircraft Count from Surface Radars

Figure 4.3.3-1 shows the number of aircraft and the range distribution relative to Frankfurt. The aircraft distribution in Germany was measured in two ways as shown here. In one case, multiple radars were used together in order to include all aircraft, including those that would be beyond line of sight from a single radar as shown in the plot marked "Multiple SSR Data.". The plotted data marked “Neunkirchen” was derived from a single radar, located at Neunkirchen, and in this case the center point is at Neunkirchen, which is about 20 nmi south of Frankfurt. The number of aircraft as counted using multiple radars is shown for three time on 24 May. These times are intended to show the maximum, the minimum, and a mid-range value, during the time period 10:20 to 13:27 UTC

For comparison, the corresponding aircraft measurements from Los Angeles, made in June 1999 are also plotted. This is the average range distribution, taken from Reference 10. The comparison indicates that the local density was higher in Los Angeles, but that Frankfurt has a greater density of aircraft at long range. This is seen in the slope of the curve, which indicates the range-density of aircraft (aircraft per nmi of range). For example, between 50 and 60 nmi, the Los Angeles range-density is significantly lower than in Frankfurt.

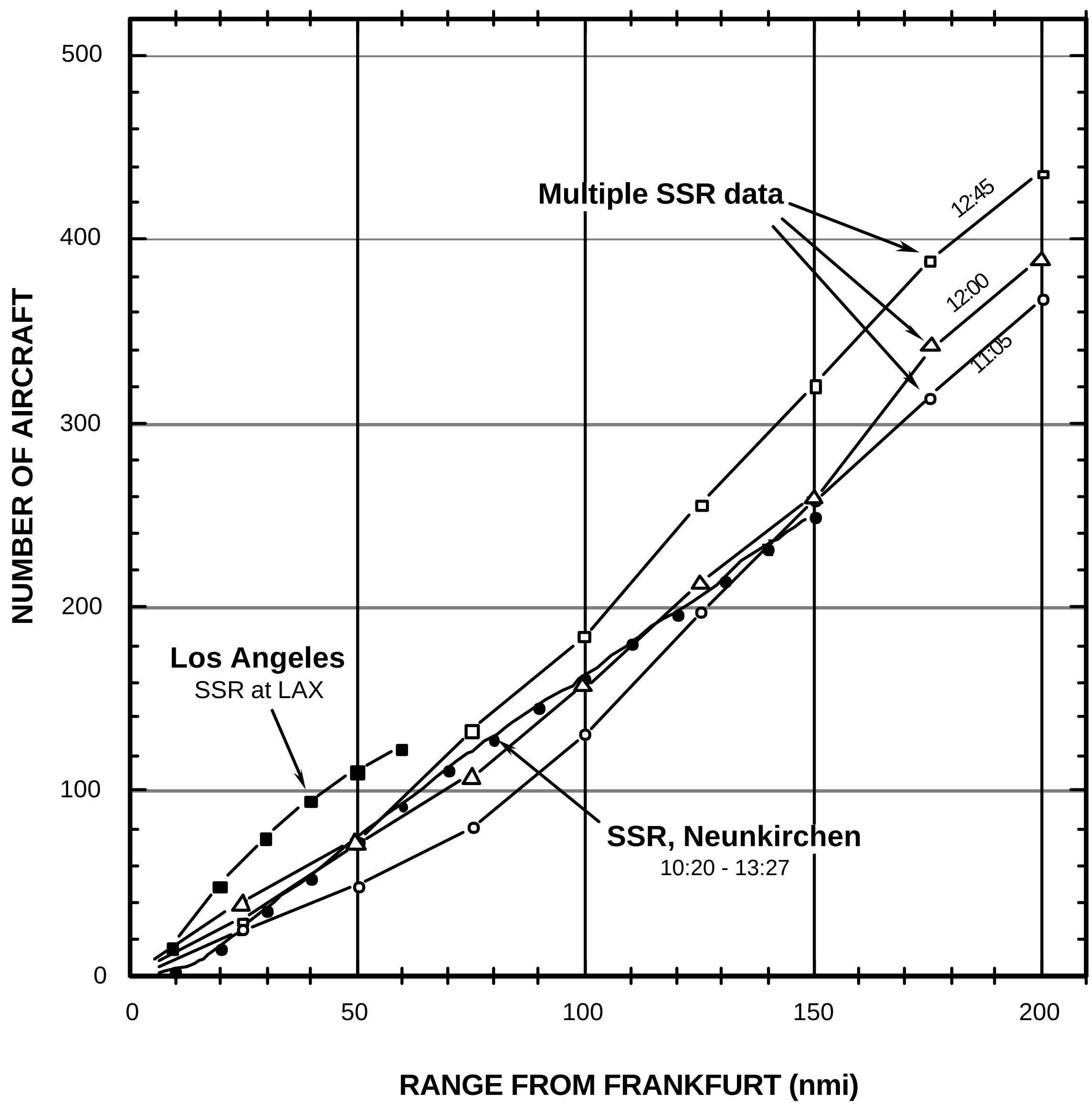


Figure 4.3.3-1. Aircraft Count and Distribution in Range, 24 May

4.3.3.1.1.1 Aircraft Count from Airborne Measurements

The RMF data was filtered for TCAS acquisition (short) Mode S squitters and from this list of short squitters the number of distinct Mode S addresses were identified as a function of time. All short squitters that were declared as either error-free or correctable to an error-free message by the RMF decoder were used to find Mode S addresses. The number of Mode S addresses should correspond to the number of Mode S-equipped aircraft that are visible to the airborne RMF. It should be noted that this number of aircraft does not represent the aircraft count within a fixed range, but rather the number of aircraft as seen by the airborne receiver and RMF's decoder implementation. Therefore, the number of aircraft detected is dependent upon aircraft transmit power, receiver threshold and decoding techniques and ultimately is dependent upon the interference environment which reduces the decoder's ability to correctly decode the Mode S squitter replies, especially the low amplitude replies.

Figure 4.3.3-2a shows the target count for each sample of the data collection from 24 May. Each point is the average target count for the specified "two minute" time interval. The target count is derived with a "two pass" process. Pass1 identifies all acquired Mode S addresses heard from at any time during the "two minute" interval. Pass 2 provides a target count for each second indicating the number of targets heard from during the last 20 seconds.

Figure 4.3.3-2a shows a gradual decrease from about 450 to 370 targets from the beginning to the end of the data collection period. There are a larger number of aircraft seen on the top antenna than the bottom throughout the day. The ATCRBS and Mode S fruit rates were both higher on the bottom antenna (see Figure 4.3.1.1.1.4-2). Investigation showed that the number of Mode S replies from aircraft below N40 was significantly higher than the number from aircraft above N40. N40 was at 22,000 ft for the entire day of 24 May.

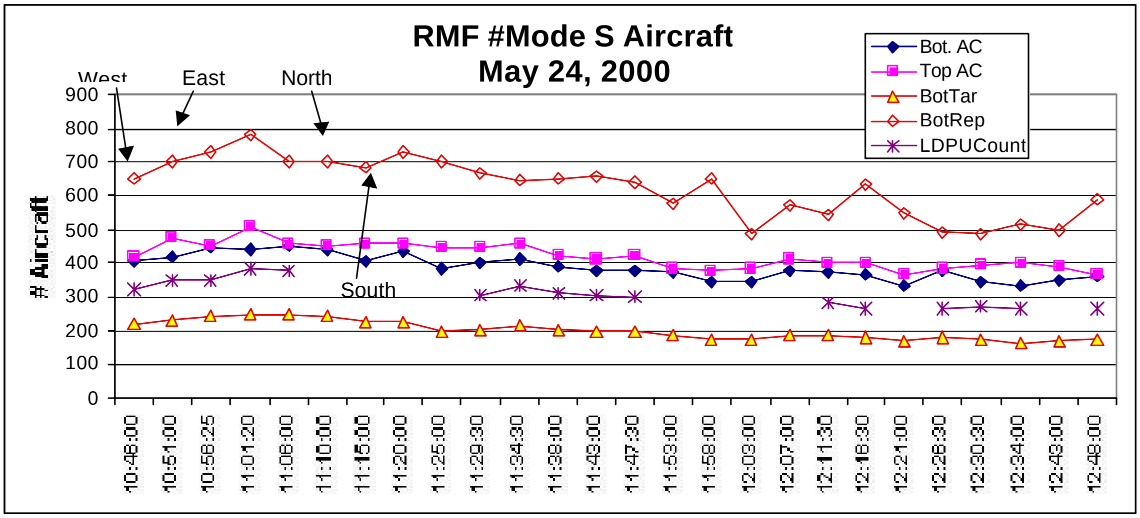


Figure 4.3.3-2a. RMF Mode S Aircraft Count Variability vs. Time, 24 May

The total aircraft count recorded within the multiple ground radar data varied during the day, which would imply that the number of Mode S aircraft should vary similarly. However, the number of Mode S addresses recorded by the RMF did not always correspond to variations in total aircraft count. This divergence in aircraft count may be a consequence of the variation in ATCRBS fruit rate during the day. Since the number of aircraft detected by RMF depends on successful decoding of the Mode S squitter, the increased fruit rate may have limited the ability of RMF to successfully decode short squitters from longer range Mode S targets, thereby effectively reducing its detection range.

Figure 4.3.3-2a shows the LDPU data appears to track the RMF data very well, but with fewer targets. The difference appears to be about 100 targets. This is probably attributable to the LDPU error correction (only Extended Squitter replies are corrected). Because of the required time to process the data, only the points indicated in the LDPU were processed. The correlation of the data to that of the RMF indicated that further processing was not required.

The number of associated replies, those replies that are received from "known" Mode S addresses, ("BotRep" on Figure 4.3.3-2a) appears to reduce from about 700/second early in the day to about 500/second at the end. The Mode S fruit rate was fairly constant throughout the day at about 1000/sec. The number of different targets reporting each second ("BotTar" on Figure 4.3.3-2a) was approximately 200 (also decreasing slightly as a function of time). Unlike "the target count", "BotTar" was not averaged over the last 20 seconds.

Figure 4.3.3-2b and Figure 4.3.3-2c are a measure of performance of the Mode S decoding of RMF for the data of 24 May. The percentage of Mode S replies that could be associated with a target is plotted against the total ATCRBS fruit rate for the same "two minute" period. This is a measure of the efficiency of the processing as a function of ATCRBS fruit.

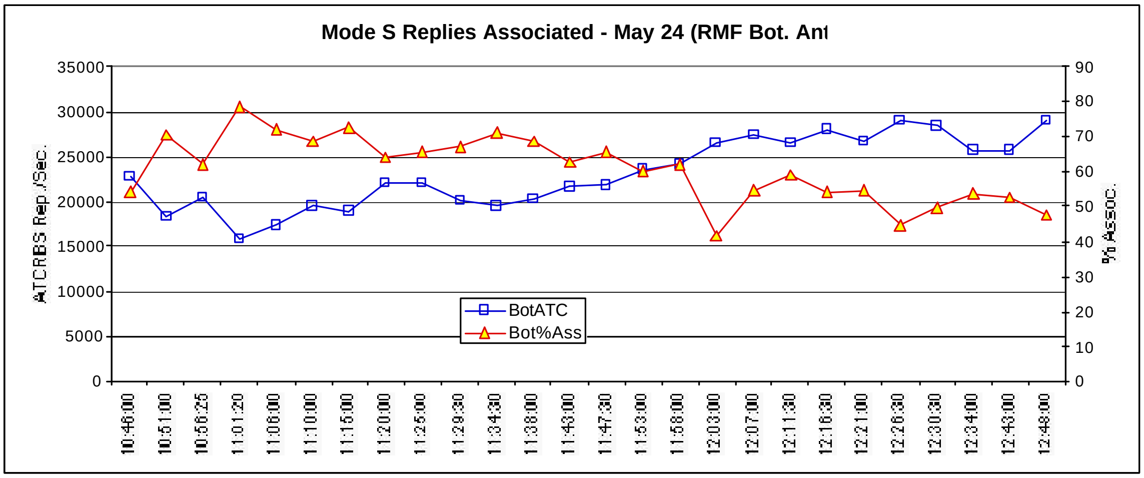


Figure 4.3.3-2b. Bottom Ant. RMF Percentage Mode S Associated Reply Count, 24 May

The average Mode S reply rate on the bottom antenna was 1036 replies per second. The percentage of replies associated with "real targets" varied from a high of 79% at 11:01 when the Mode S rate was 993 per second and the ATCRBS fruit rate was 15.8k. The lowest efficiency was at 12:03 when only 42% of the replies could be associated with an aircraft. The Mode S reply rate at this time was 1167 and the ATCRBS fruit rate was 26.5k. The reply efficiency was never higher than 60% when the ATCRBS fruit rate was higher than 24k. It was only lower than 60% once when the ATCRBS fruit rate was below this value.

The data from the top antenna (refer to Figure 4.3.3-2c) shows, much the same effect. The average Mode S reply rate on the top antenna was 836 replies per second. The highest efficiency on the top antenna was 92% (twice) when the fruit rate was 16k and 15.1k. The lowest value was 55% when the fruit rate was 24.6k.

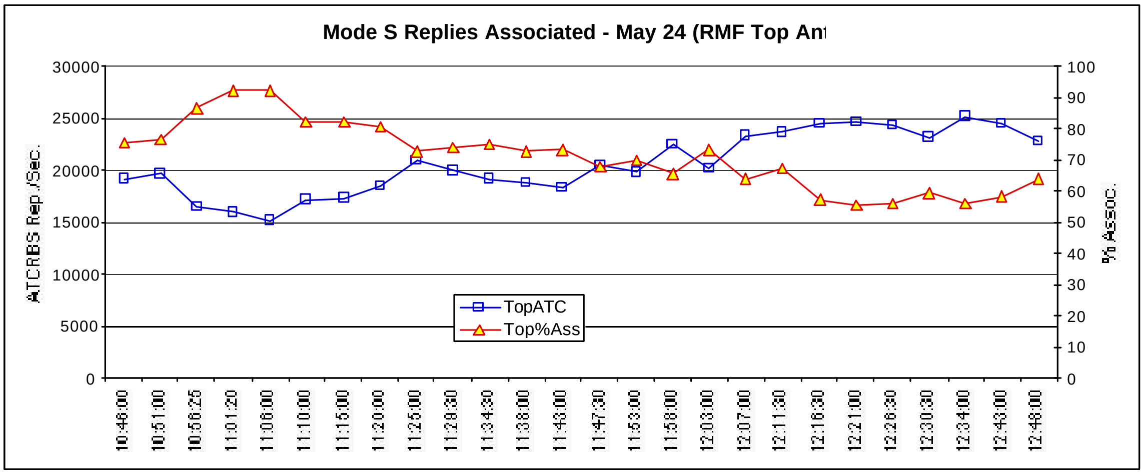


Figure 4.3.3-2c. Top Ant. - RMF Percentage Mode S Associated Reply Count, 24 May

4.3.3.1.2 Aircraft Altitude Distribution

4.3.3.1.2.1 Altitude Distribution from Ground-Based Radars

Aircraft traffic as measured by ground based radars was also analyzed to determine the altitude distribution. Figure 4.3.3-3a shows the altitude distribution of aircraft obtained from the multi-radar surveillance of all aircraft within 100 nmi of Frankfurt. The results are shown in both histogram and cumulative forms.

Use of the multi-radar data base provides good coverage around Frankfurt and throughout most of Germany, but eventually a point is reached beyond which radar surveillance does not include low-altitude aircraft. To minimize such line-of-sight limits, this analysis was applied to aircraft within 100 nmi of Frankfurt.

The results in Figure 4.3.3-1a indicate that altitudes between zero and 10,000 feet are the most common. Higher altitude aircraft are approximately uniformly distributed between 10,000 and 40,000 feet. Above 30,000 feet, the distribution is seen to be concentrated at the odd thousands, which is consistent with our understanding of the air traffic control practices in Europe. The median altitude is seen to be about 11,000 feet. This is significantly different from the altitude distribution in Los Angeles, where the median altitude was measured to be about 4000 feet (ref. 10, page 63).

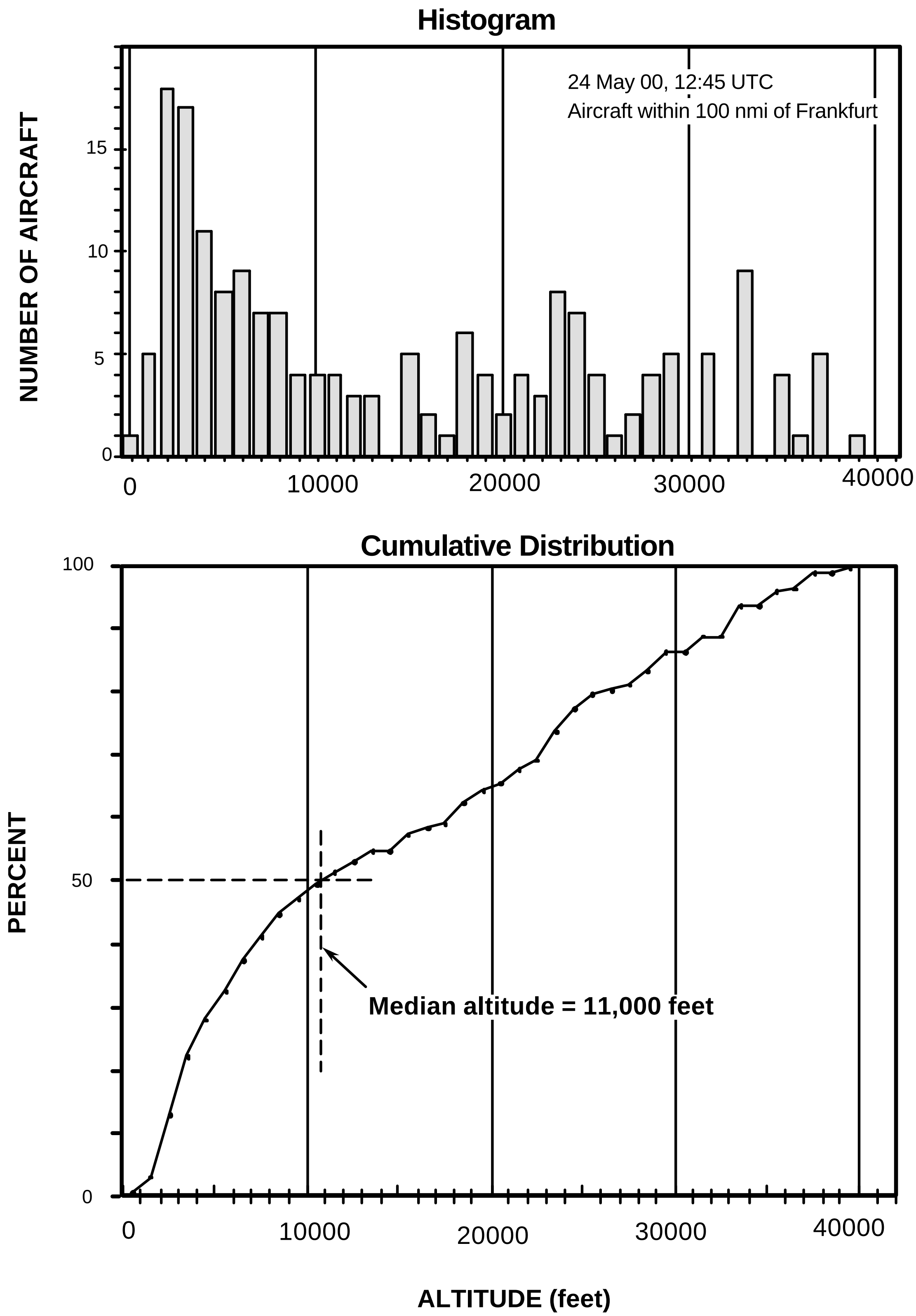


Figure 4.3.3-3a. Aircraft Altitude Distribution

4.3.3.1.2.2 Altitude Distribution from Airborne Measurements

The aircraft altitude distribution was also analyzed using airborne receptions. This analysis was based on Mode S receptions, and therefore the results give the altitude distribution of Mode S aircraft rather than all aircraft. Figure 4.3.3-3b shows the resulting altitude distribution. In this analysis, Mode S receptions were decoded in order to read the encoded altitude values and the discrete address of each aircraft. This was a complex analysis, done together with the number-of-aircraft analysis described in 4.3.3.1.1.1. Results were sorted according to address in order to count each aircraft only once, regardless of the number of replies received from that aircraft.

These results appear to be consistent with the altitude distribution based on radar data, with several differences. One difference is an increase in the proportion of high-altitude aircraft. The median altitude is approximately 30,000 feet based on airborne data, which is considerably higher than the median derived from radar data (11,000 feet). Given that these results apply to Mode S aircraft, it would be expected that the median altitude would be higher for that reason. Another difference is a greater proportion of aircraft on the ground. Such aircraft would not be expected to be included in radar surveillance, except for a radar at the same airport, and therefore would be under-represented in radar data. On the other hand, airborne receptions provide a good opportunity for counting surface aircraft and including them in the altitude distribution.

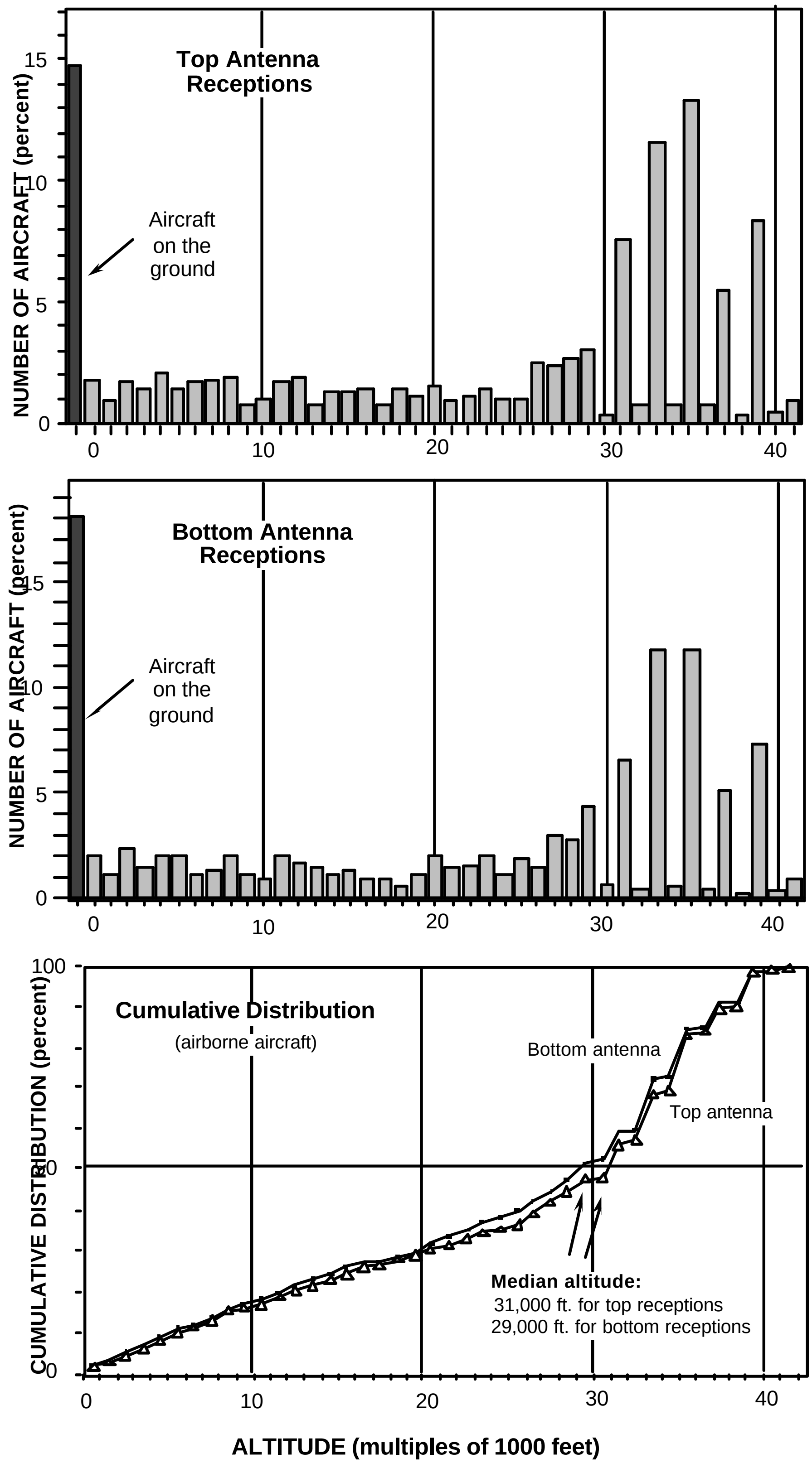


Figure 4.3.3-3b. Alt. Dist. Based on Airborne Mode S Receptions N40, 24 May

4.3.3.1.3 Percentage of Mode S Aircraft in the Total Traffic Population

The Goetzenhain radar (GOT) is not designed to output ATCRBS and Mode S reports simultaneously. Although, reports can be received on both channels, but in Mode S operation the ATCRBS output is distorted. This data is not usable for evaluations on ATCRBS/Mode S ratio.

For the count of ATCRBS reports per scan the Neunkirchen radar (NKH) has been used. This radar has the same coverage and only a slightly different position to Goetzenhain. ATCRBS recordings made during the trials are used for the SSR counts. To get Mode S counts the Goetzenhain radar had to be reconfigured to Data Link. In this configuration the radar is able to track more than 128 targets. Due to this necessary reconfiguration, recordings have been made after the trials (20th June). Figure 4.3.3-4 shows the coverage of NKH and GOT used for the calculation of the ATCRBS/Mode S ratio.

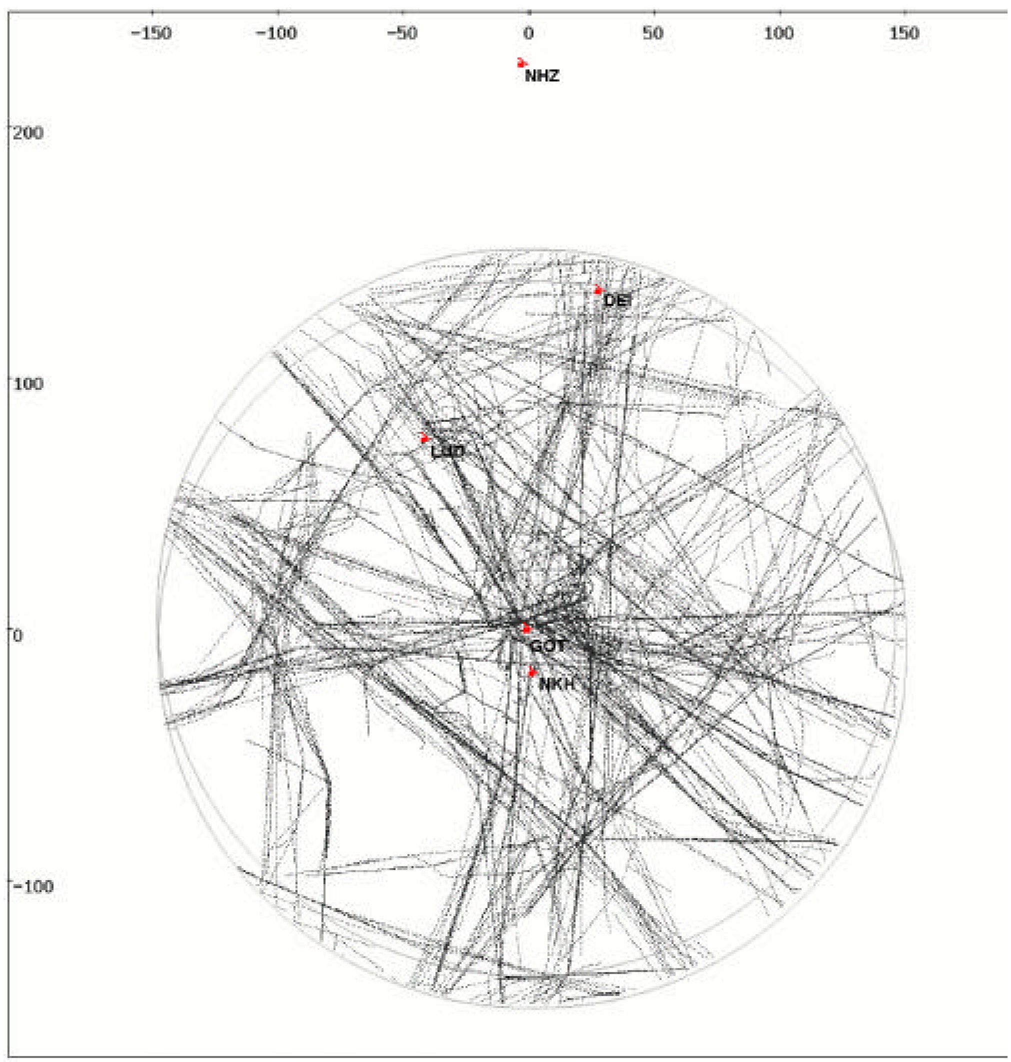


Figure 4.3.3-4. Coverage of GOT and NKH

Since the target counts are not from one source and the Mode S counts were recorded after the trials, the ratio does not give the exact picture on a particular day at a particular time, but it gives an approximation to the ATCRBS/Mode S ratio under 'normal' conditions.

For the calculation of the ATCRBS/Mode S ratio, it is assumed that the NKH radar tracks all aircraft (ATCRBS and Mode S). The difference between NKH targets and the aircraft detected by the Goetzenhain sensor is the number of ATCRBS only equipped aircraft. 24 May was chosen for the ATCRBS aircraft count and the analysis on equipage ratio between Mode S and ATCRBS. From the recordings a two hour time frame was selected (11:30 to 13:30 UTC), in which the test aircraft were flying. The results are listed in Table 4.3.3-1.

Table 4.3.3-1. ATCRBS/Mode S Ratio

Mode S ratio	**Mode S targets** [%]	**ATCRBS targets** [%]
minimum	45.2	54.8
maximum	77.8	22.2
average	53.3	46.7

Within the analyzed time frame the average number of aircraft in the coverage was for GOT 147 and for NKH 276. This makes an average share of Mode S aircraft in the entire aircraft population of more than 50%. Mainly during peak traffic conditions the percentage of Mode S equipped aircraft compared to all aircraft in the radar coverage (ATCRBS and Mode S) increased up to more than 70%.

Figure 4.3.3-5 presents the number of detected aircraft (ATCRBS and Mode S) per scan distributed over the selected time frame on 24 May (614 scans). This gives an impression of the time dependent distribution of aircraft per scan. Each single vertical line represents the number of aircraft in that particular scan. On the x-axis the scan number on the y-axis the number of aircraft can be seen. The small window gives additional overall information on the displayed data.

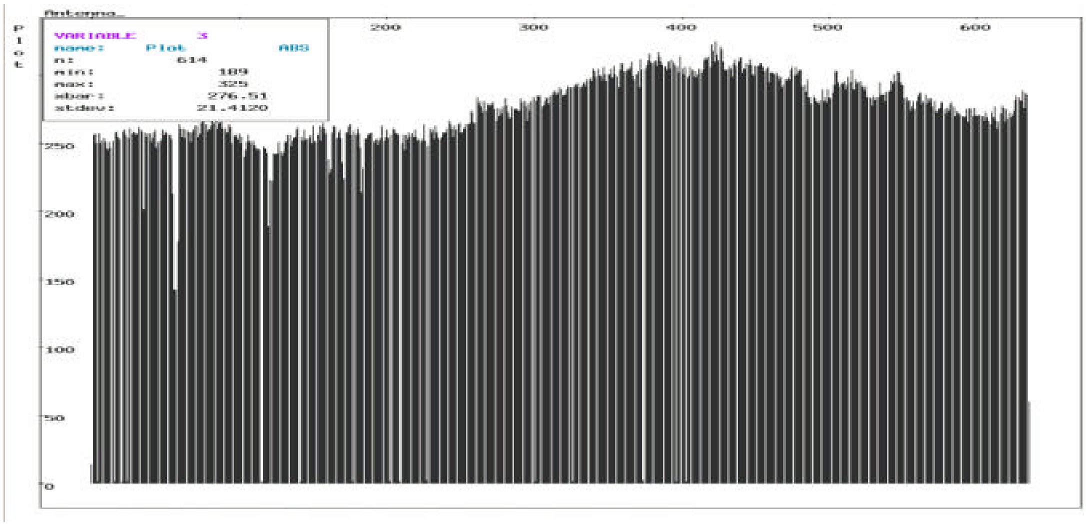


Figure 4.3.3-5. NKH Aircraft/Scan Distribution, 24 May (11:30-13:30 UTC)

In summary, among all transponder equipped aircraft in the Frankfurt airspace in May 2000, approximately 53 percent had Mode S transponders, and the remaining 47 percent had ATCRBS transponders.

4.3.3.1.4 Percentage of TCAS Aircraft in the Mode S Traffic Population

Mode S aircraft report their TCAS capability or maximum airspeed capability in the RI field of all DF=0 replies. The selection of data to be included in the reply is made by the TCAS aircraft interrogating the replying aircraft.

All the DF=0 replies of 3 sample periods near the beginning, near the middle and near the end of the flight of 24 May were analyzed to get the TCAS information. Only aircraft with at least 25 DF=0 replies were included in the analysis. There were a total of 838 aircraft that met this criteria.

There are five different values for TCAS in the RI field. They are:

RI=0 No on-board TCAS

RI=1 Not assigned

RI=2 On-board TCAS with resolution capability inhibited (traffic advisory mode)

RI=3 On-board TCAS with vertical-only resolution capability

RI=4 On-board TCAS with vertical and horizontal resolution capability

There should be none that report RI=1 (undefined) and RI=4 (vertical and horizontal resolution capability). The data (see Figure 4.3.3.1.5a) showed that 18% of the aircraft indicated "No TCAS, 6% reported the "Not Assigned" value, 6% indicated TCAS in Traffic Advisory (TA) Mode and 71% indicated TCAS with vertical resolution capability. Aircraft that are equipped with TCAS indicate "TA" mode when landing and taking off. No RI=4 codes were observed.

In summary, among all Mode S equipped aircraft in the Frankfurt airspace in May 2000, approximately 81 percent were equipped with TCAS. In making this conclusion, we are considering the reporting of RI = 1 as unknown, and not including these in the totals.

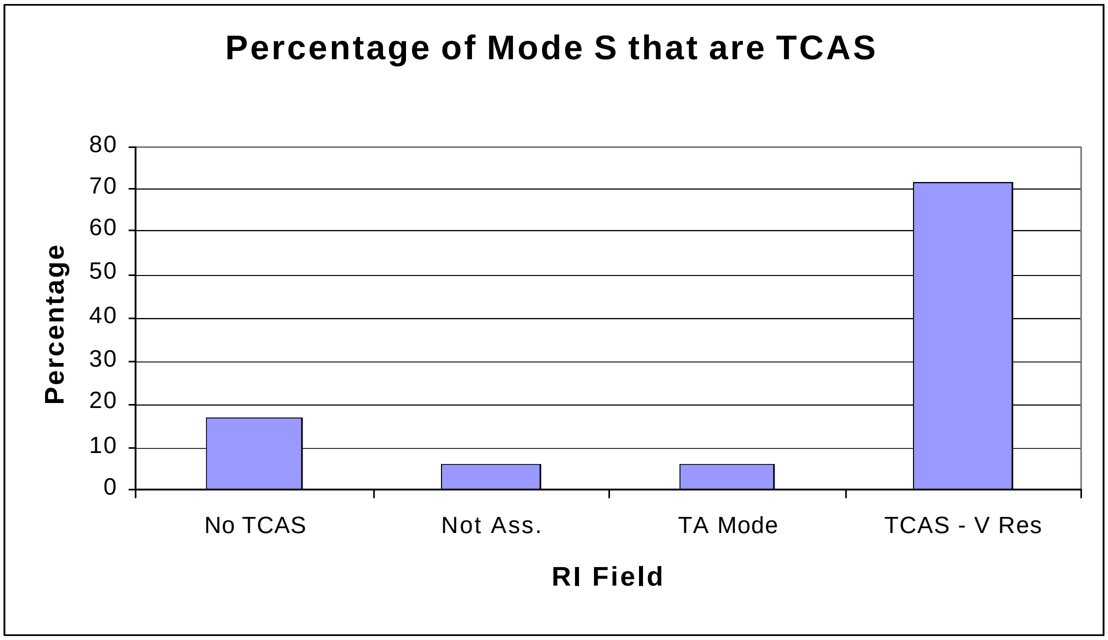


Figure 4.3.3-5a. Percentage of TCAS Aircraft in the Mode S Traffic Population

4.3.3.2 Day-to-Day Variations in Aircraft Traffic

After studying the aircraft traffic density on 24 May, and its distributions in range and altitude (documented in 4.3.3.1 above), the analysis was extended to other days. This is a time consuming process, requiring multi-radar data processing, and for that reason it was carried out for just three snapshots on Saturday 20 May and two snapshots on Friday 19 May. As was done for 24 May, the times of the snapshots were selected to be the maximum, the minimum, and for 20 May a typical mid-value condition during the test period, based on preliminary data obtained from one radar.

Two other snapshots were also analyzed for comparison. One was the selected to be the maximum aircraft density in the month of May 2000, and the other was selected to be the maximum density in the entire year 2000.

The results exhibit considerable variation in aircraft density from day to day and as a function of time on a single day. Figure 4.3.3-6 summarizes the day-to-day variations, by showing the total number of aircraft within 100 nmi of Frankfurt, for each of the snapshots. The monthly maximum and the yearly maximum are also plotted here for comparison. The lower plot summarizes the altitude distribution by showing the median altitude for each snapshot.

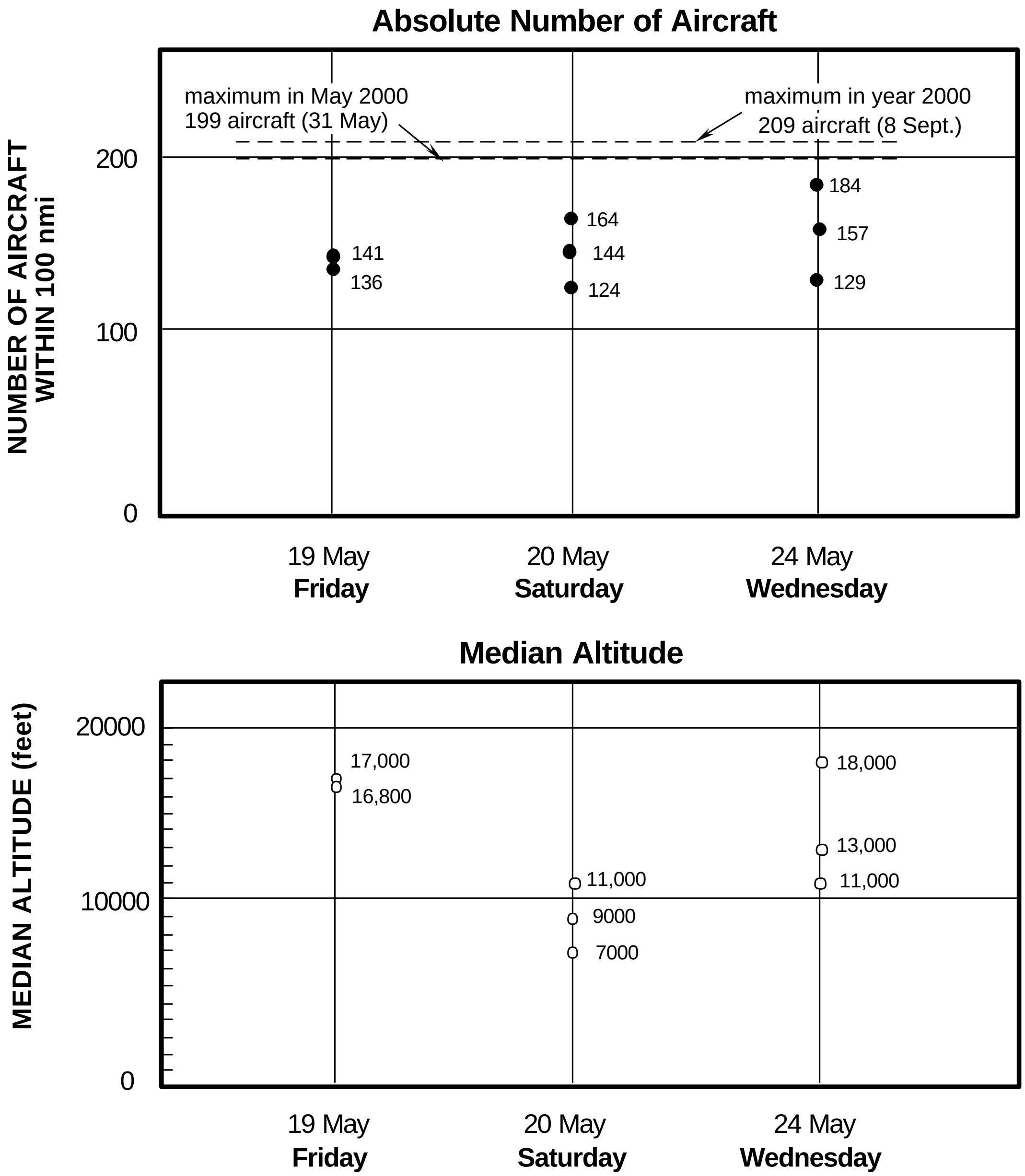


Figure 4.3.3-6. Day-to-Day Differences in Aircraft Density and Median Altitude

The results in Figure 4.3.3-6 indicate that 24 May experienced the maximum overall density of aircraft, among the three test day cases analyzed. The results also indicate that Saturday was different from the weekdays, in the sense that the median altitude was significantly lower. This suggests the presence of more aircraft flying at low altitudes and/or fewer aircraft at high altitudes on Saturday.

The changes in altitude distribution are shown more in more detail in the next figure (4.3.3-7). This is the cumulative altitude distribution for each of the three test days. The monthly maximum and the yearly maximum are also shown. For the test days, where we have processed several snapshots, these were averaged together for use in this figure, so that each day is represented by one curve.

The altitude differences appear clearly in this figure, as do the changes in absolute aircraft density. Absolute density appears as the value at the far right, which is simply the total number of aircraft. As was seen in the preceding figure, 24 May stands out as having the maximum aircraft density in the three days analyzed, whereas the monthly maximum was substantially higher than that, and the yearly maximum was somewhat higher still.

Looking at the shapes of the altitude distributions, several conclusions come to light: (1) Comparing Saturday with the other two test days, Saturday had a greater number of low altitude aircraft (below 10,000 feet) and a smaller number of high altitude aircraft. (2) On all three test days, the aircraft above 10,000 feet were approximately uniformly distributed up to 40,000 feet, with essentially no aircraft higher. They were uniformly distributed in the sense that there were approximately the same number of aircraft within each 10,000 foot band (10 to 20K, 20 to 30K, and 30 to 40K). (3) Between 29,000 and 39,000 feet, the aircraft flew mostly at odd thousands, which was evident on every day. (4) When the yearly maximum occurred, there were an especially large number of low-altitude aircraft; whereas the number of aircraft above 10,000 feet was not especially large.

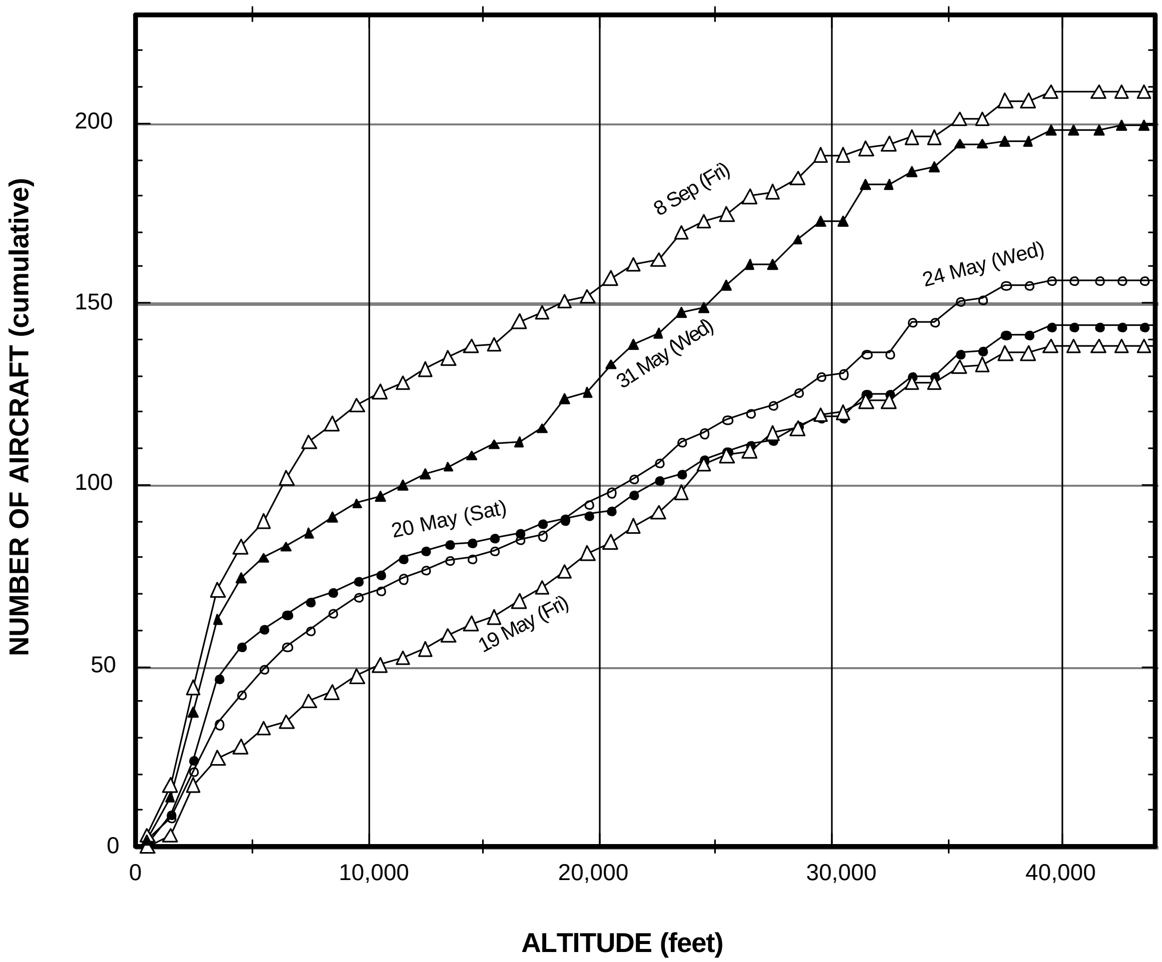


Figure 4.3.3-7. Day-to-Day Differences in Aircraft Altitude Distribution

4.4 AIR-TO-AIR RECEPTION OF EXTENDED SQUITTERS

4.4.1 LDPU-based Measurements

Measurements were made using LDPU receivers installed on the three project aircraft (N40, the FAA Boeing B727 (D-CFMC) the Flight Inspection International Beech King Air, and the NLR Metroliner (PH-NLZ). The extraction tools supplied by UPS AT were used to convert the log files recorded by the LDPUs into ASCII data files, which were then analyzed using standard analysis packages. For each of the tracks recorded by an LDPU, the following track properties were computed:

1) Ground track as a function of time (to illustrate any large gaps in position reporting),

2) Update interval as a function of range,

3) Per message update probability as a function of range.

4.4.1.1 LDPU Air-Air Performance for 24 May

On 24 May N40 flew in a holding pattern over Frankfurt Main airport. While N40 was holding, the NLR Metroliner flew out and back to the north (towards Hamburg), the FII King Air flew out and back to the southeast (towards Munich), and several British Airways B757 targets of opportunity flew in the surrounding area. It should be noted that 164 minutes after session start NLR stopped LDPU operations, and then at the 170th minute it also ceased 1090 transmissions because an emergency light turned on. At that time NLR was returning to Wiesbaden.

Air-to-air performance was analyzed using the LDPU reception logs collected on each project aircraft. The LDPU logs consist of GPS timestamped position records. Each record also includes information such as transmitter 24-bit ICAO address, Extended Squitter count and a signal level measurement. Air-to-air performance analysis was done per aircraft pair including any BA targets of opportunity (however there were no reception logs from such aircraft). Analysis results are presented per aircraft pair and in terms of a chart of the received aircraft tracks, altitudes and relative range versus trial time, position update intervals versus range, and finally estimated Extended Squitter reception probabilities versus range.

Figures 4.4.1-1a to e show the pairwise results obtained for the NLR and FII aircraft. In particular Figure 4.4.1-1a shows the lat/long track of NLR as recorded on FII, and the track of FII as recorded on NLR[1]. Each track point corresponds to a position record in the

[1] The NLR LDPU log presented anomalies during this session. Lat, long, and altitude values appeared to be corrupted, while GPS timestamps and the Extended Squitter counts were correct. The GPS timestamp of each NLR log record was used to extrapolate the correct values for lat, long and alt from other logs collected at the same time. These other logs include a separate GPS recording collected by the Flight Information System

LDPU log. The position record can be assimilated to a state vector update. The “latitude” and “longitude” values are the aircraft position *decoded* by the LDPU. If an even and odd CPR message are received in the appropriate time window, this position is globally unambiguous. If not, the LDPU calculates position based on the position of the own-ship. CPR leads to outliers in the log file when a track must be re-established for any of the following reasons:

(a) power-up of the LDPU

(b) 10-second gap in message reception

(c) air/ground or ground/air transition which also triggers reacquisition

Normally the logged position reflects the decoded CPR from the position message. If a velocity squitter is received and no position, the LDPU extrapolates lat/lon from the previous position. If the velocity-only condition persists for 10 seconds the velocity data is logged but the position is marked as zero. Invalid positions appear in the log as lat/lon = 0,0. Outliers have been filtered out in the plots of Figure 4.4.1-1a and in all subsequent track plots.

Gaps in the tracks of Figure 4.4.1-1a indicate areas where the LDPU did not log any position reports because it did not receive sufficient Extended Squitters in accordance with the rules stated above. The tracks of Figure 4.4.1-1a could be compared with the corresponding radar tracks shown in Chapter 3. It can then be seen that air-to-air coverage missed only the remotest parts of the two tracks.

Figure 4.4.1-1b shows the range between NLR and FII and their corresponding barometric altitudes versus trial time. Trial time is measured relative to the trial session start (10:20:32.677). For the altitude chart, one dot is plotted per position record in the LDPU log. The above chart shows that NLR flew most of the time at FL 200 while FII flew at FL 225. Gaps in the altitude chart indicate periods where no position reports were logged. Range has been calculated as great circle horizontal distance (no slant correction) in nautical miles. One range dot is plotted per NLR position recorded on the FII log (the corresponding FII position is obtained from the FII log own positions by interpolation on the basis of GPS timestamp). Figures 4.4.1-1a and b indicate that the session can be divided in two parts: In the first part FII and NLR flew outwards away from Wiesbaden and away from each other, and in the second part they flew inwards converging towards Wiesbaden. In this second inbound part FII and NLR lost each other at the 160th min, e.g., ten minutes prior to the NLR termination of 1090 transmissions mentioned above. At that point the two aircraft were 45 nmi apart and they were both descending. The FII was at only 700 ft altitude while NLR was at 7000 ft.

Figure 4.4.1-1c plots the FII update intervals (in seconds) in the NLR log versus the horizontal distance (in nmi) between the two aircraft. Update intervals were calculated as the difference of the GPS timestamp of each position record in the log from the timestamp of the previous record. These intervals can be interpreted as the periods between successive state vector updates. In accordance with the LDPU rules[1] for logging reports, each such update involves the reception of either a position or velocity squitter, or both.

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onboard the NLR aircraft (resolution ~ 0.1 sec) and the own position records of the FII and N40 logs (resolution ~ 1 sec).

It should be noted that FII transmitted only position squitters and FID (e.g., no velocity or status squitters). The NLR aircraft transmitted both position and velocity squitters but no identity or status. Consequently in the case of the FII, the observed update intervals are obtained solely on the basis of position messages, i.e., the update intervals are the result of transmitting approximately one half the normal number of Extended Squitters.

Figure 4.4.1-1c also shows the 95% containment update interval values of the raw update intervals. These containment values are calculated as the minimum update interval values that are exceeded by at most 5% of the observed raw update interval values within a 5 nmi distance bin. In other words 95% of the observed raw update interval values within each bin are less than the corresponding update containment value.

Figure 4.4.1-1d plots the NLR update intervals (in sec) in the FII log versus distance. The 95% containment values are also shown. It can be seen that 95% of the recorded update intervals stay below 15 sec for ranges up to 80 nmi. Beyond 80 nmi, there are fewer reports received and the variation of update intervals increases significantly. Comparison with Figure 4.4.1-1c shows that the FII update interval on NLR tended to be somewhat lower than NLR on FII up to 80-90 nmi despite the fact that FII transmitted only half the nominal number of Extended Squitters. This suggests that the reception probability in the direction FII->NLR must have been better than in the reverse direction. This can be confirmed in the following Figure 4.4.1-1e.

Figure 4.4.1-1e plots the NLR and FII per Extended Squitter reception probabilities versus the horizontal distance (in nmi) between the two aircraft. Reception probabilities were calculated separately for the outbound and return flight legs (see the tracks in Figure 4.4.1-1a). Message (individual Extended Squitter) reception probability has been calculated from the Extended Squitter counts recorded in the LDPU log with each position report[2] and the corresponding GPS reception timestamps. The squitter count was averaged over a 24-second wide time window to produce the aggregate reception probability. The time window moved with each position record in the LDPU log[2].

Figure 4.4.1-1e shows that reception probability tends to drop monotonically with range. There are noticeable differences between the reception probabilities of outbound and return flight legs. For example FII squitter reception on NLR tends to be better while the FII is outbound (to the southeast) relative to its return. These differences must be due to antenna gain variations dependent on aspect angles. NLR-> FII had generally a lower reception probability than FII->NLR.

Figures 4.4.1-2a to 4.4.1-2e show the results of pairwise performance analysis for the NLR and N40 aircraft. In particular Figure 4.4.1-2a shows the track plots of NLR as recorded on the N40 and the N40 track plots as recorded on NLR[1]. Comparison with Figure 4.4.1-1a shows that the N40 captured a greater part of the NLR trajectory than FII. Indeed FII is missing the final part of the NLR track that was recorded on the N40. This is because

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[2] The LDPU log does not record individual squitters only position reports. Each position report also indicates the number of Extended Squitters received since the previous report. Consequently Extended Squitter analysis has been bounded by the position report resolution of the LDPU log (~ 1 sec but variable depending on message loss).

FII lost NLR on the 160th minute when it had descended to an altitude of 700 ft (see Figure 4.4.1-1b).

Figure 4.4.1-2b shows the altitude variations of N40 and NLR and their horizontal distance versus trial time (trial time starts at the same point for all 4.4.1 figures, i.e., at 10:20:32.677). In this Figure NLR altitude is plotted per NLR position record logged on N40, while N40 altitude is plotted per own position record in the N40 log. Range is calculated per NLR position record in the N40 log. It can be seen that N40 continued receiving NLR reports until the 170th minute, although there was an interruption between the 165th and 169th minute. At that point NLR stopped Extended Squitter transmissions due to an emergency incident. Similarly NLR received N40 squitters up to the 164th minute at which point it stopped LDPU operation.

Figures 4.4.1-2c and d show the update periods of the NLR and N40 reports, respectively, as well as their 95% containment curves (5-nmi distance bins). It is noticeable that the update periods of N40 reports received on NLR remained within 10 sec up to 120 nmi, while the update periods of NLR reports stayed within 10 sec only up to 70 nmi. These differences are also reflected in the reception probabilities (see below).

Figure 4.4.1-2e plots the reception probabilities of NLR and N40 reports distinguishing between the inbound and outbound NLR flight legs. It should be noted that N40 transmitted position, velocity, and FID squitters, while NLR transmitted only position and velocity. Figure 4.4.1-2e indicates that probabilities tend to drop monotonically with distance, similarly to what was observed in the case of Figure 4.4.1-1e. There are noticeable performance differences between the inbound and outbound NLR legs. N40 reception on NLR during the NLR inbound (return) leg gave the best performance. Extended Squitters from NLR were received by N40 at almost double the rate while NLR was northbound (outbound) relative to the performance during its return.

Figures 4.4.1-3a to f show the pairwise performance analysis results for the FII and N40 aircraft. In particular Figure 4.4.1-3a shows the track plots of the N40 as recorded on the FII and the track plots of the FII as recorded on the N40. The N40 captured the greatest part of the FII trajectory. Comparison with Figure 4.4.1-1a shows that the N40 captured a greater part of the FII track than NLR. This is because the NLR aircraft flew much further away from FII than the N40, which stayed in a holding pattern near Langen.

Figure 4.4.1-3b shows the altitudes and relative range of the two aircraft versus trial time. FII altitude is plotted per FII record on the N40 log. N40 altitude is plotted per N40 own record on the N40 log. Range is calculated per FII record on the N40 log. The FII aircraft continued receiving N40 squitters up to the 163rd minute, at which point the FII landed in Wiesbaden and stopped LDPU operation.

Figures 4.4.1-3c and d show the FII and N40 update periods derived from the N40 and FII LDPU logs, respectively, plotted versus range. These Figures also show the 95% containment curves (5-nmi distance bins) of the raw update period values. N40 update periods tended to vary less than the FII ones up to about 90 nmi. As noted earlier FII transmitted at approximately half the nominal Extended Squitter rate (only position squitters and FID), while the N40 transmitted at the standard rate.

Figure 4.4.1-3e shows N40 Extended Squitter reception probabilities on the FII versus range separately for the inbound and outbound legs of the FII flight. Similarly Figure 4.4.1-3f plots FII Extended Squitter reception probabilities on the N40 versus range, again separately for the inbound and outbound legs of the FII flight. There was clearly strong sensitivity to aspect angle. Squitter reception from FII was dramatically better while the FII was outbound (to the southeast) relative to its return.

Figure 4.4.1-4 and Figure 4.4.1-5 refer to the reception of the same BA target of opportunity (BA-400652_h) as recorded on the N40 and FII, respectively. Figures 4.4.1-4a and 5a show the BA-400652_h track plots superimposed with the N40 and FII track plots (both obtained from the N40 log, since there are no 1090 reception recordings available from BA aircraft). The BA target of opportunity, actually approaches from the west, overflies Langen, and lands to the east.

Figures 4.4.1-4b and 5b show aircraft altitudes and horizontal range versus trial time. Range has been plotted per BA-400652_h record in the N40 and FII logs. It can be seen that the BA aircraft appeared while FII was still on the ground. The latter took off while the BA aircraft was approaching Langen. Then, they followed parallel paths albeit at rather different altitudes with the BA aircraft proceeding to descend for its eventual landing. The N40 was already en route when BA-400652_h first appeared. The latter flew towards the N40 while the latter kept flying its holding pattern. Eventually the BA aircraft overflew the N40 (FL 370 versus FL 220) before proceeding to descend to the east.

Figure 4.4.1-4c plots the BA-400652_h update intervals in the FII log and their 95% containment values. Only the period after FII take-off has been taken into account in this Figure (e.g., after the 40th minute). It should be noted that the BA aircraft transmitted position and velocity squitters as well as the FID (but no status squitter). Figure 4.4.1-5c provides the equivalent plots for BA-400652_h reception on the N40. In the latter case the whole BA flight has been taken into account. It can be seen that BA-400652_h update intervals stay below 15 sec for up to 60 nmi in the case of FII reception and up to 90 nmi in the case of N40 reception.

Figure 4.4.1-4d shows the BA-400652_h Extended Squitter reception probability on FII versus horizontal range. Only the part where both aircraft were flying has been taken into account in the calculations (e.g., after the 40th minute). Figure 4.4.1-5d shows the corresponding plot for reception on the N40. It can be seen that Extended Squitters from the BA aircraft are received on N40 with greater than 25% probability for ranges out to 80 nmi. On the FII the corresponding range limit is much lower, ~ 50 nmi. In both cases reception probability varies relatively monotonically with range.

The project aircraft LDPU logs also contain reports from two other BA targets of opportunity, namely BA-400664_h and BA-400663_h. However, these targets of opportunity were at long ranges (> 100 nmi) and hence there were few reports logged for them. Reception probability was less than 20% in all these cases. These BA targets of opportunity have not been analyzed further.

4.4.1.1.1 NLR and FII Aircraft Pairwise Air-to-Air Performance

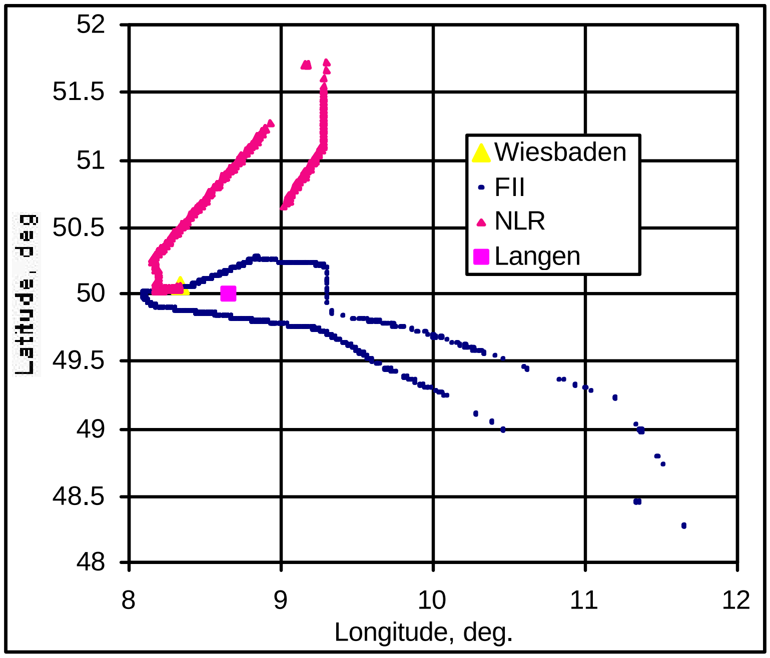

Figure 4.4.1-1a. Received Tracks, NLR and FII Pairwise Air-to-Air Performance

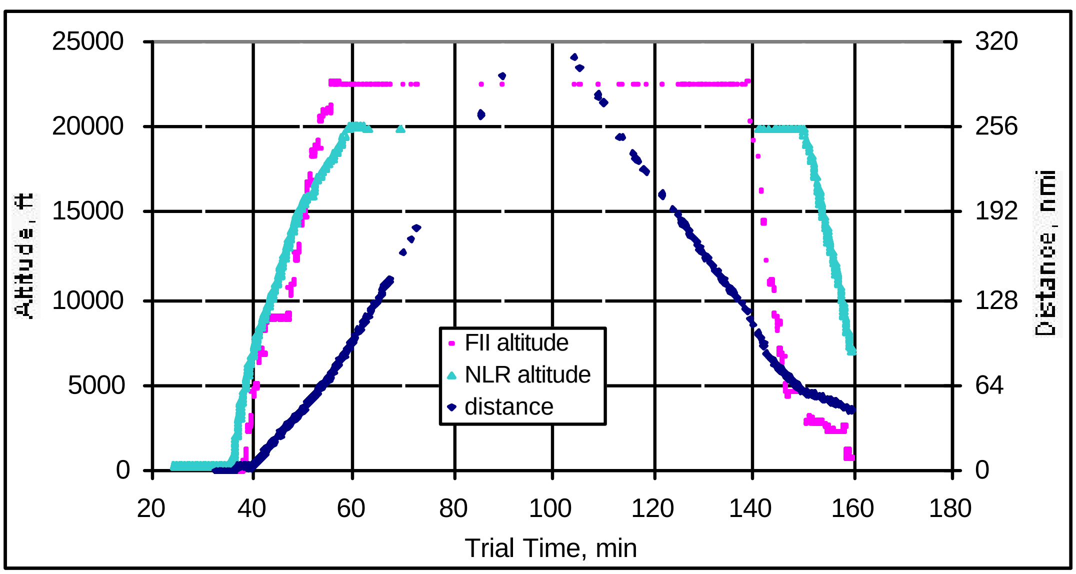

Figure 4.4.1-1b. Alt. vs. Range, NLR and FII Pairwise Air-to-Air Performance, Start Time: 10:20:32.67

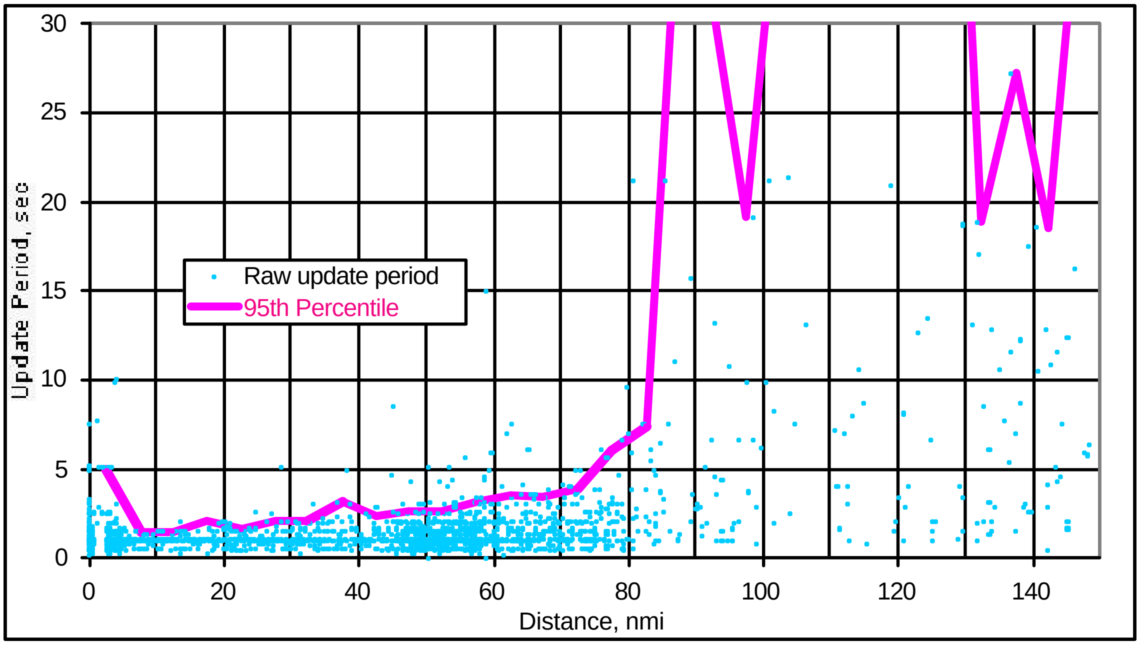

Figure 4.4.1-1c. Surveillance Update Periods,

FII Transmissions Received on NLR LDPU, 24 May

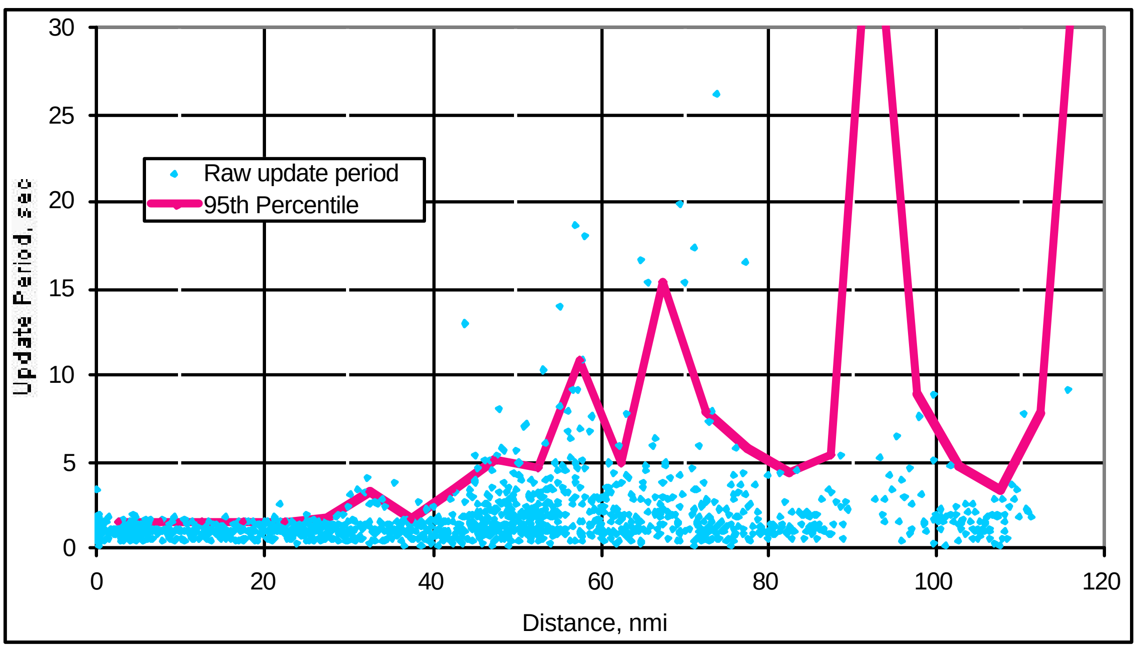

Figure 4.4.1-1d. Surveillance Update Periods,

NLR Transmissions Received on FII LDPU, 24 May

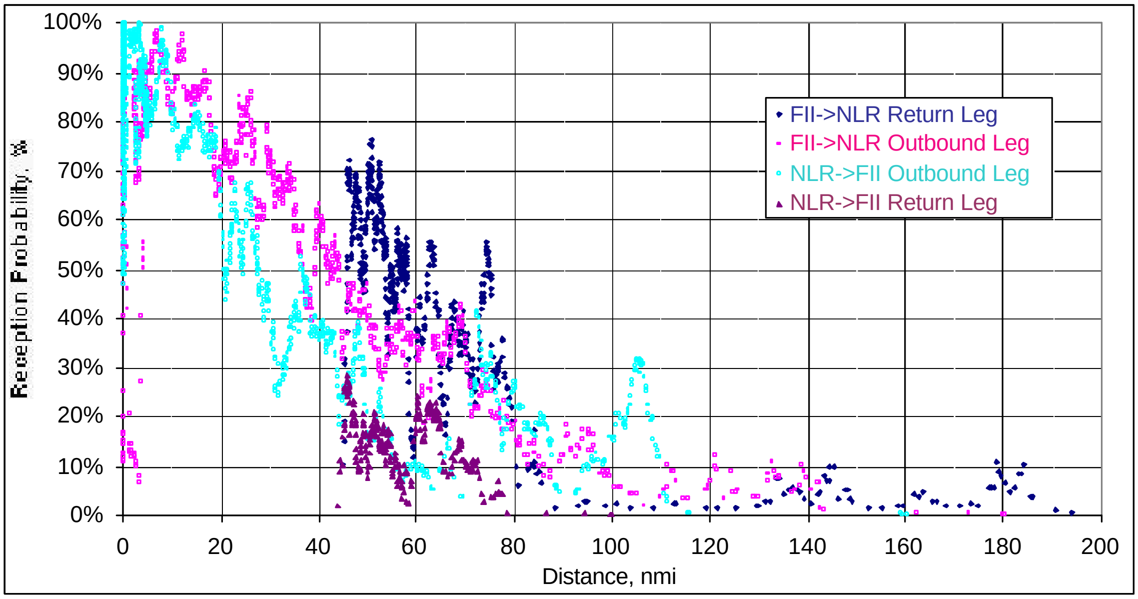

Figure 4.4.1-1e. Reception Probability, NLR and FII Pairwise Air-to-Air Performance

4.4.1.1.2 NLR and N40 Aircraft Pairwise Air-to-Air Performance

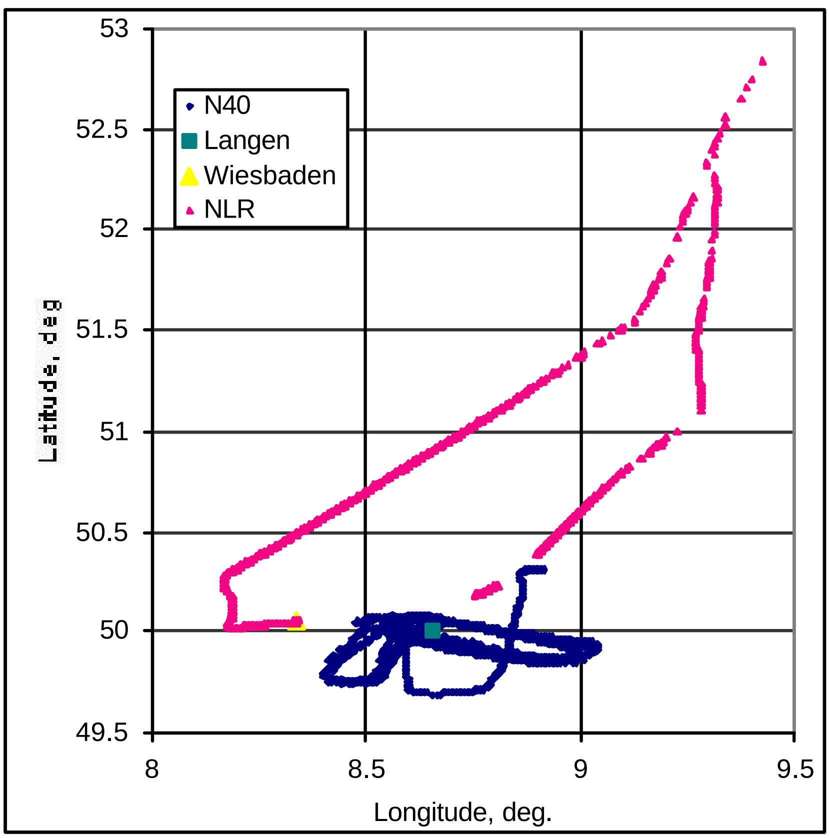

Figure 4.4.1-2a. Received Tracks , NLR and N40 Pairwise Air-to-Air Performance

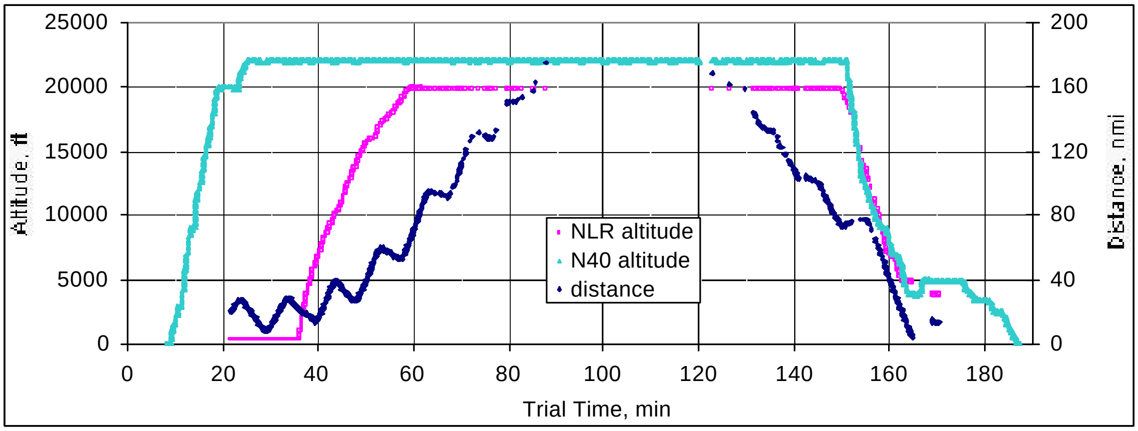

Figure 4.4.1-2b. Alt. vs. Range, NLR and N40 Pairwise Air-to-Air Performance,

Start Time: 10:20:32.677

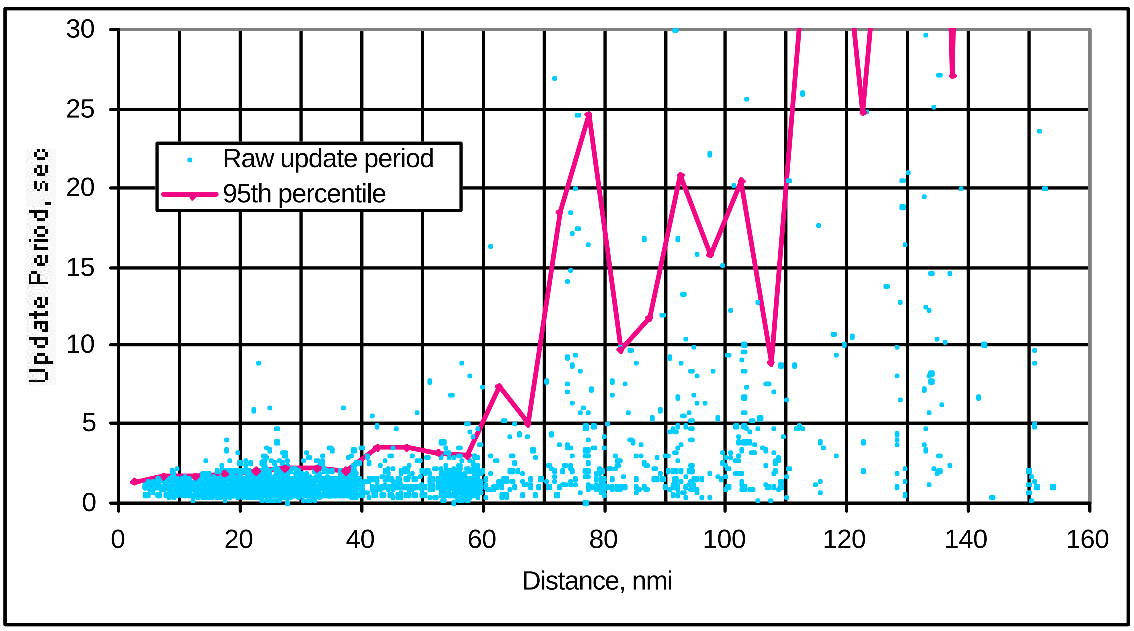

Figure 4.4.1-2c. Surveillance Update Periods,

NLR Transmissions Received on N40 LDPU, 24 May

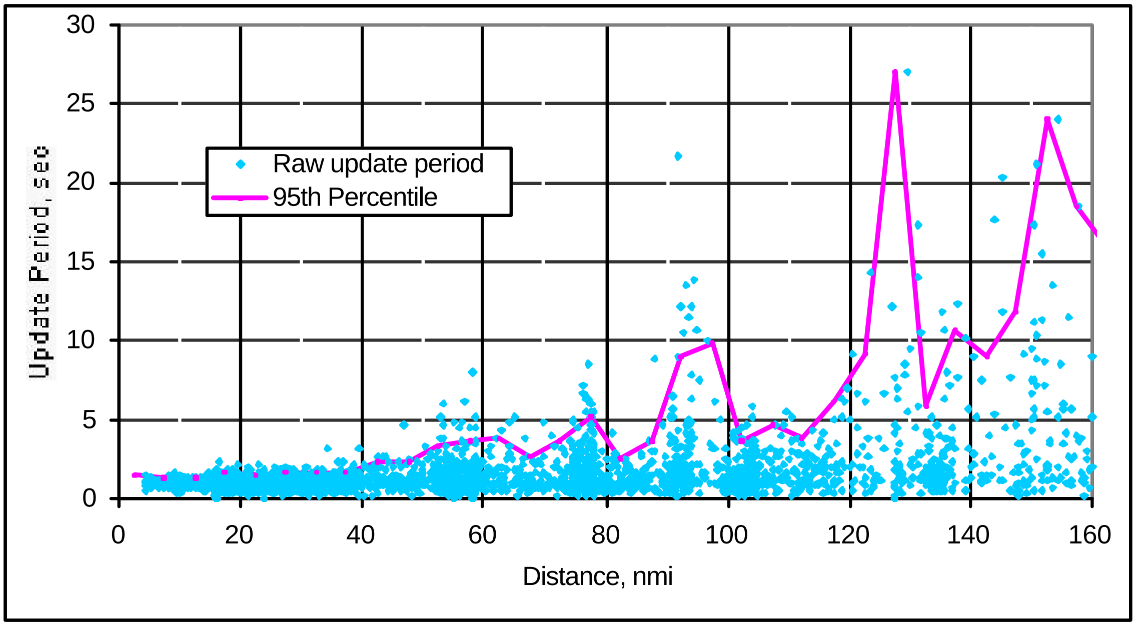

Figure 4.4.1-2d. Surveillance Update Periods,

N40 Transmissions Received on NLR LDPU, 24 May

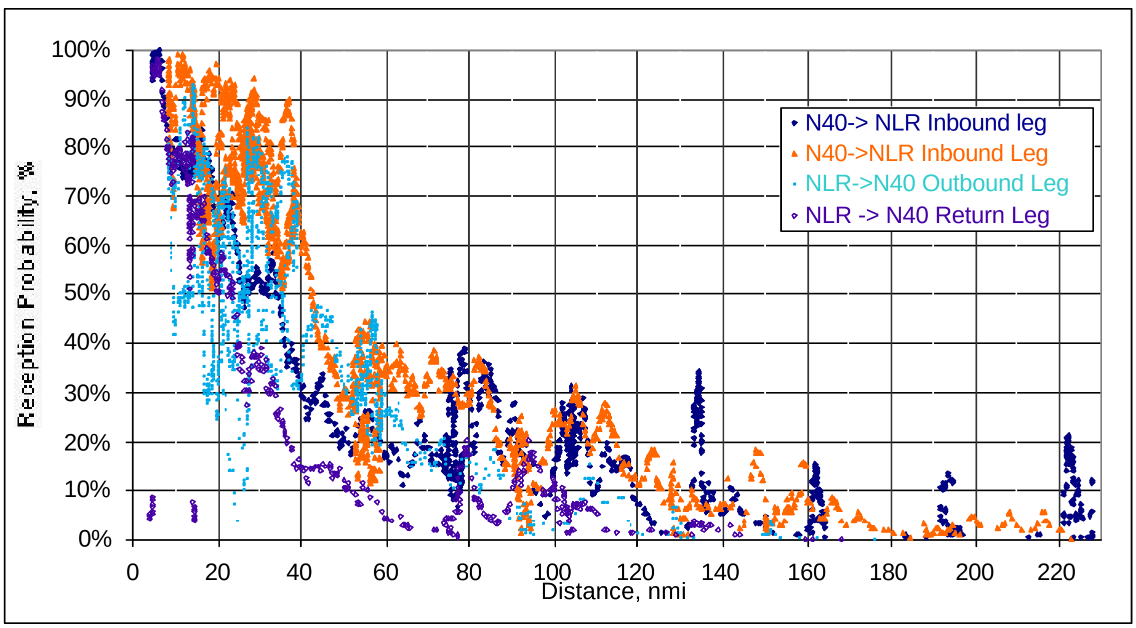

Figure 4.4.1-2e. Reception Probability, NLR and N40 Pairwise Air-to-Air Performance

