5. RF ENVIRONMENT SUMMARY

5.1 Overview

The airspace surrounding Frankfurt, Germany, has been shown to have one of the highest fruit rates measured anywhere in the world, due to a combination of high traffic density and very high numbers of ground interrogators (largely military ATCRBS interrogators) that operate at high interrogation repetition frequencies (IRFs). The German CAA, Deutsche Flugsicherung GmbH (DFS) and the U.S. Department of Transportation / Federal Aviation Administration (FAA, with their subcontractor MIT Lincoln Laboratory) agreed to collaborate on a measurement activity. A primary purpose of this activity was to improve the current understanding of the RF environment in the Frankfurt area.

The main research questions that were to be addressed through this measurement activity with respect to RF load were:

1. What are peak/average 1090 MHz reply and suppression rates and the 1030 MHz interrogation rates in Frankfurt in May 2000?
2. Does the1090 MHz reply rate vary with time, location, and if so, how?
3. Can traffic count, interrogator count, and interrogator repetition frequency (IRF) explain measured fruit rates?
4. Are transponders that reply to Mode S All/Call interrogations while on the surface at Frankfurt airport a significant source of fruit?
5. What contribution to the interrogation rate (and hence the corresponding 1090 MHz reply rate) is associated with civil and military radar installations?
6. How do measured interrogation rates, reply rates, and suppression rates compare with the measurements made in 1995 in the Frankfurt area?

Some of the above questions were not answered to the full extent in this report due to the limited time available which was not sufficient to analyze all of the data in the appropriate detail.

Sections 4.3.1. and 4.3.2. present the available measurement results to the appropriate detail and are separated by the SSR reply (1090 MHz) and interrogation (1030 MHz) channels, while 4.3.3 details the aircraft distribution during the common May 2000 measurement program. Various equipment was on board the aircraft to measure similar or complementary data. Since the different analyses sources that were used, agreed in general with each other, high confidence can be given to the results. The following paragraphs summarize these results to give an overall picture on the environment during the trials period. If not stated otherwise, the results are obtained at flight level 220. In addition, open issues will be identified for future analysis either with the data already available or for further examination in future trials.

Note: The lines showing in the following figures (5.2.-1. through 5.3.4.) connecting the data points are provided only to allow the reader to clearly differentiate the data points and are not intended to depict any trend in the data

5.2 1030 MHz Interrogation Environment

The interference environment depends on the number of active interrogators (ground based or airborne), while the reply channel load also depends on the number of aircraft. While the 1030 MHz receptions were contributed by many individual radars and TCAS, some consideration was given to identification of individual radar stations. It is possible, although difficult and time consuming to identify ATCRBS interrogators based on their characteristics such as rotation time, interrogation frequency and stagger pattern. Mode S ground interrogators can, in principle, be identified by their Interrogator Identifier (II) Code, TCAS II aircraft can be identified due to their 1030 MHz broadcast. Therefore, Mode S interrogators in general can be identified. However, only one Mode S ground interrogator was operating in the trials area. The following discussion will focus on a summary of ground based and airborne interrogations.

The measured interrogation rates were found to vary with aircraft altitude and location. On two occasions during the trials a 10 minute Military Radar Shut Down (MRSD) was coordinated for 24 May and another MRSD for 25 May. Note that only military radars located in Germany were requested to be shut down. Therefore, at least military radars beyond German borders were still having an effect during MRSD periods. It turned out that those periods could not be identified as clearly as expected. There is evidence that some military radars were active in this time period (see below). Also, specific knowledge is missing about the actual time or about the duration each single radar was switched off. It may well be that some were turned off a little bit later when others were already switched on again.

In the Figure 5.2-1, MRSD (1) represents the data measured in the agreed 10 minute period, while MRSD represents a 30 minute period from 11:00 to 11:30 UTC, including MRSD (1). Results achieved more than 15 minutes after the MRSD period are described as "normal". The front part of the figures covers measurements in the Frankfurt (FFM) area, while at the end results were measured near Munich (MUC) and in the southern region (south).

The highest Mode A interrogation rates were measured on 19 and 25 May (mean and max values) and 24 May (mean only). In southern Germany the interrogation rates reach about 50 % of the Frankfurt rates measured at the same altitude. During the MRSD period on 24 May the interrogation rates decreased between 20 % and 30 %. Very similar values were measured on Saturday, 20 May. On 25 May, the MRSD (1) period is not significantly different from the MRSD or from "normal", but generally on a higher level. Since 25 May was declared as the backup day, the participation might not have been as significant.

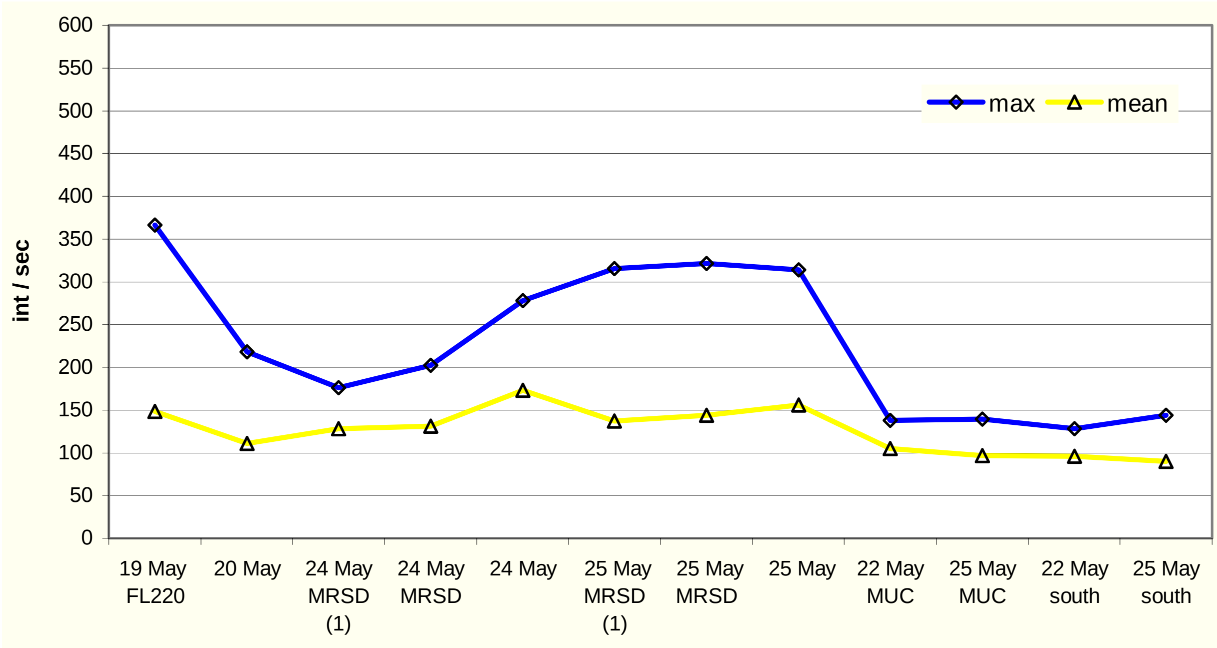


Figure 5.2-1. Mode A Interrogation Rates

(MRSD = Military Radar Shut Down)

Note: Peak values due to radar malfunction are not taken into account in this figure

As shown in Figure 5.2-2, the same result appears to apply to Mode C interrogation rates, but at a lower level in general. The maximum value on 19 May is lower than 24 and 25 May. Again a significant drop during MRSD on 24 May (more than 25 %), which this time has no correspondence in the mean values. On 25 May, interrogation rates stay at a high level.

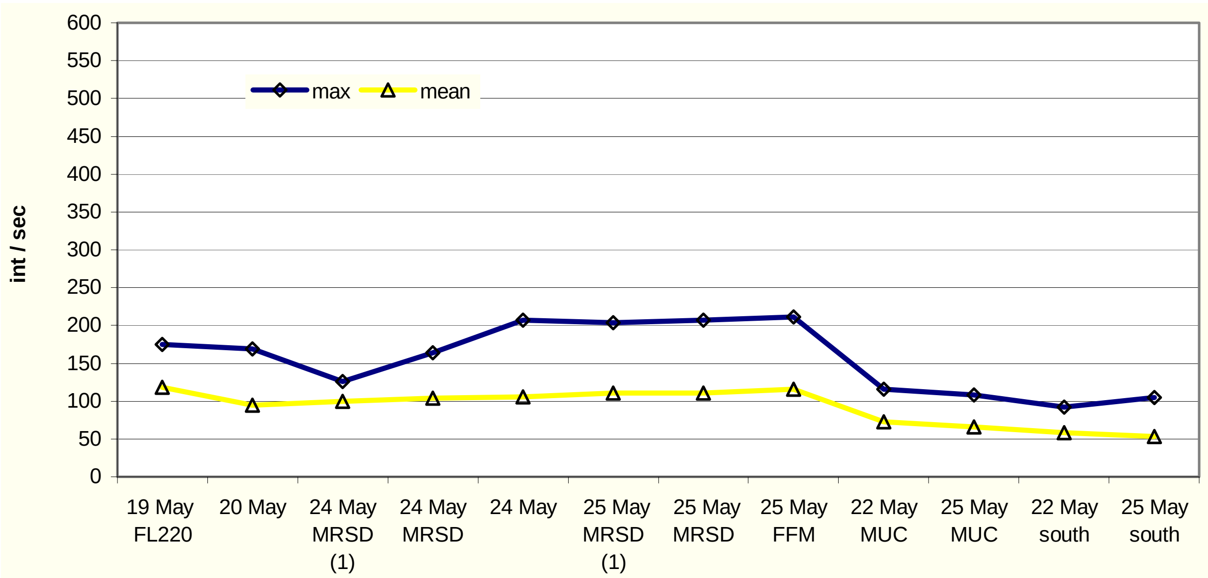


Figure 5.2-2. Mode C Interrogation Rates

(MRSD = Military Radar Shut Down)

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. By comparison the measurements made in Los Angeles [Ref 10] indicate that the ratio was nearly 1:1 in that airspace.

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. While most of the DFS interrogators use a Mode ACAC interlace Mode A interrogations rates were all the time significantly higher than Mode C rates.

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 appeared at least on two days and 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.

The number of measured suppression rates give another picture of interrogator activities on the ground and in the air. Figure 5.2-3 summarizes the measured data from 19 to 25 May. The maximum rate that appears on the 24 May data show by far the highest values, while the drops seem to correspond with the MRSD periods, this time also on 25 May. The drop in suppression rates due to the military radar shut down is in proportion to the interrogation rates: Even with different values for the different cases for mean and max the difference between with and without military radars is about 15%. In addition Figure 4.3.2-6 indicates that during that time period, military radars were still operating (ongoing Mode 2 activity during the MRSD period). The question remains if those radars were inside or outside German borders. An analysis based on the power level of received Mode 2 interrogations would give a hint but no definite answer. The bottom curve represents the maximum suppression rate generated by airborne interrogations.

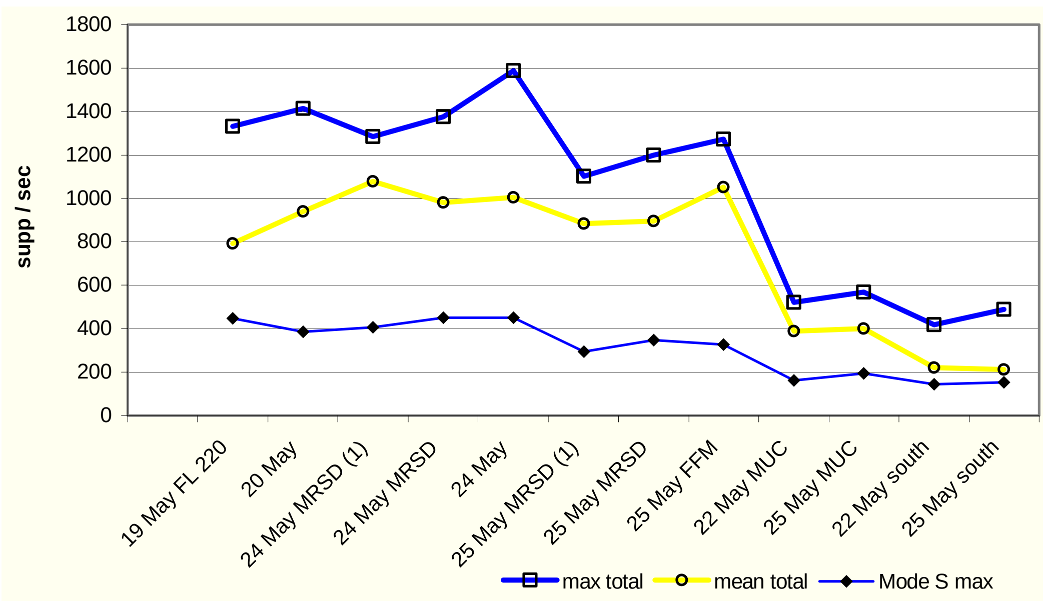


Figure 5.2-3. Summary of Suppression Rates

(MRSD = Military Radar Shut Down)

In Figure 5.2-4 the upper curve shows the maximum total suppressions, while the other curves represent mean and maximum value of suppressions generated by ground based interrogators. All values exclude suppressions generated due to Mode S interrogations. On two days, Monday 22 May afternoon and Thursday 25 May early afternoon N40 was En-route towards Munich, covering some of the South German airspace. Figures 5.2-3 and 5.2.-4 also give the impression of lower suppression rates in Munich and the whole southern German area. While the rates appear to be slightly higher in Munich than in the surrounding area, the values are 40% below those measured in the Frankfurt area.

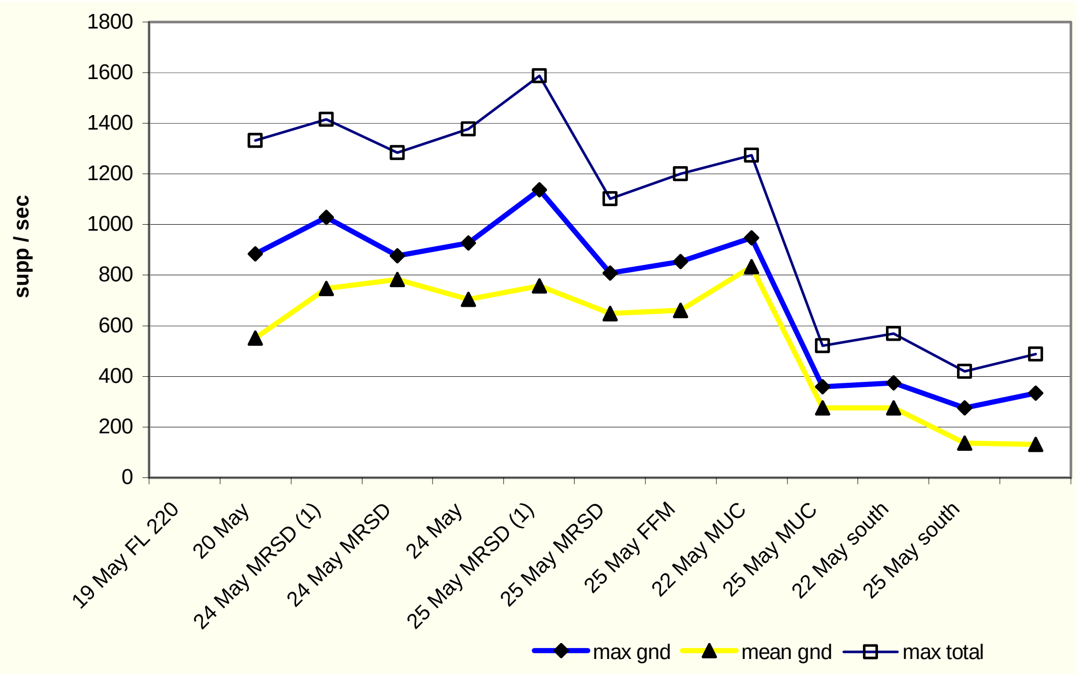


Figure 5.2-4. Summary of Ground-Based Suppression Rates

(MRSD = Military Radar Shut Down)

Figure 5.2-5 details the altitude dependence of interrogation and suppression rates. A significant decrease in maximum Mode A interrogation rates below FL 150 is apparent. The decrease in Mode C is nearly constant above FL 100. Some dependency can be seen comparing Mode S interrogation rates and suppressions, in particular at FL 100 and below.

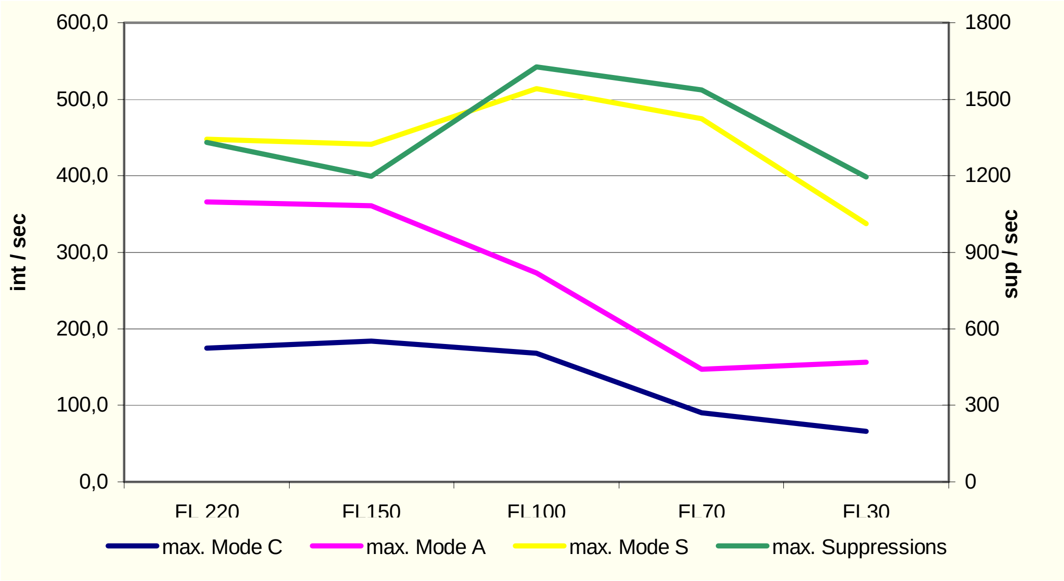


Figure 5.2-5. Altitude Dependence of Measured Interrogation Rates

5.3 TCAS II Activities in German Airspace

Due to the European mandate, the number of TCAS II equipped aircraft has increased significantly. The measurements reveal that for the Frankfurt area 80% of all Mode S equipped aircraft are also equipped with TCAS II. Figure 5.3.-1 also incorporates the four (mean) and eight (max) identified TCAS II equipped aircraft operating 1995 in the Frankfurt area (30 nmi) at the same time. 24 May shows the highest maximum values, but lowest mean values at the same time. The “max”-values for 24 May are higher than 50 aircraft.

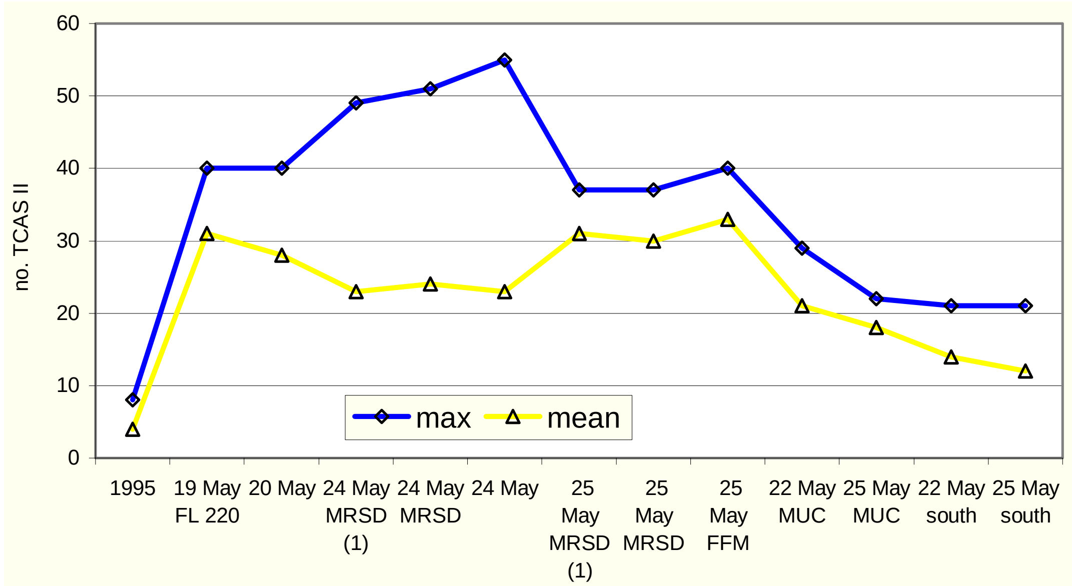


Figure 5.3-1. Number of TCAS II Equipped Aircraft

(MRSD = Military Radar Shut Down)

The number of TCAS II equipped aircraft is lower in the southern part of Germany. While the percentage for Munich varies between 50 % and 60 %, the rates drop to 30 % for the rest.

TCAS II interrogates aircraft in the vicinity either with ATCRBS-only (Mode C-only) interrogations using a specified Whisper-Shout sequence or with Mode S interrogations. Figure 5.3-2 summarizes the number of ATCRBS-only interrogations measured in the Frankfurt area. From the interrogation rates it becomes evident that TCAS is a major contributor to the environmental load. However, contrary to ground interrogators there is neither high interrogation power nor a high gain antenna. This limits interference contribution, as well as the surveillance range. TCAS interference limiting algorithms will further reduce the surveillance coverage in areas where there is a concentration of TCAS equipped aircraft. As indicated in 4.3.1 nearly all of the Mode S and ATCRBS-only activity is caused by TCAS II equipment, since there was only one Mode S radar in the area. The ground Mode S radar generated less than 5 % of the Mode S and ATCRBS-only fruit.

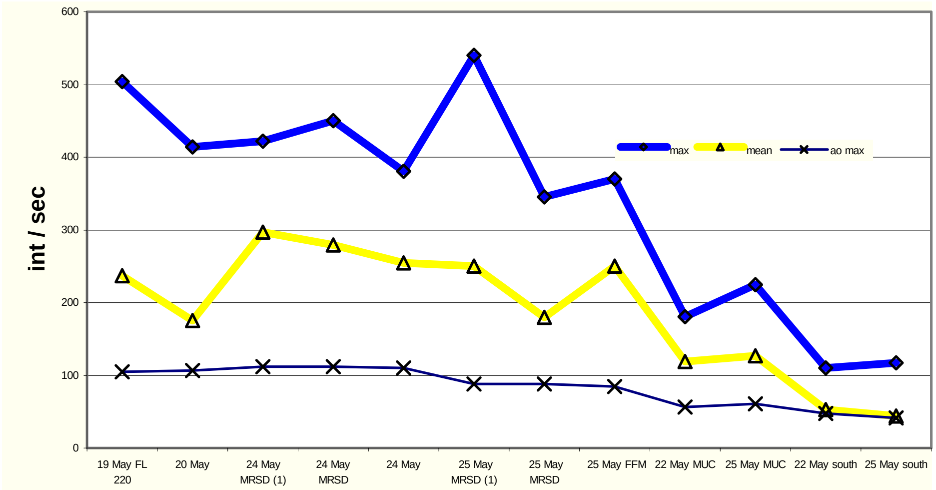


Figure 5.3-2. Distribution of ATCRBS-Only Interrogations

(MRSD = Military Radar Shut Down)

The “mean” values seem to be rather constant in Frankfurt, more variation appears for the “max”-values. The results indicate that TCAS II Mode C-only interrogations add between 25 % and 40 % (30 to 70 interrogations / sec) to the ground Mode C interrogations.

Figure 5.3-3 shows that the mean Mode S interrogation rate stays rather constant between 250 and 300 interrogations around Frankfurt, with a drop on Saturday, 20 May. The generally lower rates on 25 May also correspond to the lower number of TCAS II equipped aircraft on that day.

s

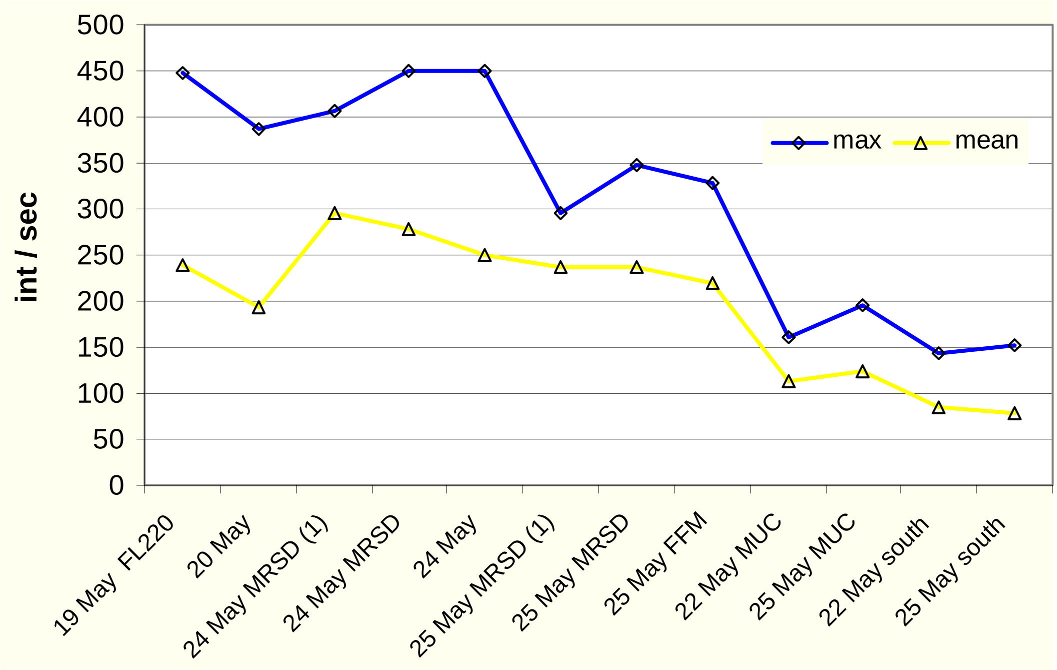


Figure 5.3-3. Distribution of Mode S Interrogation Rates

(MRSD = Military Radar Shut Down)

A slight increase in the mean Mode S interrogations can also be noticed during the MRSD phase on 24 May. This may be related to a lower interrogation rate, which reduces the fruit levels on the reply channel, thus allowing TCAS II to detect and interrogate more squittering aircraft in the vicinity. The number of TCAS II equipped aircraft is displayed in Figure 5.3-1.

Figure 5.3-4 presents ATCRBS-only interrogations. For both ATCRBS-only and Mode S interrogations the values measured around Munich and the southern part of Germany reflect the aircraft count and are about 50 % below the Frankfurt rates. While most of these interrogations result in a suppression, the bottom line indicates the maximum rate of interrogations requiring a reply from ATCRBS transponders.

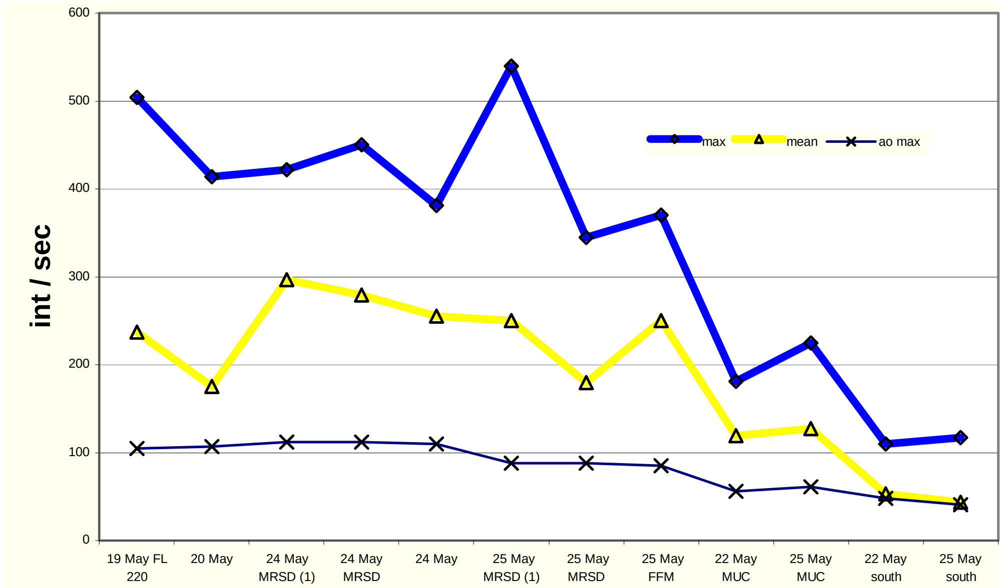


Figure 5.3-4. Distribution of ATCRBS-Only Interrogation Rates

(MRSD = Military Radar Shut Down)

5.4 Aircraft Distribution and 1090 MHz Fruit Environment

Fruit rates depend on both the interrogation rates seen by each aircraft and the distribution of aircraft within reception range of the affected receiver. Therefore it was an essential part of the Frankfurt trials that detailed measurements be made of the number and distribution of all aircraft that could be a source of interference to the ADS-B receivers located in the Frankfurt area. An estimate of at least 520 aircraft in view of a sensitive receiver on N40 was obtained as follows.

Data was (were is correct, this is inserted with apologies to our British colleagues) collected from the DFS radar surveillance system to determine the number of transponder-equipped aircraft within German airspace (approximately a 200 nmi radius surrounding Frankfurt). Because multiple radars contributed to this data set it is expected that almost all transponder-equipped aircraft are accounted for within it. From these data (summarized in Figure 4.3.3.-1) we estimate that on average about 400 aircraft were aloft within 200 nmi of Frankfurt throughout the trials period.

It was important to characterize the aircraft distribution by transponder type (Mode S vs. ATCRBS). The DFS surveillance data, because it was based on the aggregate outputs of ATCRBS interrogators, could not be used for this. Instead, the experimental Mode S sensor at Goetzenhain was configured to measure ATCRBS and subsequently Mode S aircraft counts for a 100 nmi radius surrounding Frankfurt. From these data it is estimated that the Mode S proportion of the overall traffic count varies between 50-70% throughout the airspace surrounding Frankfurt.