4.4.1.1.3 N40 and FII Aircraft Pairwise Air-to-Air Performance

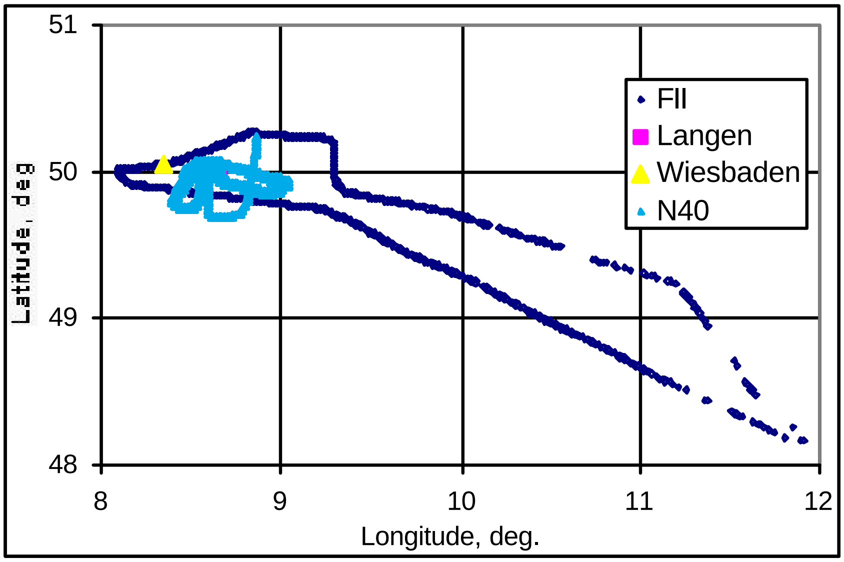

Figure 4.4.1-3a. Received Tracks , N40 and FII Pairwise Air-to-Air Performance

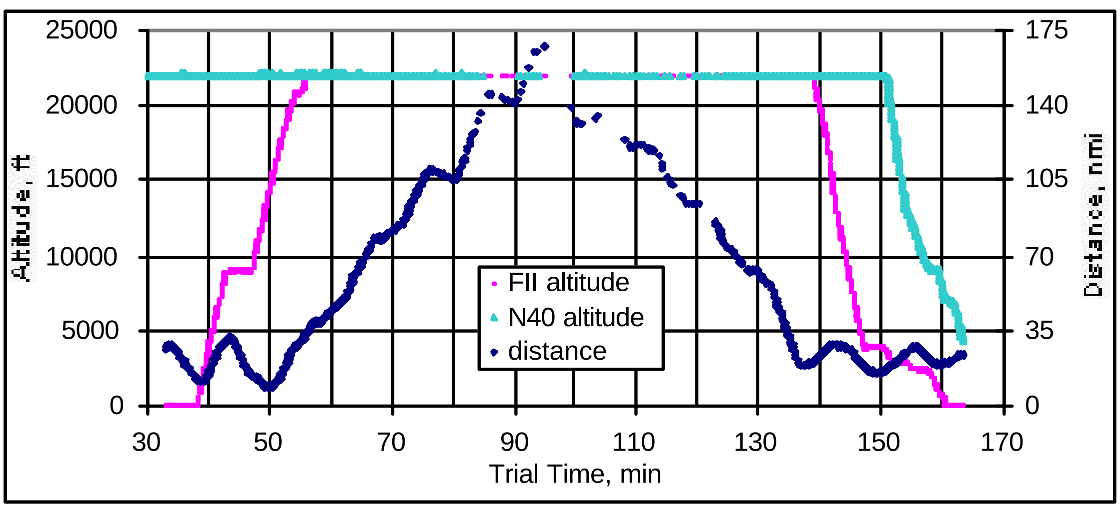

Figure 4.4.1-3b. Alt. vs. Range, N40 and FII Pairwise Air-to-Air Performance,

Start Time: 10:20:32.677

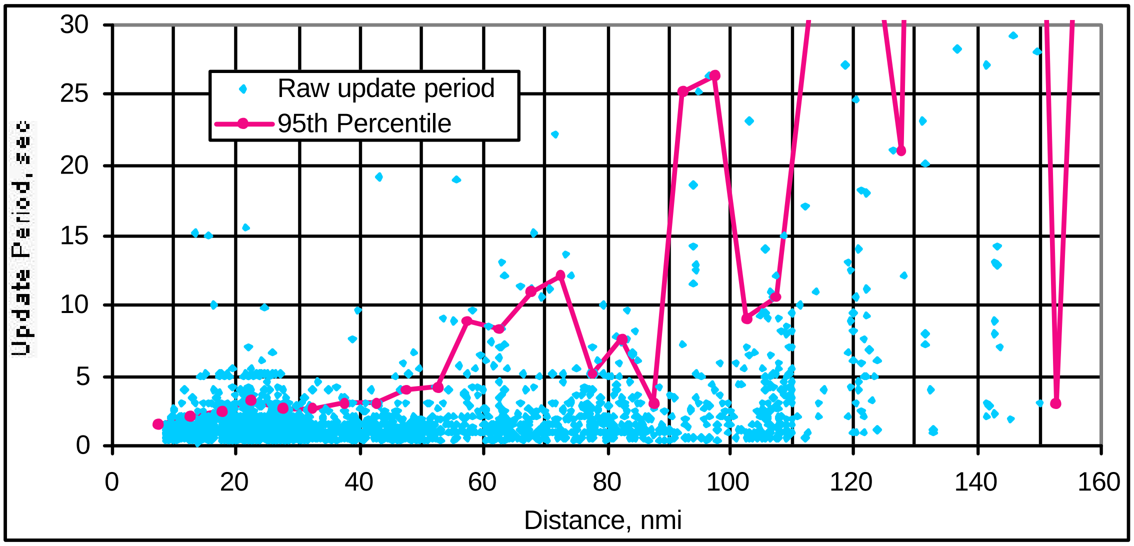

Figure 4.4.1-3c. Surveillance Update Periods,

FII Transmissions Received on N40 LDPU, 24 May

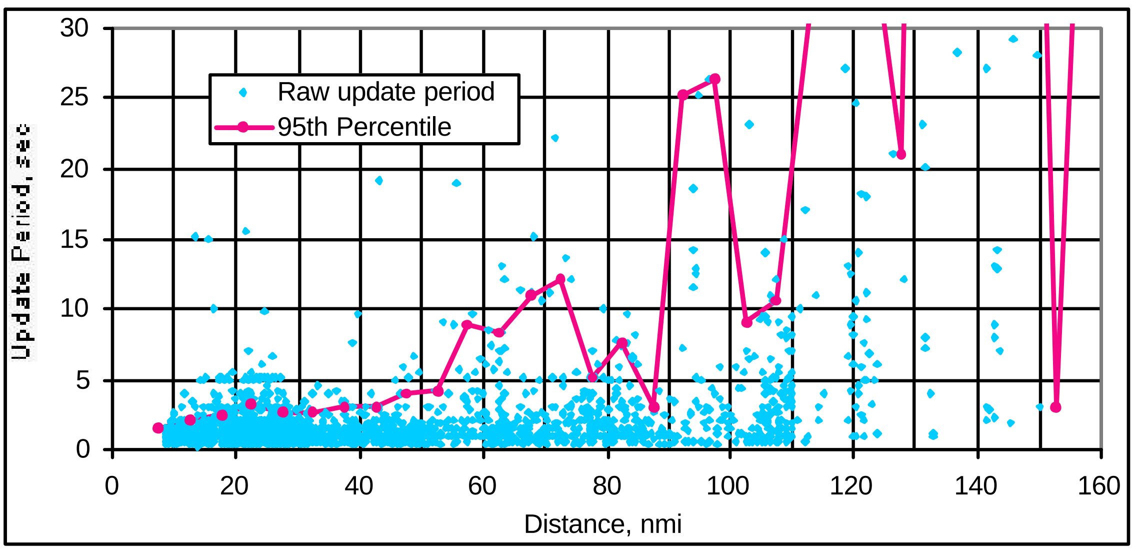

Figure 4.4.1-3c. Surveillance Update Periods,

N40 Transmissions Received on FII LDPU, 24 May

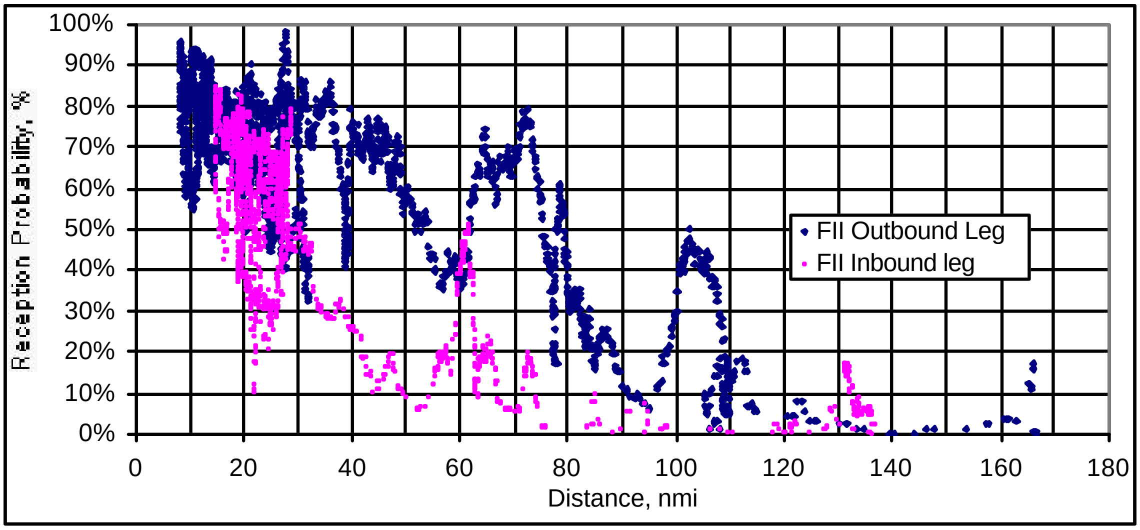

Figure 4.4.1-3e. Reception Probability, N40 Received on FII LDPU

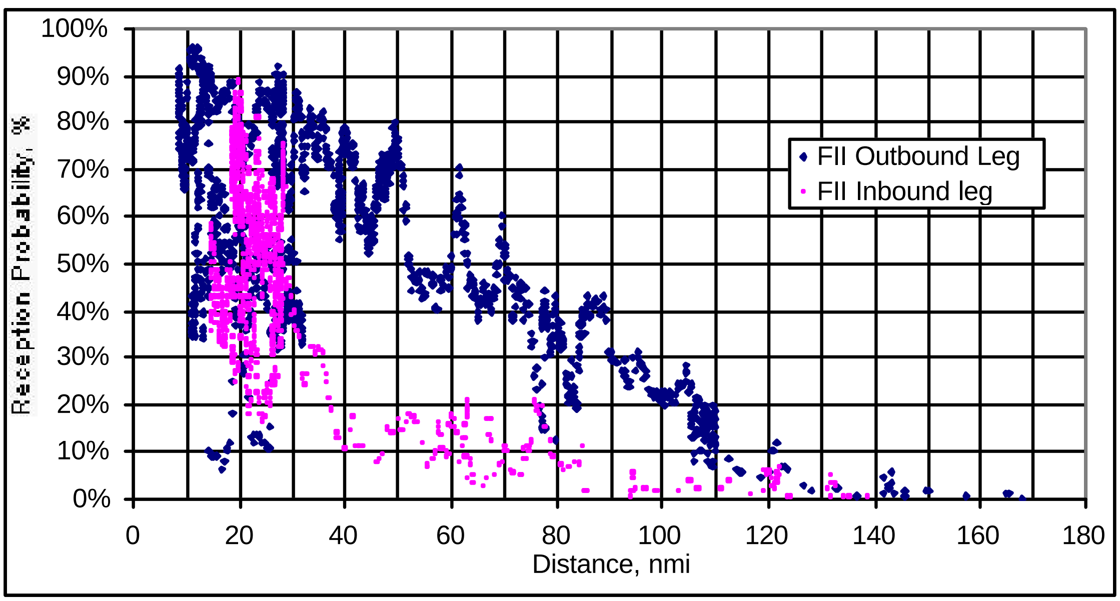

Figure 4.4.1-3f. Reception Probability, FII Received on N40 LDPU

4.4.1.1.4 Target of Opportunity BA-400652$_h$ Air-to-Air Performance on FII LDPU Receiver

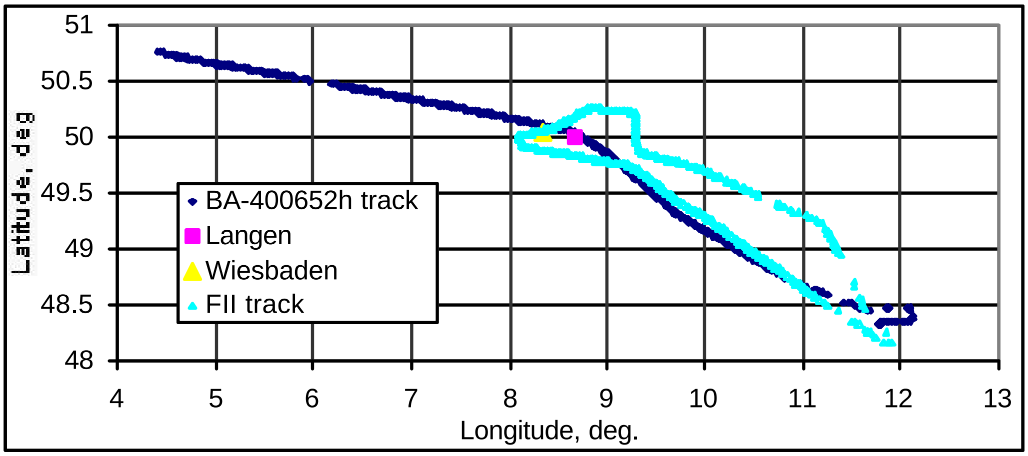

Figure 4.4.1-4a. BA-400652h Track Received at FII

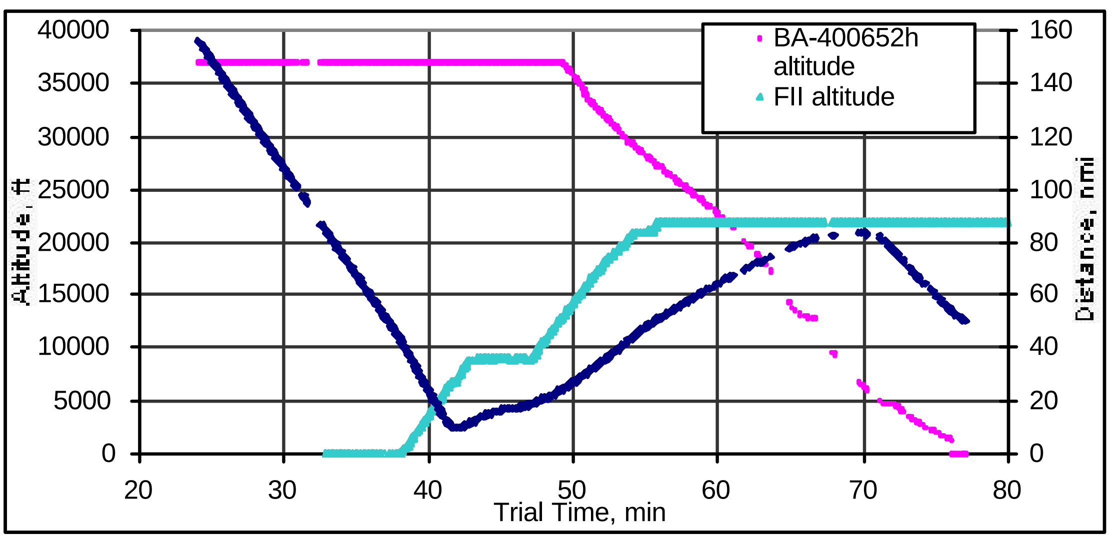

Figure 4.4.1-4b. BA-400652h Altitude and Range from FII, Start Time: 10:20:32.677

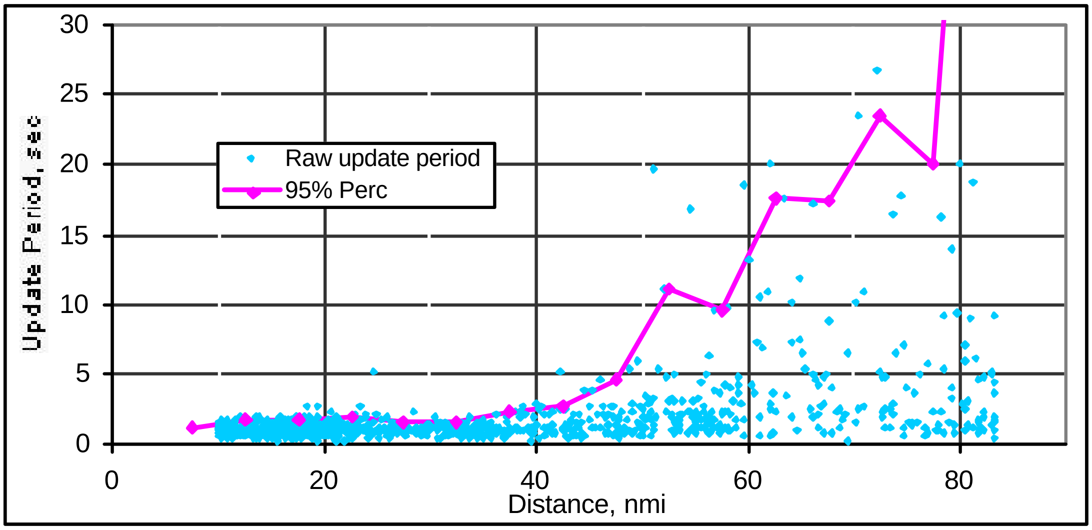

Figure 4.4.1-4c. BA-400652h Update Period on FII, Both Aircraft in Flight

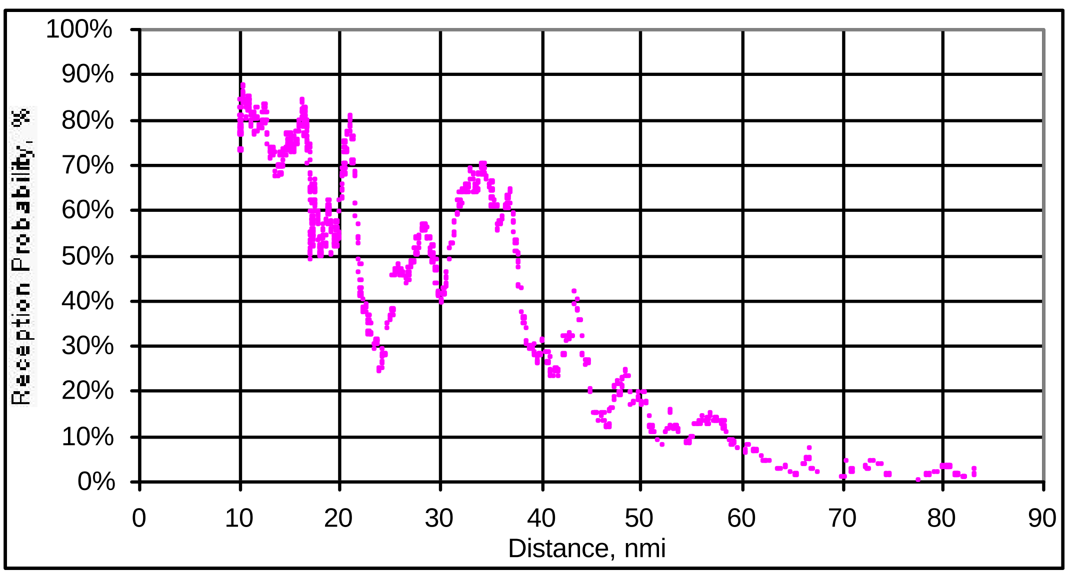

Figure 4.4.1-4d. Reception Probability, BA-400652h Received on FII LDPU, Both Aircraft in Flight

4.4.1.1.5 Target of Opportunity BA-400652h Air-to-Air Performance as Received on N40 LDPU Receiver

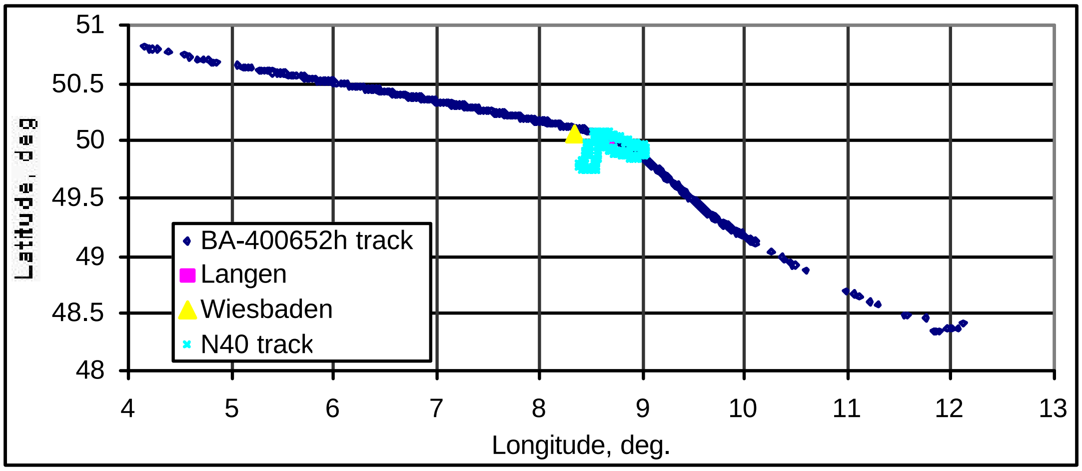

Figure 4.4.1-5a. BA-400652h Track as Received on N40

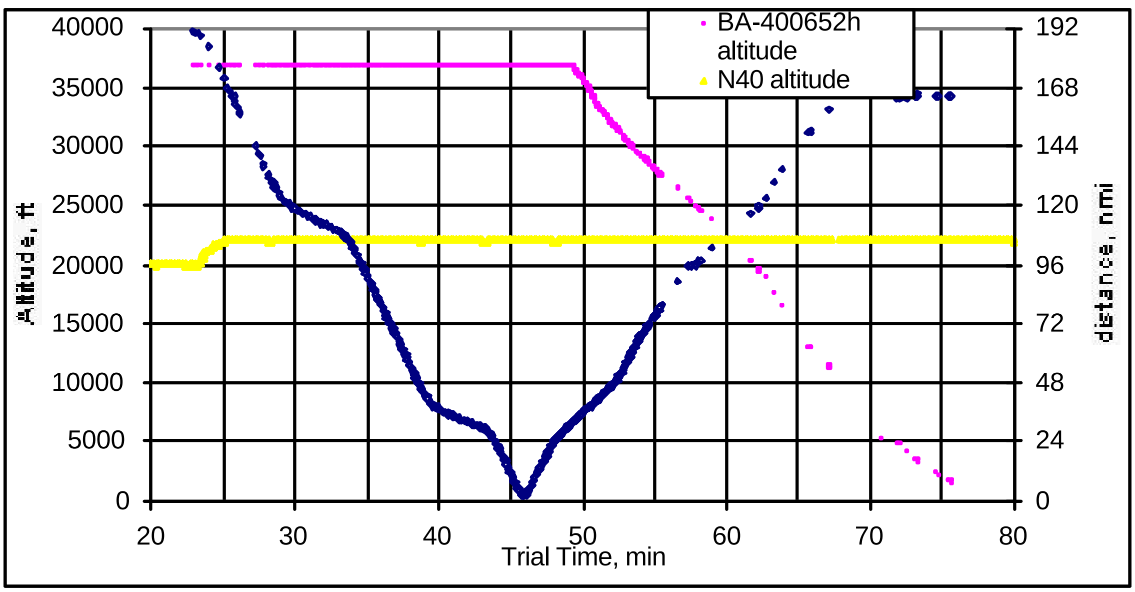

Figure 4.4.1-5b. Alt. vs. Range BA-400652h and N40 Pairwise Air-to-Air Performance,

Start Time: 10:20:32.677

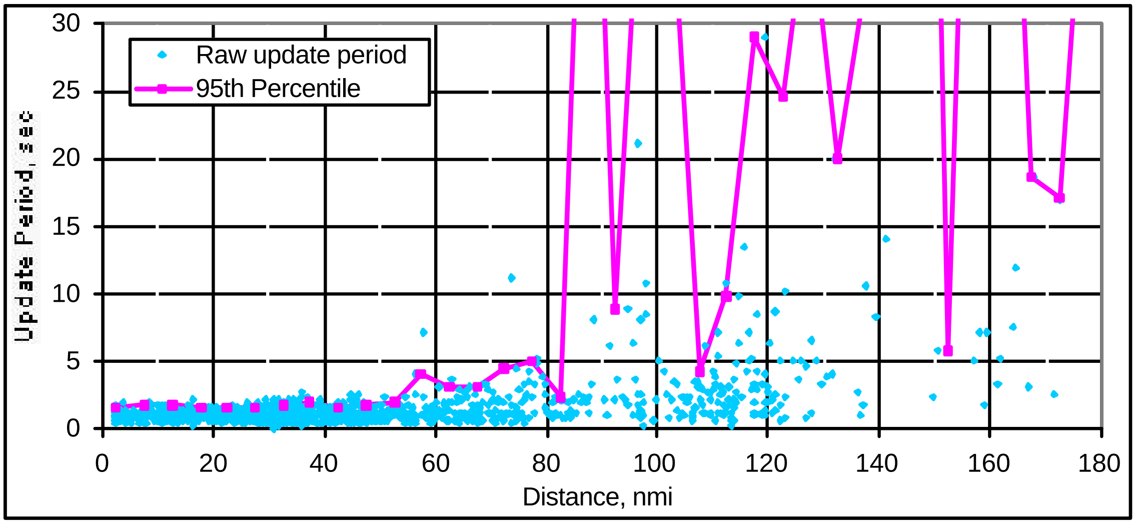

Figure 4.4.1-5c. BA-400652h Update Period as Received on N40

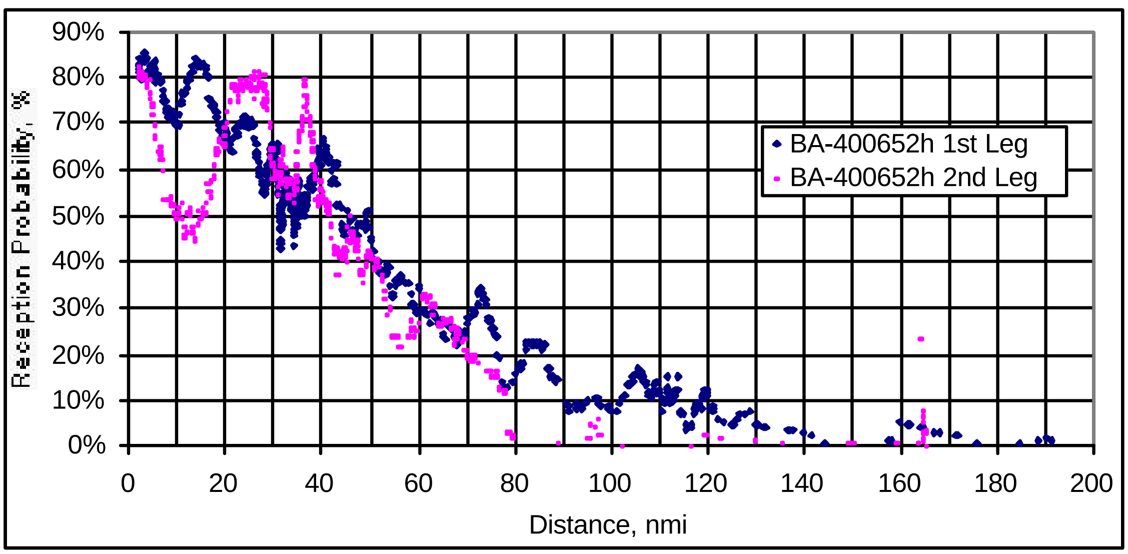

Figure 4.4.1-5d. Reception Probability, BA-400652h Received on N40 LDPU

4.4.1.2 LDPU Air-Air Performance for All Days

While the focus of the detailed analysis has been on the data collected on 24 May, significant data was collected on the four other days in which data collection flights were conducted. The following paragraphs present a summary of the air-to-air results from these other days. The recorded data was sorted according to whether aircraft were airborne or on the surface. Only cases in which both the transmitting aircraft and the receiving aircraft were airborne are included in the results that follow.

4.4.1.2.1 Results for 19 May

FAA N40 conducted a shakedown flight on Friday 19 May without the other two project aircraft. The shakedown tests were successful in determining that the instrumentation was performing as intended, both in the air and on the ground. This first test was also useful in making measurements of the interference environment. Measurements of reception performance was also found to be possible because of the presence of British Airways targets of opportunity. A long track was received for BA-400665_h during this test. A second target of opportunity (i.e., BA-400652_h) was briefly observed by N40 at ranges from approximately 145 nmi to 170 nmi. N40 was in a holding pattern near Frankfurt while BA-400665_h approached from the Northwest and overflew Frankfurt then proceeded to the Southeast. BA-400652_h was observed far North of Frankfurt flying generally from West to East.

The N40 aircraft was equipped as described in Chapter 2 of this report. The BA-400665_h and BA-400652_h aircraft were equipped with an Extended Squitter enabled air carrier class Mode S transponder. Both BA aircraft were broadcasting position and velocity Extended Squitter at the normal rate of 4.0 squitters per second. Flight ID squitters were not being transmitted by these BA aircraft.

4.4.1.2.1.1 Track Plots

The following figure indicates the ground tracks of the project aircraft and targets of opportunity.

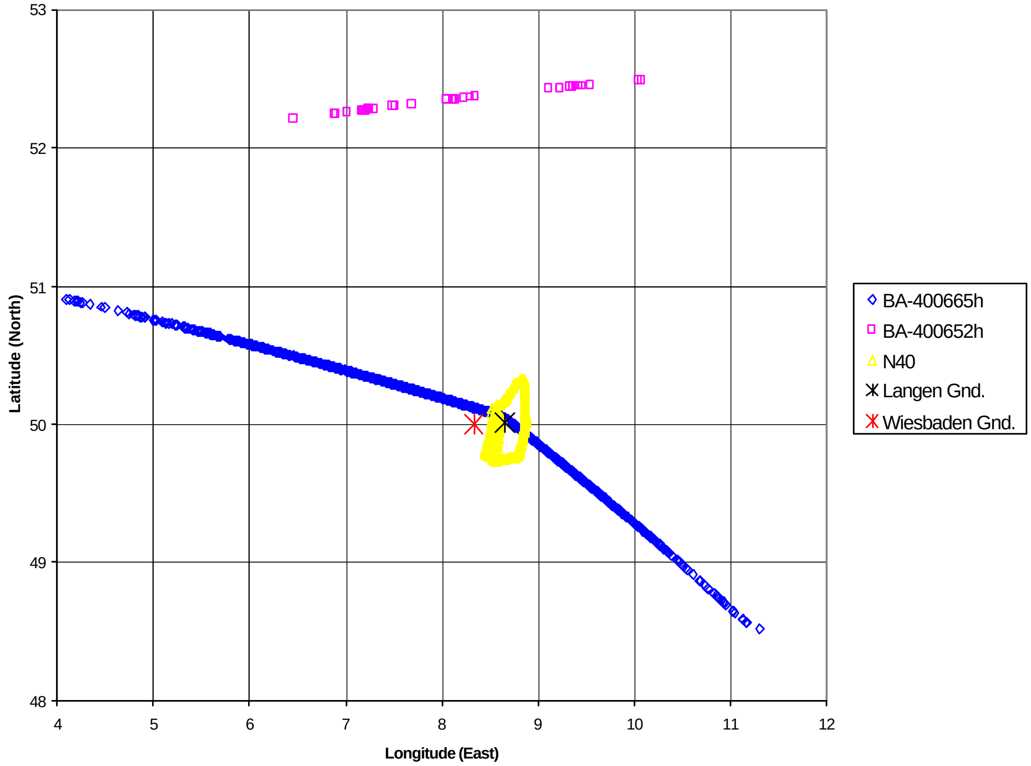

Figure 4.4.1.2.1-1. Ground Tracks, 19 May

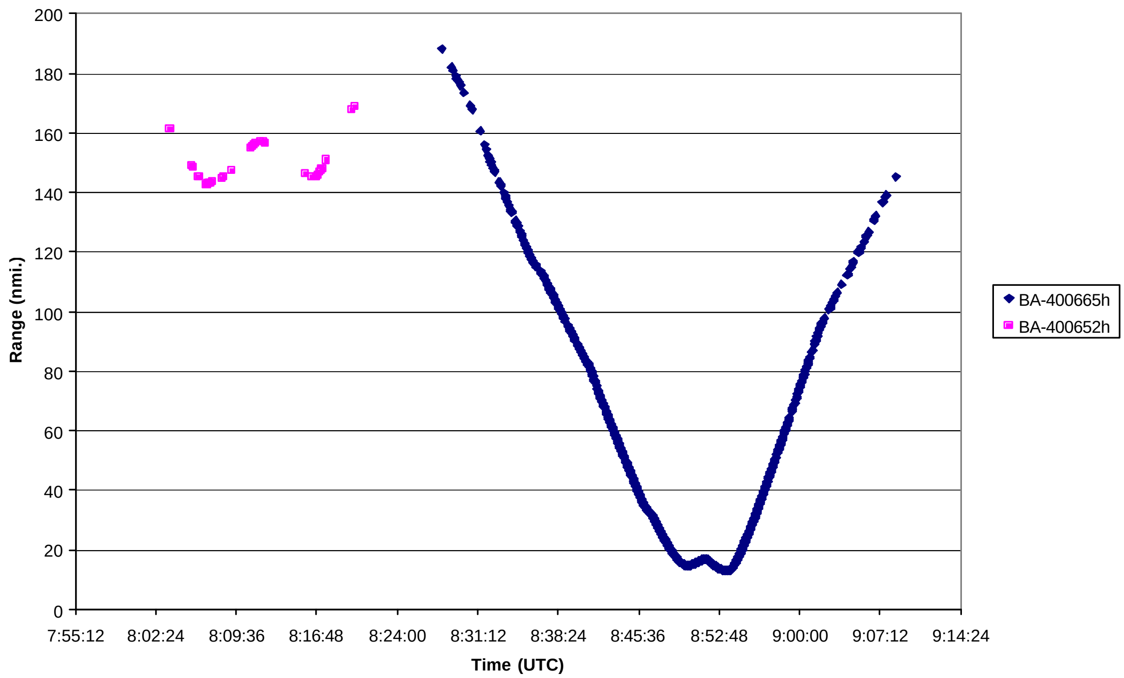

Figure 4.4.1.2.1-2. Target Aircraft Tracks as Seen by N40, 19 May

4.4.1.2.1.2 State Vector Update Period Plots

The LDPU avionics is intended to generate an ADS-B report at one-second intervals if one or more 1090 MHz Extended Squitters were received during the prior second. The following figures present the state vector update period that was received by N40 vs. target range. As per the 1090 MHz ADS-B MOPS, either a position squitter or a velocity squitter is considered sufficient to allow for an update to the state vector of the target aircraft. Any update period of greater than 24 seconds would result in a drop of the track for the target aircraft.

ADS-B MASPS requirements for air-to-air target tracking at ranges beyond 40 nmi are applicable only to targets in the forward direction and are also only applicable to applications intended for use in low density en route or oceanic airspace and are thus not directly applicable to the airspace where the evaluation was conducted.

Data points shown in Figure 4.4.1.2.1-3 as 30 seconds represent update intervals of 30 seconds or greater.

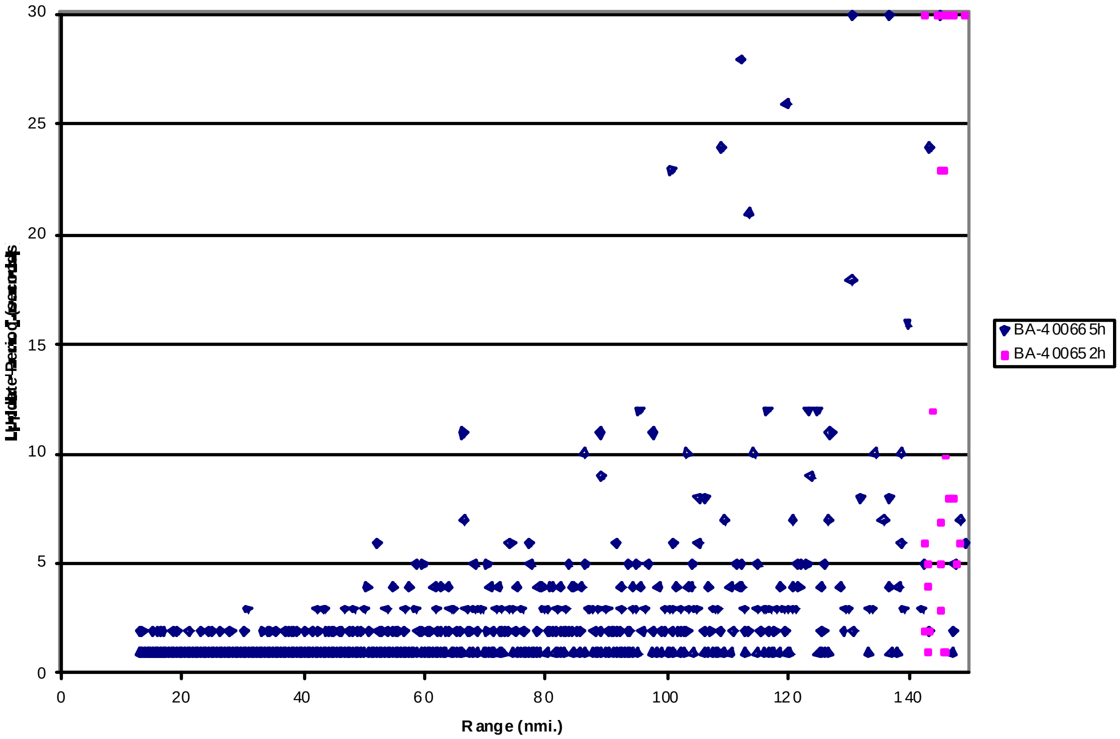

Figure 4.4.1.2.1.-3. State Vector Update Periods Measured by N40, 19 May

4.4.1.2.1.3 Reception Probability Plots

Figure 4.4.1.2.1-4 plots the measured probability of reception of individual squitters over 24 second intervals versus the target aircraft's range.

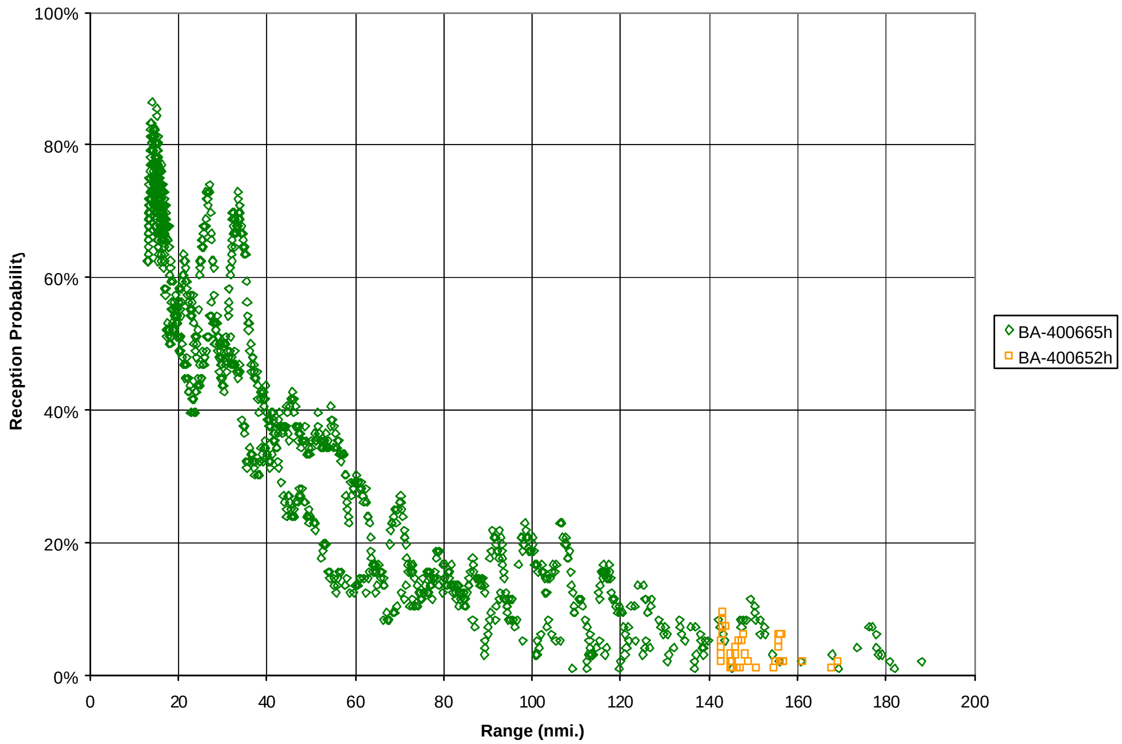

Figure 4.4.1.2.1-4. Probability of Receiving Squitters by N40, 19 May

4.4.1.2.2 Results for 20 May

All three project aircraft participated in flight tests on Saturday 20 May. Five BA targets of opportunity were also observed during the course of these flight tests.

The N40 and NLR aircraft were equipped as described in Chapter 2 of this report. The BA targets of opportunity and the N40 were broadcasting position, velocity and flight ID Extended Squitters at the normal rate of 4.2 total squitters per second. The NLR aircraft was broadcasting position and velocity squitters. The FII was broadcasting all zeros for its latitude and longitude due to a GPS interface problem. As a result no analysis of FII data is presented below.

The NLR LDPU data log had corrupted lat/long/alt values in the same manner as in the test session of the 24 May (see 4.4.1.1). The NLR log was restored using the techniques described in 4.4.1.1[3].

[3] The log GPS reception timestamps and the Extended Squitter count were correctly logged. These timestamps were use to extrapolate N40 lat, long, and altitude from the own position logs of the N40 LDPU. NLR own coordinates were extrapolated from the logs of the Flight Information System onboard the NLR Metroliner.

4.4.1.2.2.1 Track Plots

N40 departed from Wiesbaden and flew in a holding pattern near Langen. Figure 4.4.1.2.2 -1a shows the N40 track as it was recorded by its own LDPU. The NLR Metroliner departed from Wiesbaden and proceeded to the southeast then later turned to the northwest and returned to Wiesbaden. Figure 4.4.1.2.2 -1b shows its GPS track as it was recorded by the Flight Information System onboard the NLR aircraft.

One BA target of opportunity ($BA400664_h$) approached from the northwest and flew south of Frankfurt then proceeded to the southeast. Another BA aircraft ($BA\text{-}400652_h$) flew a similar path from northwest to the south of Frankfurt where it proceeded to land. Figure 4.4.1.2.2 -1c shows the tracks of the above aircraft as well as all the other targets that were logged by the N40 LDPU. Similarly Figure 4.4.1.2.2-1d shows the N40 track as it was recorded by the NLR LDPU. In all these Figures one dot has been plotted for each position record in the LDPU log.

Comparison of Figures 4.4.1.2.2-1d and 1a shows that a part of the N40 track is missing from the NLR LDPU log. This is because NLR terminated its flight before the N40 and so the last part of the N40 flight was not logged by the NLR LDPU.

Comparison of Figures 4.4.1.2.2-1b and 1c shows that N40 recorded almost the entire NLR track. Figure 4.4.1.2.2 -1c also shows that two additional BA targets of opportunity were observed on the N40, namely $BA400665_h$ (two separate flights), and $BA400668_h$. These BA aircraft were tracked only for short periods of time. This was because of their long distance from the N40 (> 160 nmi) and also the fact that these aircraft were either descending for landing or taking-off and flying away from the N40[4]. The N40 LDPU log contains a third BA target of opportunity ($BA400663_h$) at long range which is not shown in Figure 4.4.1.2.2-1c because its track was never established due to known LDPU behavior. In the following, analysis focuses on the four flights for which extensive LDPU logs were available, namely NLR, N40, BA400664h, and $BA400652_h$.

Figures 4.4.2.1.2.2-2a and 2b show the altitudes of the target aircraft as recorded on the N40 and NLR LDPU, respectively, as well as their range from N40 and NLR. Range was calculated as horizontal great circle distance from the recorded target lat/long positions using linear interpolation to find the matching receiver positions from its own log on the basis of GPS UTC timestamp. One dot has been plotted for each target record in the N40 or NLR log. It can be seen that :

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[4] Flight $BA400665_h$-a was first logged at 191 nmi and FL 145 (The N40 was at FL 220) while the BA aircraft was already descending for landing. The last logged $BA400665_h$-a position was at 169 nmi and FL 7, i.e., near the N40 radio horizon.

Similarly flight $BA400665_h$-b was first logged at 167 nmi and FL 5 while the BA aircraft was taking off and flying away from the N40. The last BA400665h-b position in the N40 log is at the distance of 205 nmi (and FL 211).

The $BA400668_h$ flight was picked at 156 nmi from the N40 and its last recorded position was at 193 nmi. Both this aircraft and the N40 were climbing after take-off (they moved from FL 94 to 193 in that period).

1) NLR and N40 flew at closely spaced cruising altitudes (FL200 versus FL220). NLR distance from N40 was initially increasing up to ~160 nmi as the N40 flew away from Wiesbaden. Then their distance kept decreasing as NLR returned back to Wiesbaden.

2) The two BA targets of opportunity flew at much higher cruising altitudes (FL330 and FL370) than the project aircraft. Their range from N40 initially decreased from 240 to about 50 nmi and then increased again. BA400652h was descending to land at this second phase.

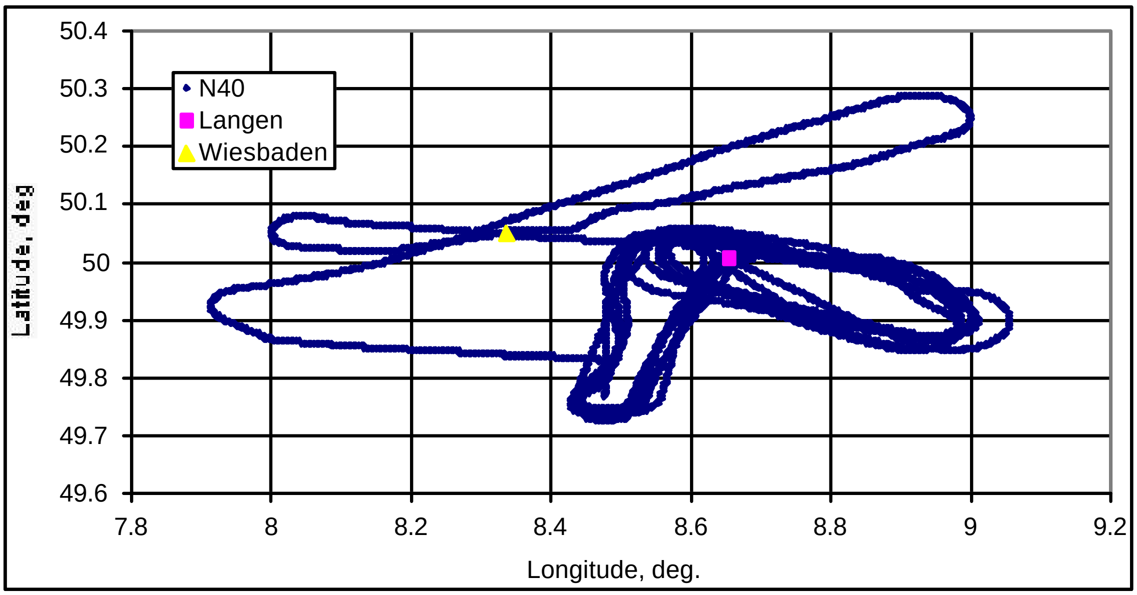


Figure 4.4.1.2.2-1a. N40 LDPU Recorded Own Track, 20 May

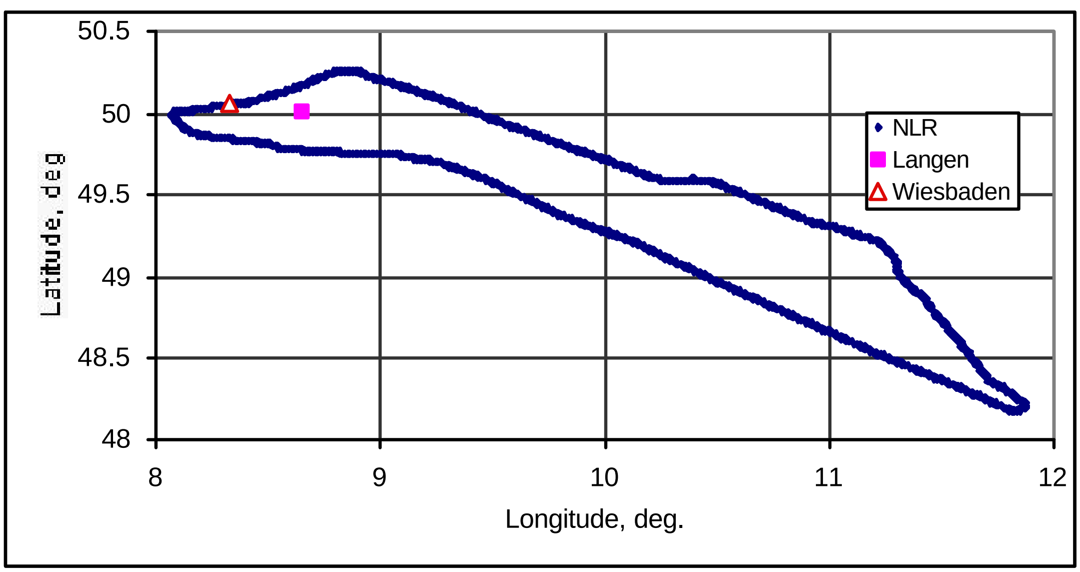


Figure 4.4.1.2.2-1b. NLR Recorded Own GPS Track, 20 May

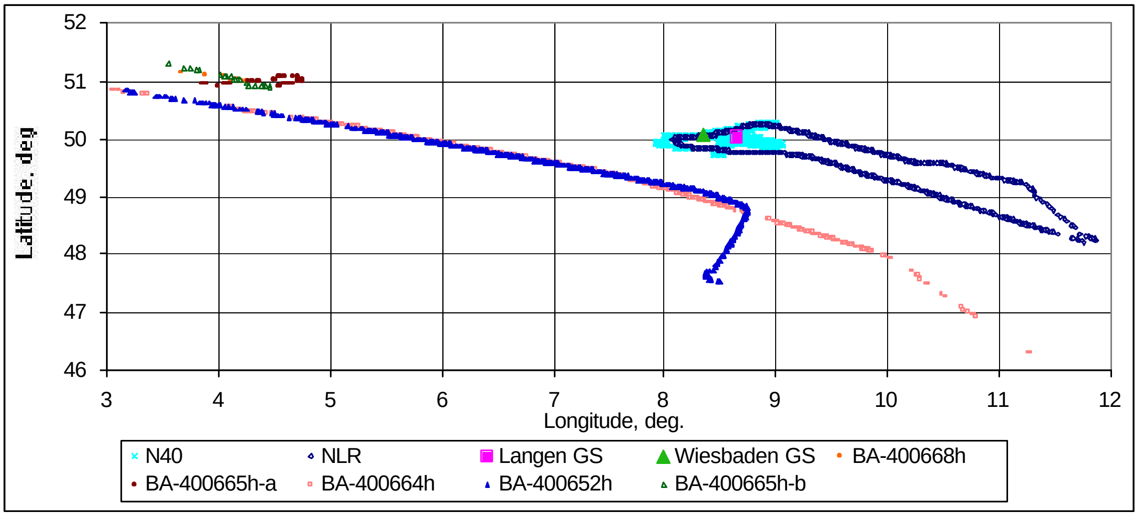


Figure 4.4.1.2.2-1c. Target Tracks Recorded on N40 LDPU, 20 May

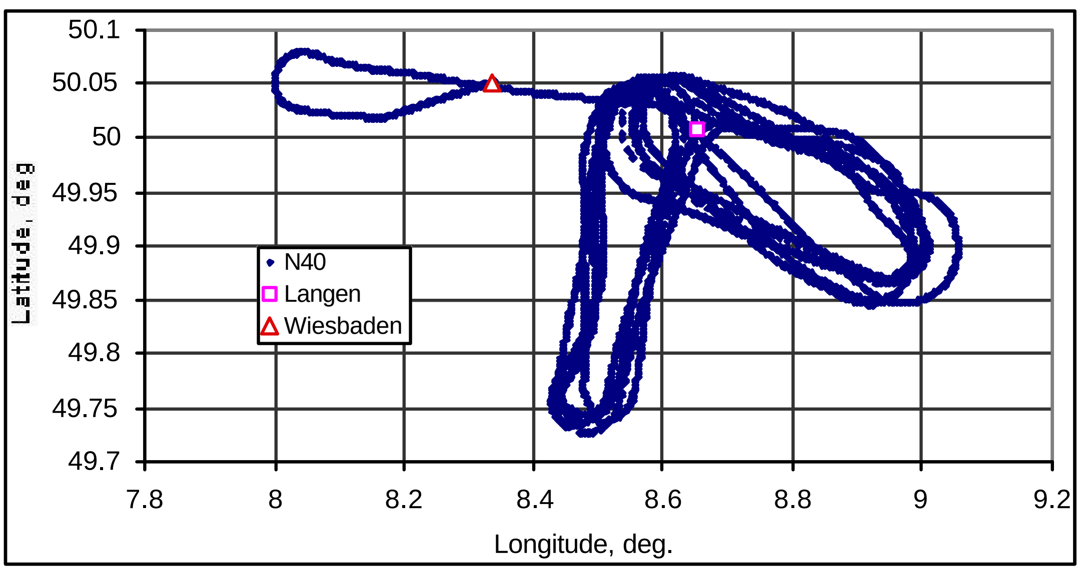


Figure 4.4.1.2.2-1d. N40 Track Recorded on NLR LDPU, 20 May

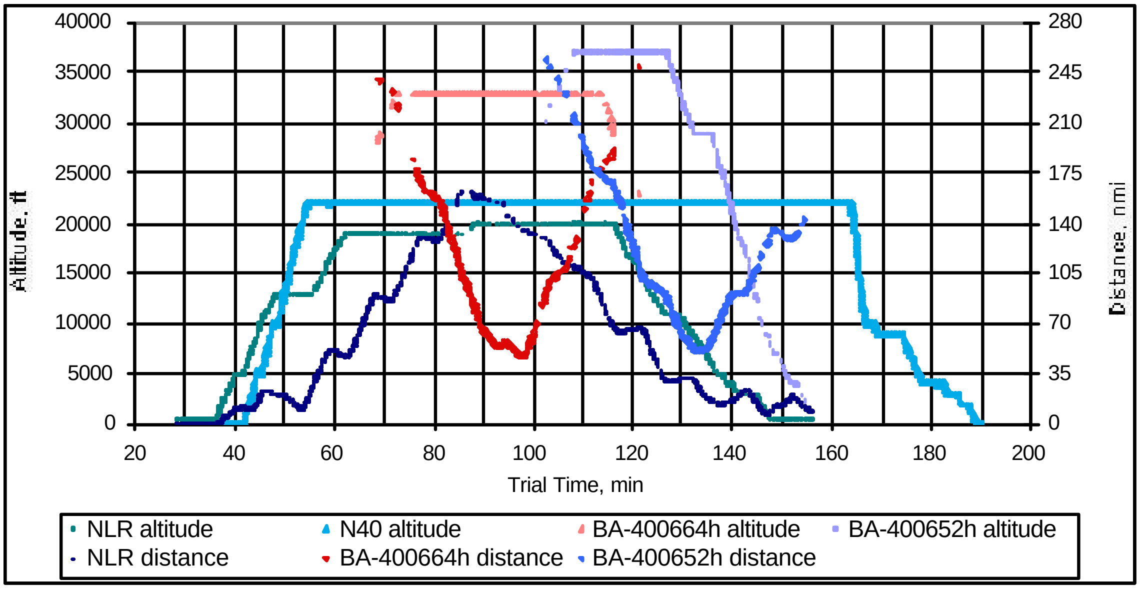


Figure 4.4.1.2.2-2a. Target Altitudes and Ranges from N40, 20 May

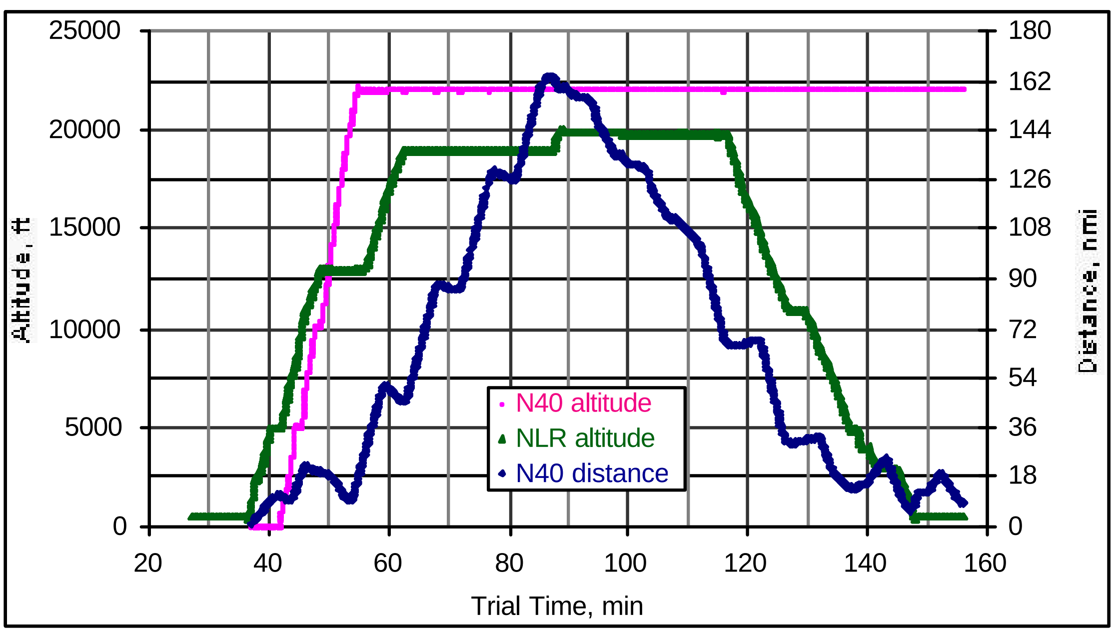


Figure 4.4.1.2.2-2b. N40 Altitudes and Ranges from NLR, 20 May

4.4.1.2.2.2 State Vector Update Period Plots

The following figures 4.4.1.2.2-3a through 3d plot target update periods versus target range. The update periods refer to the target records in the receiver LDPU log. It can be considered that each LDPU log record corresponds to a state vector update. It has been noted earlier that the LDPU logs a position if either a position squitter or a velocity squitter is received (see 4.4.1.1).

Raw update periods are measured as the difference of the GPS UTC timestamp from the previous record of the same target. Only those segments where both aircraft are flying have been considered. In addition to the raw update intervals, the 95th percentile containment values have also been computed. The latter are calculated as explained in 4.4.1.1, and indicate the minimum interval values that exceed 95% of the measured raw values within the same range bin (5 nmi wide).

Figure 4.4.1.2.2-3a shows the NLR update intervals measured from the N40 log. The observed update interval values stayed consistently below 5 nmi up to 70 nmi. Beyond 70 nmi interval variance increased with distance.

Figure 4.4.1.2.2-3b shows the $BA400664_h$ update intervals measured from the N40 log. In this case update intervals stayed consistently below 10 sec up to 120 nmi. The case of $BA400652_h$, shown in Figure 4.4.1.2.2-3c is very similar. It should be noted that both these aircraft flew along roughly the same path for most of the time (see Figure 4.4.1.2-1c).

Finally Figure 4.4.1.2.2-3d shows the N40 update intervals measured on NLR. In this case update intervals stayed consistently below 5 sec up to 120-125 nmi at which range some gaps > 10 sec were encountered. However there was noticeable improvement beyond that range. The N40 and NLR tracks show that gaps occurred in the range 120-125 nmi during both the outbound and the inbound NLR flight leg. In both cases NLR was cruising at a straight line, as Figure 4.4.1.2.2-3e indicates. Figure 4.4.1.2.2-3f shows the N40 tracks during the same periods. It can be seen that during the NLR outbound flight leg the gaps occurred while the N40 (N40 track1) was flying in a straight line away from NLR (NLR track1) and before N40 entered into a turn. During the NLR inbound flight leg the gaps occurred while N40 was turning (N40 track2) towards NLR (NLR track2).

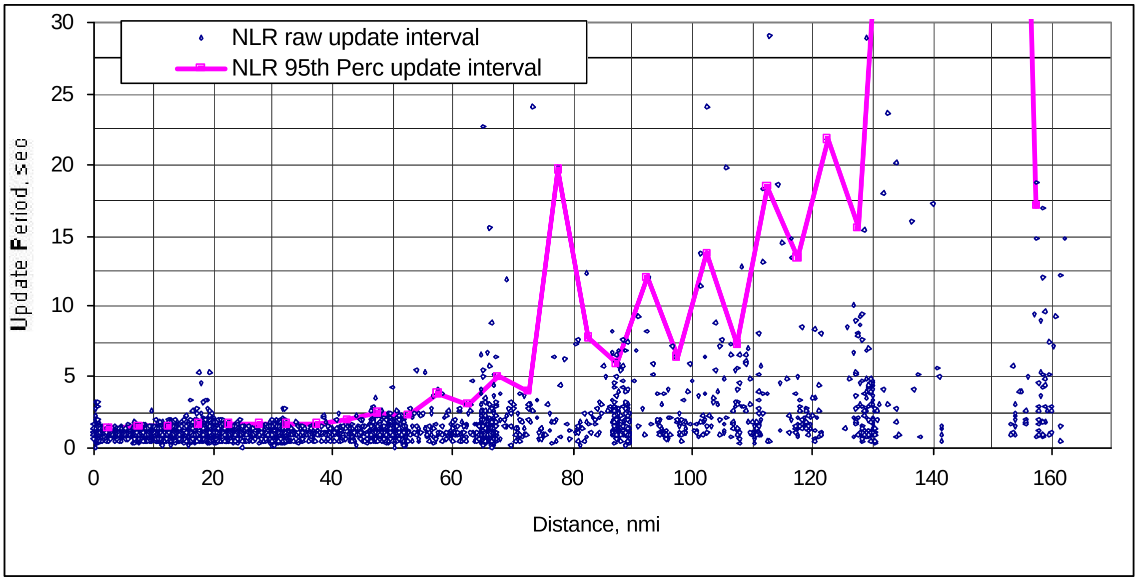


Figure 4.4.1.2.2-3a. Surveillance Update Periods,
NLR Transmissions Received on N40 LDPU, 20 May

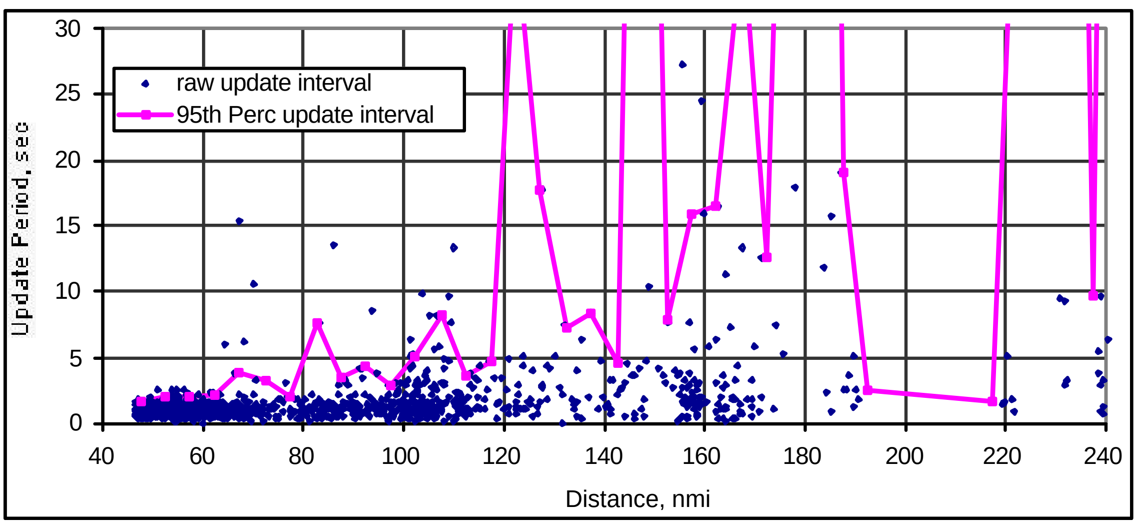


Figure 4.4.1.2.2-3b. Surveillance Update Periods,
NLR Transmissions Received on FII LDPU, 24 May

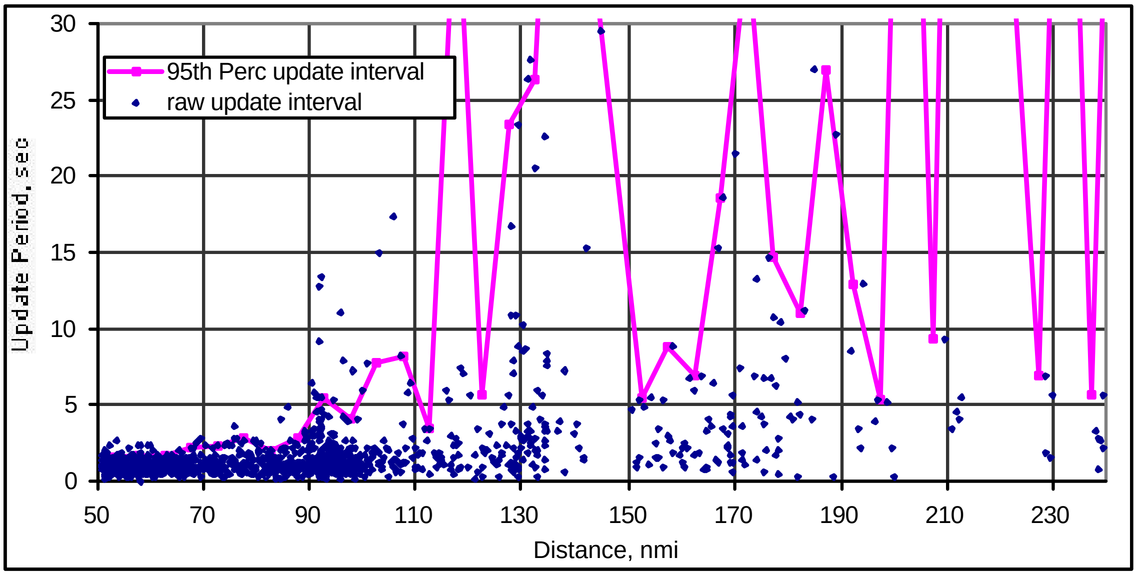


Figure 4.4.1.2.2-3c. Surveillance Update Periods,

BA-400652$_h$ Transmissions Received on N40 LDPU, 20 May

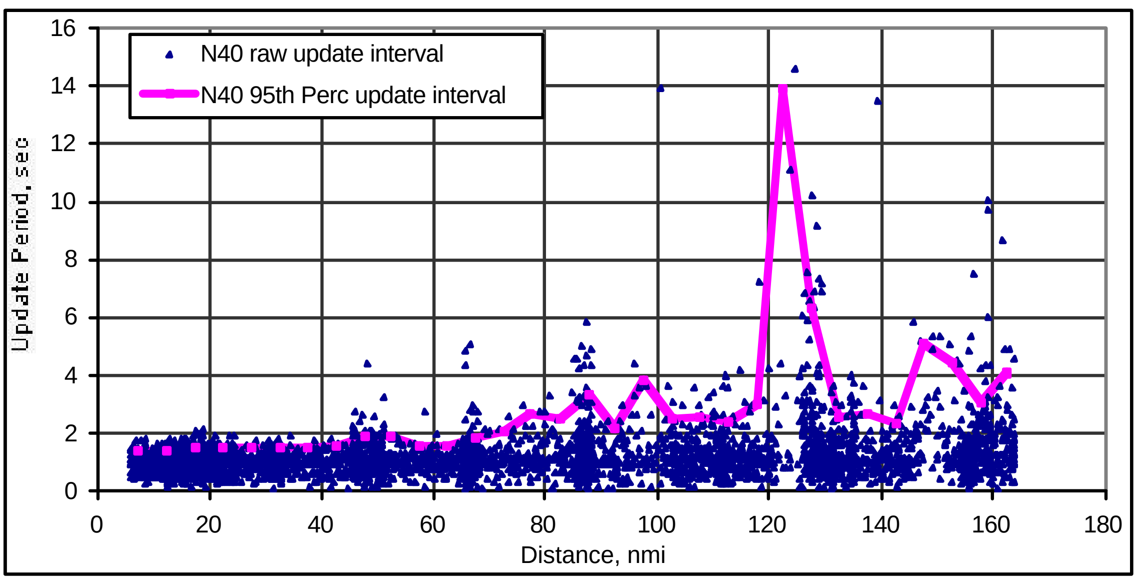
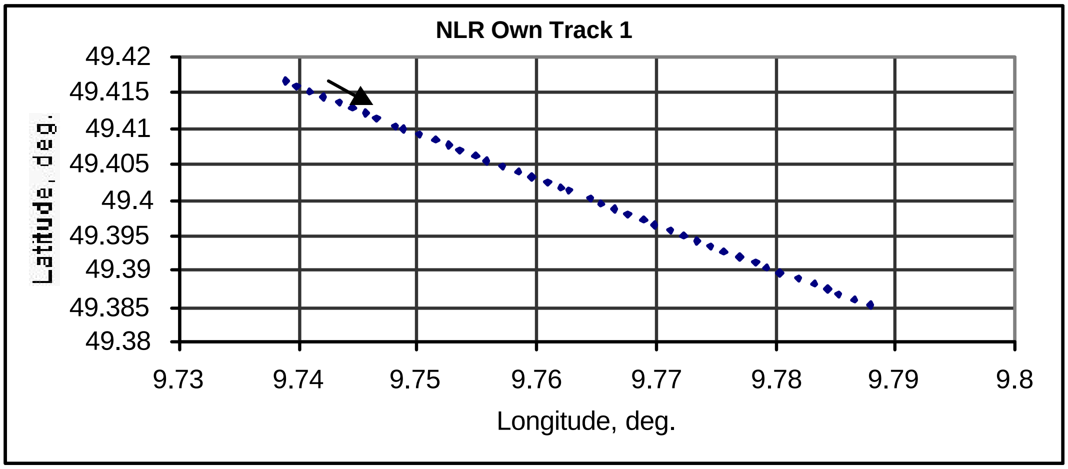


Figure 4.4.1.2.2-3d. Surveillance Update Periods,

N40 Transmissions Received on NLR LDPU, 20 May



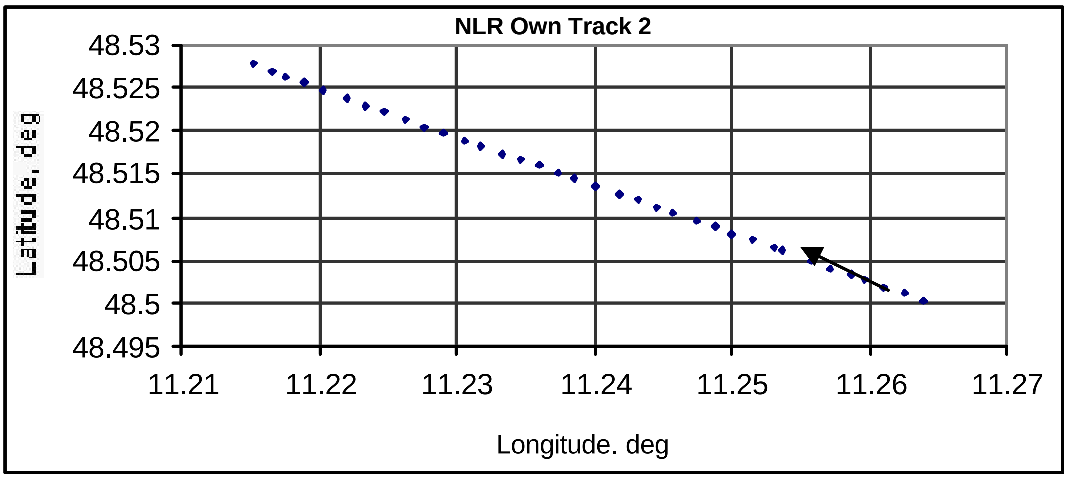


Figure 4.4.1.2.2-3e. NLR Own Tracks in Range 120-125 Nmi from N40

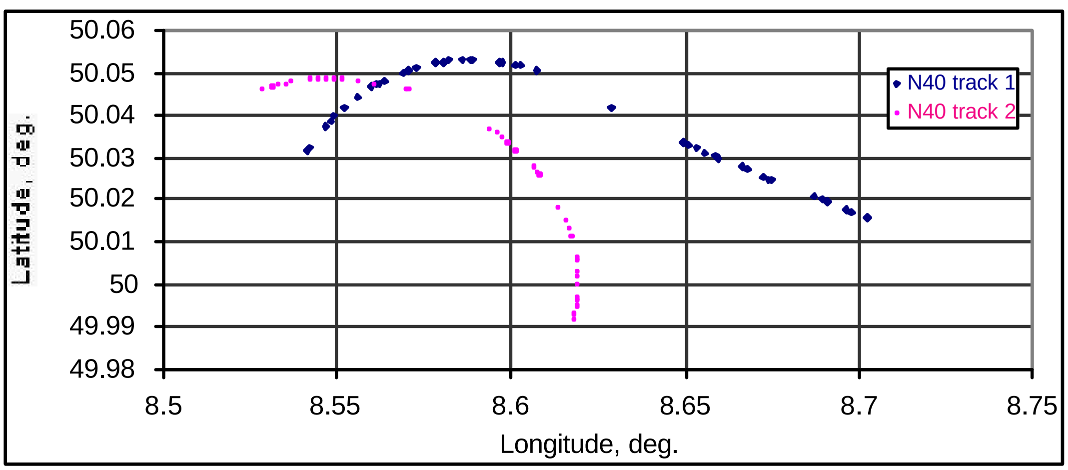


Figure 4.4.1.2.2-3f. N40 Transmissions Received by NLR In the Range 120-125 Nmi

4.4.1.2.2.3 Reception Probability Plots

Figures 4.4.1.2.2-4a through 4d plot the measured probability of reception of individual squitters versus the target aircraft's range. Reception probability is calculated over a sliding 24-second window according to the technique explained in 4.4.1.1. The 24-sec window is moved per record in the log. Range is calculated as horizontal great circle distance. Only those segments where both aircraft are flying have been considered. Reception probability is calculated separately for the incoming and outgoing segments of the target flight to check for any differences due to aspect angle considerations.

Figure 4.4.1.2.2-4a plots the NLR squitter reception probability as measured on the N40. The NLR probability drops monotonically with distance. There is little difference between the performances of the outgoing and the incoming flight leg.

Figure 4.4.1.2.2-4b plots the $BA400664_h$ squitter reception probability as measured on the N40. Again probability falls monotonically with distance. There is however a clear performance difference between the incoming and outgoing legs of the $BA400664_h$ flight. Similar observations can be made for $BA400652_h$, whose performance is shown in Figure 4.4.1.2.2-4c. In the latter's case performance in the outgoing leg may have suffered also because the aircraft was descending for landing.

Finally Figure 4.4.1.2.2-4d plots the N40 squitter reception probability as measured on NLR. Reception probability drops monotonically with range up to 100 nmi. Beyond that distance there is a noticeable difference in performance between the two NLR flight legs. There is a visible gap in reception probability around 120 nmi that was noticed also in the update interval chart of Figure 4.4.1.2.2-3d. In any case N40 reception probability on NLR is clearly better than NLR Extended Squitter reception probability on the N40 (compare with Figure 4.4.1.2.2-4a).

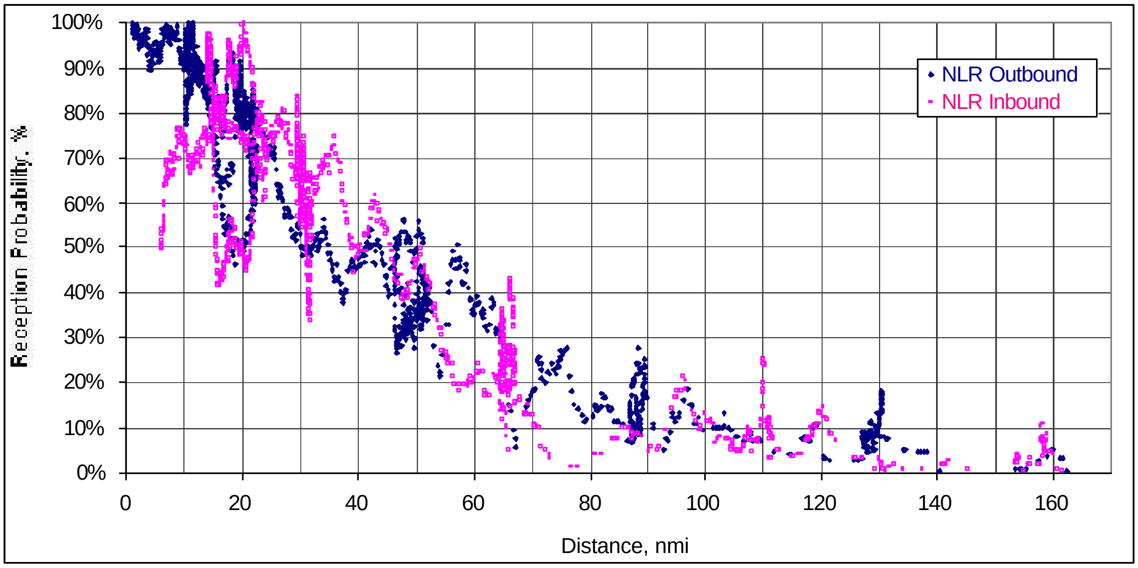


Figure 4.4.1.2.2-4a. Squitter Reception Probability vs. Range, NLR Transmissions Received on N40 LDPU, 20 May

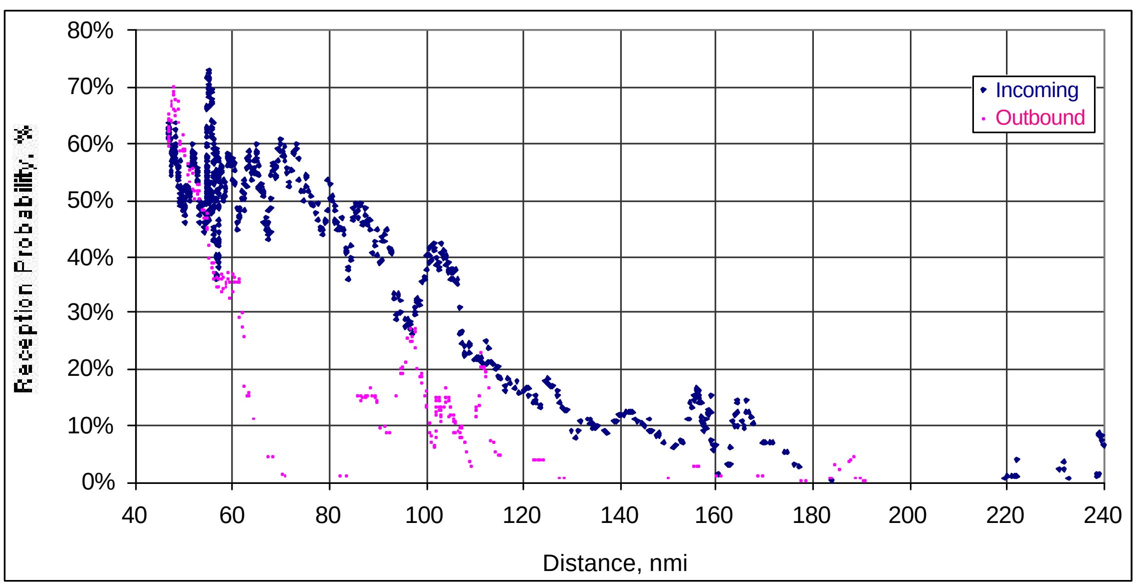


Figure 4.4.1.2.2-4b. Squitter Reception Probability vs. Range, BA-400664$_h$ Transmissions Received on N40 LDPU, 20 May

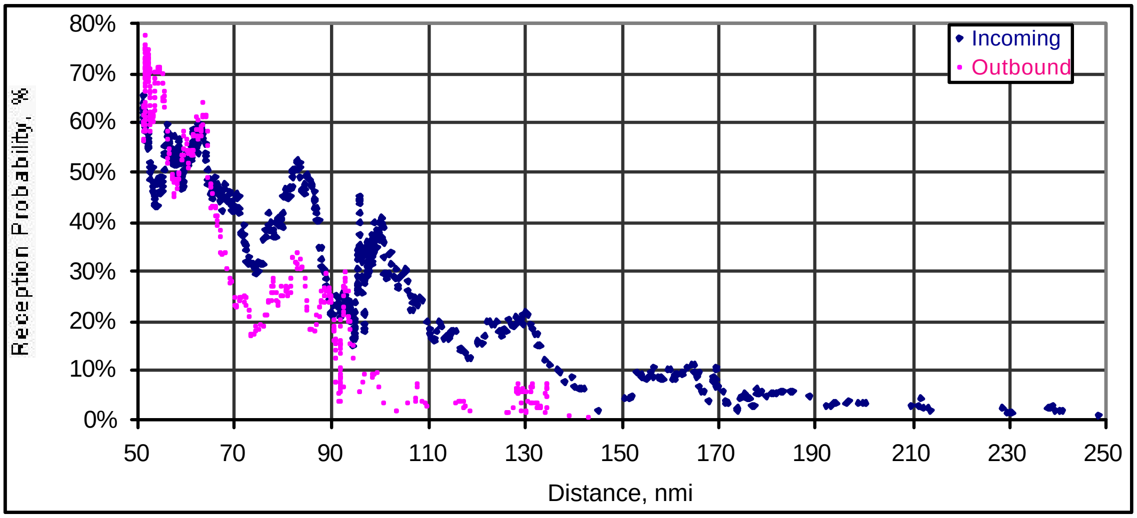


Figure 4.4.1.2.2-4c. Squitter Reception Probability vs. Range,

BA-400652$_h$ Transmissions Received on N40 LDPU, 20 May

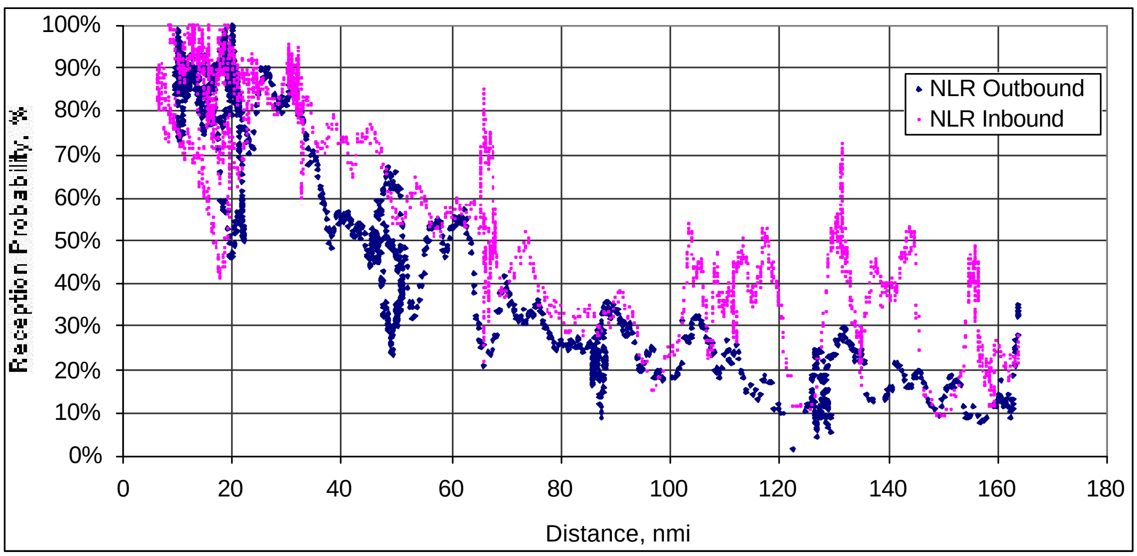


Figure 4.4.1.2.2-4d. Squitter Reception Probability vs. Range,

N40 Transmissions Received on NLR LDPU, 20 May

4.4.1.2.3 Results for 22 May

As described in 3.4, two project aircraft participated in the 1090 MHz Extended Squitter data collection on 22 May. Also the reception of 1090 MHz Extended Squitters from one British Airways “target of opportunity” has been analyzed. The flight profiles for 22 May had the FII aircraft departing Wiesbaden and entering into a holding pattern near Frankfurt where it was executing frequent maneuvers during each circuit of the "racetrack" pattern (approximately 10 minutes per circuit). The FII aircraft was broadcasting only position and flight ID Extended Squitters (i.e., no velocity squitters) for an average Extended Squitter transmission rate of 2.2 squitters per second. The second project aircraft that participated in the data collection on 22 May was the FAA N40. N40 was broadcasting position, velocity and flight ID Extended Squitters at an average rate of 4.2 squitters per second. Also a British Airways aircraft, identified as BA-400664$_h$, was observed by the 1090 MHz Extended Squitter receivers (i.e., LDPUs) onboard the FII aircraft and on N40. The FAA N40 aircraft flew on a route that took it from Wiesbaden to the southeast beyond Munich then to the northwest and finally turning to the southwest back to land at Wiesbaden. BA-400664$_h$ was observed on a route from the northwest flying generally to the southeast passing near Frankfurt and continuing on toward a destination beyond Munich. The BA-400664$_h$ aircraft was broadcasting position and velocity Extended Squitter (no flight ID) at an average rate of 4.0 squitters per second.