Recognizing that a sensitive receiver will be affected by interference from aircraft beyond 200 nmi, an estimate was made of the number of such aircraft. A count was made of the TCAS acquisition squitters visible to the RMF on N40 to the limits of the RMF sensitivity. An average of 430 distinct Mode S addresses were identified during a 2 minute averaging interval. Although Mode S addresses could be obtained by decoding Mode S replies and acquisitions, no range information was available solely through processing of the RMF data. Instead, this number was multiplied by a conservative factor accounting for the Mode S equipage ratio to obtain an estimate that at least 520 aircraft were visible to a sensitive receiver on N40. Moreover, it was possible to use the DFS multiradar data as a cross check. In this case, it was estimated that 200 of the 430 distinct Mode S addresses were within the overall aircraft count based on radar data (applying the estimate of 50% Mode S equipage as a portion of all transponder-equipped aircraft). This left 230 Mode S aircraft that likely were located beyond the 200 nmi radar limit. Again applying the 50% Mode S equipage ratio, this yields an estimate of 440 total aircraft beyond 200 nmi, or a total of 840 transponder-equipped aircraft within view of a sensitive receiver located on N40. The more conservative estimate of 520 aircraft was chosen as the average estimate of aircraft count.

Analysis of multiple ground radar recordings reveal that altitudes between zero and 10,000 feet were the most common. Higher altitude aircraft are approximately uniformly distributed between 10,000 and 40,000 ft. Above 30,000 ft, the distribution is seen to be concentrated at the odd thousands, which is consistent with the understanding of the air traffic control practices in Europe. The median altitude is seen in Frankfurt to be about 11,000 ft on work days. At weekend this value decreases to some extent. However, this is still significantly higher than the altitude distribution in Los Angeles, where the median altitude was measured to be about 4000 ft. Beside that the fruit rates do not vary with altitude as much as interrogation rates.

The trials results exhibit considerable variation in aircraft density from day to day and as a function of time on a single day. The results indicate that 24 May experienced the maximum overall density of aircraft, among the three test day cases analyzed, increasing from the beginning of the trials towards the end.. 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. While the maximum number of aircraft within 200 nmi appeared in September with 209 aircraft, the maximum value in May was about 5% lower (200 aircraft). The maximum during the trials period was with 184 aircraft another 7.5% lower.

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.

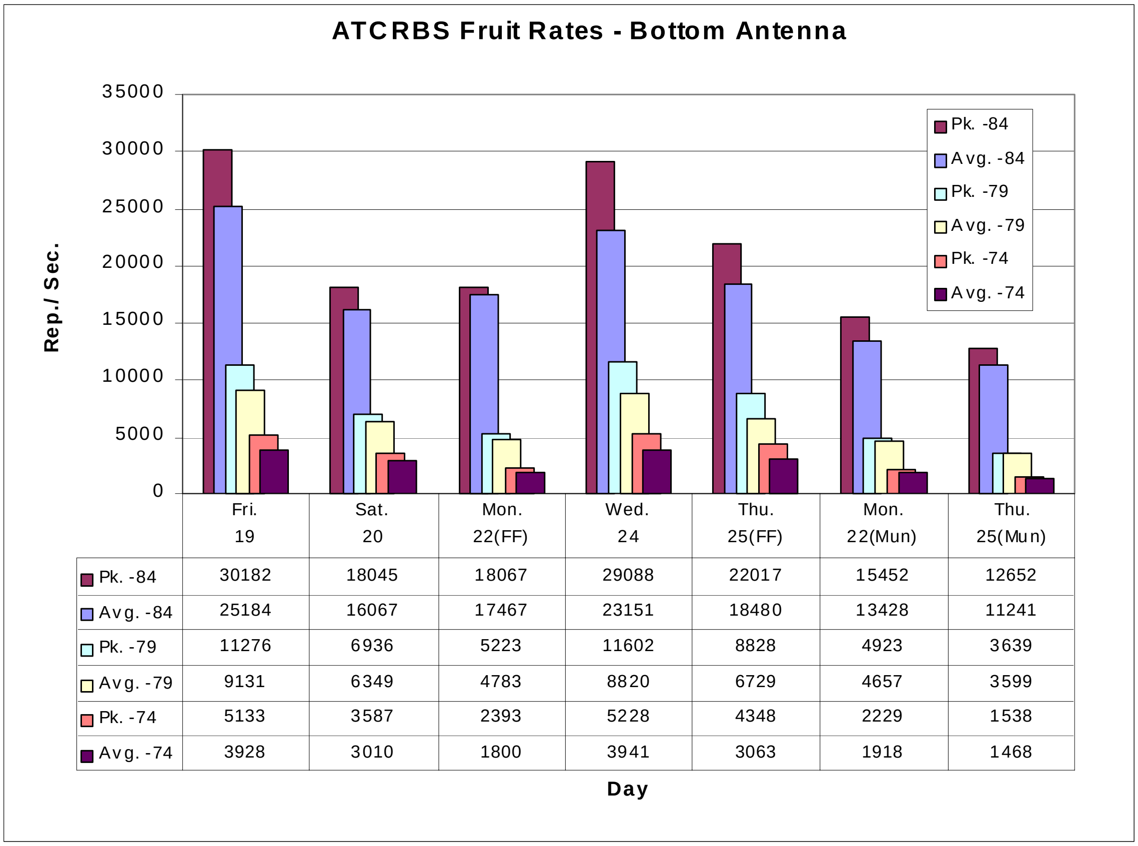
5.4.1. ATCRBS Fruit

The fruit rates measured at the bottom antenna each day were analyzed for similarities and differences in rates. Figure 5.4.-1. shows the rates for each day at the three levels presented in the "Fruit Rates as a function of Time" data. 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 en route 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 en route 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 en route to Munich produced fruit rates of 13.4k and 11.2k respectively at a level of -84dbm or greater.

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.



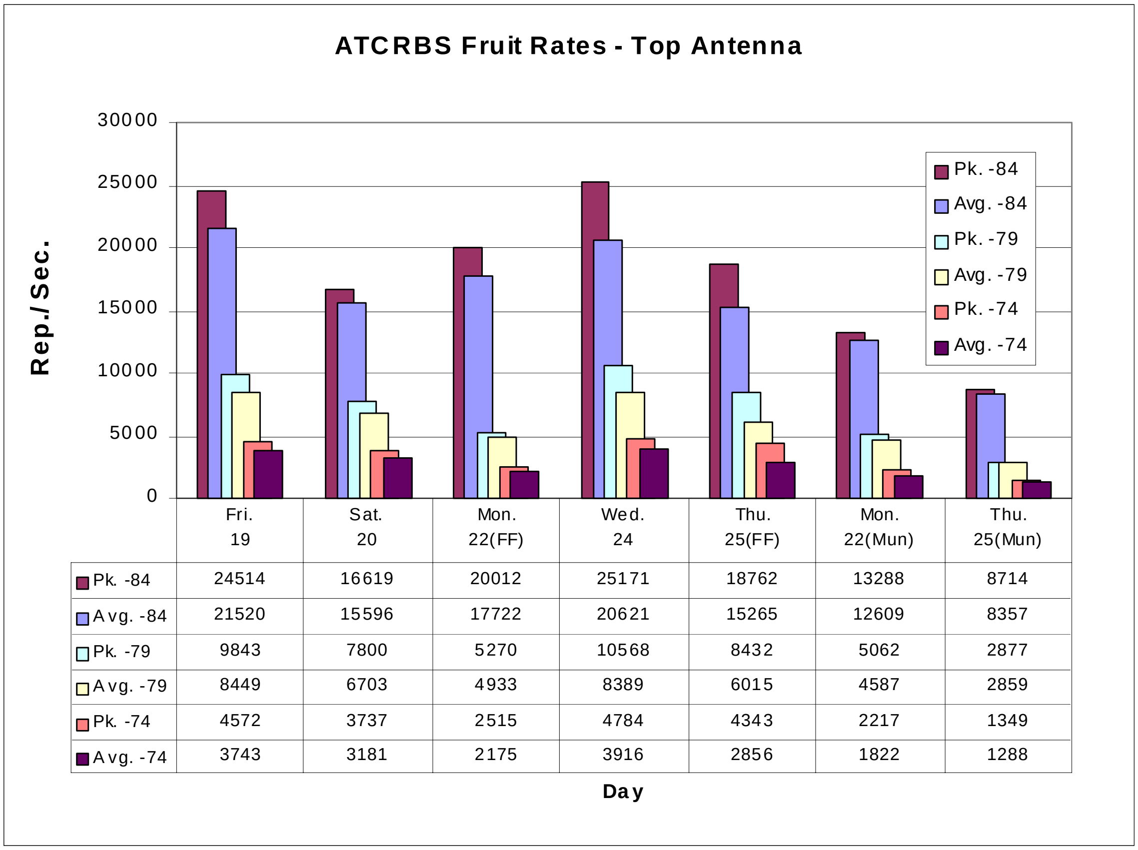
	Fri. 19	Sat. 20	Mon. 22(FF)	Wed. 24	Thu. 25(FF)	Mon. 22(Mun)	Thu. 25(Mun)
Pk. -84	30182	18045	18067	29088	22017	15452	12652
Avg. -84	25184	16067	17467	23151	18480	13428	11241
Pk. -79	11276	6936	5223	11602	8828	4923	3639
Avg. -79	9131	6349	4783	8820	6729	4657	3599
Pk. -74	5133	3587	2393	5228	4348	2229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

Figure 5.4.-1. ATCRBS Fruit Rates at 22kft To 24kft - Bottom 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 en route 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 en route 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 5.4.-2. ATCRBS Fruit Rates at 22kft to 24kft - Top Antenna

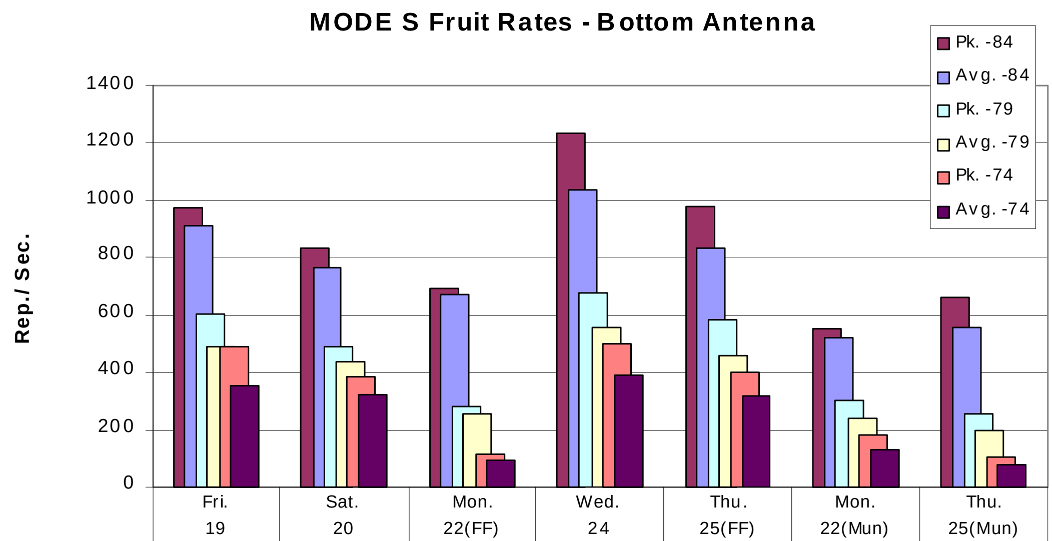
In general, fruit rates do not vary with altitude as much as interrogation rates. In particular, lower variation was experienced on Saturday, 20 May.

5.4.2. Mode S Fruit

Figure 5.4.-3. shows the Mode S fruit rates at the bottom antenna for each day at the three levels presented in the "Fruit Rates as a function of Time" data. All rates represent an average of the samples for the particular day (same as ATCRBS rates). While the curves shape in general is quite different than ATCRBS fruit, Mode S fruit rates decreased on Saturday due to lower fruit levels as well as due to the lower number of aircraft in general and TCAS equipped aircraft in particular.

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.

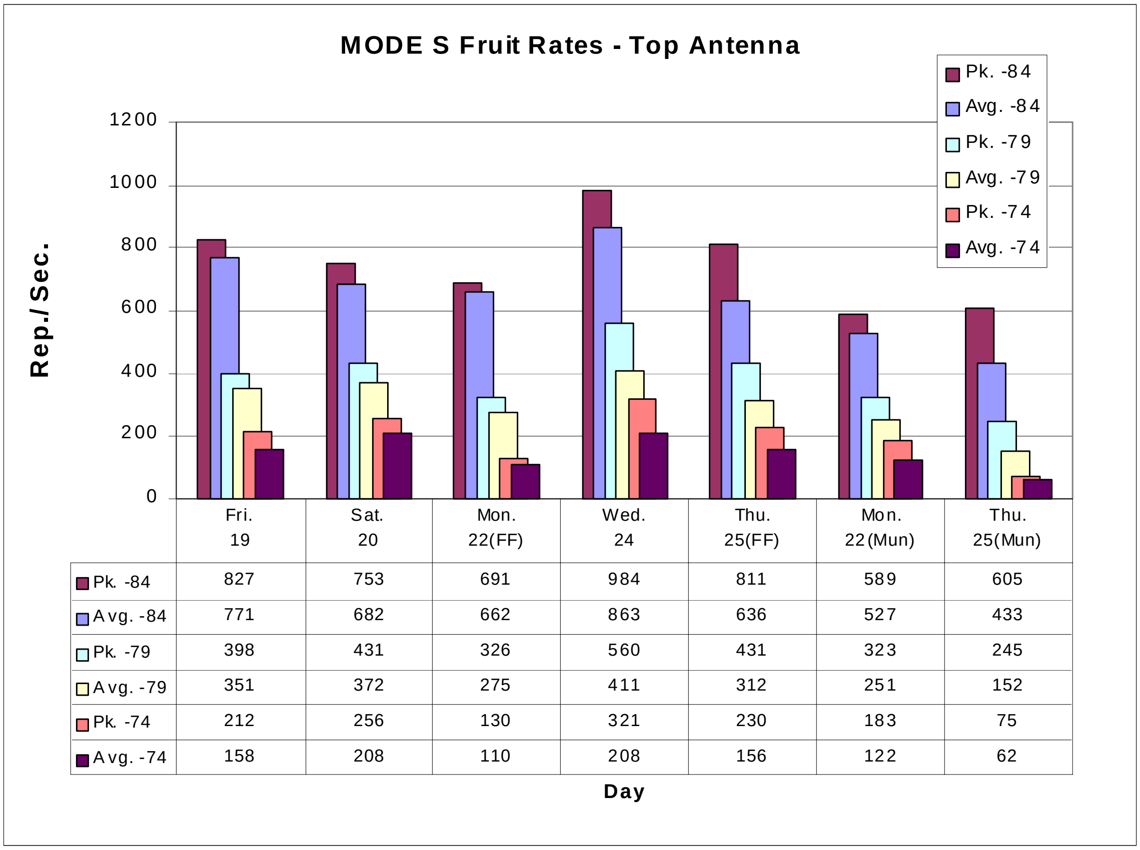


	Fri. 19	Sat. 20	Mon. 22(FF)	Wed. 24	Thu. 25(FF)	Mon. 22(Mun)	Thu. 25(Mun)
Pk. -84	974	830	693	1234	978	549	659
Avg. -84	911	766	671	1036	834	516	557
Pk. -79	604	487	280	678	577	304	252
Avg. -79	487	438	253	557	457	242	199
Pk. -74	486	383	112	502	401	182	102
Avg. -74	350	323	93	389	315	127	73

Figure 5.4.-3. Mode S Fruit Rates at 22kft to 24kft - Bottom Antenna

Figure 5.4.-4. 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, <u>for only the orbits,</u> is 1.9 at -74dbm and 1.2 at -84dbm. The ratio of bottom to top antenna fruit rates <u>for all</u> 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 5.4.-4. Mode S Fruit Rates at 22kft to 24kft - Top Antenna

5.4.3. General

At the bottom antenna, the measured fruit rates were independent of the flight level while the fruit rates measured at the top antenna increased at lower altitude and during approach in particular.