The FAA N40 and FII aircraft were equipped as described in Chapter 2 of this report. The BA-400664$_h$ aircraft was equipped with an Extended Squitter enabled air carrier class Mode S transponder.

4.4.1.2.3.1 Track Plots

The following figure indicates the ground tracks of the project aircraft and targets of opportunity.

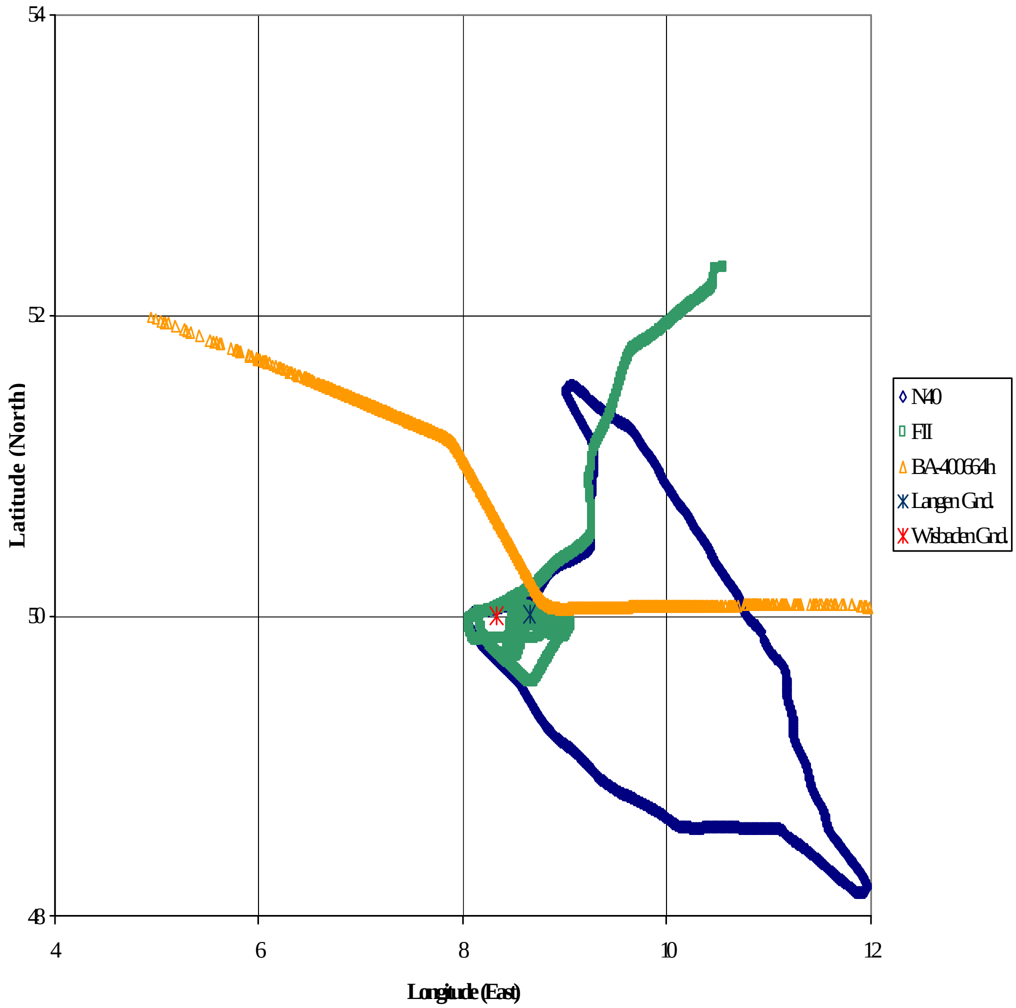


Figure 4.4.1.2.3-1. Ground Tracks, 22 May

4.4.1.2.3.1.1 Targets Tracked by FII Aircraft

Data collected onboard the FII aircraft's LDPU has been analyzed for two target aircraft (i.e., FAA N40 project aircraft and a British Airway (BA-066864) target of opportunity).

The following figure plots the actual squitter reception by the LDPU onboard the FII aircraft versus range to N40 and range to BA-066864$_h$.

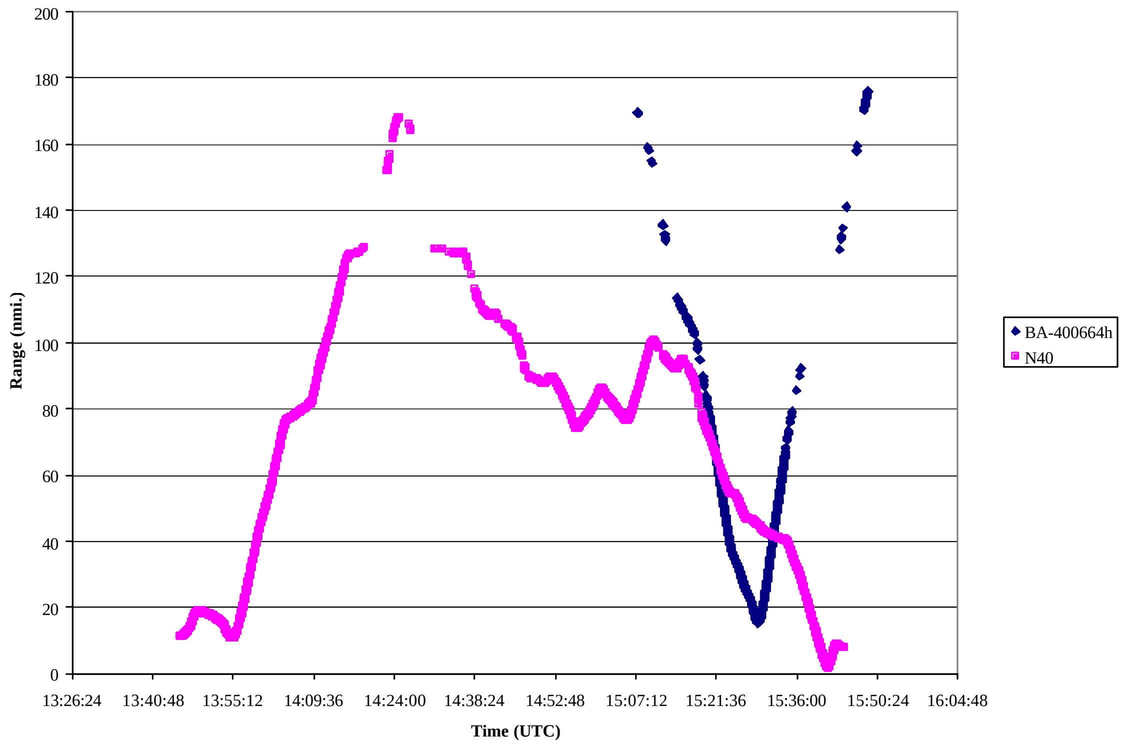


Figure 4.4.1.2.3-2. Target Aircraft Tracks as Seen by FII Aircraft, 22May

The ADS-B MASPS and 1090 MHz ADS-B MOPS allows for a maximum track coast of 24 seconds. The ADS-B MASPS requirements for longer range target tracking were based on operations that differ substantially from the scenario evaluated here (i.e., not directly applicable to an aircraft in a holding pattern). However, an analysis was performed on the data collected onboard the FII aircraft and the following results were obtained for each of the two target aircraft:

N40 - For the outbound leg of N40's flight profile no gap in reception of state vector squitters (position and/or velocity squitters) exceeded 24 seconds until N40 was at a range beyond 126 nmi. For the inbound leg of N40's flight profile no gaps in reception of state vector squitters of greater than 24 seconds were observed within a range of 92 nmi. Note that the final portion of the flight profiles (i.e., the N40 inbound segment) more closely represents a terminal traffic scenario where N40 was descending and maneuvering for a landing at Wiesbaden and the FII was breaking out of a holding pattern and descending for a landing at Wiesbaden.

BA-400664$_h$ - For BA-400664$_h$ inbound (approaching the FII aircraft) no gap in reception of state vector squitters exceeded 24 seconds once the target was within

113 nmi. For the outbound phase of the $BA\text{-}400664_h$ flight path the first gap in reception of state vector squitters exceeding 24 seconds occurred at 79 nmi.

4.4.1.2.3.1.2 Targets Tracked by FAA N40

Data collected onboard the FAA N40's LDPU has been analyzed for two target aircraft (i.e., FII project aircraft and a British Airway ($BA\text{-}400664_h$) target of opportunity).

The following figure plots actual squitter reception by the LDPU onboard the N40 versus range to the FII aircraft and the range to $BA\text{-}400664_h$ -.

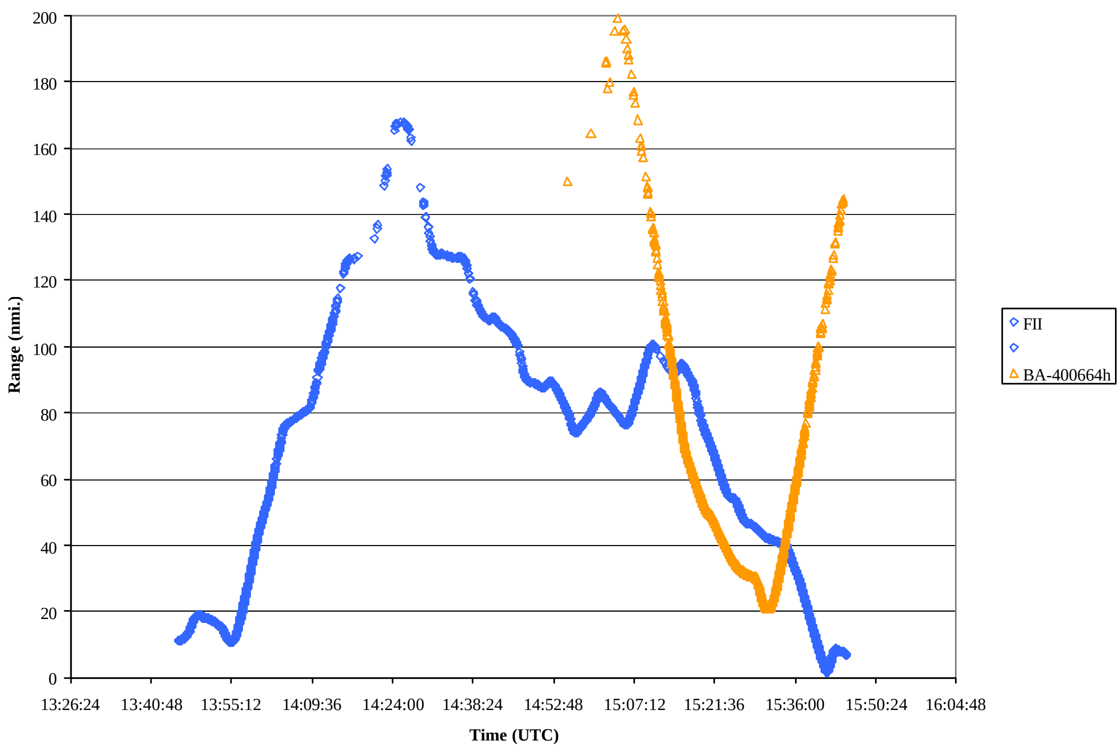


Figure 4.4.1.2.3-3. Target Aircraft Tracks as seen by N40, 22 May

The ADS-B MASPS and the 1090 MHz Extended Squitter MOPS allow for a maximum track coast of 24 seconds. An analysis was performed on the data collected onboard N40 and the following results obtained for each of the two target aircraft:

FII - When N40 was on the outbound leg of its flight profile no gap in reception of state vector squitters (i.e., reception of a position squitter) exceeded 24 seconds until the range to the FII aircraft reached 114 nmi. When N40 was on the return leg of the flight profile no gap in reception of a state vector squitters exceeded 24 seconds once the target was within 95 nmi. Note however that the FII was not transmitting velocity squitters thus reducing the rate at which state vector updates were possible (as compared to a MOPS compliant implementation).

BA-400664$_h$ - For the inbound leg of BA-066864$_h$'s flight no gap in reception of a state vector squitters exceeded 24 seconds once the target was within 140 nmi. For the BA aircraft on its outbound flight path the first gap in reception of state vector squitters exceeding 24 seconds occurred at 111 nmi

4.4.1.2.3.2 State Vector Update Period Plots

The UPSAT LDPU avionics is intended to generate an ADS-B report at one-second intervals if one or more Extended Squitters were received during the prior second. The following figures present the state vector update period that could be expected vs. target range. As per the 1090 MHz ADS-B MOPS, either a position squitter or a velocity squitter is considered sufficient to allow for an update to the state vector of the target aircraft. Any update period of greater than 24 seconds would result in a drop of the track for the target aircraft.

Note that the ADS-B MASPS requirements for air-to-air target tracking at ranges beyond 40 nmi are applicable only to targets in the forward direction and are also only applicable to applications intended for use in low density en route or oceanic airspace and are thus not directly applicable to the airspace where the evaluation was conducted.

Data points shown in Figure 4.4.1.2.3-4 and Figure 4.4.1.2.3-5 as 30 seconds represent update intervals of 30 seconds or greater.

4.4.1.2.3.2.1 Update Periods for Targets Tracked by the FII Aircraft

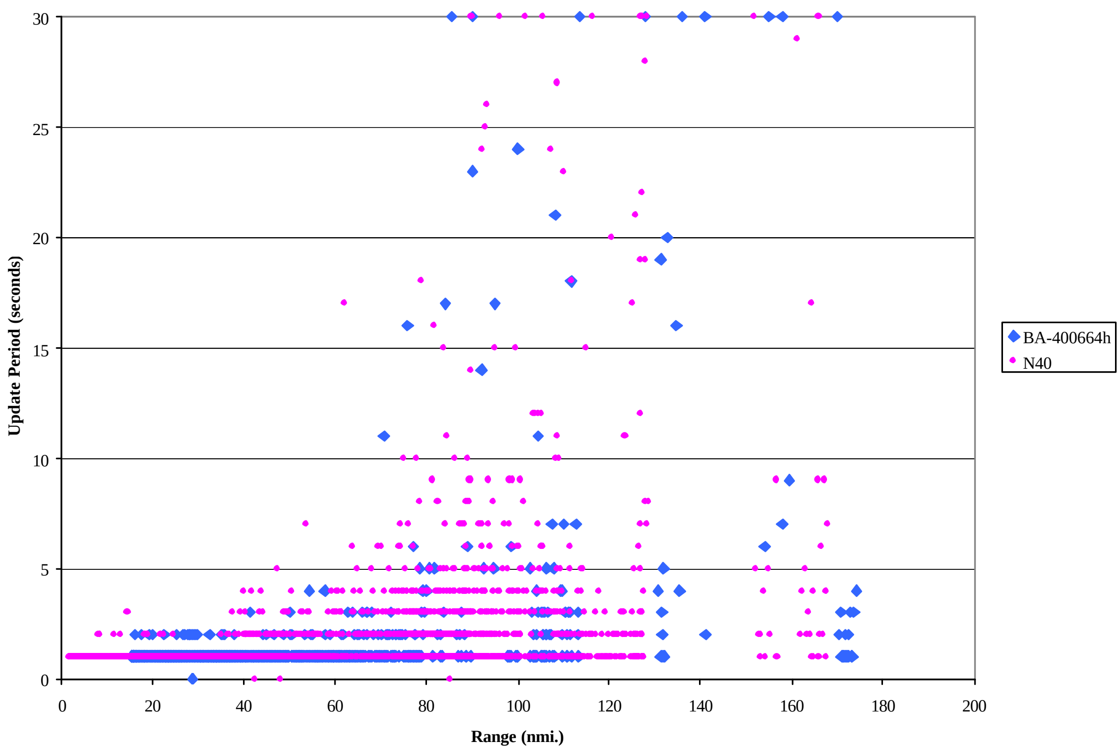


Figure 4.4.1.2.3-4. State Vector Update Periods for N40 Measured by FII aircraft, 22 May

4.4.1.2.3.2.2 Update Periods for Targets Tracked by FAA N40

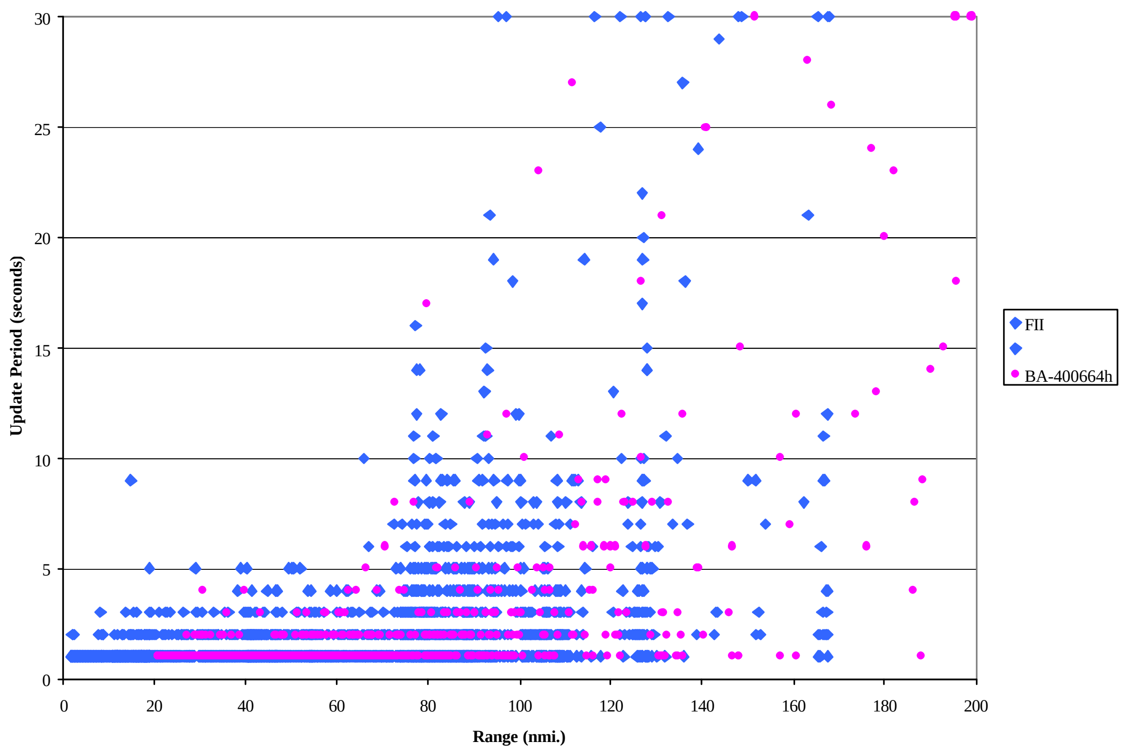


Figure 4.4.1.2.3-5. State Vector Update Periods Measured by N40, 22 May

Note FII aircraft not transmitting velocity squitters

4.4.1.2.2.3 Reception Probability Plots

4.4.1.2.2.3.1 Reception Probability Recorded by FII Aircraft

The following figure plots the measured probability of reception of individual squitters over 24 second intervals.

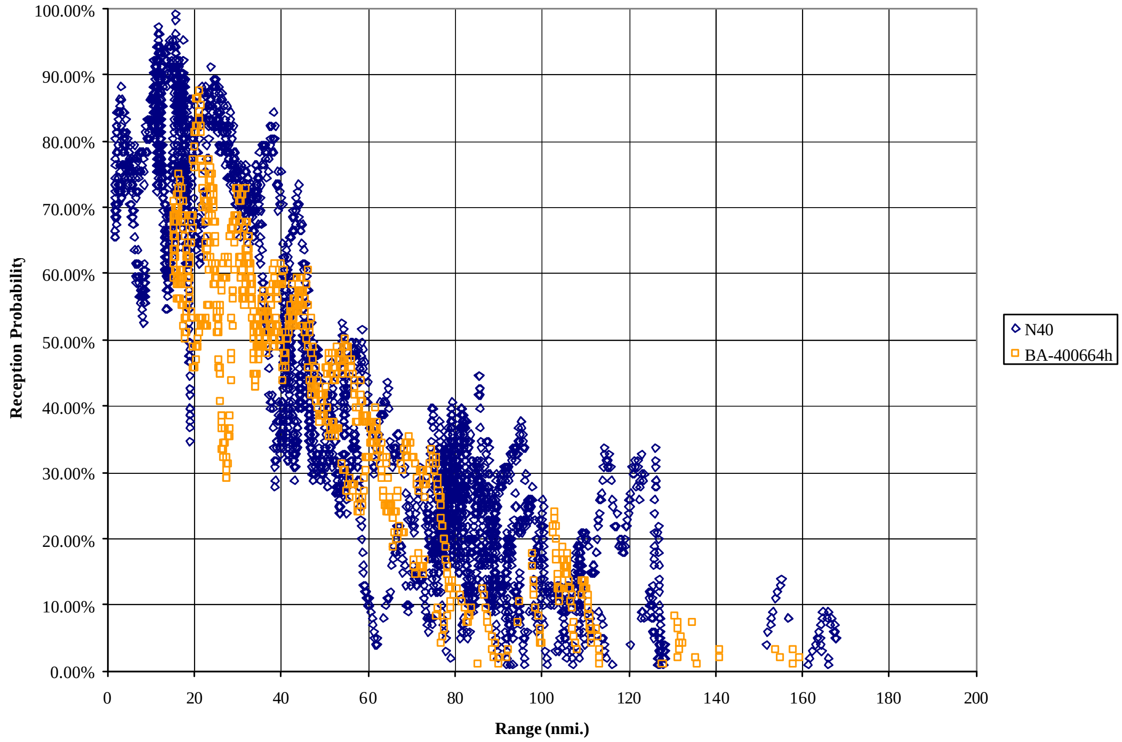


Figure 4.4.1.2.3-6. Probability of Receiving Squitters by FII Aircraft, 22 May

4.4.1.2.2.3.2 Reception Probability Recorded by FAA N40

The following figure plots the measured probability of reception of individual squitters over 24 second intervals.

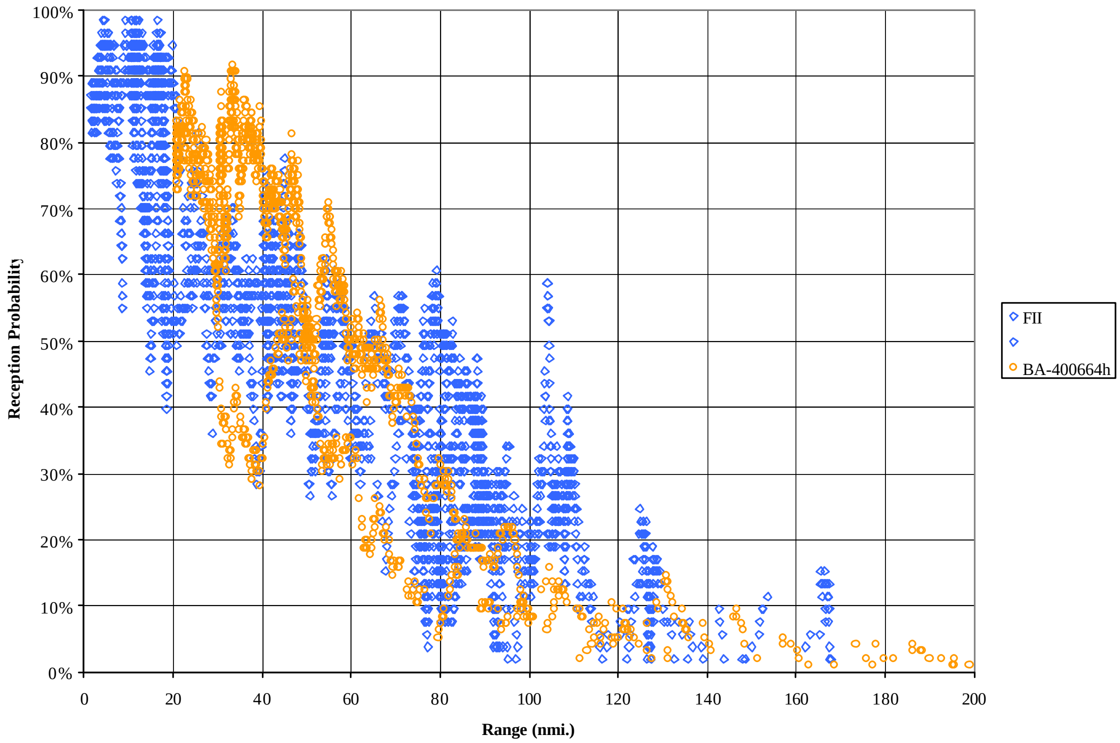


Figure 4.4.1.2.3-7. Probability of Receiving squitters by N40, 22 May

4.4.1.2.4 Results for 25 May

As described in 3.4, one the FAA N40 project aircraft participated in the 1090 MHz Extended Squitter data collection on 25 May. The FAA N40 aircraft flight path on the 25 May data collection went from the Wiesbaden area to the Southeast passing a few miles north of Stuttgart and then toward a point beyond Munich then turning Northwest to a point North of Wiesbaden then turning South toward Wiesbaden. During the data collection a target of opportunity (i.e., British Airways -BA-400663$_h$) was observed. BA-400663$_h$ was equipped with commercial TCAS avionics that supported the transmission of 1090 MHz Extended Squitters. While the specifics of the avionics installation on BA-400663$_h$ are not known, commercial TCAS avionics of the type used will typically have a transmitter power output on the range of 400 to 500 watts. The BA-400664$_h$ aircraft was broadcasting position, velocity and Flight ID Extended Squitters at an average rate of 4.2 total squitters per second.

4.4.1.2.4.1 Track Plots

The following figure indicates the ground tracks of the project aircraft and the target of opportunity.

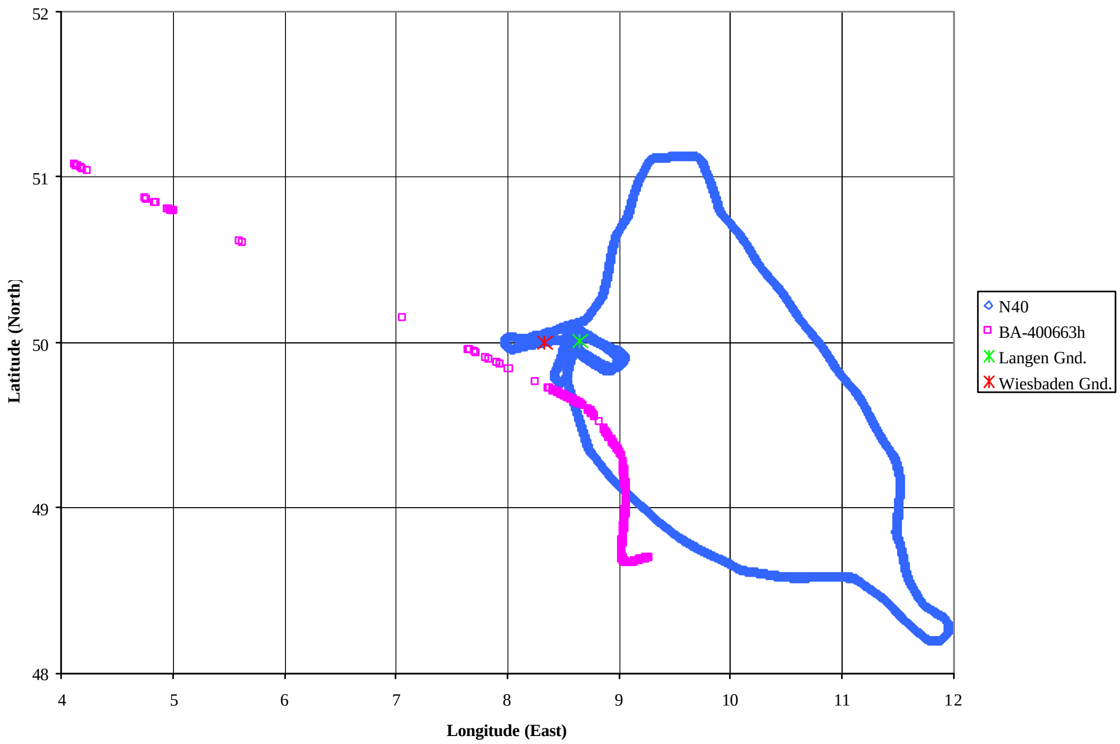


Figure 4.4.1.2.4-1. Ground Tracks, 25 May

The following figure plots actual squitter reception by the LDPU onboard the N40 versus range to BA-400663$_h$.

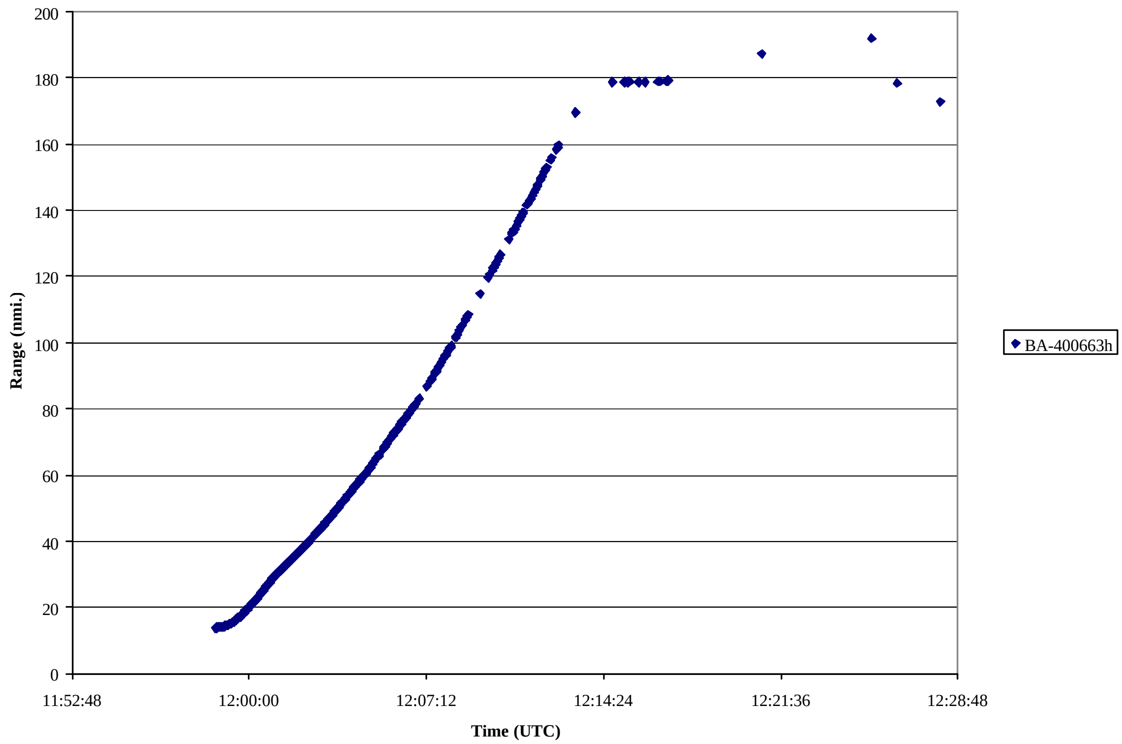


Figure 4.4.1.2.4-2. BA-400663$_h$ Track as seen by N40, 22 May

The Extended Squitter transmissions from BA-400663$_h$ were first acquired while BA-400663$_h$ was on the airport surface at Stuttgart. At the time of Extended Squitter acquisition N40 was operating at an altitude of approximately 23,000 ft approaching Stuttgart from the northwest. BA-400663$_h$ departed Stuttgart flying initially toward the west then turning north and finally turning toward the northwest. The following data includes approximately 14 minutes of reports while BA-400663$_h$ was climbing from takeoff to an altitude of approximately 28,000 ft. N40 passed approx. 13 nmi north of the BA-400663$_h$ location just before BA-400663$_h$ took off. Once BA-400663$_h$ was airborne the two aircraft were generally flying away from each other and each aircraft executed some maneuvers during the flight segments being analyzed here. This an extreme case of aircraft geometry where the target aircraft (BA-400663$_h$) is starting on the surface, 23,000 ft below own aircraft, then climbing out while both own aircraft and the target are executing maneuvers. The geometry of the aircraft for this case had the relative bearing of the target aircraft, once airborne, generally in the rear quadrant relative to own aircraft. The ADS-B MASPS requirement for ADS-B reception range is 30 nautical miles toward the rear (i.e., the longest range MASPS requirement specifies 90 nmi forward and 30 nmi aft for the long-range deconfliction application in oceanic and low density remote airspace).

4.4.1.2.4.2 State Vector Update Period Plots

The following figure present the measured state vector update period (i.e., time internal between reception of state vector squitters) vs. target range. Any update period of greater than 24 seconds would result in a drop of the track for the target aircraft. Note that the ADS-B MASPS requirements for air-to-air target tracking at ranges beyond 40 nmi are applicable only to targets in the forward direction and are also only applicable to applications intended for use in low density en route or oceanic airspace and are thus not directly applicable to the airspace where the evaluation was conducted.

Data points shown in Figure 4.4.1.2.4-3 as 30 seconds represent update intervals of 30 seconds or greater.

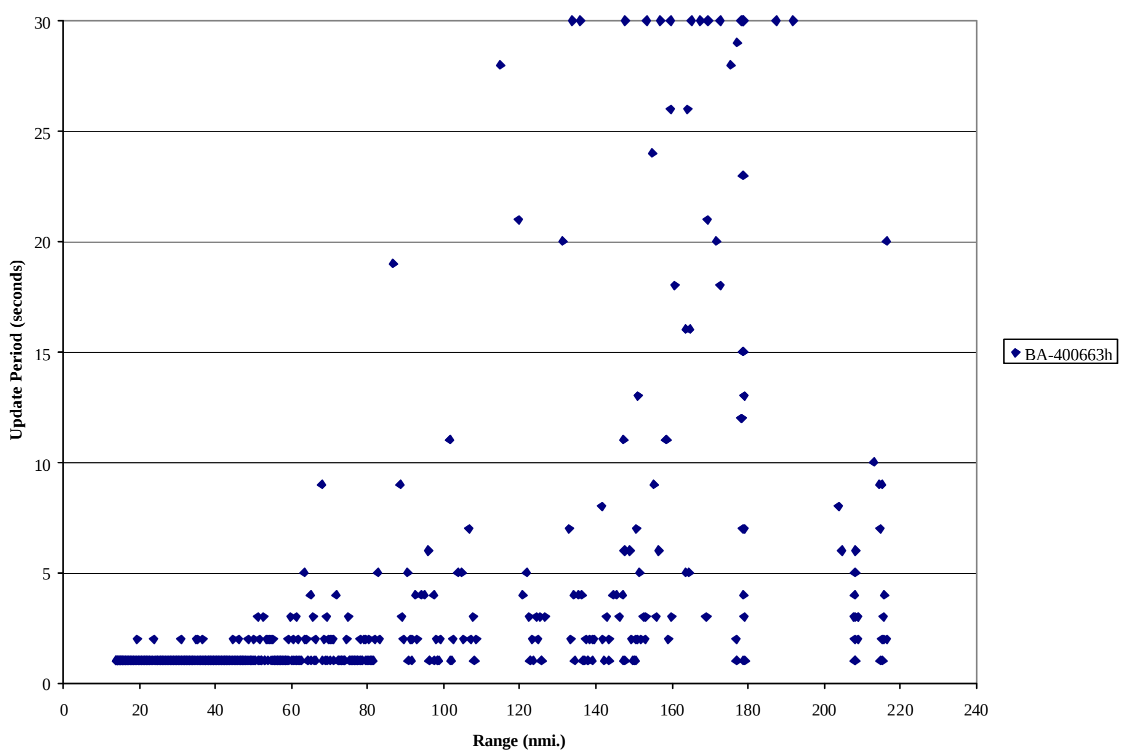


Figure 4.4.1.2.4-3. State Vector Update Period for BA-400663$_h$, Measured by N40, 25 May

4.4.1.2.4.3 Reception Probability Plots

The following figure plots the measured probability of the reception of individual squitters over 24 second intervals.

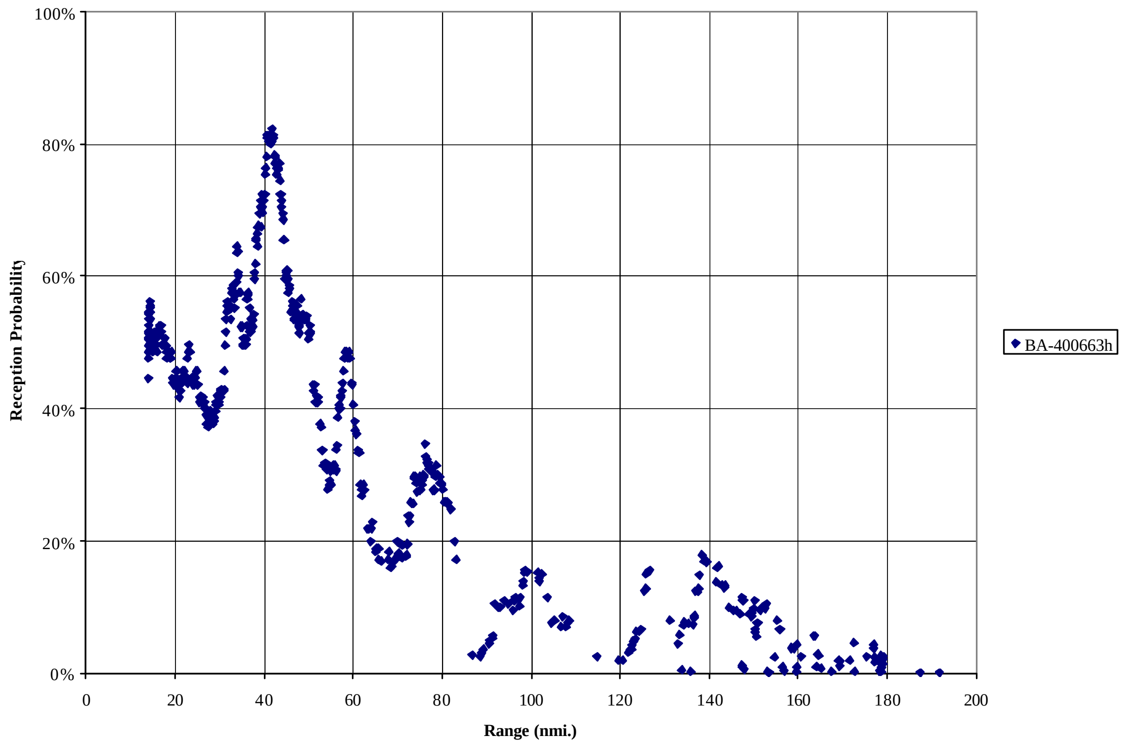


Figure 4.4.1.2.4-4. Probability of Receiving BA-400663$_h$ by N40, 25 May

4.4.1.3 Observed Errors in LDPU log

The following types of errors were observed in the LDPU logs in both air-to-air and air-to-ground reception. The frequency of such errors was lesser in the air-to-ground case.

4.4.1.3.1 Zero Values of Latitude and Longitude

These were caused by track drops due to the way in which the LDPU position tracker has been implemented. If the LDPU does not receive position squitters, it tracks target positions from velocity Extended Squitters and can maintain the track for up to 10 seconds. If the LDPU does not receive position Extended Squitters for periods exceeding 10 seconds, then it logs records with zero latitude and longitude values. This behavior is not conformant with the 1090 MOPS (DO-260), which furthermore specify a maximum tracking interval of 24 seconds. An example of the LDPU behavior is shown in the following table. The latter is extracted from the N40 LDPU log of the 24 May for the target of opportunity BA-400652$_h$. That BA target of opportunity was at more than 190 nmi from N40 and hence air-to-air reception was poor. Consequently there were periods where the Extended Squitters update intervals frequently exceeded 10 sec and caused the tracking algorithm implemented in the LDPU to drop the track. Zero lat/long records were not taken into account in the update interval analysis presented in this chapter (but they were included in reception probability calculations).

Squitter Type	Lat.	Long.	Altitude	Signal Level	Squitter Count	error corrected	UTC Time
pos	51.05945	12.57428	31375	50	3	2	10:37:11.325
pos	51.05671	12.58958	31475	64	4	2	10:37:15.609
pos	50.95221	13.15888	34300	58	1	0	10:39:55.487
vel	50.94966	13.17244	34360	54	2	1	10:39:58.911
vel	0	0	0	48	1	0	10:40:14.987
pos	50.93811	13.50432	34725	54	2	1	10:40:16.599
vel	0	0	0	63	1	0	10:40:35.253
pos	50.91854	13.60762	35350	55	2	0	10:40:45.668
vel+pos	50.90258	13.42128	35875	62	2	2	10:41:09.535
vel	0	0	0	58	1	0	10:41:28.729
vel	0	0	0	65	1	0	10:41:59.846
pos+vel	50.86533	13.61562	36850	52	3	0	10:42:04.847
vel	50.86237	13.63107	36897	65	4	0	10:42:09.073
pos	50.86206	13.63247	36925	59	5	0	10:42:09.626
vel	50.85627	13.66272	36943	46	6	1	10:42:17.841

4.4.1.3.2 Outliers in Latitude and/or Longitude

These occurred rarely, generally when the LDPU track acquisition algorithm failed to acquire correctly. Track acquisition requires the reception of both an even and an odd position squitter. When reception performance is poor, it is possible albeit unlikely that only of the two types will be received for some time. The worst example was seen on the 20 May in the N40 LDPU log (see extract in the following table) for the target of opportunity BA-400663$_{h.}$ The LDPU failed to acquire correctly this track for a period of 53 minutes. The target was more than 180 nmi from N40.

Squitter Type	Latitude	Longitude	Altitude	SigLevel	Squitter Count	Error Corrected	UTC Time
pos	51.91398	11.13855	23175	48	1	1	13:56:43.058
vel	51.91491	11.14645	23236	50	2	1	13:56:44.634
pos	51.93049	10.97639	24150	43	1	0	13:57:20.811
pos	51.96808	11.27631	26300	43	2	0	13:58:49.265
pos	52.01801	11.67555	28800	45	1	0	14:00:41.975
pos	52.01906	11.68433	28856	50	2	0	14:00:44.152
pos	52.04172	12.15511	29975	58	1	1	14:01:35.228
pos	52.06541	12.35443	31425	64	1	1	14:02:29.764
pos	52.16429	12.987	35425	42	1	1	14:05:28.530
pos	52.19448	12.78242	35875	36	1	1	14:05:55.551
pos	52.30248	13.03054	37000	47	2	2	14:07:22.780
pos	52.30608	13.03854	37000	48	3	2	14:07:25.640
pos	52.30608	3.038557	37000	49	4	2	14:07:26.911
pos	52.31278	3.054199	37000	49	6	2	14:07:31.101
pos	52.32101	3.073425	37000	44	7	2	14:07:37.950
pos	52.37163	13.18999	36975	42	1	0	14:08:19.635

Squitter Type	Latitude	Longitude	Altitude	SigLevel	Squitter Count	Error Corrected	UTC Time
vel	52.38341	13.21773	36985	48	2	0	14:08:29.084
pos	52.41715	13.29696	37000	53	1	0	14:08:58.000

Outlier records have been removed from the set processed in the performance analysis/

4.4.1.3.3 Phantom ICAO Addresses

In almost all recordings the LDPU log contained Extended Squitters records with addresses from unknown aircraft. Examples are shown in the table below from the N40 LDPU log of the 24 May. There was always a single record logged per unknown address. Neither the Mode S radar at Goetzenhein nor the ANS-MAGS station at Langen detected those addresses. The cause of these LDPU erroneous records is not known. These records have not been included in the analysis calculations

ICAO Address	Squitter Type	Latitude	Longitude	Altitude	SigLevel	Squitter Count	Error Corrected	UTC Time
4D9ED2	pos	52.07771	11.99821	49250	54	1	1	10:30:24.812
E9D574	vel	48.84659	8.335447	20700	78	1	1	10:33:02.877
9D49A0	pos	50.50746	6.317804	5800	71	1	1	10:33:07.725
6DFFFF	pos	52.417	8.024654	21250	40	1	1	10:34:14.395
D24BFF	pos	52.46058	8.010407	28625	25	1	1	10:34:49.571
4DF875	pos	47.62028	6.978571	35250	92	1	1	10:36:53.601
F32D1D	pos	52.8843	8.583756	-3276800	26	1	1	10:37:04.369
148AFF	pos	50.0247	3.762581	11675	117	1	1	10:38:36.861
5F0787	pos	52.73875	9.658034	82400	66	1	1	10:42:00.341
7B0D99	pos	52.14774	13.22097	47125	66	1	1	10:44:52.162
3E52E8	pos	52.6874	12.49373	-3276800	111	1	1	10:45:37.648
359EC	pos	50.82415	9.76249	-225	39	1	1	10:48:13.065
CEC275	pos	48.58968	4.12601	41675	29	1	1	10:52:41.143
12FE1	pos	49.48832	3.850193	2320500	51	1	1	11:00:03.364
DF8CFF	vel	0	0	0	72	1	1	11:04:00.291
247543	pos	50.15937	6.927609	19925	69	1	1	11:10:25.264
3E56C3	pos	49.80043	10.8281	49500	44	1	1	11:11:31.603
9B4567	Surf	50.17351	9.788947	0	28	1	1	11:19:29.352
B2F8D5	pos	50.18847	5.734499	6275	61	1	1	11:19:31.270
2B29BD	pos	0	0	36375	45	1	1	11:22:27.953
2E355B	pos	48.53047	6.1988	72100	35	1	1	11:24:43.305
B76D92	pos	52.02357	12.45575	48050	27	1	1	11:25:43.008
5744AF	pos	49.26263	5.686498	39925	44	1	1	11:26:05.380

4.4.1.3.4 GPS /UTC Time Negative Shifts

The LDPU logs a GPS derived UTC reception timestamp with each record. Records are logged in time sequence, there were however a few (generally ≤ 2 per session) records observed whose timestamp was not in sequence. The other fields contained within such record appeared to be in the correct sequence. An example is shown in the table below (FII log 24 May for N40 Extended Squitters). These incidents may have been due to buffering in the LDPU and inter-processor communication delays with the built-in GPS.

In the analysis, the timestamps of such records have been corrected on the basis of distance between successive positions.

Squitter Type	Lat.	Long.	Alt.	SigLevel	Squitter Count	Error Corrected	UTC Time
pos+vel	49.94649	8.930855	21925	92	145	12	10:45:22.964
vel	49.94702	8.929181	21939	91	146	12	10:45:23.317
pos+vel	49.94709	8.928988	21925	94	148	12	10:45:24.047
pos+vel	49.94765	8.927314	21950	95	150	12	10:45:25.165
pos+vel	49.94842	8.925083	21950	96	153	12	10:45:26.600
pos+vel	49.94865	8.924439	21950	88	155	12	10:45:26.035
pos+vel	49.94928	8.922529	21975	93	157	12	10:45:27.106
pos+vel	49.95033	8.919654	21975	42	161	12	10:45:28.918
FID+pos +vel	49.95086	8.918366	21975	90	164	12	10:45:29.754
pos+vel	49.95157	8.916435	21975	94	167	12	10:45:30.848
pos+vel	49.95222	8.914869	21975	96	169	12	10:45:31.895

4.4.2 TCAS 2000-Based Measurements

Measurements were made using a TCAS 2000 system installed on N40, the FAA Boeing B727. The recorded data was analyzed in a similar manner to the data from the LDPU. For each of the tracks recorded by TCAS, the following track properties were computed:

1) Ground track as a function of time (to illustrate any large gaps in position reporting),

2) Update interval as a function of range,

3) Per message update probability as a function of range (from which MASPS-compliance may be estimated).

4.4.2.1 TCAS Air-Air Performance for 24 May

The description of the flight pattern and the aircraft involved are described in the first paragraph of 4.4.1.1 .(LDPU Air-Air Performance for 24 May) Basically, N40 was in a holding pattern over Frankfurt Main Airport.

4.4.2.1.1 Probability vs. Range and Power

The per message reception probability was calculated for each of the tracks recorded by TCAS on 24, May. The probability as a function of range (calculated over a 24-second window) is shown in Figure 4.4.2-1 for all aircraft. The analysis of the TCAS data used the entire track; it did differentiate between inbound and outbound legs of the flight pattern. The BA target of opportunity, BA-400652h, actually approaches from the west, overflies N40, lands to the east, and returns along a very similar track. Extended Squitters from BA-400652h are received on N40 with greater than 25% probability for ranges out to 65 nautical miles.

The TCAS Figure 4.4.2-1 corresponds to LDPU figures: 4.4.1-2e (N40- NLR), 4.4.1-3e (N40-FII) and 4.4.1-4d (N40- BA-400652h)

Figure 4.4.2-2 shows the probability of reception as a function of the power the Extended Squitter was received.

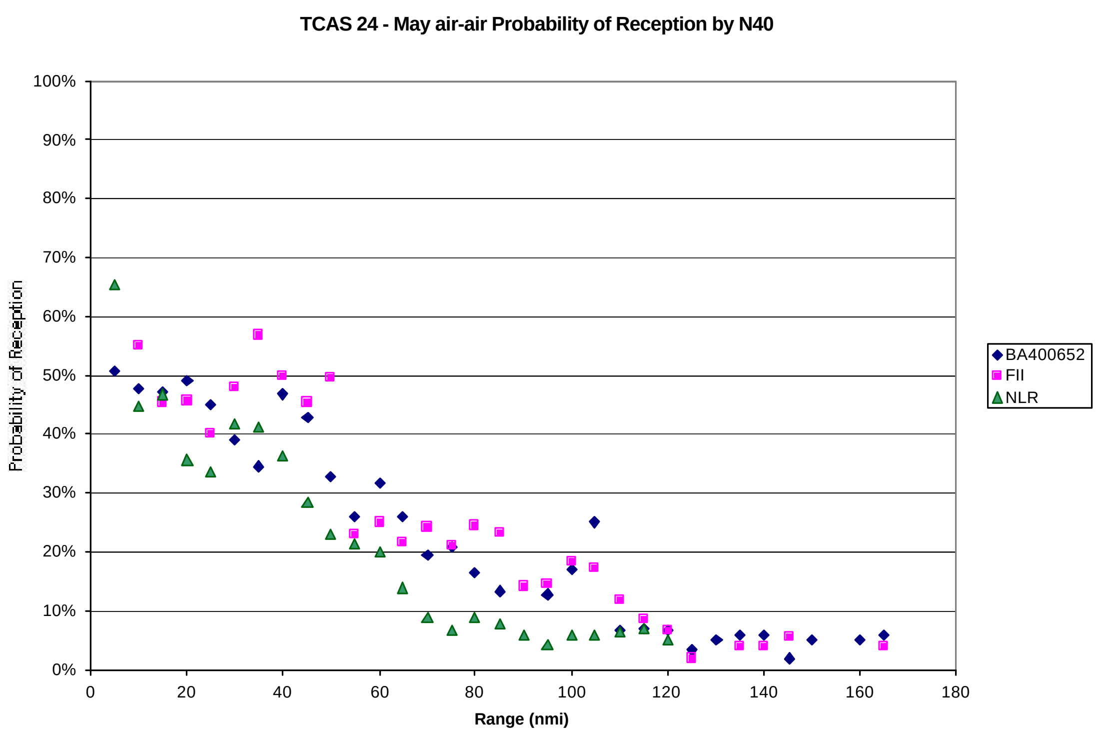


Figure 4.4.2-1. TCAS Ext. Sq. Reception Probability vs. Range, 24 May

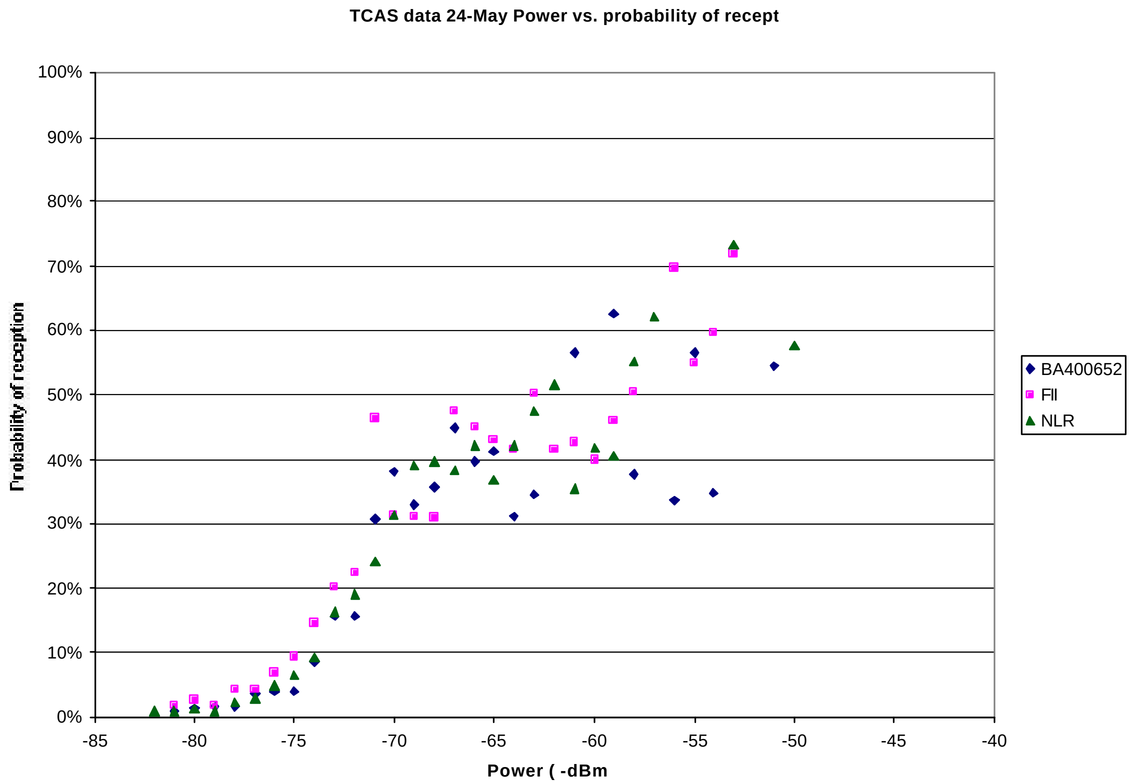
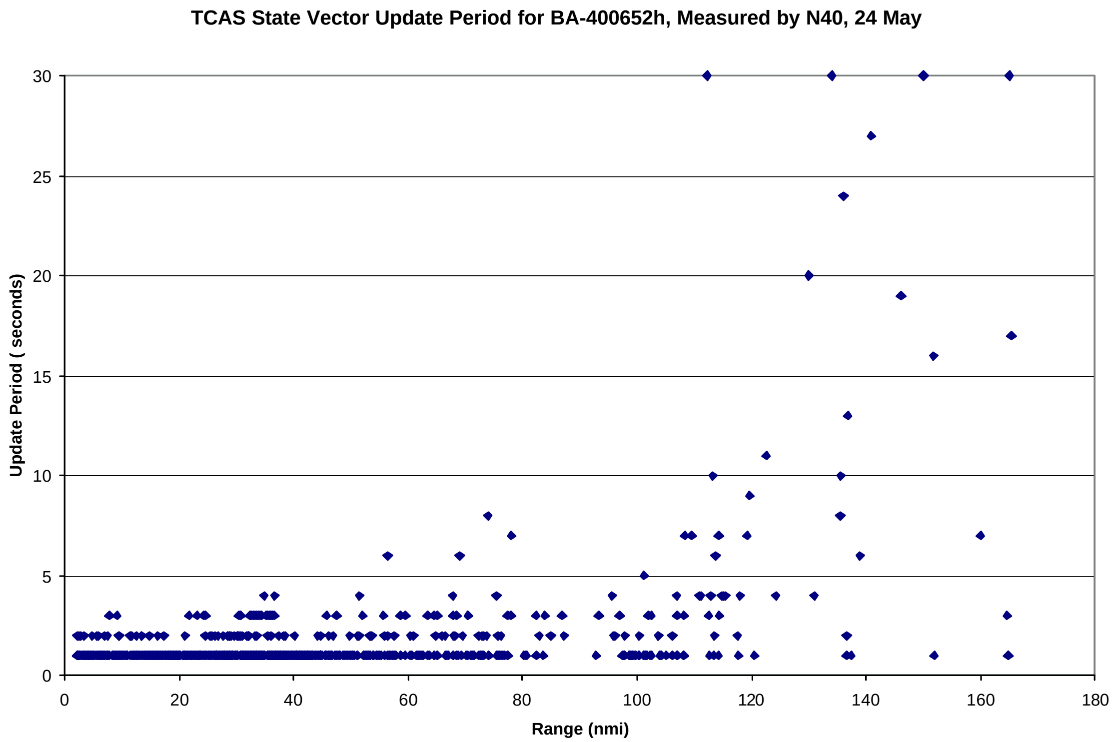


Figure 4.4.2-2. TCAS Ext. Sq. Reception Probability vs. Power, 24 May

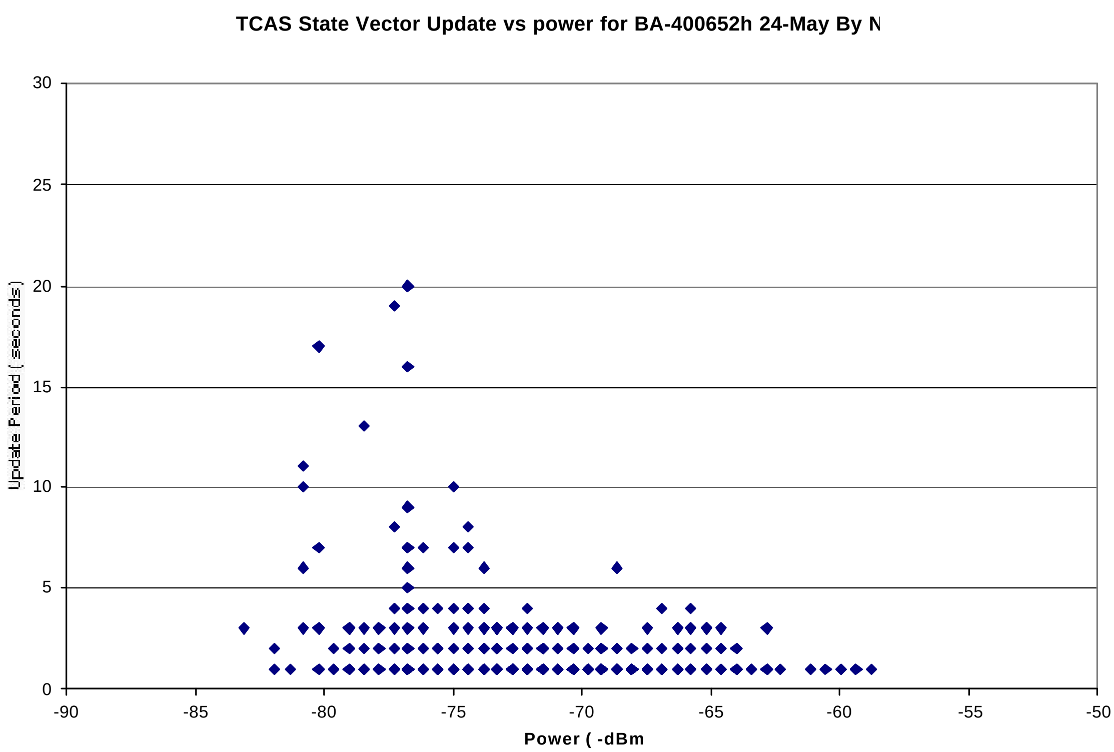
4.4.2.1.2 Update int. vs. Range and Power

Update intervals were calculated as the number of seconds between the reception of messages that would constitute a state vector update. This was assumed to be either a position or velocity squitter, or both. For receptions on N40 of the FII aircraft, in Figure 4.4.2-5 these update intervals are obtained solely on the basis of position messages for the FII aircraft, because that platform was not configured to transmit velocity squitters. Thus, the update intervals are the result of transmitting approximately one half the normal number of Extended Squitters. The target of opportunity, BA-400652h in Figure 4.4.2-3 shows update intervals recorded that are the result of transmissions of both velocity and position Extended Squitters.

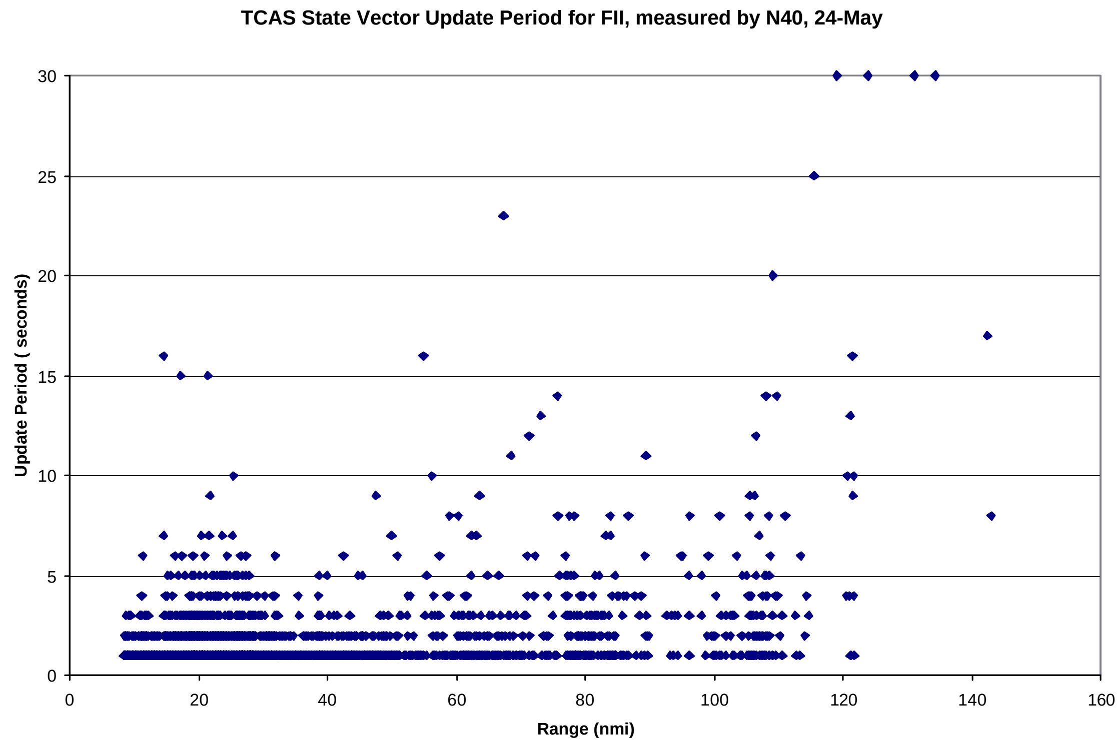
Figures 4.4.2-4, 4.4.2-6 and 4.4.2-8 show the update interval as a function of the power the Extended Squitter was received.



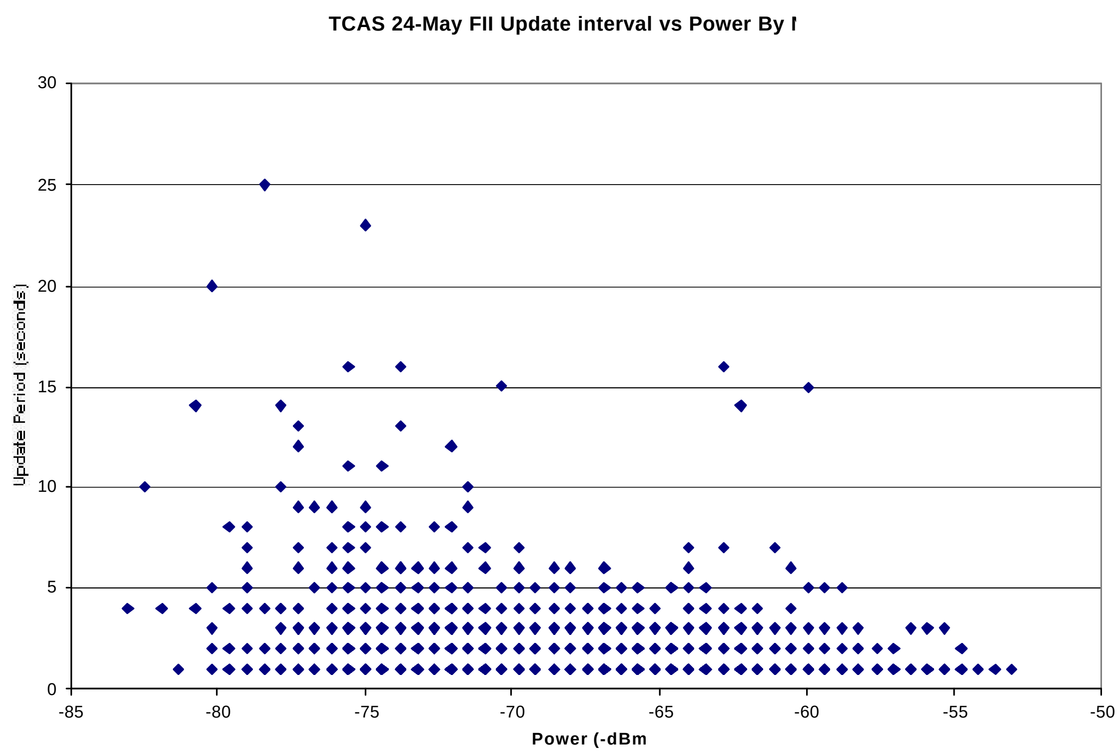
Figures 4.4.2-3. TCAS: BA-400652 $_h$ Ext. Sq. Update Interval vs. Range, 24 May



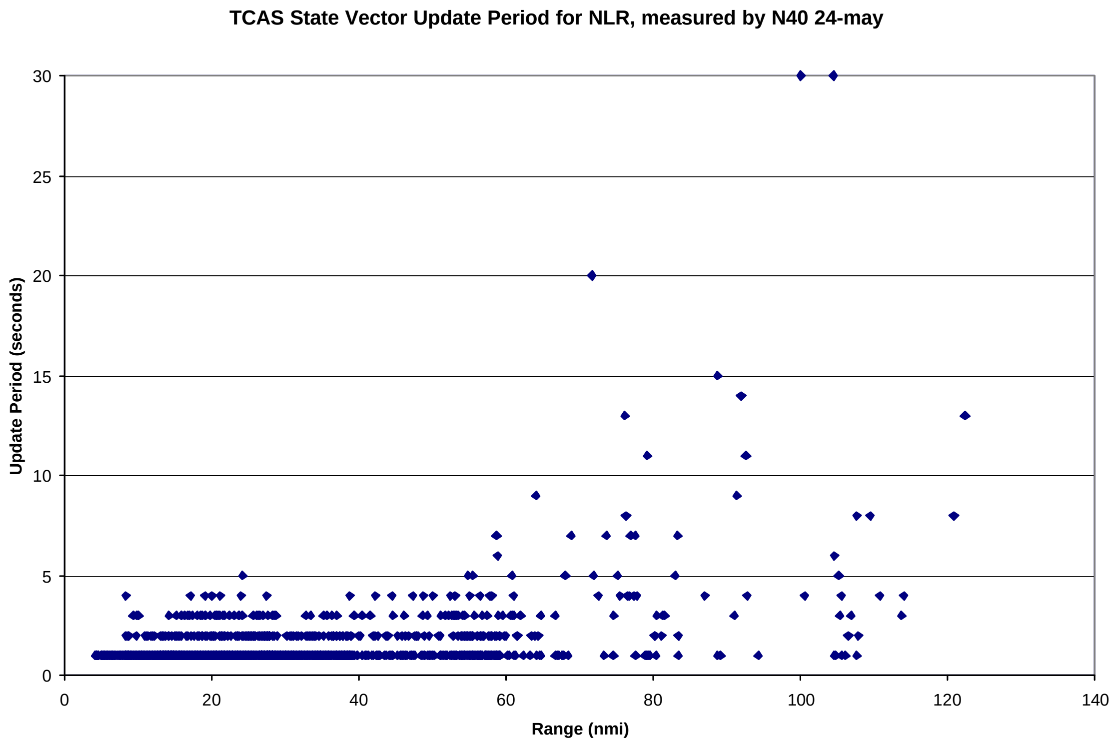
Figures 4.4.2.-4. TCAS: BA-400652 $_h$ Ext. Sq. Update Interval vs. power, 24 May



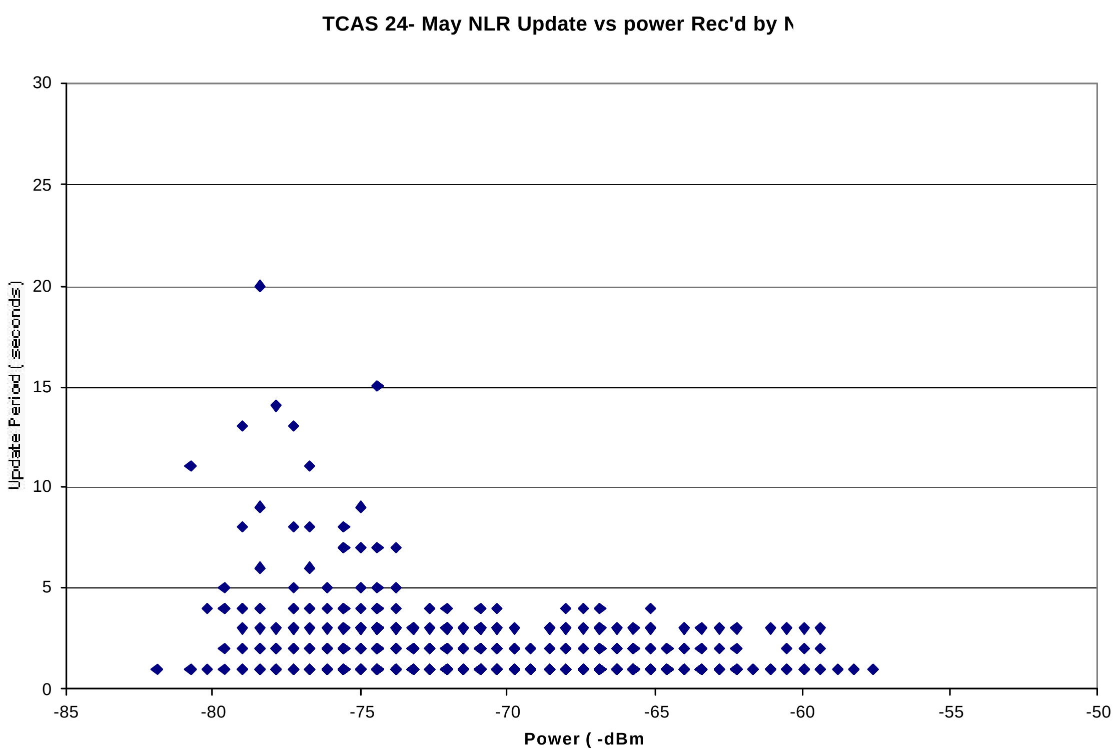
Figures 4.4.2.-5. TCAS: FII Ext. Sq. Update Interval vs. Range, 24 May



Figures 4.4.2.-6. TCAS: FII Ext. Sq. Update Interval vs. Power, 24 May



Figures 4.4.2.-7. TCAS: NLR Ext. Sq. Update Interval vs. Range, 24 May



Figures 4.4.2.-8. TCAS: NLR Ext. Sq. Update Interval vs. power, 24 May

4.4.2.1.3 Track Plots

The Extended Squitter tracks that were received by TCAS are shown in Figure 4.4.2-9. Figure 4.4.2-10 is the track plots of all aircraft, which shows the ranges that were received. Ranges up to 80 nautical miles were received consistently. The BA aircraft track is shown in figure 4.4.2-11a.

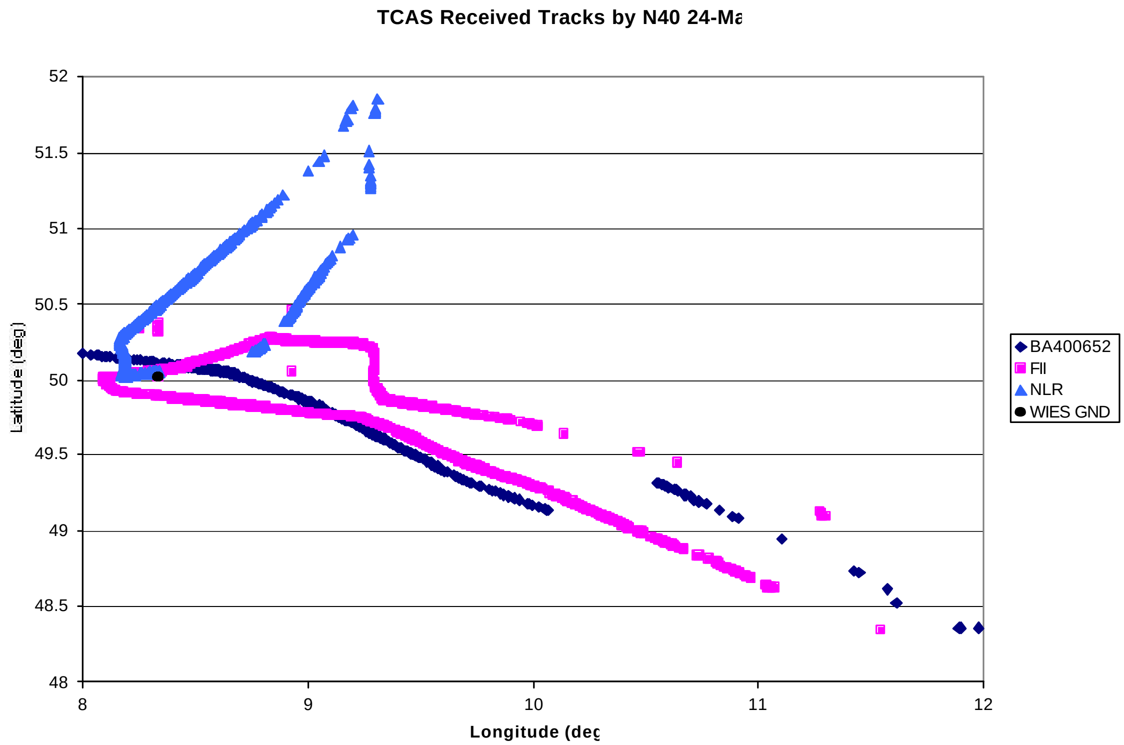


Figure 4.4.2-9. TCAS Ext. Sq. Tracks Latitude vs. Longitude, 24 May

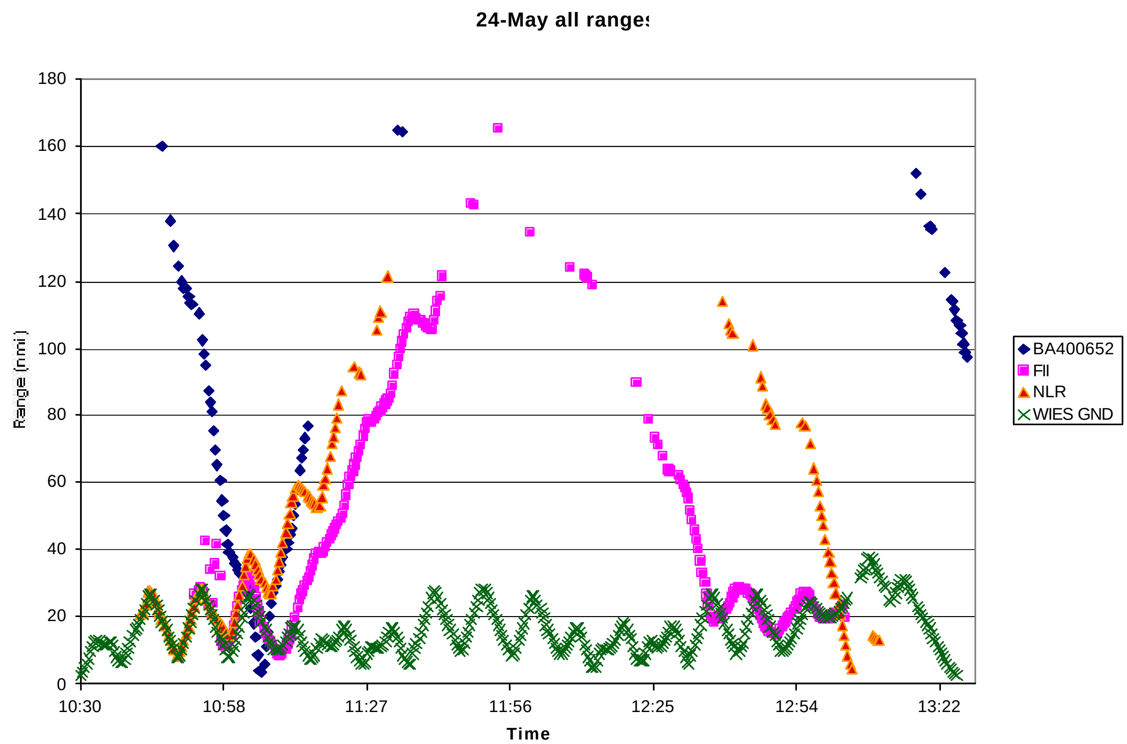


Figure 4.4.2-10. TCAS Ext. Sq. Tracks Range vs. Time, 24 May

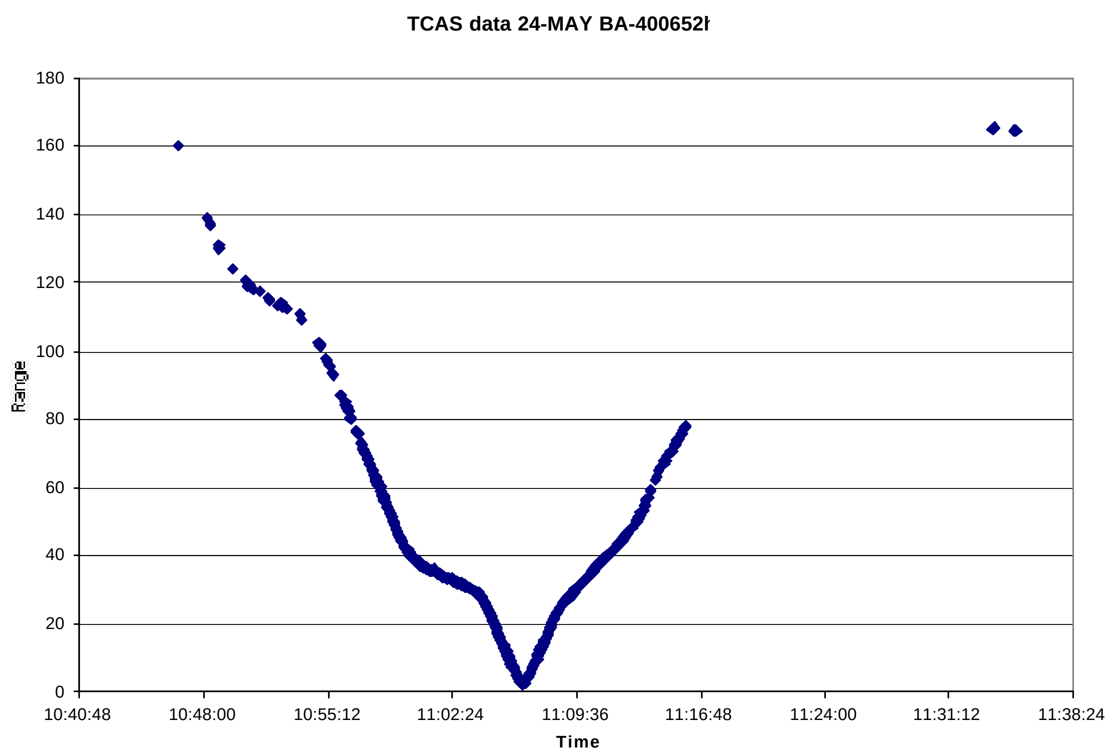


Figure 4.4.2-11a. TCAS: BA-400652 $_h$ Ext. Sq. Track Range vs. Time, 24 May

4.4.2.1.4 Received Power vs. Range

The TCAS was capable of recording the power level at which the Extended Squitter was received. Figure 4.4.2-11b shows the received powers of all Extended Squitters as a function of range received on 24 May.