During MRSD (when interrogation rates dropped by 25 % to 30 %) fruit rates at the bottom antenna decreased by about 50 % while those measured at the top antenna stayed rather stable. These effects are more pronounced on 24 May than on 25 May.

While the highest fruit rates on the top antenna were measured in the Frankfurt area on 22 May, measured rates on the bottom antenna were quite "normal" or even lower at the same time. But in general, higher fruit rates were detected at the bottom antenna most of the time.

Fruit rates measured on Saturday 20 May were about 50 % lower than on the day before. On Monday 22 May, 30 % less fruit was measured than on Friday 19 May. In the southern part of Germany the decrease in fruit values vary between 20 % and 50 % compared with the Frankfurt environment.

The Mode S fruit rate is about 10 % of the ATCRBS fruit rate or even less. Since there was only one Mode S ground interrogator, more than 75 % of the reply channel

Mode S load is generated through TCAS II activity. The Mode S fruit environment for all days is summarized in Figure 5.4-5. The rates stay rather constant. It turns out that the reply rates are higher after the MRSD, when the interrogation rates increased as well.

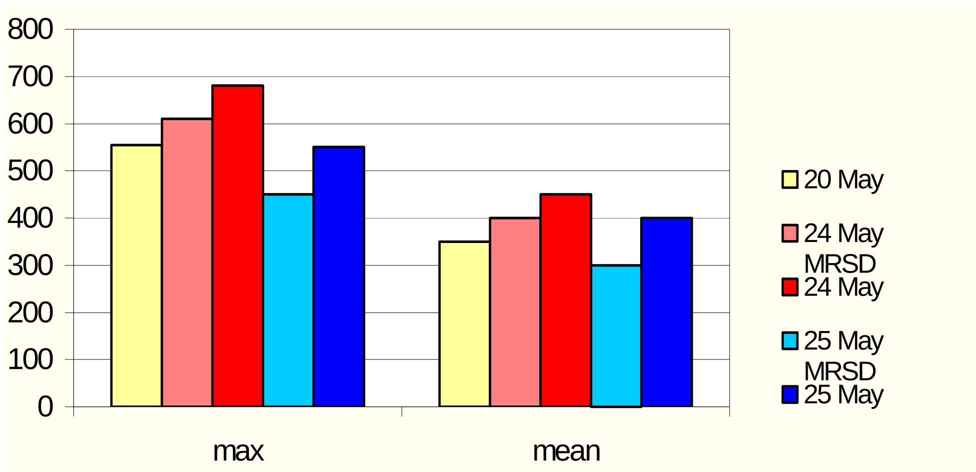


Figure 5.4.-5. Mode S Fruit Rate Summary in the Frankfurt Area

(MRSD = Military Radar Shut Down)

5.5 Comparison with Earlier Measurements

5.5.1 Frankfurt 1995

1995 measurements were conducted at FL 100 (Frankfurt and southern Germany), FL 150 (Frankfurt) and FL 170 (southern Germany). Comparable data were collected during 19 May 2000, when N40 was flying at FL 100 and FL 150 around Frankfurt. Figure 5.5-1 shows the different values measured at various altitudes. The suppression rates in the Frankfurt area stayed rather constant in the mean values, while there are no comparable data for the maximum values.

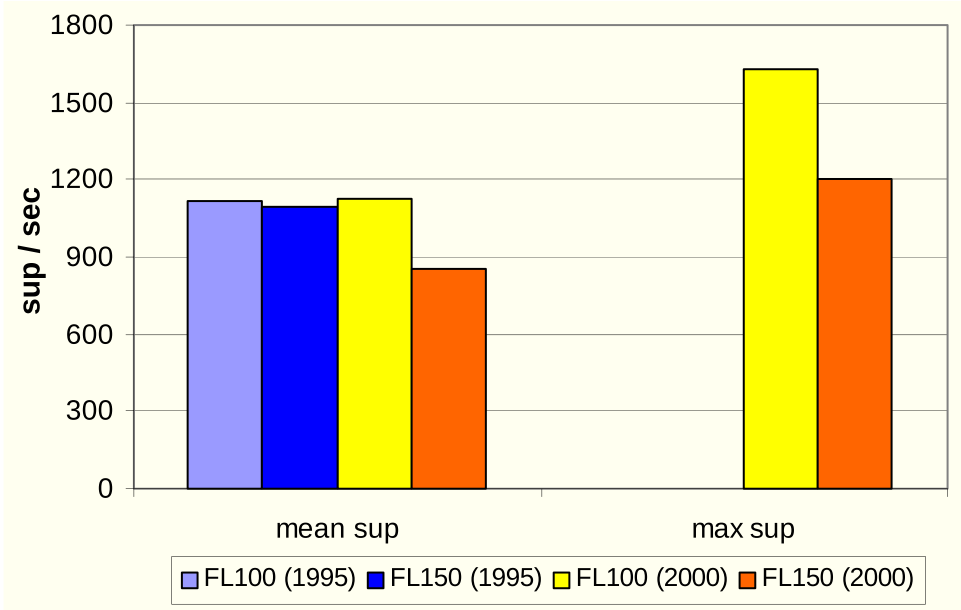


Figure 5.5-1. Comparison of Suppression Rates in the Frankfurt Area (1995 / 2000)

There were about 800 suppressions per second measured in southern Germany in 1995, the rate measured in 2000 is about half that value. But the limited available measured interrogation rates do not indicate any decrease in main-beam interrogations compared with 1995.

Figure 5.5-2 summarizes the interrogation rate results. As described in 4.3 there is an altitude dependence of the measured rates. Usually, interrogation rates measured at the bottom antenna increase with altitude. The Mode C and Mode A rates are of the same order in 1995 and 2000. In 1995, both, Mode C and Mode C-only interrogations were counted as Mode C. In 2000, Mode C-only interrogations were counted separately. This explains, why there was no ATCRBS-only count in 1995. In 2000, ATCRBS-only interrogations are similar in number to Mode S. In general, the number of Mode S interrogations has more than doubled since 1995 for both Frankfurt and southern Germany.

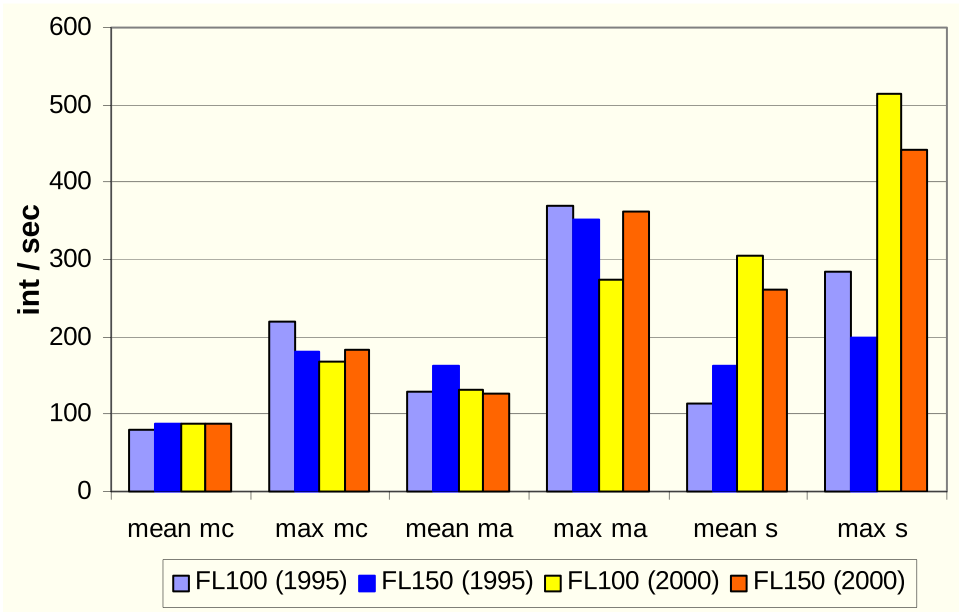


Figure 5.5-2. Comparison of Interrogation Rates in the Frankfurt area (1995 / 2000)

5.5.2 Comparison of Frankfurt and Los Angeles

The airborne fruit measurements made in Frankfurt can be compared against similar measurements made in the Los Angeles Basin in 1999 [Ref 10]. Figure 5.5-3 shows a fruit-rate comparison, using the maximum rate observed in the five days of testing in Frankfurt. For comparison, the maximum fruit rate measured in the four days of testing in LA is also shown. Only top-antenna data is shown here because the available data for maximum fruit in LA was limited to top-antenna receptions.

The comparison indicates that Frankfurt has a consistently higher fruit environment than LA. There is also a difference in the fruit power distributions. When compared for fruit rates at -74 dBm and stronger, which is applicable to TCAS receptions, there is only a small difference between Frankfurt and LA, about 1.5 dB. But when compared including weaker fruit receptions, down to -84 dBm, as would be applicable for long-range ADS-B, the Frankfurt fruit environment exceeds the LA environment by a substantially greater amount, about 3 dB.

This difference in fruit distributions appears to be consistent with an observed difference in aircraft distributions. As shown in 4.3.3, Los Angeles exhibits a very high density of aircraft at short range, near the city, with much lower density at long range from LA. Frankfurt on the other hand does not exhibit such a high aircraft density near Frankfurt, but the density is maintained at a high level away from the city. This difference in the air traffic distributions would be expected to cause the fruit distributions to differ, qualitatively, in the manner seen in Figure 5.5-3.

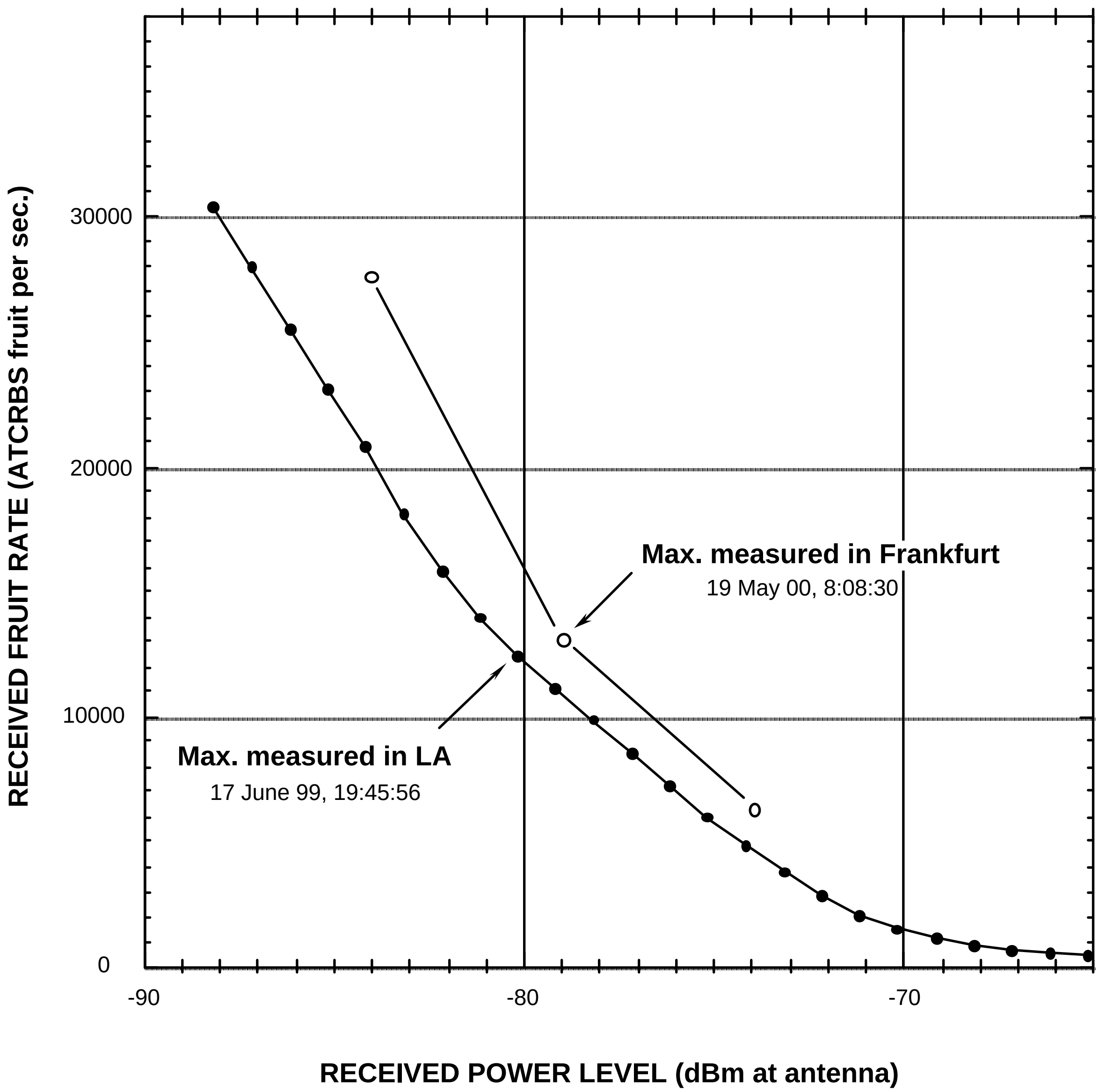


Figure 5.5-3. Comparison Between Frankfurt and Los Angeles (Top Antenna).

5.6 Evolution of the SSR and Surveillance Environment in Germany

During 1995 the DFS REMP (Radar Renewal and Modernization Program) was in progress, but still most of the German radars were operating with sliding window techniques. Since then, nearly all civil radars have been converted to monopulse which use lower interrogation rates. In parallel to the radar modernization, DFS is also operating the new ATM system (Air Traffic Management) P1 including a modern multi radar tracker. Taken together, REMP and P1 have improved the ATM capabilities. However, due to RF congestion and Mode A code shortage, DFS had to move forward to install Mode S radar sensors and adapt ATM systems to cope with Mode S data. A P1 revision is in preparation to allow Mode S data processing. In addition, a program was set up together with the Netherlands and Switzerland to install modern Mode S radars. While these new radars will cover the airspace above FL 100 and the major TMAs (Berlin, Duesseldorf, Frankfurt and Munich) in a first step, some conventional monopulse SSRs will stay operational for some time. Depending on the increase in air traffic and the enhancements achieved during Mode S implementation (sensor and ATM systems) DFS may decide on further improvements.

To achieve the necessary benefits with the ground infrastructure to fulfill user requirements (code availability) and cope with the increasing air traffic in a safe manner (reduce RF load) Germany, like other states in core Europe, mandated Mode S equipage for IFR traffic from 2003 onwards and for VFR traffic from 2005. Therefore, it is assumed that most of the aircraft flying in Germany will be Mode S equipped. At the same time about half the DFS radar sensors will operate in Mode S. This will reduce the fruit load under the same traffic density conditions.

The use of aircraft derived data for surveillance and traffic management will improve the overall system. ADS-B is an opportunity for improvements with additional challenges. Any surveillance technique that is intended as a future replacement for the current secondary surveillance radar system in support of ATC activities must provide at least the same level of performance as the existing system. In addition, a safe implementation of new techniques is required.

The performance of a surveillance system necessary for its use in a given area is to be defined by the responsible authorities. Their decisions will be based on operational requirements and the type of airspace to be covered by this system. In general there are three types of airspace: (1) remote areas, (2) transition areas, and (3) high traffic density airspace.

Most of the German airspace belongs to the third category, high traffic density airspace. Some smaller areas in the northern part might be considered as transition areas. An ADS-B system might be used in Germany at some stage to supplement existing radar structure. Of course, replacement of existing surveillance structure will require at least the same system performance as radar service. A pre-requisite for such a system performance are fallbacks for surveillance applications. An implementation of a new system like ADS-B would be a special challenge to cope with the increasing traffic density while allowing a safe implementation. Any installation will be application and benefit driven.

The highest potential is expected for terminal and ground movement areas, where applications like precision runway monitoring or advanced surface guidance and control systems may be considered. Regional airports not equipped with a terminal radar or any other surveillance means may sufficiently benefit from a single ADS-B receiver station (covering one or more sectors), supplementing the existing surveillance infrastructure. Major TMAs as mentioned above are equipped with two terminal radars in addition to en-route radars covering the same airspace. Any ADS-B system substituting for one terminal radar and supplementing the other will require a multi sensor configuration. Depending on the geographical environment it is assumed that at least four sensors would be required to cover an airport or terminal area. In a similar way it is assumed that ADS-B en route applications in Germany would be based on a multi-sensor system, even in the northern part, which might be considered as transition airspace. Any requirement for a specific surveillance application would have to be considered under several conditions including the assumption of an appropriate sensor configuration.

6. COMPARISON WITH ADS-B PERFORMANCE REQUIREMENTS

6.1 ADS-B PERFORMANCE REQUIREMENTS

6.1.1 Sources of Requirements

Three sources for the ADS-B performance requirements have been considered for this study. Currently the most comprehensive source for ADS-B performance requirements is the RTCA Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B), DO-242 [Ref.6]. The second source of ADS-B requirements considered was the ICAO Manual of Air Traffic Services Data Link Applications, ICAO Doc 9694 [Ref. 18], and the third source of requirements considered were preliminary European requirements for ADS-B provided by the Eurocontrol ADS Programme.

Although the RTCA DO-242 standard was coordinated with EUROCAE they represents only the U.S. requirements for ADS-B. RTCA has initiated an activity to update DO-242 and new and/or revised requirements may emerge from this on-going activity. ICAO Doc 9694, Chapter 9 defines the operational requirements for ADS-B in support of aircraft-to-ground surveillance needed to support air traffic services.

The Eurocontrol input represents an informal consensus position on those areas in which the required ADS-B performance may potentially be different in Europe as compared to the U.S. requirements expressed in RTCA DO-242. The requirements currently proposed by Eurocontrol will need European harmonization.

It should be noted that the specific 1090 MHz Extended Squitter requirements are contained in Minimum Operational Performance Standards (MOPS) that are a joint RTCA and EUROCAE document that represent the consensus U.S. and European position. RTCA [Ref. 16] and EUROCAE [Ref. 19] have published the first version of the Extended Squitter MOPS. A second edition of the extended MOPS is currently under development by RTCA.

6.1.2 Scope of ADS-B Performance Requirements

ADS-B performance requirements have been documented for the following aircraft, surface vehicle and ADS-B ground station cases:

1. En Route and Terminal Airspace
   a) Airborne aircraft-to-airborne aircraft (also applies to oceanic/remote airspace)
   b) Airborne aircraft-to-ADS-B ground station

2. Airport
    a) Surface aircraft or vehicle-to-surface aircraft or vehicle
    b) Surface aircraft or vehicle-to-ADS-B ground station
    c) Aircraft on approach-to-aircraft on approach
    d) Aircraft on approach-to-ADS-B ground station

Eurocontrol requirements address ground-based separation responsibility applications (such as Enhanced Surveillance) and selected delegated separation responsibility applications (such as Station Keeping, Simultaneous Approaches etc.) Eurocontrol assumes that ADS-B will co-exist with at least one additional Surveillance Data Source (e.g. SSR in Managed Airspace/Low-Density Airspace, SSR Mode S in Managed Airspace/High-Density Airspace etc.), as proposed in the Eurocontrol ADS Concept document.

The ADS-B performance requirements for each of the above general cases are driven by the specific set of operational applications for which the ADS-B information is being used. The above cited sources (6.1.1) for the ADS-B performance requirements have considered a broad set of candidate ADS-B applications. Note there are certain related ground station-to-aircraft broadcast applications that may use the same radio frequency spectrum as the ADS-B service but are outside the scope of the above-cited ADS-B performance standards. One such example is a traffic information service broadcast (TIS-B) capability.

The focus of the ADS-B evaluations described in this report was on the terminal and to a lesser extent the en route, surveillance services listed under item 1. above. The ADS-B ground stations used for the evaluation were representative of the type envisioned for providing ATC surveillance services in high traffic density terminal and en route environments. Furthermore, the flight paths of the project aircraft were selected to collect data in the existing terminal and en route environments. However, the two ground station antenna locations were more representative of a terminal ground station configuration and were not intended to support the validation of the maximum en route range requirements. However, the results of these studies may contribute to a better understanding of the ability of the 1090 MHz Extended Squitter technology to satisfy certain of the other requirements for which the test configuration was not optimal.

6.1.3 Air-to-Air ADS-B Requirements

The ADS-B MASPS, RTCA DO-242 [Ref. 6] defines the air-to-air performance requirements for ADS-B for a specific set of ADS-B applications. Also DO-242 defines five classes of ADS-B aircraft equipage. The flight tests and evaluation results reported herein focused on the longer-range air-air performance. Table 6.1-1 summarizes the ADS-B air-to-air performance requirements for the applications where the results of this study would be most applicable. For example, short-range encounters applicable to the conflict and collision avoidance application were not included in the evaluation and therefore this application is not listed in Table 6.1-1. The requirements presented in

Table 6.1-1 are extracted from the more detailed requirements defined in DO-242. The requirements in Table 6.1-1 apply to the most demanding longer range air-to-air applications that are applicable to the most capable classes of aircraft equipage. Note that DO-242 defines the flight path deconfliction application as applicable to "cooperative separation in oceanic/low density en route airspace." Since the airspace in which the flight evaluations were conducted was high-density terminal and en route airspace, the most demanding air-to-air range requirements of the deconfliction application do not directly apply. However, one desired result of the evaluation is a determination of the range to which such an application could be supported in the high traffic density and high RF interference environment around Frankfurt as this represents a worst case environment for air-to-air 1090 MHz Extended Squitter reception.

Eurocontrol ADS-B requirements foresee the following air-to-air applications:

1. Conflict Detection and Resolution
2. Enhanced Visual Acquisition
3. Station Keeping
4. Simultaneous Approaches
5. Free-Flight (including flight path deconfliction)

Table 6.1-1. Summary of Air-Air ADS-B Performance Requirements

ADS-B Application	Required Air-Air Tracking Range	Required State Vector Update Period (95th Percentile)	Required Intent Update Period (95th Percentile)	Required Air-Air Acquisition Range
Separation Assurance & Sequencing	20 nmi 40 nmi	7 seconds 12 seconds	14 seconds 24 seconds	40 nmi
Flight Path Deconfliction (see note 3)	90 nmi (120 nmi desired) * see Notes 1, 2 & 3	12 seconds	24 seconds	90 nmi

Note 1: *The stated range requirement from DO-242 (i.e., 90 nmi required, 120 nmi desired) applies only in the forward direction. DO-242 further requires for the flight path deconfliction application a range of 45 nmi to the port and starboard and 30 nmi to the aft.*

Note 2: *Eurocontrol proposed air-to-air ADS-B requirements are similar with a possible extension of flight path deconfliction range to 150 nmi in the forward direction reduced to 75 nmi in the aft. It is also thought that intent may include up to four Transition Change points (TCPs), which should be received within 24 sec with 95% confidence.*

Note 3: *DO-242 limits the applicability of the Flight Path Deconfliction application to oceanic and low-density en route airspace. Eurocontrol proposed extensions (see Note 2 above) are primarily for A3/A2 class aircraft. They are foreseen for supporting the future delegation of separation assurance to the aircraft particularly in the domain of "strategic cooperation"[1]. Such operations in higher density airspace are not excluded.*

Target acquisition requires reception of position and velocity information as necessary to establish a target track, the reception of intent information and the reception of flight ID. Once initial acquisition has been accomplished the update period of state vector information and intent updates must be sufficient to allow a valid track to be maintained on the target. A key performance measure is the range at which full target acquisition can be considered to have been successfully completed and within which the ADS-B system is capable to maintaining a track on the target, and will have knowledge of the target's intent.

6.1.4 Air-to-Ground ADS-B Requirements

RTCA DO-242, ICAO Doc 9694 and Eurocontrol have each defined the air-to-ground performance requirements for ADS-B for a specific set of ATC surveillance applications. RTCA DO-242 has stopped short of explicitly stating air-to-ground performance requirements. Rather performance values are presented as a "summary of ATS provider surveillance and conflict management current capabilities." Table 6.1-2 summarizes the ADS-B air-to-ground performance requirements based on the three sources of requirements described above. Table 6.1-2 presents the requirements associated with only the most demanding air-to-ground applications. Note that although the airport surface operational domain is addressed by the ADS-B MASPS and ICAO Doc 9694 it was not included in the evaluation nor is it included in Table 6.1-2. Also note that very little data was collected that would be applicable to a parallel runway conformance monitoring application as the evaluation of this aspect of the system performance was not an object of the evaluation.

Eurocontrol ADS-B requirements foresee the following air/ground applications:

1. ATS Surveillance and ATS Surveillance plus Intent
2. ATS Enhanced Surveillance and ATS Enhanced Surveillance plus Intent
3. Surface Movement Guidance and Control System (SMGCS)

Note: *These requirements are not presented in Table 6.1-2 since the test configuration was not intended to provide surface coverage.*

[1] Strategic cooperation: To help the pilot manage his own route with agreement of other aircraft and ATC possibly over a long time horizon. Autonomous aircraft under free flight conditions is one such case.

Table 6.1-2. Summary of Air-to-Ground ADS-B Performance Requirements

ADS-B Application	Required Operational Radius (see note 1)	ICAO and RTCA Required State Vector Update Period (98th Percentile)	Eurocontrol Required State Vector Update Period
En Route ATC Surveillance	200 nmi (ICAO/RTCA) 150 nmi (Eurocontrol, single ground station)	12 seconds	10 seconds (98th percentile for classic ATS and 99th percentile. for enhanced ATS)
Terminal ATC Surveillance	60 nmi	5 seconds	5 sec (98th percentile for classic ATS and 99th percentile. for enhanced ATS)
Parallel Runway Conformance Monitoring	10 nmi	1 second for 1000 ft runway separation	1.5 sec (95%) & 3 sec (99%) for 1000 ft runway separation 3 sec (95%) & 7 sec (99%) for 2500 ft runway separation

Note 1: Neither the RTCA nor ICAO standards preclude the use of a ground configuration employing multiple ADS-B ground stations as a mean of satisfying the operational coverage area requirements and/or update rate requirements. Eurocontrol requirements refer to a single ground station.

Note 2: Eurocontrol proposed air-ground requirements also include:

a. Reception of up to four TCPs within 24 seconds to a range of 150 nmi with 95% confidence with both classic and enhanced ATS. This intent information will serve for future MTCD applications as well as flight plan conformance checking. The downlink of up to four TCPs should be mandatory for A2/A3 class aircraft. One option for the downlink of the above intent information is broadcast of a separate squitter for *each TCP with period 1.7 seconds (an alternative is to use the addressed Mode S datalink)*

b. Reception of both position and velocity squitters for report updates in enhanced ATS. (To improve tracking quality)

c. Reception of heading, airspeed and selected altitude for enhanced surveillance within a 5-second period at 98% confidence. This information will be supplied to the Controller Display (CAP parameters). The 1090 System Description in the TLAT report recommends that the downlink of such additional information should be done via the addressed Mode S datalink and not through broadcasting

6.1.5 ADS-B Performance Requirements within the Context of 1090 MHz Extended Squitter

The above discussion on ADS-B requirements has been in the context of an ADS-B service independent of the characteristics of any specific ADS-B technology. This study is focused exclusively on the performance measured for one specific ADS-B technology (1090 MHz Extended Squitter). Therefore, the above-described ADS-B performance requirements must be applied to the specific 1090 MHz Extended Squitter mechanisms. However the limitations of the test configurations and tests scenarios must also be considered.

1090 MHz Extended Squitter transmits separate squitters for position, velocity, flight ID, and intent information. The Table 6.1-3 shows the minimum set of squitters that must be received in order to achieve the initial acquisition and for target tracking for the air-to-air case. The specific characteristics of the 1090 MHz Extended Squitter avionics, as defined by the associated RTCA/EUROCAE Minimum Operational Performance Standards (MOPS), have been accounted for. The existing MOPS defines that tracks will be coasted for 24 seconds, therefore unless a position or velocity squitter is received within less than 25 seconds the track may be dropped and the initial acquisition process initiated with the reception of the next position squitter. Note that a change/correction to the MOPS is pending (within RTCA/SC-186/WG3) that will allow for a more rapid re-acquisition of a track, following a gap in state vector reception of greater than 24 seconds and no longer than 120 seconds. The MOPS defines a state vector tracker function that will produce a valid track update based on the reception of any combination of position squitters and/or velocity squitters within the update interval. Thus the reception of a single position or a single velocity squitter is sufficient to successfully provide a track update. For this study the reception of either a position or velocity squitter is assumed as the minimum requirement for track updates. This is considered the baseline requirement for air-air surveillance.

However, it is recognized that certain applications that use ADS-B reports may require, or desire, to have both a position and a velocity squitter received in order to produce a track update. One such application specifically identified by DO-242 is the

Conflict Avoidance and Collision Avoidance application. This is a short-range application operating at air-to-air ranges out to 20 nmi and was not directly studied in this evaluation. However, the consequence of such a requirement for reception of both position and velocity squitters within the specified update interval has been considered in the analysis presented in 6.1.5.1.

Table 6.1-3. Squitter Types Required for Initial Acquisition and for Target Tracking

Squitter Type	Initial Acquisition	Target Track Update	Intent Update
Position	one "even" and one "odd" received within a 10 second interval	one position <u>or</u> one velocity squitter received	not applicable
Velocity	one received to fully establish track	one position <u>or</u> one velocity squitter received	not applicable
Flight ID	one received	not defined	not defined
Intent	Intent (TCP and TCP+1) received	not applicable	one of each required type (see note)

Note: DO-242 requires TCP and TCP+1. EUROCONTROL has identified a potential requirement for up to 4 TCPs to be required for /Intent Update. The TLAT 1090 System Description suggests that the two additional TCPs might be broadcast as separate squitter messages. The associated application and operational requirements are still being developed. Future updates to DO-242 or other standards documents may reflect such additional requirements.