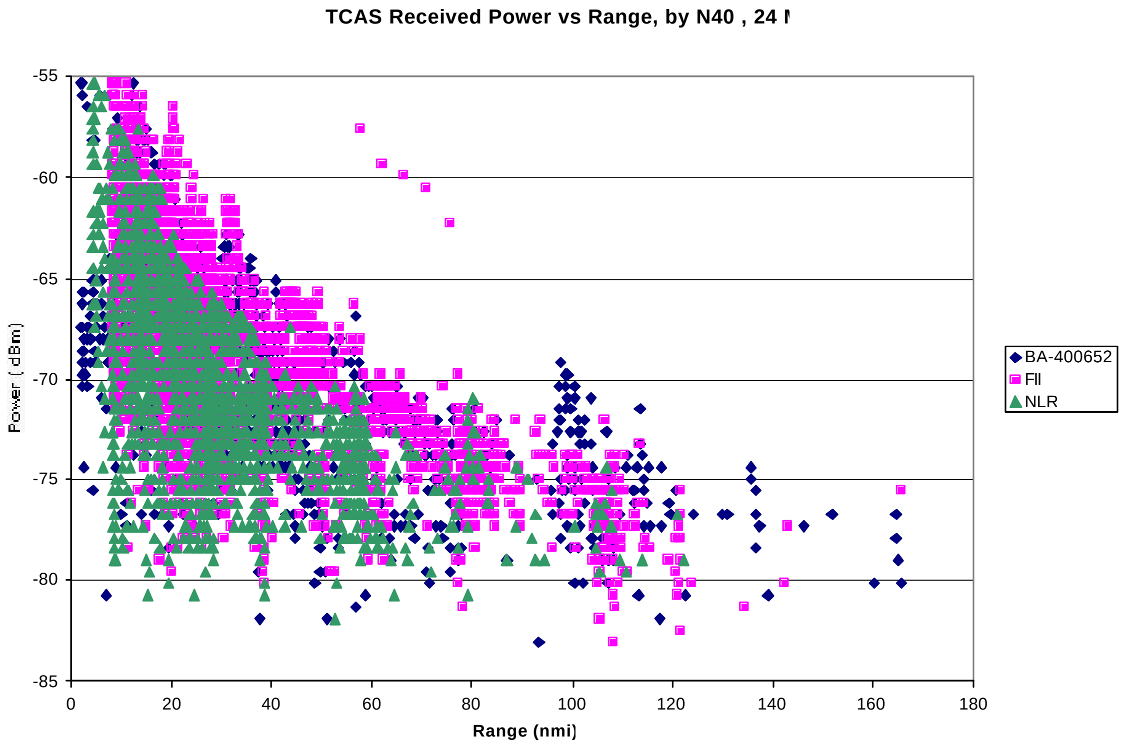


Figure 4.4.2-11b. Received Power vs. Range for All Ext. Squitters, 24 May

4.4.2.2 TCAS Air-Air Performance for All Days

While the focus of the detailed analysis has been on the data collected on 24 May, significant data was collected on the four other days in which data collection flights were conducted. The following paragraphs present a summary of the results from these other days.

4.4.2.2.1 Results for 19 May

This day provided data from two British Airways aircraft. The flight plans for the day were FRA profile “A", an orbit, and a holding pattern, profile,”2”. The only air-air receptions were from the British Airways aircraft; BA-400665h and BA-400652h.

TCAS received only a handful of Extended Squitters from BA-400652h. There are 3 points on Figure 4.4.2-12 for this aircraft . BA-400665h was received with around 40 % probability at less than 40 nautical miles. Figure 4.4.2-13 shows the power at which 40 % of the messages were received was between -70 and -60 dBm. The track plot of BA-400665h is shown in Figure 4.4.2-14. There is a solid track from about 120 miles. The update interval is less than 5 seconds when the range is less than 70 nautical miles. (Figure 4.4.2-15). The update period as a function of power is shown in Figure 4.4.2-16a.

Figure 4.4.2-16b shows the received powers of all Extended Squitters as a function of range received on 19 May.

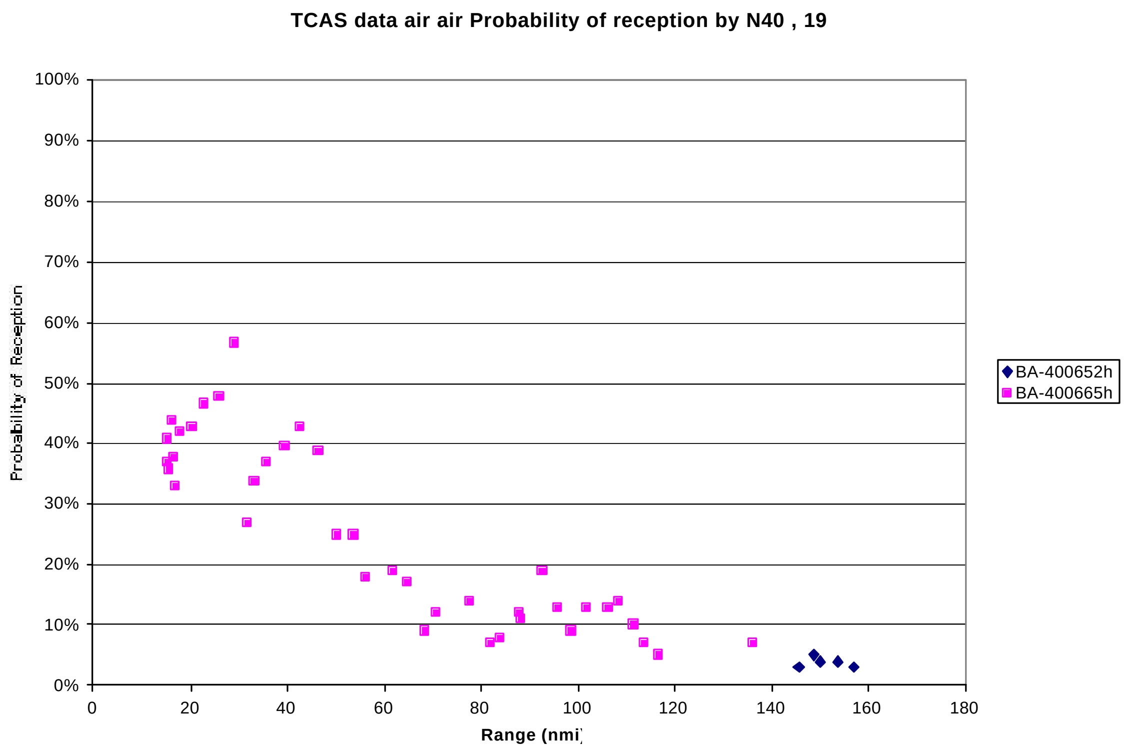


Figure 4.4.2-12. TCAS Ext. Sq. Reception Probability vs. Range, 19 May

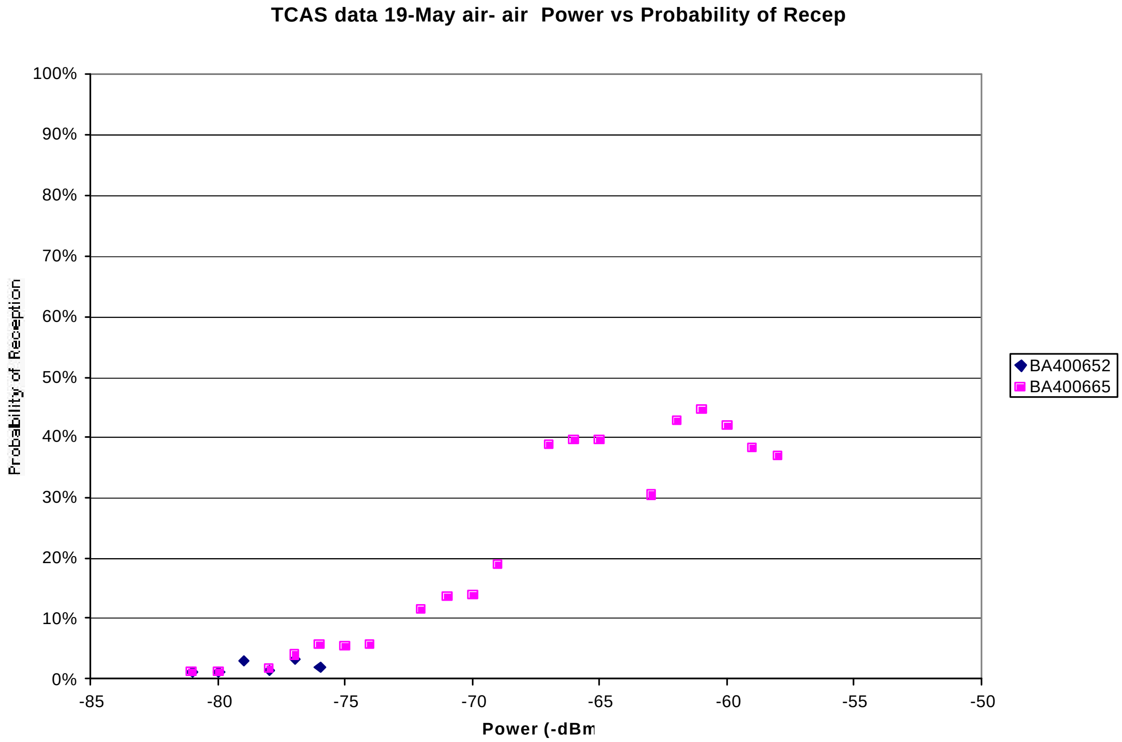


Figure 4.4.2-13. TCAS Ext. Sq. Reception Probability vs. Power, 19 May

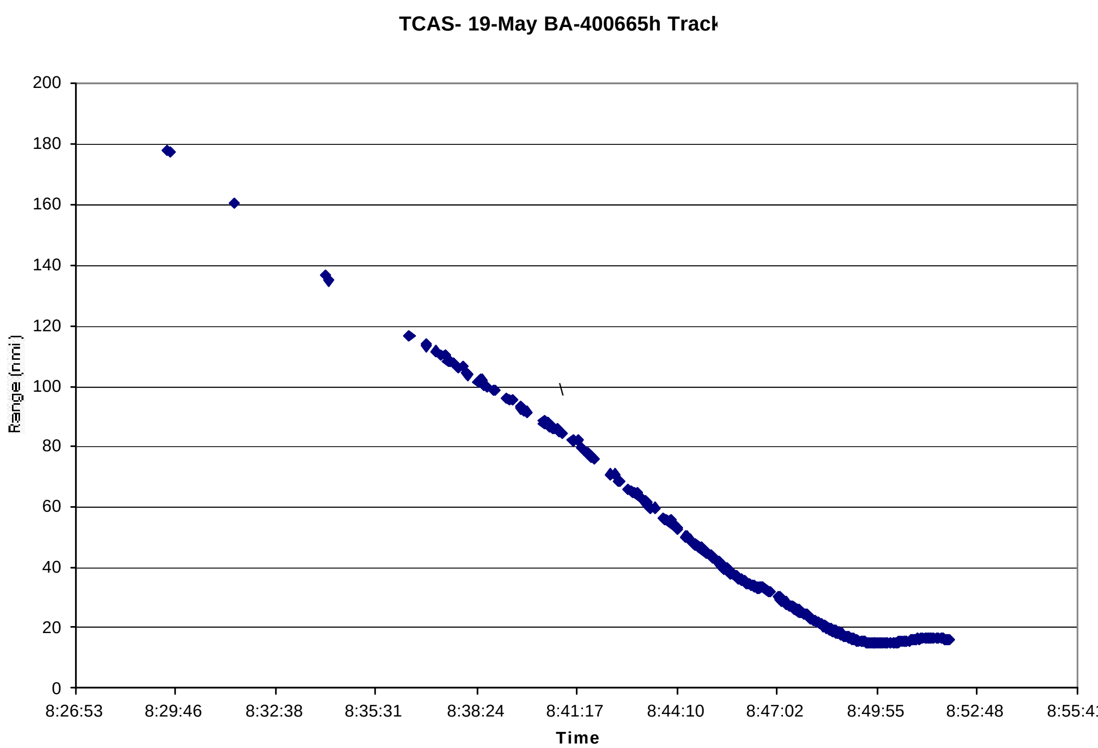


Figure 4.4.2-14. TCAS: BA-400665 $_h$ Ext. Sq. Track Range vs. Time, 19 May

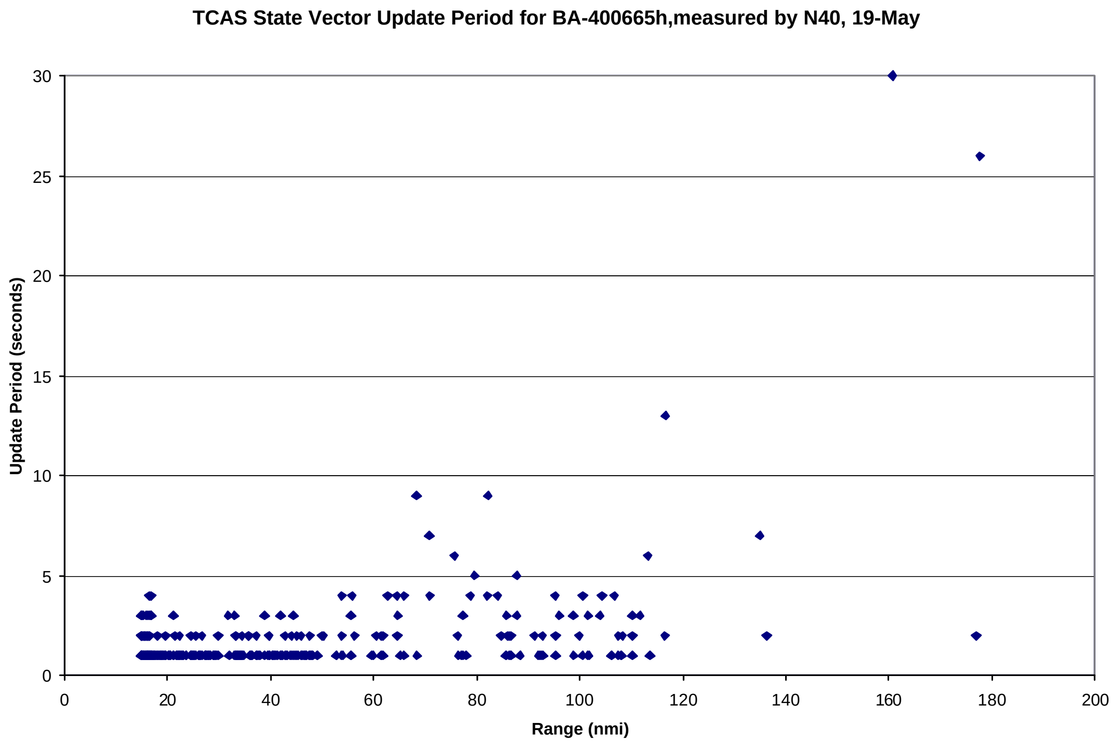


Figure 4.4.2-15. TCAS: BA-400665 $_h$ Ext. Sq. Update Interval vs. Range, 19 May

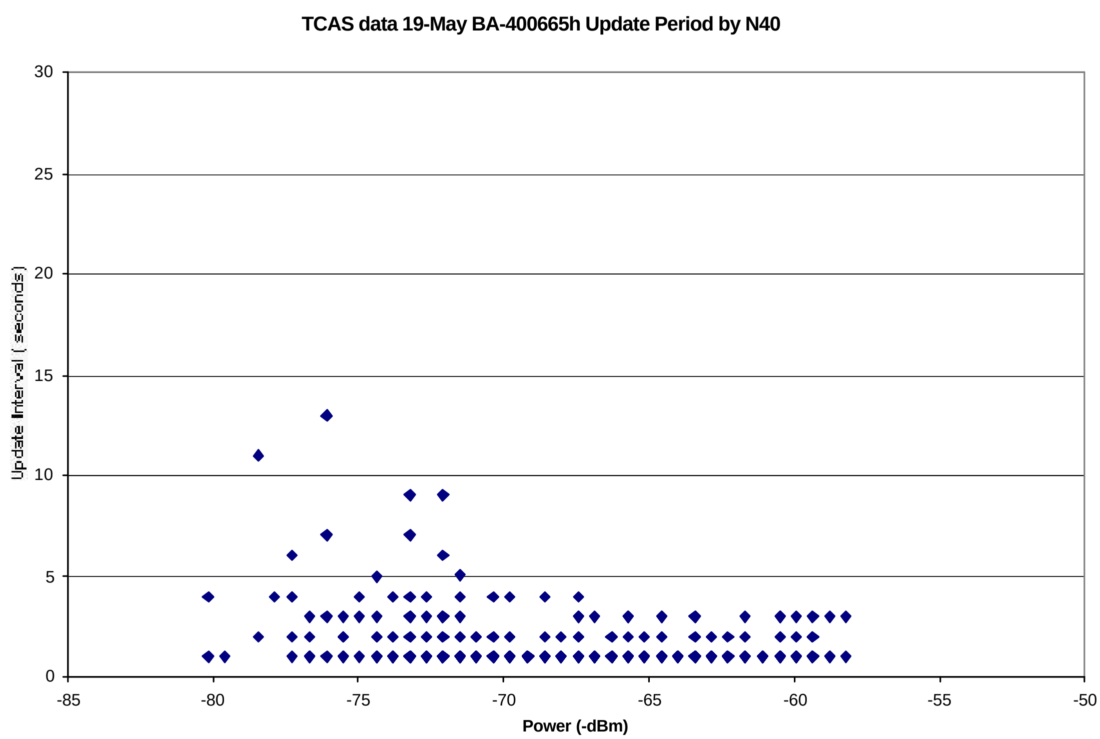


Figure 4.4.2-16a. TCAS: BA-400665 $_h$ Ext. Sq. Update Interval vs. Power, 19 May

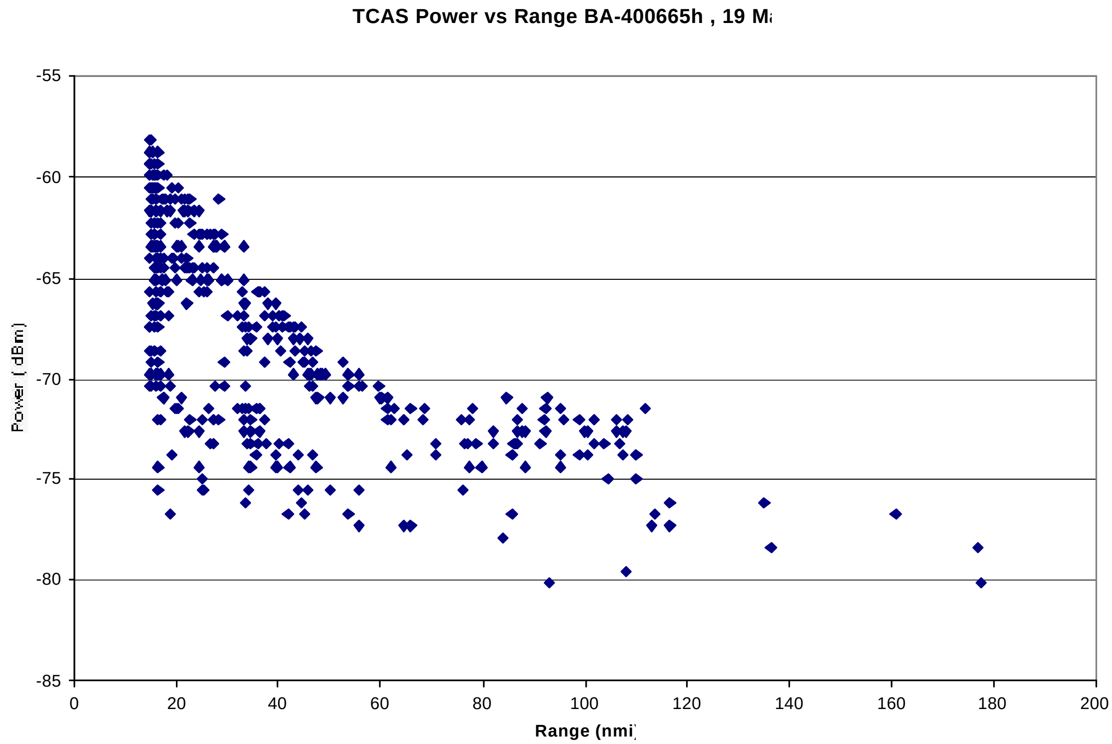


Figure 4.4.2-16b. Received Power vs. Range for All Ext. Squitters, 19 May

4.4.2.2.2 Results for 20 May

This flight period was to obtain the weekend fruit rates. The FAA N40 was in a holding pattern over Frankfurt Main. There were two planned participants; the FII and the NLR aircraft. This day provided data from two British Airways aircraft: BA-400664h and BA-400652h.

It should be noted that the FII aircraft did not provide latitude or longitude information on this day. The data from this aircraft are not included in any analysis that is range dependent.

Figure 4.4.2-17 shows that the British Airways targets of opportunity are received with a greater probability for range than the NLR aircraft. All airborne aircraft had probability of 30 % receptions when range was less than 40 nautical miles. The probability of reception as a function of power is shown in figure 4.4.2-18. The update intervals for the two BA aircraft are found in figures 4.4.2-19 - 4.4.2-22. For ranges between 50 and 100 nautical miles the update intervals are typically one second.

The track plots of the 2 BA aircraft and the NLR are in figures 4.4.2-23 - 4.4.2-25a . When the NLR aircraft was more than 100 nautical miles from N40, the track is missing, while the 2 BA aircraft have solid tracks out to that range.

Figure 4.4.2-25b shows the received powers of all Extended Squitters as a function of range received on 20 May.

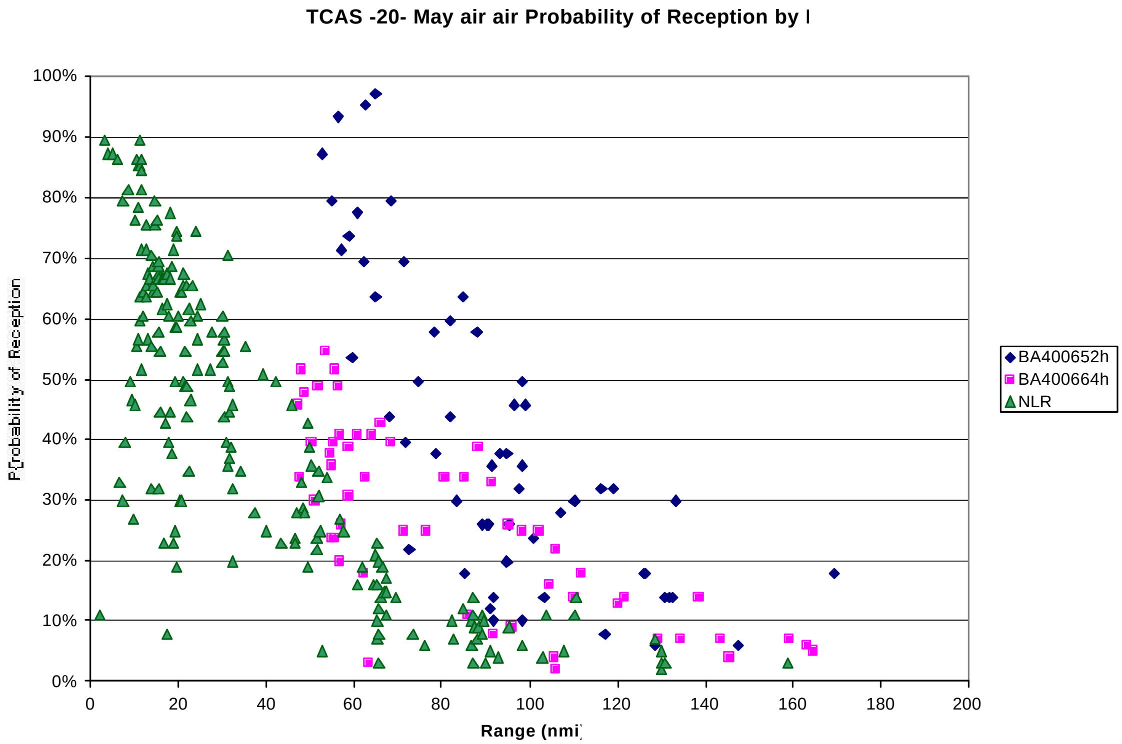


Figure 4.4.2-17. TCAS Ext. Sq. Reception Probability vs. Range, 20 May

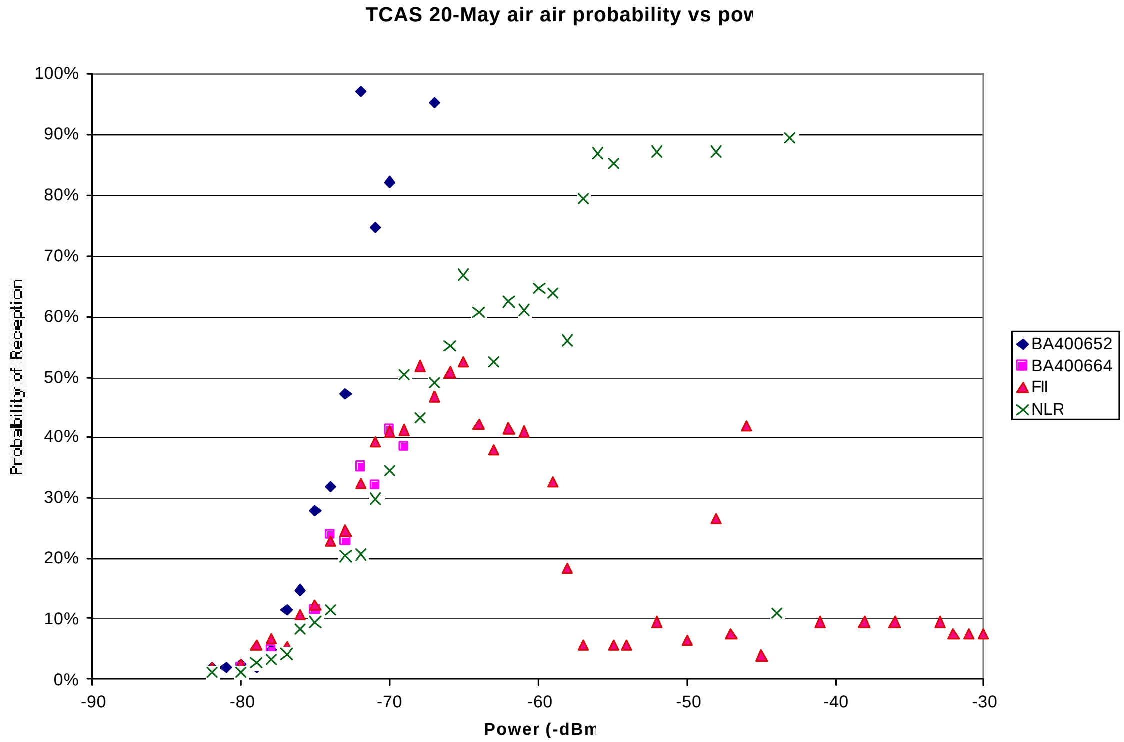


Figure 4.4.2-18. TCAS Ext. Sq. Reception Probability vs. Power, 20 May

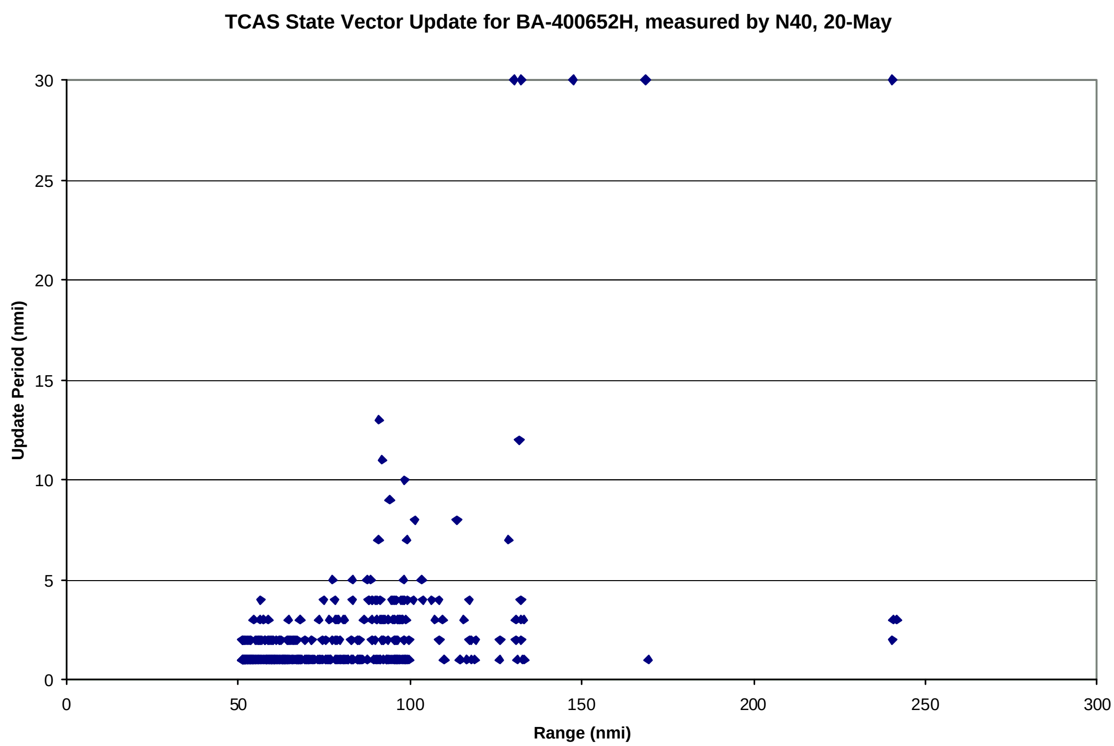


Figure 4.4.2-19. TCAS: BA-400652 $_h$ Ext. Sq. Update Interval vs. Range, 20 May

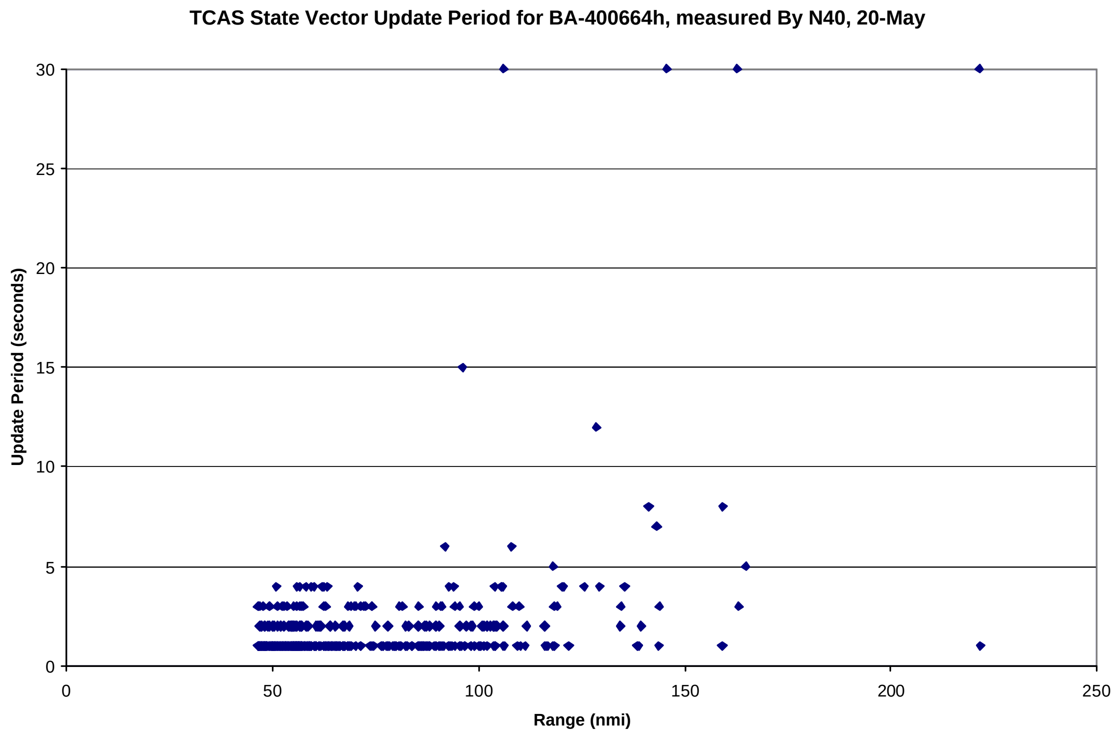


Figure 4.4.2-20. TCAS: BA-400664 $_h$ Ext. Sq. Update Interval vs. Range, 20 May

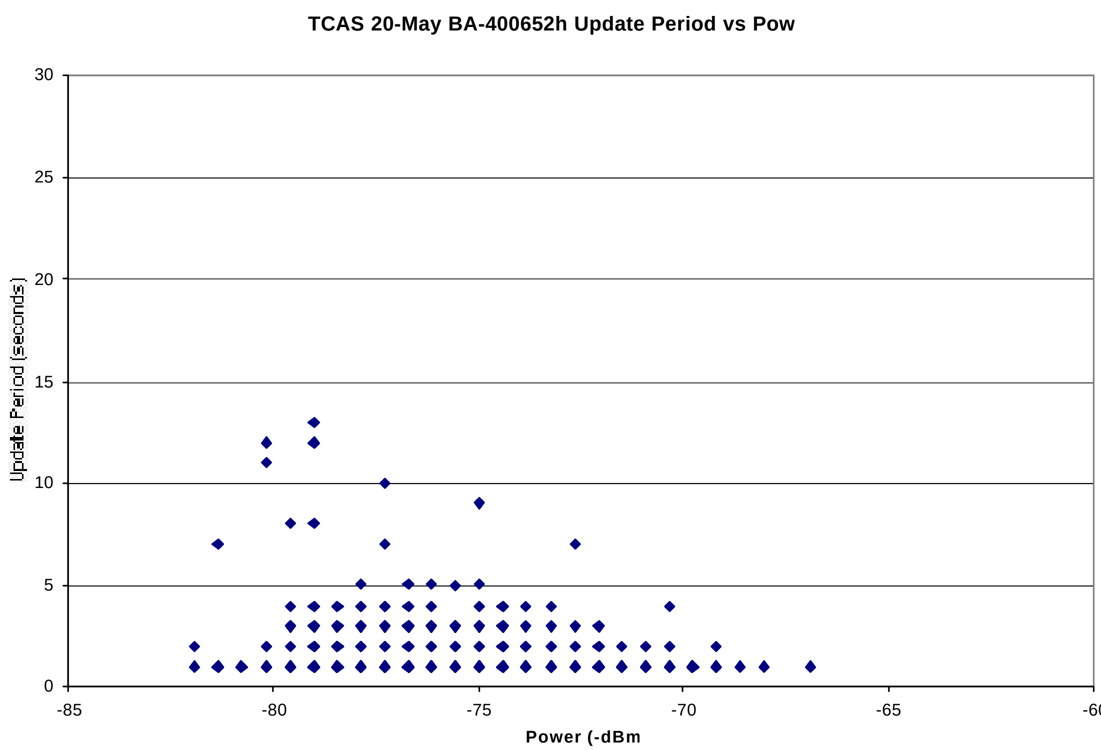


Figure 4.4.2-21. TCAS: BA-400652 $_h$ Ext. Sq. Update Interval vs. Power, 20 May

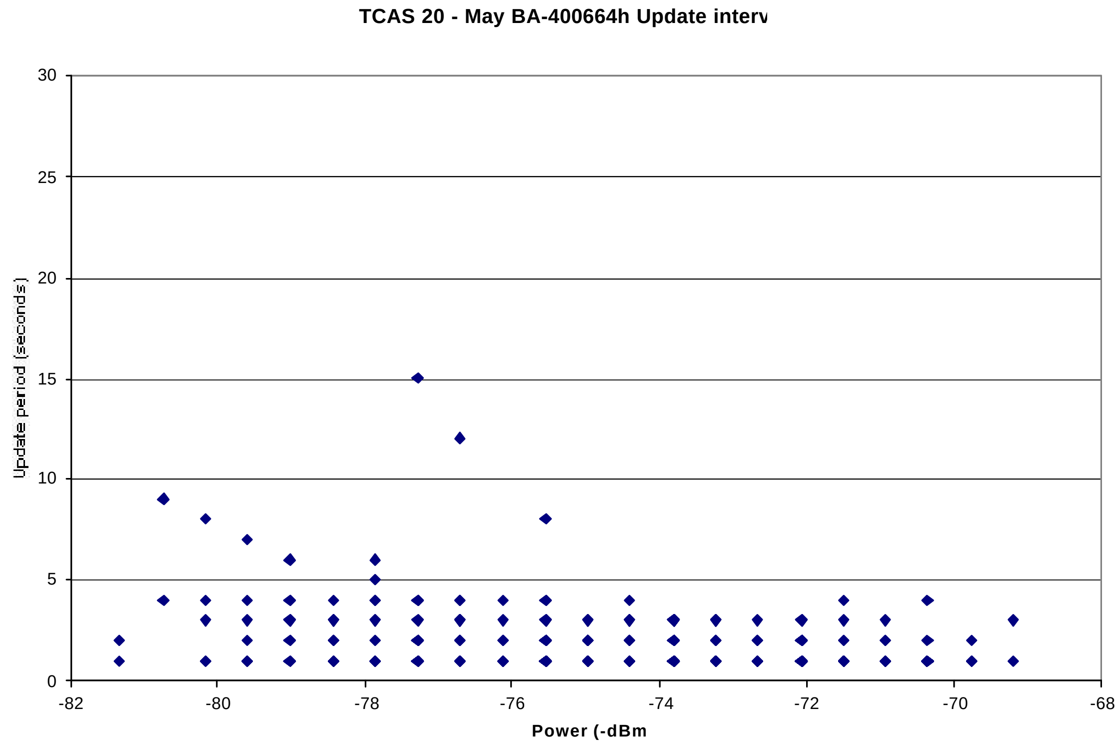


Figure 4.4.2-22. TCAS: BA-400664 $_h$ Ext. Sq. Update Interval vs. Power, 20 May

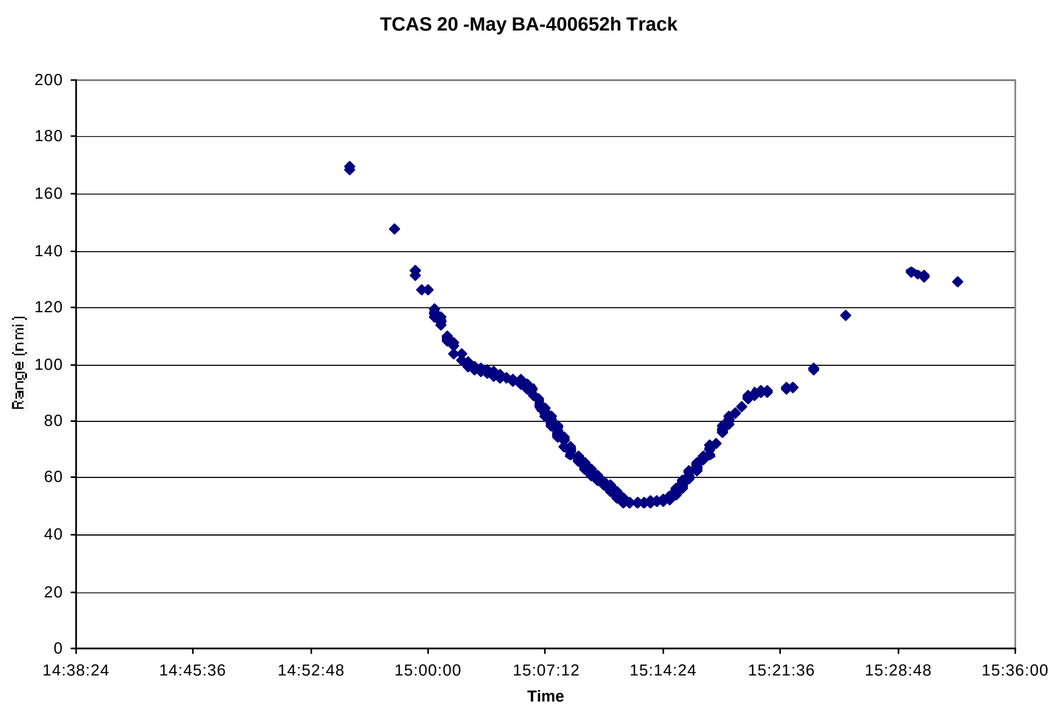


Figure 4.4.2-23. TCAS: BA-400652 $_h$ Ext. Sq. Track Range vs. Time, 20 May

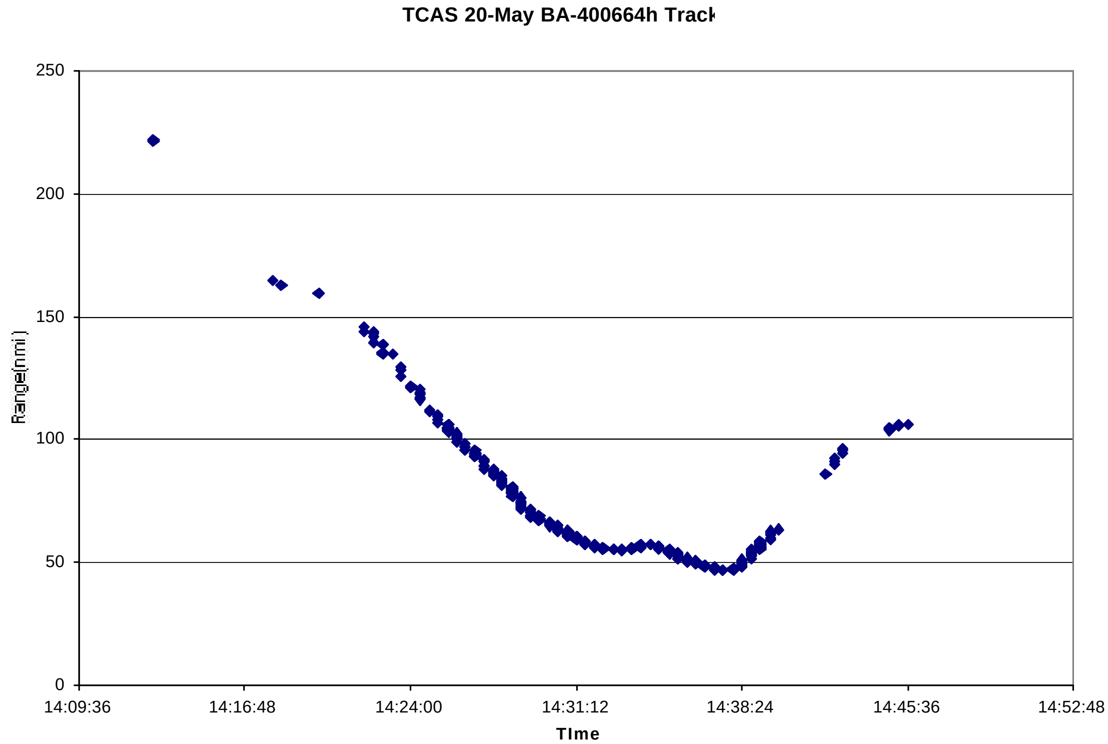


Figure 4.4.2-24. TCAS: BA-400664 $_h$ Ext. Sq. Track Range vs. Time, 20 May

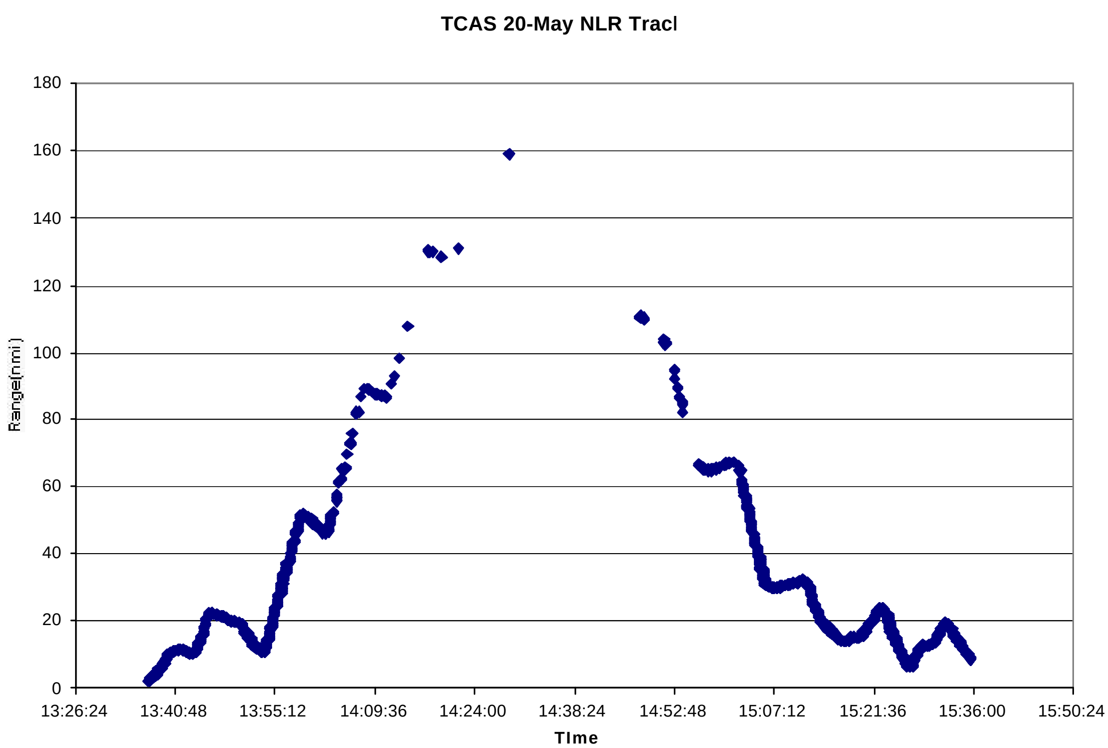


Figure 4.4.2-25a. TCAS: NLR Ext. Sq. Track Range vs. Time, 20 May

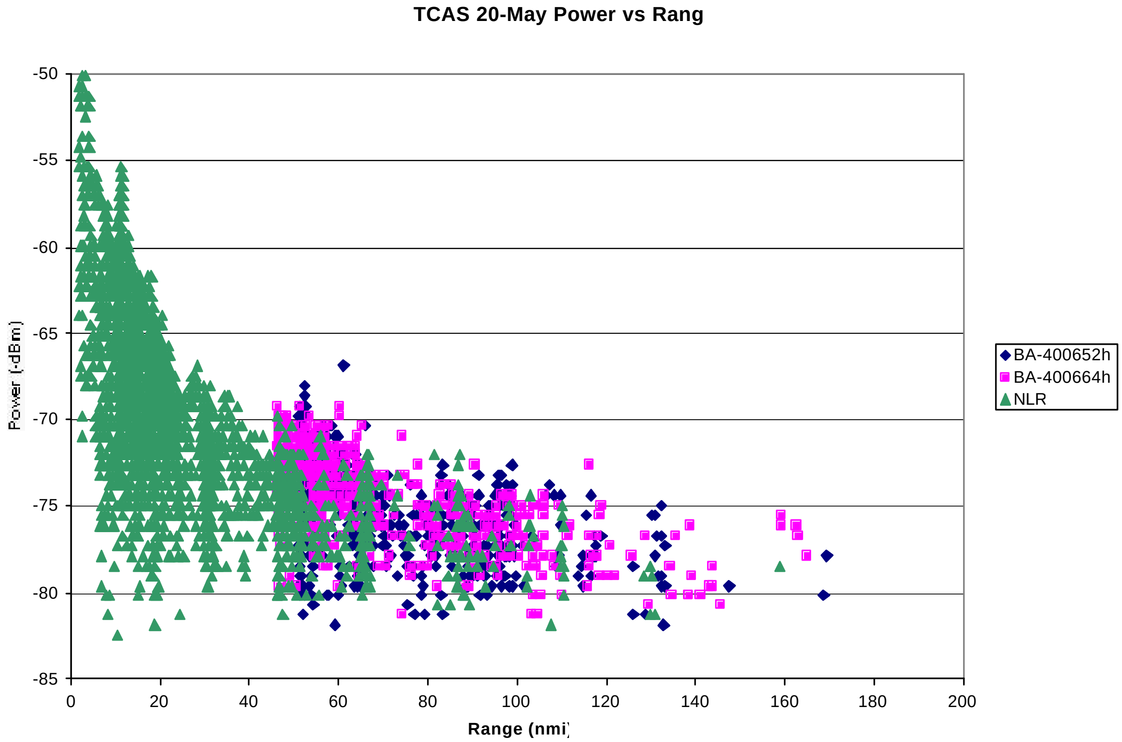


Figure 4.4.2-25b. Received Power vs. Range for All Ext. Squitters, 20 May

4.4.2.2.3 Results for 22 May

As described in 3.4, one other project aircraft participated in the Extended Squitter data collection on 22 May. Also the reception of Extended Squitters from one British Airways target of opportunity has been analyzed. The flight profiles for 22 May had the FII aircraft departing Wiesbaden and entering into a holding pattern near Frankfurt where it was executing frequent maneuvers during each circuit of the "racetrack" pattern (approximately 10 minutes per circuit). The FII aircraft was broadcasting only position and flight ID Extended Squitters (i.e., no velocity squitters) for an average Extended Squitter transmission rate of 2.2 squitters per second.

Figure 4.4.2-26 show the two aircraft and the probabilities of reception as a function of range. It can be seen that at ranges up to 50 nautical miles, a greater than 40 % reception can be expected. The curves for both the BA and FII aircraft are similar. The figure 4.4.2-27 shows the probability of reception as a function of power. Once again the both aircraft have similar curves.

The state vector update period charts for the BA-400664h are figures 4.4.2-28 and 29. The update period there was no gap greater than the 24-second coast that is allowed by the MASPS for a 120-mile range.

The track plots of the BA-400664h and FII aircraft are shown in Figures 4.4.2-30 and 31a. The FII aircraft is tracked consistently for a range up to 100 miles and then contains gaps until the plane is once again within 100 miles. The BA-400664h track is also with gaps within the 100 miles.

Figure 4.4.2-31b shows the received powers of all Extended Squitters as a function of range received on 22 May.

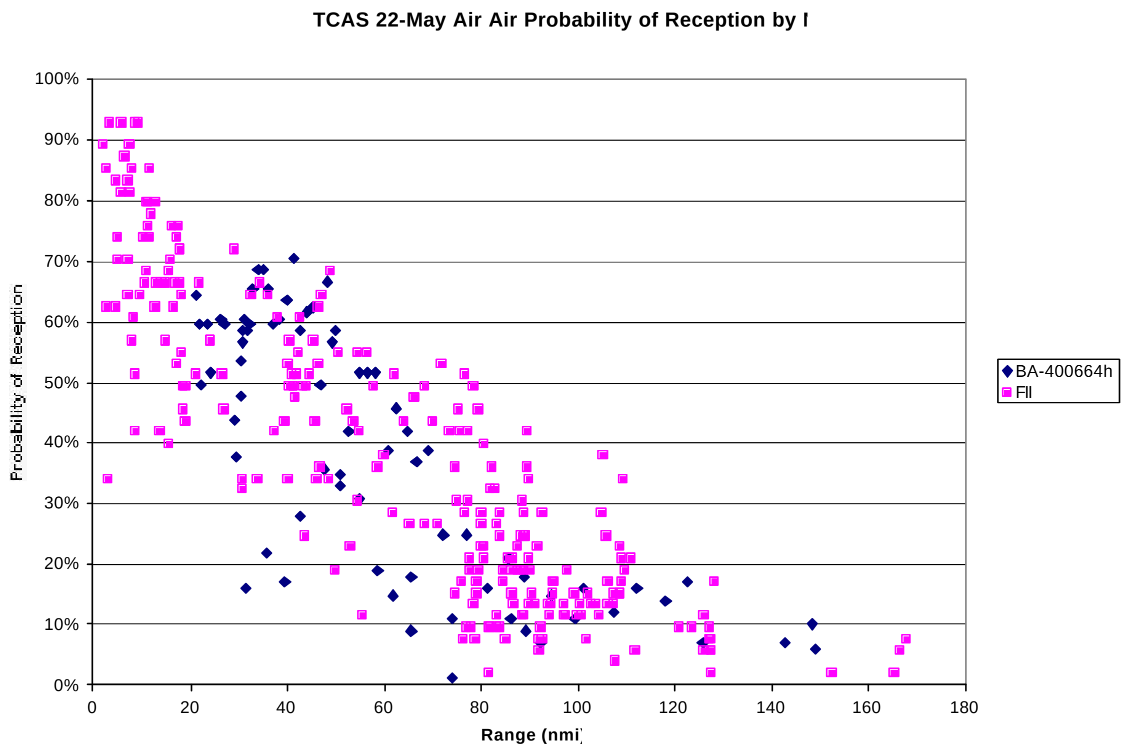


Figure 4.4.2-26. TCAS Ext. Sq. Reception Probability vs. Range, 22 May

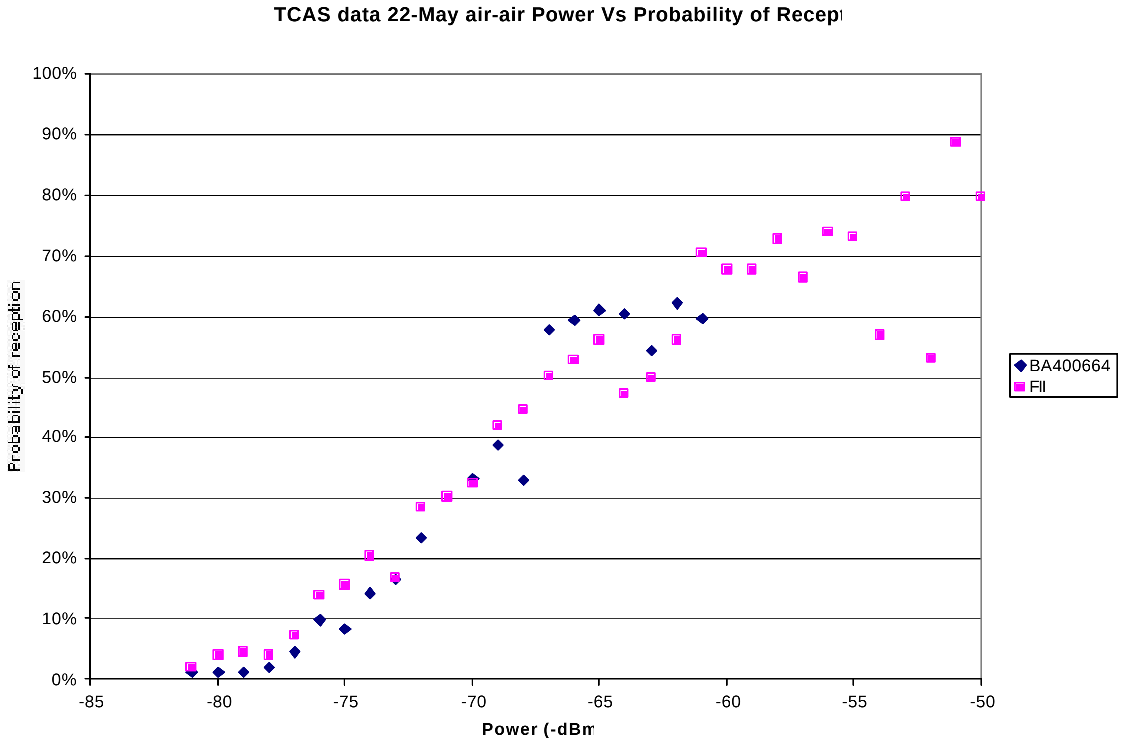


Figure 4.4.2-27. TCAS Ext. Sq. Reception Probability vs. Power, 22 May

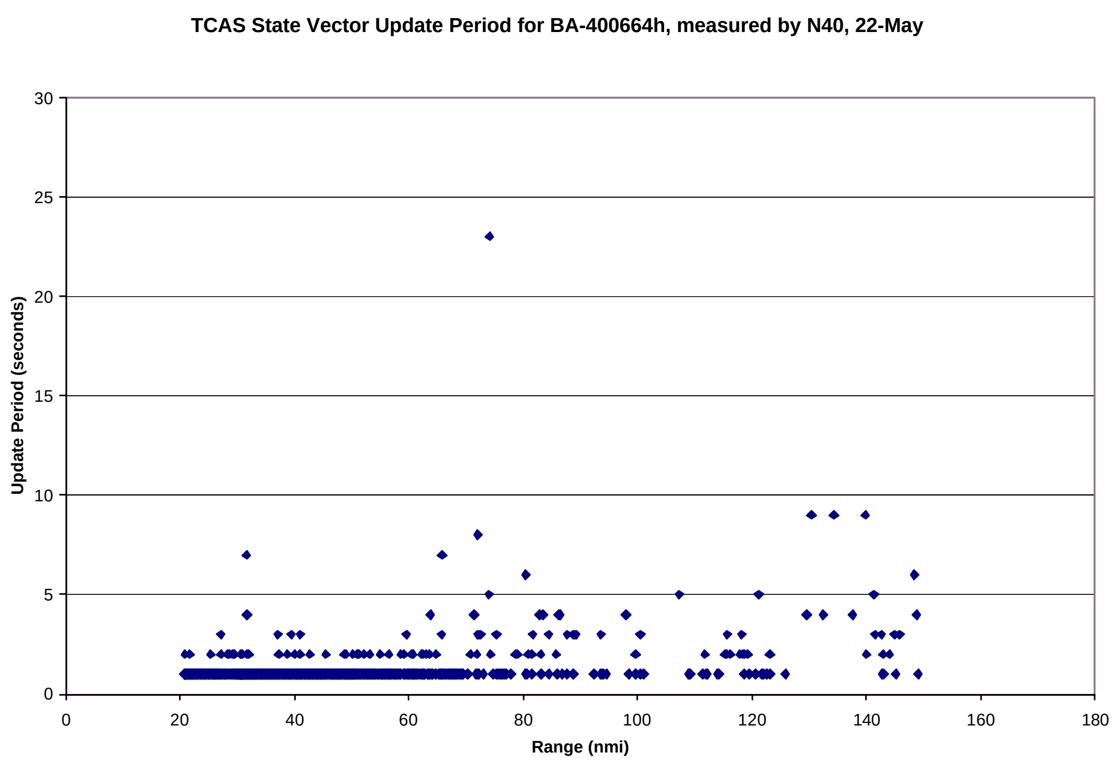


Figure 4.4.2-28. TCAS: BA-400664 $_h$ Ext. Sq. Update Interval vs. Range, 22 May

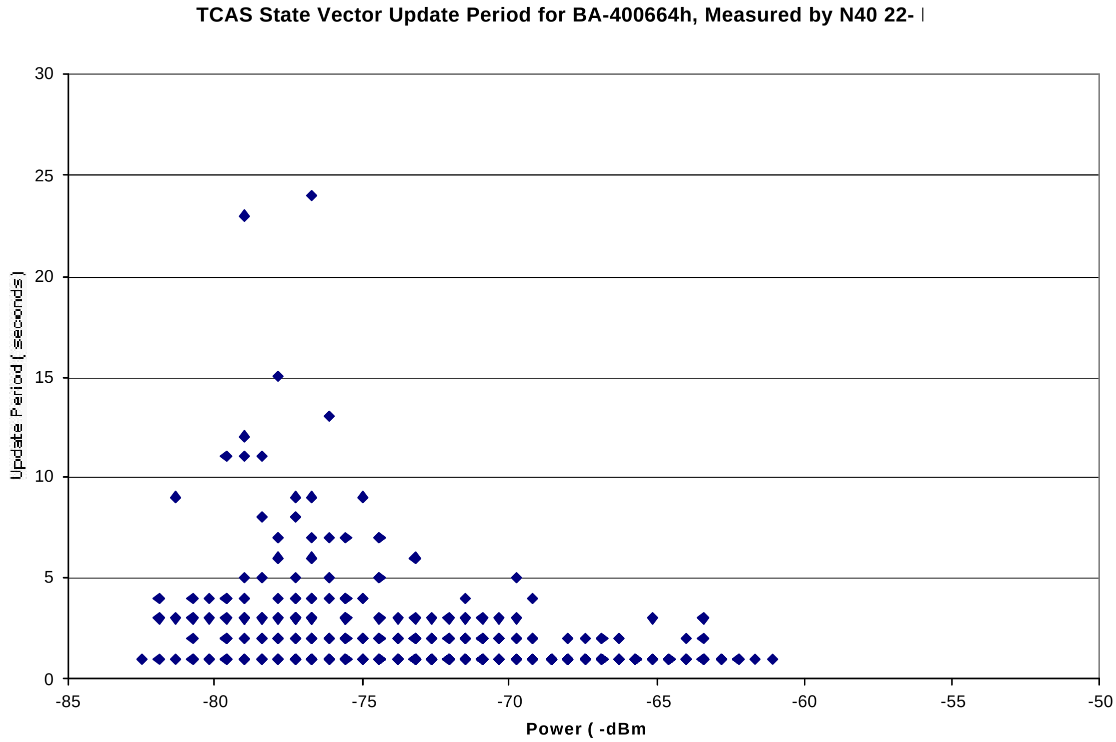


Figure 4.4.2-29. TCAS: BA-400664 $_h$ Ext. Sq. Update Interval vs. Power, 22 May

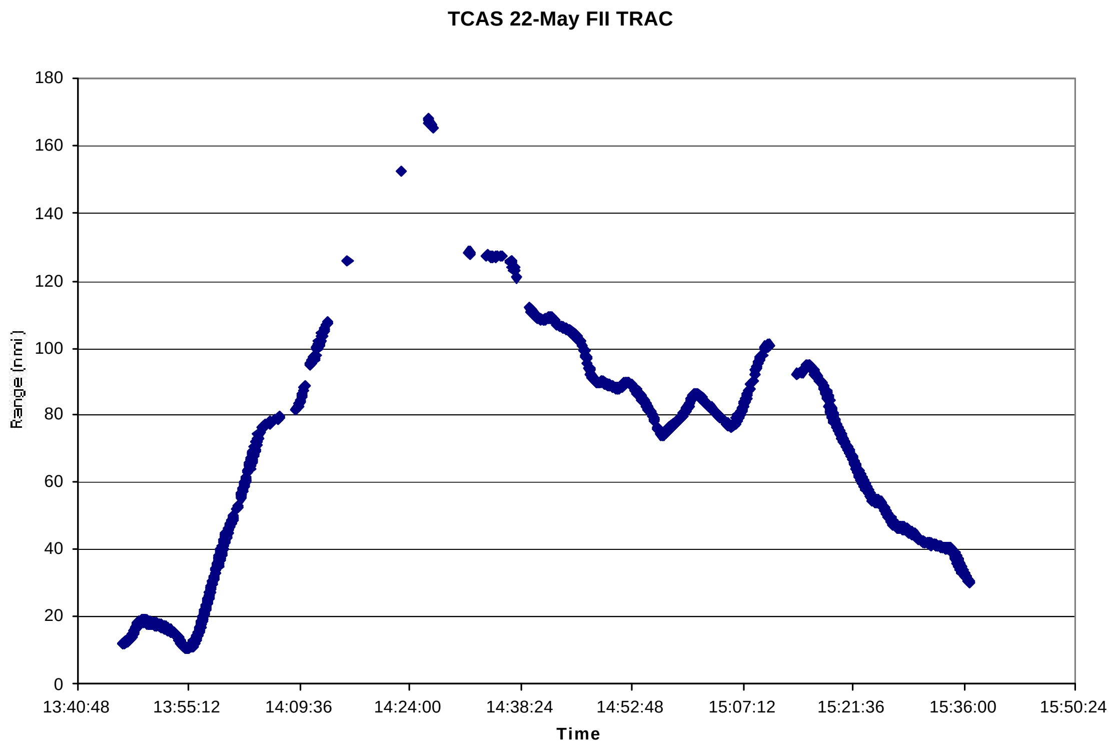


Figure 4.4.2-30. TCAS: FII Ext. Sq. Track Range vs. Time, 22 May

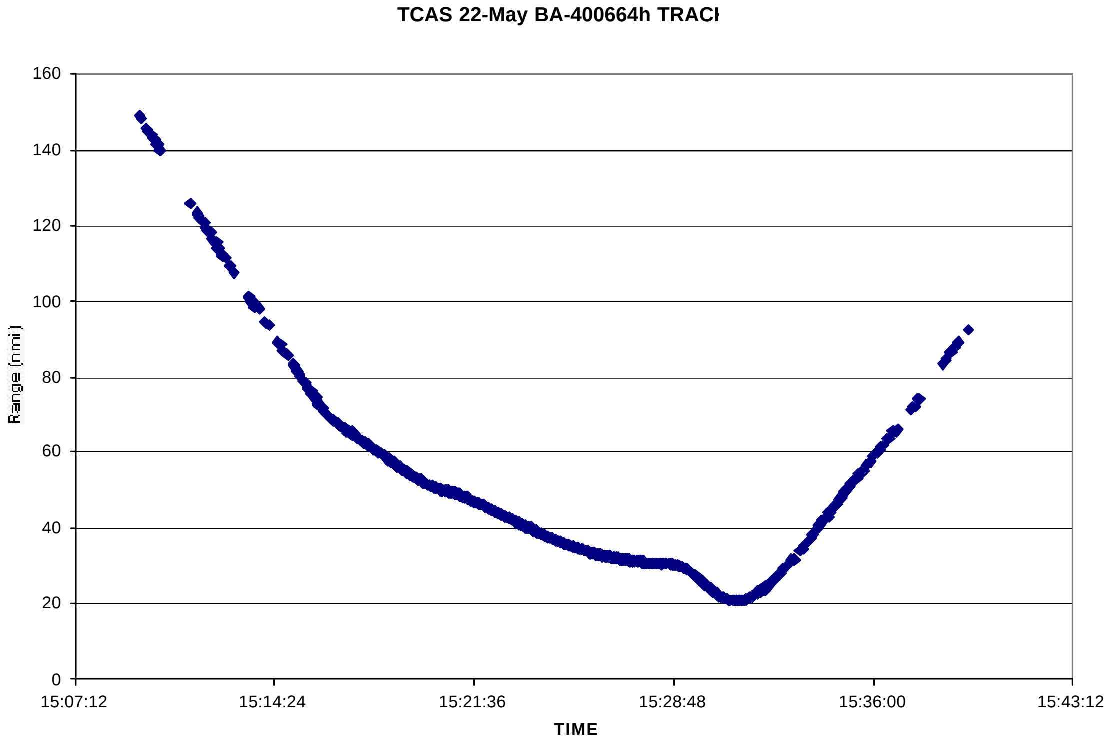


Figure 4.4.2-31a. TCAS: BA-400664 $_h$ Ext. Sq. Track Range vs. Time, 22 May

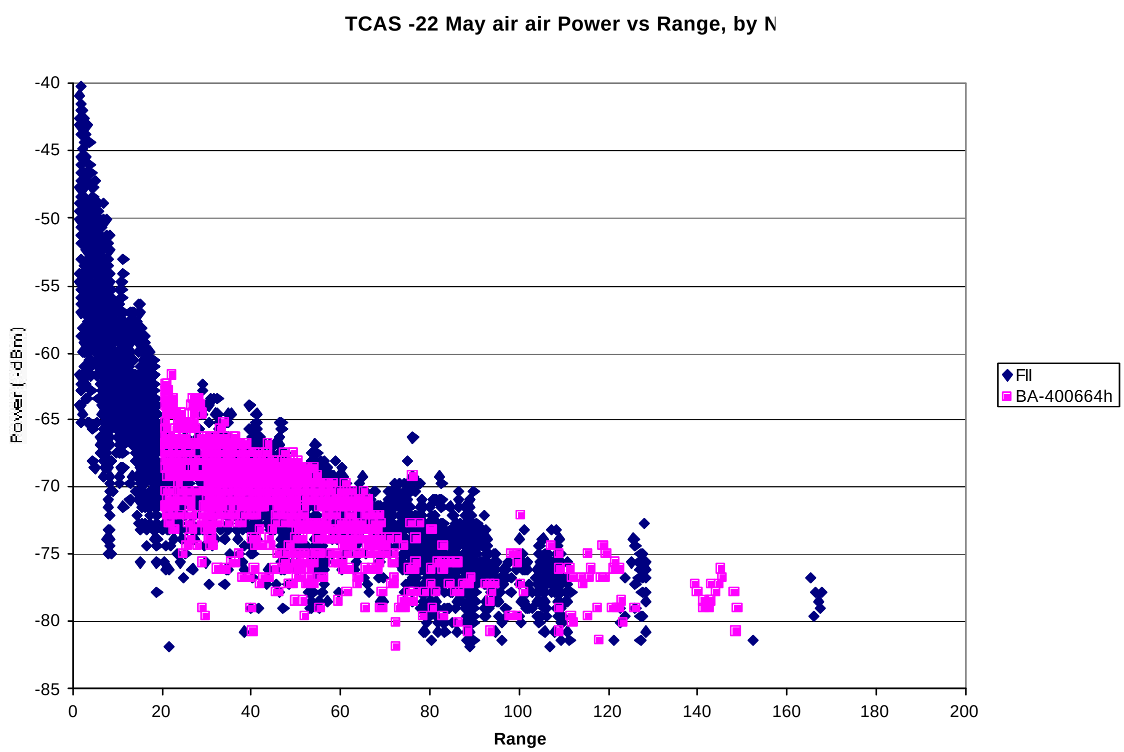


Figure 4.4.2-31b. Received Power vs. Range for All Ext. Squitters, 22 May

4.4.2.2.4 Results for 25 May

This day provided data from one British Airways target of opportunity. The only air-air receptions were from BA-400663h.

The probability of reception as a function of range and power are shown in figures 4.4.2-32 and 33. There is a lower probability of reception when the aircraft are with 30 miles than when at 50. This could be due to the orientation of the aircraft.

The state vector update period for BA-400663h as a function of range and power are shown in figures 4.4.2-34 and 35. For the duration of the track, the state vector update period is within the 24 seconds.

The track of BA-400663h is shown in Figure 4.4.2-36. There is a solid track for ranges under 80 miles.

Figure 4.4.2-37 shows the received powers of all Extended Squitters as a function of range received on 25 May.

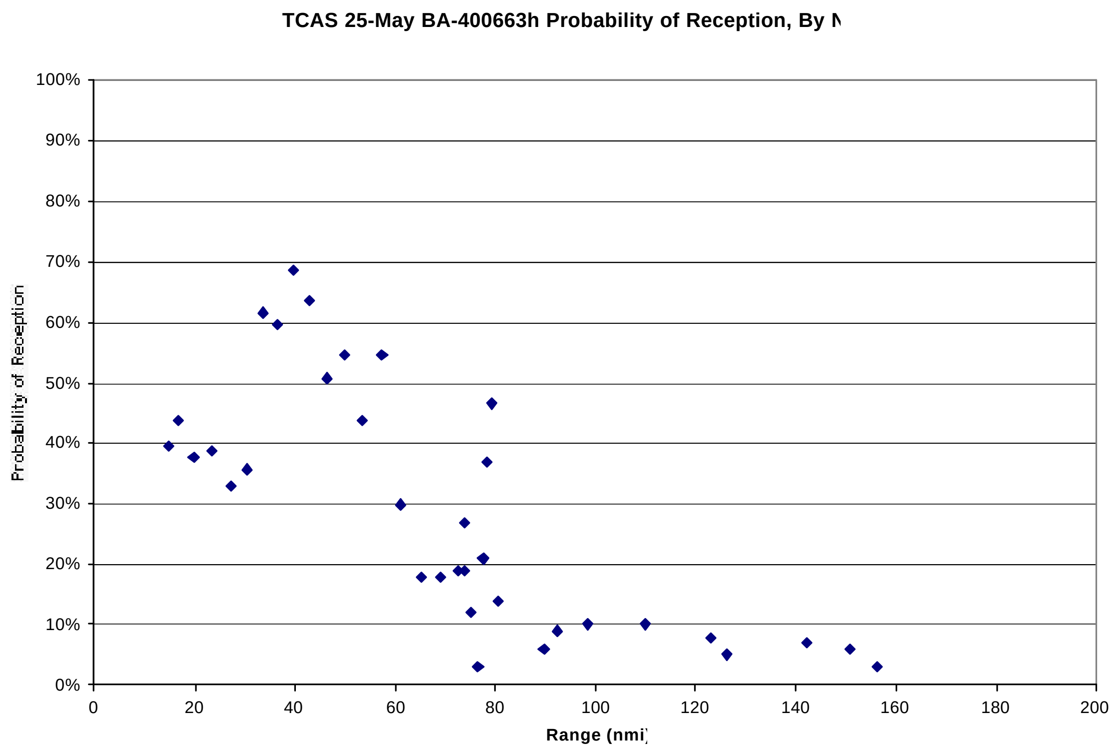


Figure 4.4.2-32. TCAS: BA-400663 $_h$ Ext. Sq. Reception Probability vs. Range, 25 May

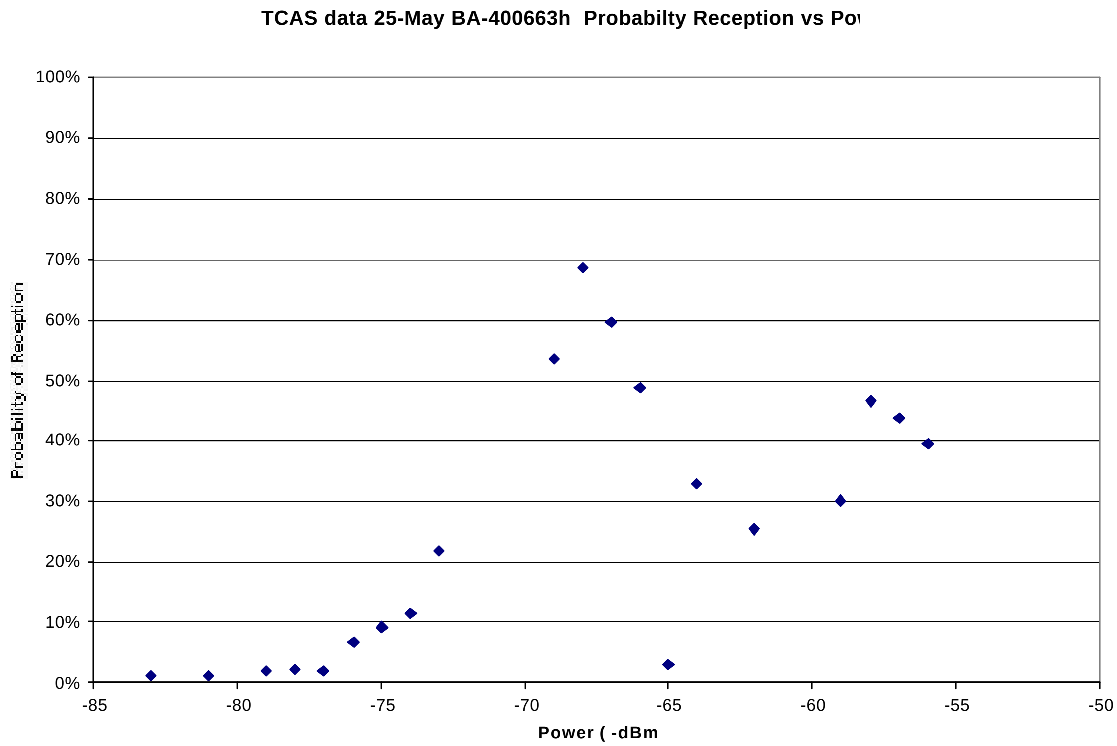


Figure 4.4.2-33. TCAS: BA-400663 $_h$ Ext. Sq. Reception Probability vs. Power, 25 May

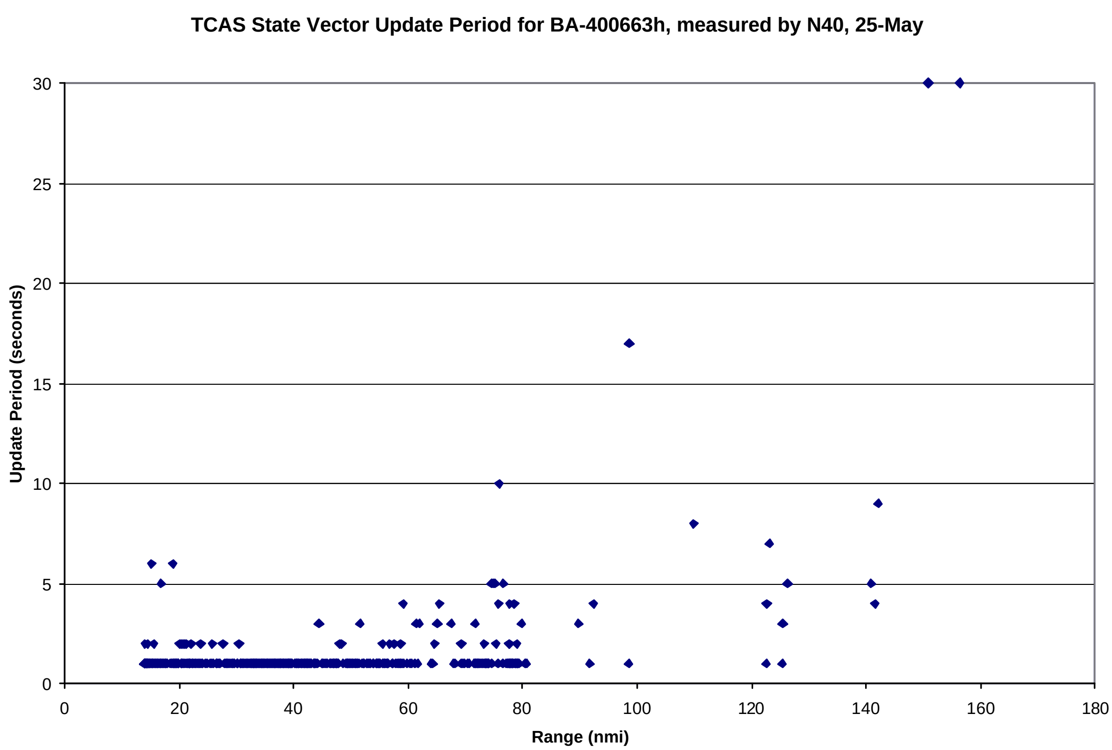


Figure 4.4.2-34. TCAS: BA-400663 $_h$ Ext. Sq. Update Interval vs. Range, 25 May

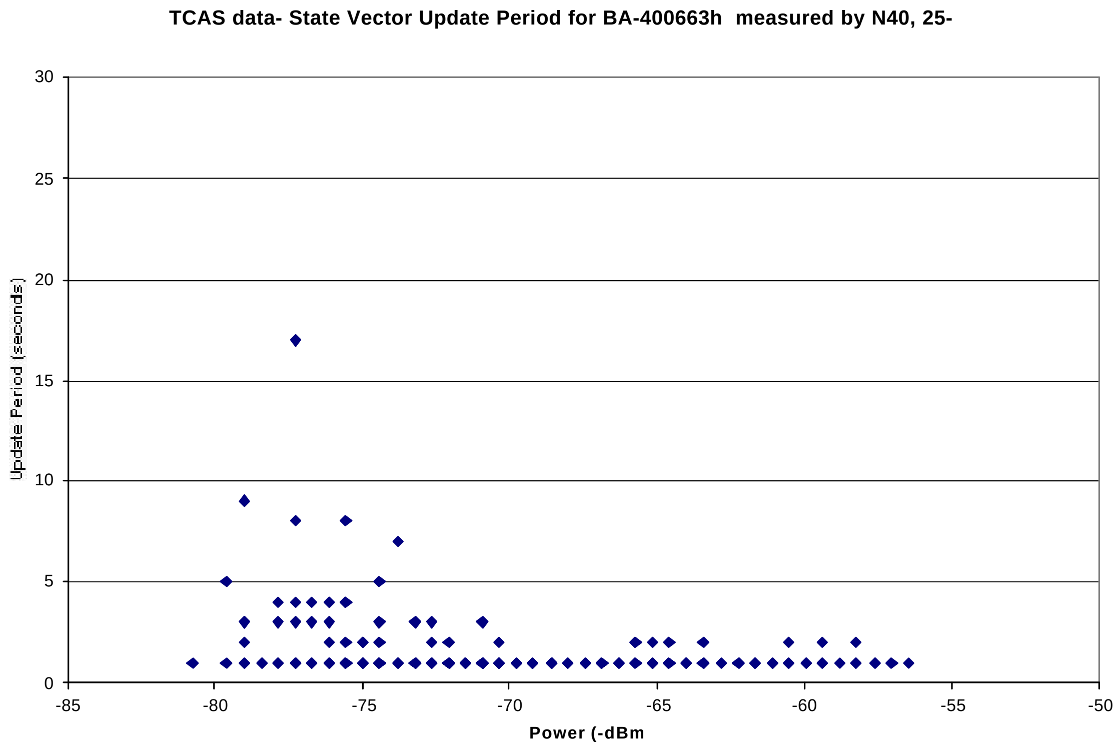


Figure 4.4.2-35. TCAS: BA-400663 $_h$ Ext. Sq. Update Interval vs. Power, 25 May

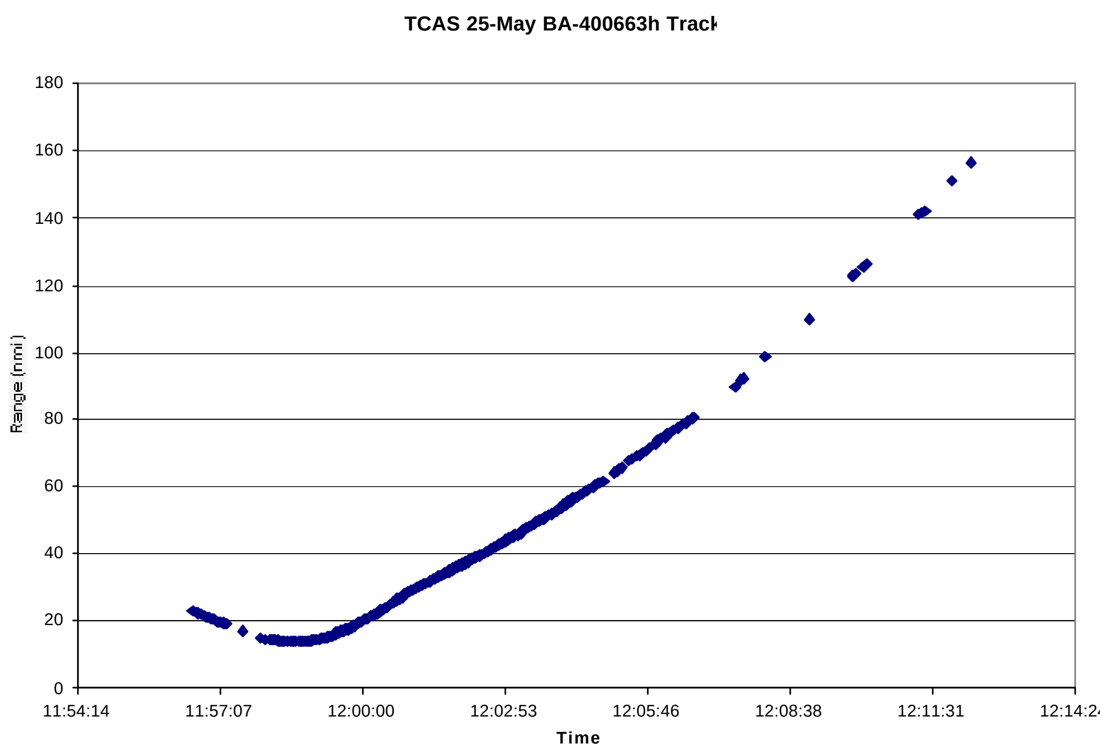


Figure 4.4.2-36. TCAS: BA-400663 $_h$ Ext. Sq. Track Range vs. Time, 25 May

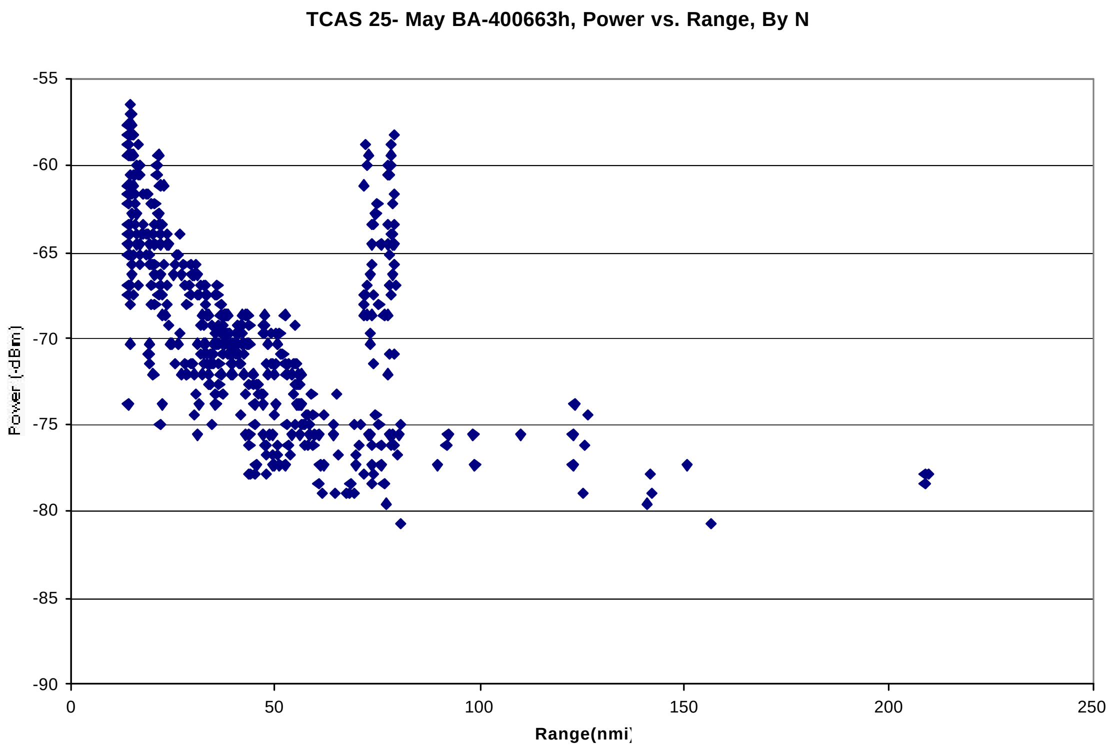


Figure 4.4.2-37. Received Power vs. Range for All Ext. Squitters, 25 May

4.5 AIR-TO-GROUND RECEPTION OF EXTENDED SQUITTERS

4.5.1 Overview

Results were obtained using LDPU, ANS-MAGS and ERA receivers at Langen, and with the LDPU and the RMF at Wiesbaden. The two sites also varied in the surrounding multipath environment. The Wiesbaden site was severely restricted in any direction outside of the wedge 0-130 degrees. This was the wedge covered by the adjacent sectors of the multisector antenna. The Langen site had fairly good coverage except (1) in southeast direction where the line of sight was partly shielded by a nearby building and (2) to the north and northwest due to the Taunus Mountains. In addition, distant hills at other azimuths may have limited the ultimate line-of-sight range to targets in the main beams.

4.5.2 Air-to-Ground Reception Performance for 24 May

4.5.2.1 Langen Performance

4.5.2.1.1 Langen LDPU Air-Ground Performance 24 May

The logs collected on the LDPU installed at Langen were analyzed to measure air-to-ground performance for all the Extended Squitter targets that were detected on 24 May. The Langen LDPU logs are identical in format to those produced by the airborne LDPUs. Consequently the same performance analysis techniques were applied as in the air-to-air case (see 4.4.1.1).

On 24 May two sets of recordings were collected on the Langen LDPU. The first set contained data from the period just before the start of the proper trial session. During that period the FII aircraft flew to Wiesbaden and there was also one BA target of opportunity (BA-400664$_h$). The FII flight was almost entirely within the north-sector beam of the Langen ground station antenna. At the same time, BA-400664$_h$ traversed the north sector from east to west at 37000 ft.

The second Langen LDPU log set contained data collected during the proper trial session. All three project aircraft were tracked plus four BA targets of opportunity. As explained in Chapter 3 the FII aircraft flew within the southeast sector, the NLR Metroliner flew within the north sector, and the N40 flew holding patterns near Langen but mostly to the southwest, e.g., outside the two Langen antenna beams. There were two BA flights (BA-400663$_h$ and BA-400652$_h$) tracked from northwest to southeast and another one (BA-400652$_h$) from southeast to northwest. These three fights overflew Langen and their northwestern part was outside coverage of the two Langen antenna beams. The fourth BA target of opportunity (BA-400664$_h$) was tracked traversing the north sector from west to east following the reverse path from what had been recorded in the first log.

Figure 4.5.2.1-1a shows the tracks of all the aircraft recorded in the two logs of the Langen LDPU except for the N40 track (it would have been barely visible because of its small scale). A single dot has been plotted for each position report in the LDPU log. The boundaries of the two main antenna beams at Langen are also shown. It should be noted that southeast-sector coverage was severely obstructed by buildings in the vicinity of the Langen antenna. It was therefore expected that coverage in the southeast sector would not be as good as in the north sector. Figure 4.5.2.1-1a confirms this expectation.

Figure 4.5.2.1-1a indicates that the Langen antennas provided quite extensive coverage outside the main beams. This is also evident from Figure 4.5.2.1-1b that shows the N40 track recorded by the Langen LDPU. A large part of the N40 track outside main beam coverage was captured. This observation is further confirmed by Figure 4.5.2.1-1c, which shows the short squitter plots recorded on the Langen LDPU. The latter figure also illustrates the extensive coverage outside the two main beams. Nevertheless, in the subsequent analysis only the flight segments lying within main beam antenna coverage have been taken into account.

The "spaghetti plot" shown in Figure 4.5.2.1-1c provides a way of assessing Mode S reception performance based on a large number of operational aircraft flying at the time of the test. All Mode S transponders transmit short squitters, once per second. For each Mode S aircraft, reception of short squitters by the LDPU indicates reception quality, although the LDPU data does not indicate the location of the aircraft. On the other hand, a Mode S radar can be used to determine the aircraft location and the corresponding 24-bit address. Subsequent analysis of the data recorded both by the radar and the LDPU receiver allows this plot to be made. The spaghetti plot is constructed as follows. For each scan of the radar (Goetzenhain Mode S radar used here), a small point is plotted showing the current aircraft location. The LDPU receptions are then examined to determine whether short squitters were received from that aircraft during the scan. If not the plotted point is changed to a larger red symbol, to indicate a flaw in LDPU reception. The line-of-sight limits for the Langen site (described above in connection with Figure 2.3-5) were used to limit consideration to aircraft above the horizon. Specifically, for the data plotted in Figure 4.5.2.1-1c, the horizon used for analysis was 4 degrees between 135 and 150 degrees azimuth, and 2 degrees otherwise. Note that only two antenna sectors were being used during these tests, so reception quality should be judged only within these two sectors, as marked in the figure. The results in figure 4.5.2.1-1c indicate good reception quality for nearly every aircraft in the airspace during the time of the test.

Another spaghetti plot, generated under different conditions, is shown in Figure 4.5.2.1-1d for comparison. In this case the horizon filtering for the nearby buildings was not applied. Therefore the effects of these buildings can appear as degraded reception, particularly when comparing this plot with the previous one. The results indicate that reception is degraded for aircraft located in the airspace behind these buildings, as might be expected.

Figures 4.5.2.1-2a through 2d show the altitudes and ranges from Langen of all the aircraft tracked by the Langen LDPU. One dot has been plotted for each record in the Langen LDPU log. Range has been calculated as horizontal great circle distance (no slant correction was applied). In particular, Figure 4.5.2.1-2a shows the altitudes and ranges of the FII and BA-400664h$_h$ flights that were tracked in the pre-trial session. Both these flights were within north-sector Langen beam coverage. Figure 4.5.2.1-2b shows the equivalent charts for the two flights (NLR and BA-400664$_h$) in the north sector which were tracked during the proper trial session. Figure 4.5.2.1-2c shows the altitudes and ranges from Langen of the three targets that flew through the southeast sector. Finally Figure 4.5.2.1-2d shows the altitude and range of the N40 flight, which was mostly outside main beam coverage. The above figures indicate that the BA targets of opportunity were at much higher cruising altitudes (> FL 350) than the project aircraft (FL200-220). Furthermore, in the north sector the BA targets passed at much longer ranges from Langen than the project aircraft. In the southeast sector, all BA targets tended to either be descending for landing or climbing after take-off. N40 stayed within very close range of Langen (< 28 nmi).

Figures 4.5.2.1-3a through 3c show the variation of update intervals (in seconds) with range for the three project aircraft (considering only positions within main antenna beam coverage at Langen) during the proper trial session. Update intervals were calculated as the difference of the GPS reception timestamp from the previous record of the same target in the LDPU log. This assumes that LDPU records are equivalent to state vector updates. The same assumption was made in the air-to-air case (the reasons are explained in 4.4.1.1). Range was calculated as horizontal great circle distance (in nmi) from Langen using the coordinates specified in the target record. Figures 4.5.2.1-3a through 3c also show the 98% percentile containment values of the raw update intervals. These values provide an upper bound on the dispersion of the raw update intervals and have been calculated as the minimum interval values exceeding 98% of the observed raw values within a 5 nmi distance bin (2 nmi in the case of N40 because it covered a much smaller range). Distance bins were defined consecutively as distances 0-5, 5-10, 10-15, (0-2, 2-4, 4-6, . in the N40 case) and so on .

Figure 4.5.2.1-3b indicates that NLR update intervals stayed below 5 sec for up to 130 nmi from Langen. Beyond that range update intervals varied widely. FII maintained update intervals below 5 sec only up to 100 nmi, hence it performed less well than NLR (see Figure 4.5.2.1-3a). It should be noted that FII flew in the southeast sector while NLR flew in the north sector. In the N40 case (see Figure 4.5.2.1-3c), the aircraft stayed within 28 nmi of Langen. There was very little variation in the update intervals that stayed below 2 sec except at very close ranges (< 5 nmi) where it is likely that the Langen antenna cone of silence affected the results.

Figure 4.5.2.1-4a compares the FII update intervals with those obtained for the two BA targets of opportunity that flew in the southeast sector. Update intervals are expressed in terms of their 98^{th} percentile containment values (5 nmi distance bins). Only the flight segments within the southeast sector were taken into account in the calculations. There is remarkably good agreement between the results of the three flights. This could be attributed to the similar paths followed by the three aircraft (see Figure 4.5.2.1-1a) although their altitudes differed (see Figure 4.5.2.1-2c).

Figure 4.5.2.1-4b through 4d show the corresponding air-to-ground Extended Squitter probabilities of decode for each of the above three aircraft versus range from Langen. Extended Squitter decode probabilities were estimated from the Extended Squitter count included in each LDPU record and using a 24-sec sliding window, which moved per LDPU log record (~ 1 sec steps, see also 4.4.1.1). Again only records within southeast beam coverage were taken into account in the calculations. Only the FII reception probability appears to drop monotonically with distance (see Figure 4.5.2.1-4b). The FII reception probability stayed above 10% up to 110 nmi. In the case of the BA targets of opportunity, reception probability appears to drop as they approach Langen and gain altitude (see Figure 4.5.2.1-4c and d). This behavior might be related to the Langen antenna cone of silence (the antenna manufacturer did not release data on that subject). In the case of BA-400652 $_h$ there is a noticeable difference between the two flight legs (inbound and outbound). Indeed it can be seen from Figure 4.5.2.1-4c that the outbound leg reception probability crosses the 10% threshold at 100 nmi, while in the inbound leg the same threshold is crossed at 120 nmi. These differences could be attributed to aspect angle considerations similar to what was observed in the air-to-air performance analysis (see 4.4.1.1).

Figure 4.5.2.1-5a compares the update intervals versus range from Langen of all four flights that were tracked in the north sector. Update intervals have been plotted in terms of their 98th percentile containment values using the calculation method described previously and taking into account only records lying within north beam coverage. The two BA targets of opportunity produced similar performance, which should be expected since it was the same aircraft (BA-400664 $_h$) flying almost the same path but in opposite directions (see Figure 4.5.2.1-1a and 4.5.2.1-2a and b). The BA aircraft maintained update intervals below 5 sec up to 150 nmi, while the NLR aircraft (which flew at FL 200 versus 370-390 for the BA aircraft) did so for up to 140 nmi and FII only up to 80 nmi. The latter aircraft had the lowest cruising altitude (FL 170).

Figures 4.5.2.1-5b through 5e show the air-to-ground Extended Squitter decode probabilities for each of the north-sector aircraft versus range from Langen. The calculation method has been explained previously. All these figures use exclusively records lying within north-sector antenna coverage. NLR and FII reception probabilities tend to fall monotonically with distance from Langen but is clear that there is a difference between the two NLR flight legs (outbound and inbound). This is presumably due to aspect angle considerations. A similar but lesser performance difference can be detected between the two halves of the BA-400664 $_h$ -b flight (Figure 4.5.2.1-5c), which could also be attributed to aspect angle. However, this factor is less evident with the other BA-400664 $_h$ flight (Figure 4.5.2.1-5d) which followed the opposite flight path. Comparison of the reception probability curves of the four flights produces the same conclusions as with the update intervals. Thus NLR reception probability stays above 10% up to 140 nmi, while FII does the same only up to 90 nmi. The BA flights achieve the same performance up to 160 nmi.

Comparison of the north and southeast-sector results shows that the best results were achieved in the north and therefore confirms the expectation that the southeast-sector obstructions mentioned earlier tended to limit performance in that sector.

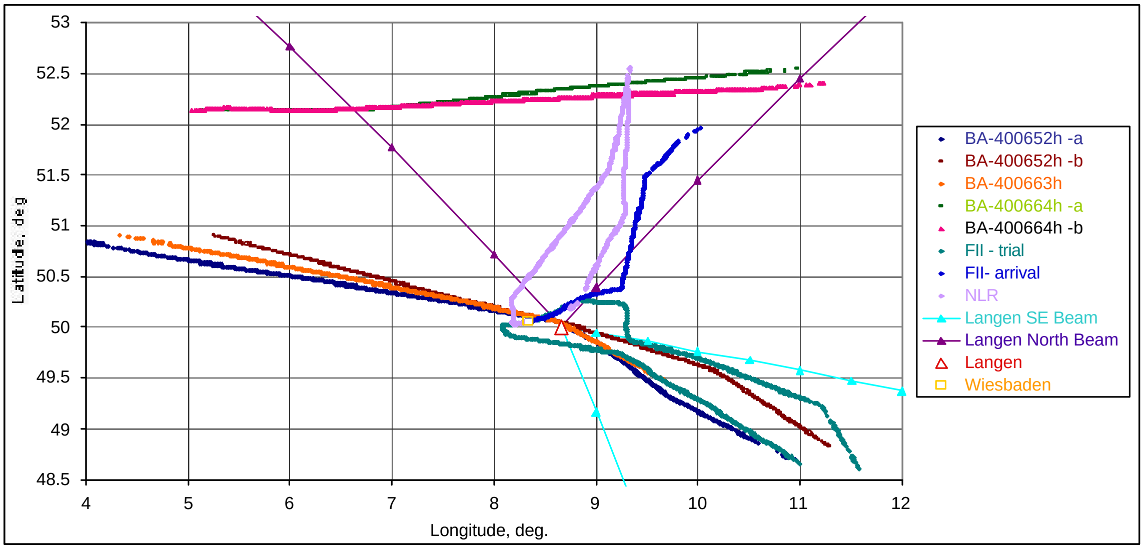


Figure 4.5.2.1-1a. Ext. Squitter Target Track Plots Recorded on Langen LDPU , 24 May

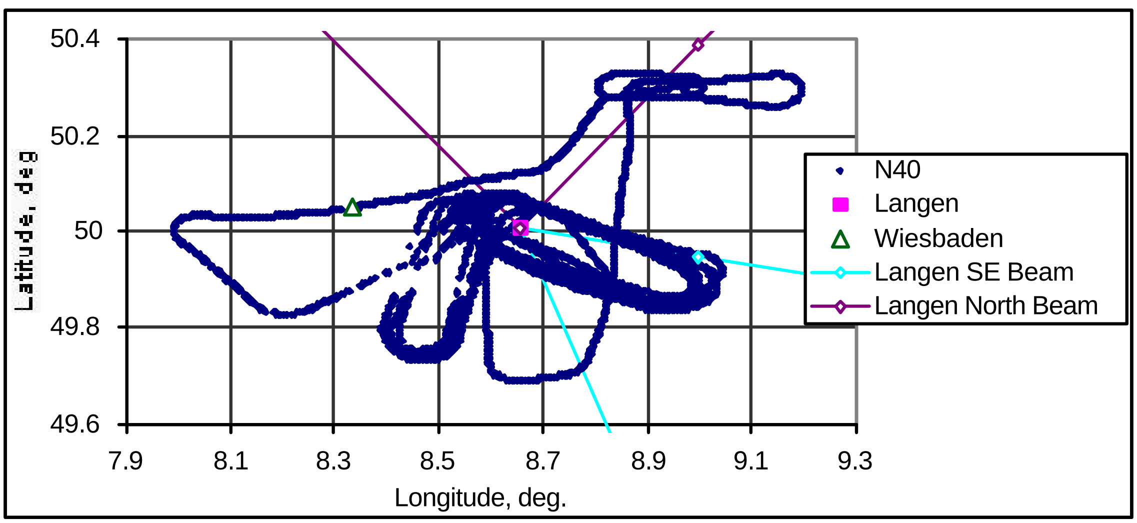


Figure 4.5.2.1-1b. N40 Track Recorded on Langen LDPU , 24 May

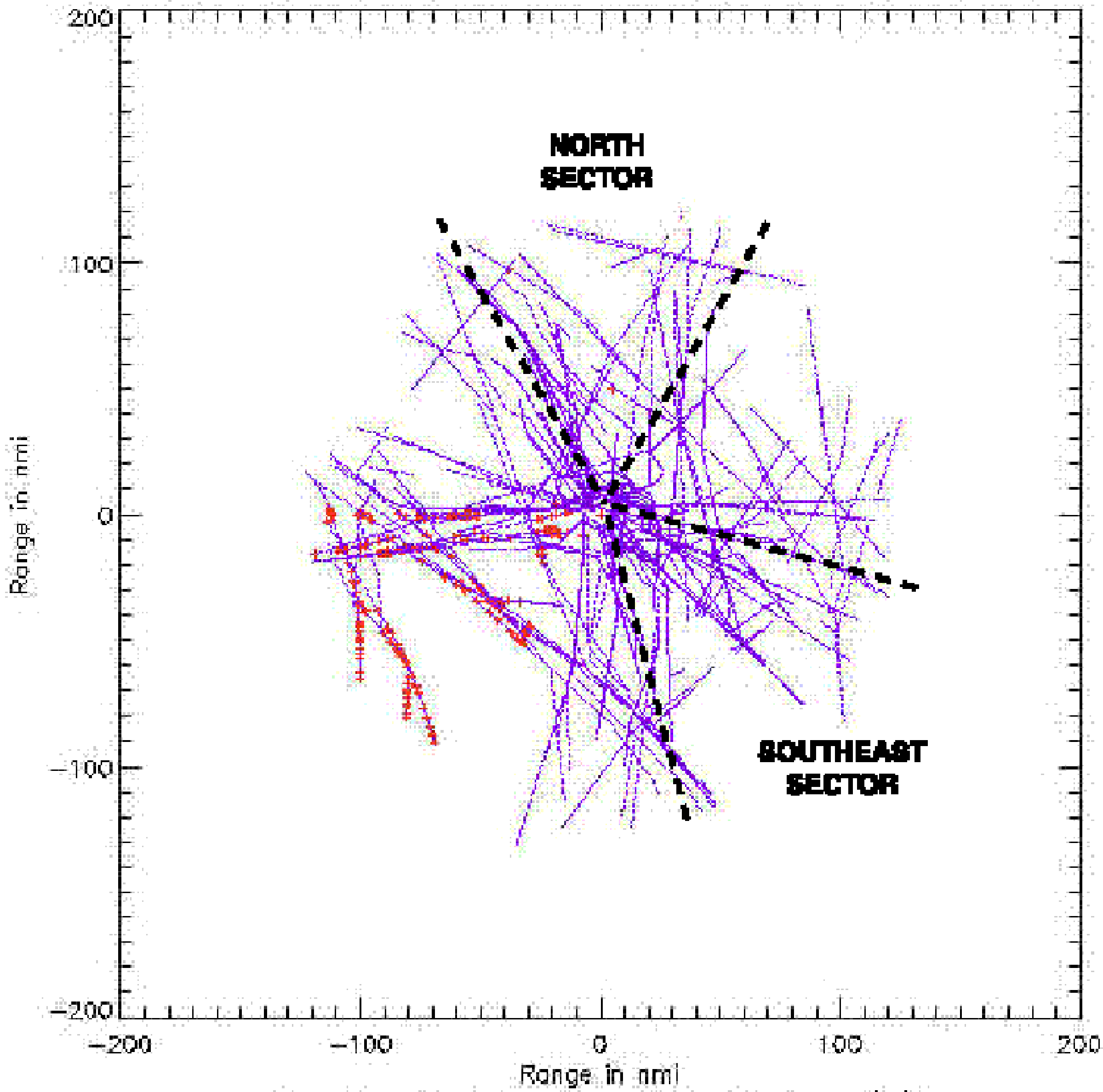


Figure 4.5.2.1-1c. Langen LDPU Short Squitter Plot, 24 May

Note. Short Squitter receptions shown in this format indicate LDPU reception performance based on transmissions from existing aircraft currently flying in the local airspace. All Mode S transponders transmit short squitters, once per second. For each Mode S aircraft, reception of short squitters by the LDPU indicates reception quality, although the LDPU data does not indicate the location of the aircraft. At the same time, a Mode S radar is used to determine the aircraft location and the corresponding 24-bit address. Subsequent analysis of the data recorded both by the radar and the LDPU allows this plot to be made. For each scan of the Goetzenhain radar, a small point is plotted showing the current aircraft location. The LDPU receptions are then examined to determine whether short squitters were received from that aircraft during the scan. If not, the plotted point is changed to a large red symbol, to indicate a flaw in short squitter reception. See text for more specifics of the analysis. Note that only two antenna sectors were being used during these tests, so reception quality should be judged only within these two sectors, as marked in the figure. The results plotted here indicate good reception quality for nearly every aircraft in the airspace during the time of the test.

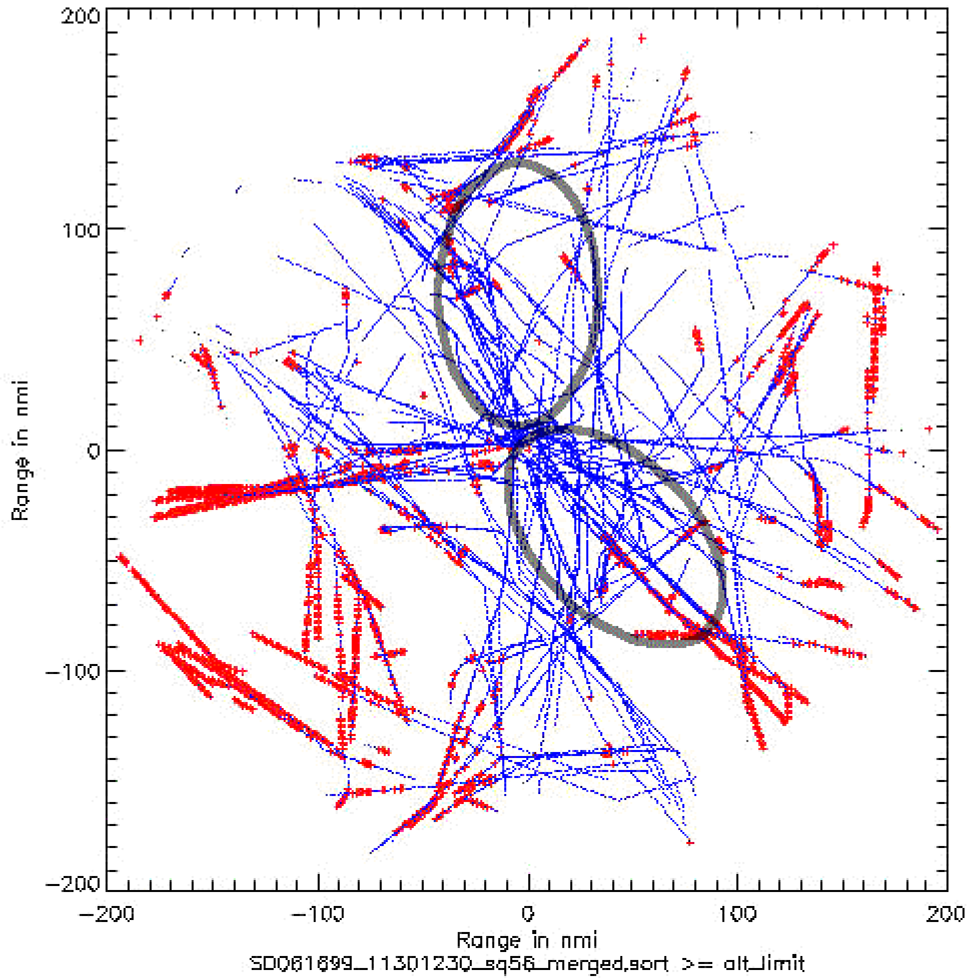


Figure 4.5.2.1-1d. Langen LDPU Alternate Short Squitter Plot, 24 May

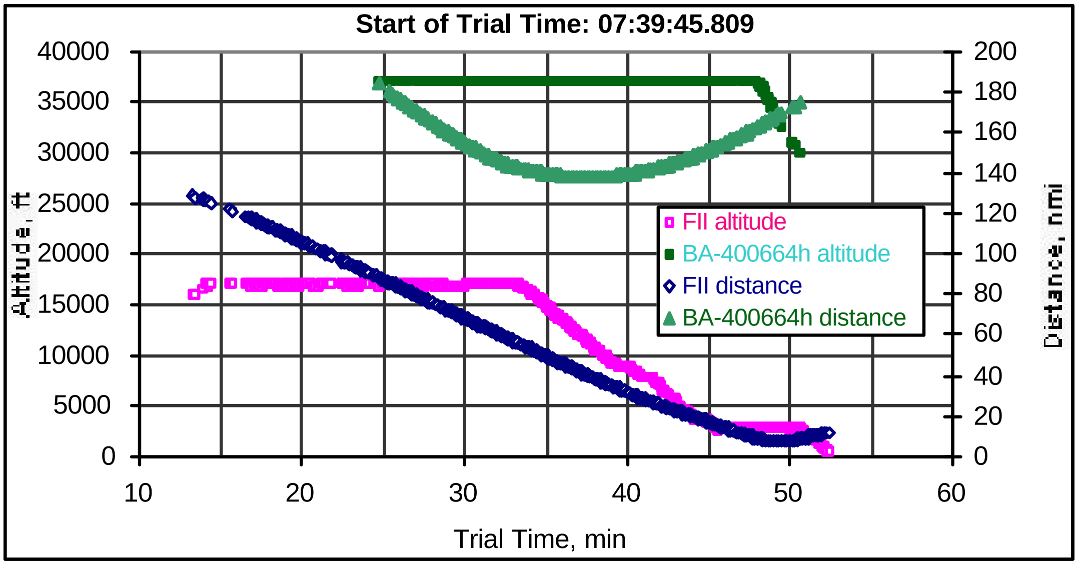


Figure 4.5.2.1-2a. North Sector Target Altitude/Range over Time, Langen LDPU, Pre-Trial 24 May

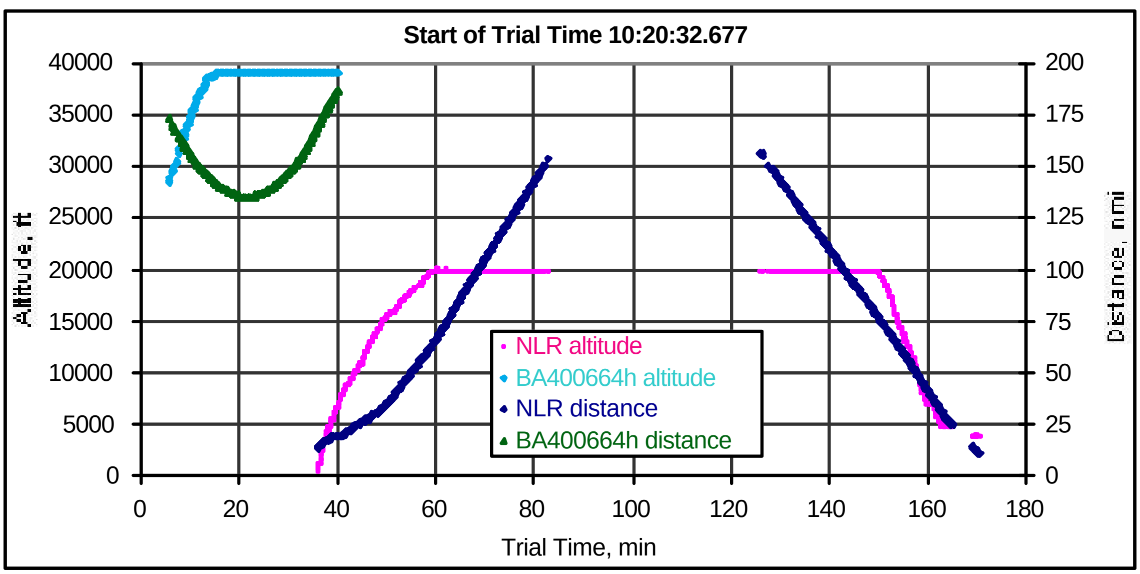


Figure 4.5.2.1-2b. North Sector Target Altitude/Range over Time, Langen LDPU, Trial 24 May

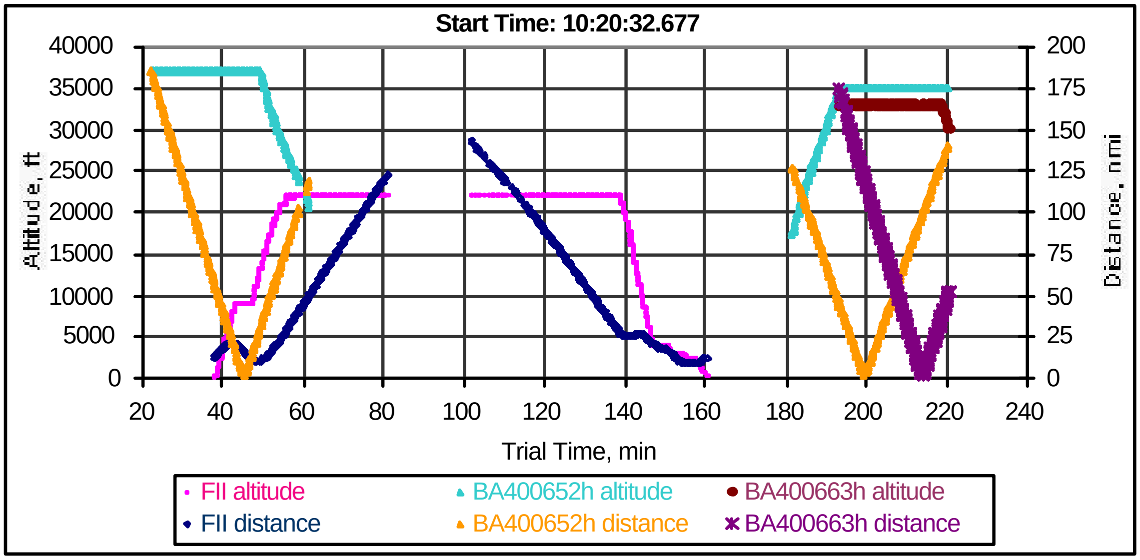


Figure 4.5.2.1-2c. SE Target Altitude/Range vs. Time, Langen LDPU, 24 May

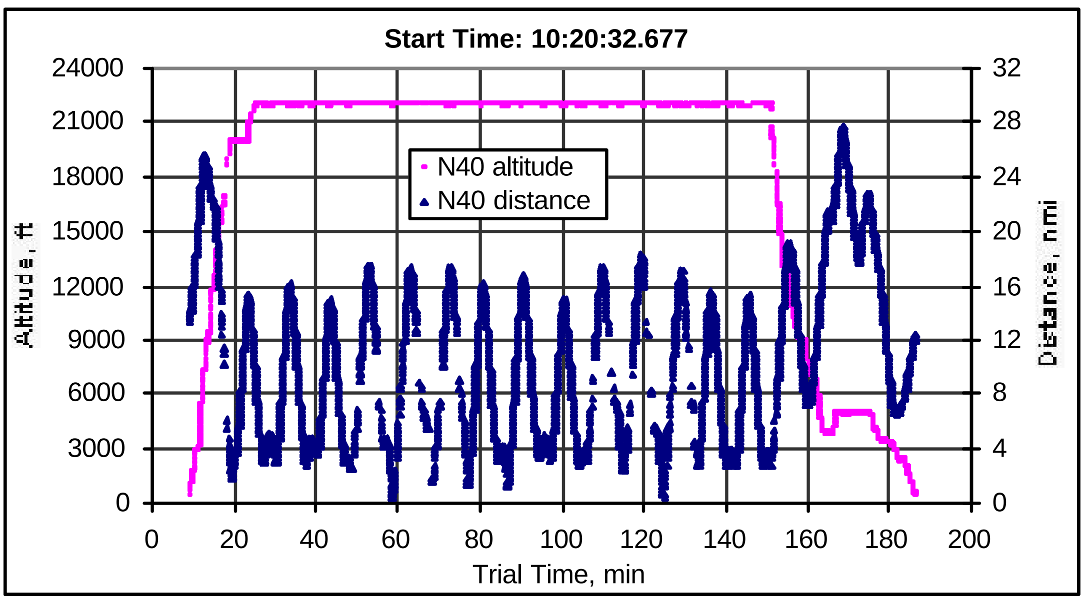


Figure 4.5.2.1-2d. N40 Altitude/Range vs. Time, Langen LDPU, 24 May

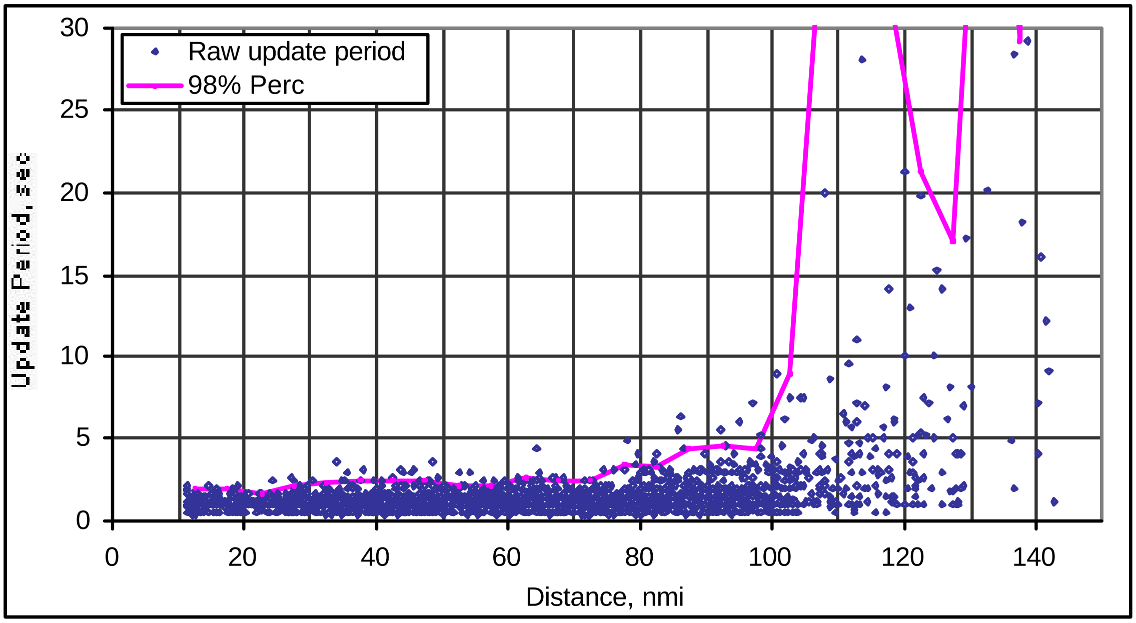


Figure 4.5.2.1-3a. FII Update Intervals vs. Range, Langen LDPU

Southeast Beam Reports, 24 May

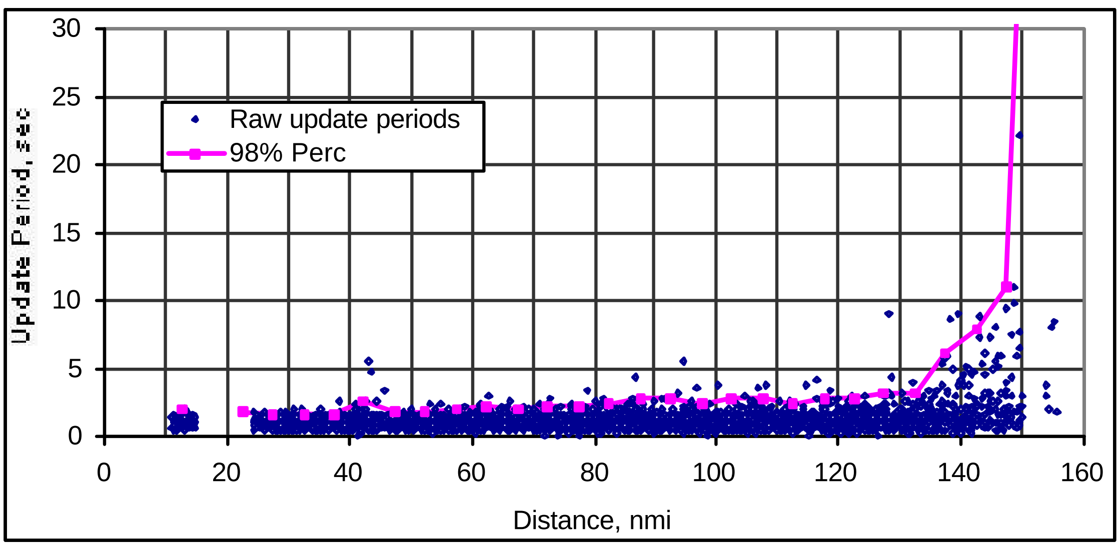


Figure 4.5.2.1-3b. NLR Update Intervals vs. Range, Langen LDPU

North Beam Reports, 24 May

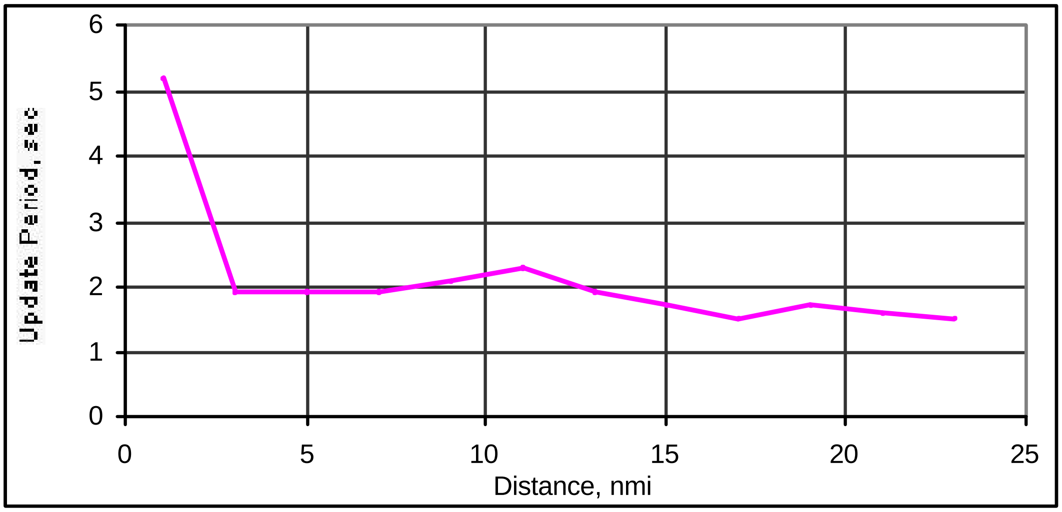


Figure 4.5.2.1-3c. N40 98th Percentile Update Intervals vs. Range

Langen LDPU In-Beam Reports ,24 May

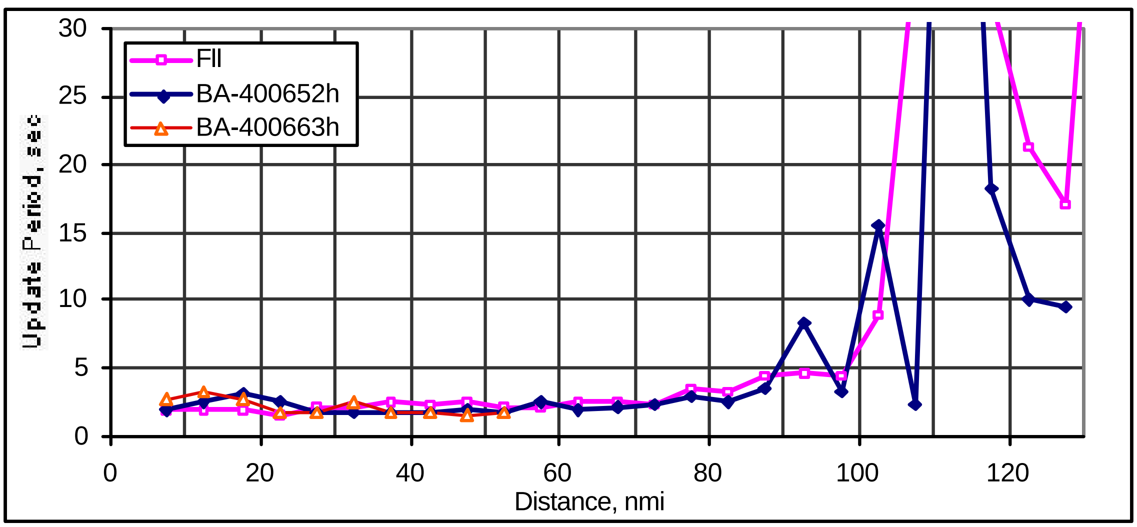


Figure 4.5.2.1-4a. SE Sector Target 98th Percentile Update Periods

Langen LDPU, 24 May

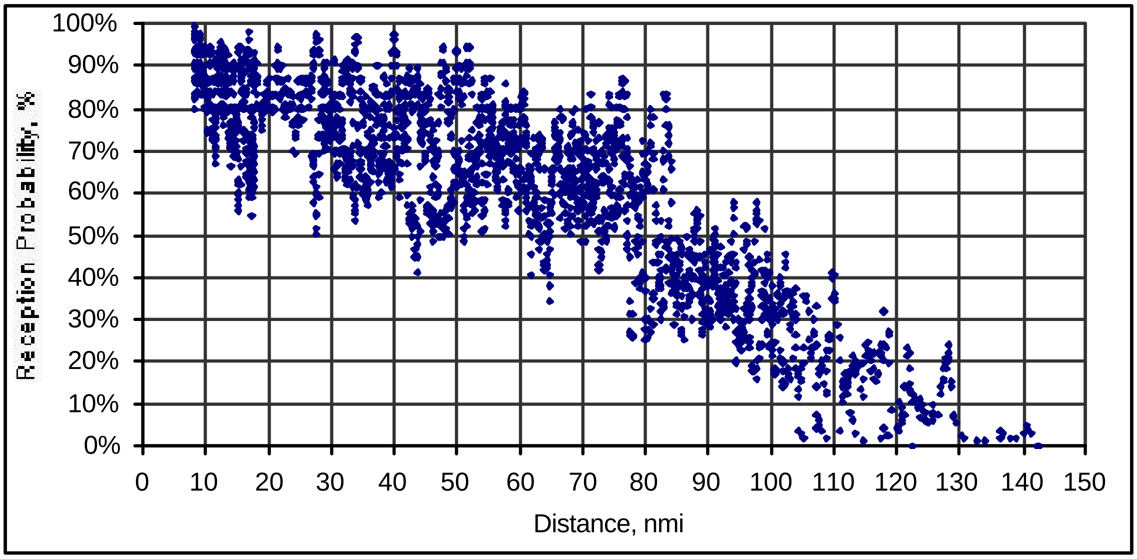


Figure 4.5.2.1-4b. SE Sector FII Ext. Squitter Reception Probability

Langen LDPU, 24 May

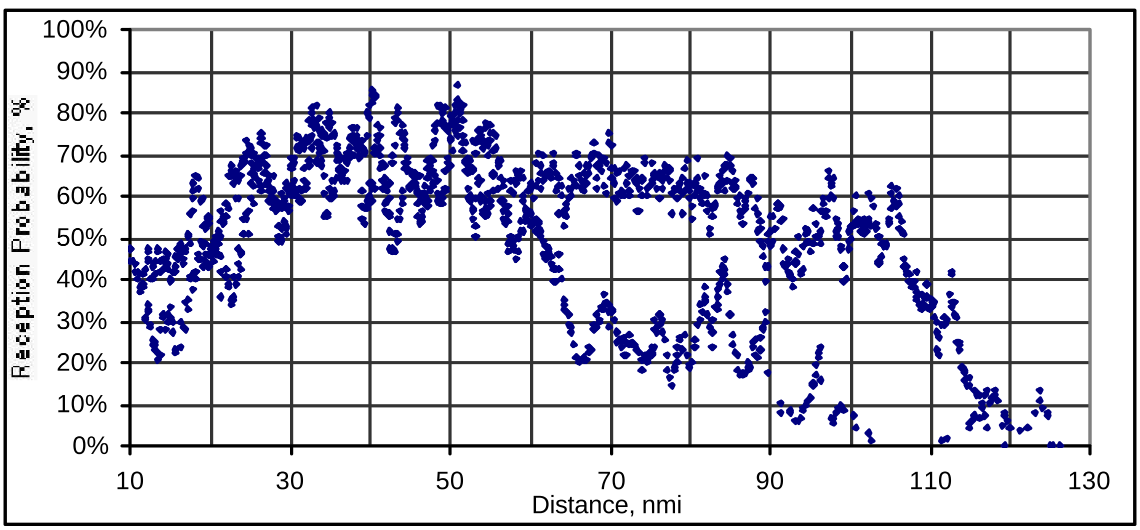


Figure 4.5.2.1-4c. SE Sector BA-400652$_h$ Ext. Squitter Reception Probability

Langen LDPU, 24 May

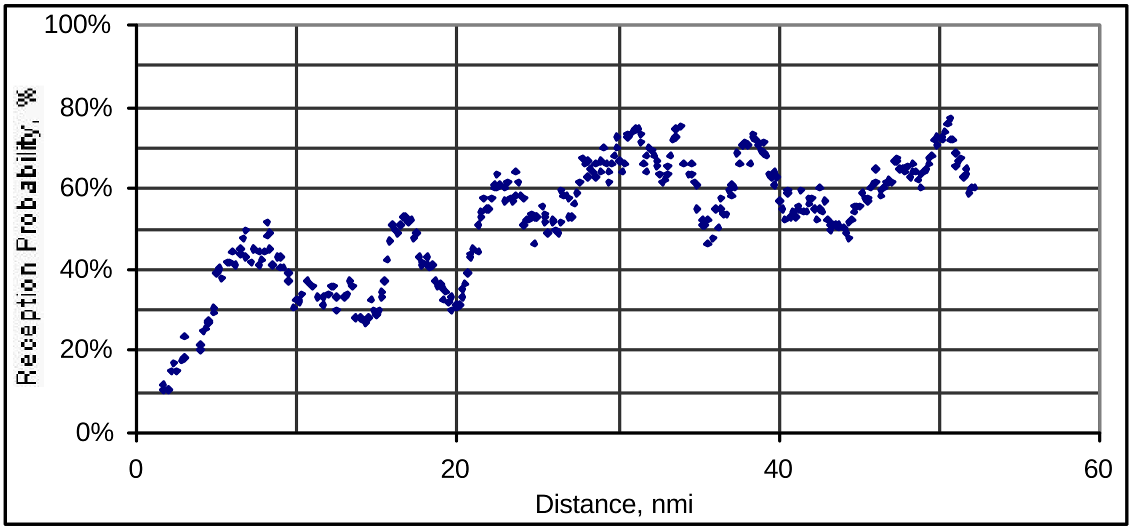


Figure 4.5.2.1-4d. SE Sector, BA-400663$_h$ Ext. Squitter Reception Probability

Langen LDPU, 24 May

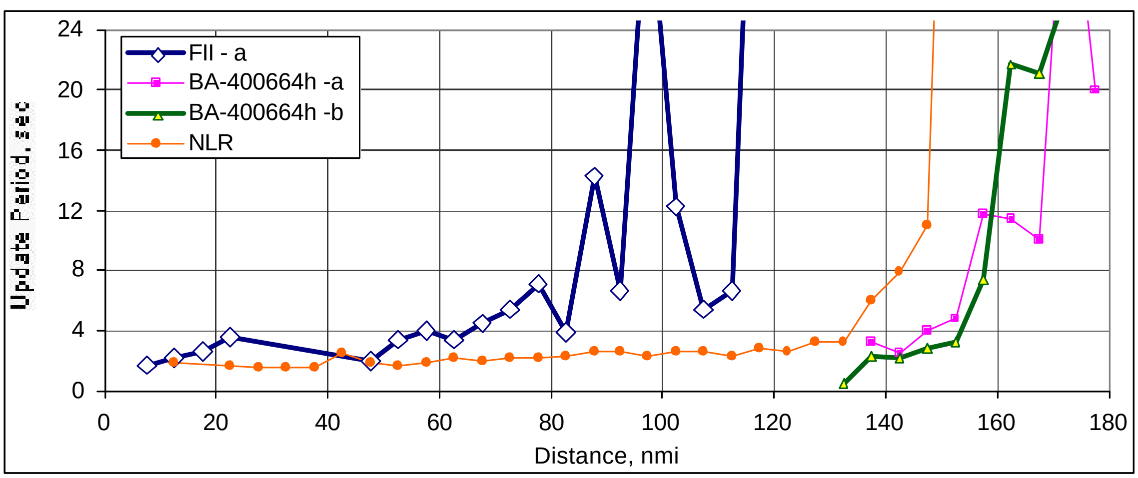


Figure 4.5.2.1-5a. North Sector Targets 98th Percentile Update Periods

Langen LDPU, 24 May

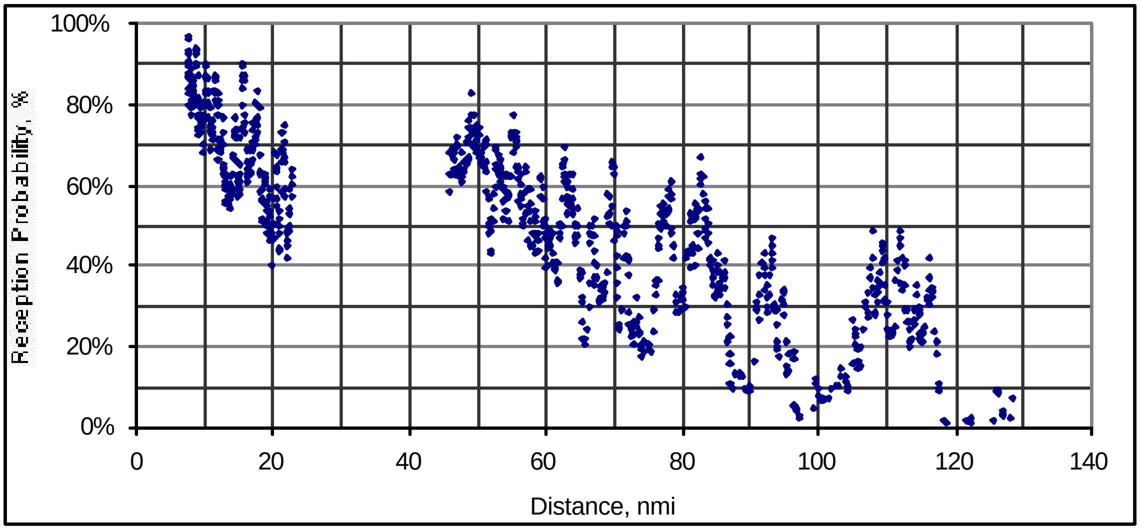


Figure 4.5.2.1-5b. North Sector, FII Ext. Squitter Reception Probability

Langen LDPU, 24 May

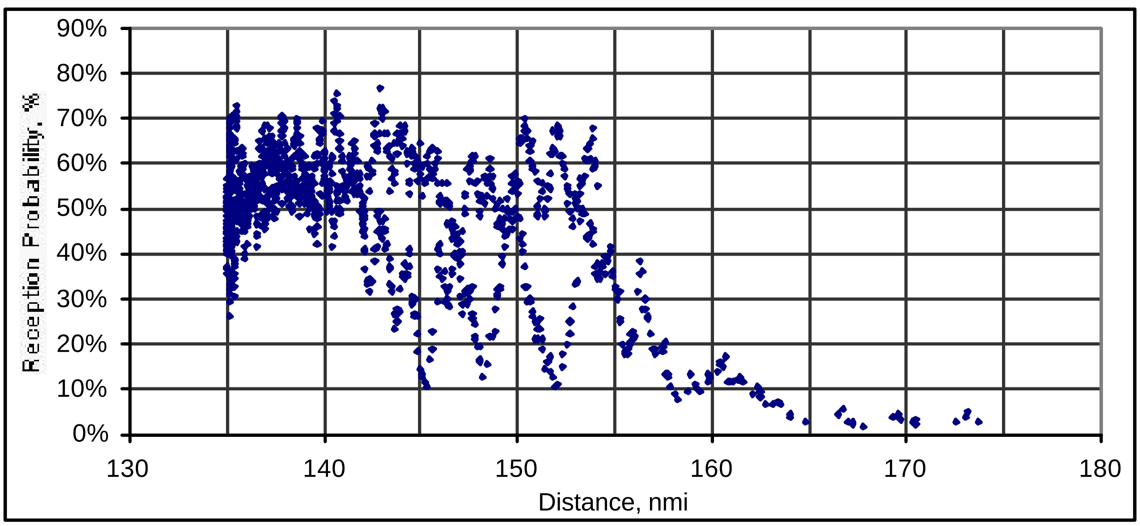


Figure 4.5.2.1-5c. North Sector, BA-400664$_h$-b Ext. Squitter Reception Probability

Langen LDPU 24 May

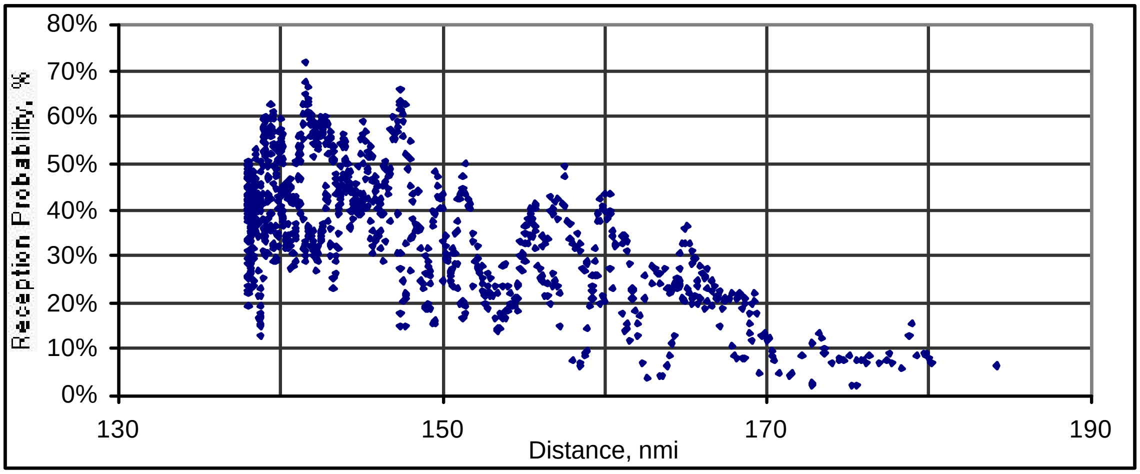


Figure 4.5.2.1-5d. North Sector, BA-400664$_h$-a Ext. Squitter Reception Probability

Langen LDPU 24 May

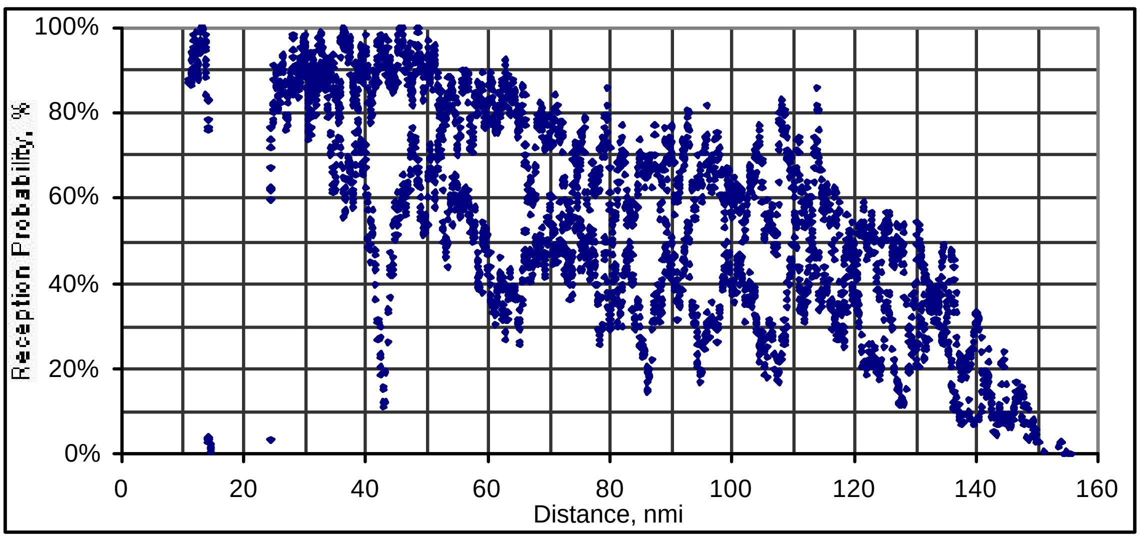


Figure 4.5.2.1-5e. North Sector, NLR Ext. Squitter Reception Probability

Langen LDPU 24 May

4.5.2.1.2 Langen ANS-MAGS Receiver Air-Ground performance 24 May

Measurements were made with the ANS-MAGS ground station (which utilized a single channel receiver). Only data within the antenna beam have been used for the evaluation of the Extended Squitter performance. Except for 25 May, the ANS-MAGS was connected to the north sector antenna. Results were obtained from the original station data (ASCII type) using tools developed by DFS and MS Excel. The following diagrams show the resulting Extended Squitter performance using the project aircraft and a target of opportunity (BA aircraft on a scheduled flight). In addition to range oriented diagrams, performance is also shown as time oriented graphs. Since the ANS-MAGS does not provide any information on received power, analyses using such data could not be performed.

Figure 4.5.2.1-6 gives an overall picture of the tracks recorded by the ANS-MAGS ground station. The track at the upper part is the BA-400664$_h$ flown from east to west. The gaps in the right part of the track result from the low altitude of the aircraft (climbing to FL 390). This aircraft was seen at the edge of the ANS-MAGS coverage. The actual test flight, the NLR (48406F$_h$) started with the northbound leg and in the south direction toward Langen. N40 (A4AA47$_h$) and the FII aircraft (3CCE6E$_h$) are shown in the lower part of the north sector approaching Wiesbaden after the test flights. N40 flew in a holding pattern over Frankfurt while the FII aircraft flew the southeast leg. Both flights were outside the north antenna sector and have not been analyzed.

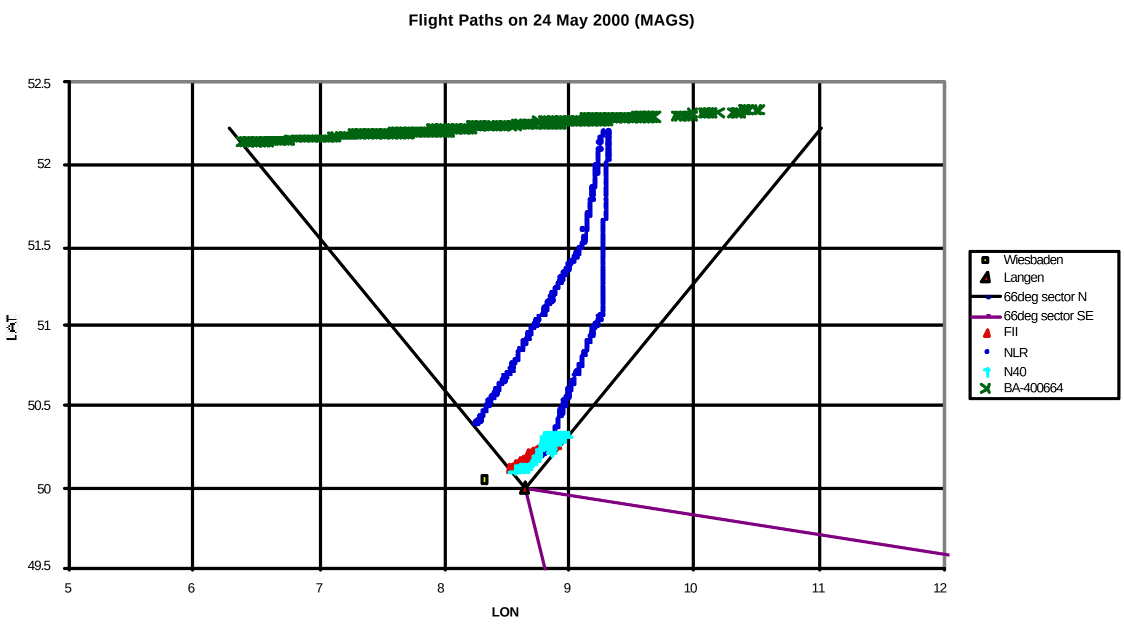


Figure 4.5.2.1-6. Langen ANS-MAGS Track Plot, 24 May

Note. *The beamwidth of the Langen sector antenna is 66 degrees. The unequal scale values for the axes make the beamwidth look wider than it actually is.*

To give a more detailed picture on the flight parameters, Figures 4.5.2.1-7 and 8 show a combination of range, altitude and reception probability vs. time. The NLR aircraft was already acquired when it entered the north antenna sector and continued flying northbound until it left the ANS-MAGS coverage at 134 nmi at 20000 ft. It entered the coverage again on the southbound leg at 135 nmi at 20000 ft and continued flying direction Langen. The gap southbound between 24 nmi and 14 nmi was caused by an intentional interruption of 1090 transmission by the crew. Due to an emergency the NLR finally stopped 1090 transmissions at 11 nmi in 3900 ft and left the ANS-MAGS coverage approaching Wiesbaden.

The BA-400664$_h$ was crossing the north sector from east to west. It entered the coverage at 155 nmi at 34000 ft climbing to its cruising altitude of 39000 ft and left the coverage at 152 nmi and 39000 ft. This target of opportunity is a good example to show the ANS-MAGS performance at the edge of its receiving coverage.

Reception probabilities have been calculated based on the formula described in Chapter 5. This is valid for all reception probabilities calculated with ANS-MAGS data.

Figure 4.5.2.1-9 gives a more detailed picture on the reception probabilities calculated from ANS-MAGS data recorded on 24 May. The diagrams show the interdependence between reception probability and range. In addition to the reception probability the aircraft altitude is shown to avoid misinterpretations. On the outbound (north) leg the reception probability decreases with increasing range. This behavior is as expected. But on the inbound leg the reception probability values are much smaller than on the outbound flight. This could be caused by the antenna position on the aircraft fuselage and the corresponding aspect angle to the receiver and/or by a changed interference environment (higher fruit rates) during the flight. The same effect has been observed on the N40 flight on 25 May.

A very important parameter for the performance assessment and the comparison with current application requirements is the update interval of Extended Squitter reports. The diagrams in Figure 4.5.2.1-10 show the update interval calculated by using the “time of arrival” information of the ANS-MAGS data. Except for one case during the NLR flight the update intervals were as expected. Despite the fact that the BA-400664$_h$ was flying at the edge of the ANS-MAGS coverage, the update intervals are much better than expected. The influence of the higher altitude is clearly recognizable for this case.

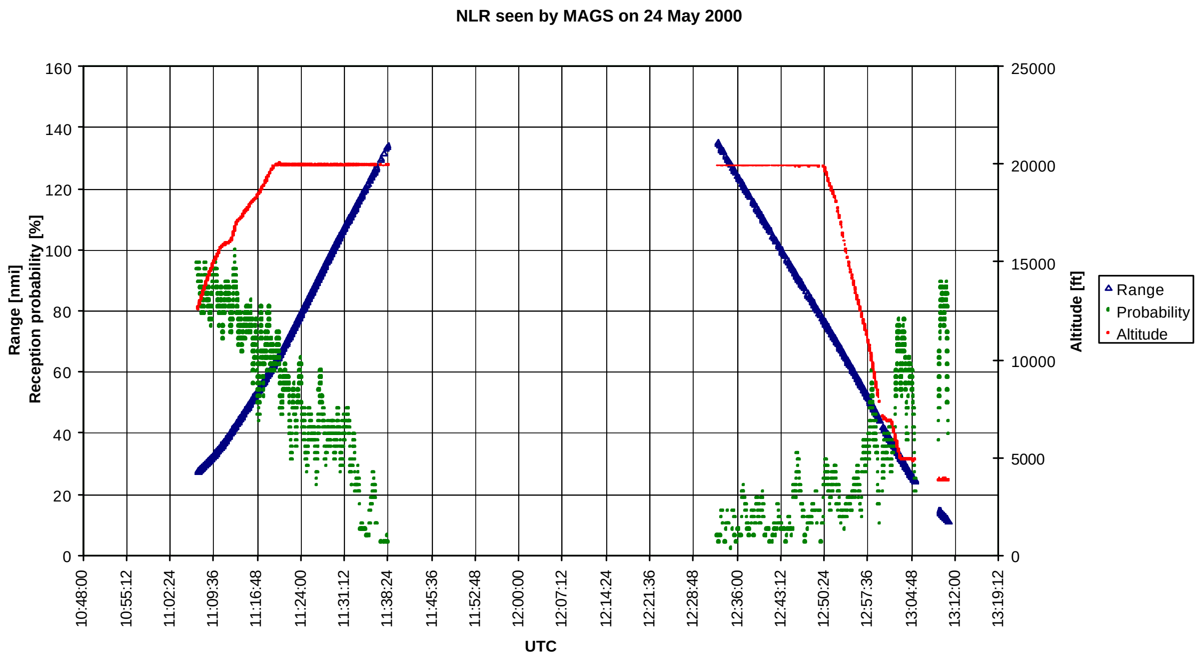


Figure 4.5.2.1-7. Langen ANS-MAGS Range, Altitude vs. Time, 24 May

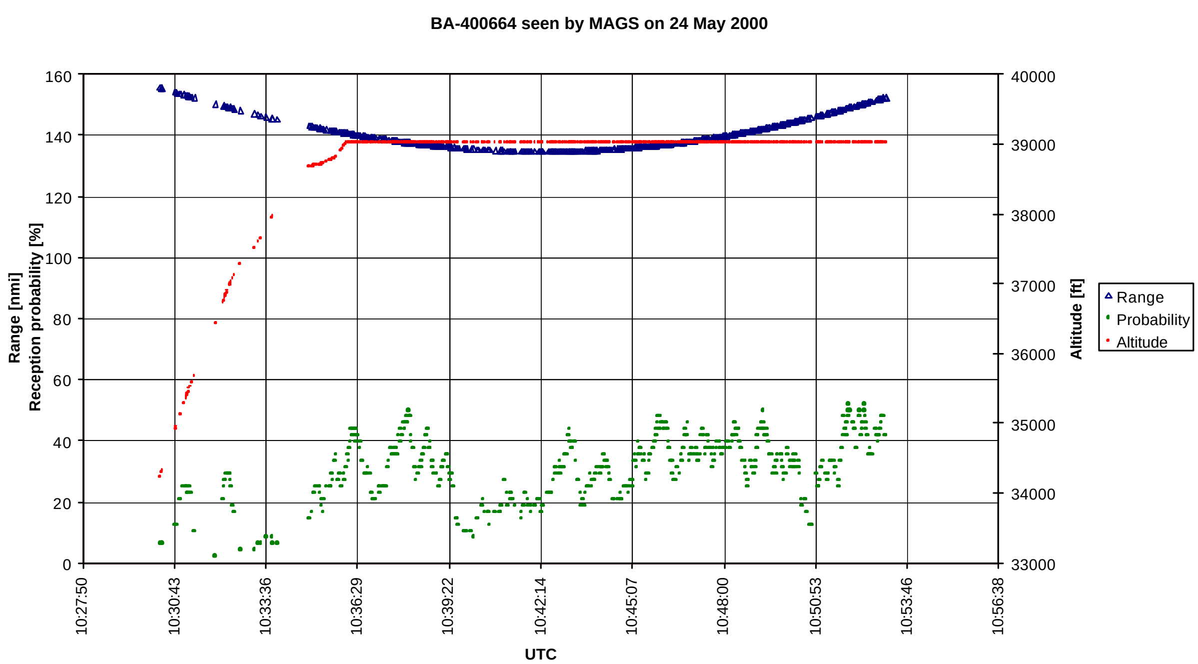
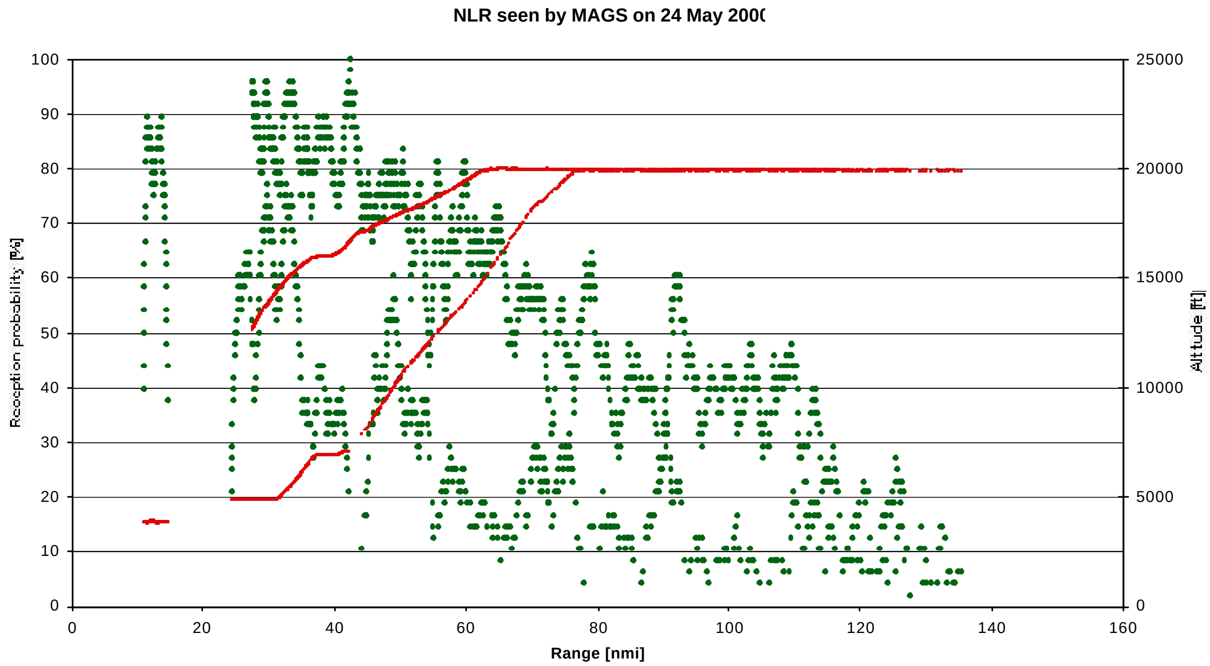


Figure 4.5.2.1-8. Langen ANS-MAGS Probability vs. Time, 24 May



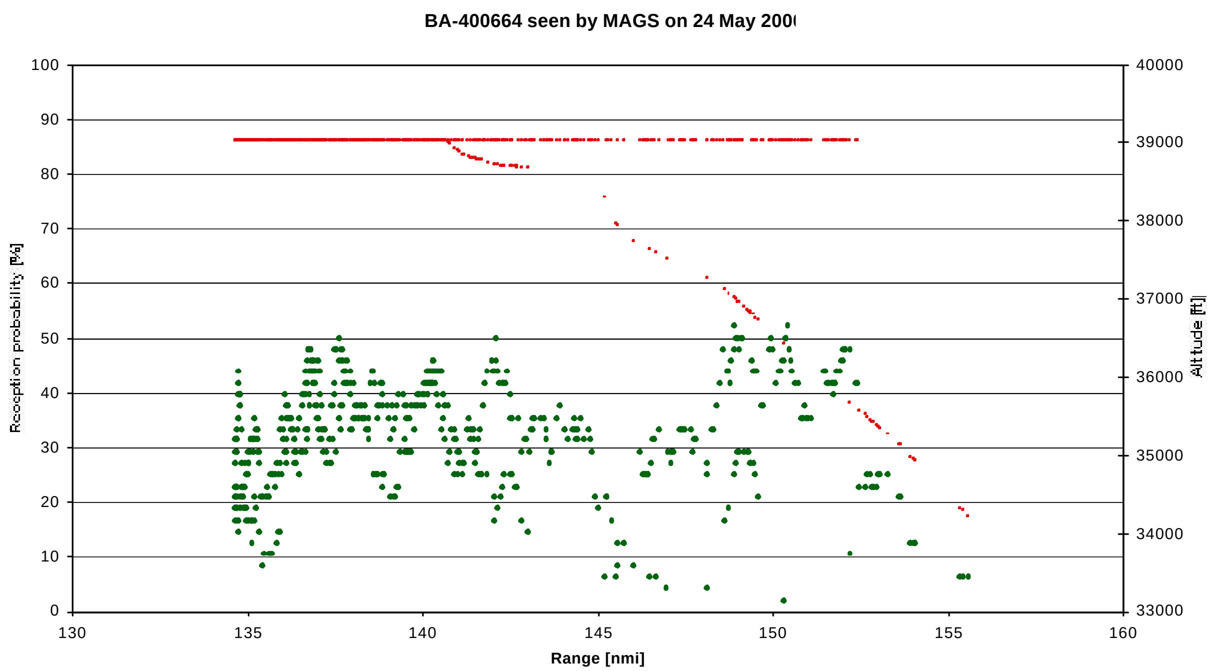
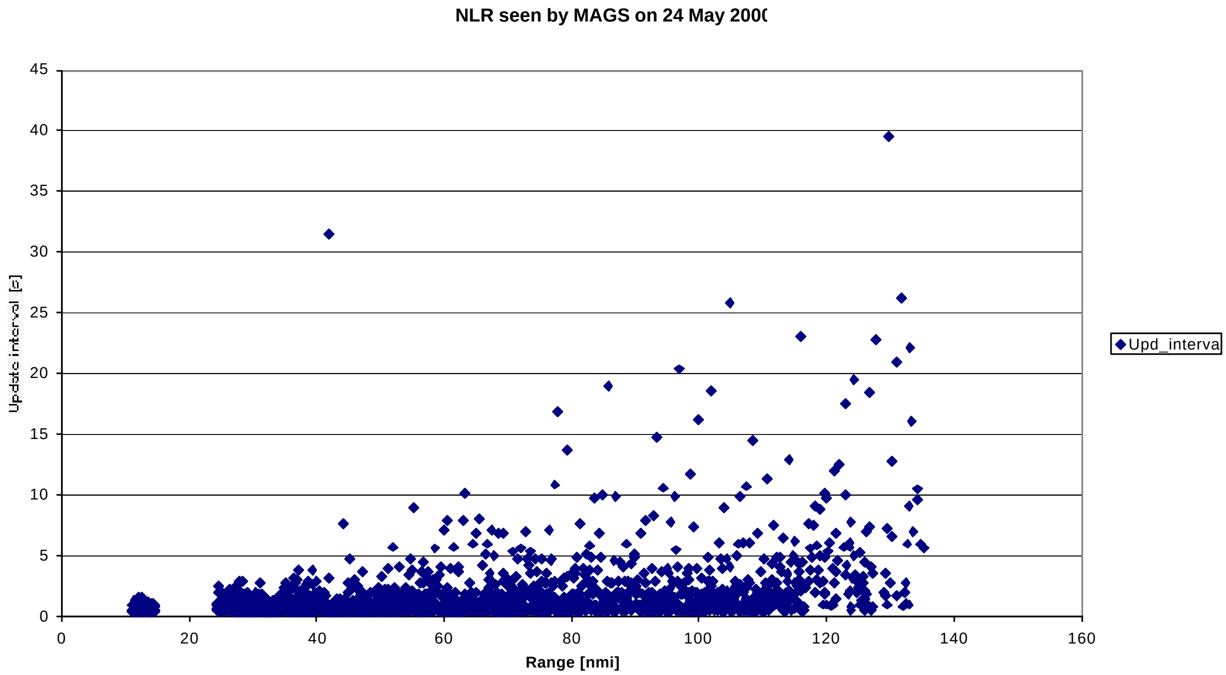


Figure 4.5.2.1-9. Langen ANS-MAGS Ext. Sq. Probability vs. Range, 24 May



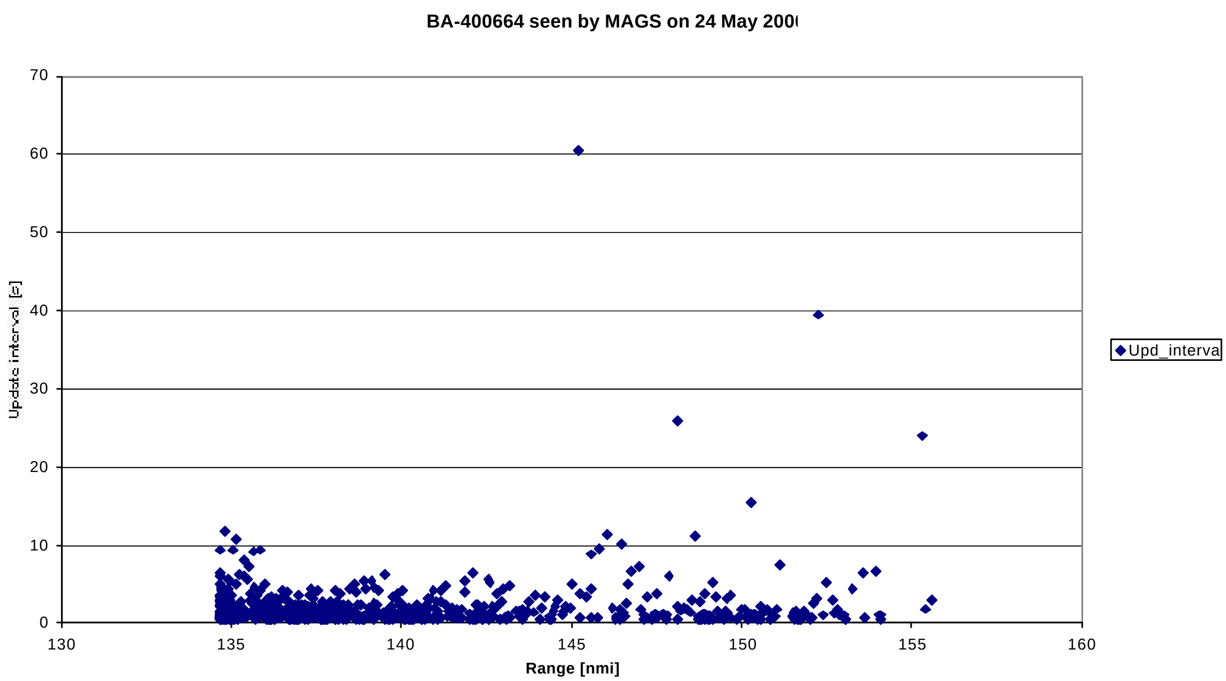


Figure 4.5.2.1-10. Langen ANS-MAGS Ext. Sq. Update Interval vs. Range, 24 May

4.5.2.1.3 Langen ERA Receiver Air-Ground Performance, 24 May

The measurements made on 24 May by the ERA ADS-B ground station (single channel receiver) allowed the processing of charts for all trial aircraft flights. Only data within the antenna beam have been used for processing of the Extended Squitter performance.