The air-to-ground case is not as fully defined for 1090 MHz Extended Squitter because the specific ground station requirements are not addressed by the MOPS or the ICAO manual The avionics are defined by the MOPS to include a state vector tracker that will produce a valid track update based on the reception of any combination of position squitter(s) and/or a velocity squitter(s). Ground station designs could implement a different approach for the state vector tracker where in the most extreme case both position and velocity squitters would be needed to produce a track update. The initial air-ground applications will most likely use ADS-B to provide an ATC surveillance capability equivalent to a secondary surveillance radar. Therefore, for the purpose of this study it was assumed, as a baseline requirement for the air-to-ground case, that a target track update will be provided based on the reception of at least one position squitter.

6.1.6 Required Squitter Reception Performance

6.1.6.1 Updates

It is possible to calculate the required probability of reception of individual squitters based on the required update period, the type(s) of squitters that must be received within that update interval and of rate at which each of these squitter type(s) are transmitted.

For example, the ADS-B MASPS requires that to support the air-to-air application of Separation Assurance and Sequencing (Table 6.1-1), ADS-B is required to communicate intent information in the form of a TCP. Furthermore, if intent changes ADS-B is required to deliver the updated information within 24 seconds, for a target at the maximum range of 40 nmi, with 95% probability. If the single-squitter reception probability is denoted as *p*, then:

$$0.95 = [1 - (1 - p)^{N}]$$

For the TCP Extended Squitter, this is: N = 24 sec. / 1.7 sec. = 14 transmissions

Where N is the number of transmissions of intent in a 24 second period and the value 1.7 sec. is the period for transmitting each of the two TCP messages.

Using N=14 in the above formula produces the result of: $p = 0.192$

For the above example there must be at least a 19.2% probability of successful squitter reception in order to support the MASPS requirement for detection of a change in intent for a target at a range of 40 nmi (the maximum range of this application).

It is noted however that certain other ADS-B applications will require the reception of additional squitters in order to have more complete knowledge of the target aircraft's intent. For example the flight path deconfliction application, as defined in the DO-242 requires receipt of both TCP and TCP+1 squitters. Considering the potential for an application that requires the reception of both the TCP and the TCP+1 squitters within a 24-second interval the formula must be modified to:

$$0.95 = [1 - (1 - p)^{N}]^{2}$$

The solution to the above calculation yields: $p = 0.229$

Note: *As noted above, Eurocontrol has identified a potential requirement for up to four TCPs to be required for Intent Update. The associated application and operational requirements are still being developed. . The TLAT 1090 System Description suggests that the four TCPs could be broadcast as separate Extended Squitters, each with a period of 1.7 sec. Consequently the minimum Extended Squitter probability that would be able to satisfy the requirement for a four TCP update within 24 sec at 95% confidence is 26.8%.*

Continuing with the Separation Assurance and Sequencing application, as indicated in Table 6.1-1, a state vector update is also required with an update period of 12 seconds, at the 95th percentile, for a target at up to 40 nmi. The 1090 MHz Extended Squitter avionics are defined by the MOPS to include a tracker that will produce a state vector update based on the reception of either a position or a velocity squitter. This means that there would be a nominal 48 transmissions (24 position and 24 velocity) within the required 12-second update period. Thus:

$$N = 12 \text{ sec} / 0.25 \text{ sec.} = 48 \text{ transmissions}$$

Continuing the calculation for the required probability of position/velocity squitter reception yields the results that: $p = 0.06$

Thus a 6% probability of squitter reception will satisfy the requirement for updates to the state vector at the required 95% probability level.

DO-242 also specifies state vector update requirements at the 99% probability level. For the above example of the Separation Assurance and Sequencing application the required update interval increases from 12 seconds to 24 seconds as the update probability increases from 95% to 99%. For this latter case:

$$N = 24 \text{ sec} / 0.25 \text{ sec} = 96 \text{ transmissions}$$

The corresponding calculation for the required probability of individual position/velocity squitter reception yields the results that: $p = 0.047$. In this case the more demanding requirement is for 12-second state vector updates at 95% probability since this requires a higher probability of individual squitter reception.

Therefore, where considering the requirements for both state vector and intent updates for the Separation Assurance and Sequencing application the dominant requirement is that for reception of intent information which requires a 22.9% probability of squitter reception. With this 22.9% probability of squitter reception the state vector update performance will well exceed the minimum baseline requirements for surveillance track updates.

One might argue that the improved performance of the tracker could be achieved if both a position and a velocity squitter were received within the update period. For this study the baseline air-to-air surveillance requirement is considered to be the reception of either a position or velocity squitter within the update period. However, as noted above the Conflict Avoidance and Collision Avoidance application, and potentially other future applications, may require, or desire, the reception of both a position and a velocity squitter within the update interval. In this case the required probability of per squitter reception, for the position and velocity squitters, would increase. For the specific case of the Conflict Avoidance and Collision Avoidance application a state vector update rate of 7 seconds at 95% probability is required at the maximum application range of 20 nmi. In this case the parameter N would be: N = 7 sec. / 0.5 sec = 14 transmissions and the second version of the above formula would be used to calculate the required probability for individual squitter reception as: $p = 0.231$. Since this specific application operates at ranges out to only 20 nmi this is a less demanding requirement that identified above for TCP and TCP+1 reception at 40 nmi, which requires a very similar probability of individual squitter reception but at a long range.

Table 6.1-4 summarizes the required individual squitter reception probability accounting for support of the tracking and intent update requirements for the air-to-air applications listed in Table 6.1-1.

Table 6.1-4. Air-Air ADS-B Squitter Reception Probability Requirements (See Note 2)

ADS-B Application	Required Air-Air Tracking Range	Required Individual Squitter Reception Probability (@ 95% S-V update probability)	Required Individual Squitter Reception Probability (@ 99% S-V update probability)	Required Intent Update Probability
Separation Assurance & Sequencing	20 nmi 40 nmi	10.1% 6.0%	7.9% 4.7%	30.5% 19.2%
Flight Path Deconfliction	90 nmi (120 nmi desired) (see Note 1)	6.0%	4.7%	22.9% (RTCA w/ TCP & TCP+1)

Note 1. *This requirement only applies in low-density airspace, which is not representative of the actual test environment. Therefore the stated range requirements are not directly applicable.*

Note 2. *These requirements are based on the existing RTCA ADS-B MASPs (DO-242) and thus represent U.S. requirements.*

Table 6.1-5 summarizes the required individual squitter reception probability for the air-to-ground applications listed in Table 6.1-2

Table 6.1-5. Air-to-Ground Individual Squitter Reception Probability Requirements

ADS-B Application	(ICAO and RTCA Requirements) Minimum Individual Squitter Reception Probability for Position Only Squitter (see Note 1)	(ICAO and RTCA Requirements) Minimum Individual Squitter Reception Probability for Position + Velocity Squitters (see Note 2)	(Eurocontrol Requirements) Minimum Individual Squitter Reception Probability for Position + Velocity Squitters (see Note 3)
En Route ATC Surveillance	15%.	17.4%	20.1% (Classic ATS) 23.3% (Enhanced ATS)
Terminal ATC Surveillance	32.3%	36.9%	36.9% (Classic ATS) 41.1% (Enhanced ATS)
Parallel Runway Conformance Monitoring for 1000 ft runway separation	85.8%.	90%	70.6% (45.8% for 2500 ft runway separation)

Note 1: *This is considered the baseline case for the US where the reception probability listed for a position squitter will result in the required state vector update rate at 98% probability.*

Note 2: *This would be a more demanding case for the US where the individual squitter reception probability listed would result in the state vector update rate, that includes reception of both updated position and velocity information, at 98% probability.*

Note 3: *The Eurocontrol requirements for state vector updates reflects a requirement to receive both a position and a velocity squitter in order to produce a state vector update. The Classic case requires to a 98%*

update probability and the enhanced ATS case requires a 99% update probability.

Note 4: *The Eurocontrol four TCP requirement would need a 26.8% minimum Extended Squitter reception probability.*

6.1.6.2 Initial Acquisition

The final aspect of the required squitter reception performance relates to the requirements for the initial acquisition of a new target. Initial acquisition can be considered to be complete when all the information indicated in Table 6.1-3 has been received. The time interval over which initial acquisition may occur is variable depending on squitter reception probability. At least two position squitters must be received within a 10-second interval in order to start a target track. The additional information required to complete the initial acquisition may be received without a specific time limit. In order to maintain the target track, the position and/or velocity squitters must continue to be received without any gaps of greater than 24 seconds. Receipt of an initial velocity squitter is required to fully establish the target's state vector track. The initial acquisition process will be complete after reception of at least one Flight ID squitter, one squitter containing the TCP and one squitter containing the TCP+1. These required remaining squitter types may be received in any sequence. The 1090 ADS-B MOPS specifies that the information received in the Extended Squitters will be stored for 250 seconds. Therefore the Flight ID and TCP information could be received either ahead or subsequent to the required state vector information. The following calculation shows the required probability of reception needed for each squitter type.

As a result of the encoding technique used for the position information, one "even" and one "odd" position squitter must be received within a 10-second interval in order to determine the aircraft's unambiguous global position (as per the 1090 ADS-B MOPS). Position squitter transmissions alternate between "even" and "odd." Thus one "even" and one "odd" position squitter is transmitted each second. For this case N = 10 sec. / 1.0 per sec. = 10

The per squitter reception probability required to achieve a 95% probability of reception of both an "even" and an "odd" position squitter within the first 10 second interval is: $p = 0.308$. However, this event need only occur once in order to achieve target acquisition. A lower probability of individual squitter reception would result in a longer time required to achieve initial acquisition of the target's position. For example if the probability of individual squitter reception were 22.9% then reception of both an "even" and an "odd" position squitter within a 10 second interval could be achieved with 95% probability after approximately 15 seconds. Figure 6.1-1 shows the relationship between time required for initial position acquisition, at 95% probability, versus the probability of reception of individual squitters.

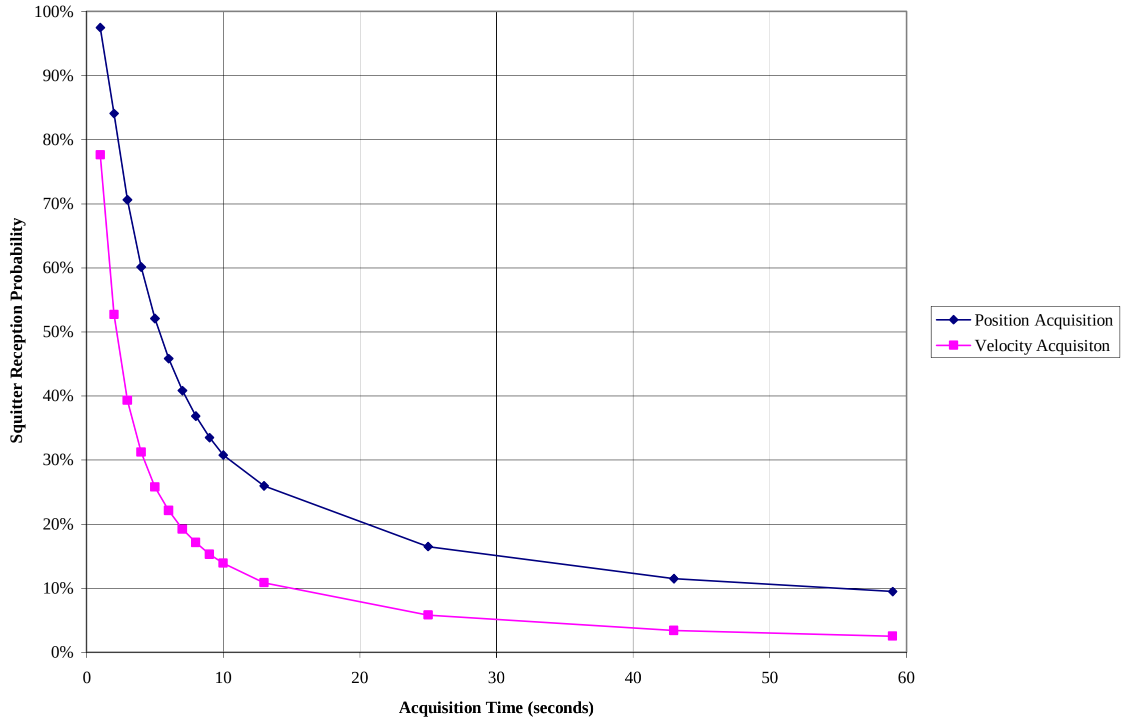


Figure 6.1-1. Position and Velocity Acquisition Time as a Function of Probability of Individual Squitter Reception

The second item required to complete the state vector acquisition process is the receipt of a velocity squitter. This may occur during the same time interval as the acquisition of the target's position information. Only a single velocity squitter is required and as shown in Figure 6.1-1 for any given individual squitter reception probability, the required time for acquisition of velocity information will be substantially less than for the position information. Note that once established the target's state vector track can generally be maintained with a relative low reception probability (as low as 6% probability of reception as shown in Table 6.1-4).

The complete acquisition of a target requires the reception of at least one of each the following additional three additional types of squitters: (1) Flight ID and Type; (2) Current TCP; and (3) Next TCP containing the TCP+1. The reception of any or all of these additional types of squitters may occur starting up to 250 seconds prior to establishing the state vector track on the target (as per the 1090 ADS-B MOPS). As an example we can calculate the time required for initial acquisition of each type of required information assuming a squitter reception probability of 22.9%, as previously shown to satisfy the update requirements for TCP and TCP+1 information. The approximate time required to acquire (at 95% probability) each category of information is listed below:

15 sec.: Position (globally unique)

6 sec.: Velocity

57 sec.: Flight ID and Type

24 sec.: Current TCP and TCP+1 (also TCP+2 and TCP+3 in the Eurocontrol case)

Note the reception of the squitters that convey the above information can occur in parallel. As indicated in the above example, the acquisition of the Flight ID and Type Squitter will require the longest time, due to the having the lowest transmission rate (i.e., once per 5 seconds) and is clearly the dominate factor in the overall initial target acquisition process. In some cases it may be possible to acquire the Flight ID and Type squitter before the reception probability is sufficient to allow a target track to be maintained. The 1090 ADS-B MOPS allows for this information to stored for up to 250 seconds in the absence of having a current track on the target. Since the reception of a single Flight ID and Type squitter is sufficient, as there are no specified update requirements, this may not be as dominate a factor in the acquisition of a target as it might appear. At the assumed 22.9% probability of individual squitter reception all information, except for the Flight ID and Type, would be acquired within approximately 24 seconds at 95% probability.

Rather than relying on the estimates for target acquisition based solely on the above probability of reception calculation, it is appropriate to verify the actual measured time required to initiate a state vector track and also the time required to receive the Flight ID and Type squitter. Note that the airborne installations used for this evaluation did not broadcast TCP and TCP+1 squitters therefore the actual performance for reception of these squitter types cannot be directly measured.

Note: A transmission rate of once per 2.5 seconds for the Flight ID and Type squitter was intended to be specified in RTCA DO-260. Due to an oversight, it was included only in Appendix A and not in the body of the MOPS. Incorporation of the change to the MOPS to make this correction has already been approved by SC-186 WG-3 and will appear in DO-260 Rev A.