Figures 4.5.2.1-11a through c show the tracks of NLR, FAA and FII aircraft. The boundaries of the antenna beam are shown in these figures. Figures 4.5.2.1-12a through c show the interdependence between reception probability and range for all three aircraft. Figures 4.5.2.1-1a through c represent the combination of altitude, range and reception probability versus time. Figure 4.5.2.1-1a documents the expected characteristic; reception probability decreases with higher altitude and range.

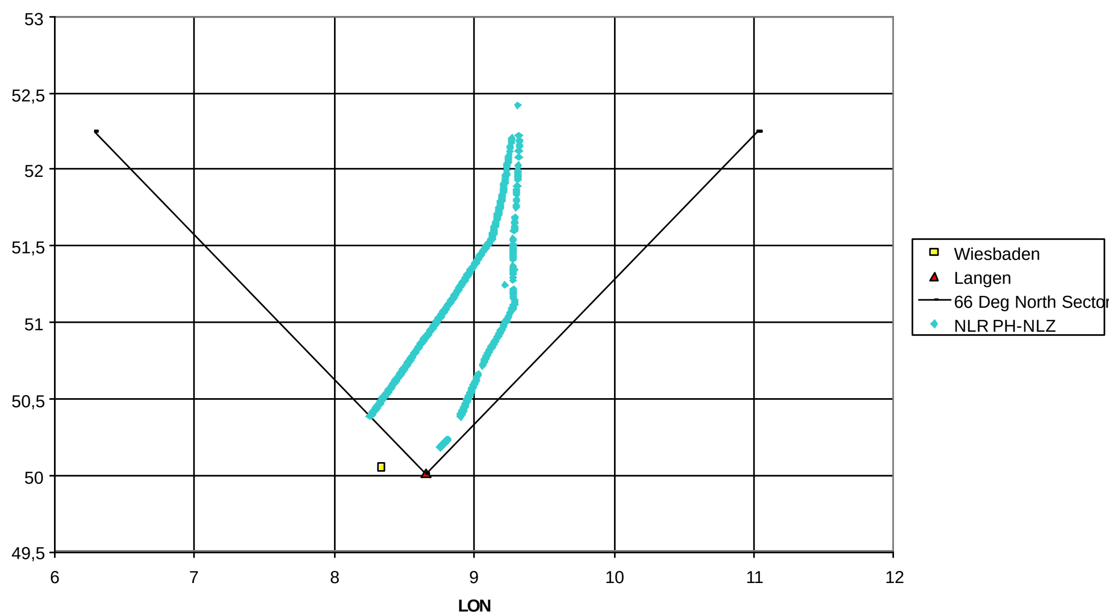


Figure 4.5.2.1-11a. Langen ERA NLR Ext. Squitter Track Plot, 24 May

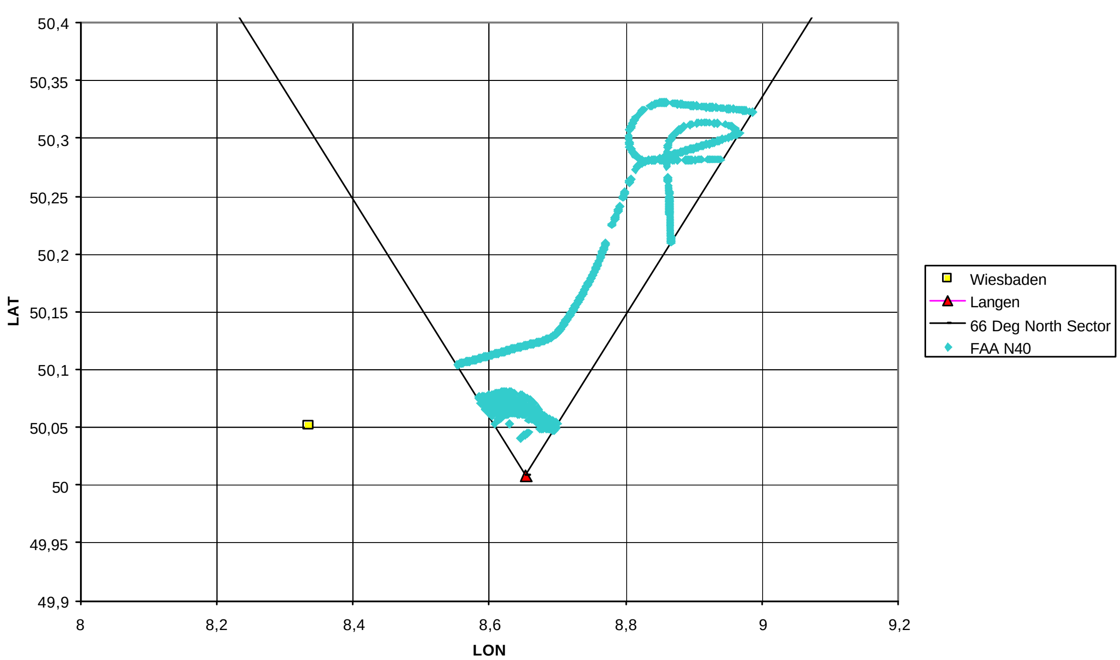


Figure 4.5.2.1-11b. Langen ERA N40 Ext. Squitter Track Plot, 24 May

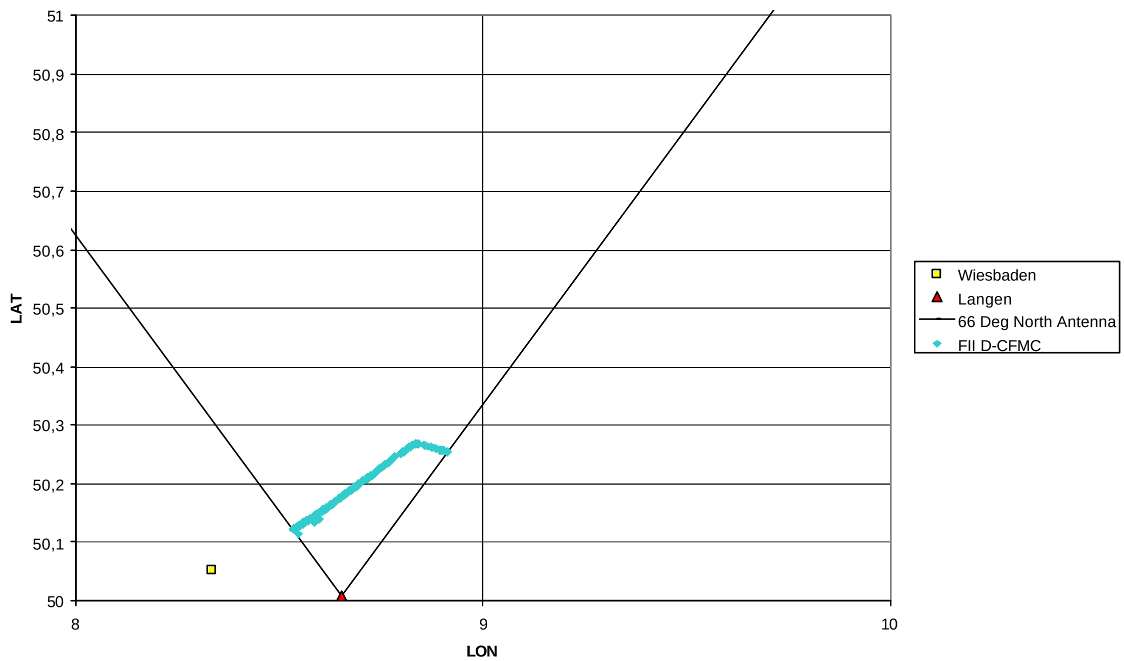


Figure 4.5.2.1-11c. Langen ERA FII Ext. Squitter Track Plot, 24 May

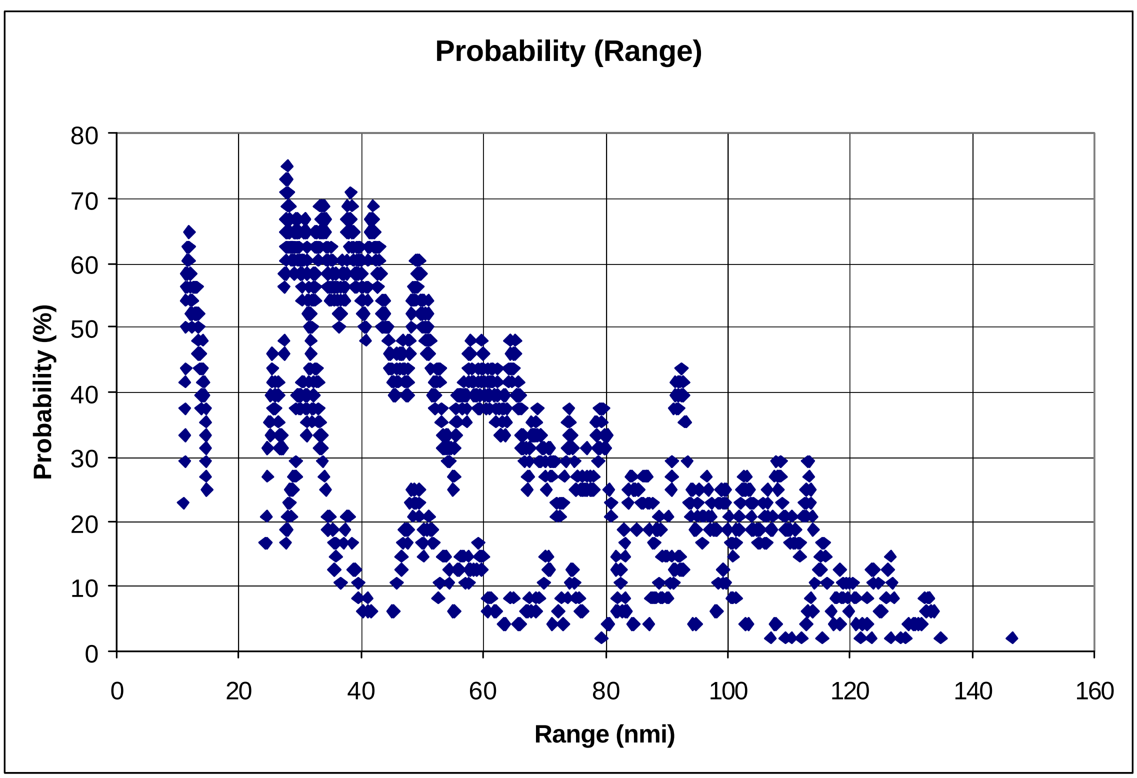


Figure 4.5.2.1-12a. Langen ERA NLR Ext. Squitter Probability vs. Range, 24 May

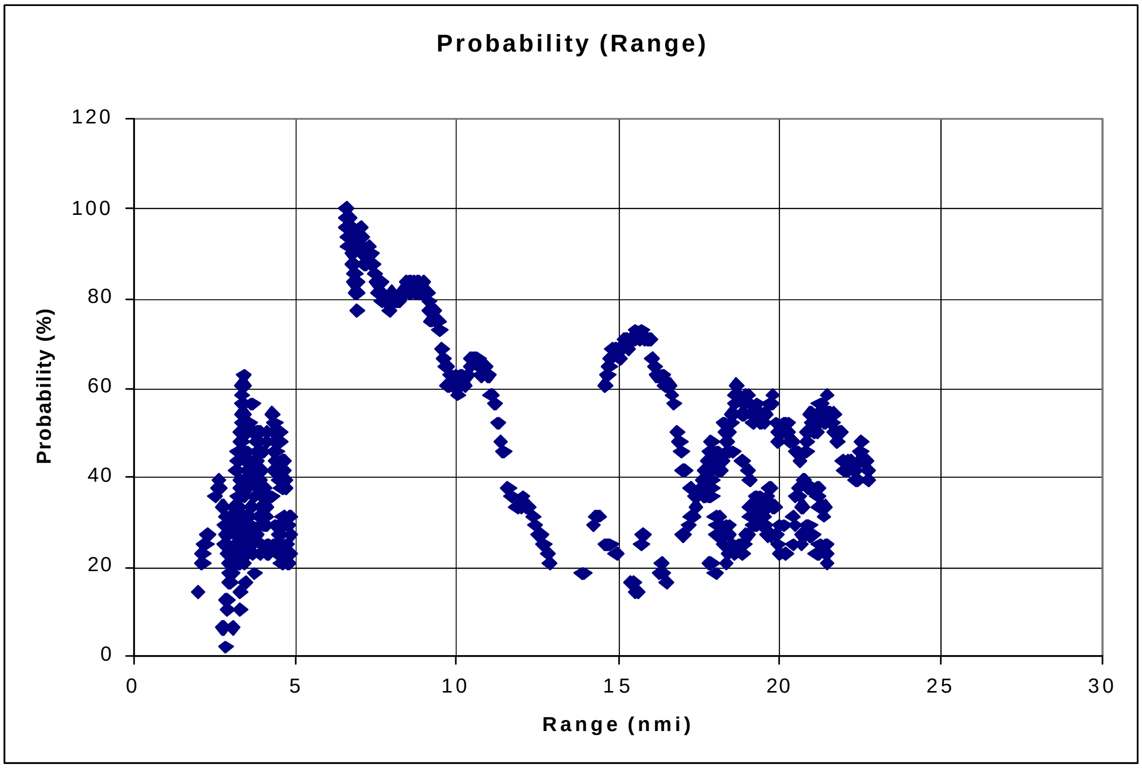


Figure 4.5.2.1-12b. Langen ERA N40 Ext. Squitter Probability vs. Range, 24 May

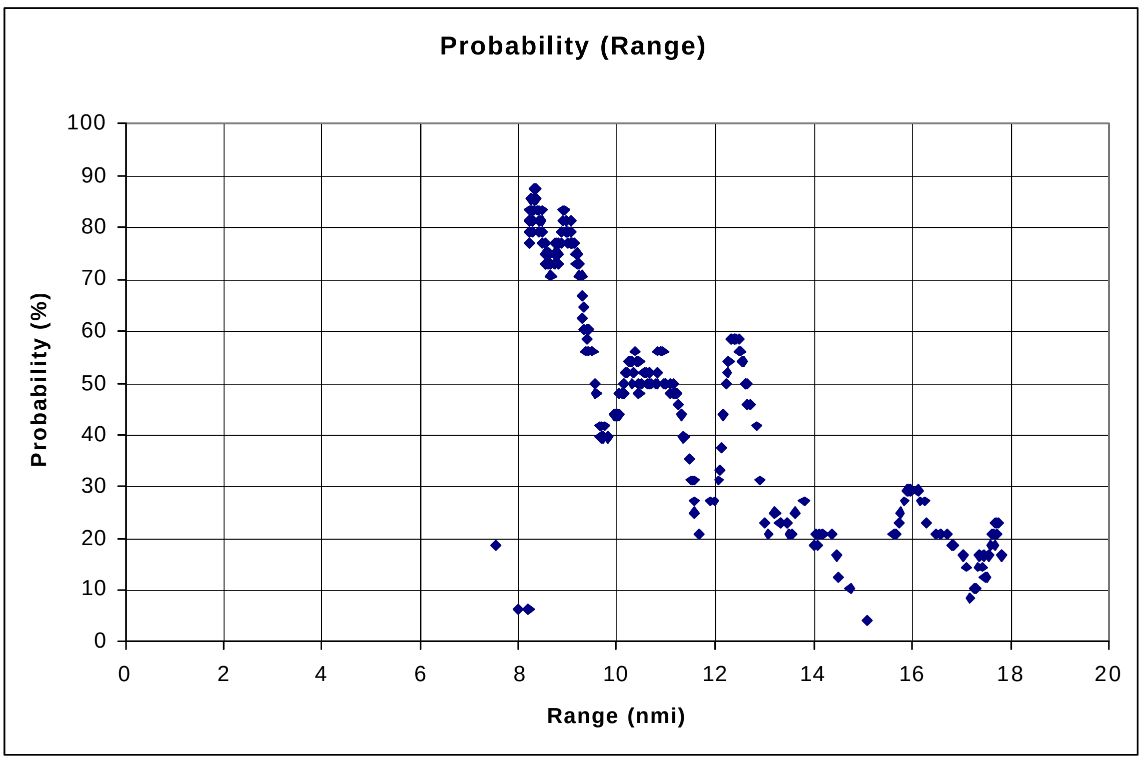


Figure 4.5.2.1-12c. Langen ERA FII Ext. Squitter Probability vs. Range, 24 May

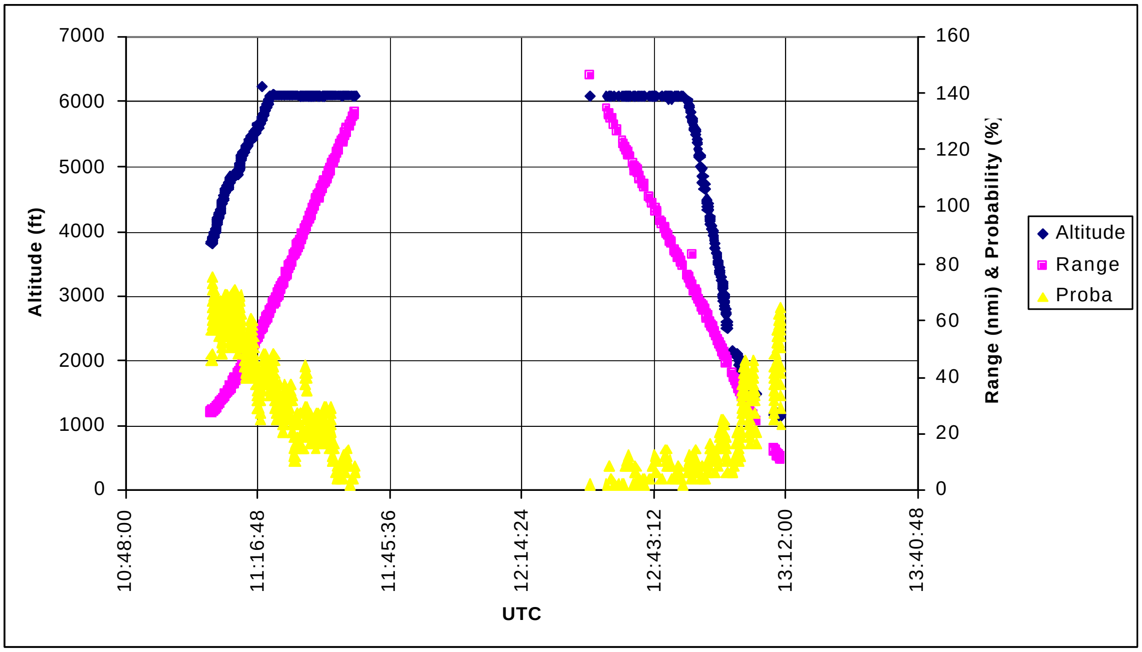


Figure 4.5.2.1-13a. Langen ERA NLR Ext. Squitter Altitude/Range/Probability vs. UTC, 24 May

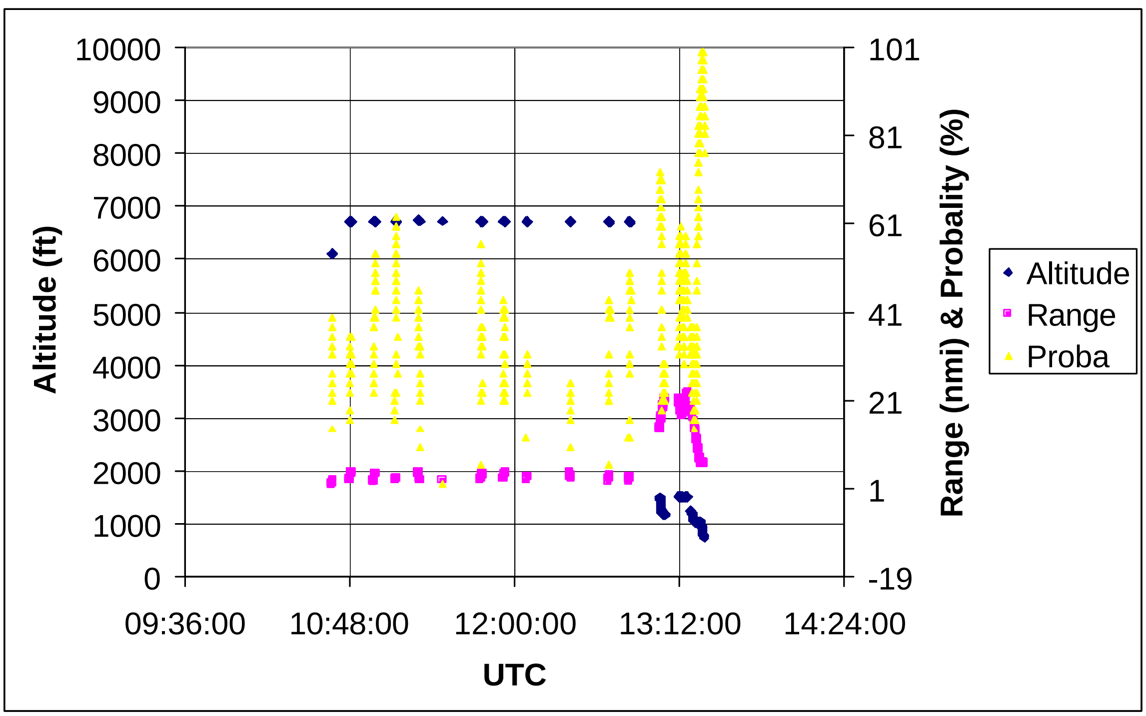


Figure 4.5.2.1-13b. Langen ERA N40 Ext. Sq. Altitude/Range/Prob. vs. UTC, 24 May

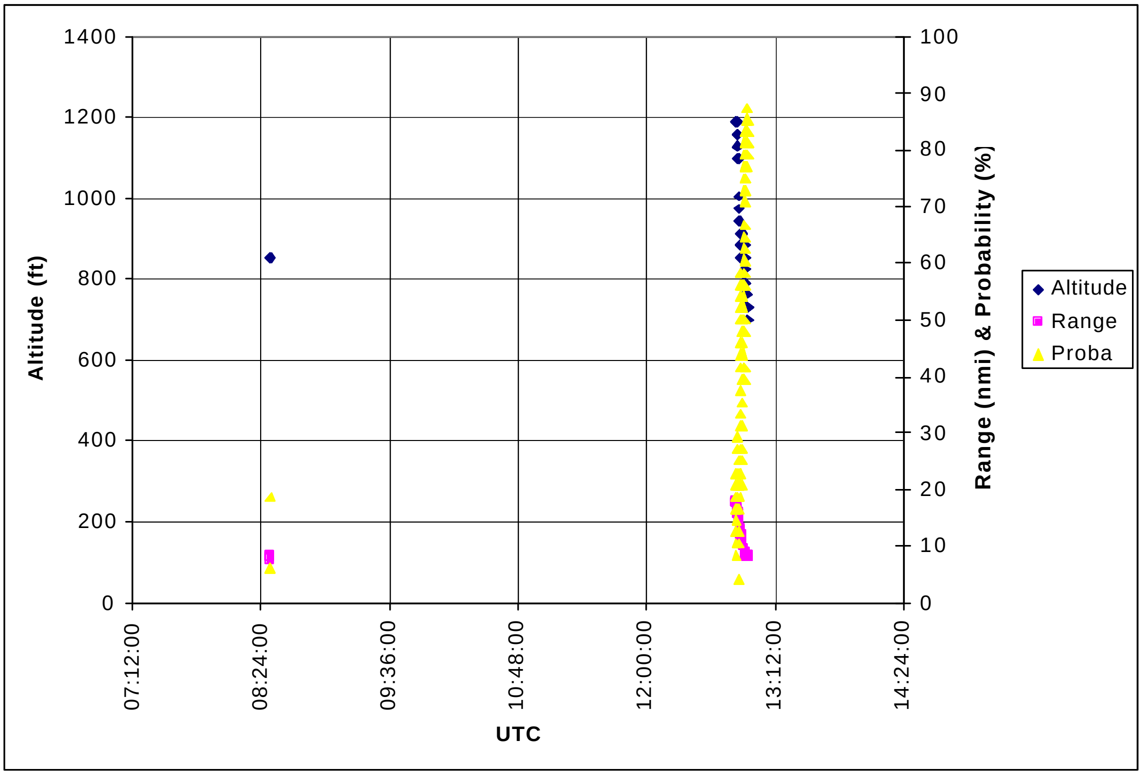


Figure 4.5.2.1-13c. Langen ERA FII Ext. Squitter Alt./Range/Prob. vs. UTC, 24 May

4.5.2.2 Wiesbaden Performance

List of Extended Squitter equipped aircraft tracks seen by Wiesbaden ground station during interval 8:19 - 13:28 UTC on 5-24.

ICAO ID (dec)	ICAO ID (hex)	Number of Receptions	Start time (5-24)	End time (5-24)	Aircraft
10791495	A4AA47	10358	10:28:46	13:28:34	N40
3985006	3CCE6E	6406	8:19:19	13:04:06	FII Beech King Air
4195922	400652	1528	10:54:58	13:28:48	BA950M
4195940	400664	949	8:19:19	10:47:19	BAW983
4735087	48406F	3349	10:42:04	13:10:55	NLR Metroliner

4.5.2.2.1 LDPU Receiver

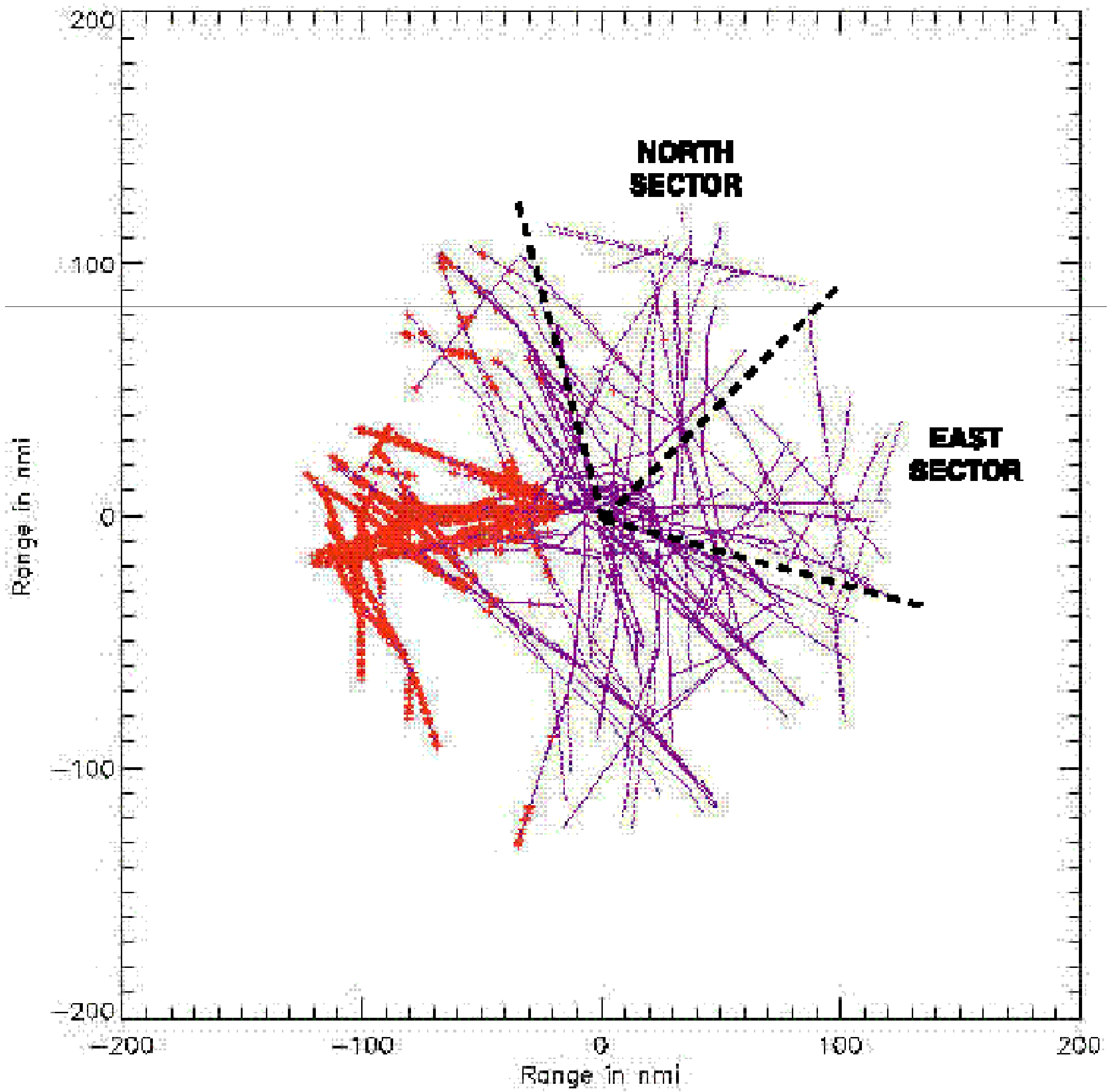


Figure 4.5.2.2-1. Wiesbaden LDPU Short Squitter Plot, 24 May

Note. Short Squitter receptions shown in this format indicate LDPU reception performance based on transmissions from existing aircraft currently flying in the local airspace. All Mode S transponders transmit short squitters, once per second. For each Mode S aircraft, reception of short squitters by the LDPU indicates reception quality, although the LDPU data does not indicate the location of the aircraft. At the same time, a Mode S radar is used to determine the aircraft location and the corresponding 24-bit address. Subsequent analysis of the data recorded both by the radar and the LDPU allows this plot to be made. For each scan of the Goetzenhain radar, a small point is plotted showing the current aircraft location. The LDPU receptions are then examined to determine whether short squitters were received from that aircraft during the scan. If not, the plotted point is changed to a large red symbol, to indicate a flaw in short squitter reception. See text for more specifics of the analysis. Note that only two antenna sectors were being used during these tests, so reception quality should be judged only within these two sectors, as marked in the figure. The results plotted here indicate good reception quality for nearly every aircraft in the airspace during the time of the test.

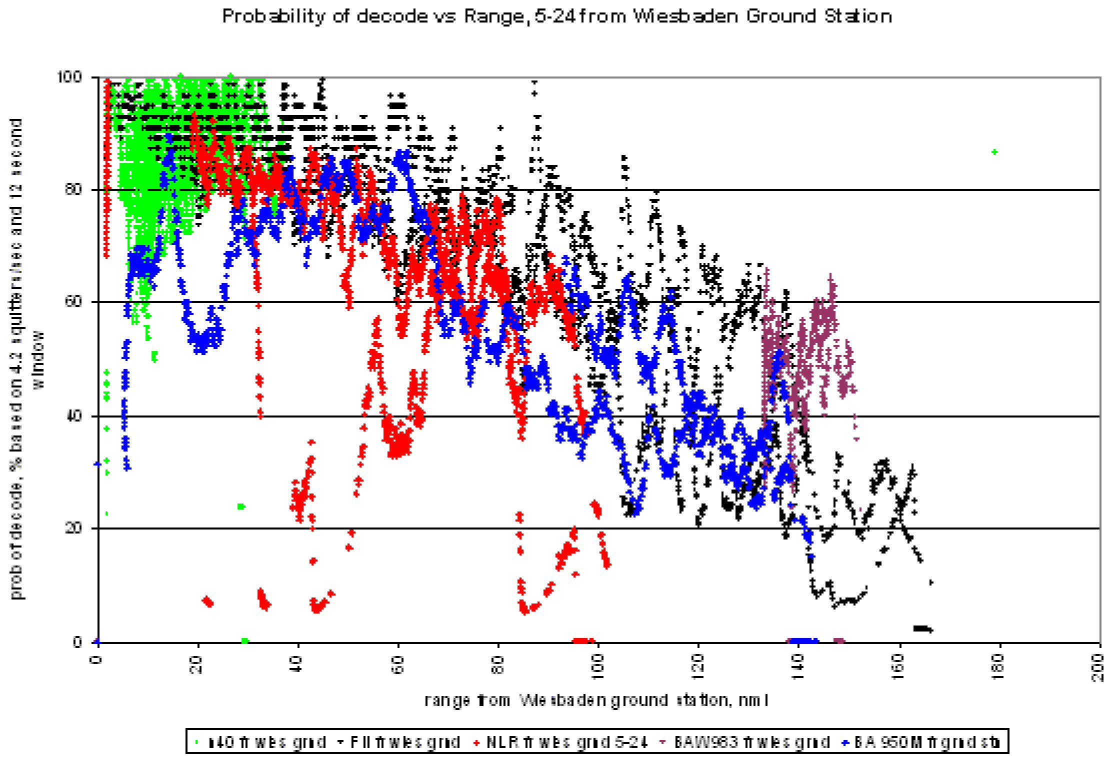


Figure 4.5.2.2-2. Wiesbaden LDPU Ext. Sq. Probability vs. Range, 24 May

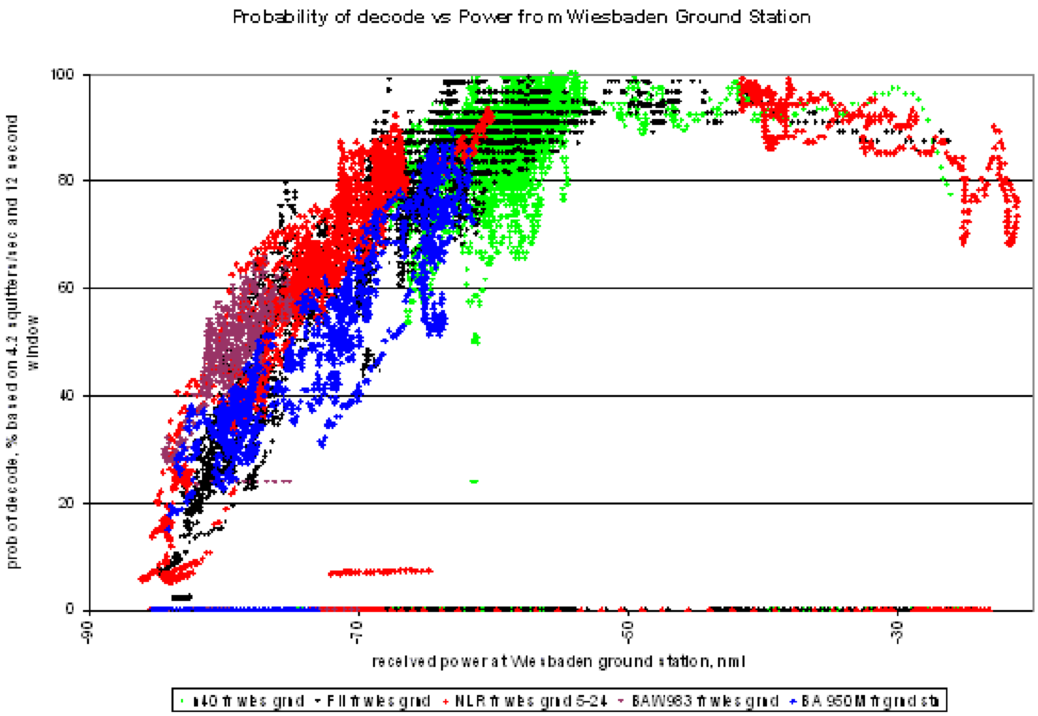
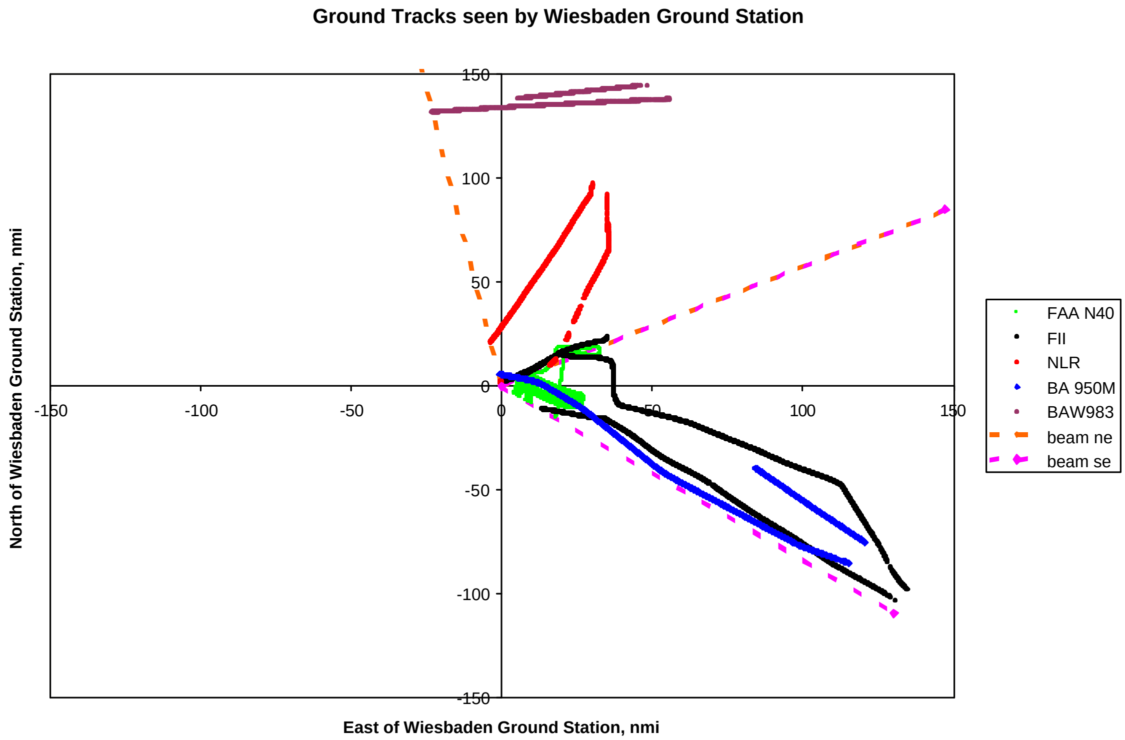


Figure 4.5.2.2-3. Wiesbaden LDPU Ext. Sq. Probability vs. Power, 24 May



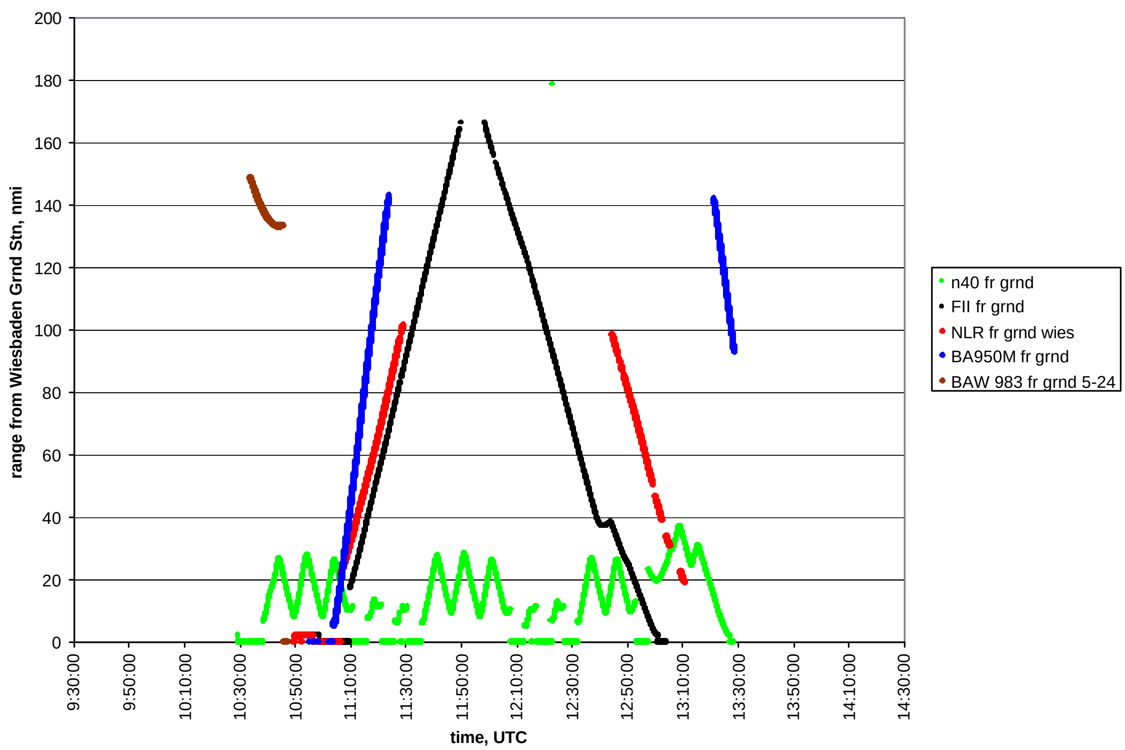


Figure 4.5.2.2-4. Wiesbaden LDPU Track Plot, 24 May

4.5.3 Air-to-Ground Reception Performance for All Days

4.5.3.1 Langen Performance

4.5.3.1.1 Langen LDPU Air-Ground Performance 20 May

The logs collected on the LDPU installed at Langen were analyzed to measure air-to-ground performance for all the Extended Squitter targets that were detected on the 20 May. The same performance analysis techniques were applied as in the logs of 24 May (see 4.5.2.1.1).

On 20 May two sets of recordings were collected on the Langen LDPU. The first set contained data from the period just before the start of the proper trial session. During that period the NLR Metroliner flew to Wiesbaden and in that period four BA targets of opportunity were also observed. Figure 4.5.3.1.1-1a shows their track plots as recorded in the Langen LDPU. It can be seen that there was one BA target of opportunity (BA-400668$_h$) traversing the north sector from east to west, two BA flights in the southeast sector (of the same aircraft: BA-40063$_h$), and one BA flight (BA-400665$_h$) which stayed outside Langen main beam coverage.

The second Langen LDPU log set contained data collected during the proper trial session. All three project aircraft participated and two BA targets of opportunity were also observed. Figure 4.5.3.1.1-1b shows the track plots logged by the Langen LDPU, except for the N40 whose track is plotted separately in Figure 4.5.3.1.1-1c (different scale). The FII aircraft does not appear in Figure 4.5.3.1.1-1b because its reports contained zero lat/long values. It turned out that FII was squittering zero lat/long throughout the trial session because of some configuration error. The FII log will not be discussed further in this section. The N40 flew a series of holding patterns close to Langen and remained only partly within main beam coverage (see Figure 4.5.3.1.1-1c). Furthermore, as Figure 4.5.3.1.1-1b shows, one of the two BA targets of opportunity (namely BA-400652$_h$) stayed completely outside main beam coverage. The other (BA-400664$_h$) arrived from the west and crossed into the southeast beam until its eventual disappearance.

Figures 4.5.3.1.1-1a through 1c confirm that the Langen antennas provided quite extensive coverage outside the main beams. In the subsequent performance analysis only the flight segments lying within main beam antenna coverage have been taken into account. It has also been pointed out previously that the position of the Langen antenna was not optimal and there were significant obstacles in the southeast direction. Therefore southeast beam coverage should be lesser than that of the north beam at low altitudes.

Figures 4.5.3.1.1-2a through 2c show the altitudes and ranges from Langen of the aircraft tracked by the LDPU. One dot has been plotted for each record in the LDPU log. Range has been calculated as horizontal great circle distance (no slant correction was applied). In particular, Figure 4.5.3.1.1-2a shows the altitudes and range from Langen of the flights that were tracked during the pre-trial session. Figure 4.5.3.1.1-2b shows the equivalent charts for the flights that were tracked in the southeast sector during the proper trial session. Finally, Figure 4.5.3.1.1-2c shows the altitude and range from Langen of the N40 flight.

The above figures indicate that the BA targets of opportunity were at much higher cruising altitudes (FL 300-370) than the project aircraft (FL150-250), and were tracked to much longer ranges from Langen. The N40 stayed within very close range of Langen (< 30 nmi).

Figures 4.5.3.1.1-3a through 3d show the variation of update intervals (in seconds) with range from Langen for the project aircraft and the BA targets of opportunity, considering only positions within main antenna beam coverage. Update intervals and their 98th percentile containment values were calculated according to the method explained in 4.5.2.1.1. For the 98th percentile containment values, 5 nmi distance bins (2 nmi in the case of N40 because it covered a much smaller range) were used.

Figure 4.5.3.1.1-3a shows the update intervals of NLR and BA-4006068$_h$ reports (both flights were in the north sector) from the first LDPU log. NLR report intervals stayed below 10 sec up to 90 nmi from Langen, while BA-400668$_h$ report intervals did so up to 165 nmi. It should be noted however that BA-400668$_h$ flew at much higher altitudes than NLR (FL 350 versus 150).

Similarly Figure 4.5.3.1.1-3b shows the update intervals of the two BA flight legs flown by BA-400663$_h$ passing through the southeast-sector beam (first LDPU log). Update performance was practically identical in the two legs up to 100 nmi from Langen. BA-400663$_h$ -a flew in from the west and started descending after overflying Langen. BA-400663$_h$ -b followed the opposite path, flying in from the east while climbing to its cruising level. Consequently in both cases range in the southeast sector beam may have been limited by the aircraft altitude and the elevated horizon of the Langen antenna.

Figure 4.5.3.1.1-3c shows the update intervals of the two flights in the southeast sector (NLR and BA-400664$_h$) that were recorded during the proper trial session (2nd LDPU log). In this case, BA-400664$_h$ cruised at high altitude (FL 330) through the southeast sector and its update intervals stayed below 10 sec beyond 190 nmi. On the contrary, NLR cruised at FL 200 and its update intervals stayed below 10 sec only up to 105 nmi.

Finally, Figure 4.5.3.1.1-3d shows the N40 update intervals for those segments of its flight path that fell within north or southeast beam coverage. The N40 stayed within close range of Langen but was flying holding patterns and hence turning often. Nevertheless N40 update intervals stayed practically below 2 sec except when at very close range to Langen (< 2.5 nmi), in which case the Langen antenna cone of silence may have affected the results.

Figures 4.5.3.1.1-4a through 4d show the air-to-ground Extended Squitter probabilities of decode for each aircraft versus range from Langen. Extended Squitter decode probabilities were estimated according to the method explained in 4.5.2.1.1 using a 24-sec sliding window. Only records within main beam coverage were taken into account in the calculations.

Figure 4.5.3.1.1-4a shows the Extended Squitter reception probabilities for NLR and BA-40068$_h$ (1st LDPU log). Both flights passed through the north-sector beam. Both aircraft transmitted position and velocity squitters but only the BA aircraft transmitted FID. The NLR reception probability declined only slightly up to 80 nmi and dropped quickly beyond that distance. BA-400668$_h$ reception probability also dropped quickly but only after 140 nmi.

Figure 4.5.3.1.1-4b shows the Extended Squitter reception probabilities for the two BA-400663$_h$ flights that took off and landed within the southeast sector in the pre-trial session (1st LDPU log). The BA aircraft squittered position, velocity, and FID. Their reception probability performances are similar up to 80 nmi from Langen. Beyond that distance, BA-400663$_h$ -b performs somewhat better but in both cases performance is probably limited by the Langen antenna horizon.

Figure 4.5.3.1.1-4c shows the Extended Squitter reception probabilities for the two flights (NLR and BA-400664$_h$) that were tracked in the southeast sector during the proper trial session (2nd LDPU log). NLR squittered position and velocity but no FID, while the BA aircraft broadcast all three squitter types. NLR reception probability declined more rapidly beyond the 80th nmi from Langen, while BA-400664$_h$ reception probability remained fairly stable up to 160 nmi. Ba400664$_h$ performance is indeed quite comparable to the performances seen in the north sector for similar flight altitudes (> 30000 ft).

Finally Figure 4.5.3.1.1-4d shows the N40 reception probability versus range from Langen during the proper trial session (for in-beam reports). N40 squittered position, velocity and FID reception probability stayed above 50% except at very close distances (< 3 nmi) from Langen

Comparison of the update interval and decode probability results shows that both types of analysis led to similar conclusions. The LDPU logs a report even when only one (velocity or position) squitter is received therefore update intervals tends to remain low until the Extended Squitter reception probability drops to very low values.

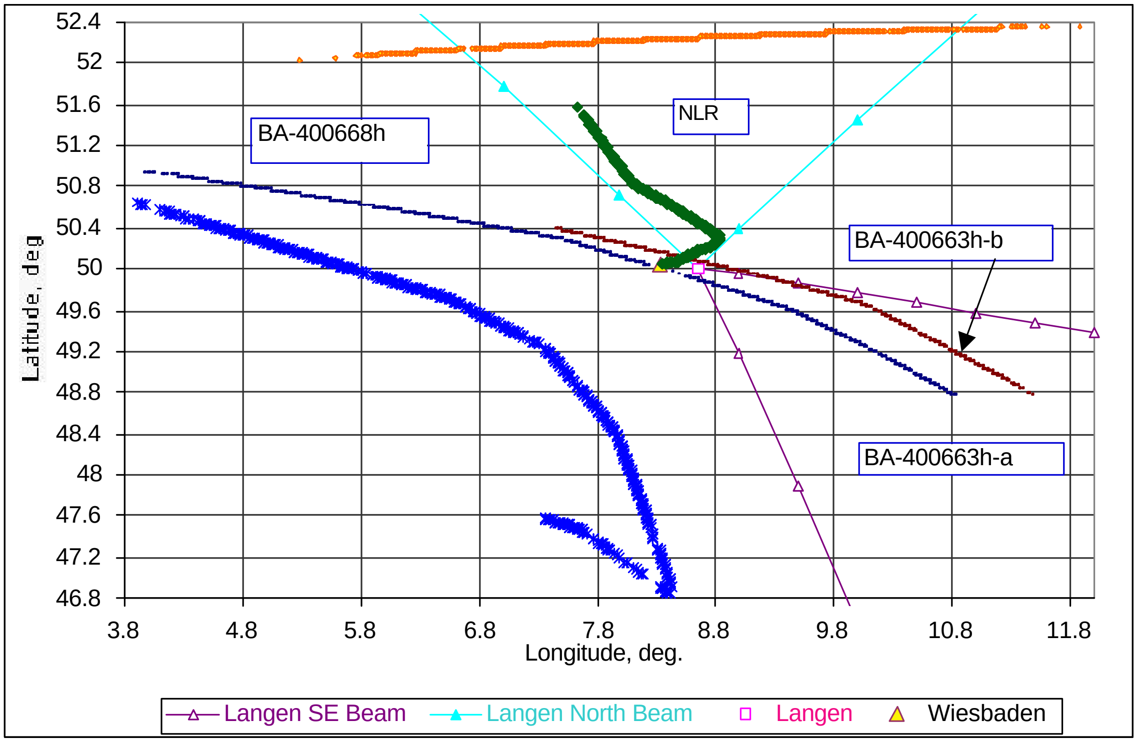


Figure 4.5.3.1.1-1a. Ext. Squitter Target Track Plots Langen LDPU

Pre-Trial, 20 May

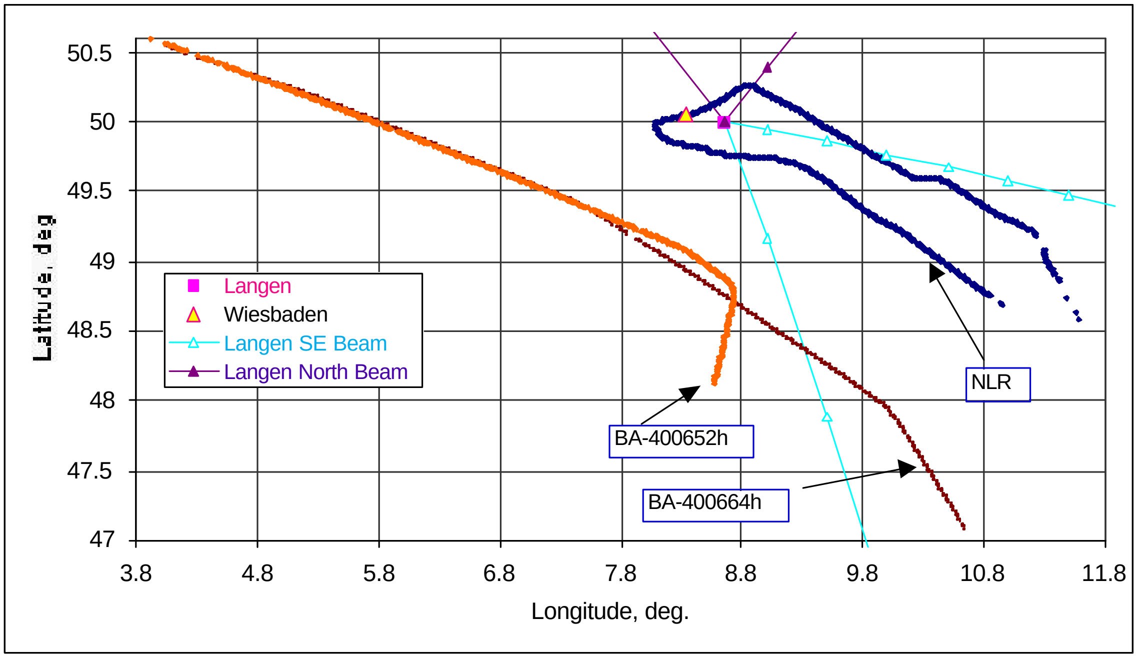


Figure 4.5.3.1.1-1b. Ext. Squitter Target Track Plots, Langen LDPU Pre-Trial, 20 May

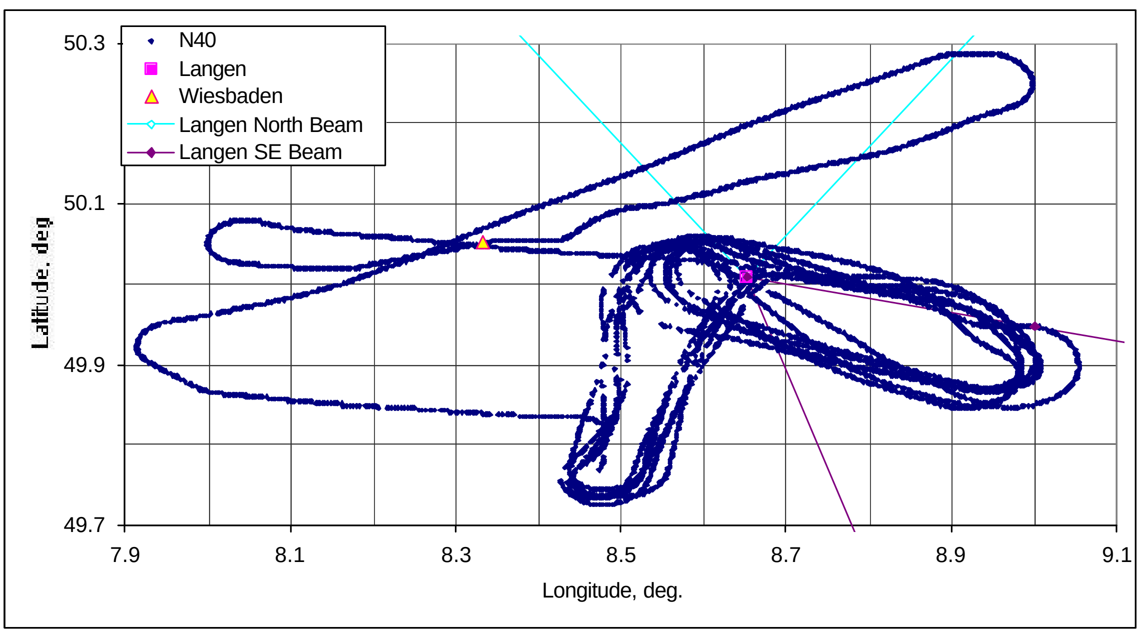


Figure 4.5.3.1.1-1c. N40 Track Plots, Langen LDPU, 20 May

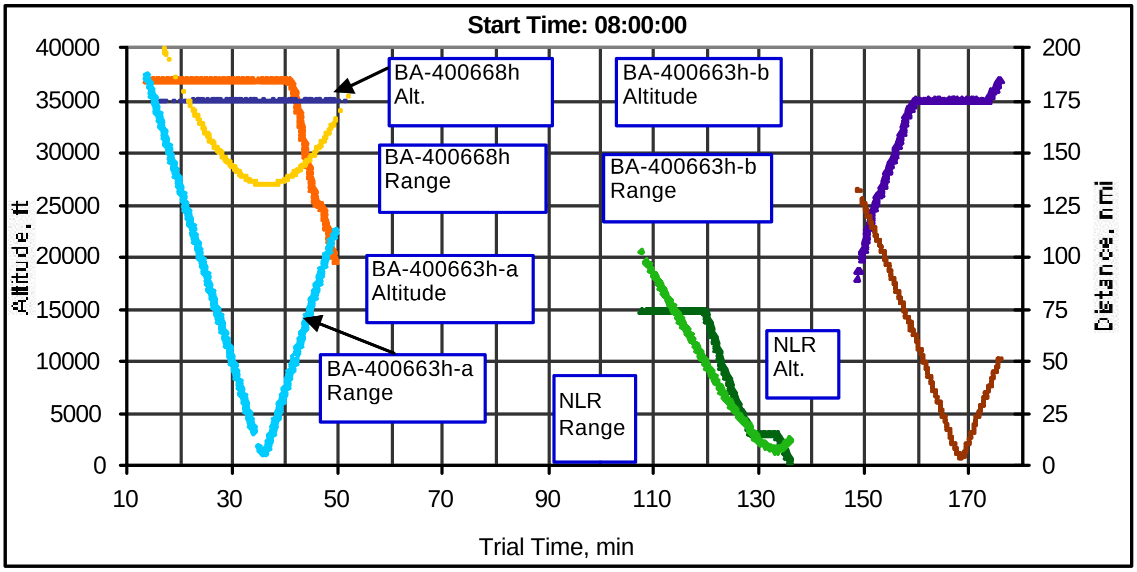


Figure 4.5.3.1.1-2a. Target Altitude and Range over Time, Langen LDPU Pre-Trial, 20 May

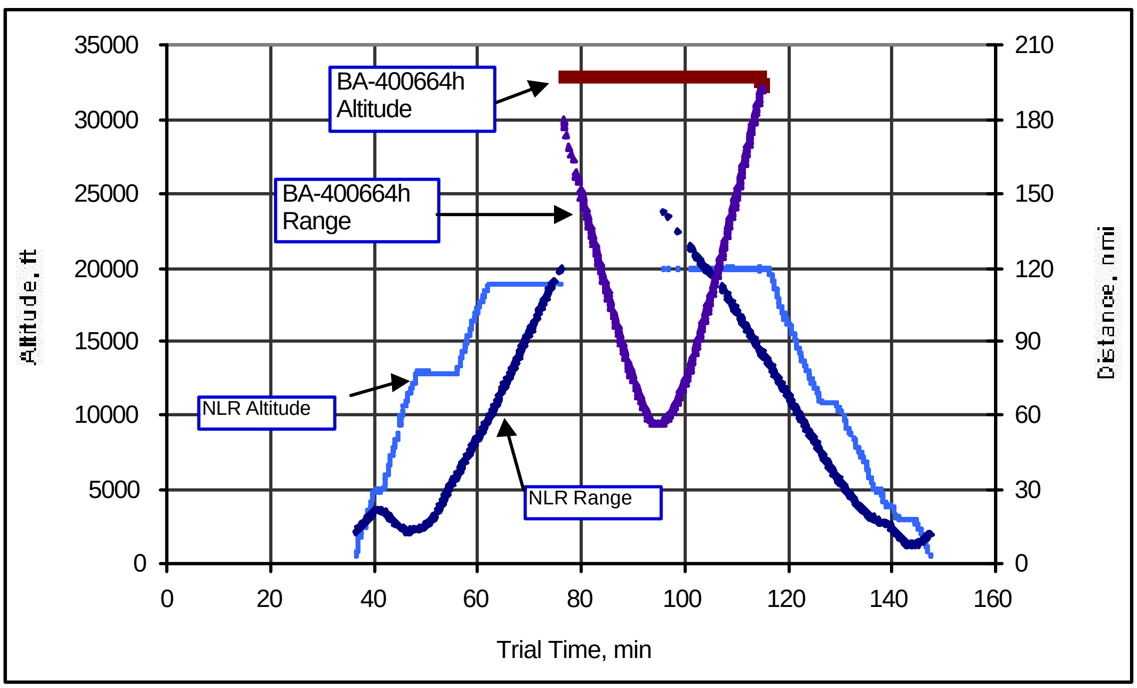


Figure 4.5.3.1.1-2b. Target Altitude and Range over Time, Langen LDPU 20 May

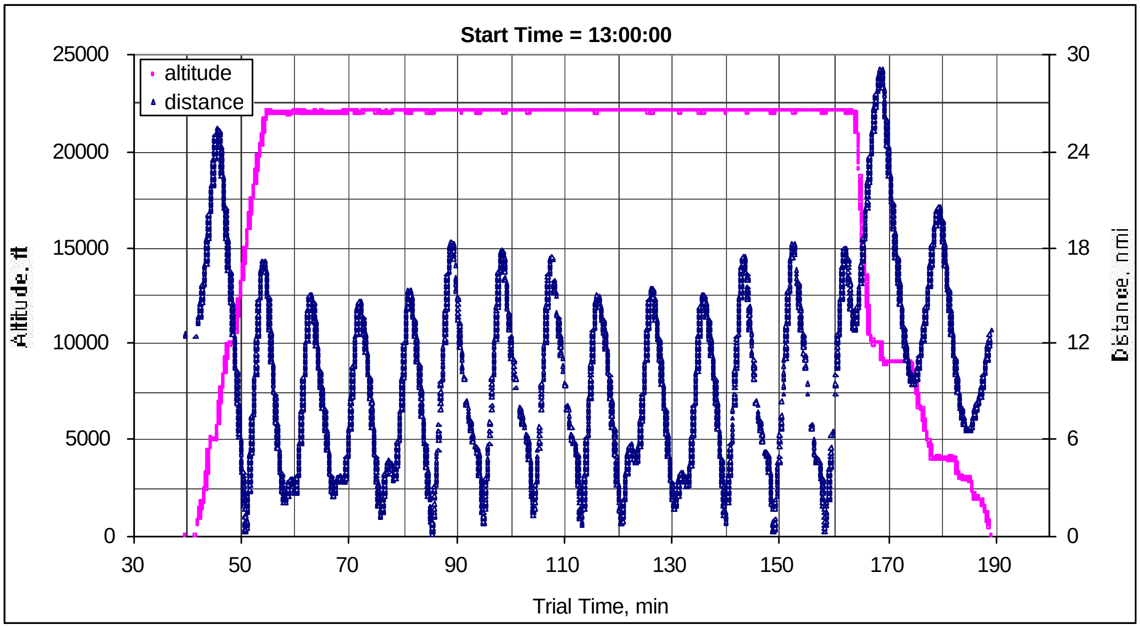


Figure 4.5.3.1.1-2c. N40 Altitude and Range vs. Time, Langen LDPU 20 May

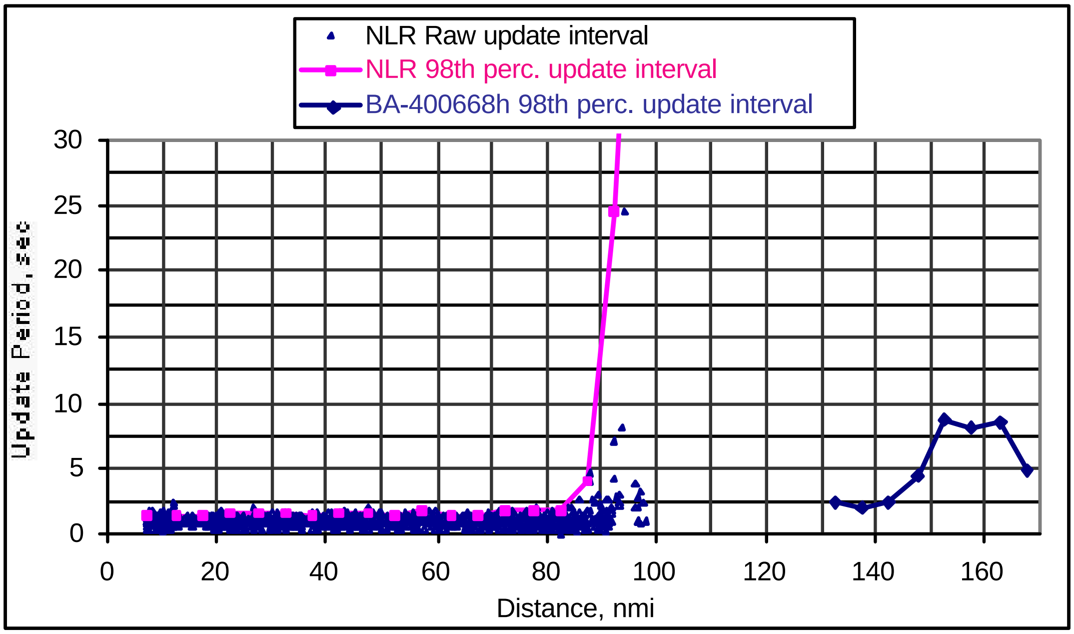


Figure 4.5.3.1.1-3a. Update Intervals vs. Range, Langen LDPU

Pre-Trial North Beam Reports, 20 May

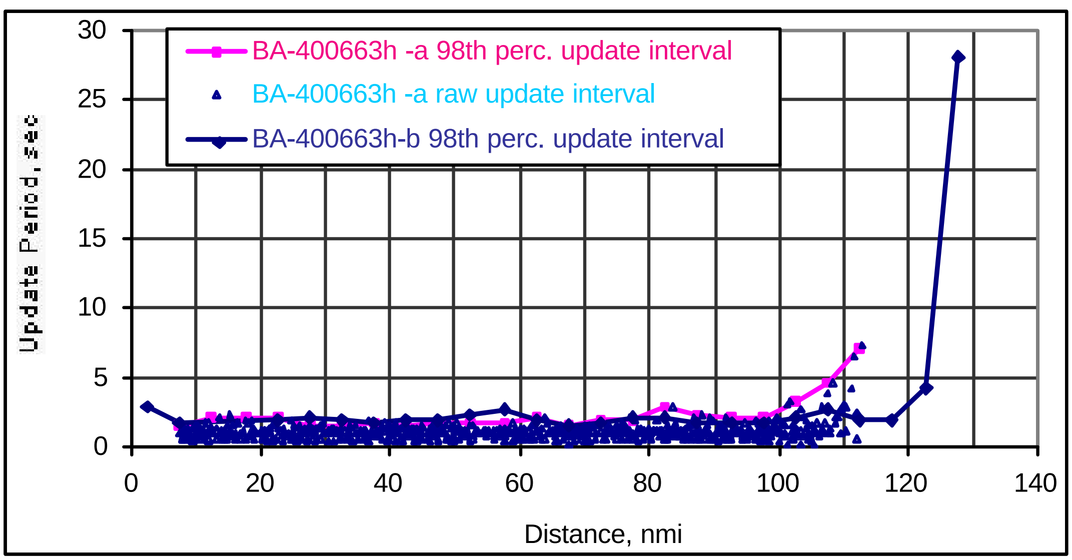


Figure 4.5.3.1.1-3b. Update Intervals vs. Range, Langen LDPU

Pre-Trial SE Beam Reports, 20 May,

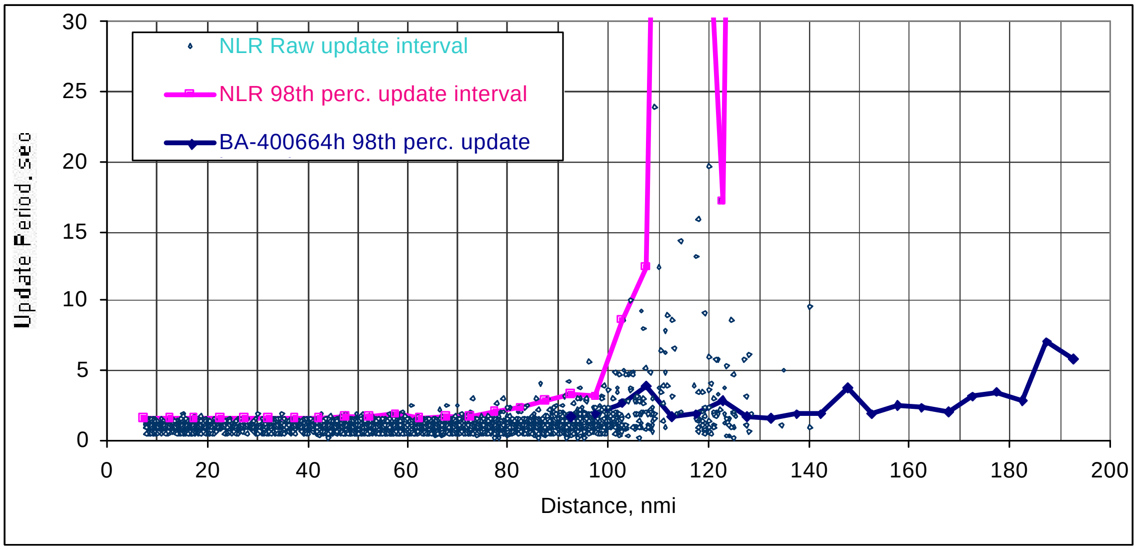


Figure 4.5.3.1.1-3c. Update Intervals vs. Range, Langen LDPU SE Sector Reports, 20 May

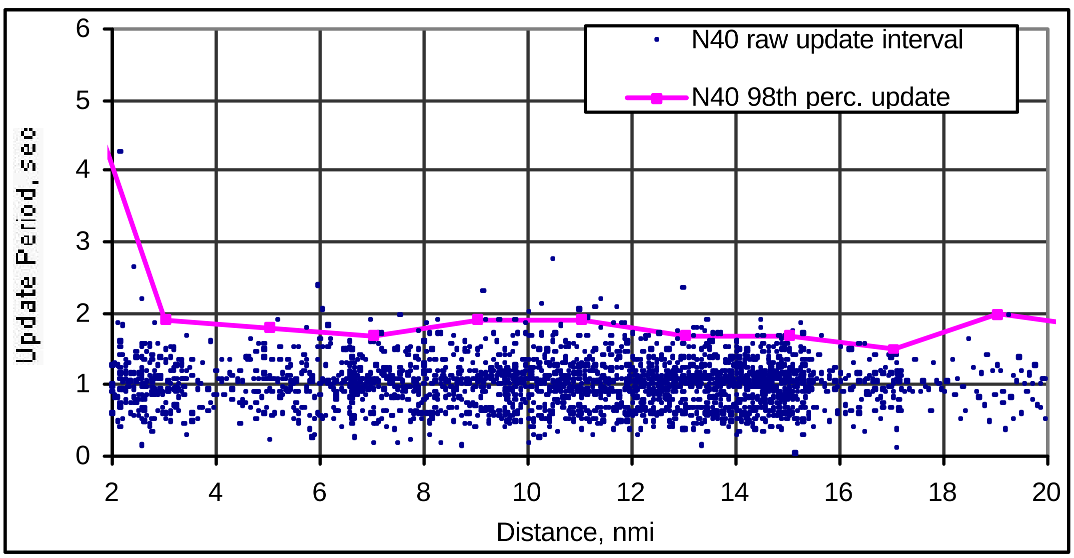


Figure 4.5.3.1.1-3d. N40 update Intervals vs. Range at Langen LDPU, 20 May

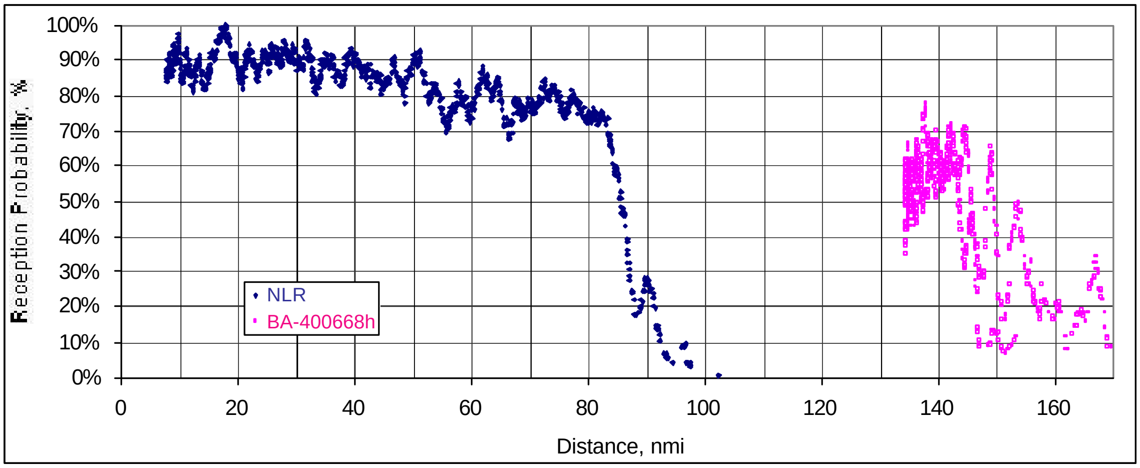


Figure 4.5.3.1.1-4a. Ext. Squitter Reception Probability vs. Range

Langen LDPU North Sector, Pre-Trial 20 May

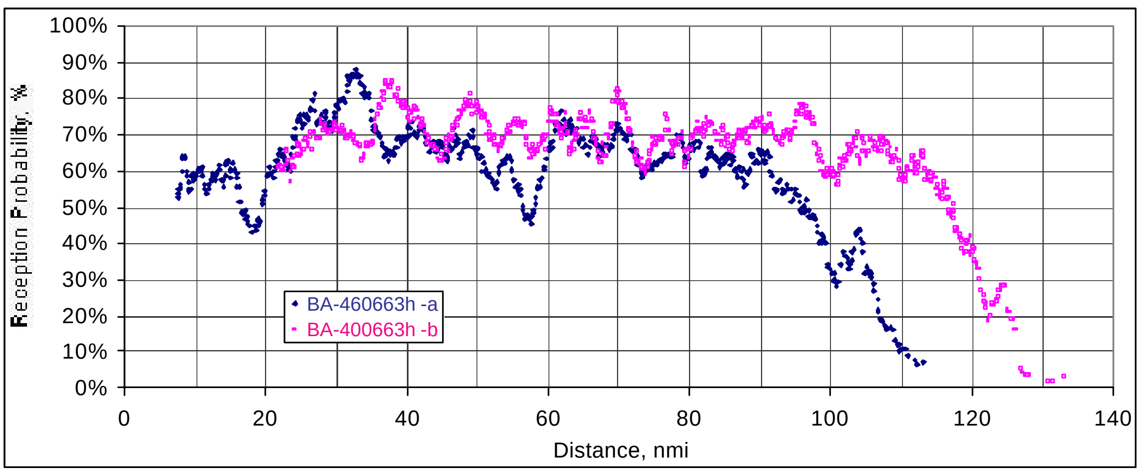


Figure 4.5.3.1.1-4b. Ext. Squitter Reception Probability vs. Range

Langen LDPU SE Sector, Pre-Trial 20 May

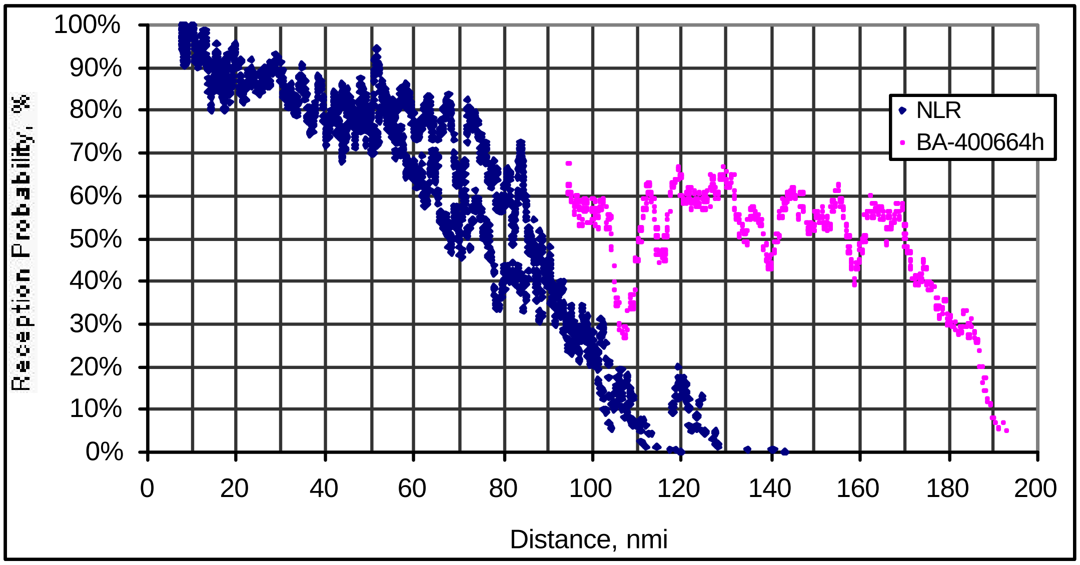


Figure 4.5.3.1.1-4c. Ext. Squitter Reception Probability vs. Range

Langen LDPU SE Sector , 20 May

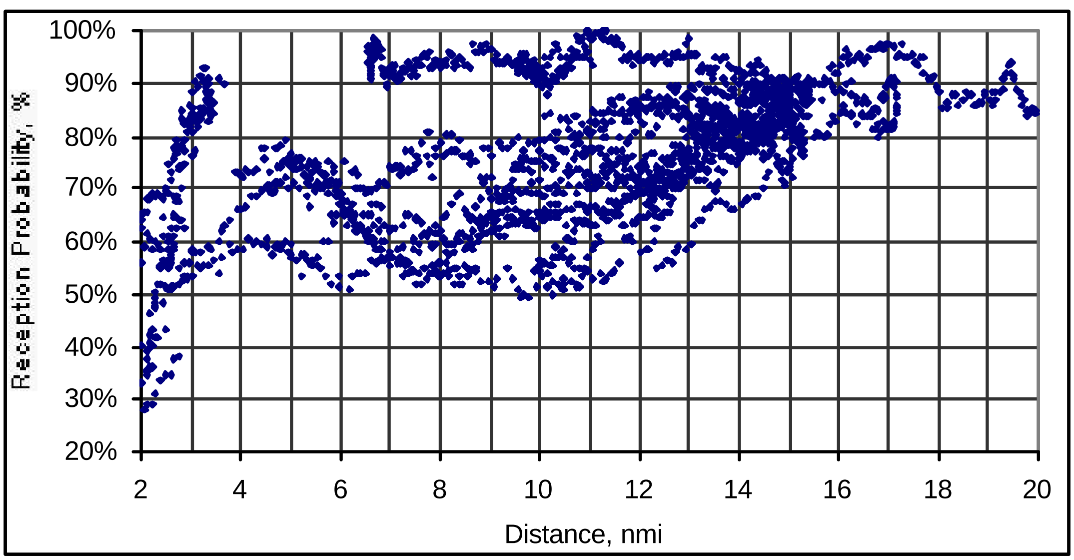


Figure 4.5.3.1.1-4d. N40 Ext. Squitter Reception Probability vs. Range

Langen LDPU, 20 May

4.5.3.1.2 Langen ANS-MAGS Receiver Air-Ground performance all days

As indicated in 4.5.2.1.2 analyses were performed to produce a detailed picture of the performance of Extended Squitter received by the ANS-MAGS station. This section will provide information on analysis results of all flight days. Comparable cases have been grouped together in figures. Analyses concerning received power were not made because the ANS-MAGS does not provide such information. Since the 24 May data is already analyzed and described in detail in 4.5.2.1.2, this section mainly focuses on the other flight days and flights through the southeast antenna sector used by the ANS-MAGS on 25 May. Squitter update intervals and reception probabilities were calculated only by using position squitter information provided by the ANS-MAGS.

Figure 4.5.3.1.2-1 shows an overview of project aircraft and a BA target of opportunity. Tracks were recorded with the ANS-MAGS receiver during all flight days (including the 24 May). Several project aircraft tracks through the ANS-MAGS coverage heading toward Wiesbaden at low altitudes are not displayed to avoid overloading the figure with unnecessary information. No track data for 20 May are displayed. On this day the FII was flown on a north-south profile within the north antenna sector, but its Extended Squitter contained a wrong fixed position outside the German airspace and the other project aircraft were received only during the approach to Wiesbaden.

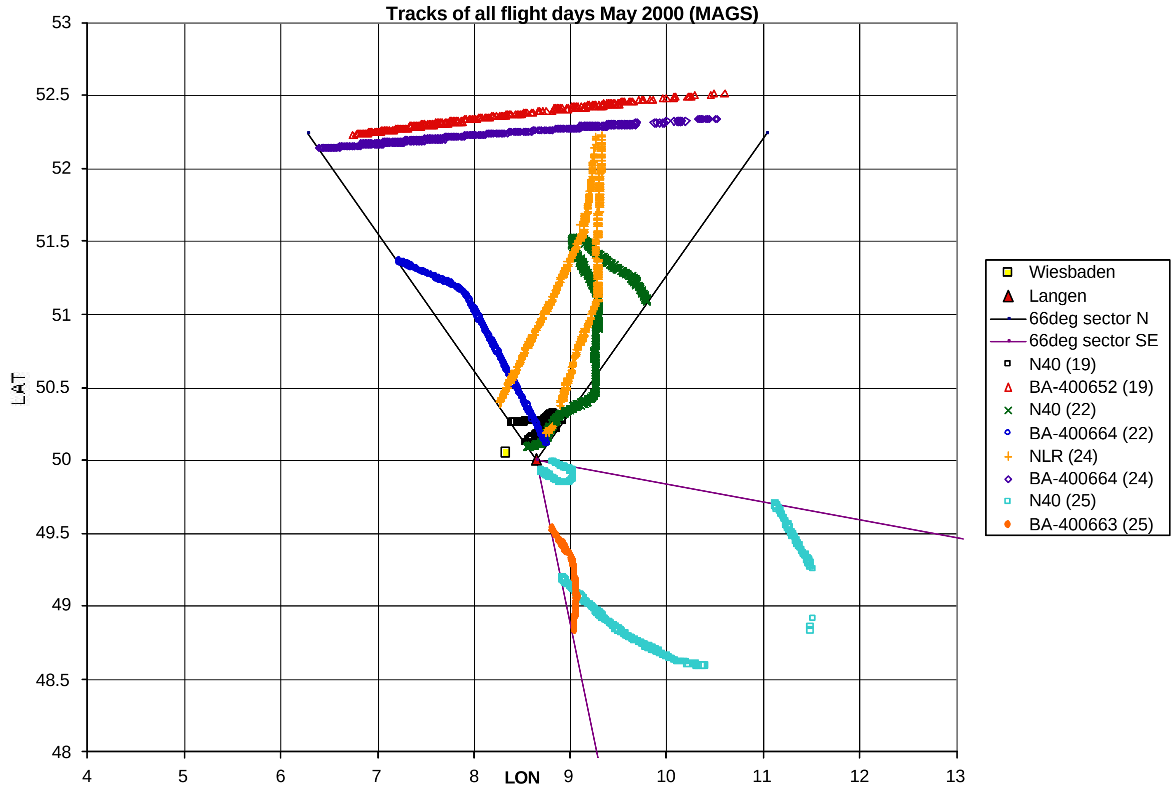


Figure 4.5.3.1.2-1. Langen ANS-MAGS Track Plot, All Days

Note. *The beamwidth of the Langen sector antennas is 66 degrees. The unequal scale values for the axes might the beamwidth look wider than it actually is.*

The curves in Figure 4.5.3.1.2-2 are mean values calculated from all project and BA flights of all flight days. They give an overall view on the performance of the ANS-MAGS ground station. The update interval peak and the drop of the probability at 130 nmi represent the end of the coverage for a maximum altitude of 22000 ft. The same appears at 170 nmi for the BA flights at high altitudes (35000 - 39000 ft). In consideration that no special optimized equipment (the ground station itself and peripherals) has been used for the trials and the site was non-optimal, the results are better than expected.

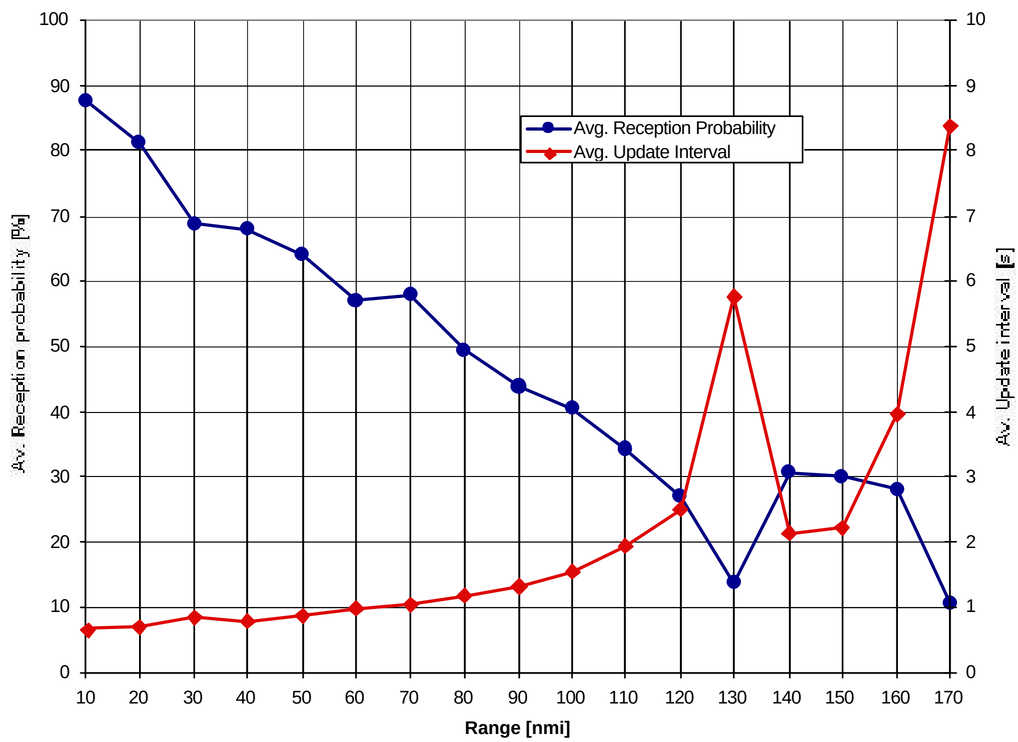


Figure 4.5.3.1.2-2. Langen ANS-MAGS Average Probability and Update Interval vs. Range, All Days

Figure 4.5.3.1.2-3 presents the measured range, altitude and probability of reception versus time. This figure shows project flights and targets of opportunity received by the ANS-MAGS ground station, their range and altitude and the corresponding reception probability values. Since the NLR flight on 24 May is already described in 4.5.2.1.2 and its curves would overlap N40 (25) and BA-400663$_{h,}$, it is not presented here. There are two main groups of flights indicated. One with the BA aircraft flying at high altitudes and long ranges (left part) and one with project and BA aircraft flying at medium and low altitudes and various ranges (right part). Normal behavior was observed, the reception probability corresponds to the range and altitude of the flight as expected.

Only N40 on the 25 May flight is a conspicuous case. On the outbound leg the probability is better than on the inbound one. This is unexpected and similar the NLR case described in 4.5.2.1.2. It could be caused (as for the NLR case) by the antenna position on the aircraft fuselage and the corresponding aspect angle to the receiver and/or by a changed interference environment during the flight.

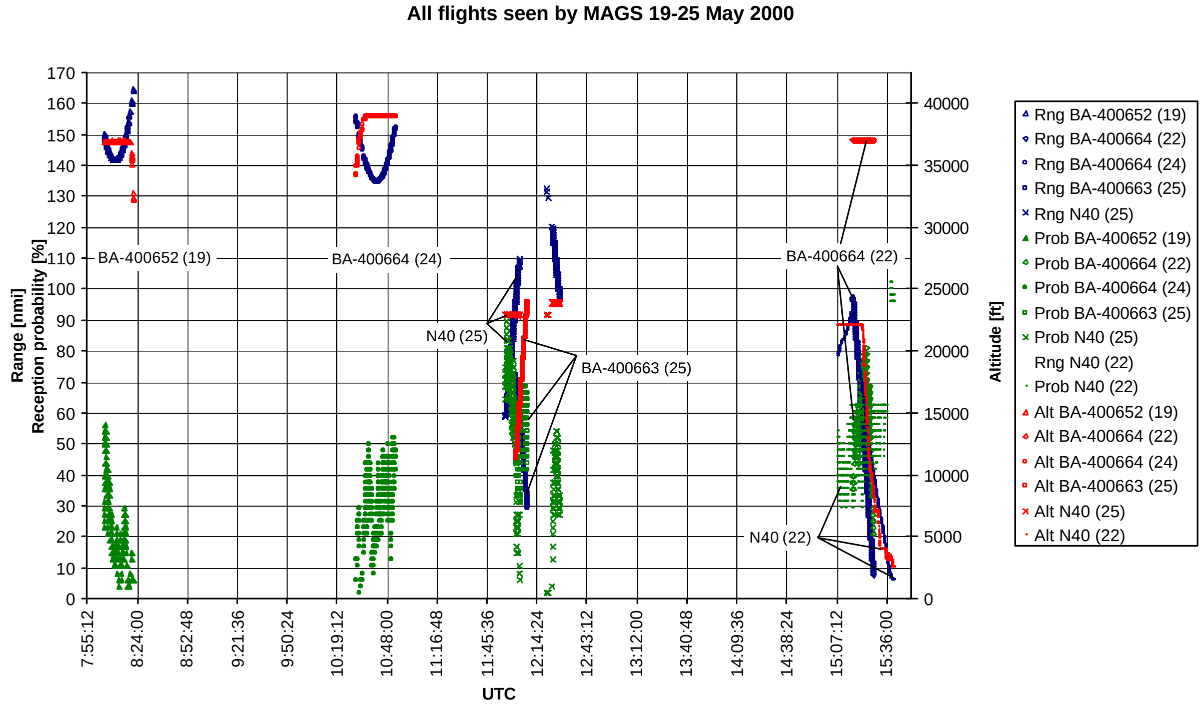


Figure 4.5.3.1.2-3. Langen ANS-MAGS Range, Altitude, Probability vs. Time, All Days

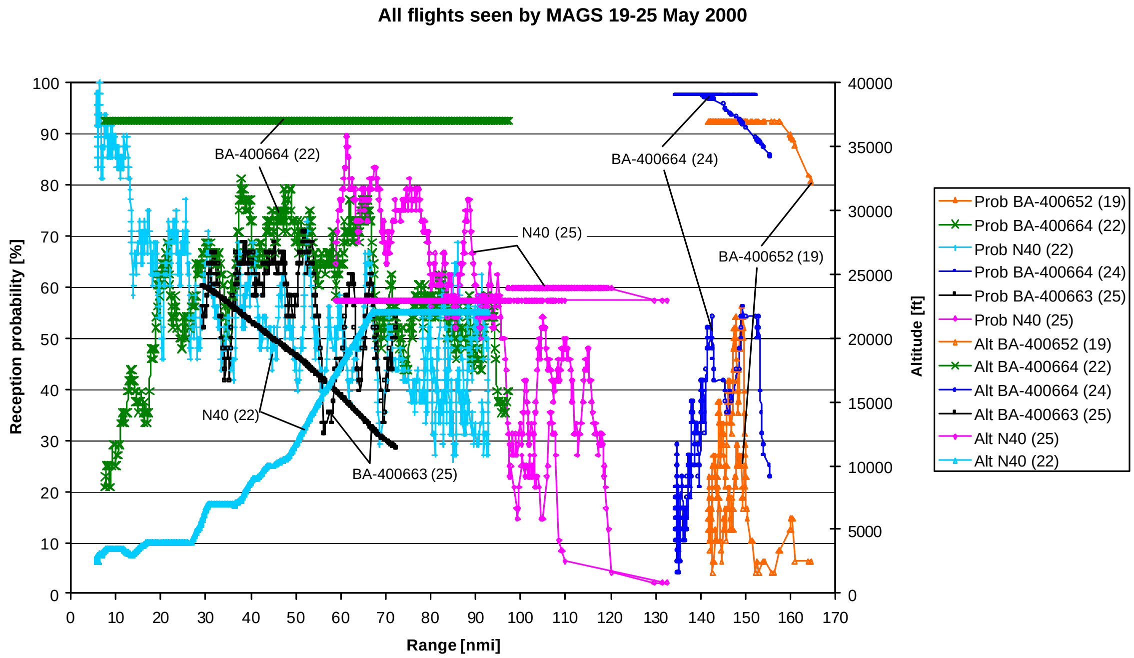
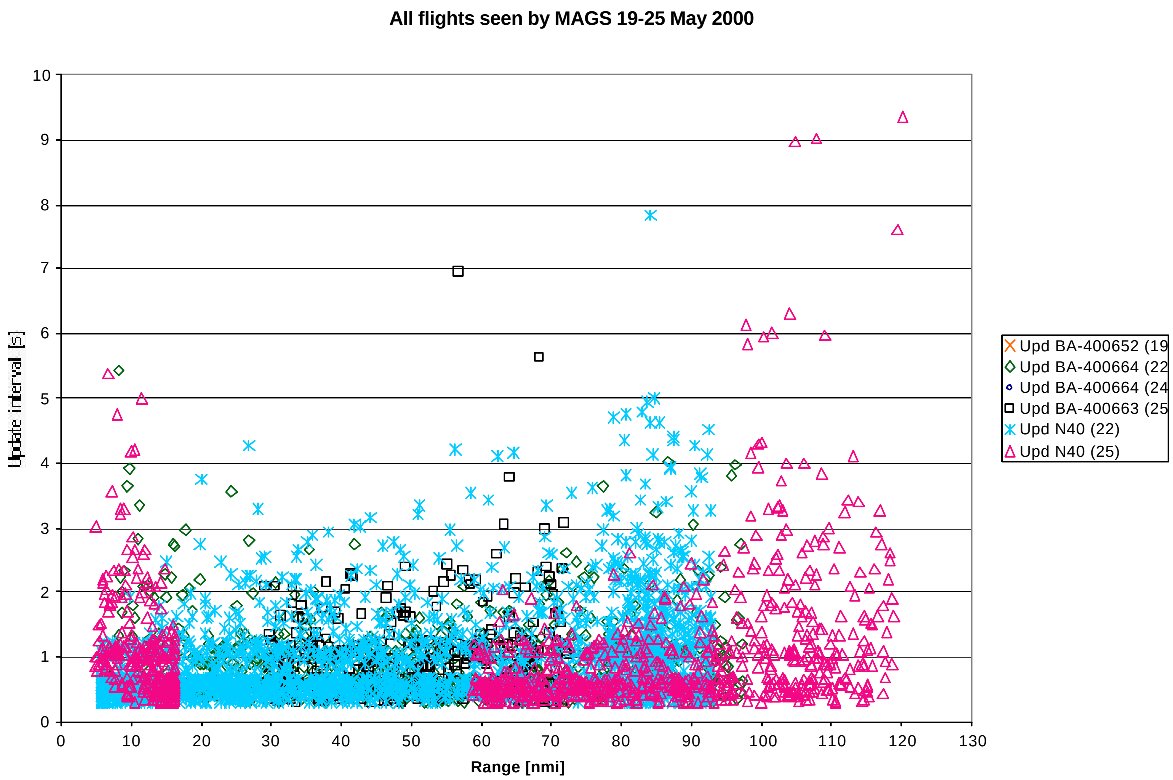


Figure 4.5.3.1.2-4. Langen ANS-MAGS Ext. Sq. Probability vs. Range, All Days

Figure 4.5.3.1.2-5 presents the reception probabilities in a more detailed way showing the different aircraft with their altitude and reception probability vs. range. The influence of altitude and range on the reception probability is clearly recognizable. The BA flights at high altitudes and long ranges have similar probability values as flights at medium and low altitudes and ranges from 5 to 120 nmi.

Squitter update intervals are presented in Figure 4.5.3.1.2-5. The figure is split into two diagrams presenting ranges from 5 to 130 nmi and 130 to 170 nmi. As seen in the upper diagram, the update intervals of the position squitter is below 10 seconds. This should be sufficient for most applications. Update intervals at long ranges show a different behavior, seen in the lower diagram. While BA-400664$_h$ (24) still has relatively short update intervals the BA-400652$_h$ (19) intervals have a completely different distribution and they are much longer. This is caused by different aircraft ranges and altitudes. The BA-400652$_h$ (19) is flying at a lower altitude and at a longer range than the BA-400664$_h$ (24). At this range the end of the ANS-MAGS coverage is reached for that altitude (37000 ft).



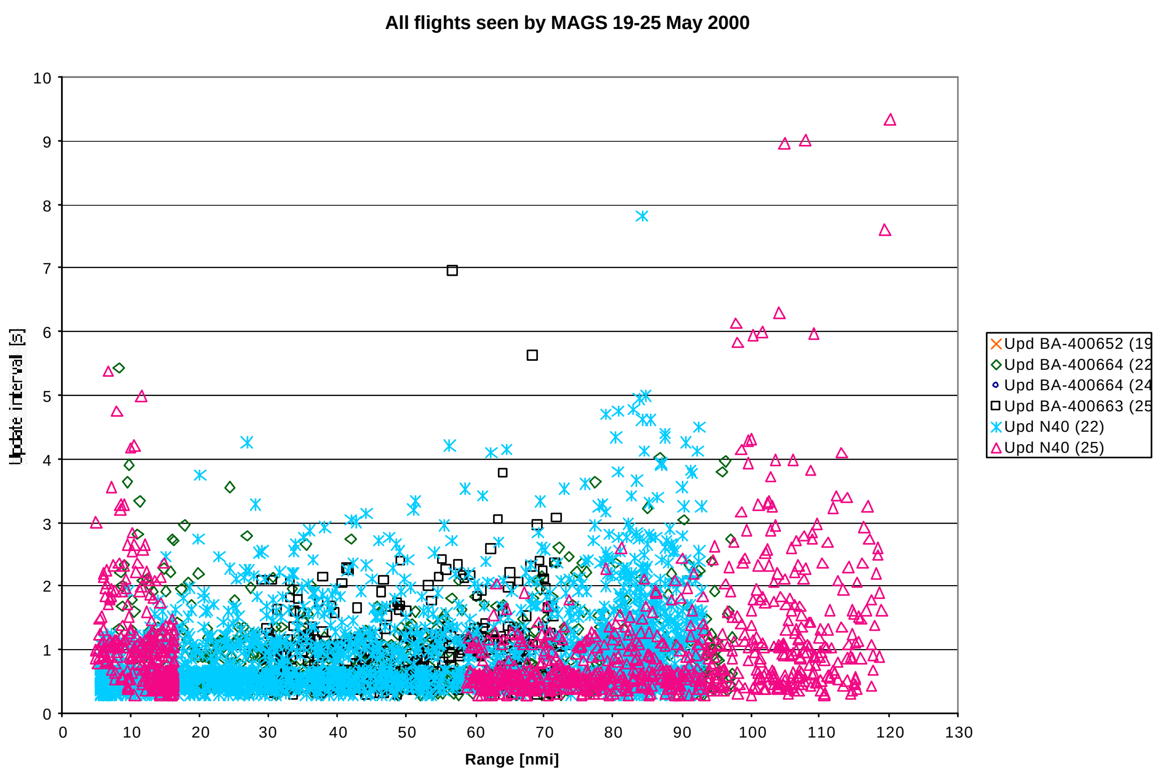


Figure 4.5.3.1.2-5. Langen ANS-MAGS Ext. Sq. Update Interval vs. Range, All Days

4.5.3.1.2.1 Special observations

The next two figures present two interesting cases observed during data analysis. The first case is a detected update probability difference between outbound and inbound directions. The second case is an update probability difference between a weekday flight and a flight performed on a weekend.

Figure 4.5.3.1.2-6 presents the first case (outbound/inbound flights) and it was detected after data analysis of two different project flights. The aircraft were flying in different sectors and on different days (NLR on 24 May and north, N40 on 25 May and southeast), but on almost the same altitudes and time frame.

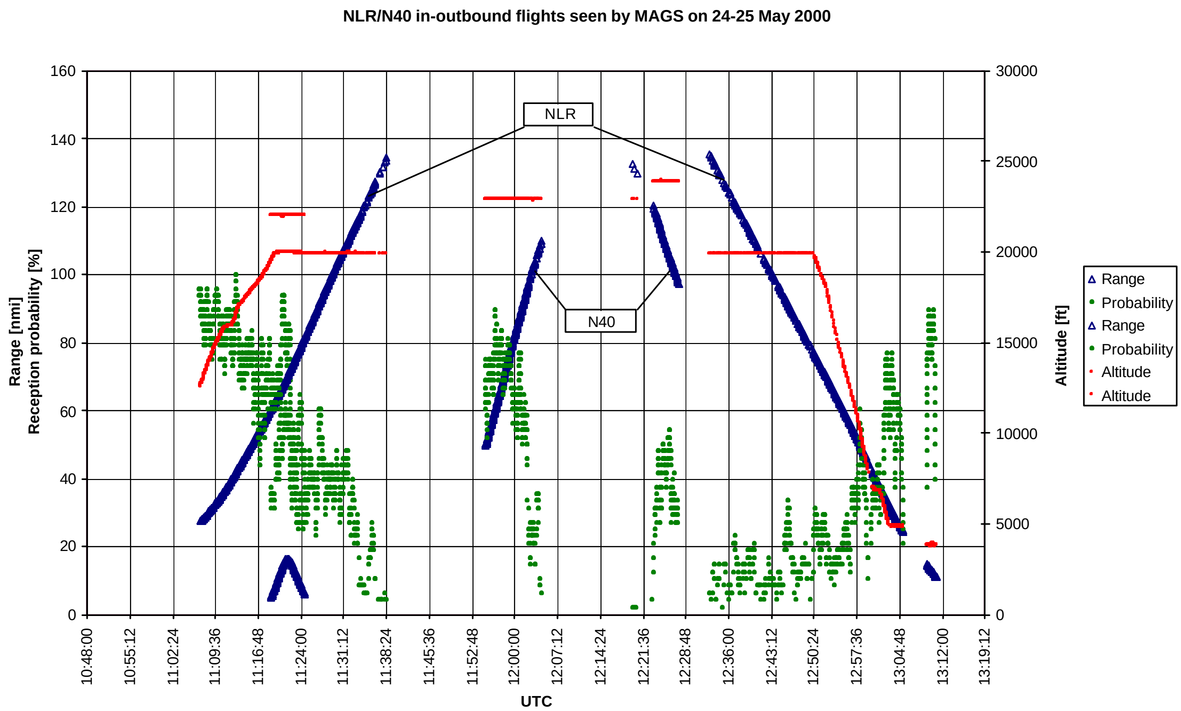


Figure 4.5.3.1.2-6. Langen ANS-MAGS NLR and N40 Inbound-Outbound Differences, 24 and 25 May

Comparing reception probability values of both flights for inbound and outbound at a particular range (e.g., 100nmi), a difference of about 20 % can be seen. Possible causes can be the antenna position on the aircraft fuselage and the corresponding aspect angle to the receiver, a changed interference environment (higher fruit rates) during the inbound parts of the flights or a combination of both.

Figure 4.5.3.1.2-7 presents the reception probability difference between weekday and weekend flights. It shows N40 approaching Wiesbaden on Saturday 20 May and Monday 22 May. The aircraft was flying the same profile on both days (NE to SW through the ANS-MAGS north antenna sector) and at almost the same time. There was only a time difference of 30 minutes between both flights. Calculating the reception probability mean values the Saturday flight has a 9 % better performance. This is probably caused by the lower number of aircraft in the coverage and thus weaker fruit interference.

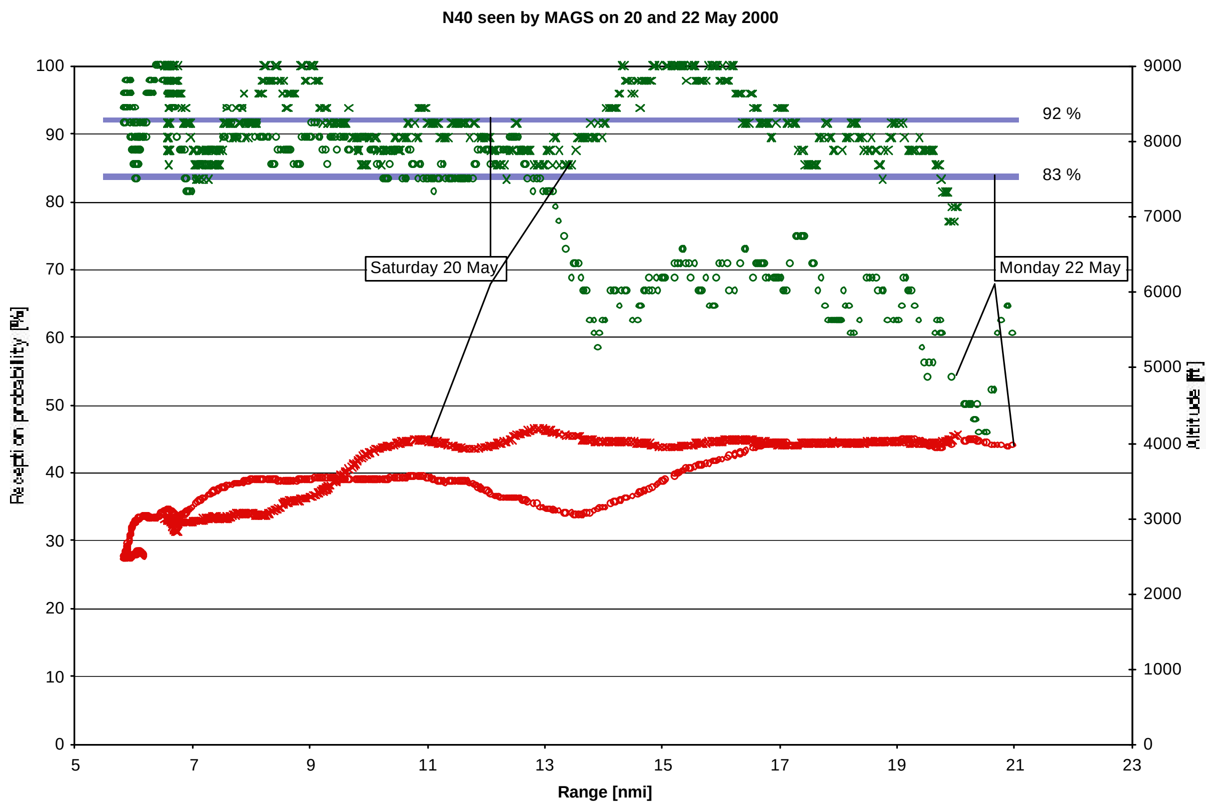


Figure 4.5.3.1.2-7. Langen ANS-MAGS N40 Day-to-Day Reception Probability Differences, 20 and 22 May

Both cases need further investigation, especially a comparison with RMF Fruit rates measured at Wiesbaden. This would clarify the influence of the Fruit interference on Extended Squitter air-ground performance within the Frankfurt environment.

4.5.3.1.3 Langen ERA Receiver Air-Ground Performance for All Days

The first part of this section includes the figures documenting individual aircraft flights in various dependency graphs. Figures 4.5.3.1.3-1 through 3 show flight track, reception probability versus time and combination of altitude, range and reception probability versus time for FAA aircraft on 19 May.

Next are figures from the measurements on 20 May. Figures 4.5.3.1.3-4a and 4b show the tracks of NLR, FAA and FII aircraft. The boundaries of the antenna beam are shown in these figures. The track of FII looks to be completely out of the main beam. Figures 4.5.3.1.3-5a and 5b show the interdependence between reception probability and range for all three aircraft. Figures 4.5.3.1.3-6a through c show combination of altitude, range and reception probability versus time. Figure 4.5.3.1.3-6c shows direct interdependence between altitude and reception probability in the case of constant range.

Figures 4.5.3.1.3-7 through 9 document the flights of FAA and FII aircraft on 22 May. Figure 4.5.3.1.3-10a through c describes the flight of FAA aircraft on 25 May. The antenna beam is not in the north direction but in the direction of 135 degrees.

The next part of this section presents summary graphs of all data collected by the ERA ADS-B ground station. Figure 4.5.3.1.3-11 shows reception probability vs. range. The probability decreases with increasing range mainly as expected. Figure 4.5.3.1.3-12 represents update interval vs. range. We can notice that update interval gradually drops with the range. Figure 4.5.3.1.3-13 shows update interval vs. altitude. Figure 4.5.3.1.3-14 represents reception probability vs. altitude. It is very interesting to notice the minimum of the reception probability by the altitude between 2000 and 3000 metres. Figure 4.5.3.1.3-15a describes track plot and figures 4.5.3.1.3-15b and c detailed views of this plot.

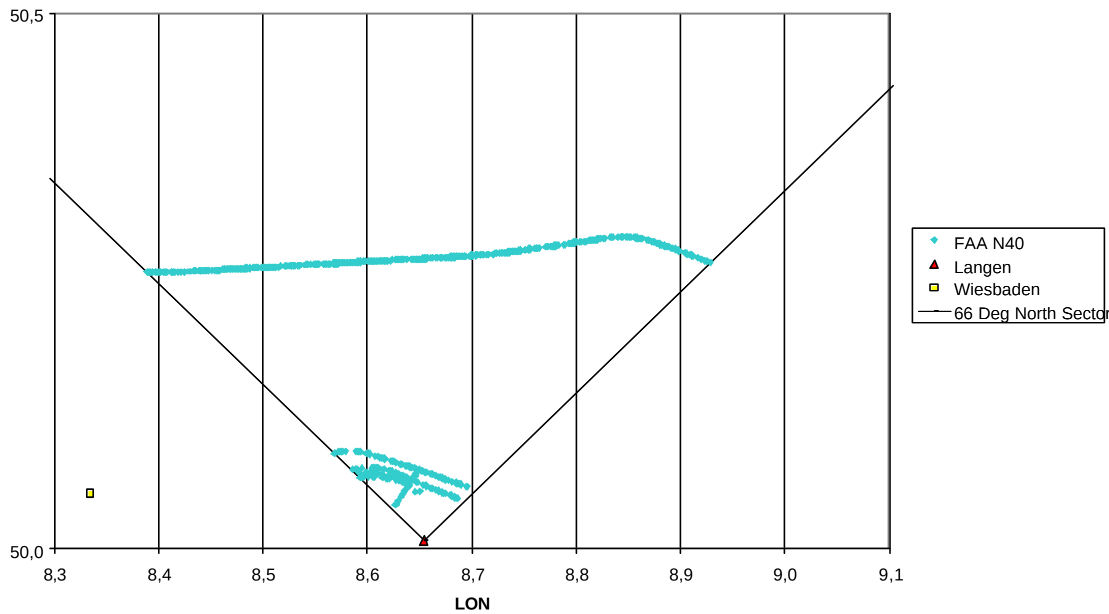


Figure 4.5.3.1.3-1. Langen ERA N40 Ext. Squitter Track Plot, 19 May

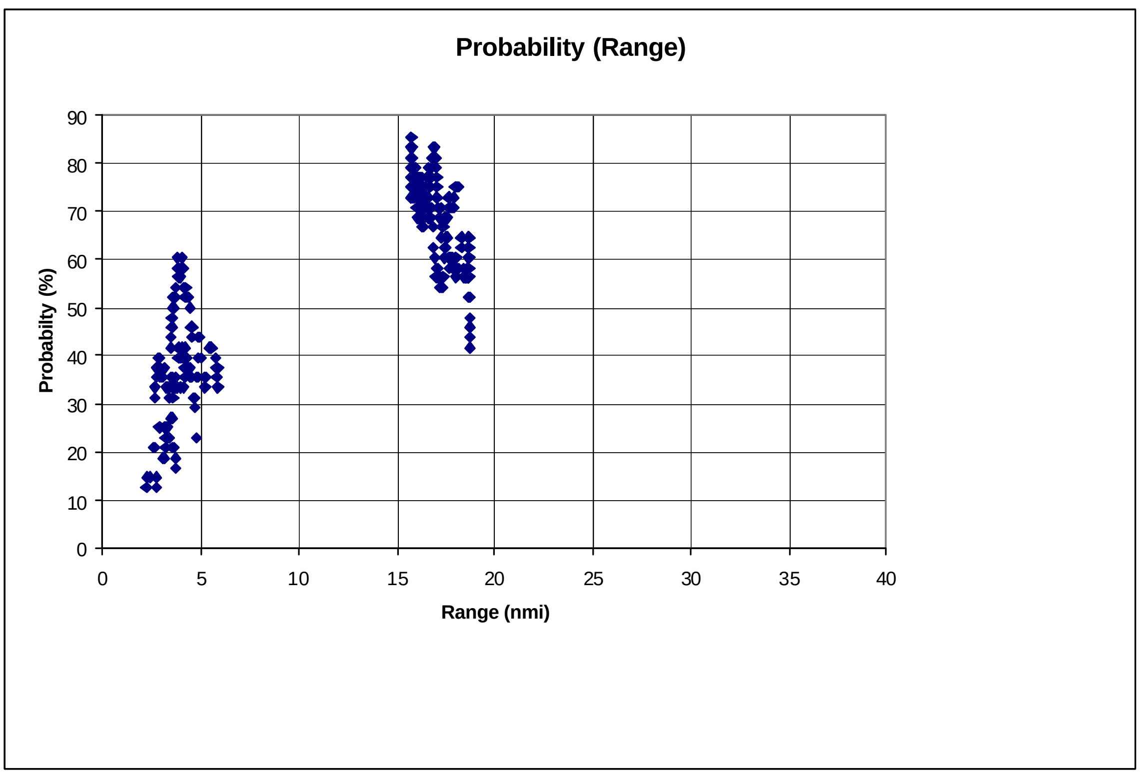


Figure 4.5.3.1.3-2. Langen ERA N40 Ext. Squitter Probability vs. Range, 19 May

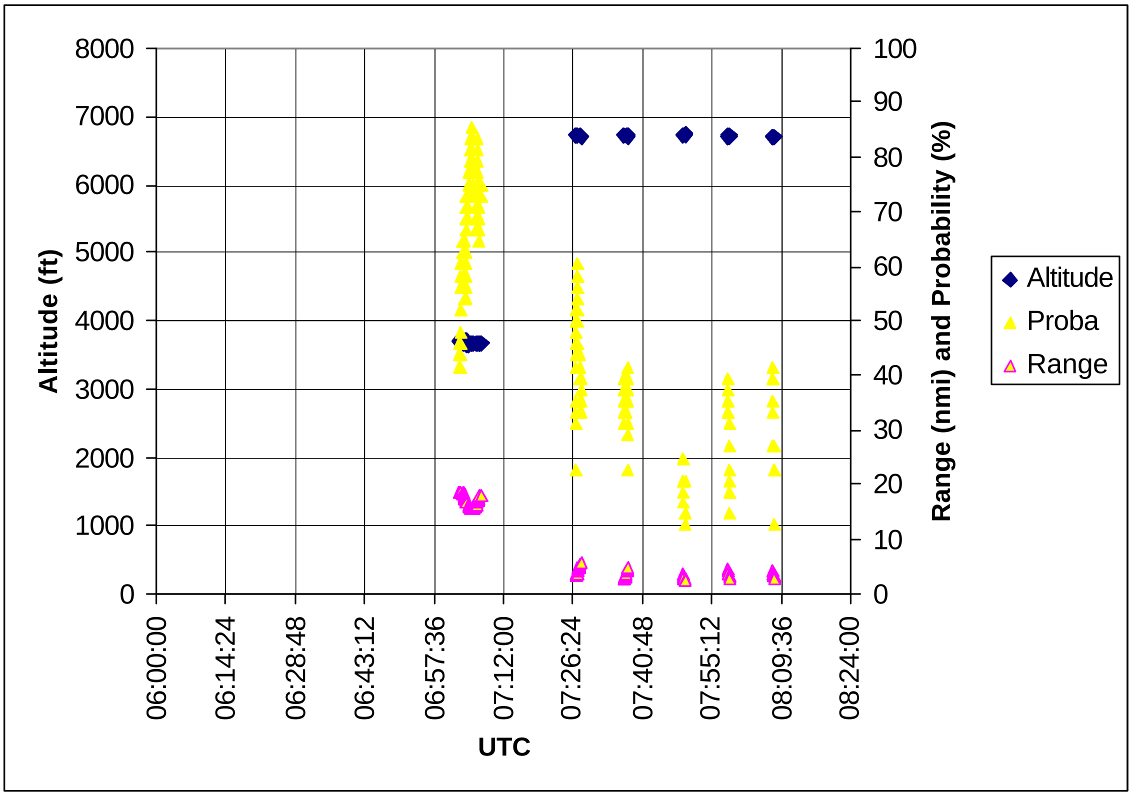


Figure 4.5.3.1.3-3. Langen ERA FAA Ext. Squitter Altitude/Range/Probability vs. UTC, 19 May

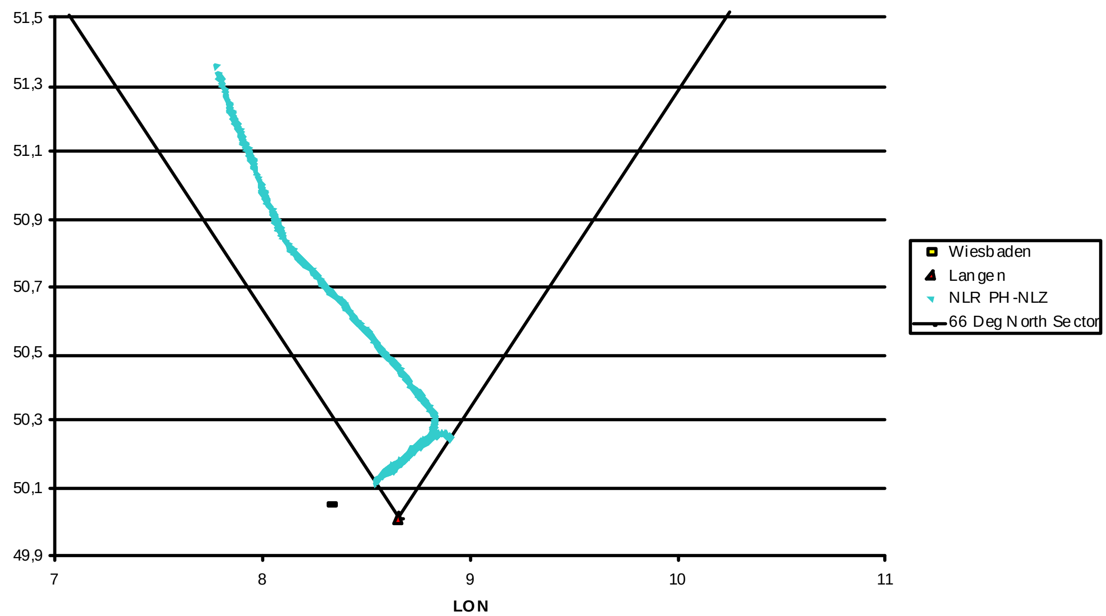


Figure 4.5.3.1.3-4a. Langen ERA NLR Ext. Squitter Track Plot, 20 May

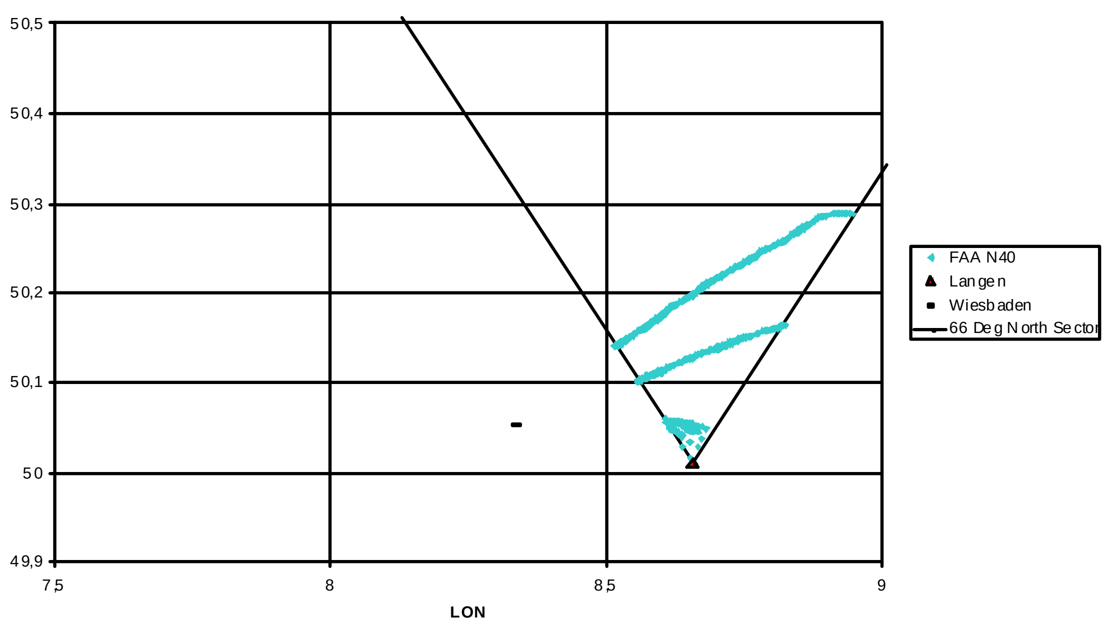


Figure 4.5.3.1.3-4b. Langen ERA N40 Ext. Squitter Track Plot, 20 May

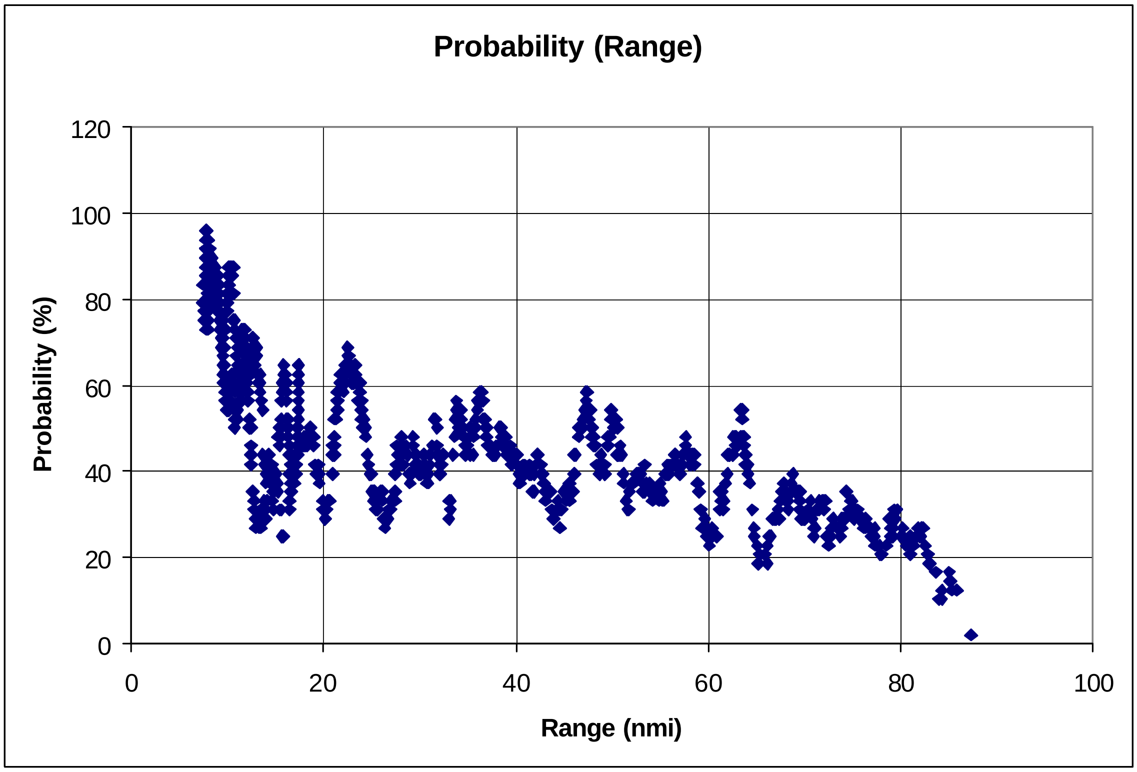


Figure 4.5.3.1.3-5a. Langen ERA NLR Ext. Squitter Probability vs. Range, 20 May

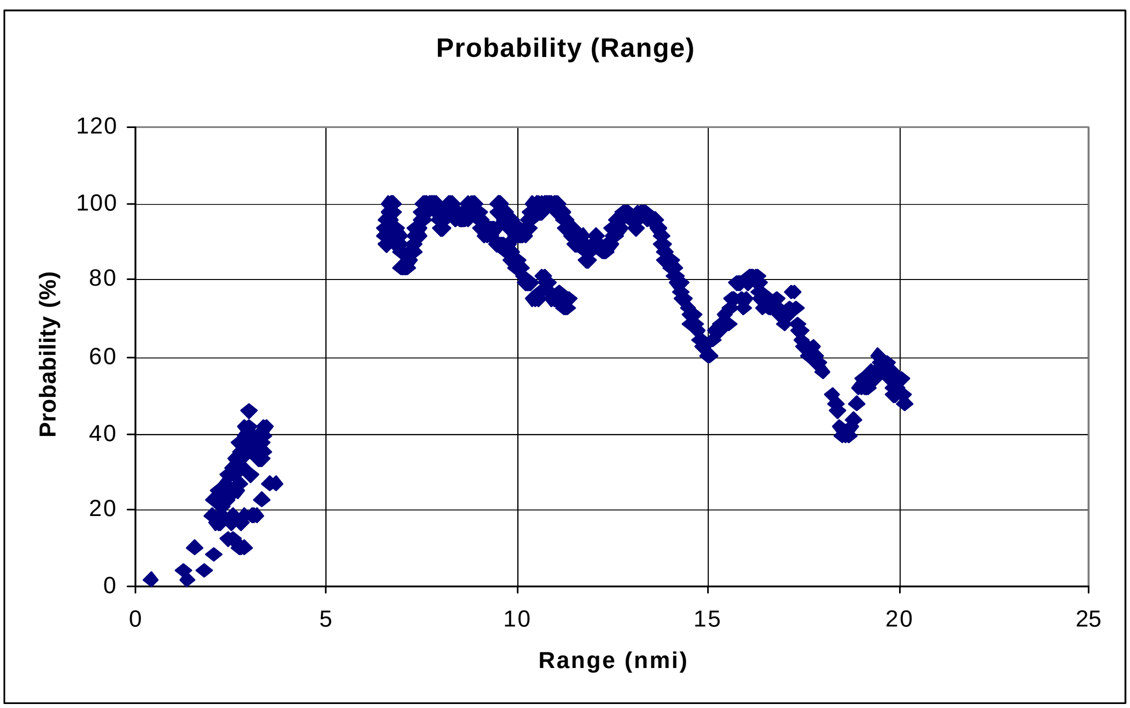


Figure 4.5.3.1.3-5b. Langen ERA N40 Ext. Squitter Probability vs. Range, 20 May

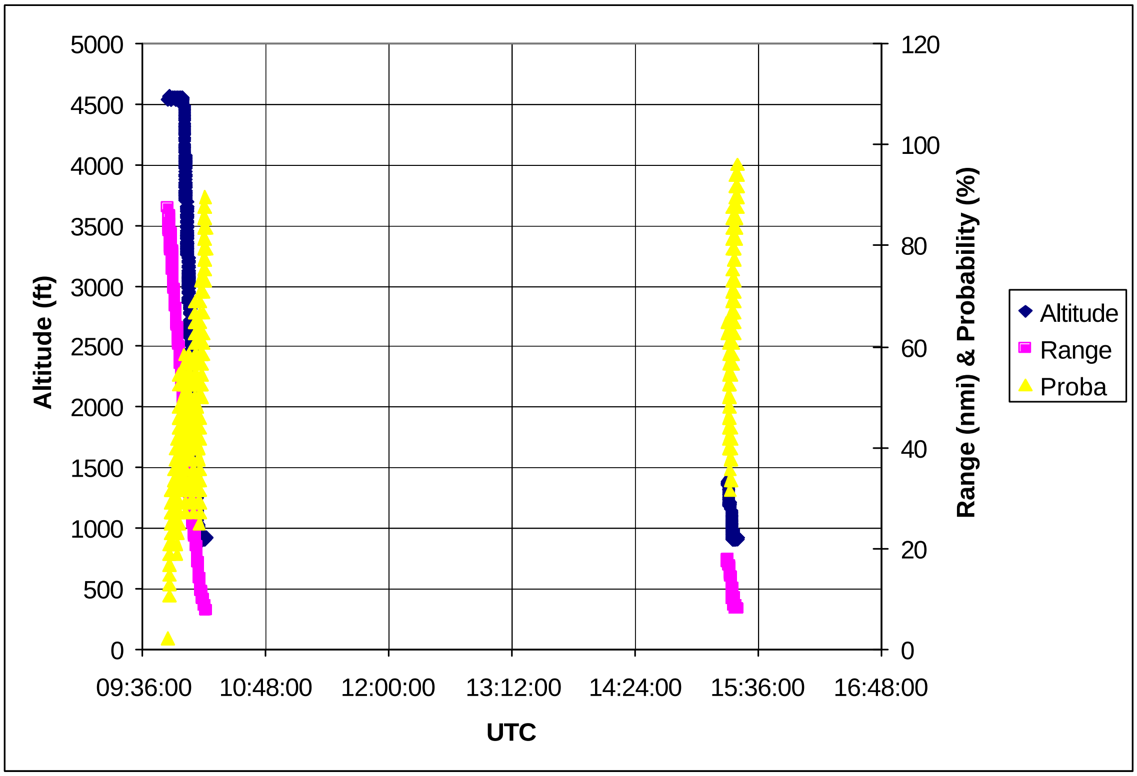


Figure 4.5.3.1.3-6a. Langen ERA NLR Ext. Squitter Alt./Range/Prob. vs. UTC, 20 May

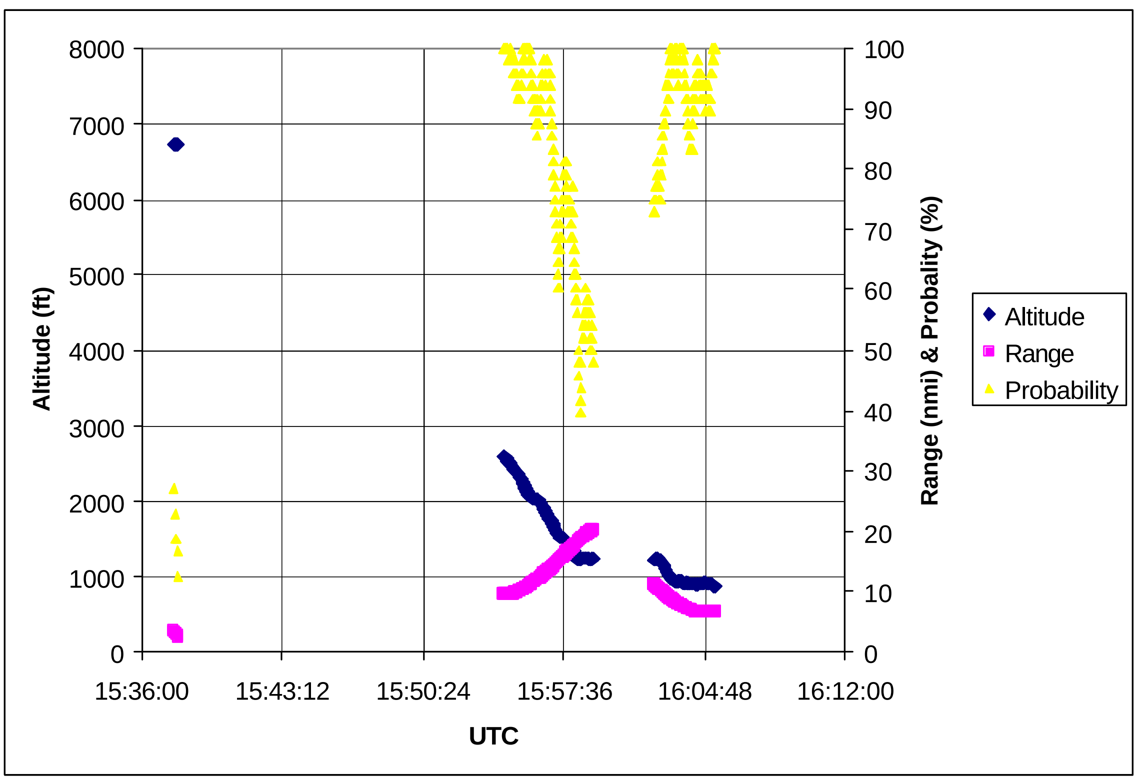


Figure 4.5.3.1.3-6b. Langen ERA N40 Ext. Squitter Alt./Range/Prob. vs. UTC, 20 May

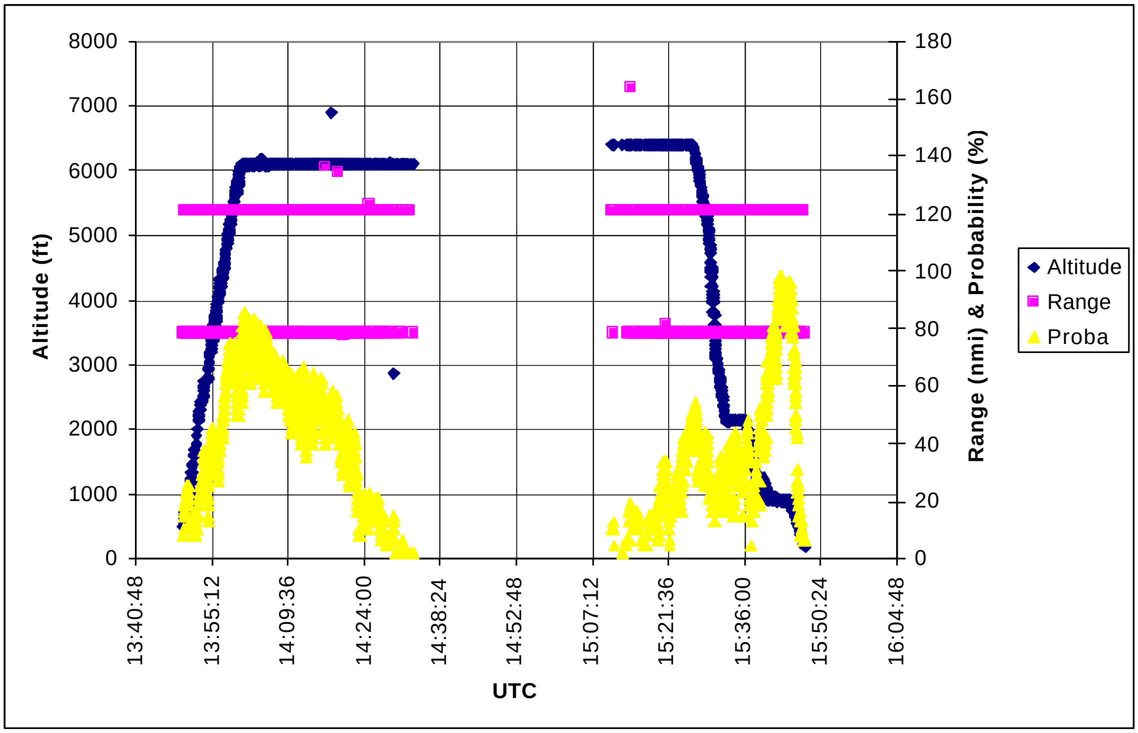


Figure 4.5.3.1.3-6c. Langen ERA FII Ext. Squitter Alt./Range/Prob. vs. UTC, 20 May

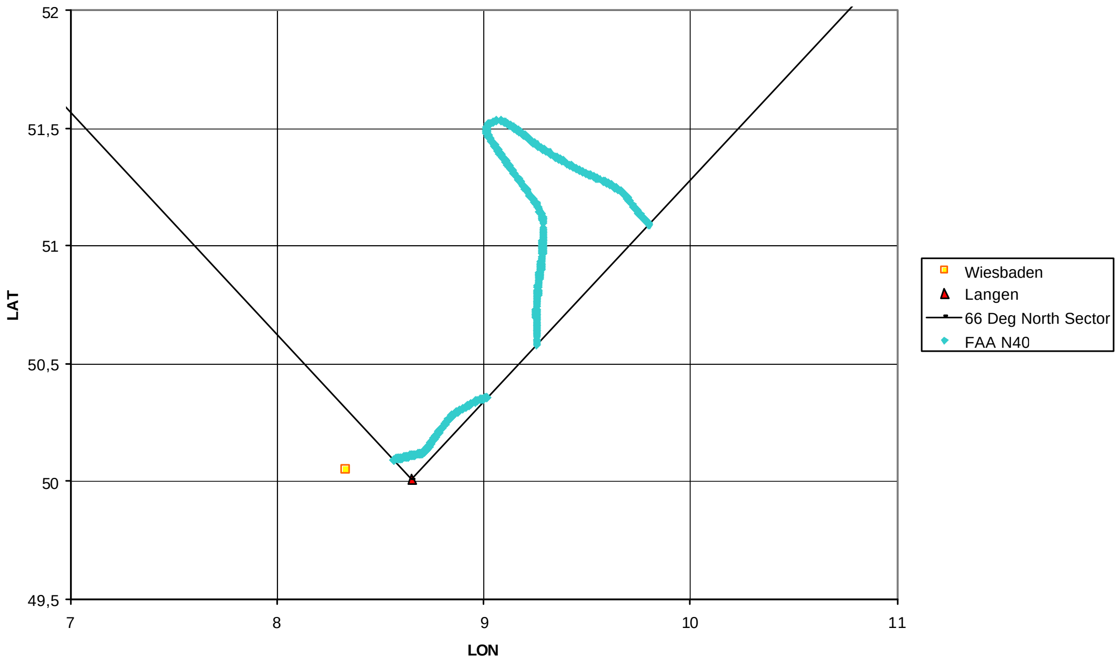


Figure 4.5.3.1.3-7a. Langen ERA N40 Ext. Squitter Track Plot, 22 May

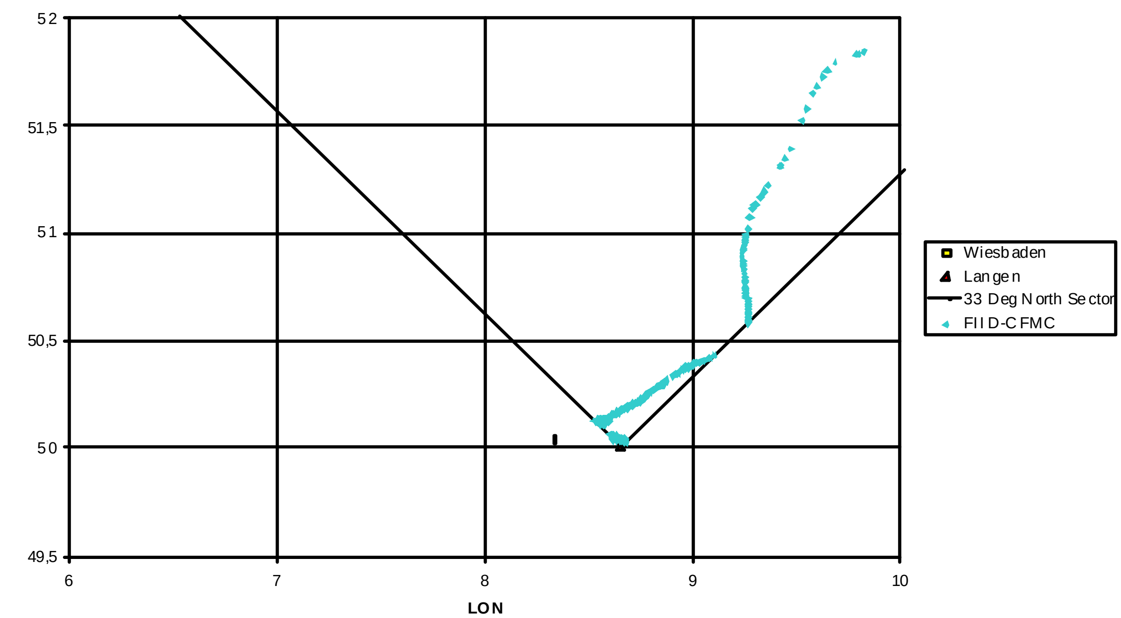


Figure 4.5.3.1.3-7b. Langen ERA FII Ext. Squitter Track Plot, 22 May

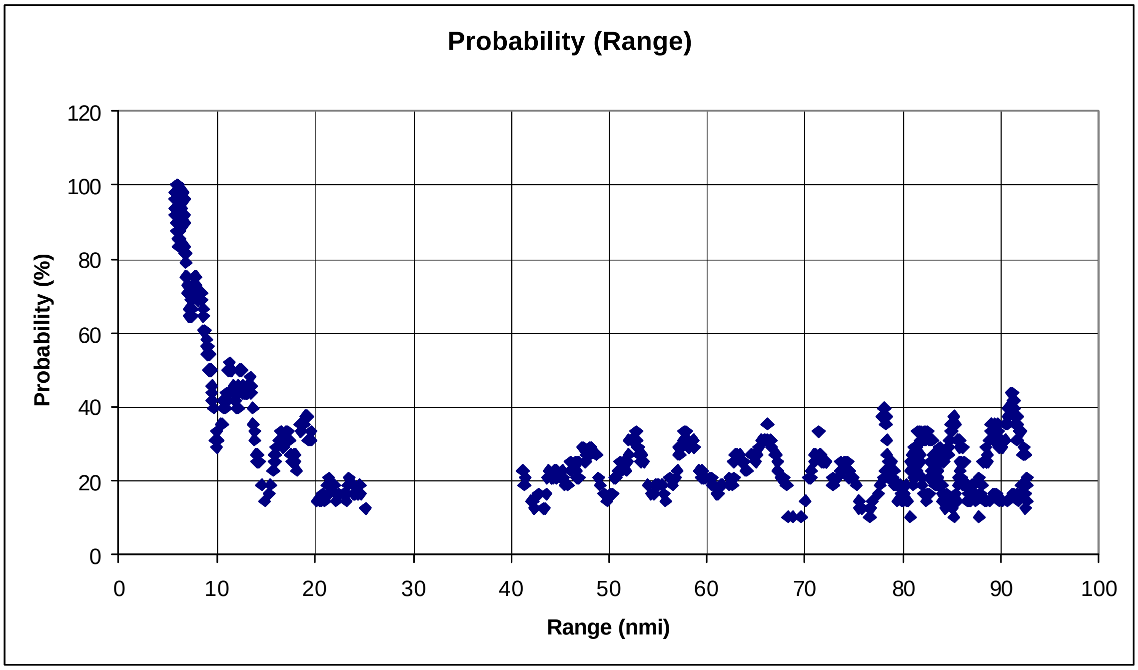


Figure 4.5.3.1.3-8a. Langen ERA N40 Ext. Squitter Probability vs. Range, 22 May

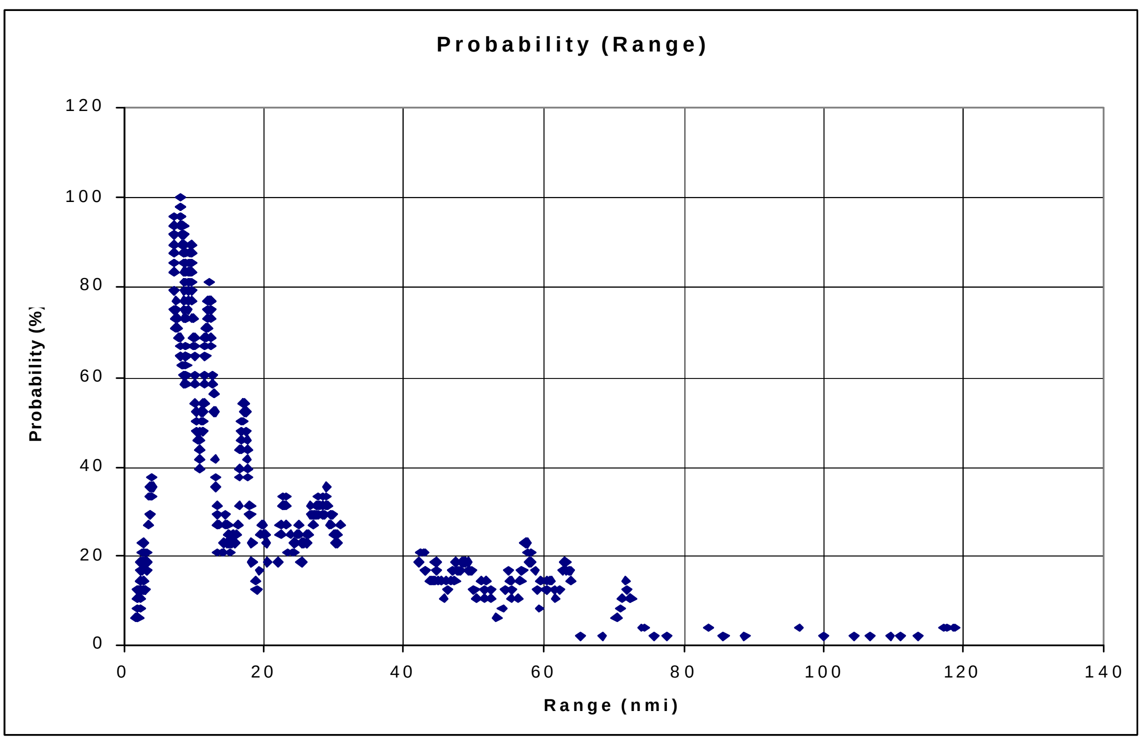


Figure 4.5.3.1.3-8b. Langen ERA FII Ext. Squitter Probability vs. Range, 22 May

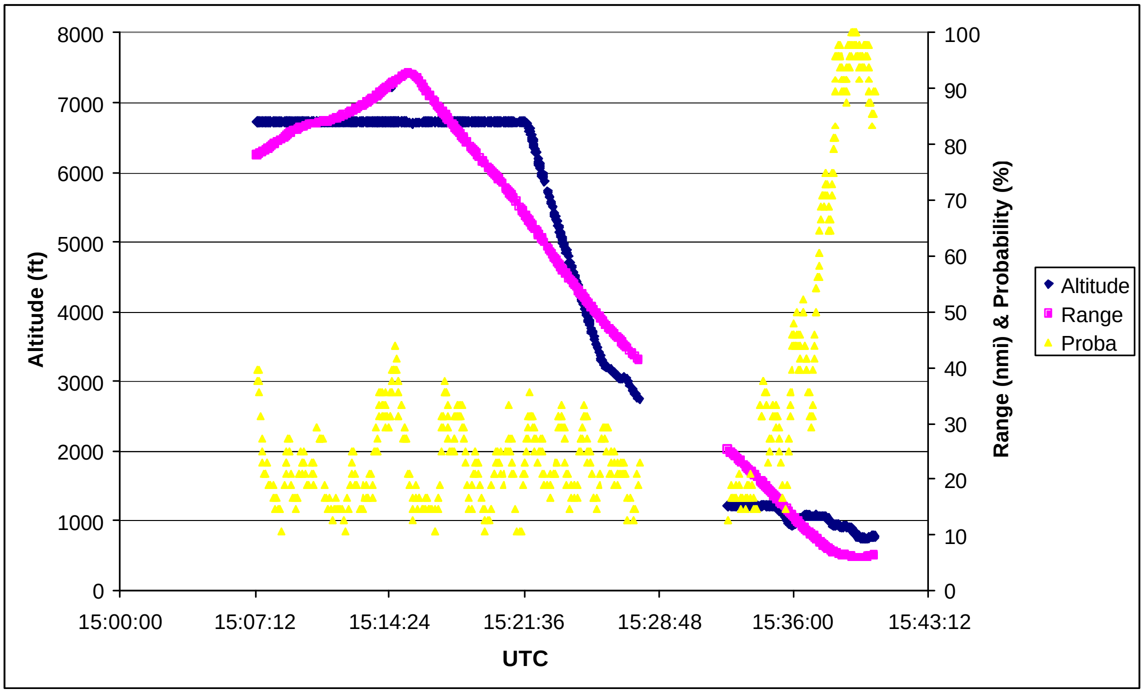


Figure 4.5.3.1.3-9a. Langen ERA N40 Ext. Squitter Alt./Range/Prob. vs. UTC, 22 May

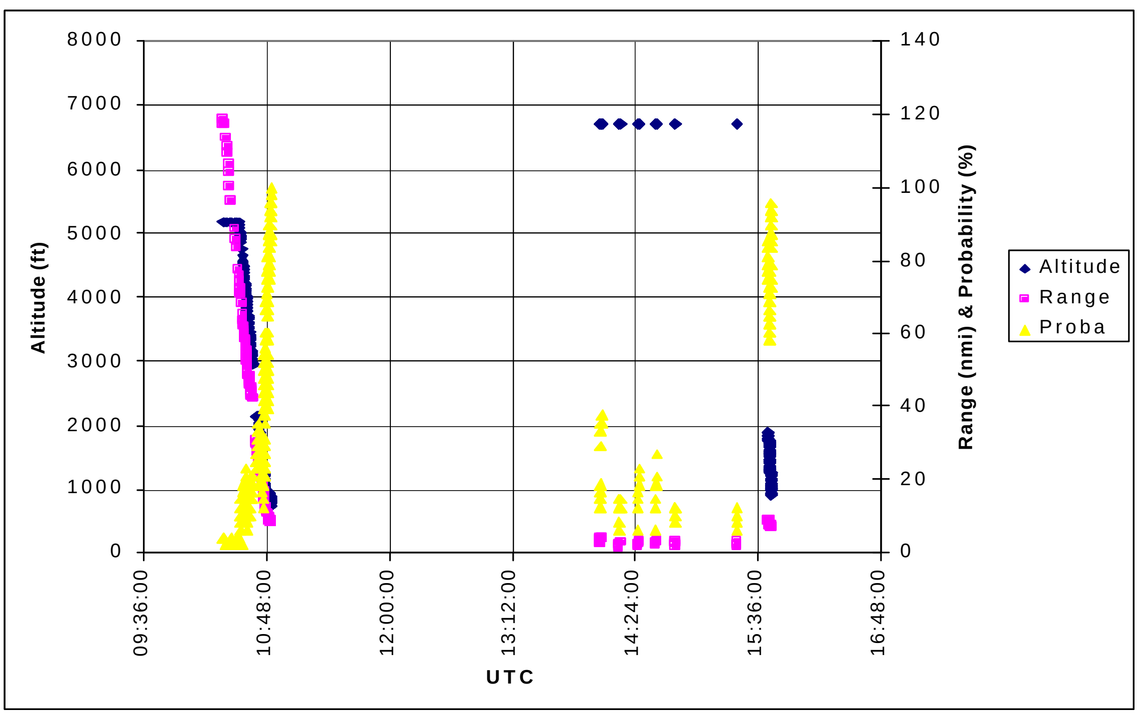


Figure 4.5.3.1.3-9b. Langen ERA FII Ext. Squitter Alt./Range/Prob. vs. UTC, 22 May

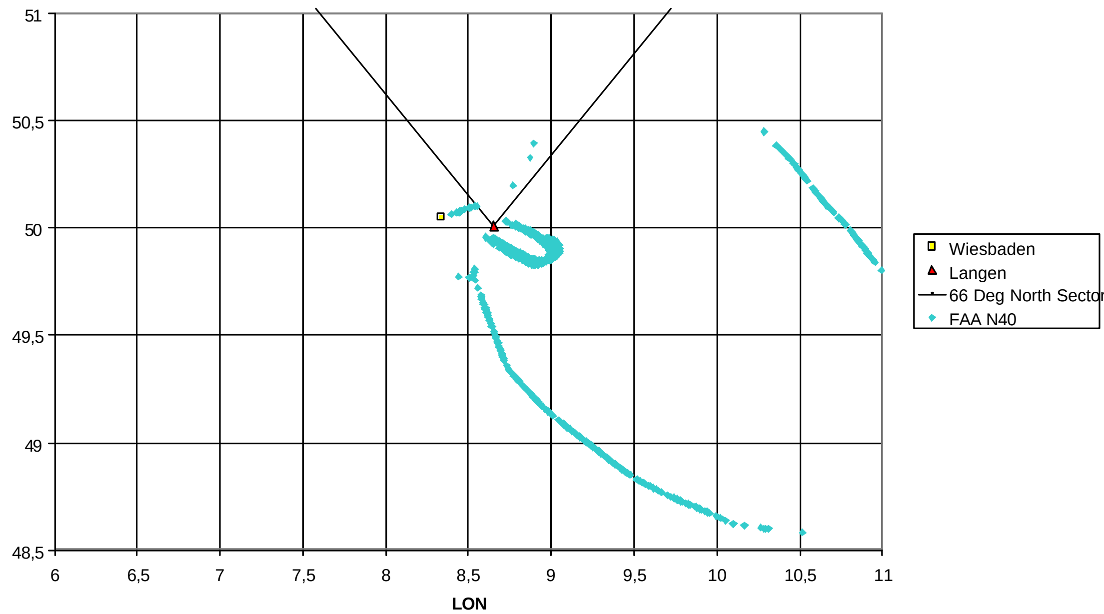


Figure 4.5.3.1.3-10a. Langen ERA FAA Ext. Squitter Track Plot, 25 May

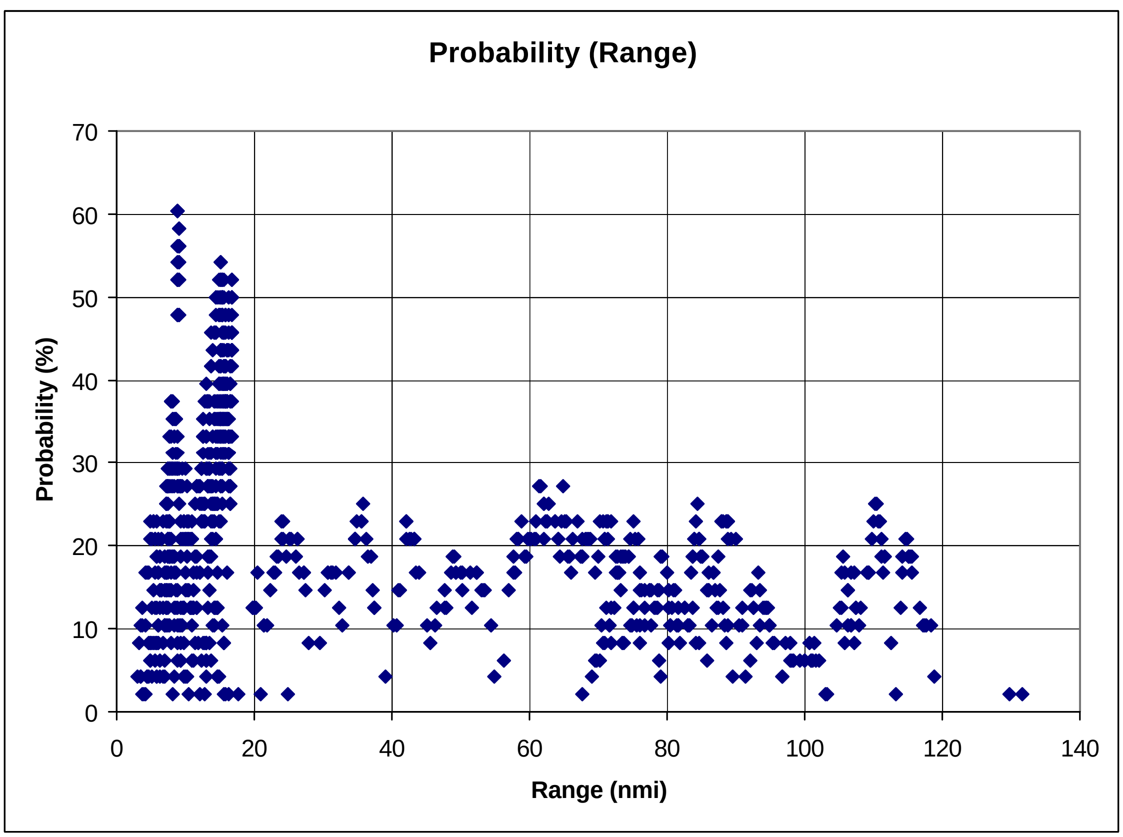


Figure 4.5.3.1.3-10b. Langen ERA FAA Ext. Squitter Probability vs. Range, 25 May

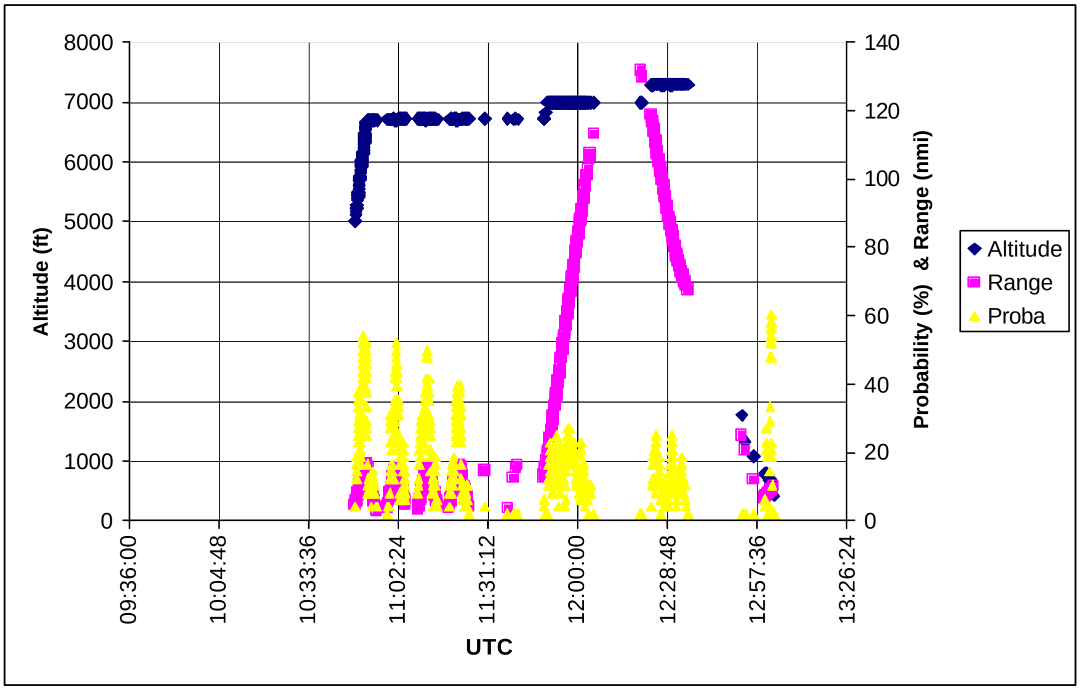


Figure 4.5.3.1.3-10c. Langen ERA N40 Ext. Sq. Alt./Range/Prob. vs. UTC, 25 May

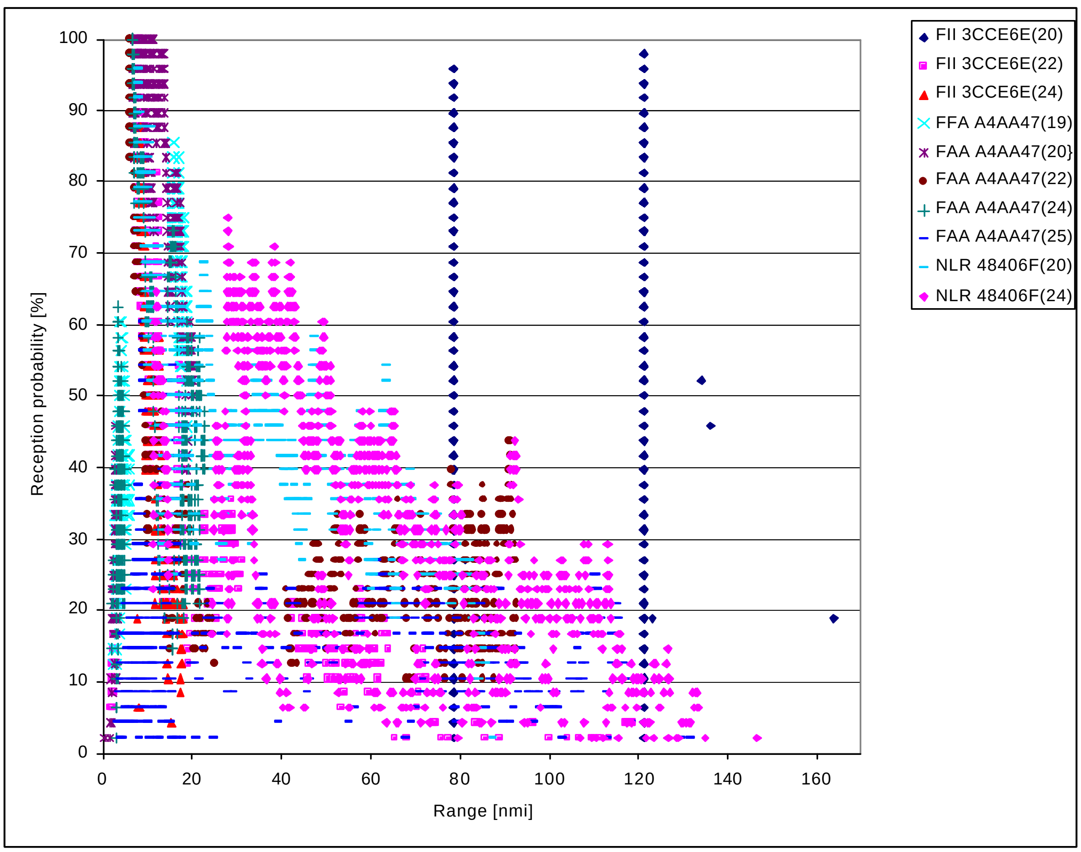


Figure 4.5.3.1.3-11. Langen ERA Ext. Squitter Prob. vs. Range Summary, All Days

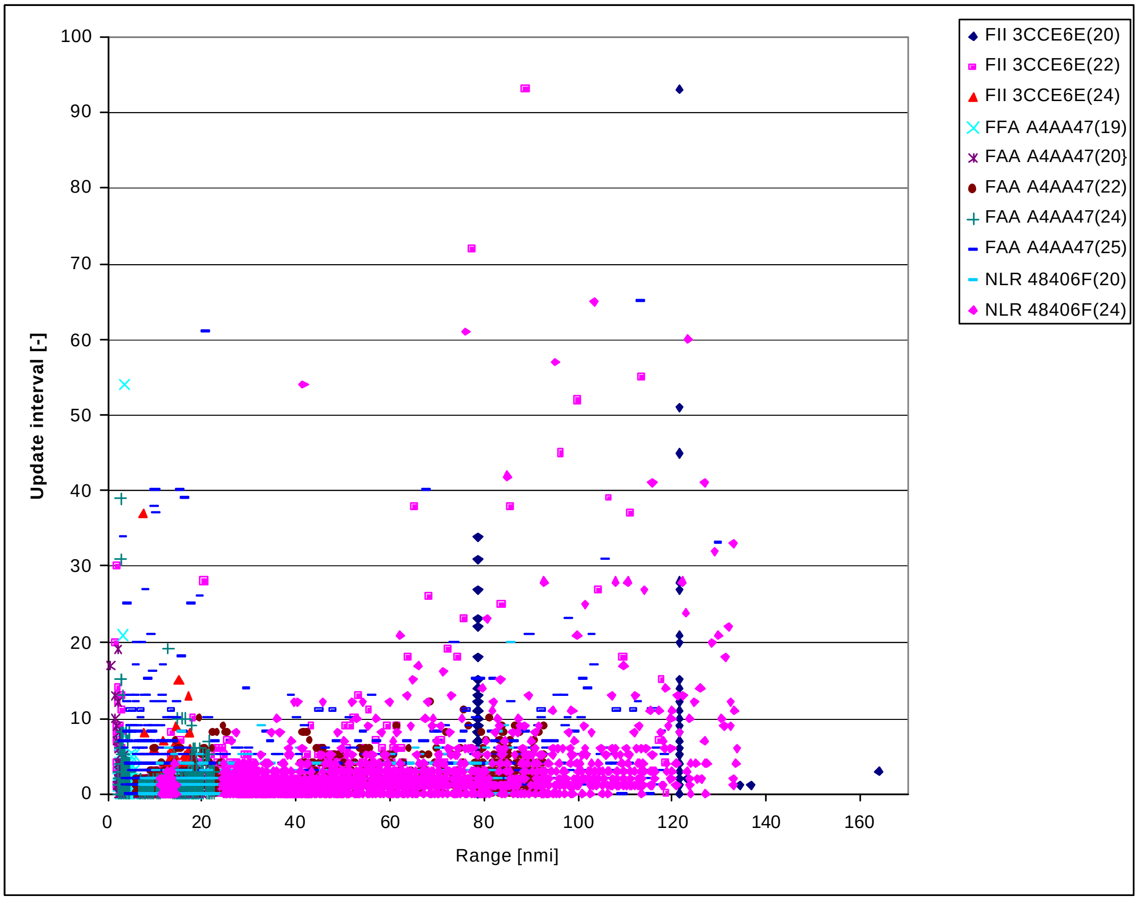


Figure 4.5.3.1.3-12. Langen ERA Ext. Sq. Update Interval vs. Range Summary, All Days