6.2 COMPARISON OF THE LDPU AIR-TO-AIR RESULTS WITH SELECTED APPLICATION REQUIREMENTS

This section presents the results of the analysis of LDPU data for the air-to-air case and compares the measured performance against the requirements described in 6.1. Chapter 4 has presented an overview of the air-to-air measurements and a summary of the results obtained. The following material presents the results of the further analysis of the data. Specific emphasis has been given to the cases were the measured performance was less than expected or less than typical. This has been done in order to better understand if the cases where the performance was less than expected or typical indicate inherent limitations of the system or are the consequence of specific limitations of the test environment (e.g., poor antenna locations, installation problems, etc.).

The following material also includes an analysis of the probability of Extended Squitter reception as a function of the relative bearing of the target aircraft, in the horizontal plane, from own aircraft. Target bearing has been sorted into four 90^o quadrants (forward, starboard, aft, port) for the purpose of this analysis. Two filters were applied to the specific reception probability data to be plotted. First all data collected when either own aircraft or the target aircraft was at an altitude of less than 1000 ft is not used for the plots. Second, if ownship is maneuvering with more than a modest turn rate (i.e., maneuvers in only the horizontal plane) the data is not plotted. This latter filter was applied because the project aircraft were frequently following flight profiles that included very frequent changes in heading that would not be typical of a normal flight profile.

The probability of reception for 1090 MHz Extended Squitters was analyzed using a 24 second sliding window. A data point is produced, and included on the following plots, for each case where the LDPU logged the reception of at least one state vector squitter (i.e., position or velocity) during the previous second. It should be noted that for the case where the reception of state vector updates were being logged for each successive one- second interval, even a very short term degradation in reception of squitters (such as a four- second gap in the reception) can produce many successive data points (up to 24) on the following plots showing a degraded reception probability. Such an event will appear as a sharp drop and rapid recovery in reception probability occurring within the span of a very few miles of target range. While such short duration events may produce a significant impact on the following plots, they are of little or no operational consequence to most, or in most cases all applications that will utilize the ADS-B surveillance information. The following reception probability versus target range plots include two lines indicating the required level of reception performance. The upper line indicates the reception probability needed to receive the TCP and TCP+1 information with the update rate required by the ADS-B MASPS as a function of target range. The lower line indicates the reception probability needed to receive the state vector updates with the required update rate required by the ADS-B MASPS as a function of range. The requirements of the above mentioned applications have been merged and the most demanding requirement is indicated for a given target range. Note that the use of dashed lines in the figures indicates requirements associated with the Flight Path Deconfliction Planning application. This application is not required by the ADS-B MASPS within the type of operation environment where this evaluation was conducted.

The ADS-B MASPS defines this application as applicable to "oceanic/low density en route airspace."

6.2.1 Analysis of the Results from 19 May

An overview of the results for 19 May is provided in 4.4.1.2.1. FAA N40 conducted a shakedown flight on 19 May and encountered a target of opportunity (BA-400665_h) during the course of the flight. A second target or opportunity (BA-400652_h) was briefly observed by N40 at ranges from approximately 145 nmi to 170 nmi but the results for this second target aircraft are not further described here. The results previously shown in Figure 4.4.1.2.1-3 would indicate that the track on BA-400665_h would have been dropped at a range beyond 112 nmi, where a gap in the update period exceeded 24 seconds. The track would subsequently have been re-acquired.

6.2.1.1 Reception Probability as a Function of Target Bearing

Figures 6.2.1-1 to 6.2.1-3 present the reception probability of individual Extended Squitters versus range. The figures cover the forward quadrant (forward $\pm 45^o$), the aft quadrant, and the port & starboard quadrants. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

Figure 6.2.1-1 plots the reception probability for the forward quadrant. The target aircraft (BA-400665$_h$) was only at a forward relative bearing from N40 for approximately 100 seconds and thus relative little data was collected for reception performance in the forward quadrant. Squitter reception probabilities of between approximately 63% and 86% were measured at target ranges from 13 to 16 nmi.

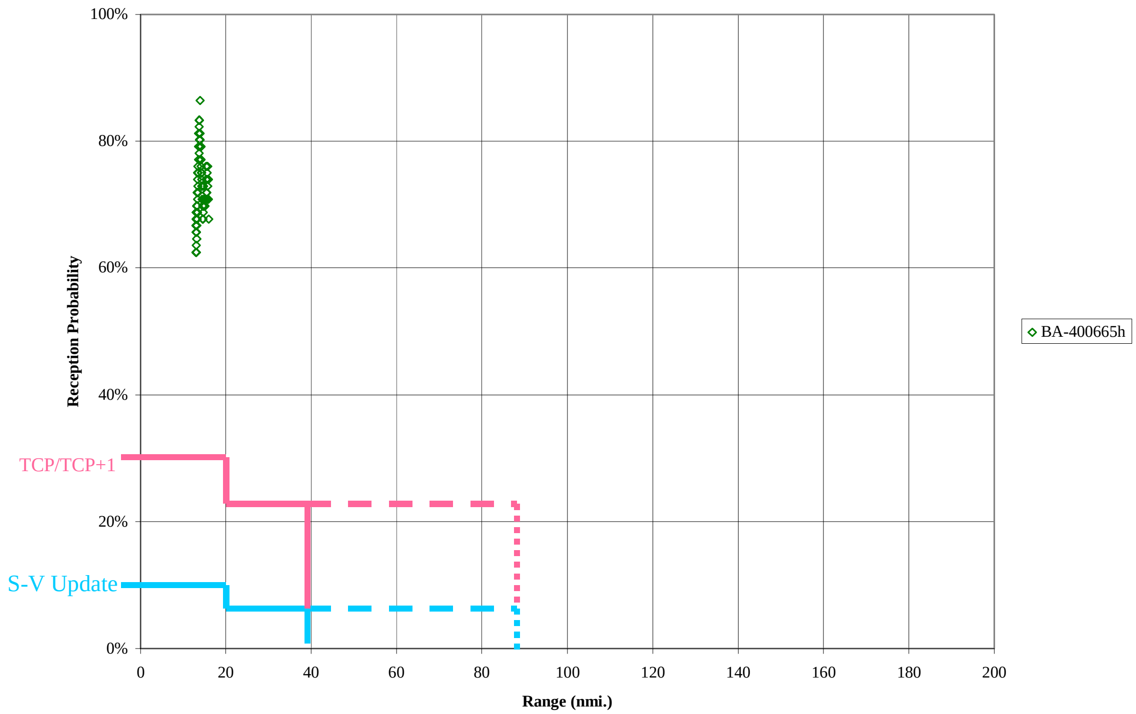


Figure 6.2.1-1. Forward Quadrant Reception Probability by N40, 19 May

Figure 6.2.1-2 plots the reception probability for the aft quadrant. The target aircraft (BA-400665$_h$) was at an aft relative bearing from N40 on two separate occasions. The first occurrence for approximately 115 seconds at short range (approximately 15 nmi) and later for approximately 215 seconds at ranges from 47 to 87 nmi thus a modest amount of data was collected for reception performance in the aft quadrant on this flight.

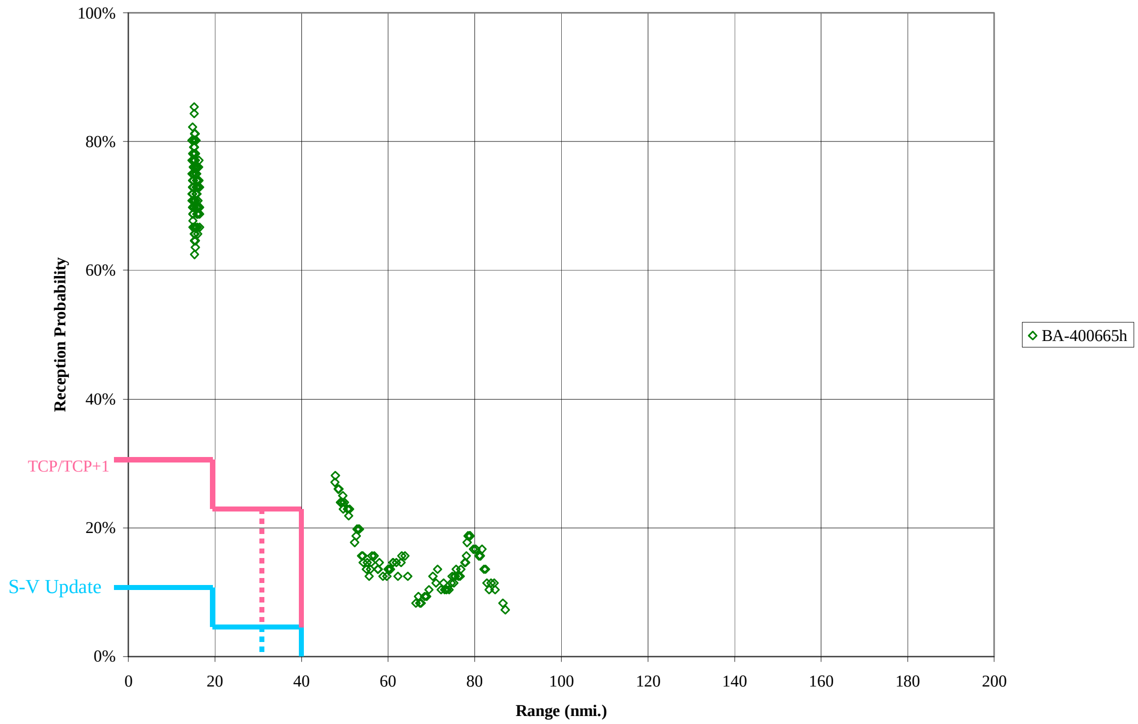


Figure 6.2.1-2. Aft Quadrant Reception Probability by N40, 19 May

Figure 6.2.1-3 plots the reception probability for the port and starboard quadrants. The target aircraft (BA-400665$_h$) was at a port or starboard relative bearing from N40 for much of the duration of the encounter. Data was collected at ranges from approximately 14 nmi out to 180 nmi, thus a significant amount of data was collected for reception performance in the port and starboard quadrants on this flight

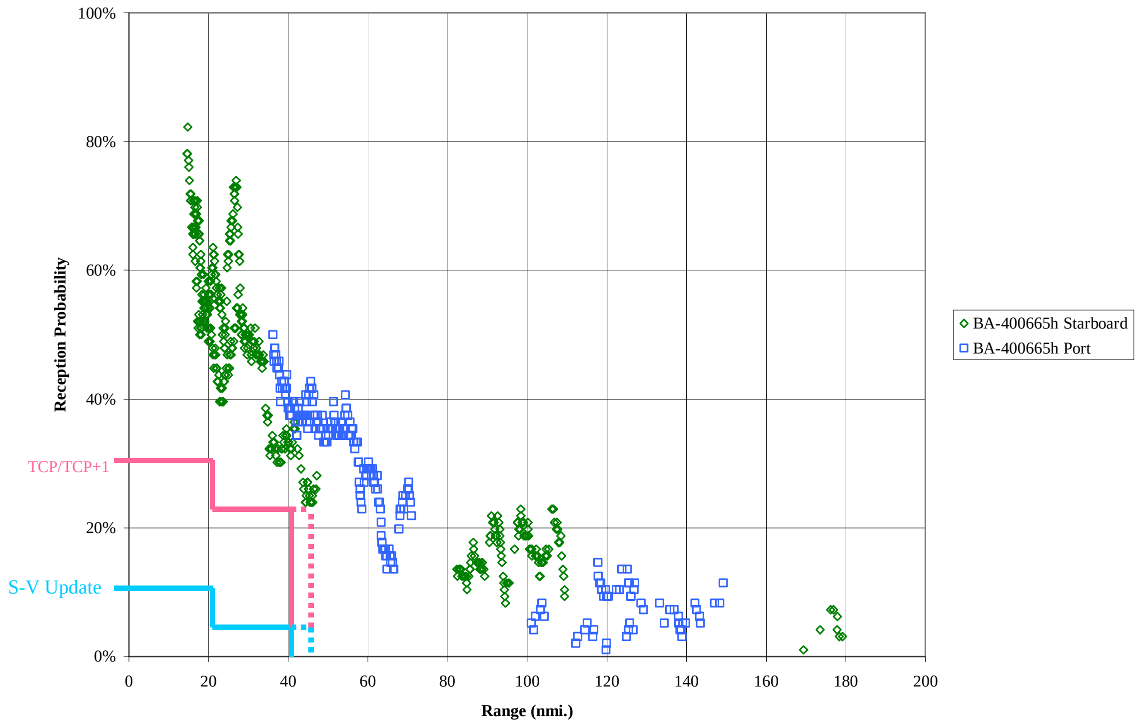


Figure 6.2.1-3. Port & Starboard Quadrants Reception Probability by N40, 19 May

6.2.1.2 Performance vs. Requirements

There was insufficient data collected for reception from the forward quadrant to draw any firm conclusions on moderate to long range reception performance. However, the data analyzed for short-range reception performance is consistent with that required by the ADS-B MASPS. Reception performance in the aft and in the port and starboard quadrants exceeds the reception performance required by the ADS-B MASPS. The measured reception probabilities as well as the measured state vector update periods shown in Figure 4.4.1.2.2-3 indicate that target tracking was achieved at ranges beyond 80 nmi.

6.2.2 Analysis of the Results from 20 May

An overview of the results for 20 May is provided in 4.4.1.2.2. All three project aircraft participated in the flight tests on 20 May. However, due to a GPS interface problem, the FII aircraft was transmitting 'all zeros' for its latitude and longitude. Also, some of the NLR aircraft's LDPU data log file data was corrupted. It was however possible to restore these NLR log corrupted entries by using data from other logs with the method explained in 4.4.1.2. As a result of these problems, analysis was performed only for data recorded by the LDPUs onboard N40 and NLR.

6.2.2.1 Reception on N40, 20 May

Valid Extended Squitters from six target aircraft were recorded (4.4.1.2). These were the broadcasts from the NLR aircraft and broadcasts from five BA targets of opportunity, of which two were at ranges allowing performance analysis (BA-400664$_h$ and BA-400652$_h$) were at ranges allowing performance analysis. Note that the Extended Squitter broadcasts from the FII aircraft were also received but without that aircraft's latitude and longitude information. The LDPU log tracks of the aircraft received on N40 are shown in Figure 4.4.1.2.2-1c and their altitude/range from N40 in Figure 4.4.1.2.2-2a. The N40 LDPU log indicates that

1. The track of the BA-400664$_h$ would have been last dropped at a distance of 159 nmi on the incoming leg of the BA-400652$_h$, while on the outbound leg it was lost for the first time at 81 nmi and subsequently re-acquired.
2. The track of the NLR aircraft would have been dropped on its outbound leg by N40 at 125 nmi and subsequently re-acquired. On its inbound leg, the NLR track would have been dropped (and re-acquired) at distances beyond 73 nmi.
3. The track of the BA-400652$_h$ would have been last dropped at 145 nmi from N40 on the incoming leg of the BA-400652$_h$, while on the outbound leg it would have been dropped for the first time at 115 nmi.