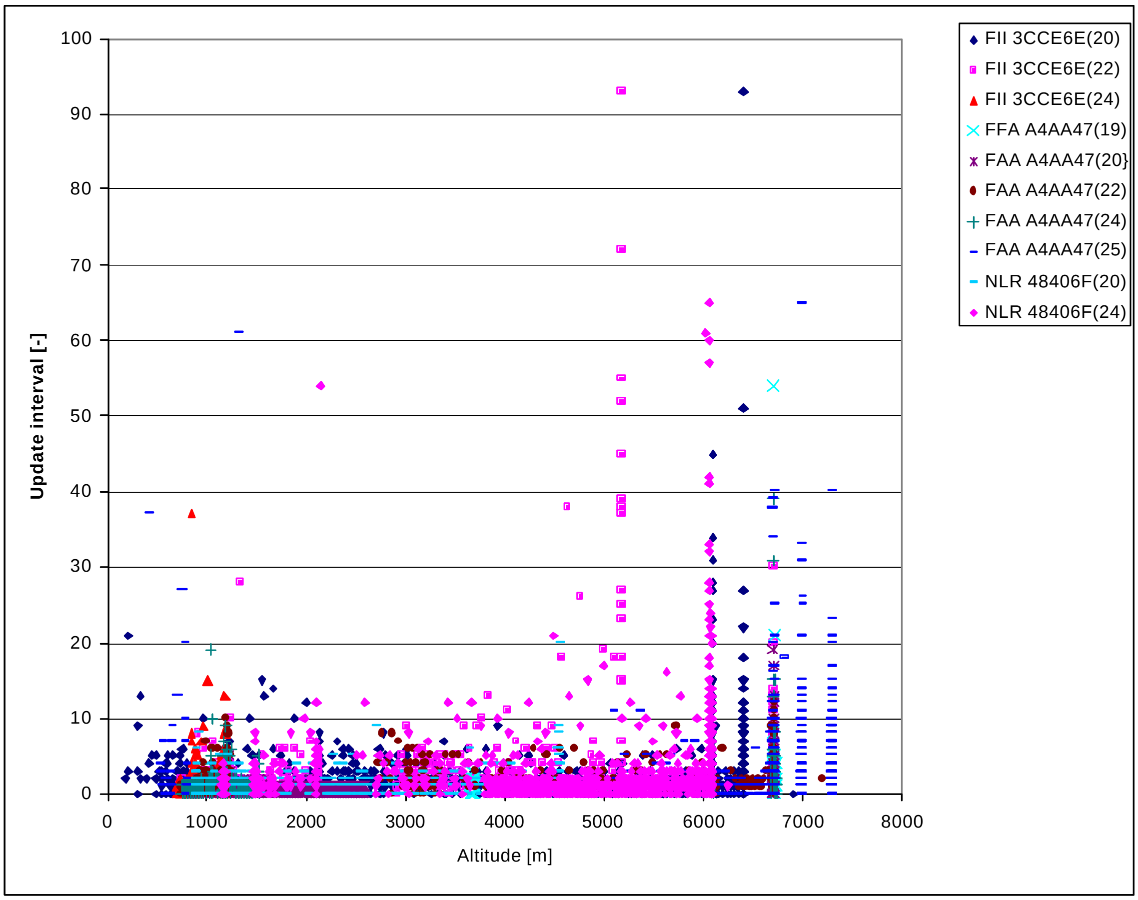


Figure 4.5.3.1.3-13. Langen ERA Ext. Sq. Update Int. vs. Altitude Summary, All Days

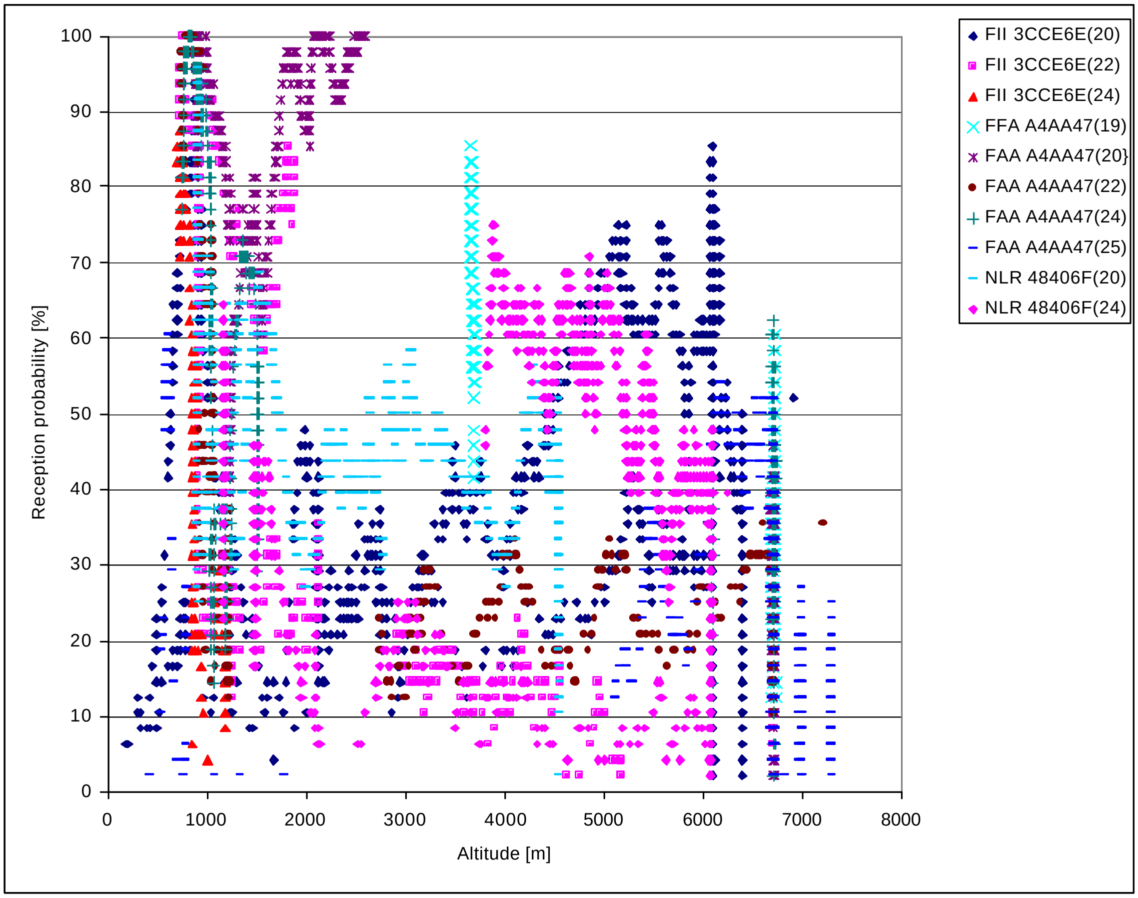


Figure 4.5.3.1.3-14. Langen ERA Ext. Squitter Prob. vs. Altitude Summary, All Days

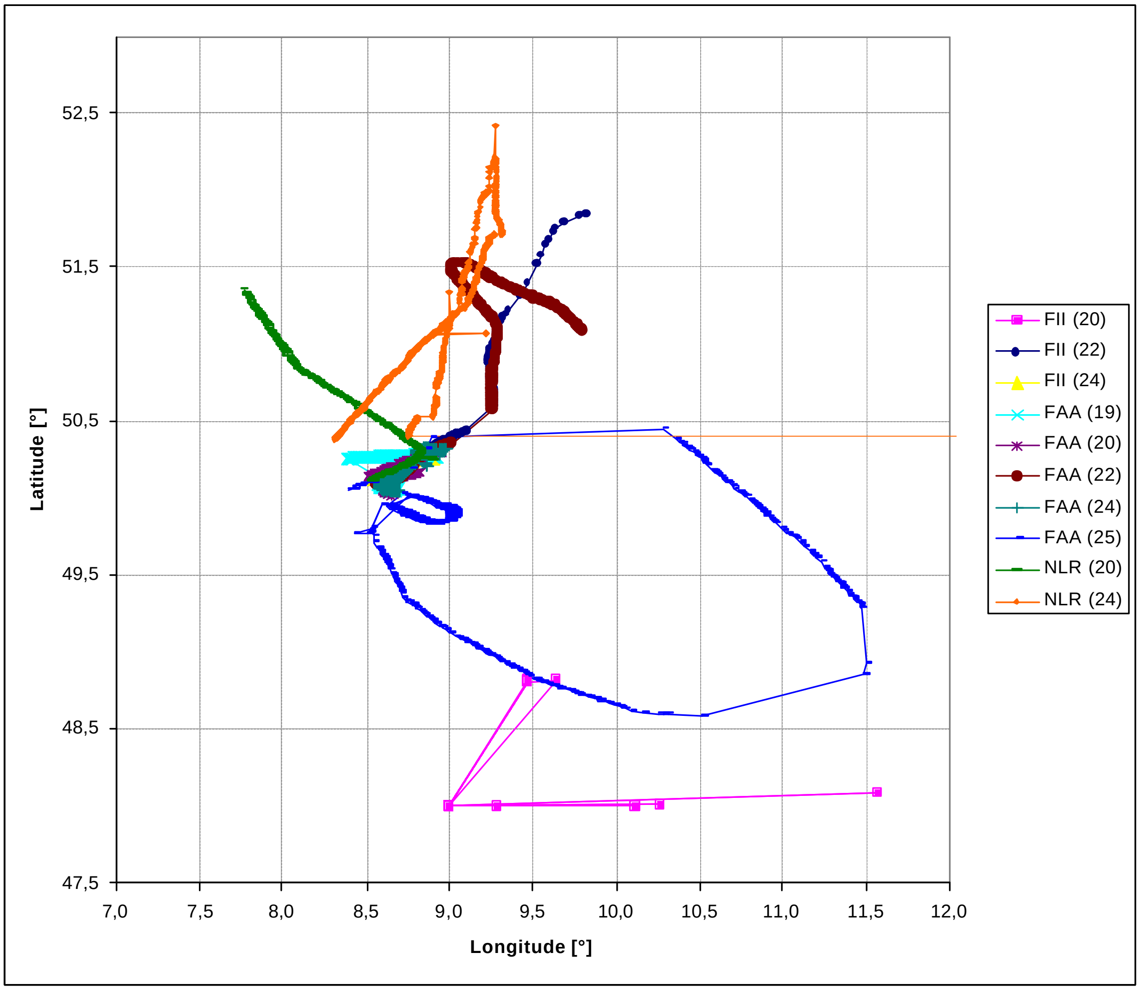


Figure 4.5.3.1.3-15a. Langen ERA Ext. Squitter Track Plot Summary, All Days

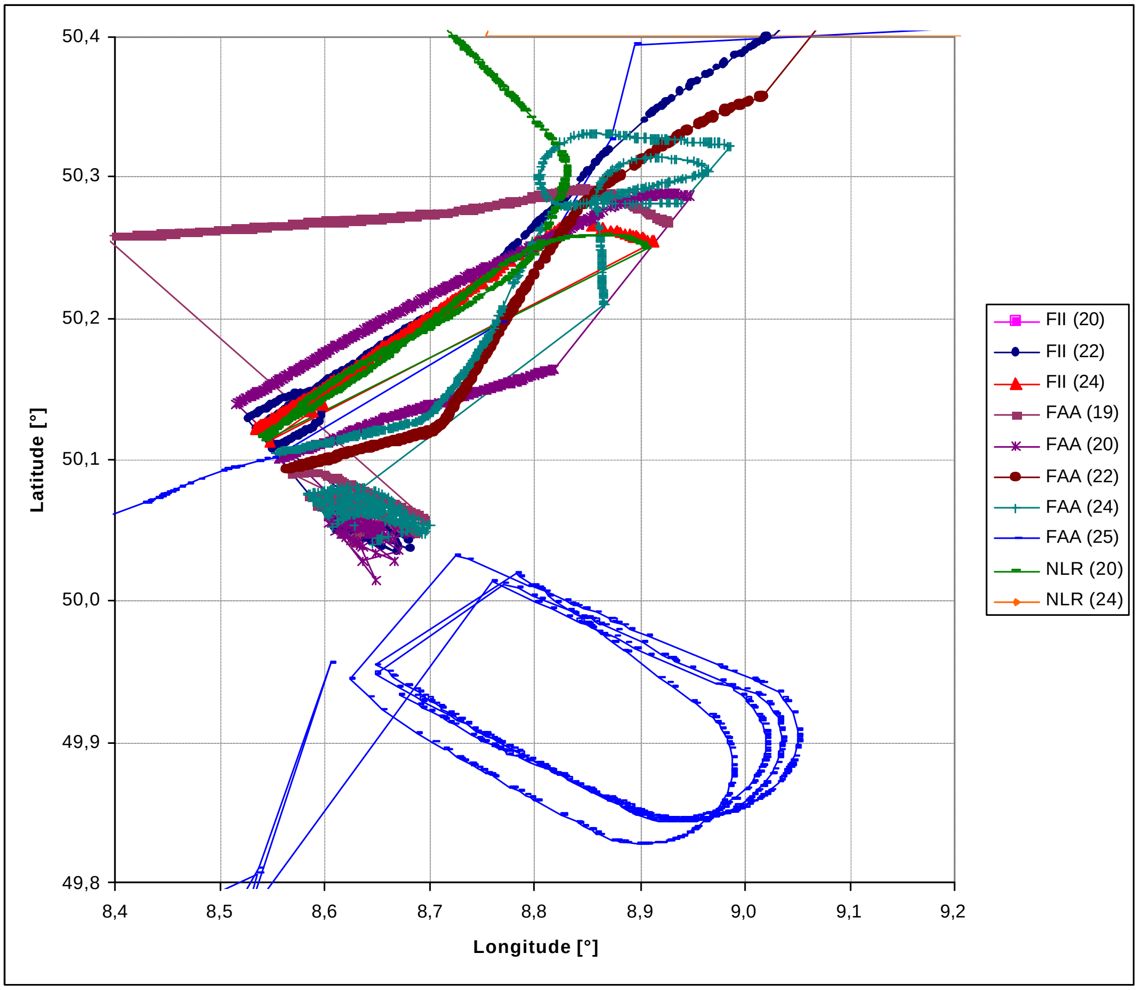


Figure 4.5.3.1.3-15b. Langen ERA Ext. Squitter Track Plot Summary Detail, All Days

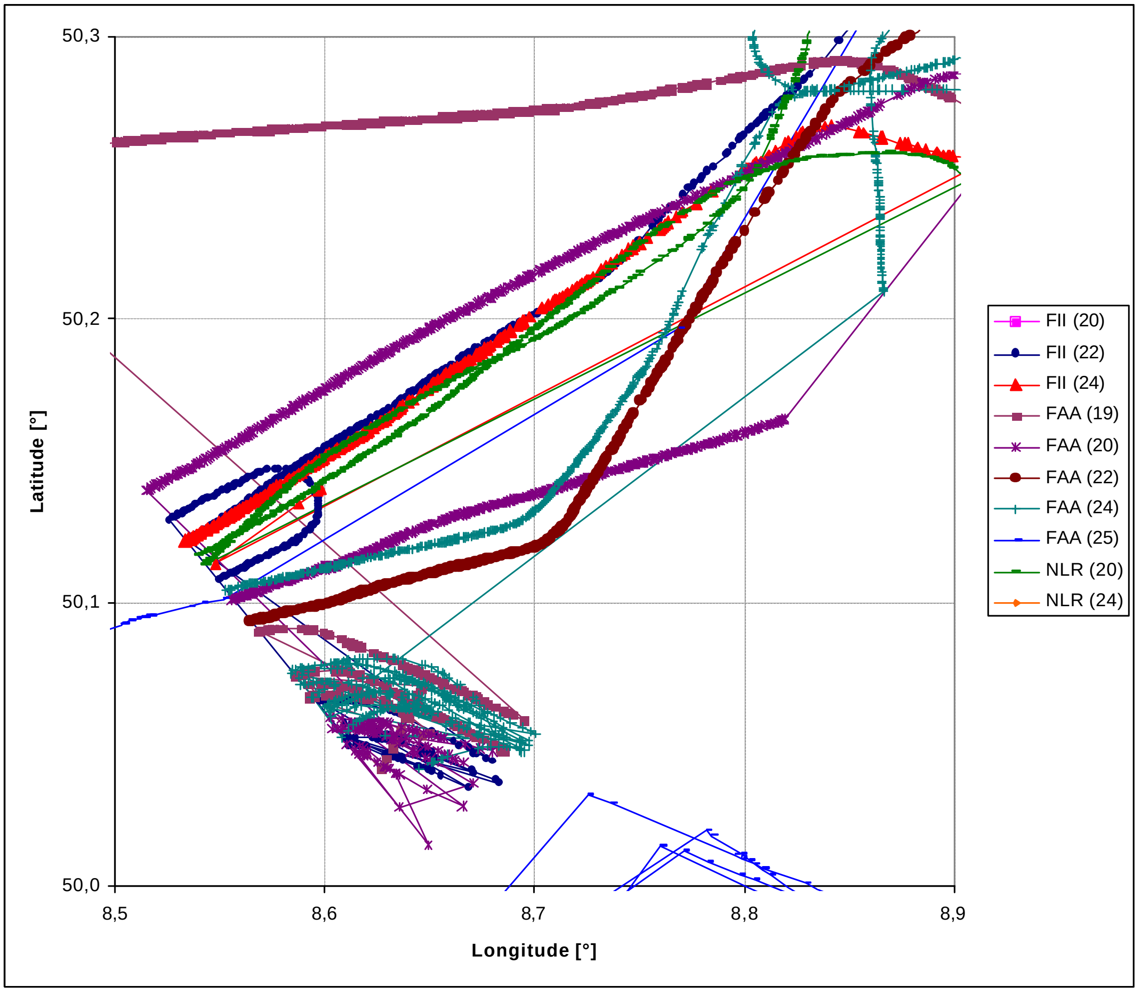


Figure 4.5.3.1.3-15c. Langen ERA Ext. Squitter Track Plot Summary Detail, All Days

4.5.3.2. Wiesbaden LDPU Extended Squitter Performance - All Days

4.5.3.2.1. Results for 19 May

Of the project aircraft only N40 participated in the data collection on 19 May. This was considered a checkout flight to verify that the systems on N40 as well as the FAA provided ground station equipment were working correctly. During the data collection at the Wiesbaden ground station, two British Airways targets of opportunity were also observed. Figure 4.5.3.2.1-1 is a plot of the ground tracks of N40 and the targets of opportunity observed during the data collection. The -3 dB cutoff of the ground station's antenna pattern (two adjacent 60 degree beams providing 120 degree coverage) is shown to indicate the ground station's primary coverage area.

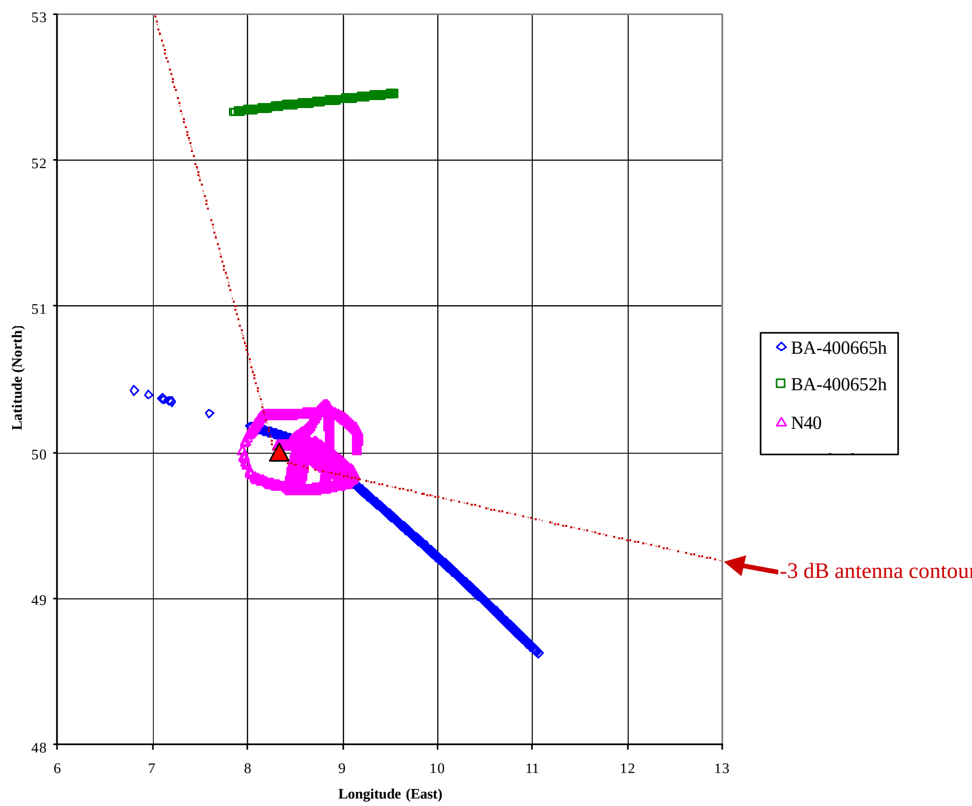


Figure 4.5.3.2.1-1 Wiesbaden LDPU Target Tracks, 19 May

The flight path of all three target aircraft included at least a segment of their flight path within the primary coverage area (i.e., within the antenna beam) of the Wiesbaden ground station. Figure 4.5.3.2.1-2 plots the probability of reception by the Wiesbaden ground station for targets within the primary coverage area and above 1000 ft altitude. By limiting the reported results to targets with the antenna's beam resulted in excluding the mid to long range data collected from BA-400665h since much of this aircraft's flight path was outside of the primary coverage area.

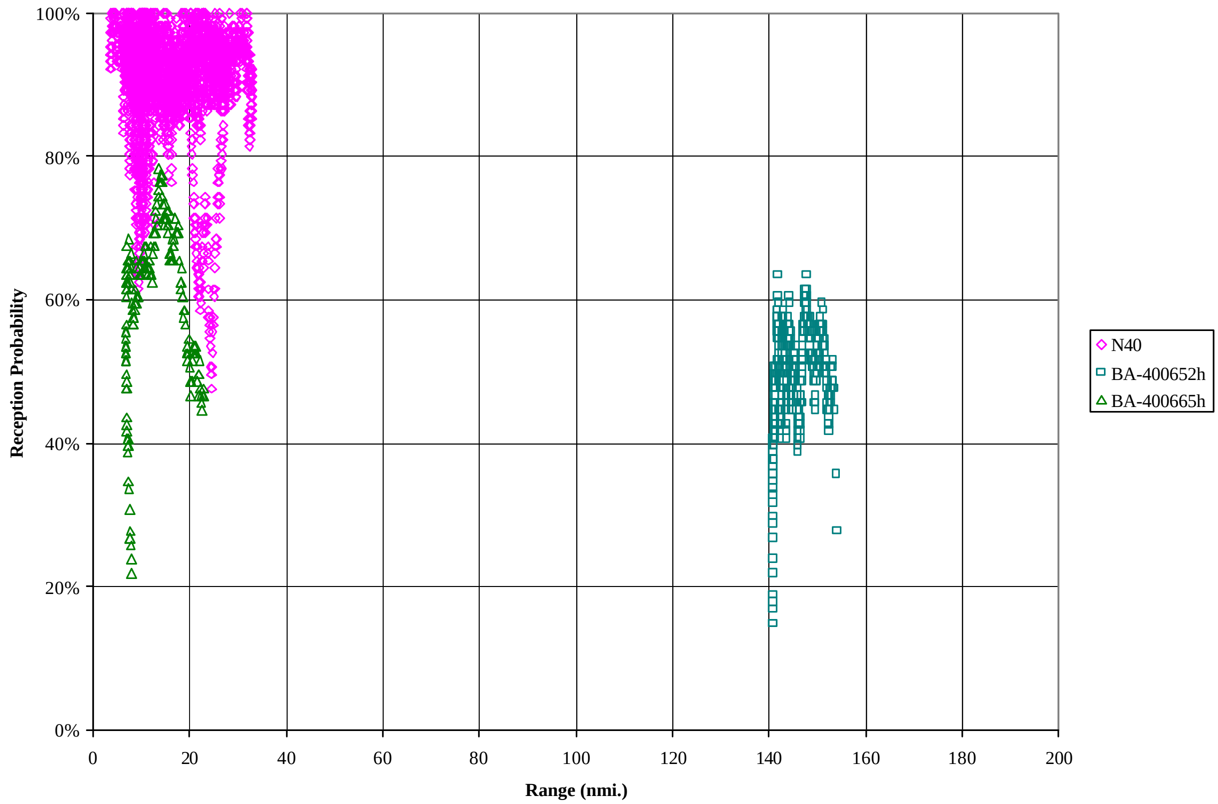


Figure *4.5.3.2.1-2 Wiesbaden LDPU In-Beam Reception Probability, 19 May*

Figure 4.5.3.2.1-3 provides the received update period by the Wiesbaden LDPU for all in-beam airborne targets.

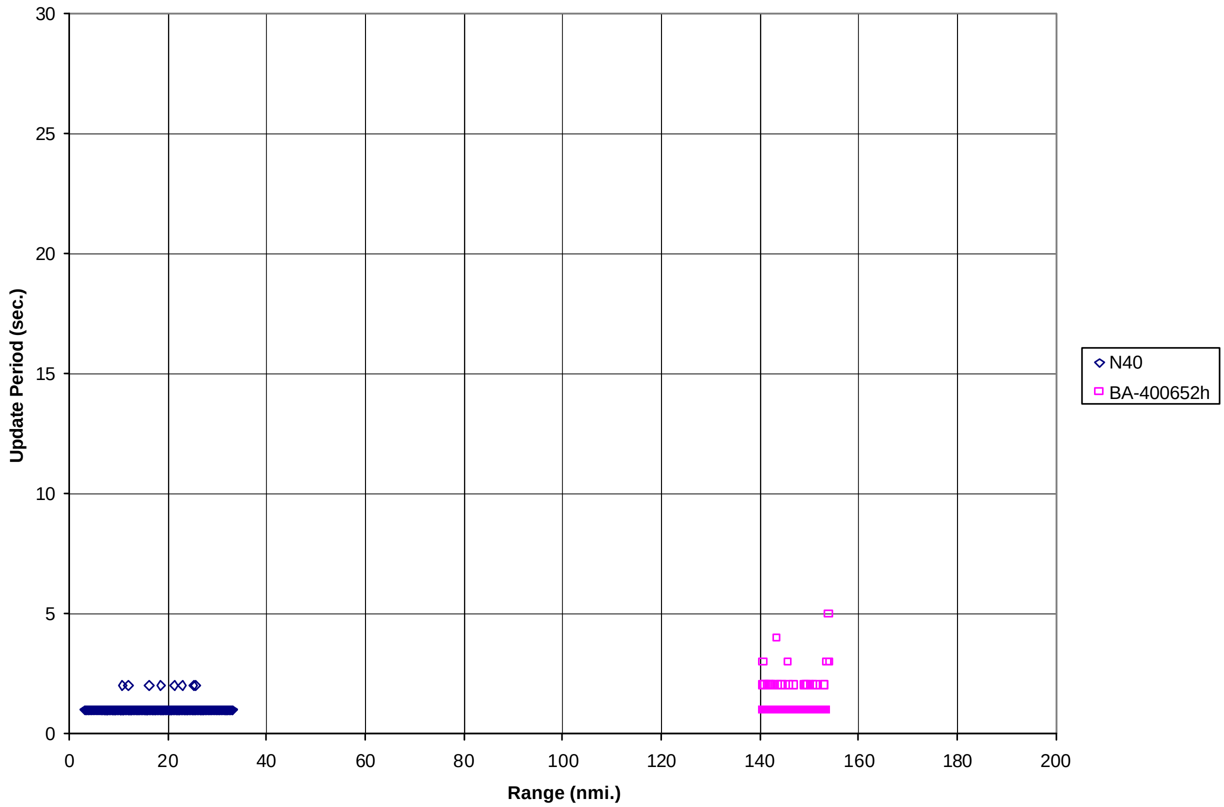


Figure 4.5.3.2.1-3. Wiesbaden LDPU In-Beam Update Period, 19 May

4.5.3.2.1.2 Results for 20 May

All three project aircraft participated in the data collection on 20 May. However, due to an GPS to LDPU interface issue on the FII aircraft it was not transmitting its position within the Extended Squitters. Therefore no results associated with the FII aircraft are included in the following material. During the data collection at the Wiesbaden ground station two British Airways targets of opportunity were also observed. Figure 4.5.3.2.1-4 is a plot of the ground tracks of N40, NLR aircraft and the targets of opportunity observed during the data collection. The -3 dB cutoff of the ground station's antenna pattern (two adjacent 60 degree beams providing 120 degree coverage) is shown to indicate the ground station's primary coverage area.

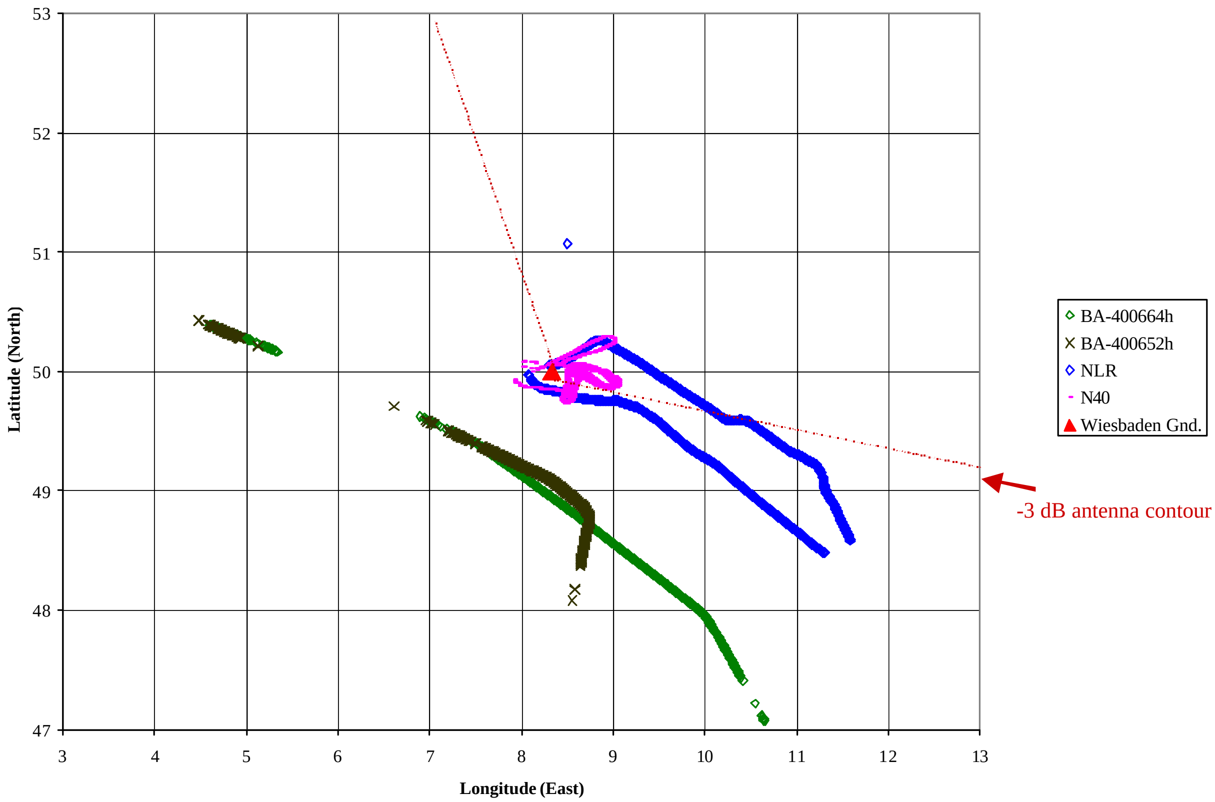


Figure 4.5.3.2.1-4   Wiesbaden LDPU Target Tracks, 20 May

The flight path of only two target aircraft (i.e., N40 and NLR) include a segment of their flight path within the primary coverage area (i.e., within the antenna beams) of the Wiesbaden ground station. Figure 4.5.3.2.1-5 plots the probability of reception by the Wiesbaden ground station for the three targets within the primary coverage area and above 1000 ft altitude. By placing these limits on the data included in the following figure, all of the data collected from the targets of opportunity were excluded. Also note that a significant portion of the NLR aircraft's flight path, including the longer range segment, was outside of the ground station's primary coverage area and is therefore also excluded from the following figure. The result was only short to mid-range data (i.e., < 67 nmi) was collected within the ground station's primary coverage area.

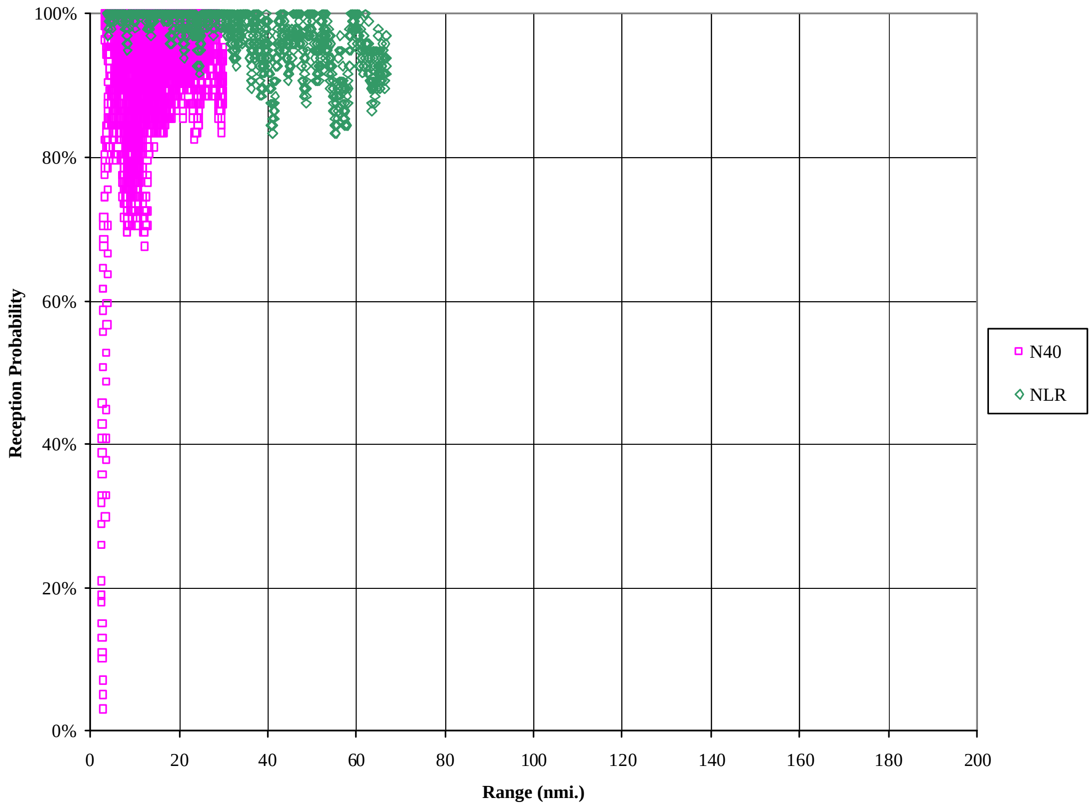


Figure 4.5.3.2.1-5. Wiesbaden LDPU In-Beam Reception Probability, 20 May

Figure 4.5.3.2.1-6 provides the received update period by the Wiesbaden LDPU for all in-beam airborne targets.

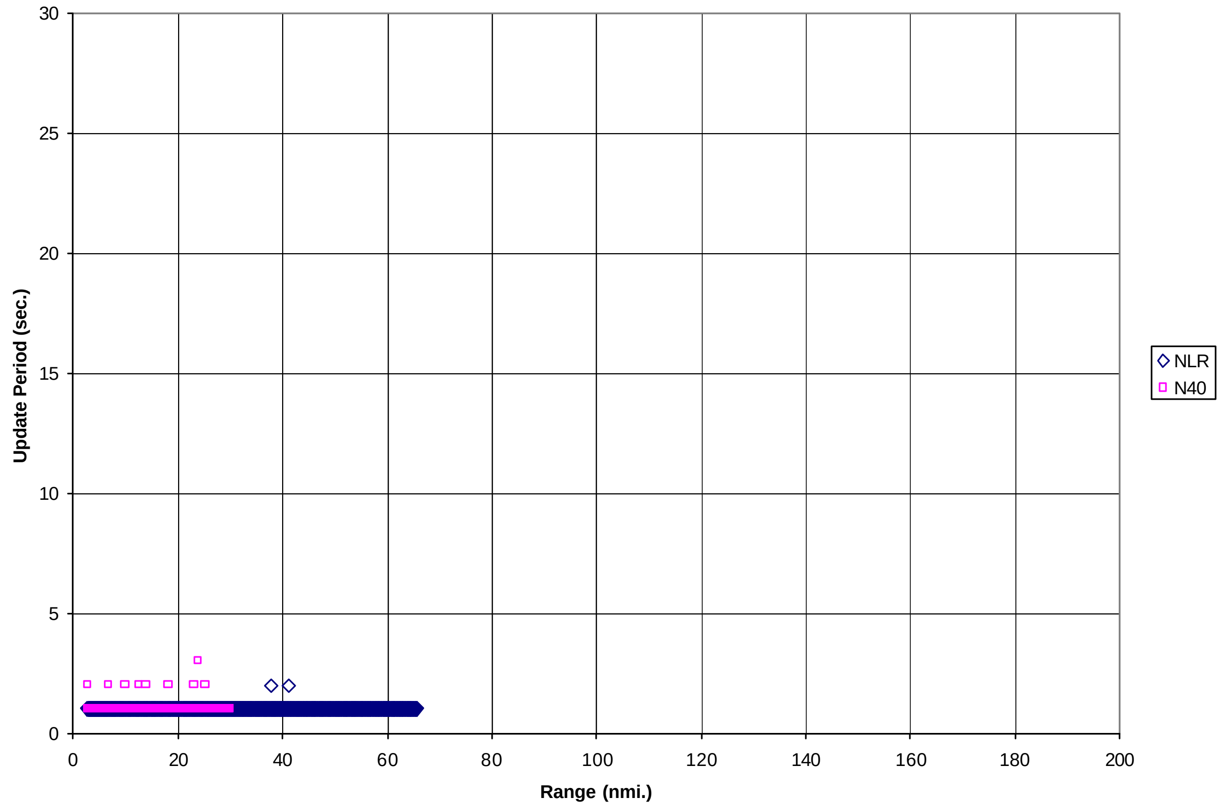


Figure 4.5.3.2.1-6. Wiesbaden LDPU In-Beam Update Period, 20 May

4.5.3.2.1.3 Results for 22 May

N40 and the FII project aircraft participated in the data collection on 22 May. During the data collection at the Wiesbaden ground station, one British Airways target of opportunity was also observed. Figure 4.5.3.2.1-7 is a plot of the ground tracks of N40, FII aircraft and the target of opportunity observed during the data collection. The -3 dB cutoff of the ground station's antenna pattern (two adjacent 60 degree beams providing 120 degree coverage) is shown to indicate the ground station's primary coverage area.

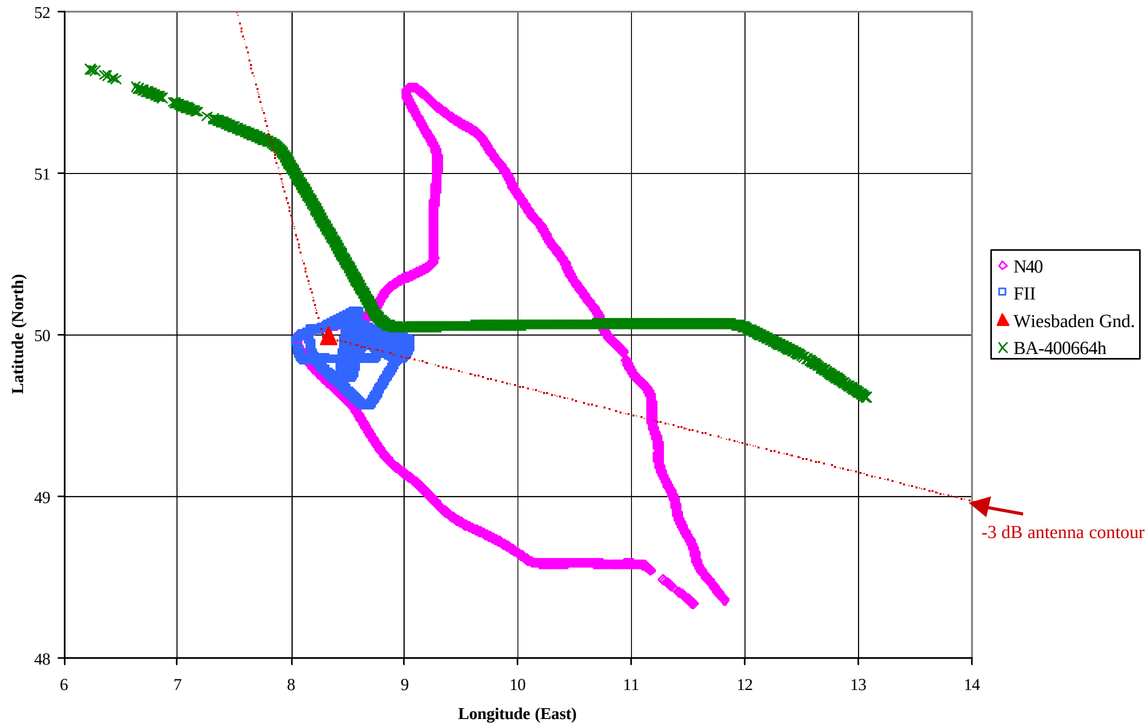


Figure 4.5.3.2.1-7. Wiesbaden LDPU Target Tracks, 22 May

The flight path of all three target aircraft (i.e., N40, FII and BA-400664h) include significant segments of their flight paths within the primary coverage area (i.e., within the antenna beams) of the Wiesbaden ground station. Figure 4.5.3.2.1-8 plots the probability of reception by the Wiesbaden ground station for the three targets within the primary coverage area and above 1000 ft altitude. By placing these limits on the data included in the following figure, a portion of the data collected from all three aircraft were excluded that plotted in the following figure.

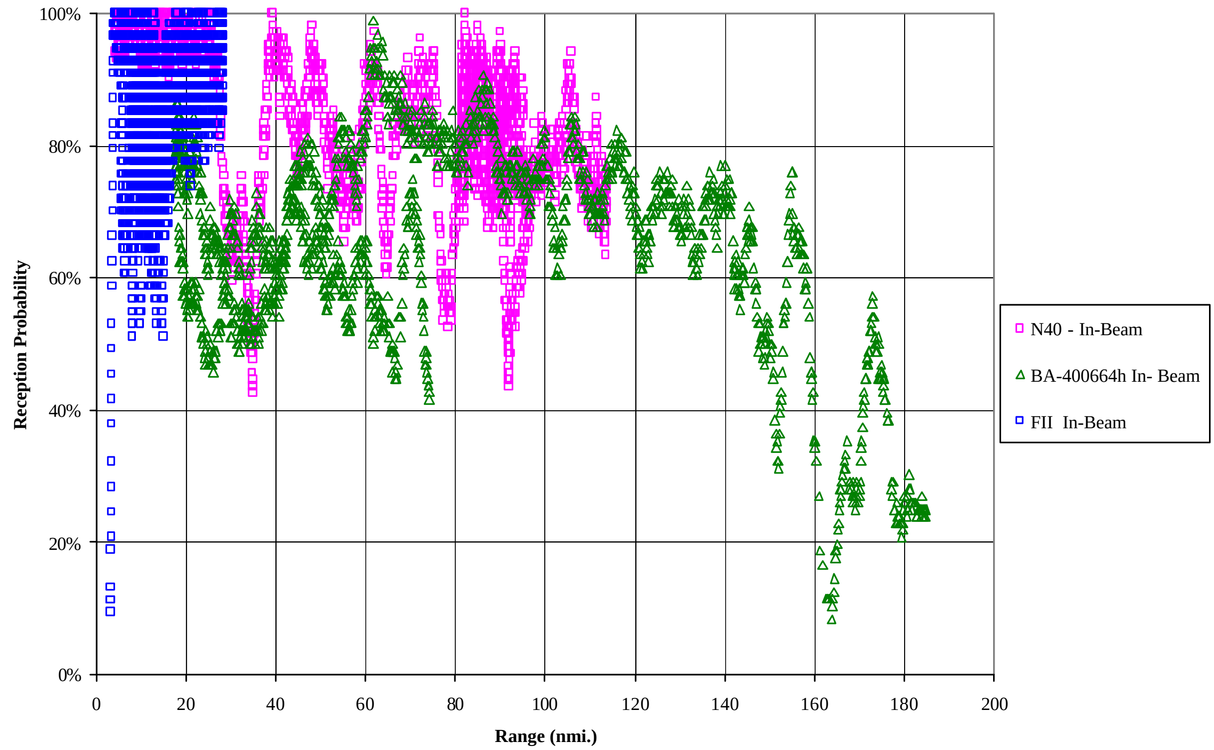


Figure 4.5.3.2.1-8. Wiesbaden LDPU In-Beam Reception Probability, 22 May

Figure 4.5.3.2.1-9 provides the received update period by the Wiesbaden LDPU for all in-beam airborne targets.

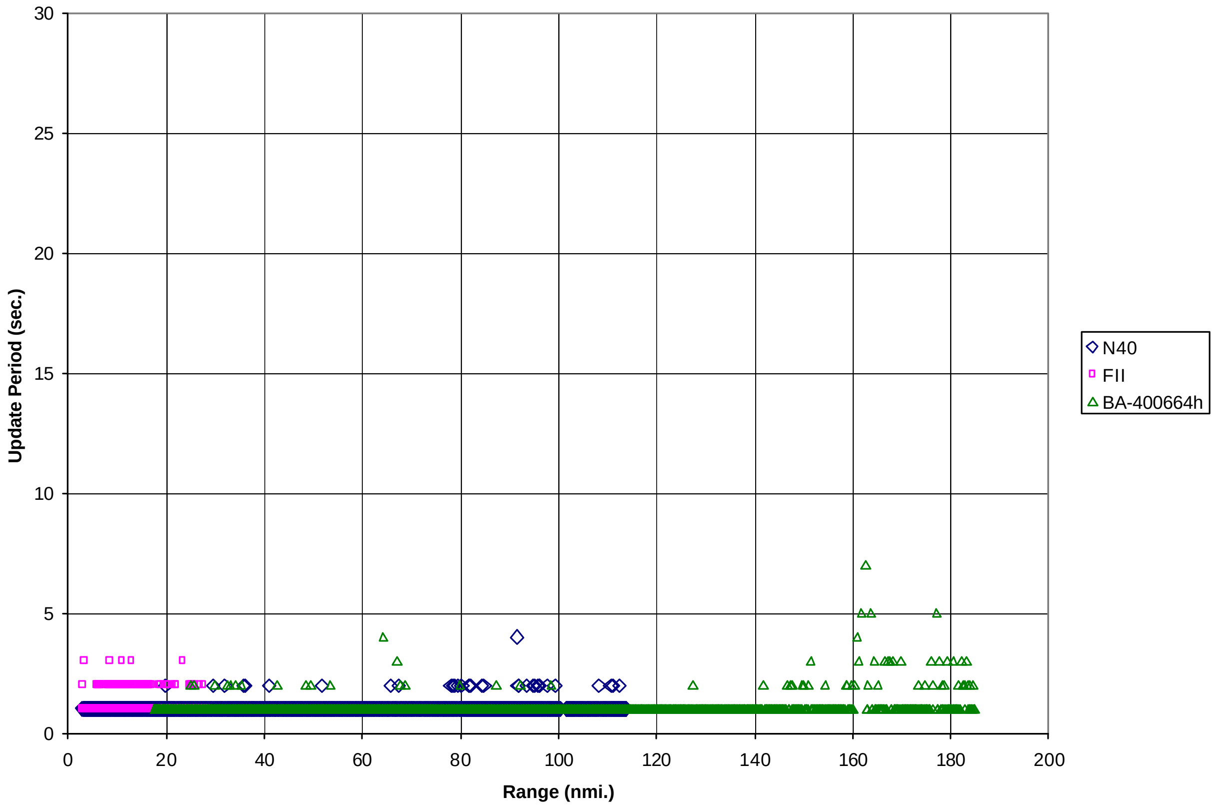


Figure 4.5.3.2.1-9. Wiesbaden LDPU In-Beam Update Period, 22 May

4.5.3.2.1.4 Results for 25 May

Of the project aircraft only N40 participated in the data collection on 25 May. During the data collection at the Wiesbaden ground station, one British Airways target of opportunity was also observed. Figure 4.5.3.2.1-10 is a plot of the ground tracks of N40, and the target of opportunity observed during the data collection. The -3 dB cutoff of the ground station's antenna pattern (two adjacent 60 degree beams providing 120 degree coverage) is shown to indicate the ground station's primary coverage area.

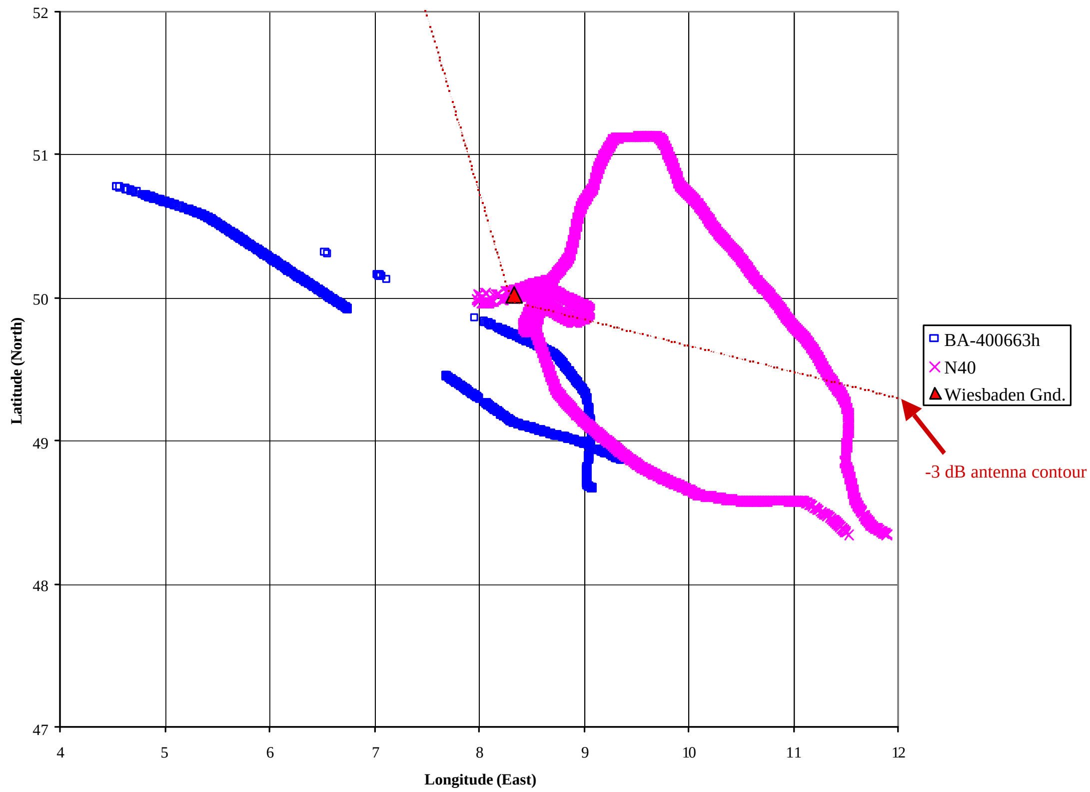


Figure 4.5.3.2.1-10. Wiesbaden LDPU Target Tracks, 25 May

The flight path of only N40 included a segment within the primary coverage area (i.e., within the antenna beams) of the Wiesbaden ground station. Figure 4.5.3.2.1-11 plots the probability of reception by the Wiesbaden ground station for the one target within the primary coverage area and above 1000 ft altitude. By placing the ground station antenna beam limits on the data included in the following figure, all of the data collected from all BA-400664h was excluded that plotted in the following figure as it's flight path remained outside the ground station's primary coverage area.

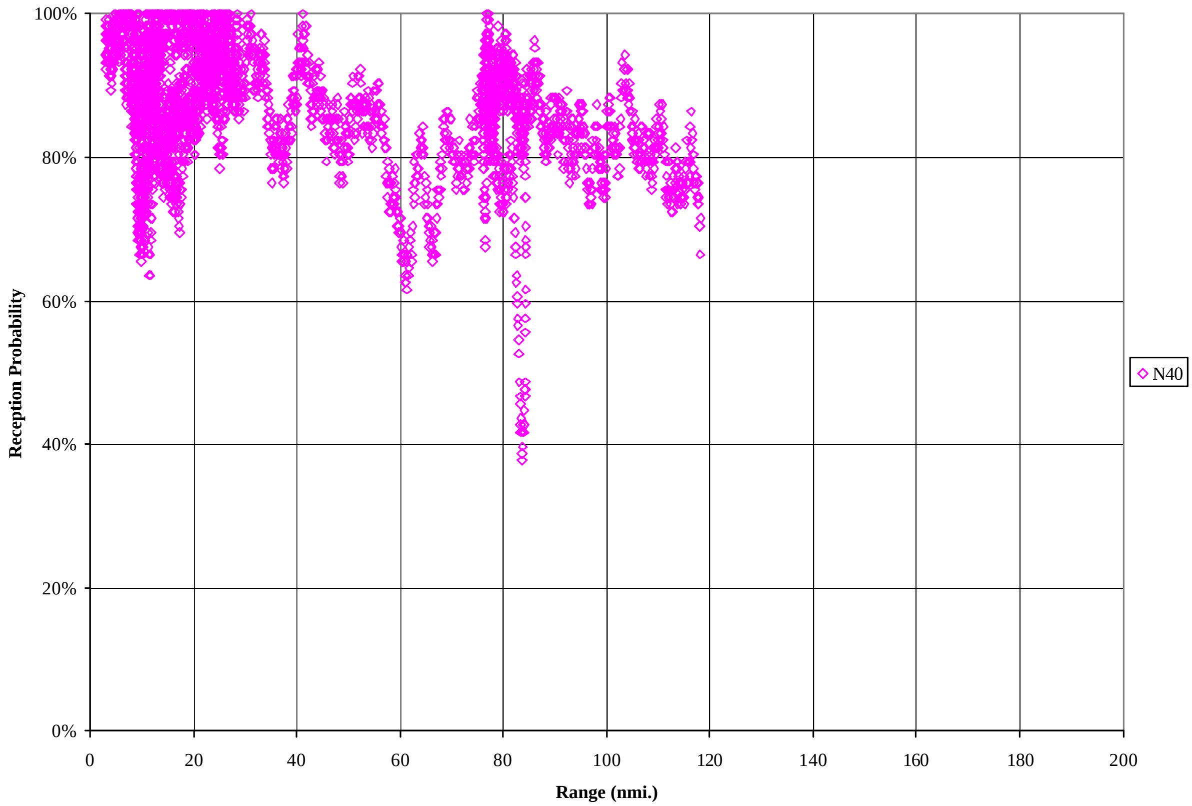


Figure 4.5.3.2.1-11. Wiesbaden LDPU In-Beam Reception Probability, 25 May

Figure 4.5.3.2.1-12 provides the received update period by the Wiesbaden LDPU for all in-beam airborne targets.

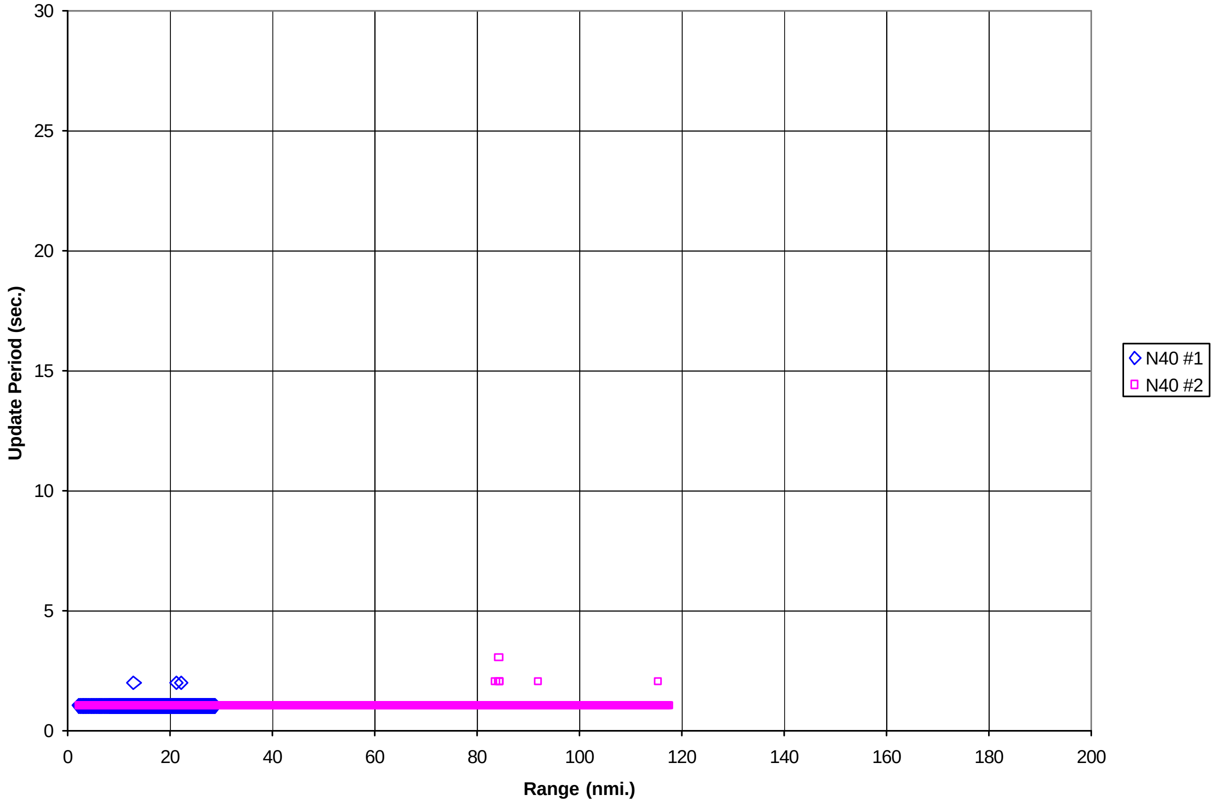


Figure 4.5.3.2.1-12. Wiesbaden In-Beam Update Period, 25 May

4.5.3.2.2 RMF Receiver

The RMF receiver installed at the Wiesbaden ground station was identical to the unit installed in the FAA B727 (N40). Only a single channel of data recording was enabled; the Wiesbaden RMF monitored 1090 MHz replies received via an omnidirectional DME antenna mounted near the 6-sector antenna.

4.5.3.2.3 Differences from Langen

The Wiesbaden ground station only had two types of receivers installed: a dual channel LDPU (with each channel connected to one of two adjacent sectors of a 6-sector antenna) and the RMF, which recorded digitized video obtained via a single channel LDPU front end connected to an omnidirectional DME antenna. An uplink transmitter was also installed at the Wiesbaden site; this uplink transmitter was connected to the omnidirectional DME antenna, and was always operating whenever flights were in progress.

4.6 GROUND-TO-AIR RECEPTION OF EXTENDED SQUITTERS

4.6.1 Overview

Various broadcast applications have been proposed for use by ADS-B-equipped aircraft. Distribution of traffic and weather data may be implemented by encoding the information into Extended Squitter message packets. The measured uplink performance of sample squitters in the Frankfurt environment offers an assessment of how well such a system might work. As a rough figure of merit, per-message reception probability of 40-50% is considered acceptable for a useful data link uplink application. This was observed from both the Langen and Wiesbaden uplink sites at N40 out to ranges of 40-50 nmi. This range is consistent with the additional line-of-sight constraint that data from a ground site must be available to aircraft at relatively low altitudes.

4.6.2 N40 Reception of Extended Squitters (22 May)

The uplink performance was calculated from data taken on 22 May, when N40 flew from Wiesbaden to Munich, north to Hamburg, and then returned to Wiesbaden, as illustrated in Figure 4.6.2-2. In this figure, the position of N40 is plotted whenever N40 received and decoded an Extended Squitter from the Wiesbaden ground station. Performance was calculated for reception of uplinks from each ground station.

4.6.2.1 Broadcasts from Langen

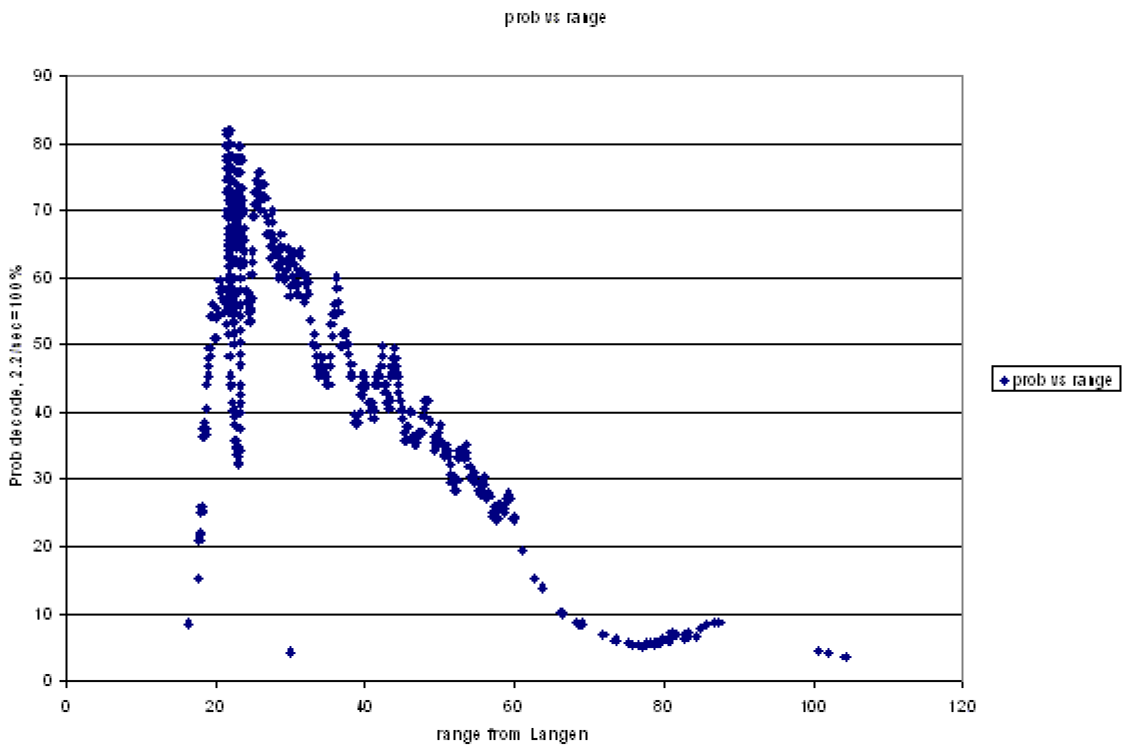


Figure 4.6.2-1. N40 Probability of Extended Squitter from Langen vs. Range,22 May

4.6.2.2 Broadcasts from Wiesbaden

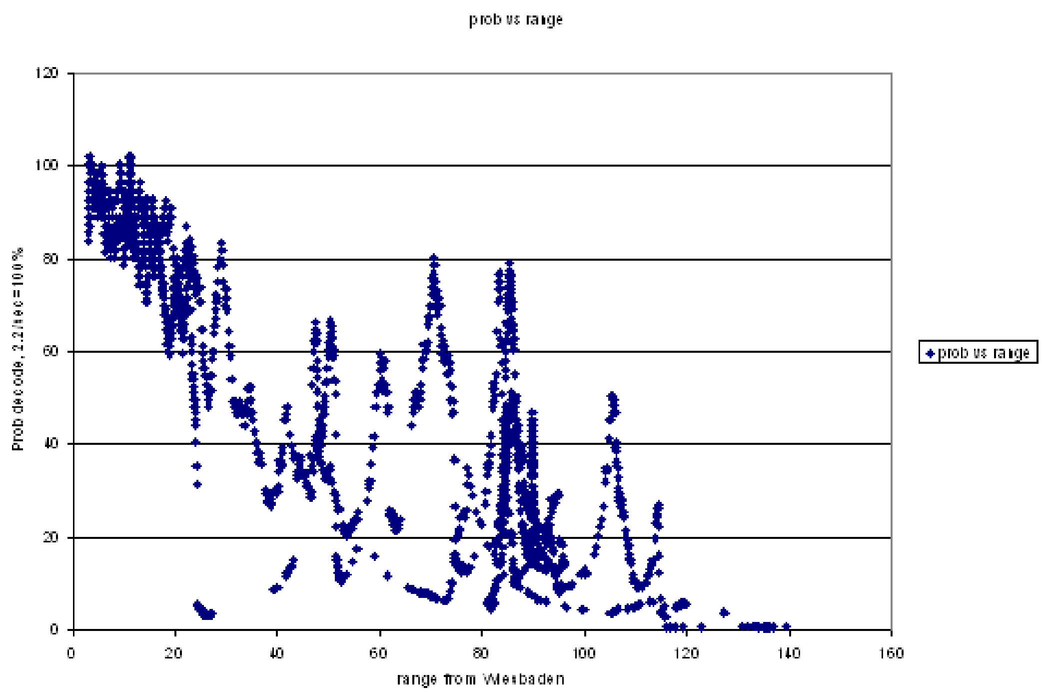


Figure 4.6.2-2. N40 Probability of Extended Squitter from Wiesbaden vs. Range, 22 May

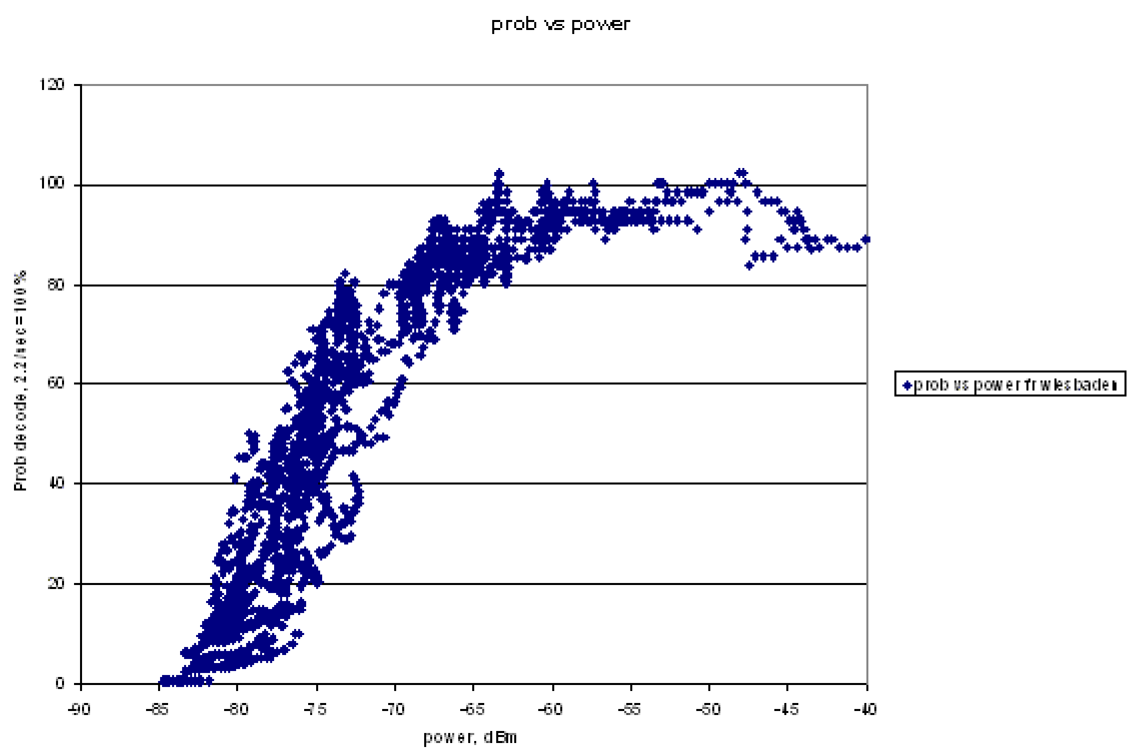


Figure 4.6.2-3. N40 Probability of Extended Squitter from Wiesbaden vs. Power, 22 May

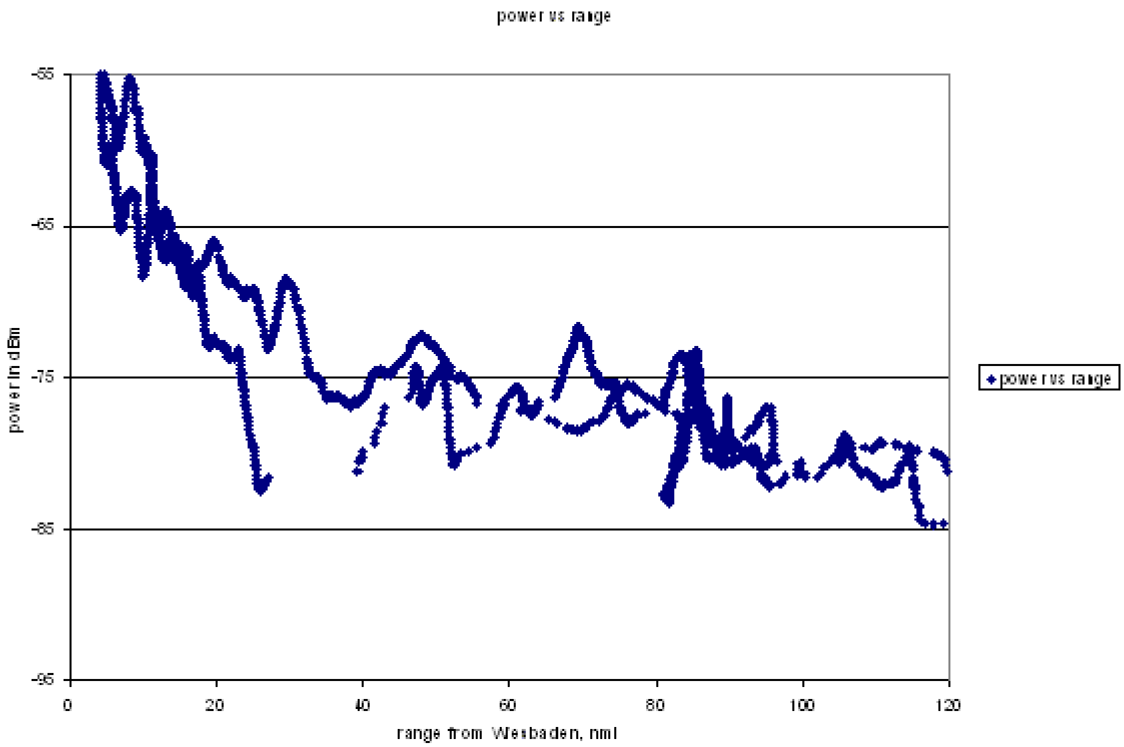


Figure 4.6.2-4. Variation of Received Power vs. Range from Wiesbaden, 22 May

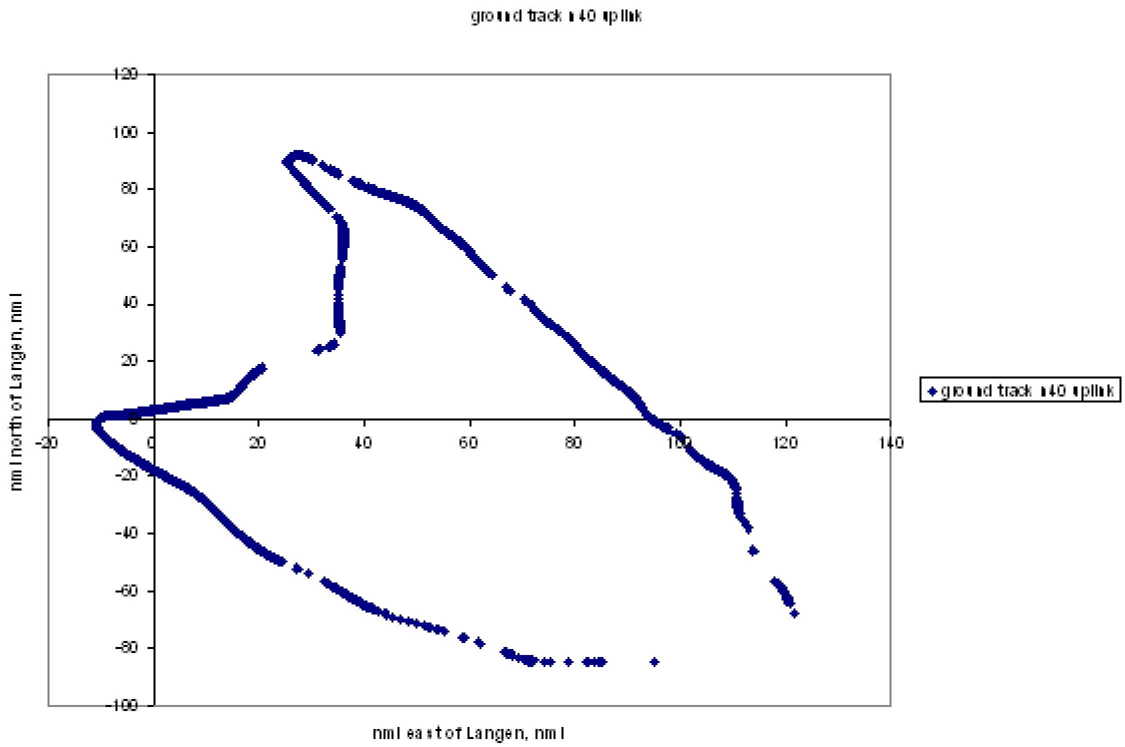


Figure 4.6.2-5. Position of N40 When It Received an Uplink from Wiesbaden, 22 May

4.7 BENCHMARK AIR-TO-AIR PERFORMANCE

The reception performance of the LDPU has been studied in more detail by setting up a comparison against known enhanced reception techniques. This was done by using the detailed RMF recordings as input to a non-real-time processing of certain specific techniques for detecting and demodulating Extended Squitter signals.

Figure 4.7-1 shows the results of this comparison. The comparison was made for data recorded during a 6-minute period on 24 May, for receptions on N40 of signals transmitted from the FII aircraft. This period was selected because observed performance was generally poorer than average during that time. TCAS reception techniques are also compared in this figure. The TCAS results shown here were obtained by processing RMF data, rather than using the actual TCAS receiver on the aircraft.

The received squitter counts were averaged over a 24-second wide time window to produce the aggregate reception probability. The LDPU reception probability has been calculated from the Extended Squitter Counts in the corresponding LDPU log file. The RMF reception probability has been calculated from the Extended Squitter messages resulting from off-line processing of the digitized video data recorded with the RMF using enhanced reception techniques. The RMF data was processed separately a second time using TCAS reception techniques. The RMF enhanced reception technique uses multiple-amplitude sampling for demodulation of information bits and confidence bits, and error detection and correction using the conservative technique followed by the brute force error correction for a maximum of 5 bits. A detailed description of the RMF enhanced reception technique and the RMF TCAS reception technique are contained in appendix B.

Figure 4.7-2 shows the air-to-air range and received power level during this 6-minute time interval. In Figure 4.7-3 the reception probability values are plotted as a function of range. This format allows a range comparison for a given level of performance. For example, as shown in Chapter 6, surveillance and intent communication is reliable whenever the per-Squitter reception probability is 23 percent or higher. Using this criterion, the results in Figure 4.7-3 indicate that range performance is increased, in this unusually bad case, from about 35 nmi for the LDPU to about 55 nmi for the enhanced techniques.

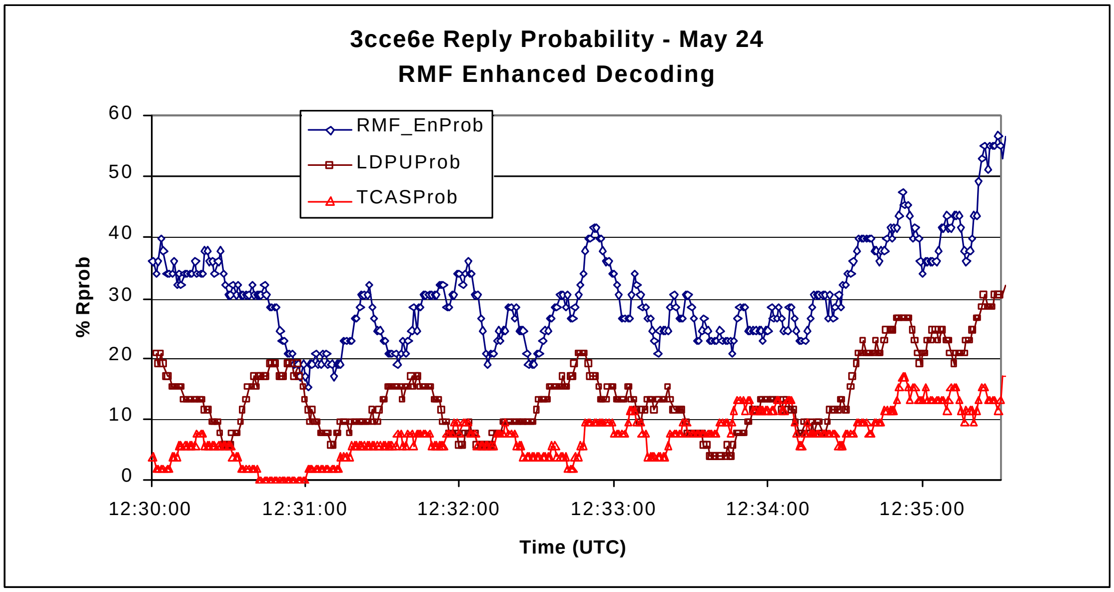


Figure 4.7-1. Comparison of LDPU against Enhanced Reception Techniques and TCAS Reception Techniques

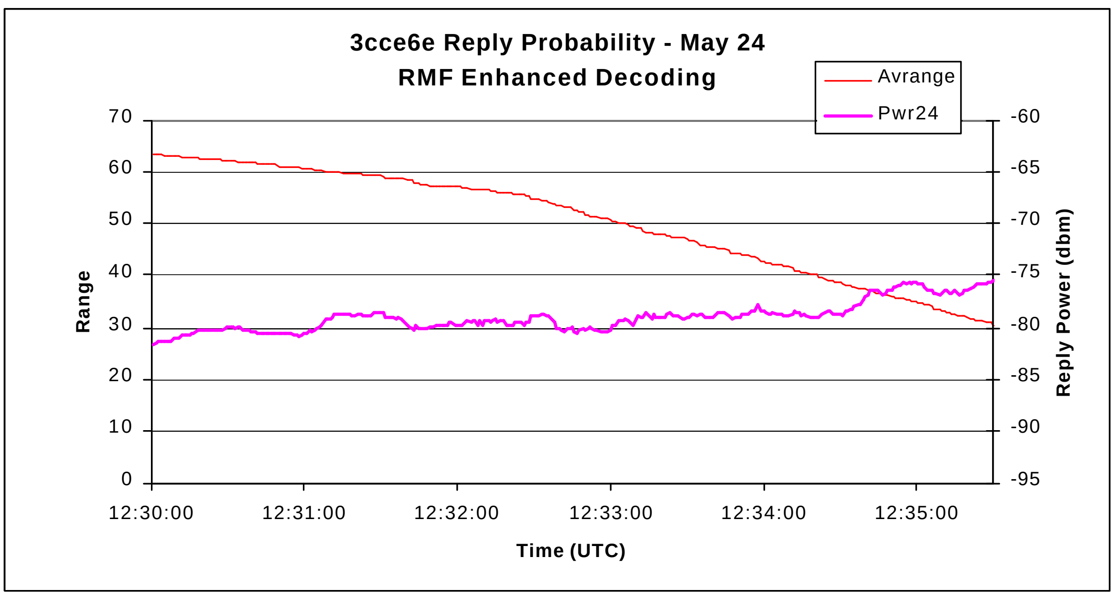


Figure 4.7-2. Air-to-Air Range and Received Power Level

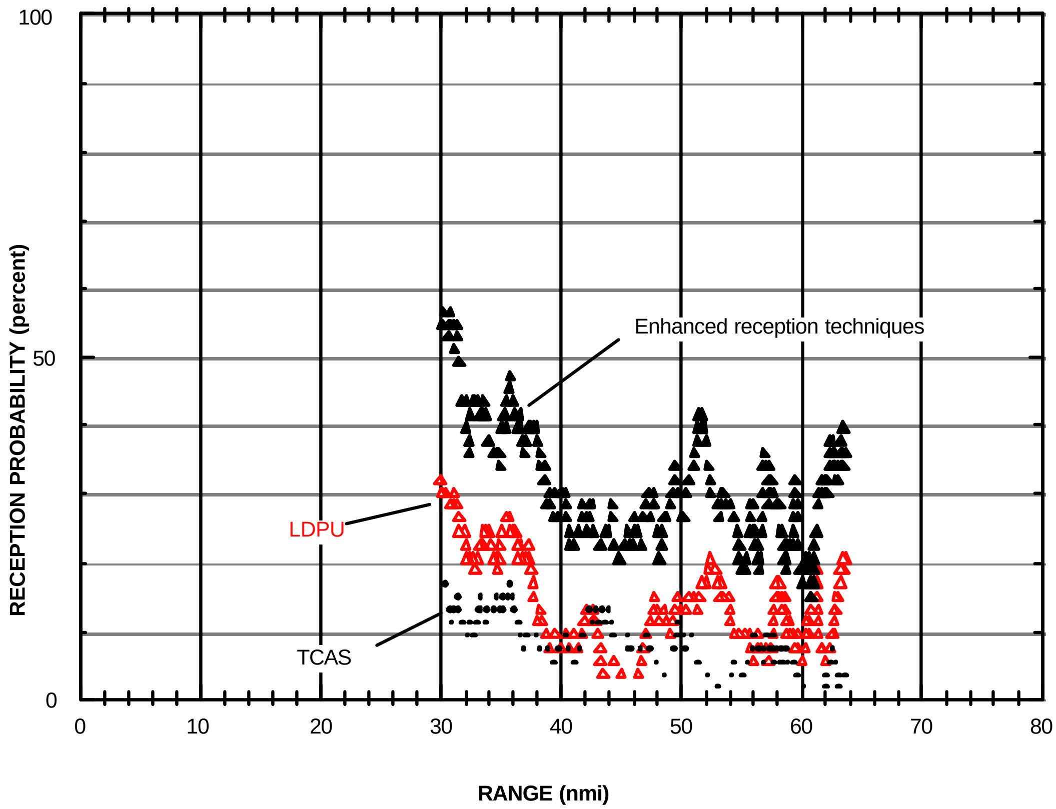


Figure 4.7-3. Enhanced Performance as a Function of Range, 24 May