6.2.2.1.1 Reception Probability as a Function of Target Bearing

Figures 6.2.2-1to 6.2.2-3 present the reception probability of individual Extended Squitters versus range. The figures cover the forward quadrant (i.e., forward $\pm 45^o$), the aft quadrant, and the port and starboard quadrants. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

Figure 6.2.2-1 plots the reception probability for the forward quadrant. Two target aircraft (NLR and BA-400664$_h$) were each only at a forward relative bearing from N40 during several relatively brief intervals. The reception of the Extended Squitters from BA-400664$_h$ was generally superior to the reception of the broadcasts from the NLR aircraft. At ranges from 10 to 22 nmi Extended Squitter reception probabilities varied from approximately 58% to 97%. At ranges from 46 to 56 nmi Extended Squitter reception probabilities of between approximately 24% and 66% were measured with squitter reception probability from the BA-400664$_h$ being 20 to 25% greater than from the NLR aircraft at similar ranges. At target ranges beyond 85 nmi the measured reception probabilities were typically between 4% and 21% with a mean value on the order of 10% out to ranges of approximately 140 nmi.

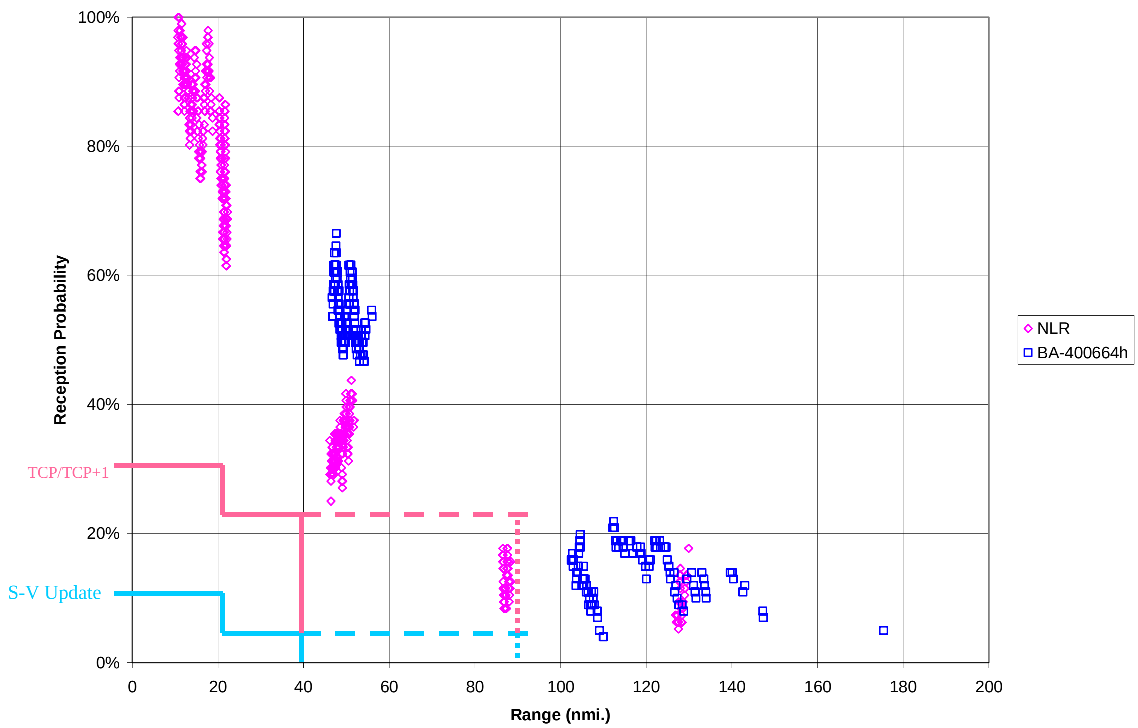


Figure 6.2.2-1 Forward Quadrant Reception Probability by N40, 20 May

Figure 6.2.2-2 plots the reception probability for the aft quadrant. The BA-400664$_h$ aircraft was at an aft relative bearing from N40 for a significant portion of the encounter with Extended Squitters received at ranges from approximately 14 to 157 nmi. The NLR aircraft was at an aft relative bearing at three separate instances at ranges of approximately 60, 90 and 160 nmi. The aft quadrant reception probabilities for the NLR aircraft are generally consistent with the reception probabilities for the BA-400664$_h$. Extended squitter reception probability at ranges of less than 40 nmi ranged from approximately 36% to 90%. At target ranges from 40 to 80 nmi the reception probably was generally between 20% and 60% with brief intervals recorded where the reception probability dropped to as low as 10%. Examination of the two intervals of reduced reception probability indicate:

1. When the NLR aircraft was at a range of 55 nmi the reception probability remained below 22% for 7 seconds
2. When the NLR aircraft was at a range of 70 nmi the reception probability remained below 20% for 12 seconds

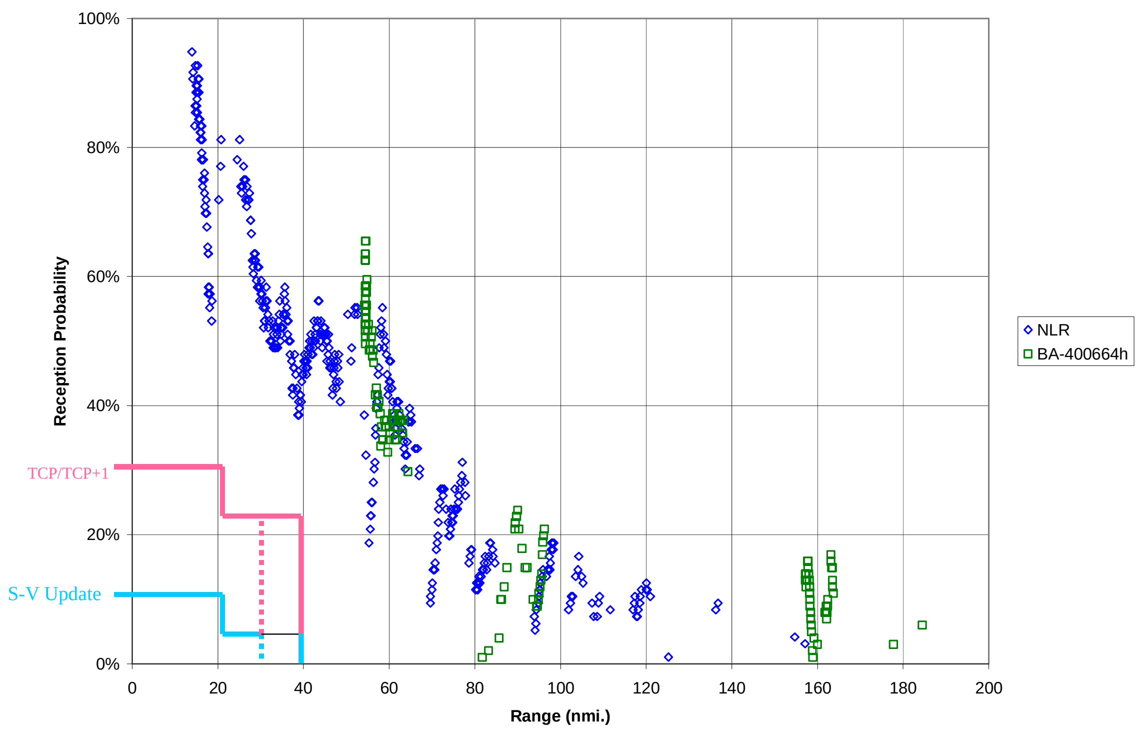


Figure 6.2.2-2. Aft Quadrant Reception Probability by N40, 20 May

Figure 6.2.2-3 plots the reception probability for port and starboard quadrants. The target aircraft (NLR and BA-400664$_h$) were each at a port or starboard relative bearing from N40 at separate discrete times. Data was collected at ranges from approximately 10 nmi out to 175 nmi, thus a moderate amount of data was collected for reception performance in the port and starboard quadrants on this flight. At target ranges of less than 80 nmi the probability of reception ranged from a low of 38% (at longer ranges) to a high of 99% at short ranges. At ranges between 80 and 105 nmi the reception probability for the broadcasts from the BA-400664$_h$ were 25% to 52% and the only 3 data points from the NLR aircraft at these ranges were at approximately 90 nmi with a reception probability varying from 16% to 19%.

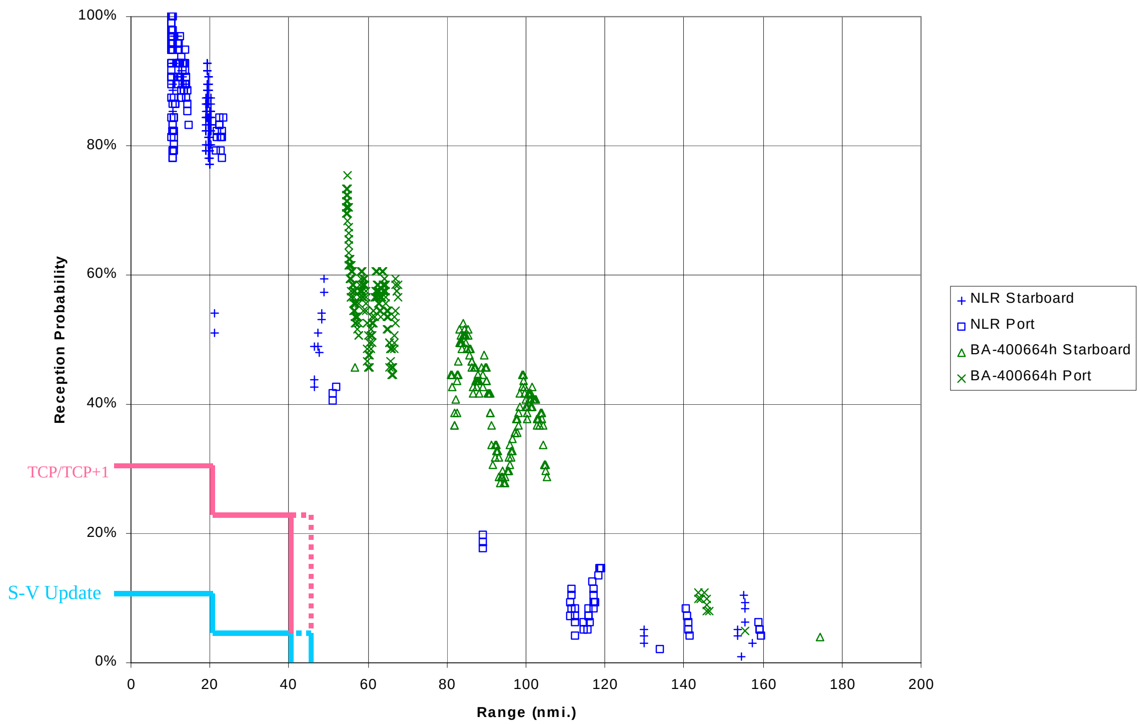


Figure 6.2.2-3. Port & Starboard Quadrants Reception Probability by N40, 20 May

6.2.2.1.2 Performance vs. Requirements

There was a modest amount of data collected for reception from the forward quadrant. Analysis of the results indicate that for the ranges up to 40 nmi (i.e., the limit of the MASPS requirements) the reception performance exceeded that required by the ADS-B MASPS. At longer ranges the reception probability for TCP and TCP+1 squitters would exceed the desired 22.9% values out to ranges of perhaps of 70 to 90 nmi but the limited data at such ranges prevents any precise determination. The data indicates that tracking of the target aircraft, with state vector updates within the 12 seconds required by the MASPS (at 95% probability), should be possible at ranges in excess of 100 nmi. Generally the reception of the Extended Squitters broadcast from BA-400664$_h$ were received with higher probability than were the broadcasts from the NLR aircraft at similar ranges. Reception performance in the aft and in the port and starboard quadrants substantially exceeded the reception performance required by the ADS-B MASPS.

6.2.2.2 Reception on NLR, 20 May

An analysis of N40 reception on the NLR LDPU has been presented in 4.1.2.2. The N40 track recorded by the NLR LDPU is shown in Figure 4.4.1.2.2-1c. The corresponding N40 altitude/range from NLR is shown in Figure 4.4.1.2.2-2b. The NLR track is shown in Fig. 4.4.1.2.2-1b. The NLR flight consisted of two legs. In the first leg NLR flies away from N40 to the southeast and in the second leg NLR returns towards Wiesbaden and approaches N40. During the outbound phase N40 was found mostly in the aft quadrant of NLR while during the inbound phase N40 was found mostly in the forward quadrant of NLR.

6.2.2.2.1 Track acquisition

The NLR LDPU acquired the N40 track while NLR was still on the ground. The NLR LDPU log indicates (Figure 4.4.1.2.2-3d) that the N40 track would not have been dropped in the duration of the NLR flight, although their maximum horizontal distance rose up to 163 nmi.

6.2.2.2.2 Reception probability

N40 Extended Squitter reception probability has been analyzed in 4.4.1.2.2. Figure 4.4.1.2.2-4d plots the N40 reception probability versus range distinguishing between the inbound and outbound NLR flight legs.

Figures 6.2.2-4 through 6 decompose N40 reception performance in three parts, corresponding to the parts of the N40 flight where N40 was in the forward, aft and port/starboard quadrant, respectively, relative to the receiver (NLR). Performance is measured in terms of message reception probability versus range. Only the part of the NLR log where both aircraft were in flight (above 1000 ft) has been taken into account.

Figures 6.2.2-4a, -5a, and 6a compare the measured Extended Squitter reception probability values in the forward, aft, and port/starboard quadrants, respectively, against the minimum reception probabilities that would theoretically be required to meet the DO-242 update interval the two TCP and State Vector requirements. The DO-242 requirements refer to two air-to-air applications (Separation Assurance & Sequencing and Flight Path Deconfliction Planning), as they have been specified in Table 6.1-4. It should be noted that DO-242 defines separate update interval requirements for forward, aft, and side receiver quadrant, respectively, only for the flight Path Deconfliction application.

Similarly, Figures 6.2.2-4b, -5b, and -6b compare the measured reception probability values against the **minimum** reception probabilities that would theoretically be required to meet the Eurocontrol proposed performance criteria for long range autonomous operations (four TCPs and state vectors up to 150 nmi range). These Eurocontrol criteria also distinguish performance requirements per target aspect angle quadrant.

Figures 6.2.2-4a and 4b plot the reception probability for the forward quadrant. These figures correspond to a large extent to the inbound N40 leg reception probability plot of Fig. 4.4.1.2.2-4d. The N40 reception probability was above the minima needed for state vector updates in both applications considered. Concerning intent, the N40 reception probability was also above the minima for RTCA requirements. It would satisfy the minimum requirement for the four-TCP case up to 95 nmi, except for an incident at 66 nmi[2].

Figures 6.2.2-5a and 5b plot the reception probability for the aft quadrant. These plots correspond to a large extent to the outbound leg reception probability plot of Fig. 4.4.1.2.2-4d. The N40 reception probability was above the minima needed for state vector updates in both applications considered. Concerning intent, the N40 reception probability was also above the minima for both RTCA and Eurocontrol requirements.

Figures 6.2.2-6a and 6b plot the reception probability for the port and starboard quadrants. The target aircraft (N40) was found in these quadrants only during relatively brief intervals. N40 reception probability satisfied both RTCA and Eurocontrol minima but the number of samples was small.

[2] This incident was a short period (~ 15 sec) in which few N40 messages were received. NLR had started its descent (FL 170) while N40 was still cruising (FL 220) and executing a turn. N40 was at ~10 deg relative bearing from NLR and both aircraft were going in the same direction (rx head to tx tail).

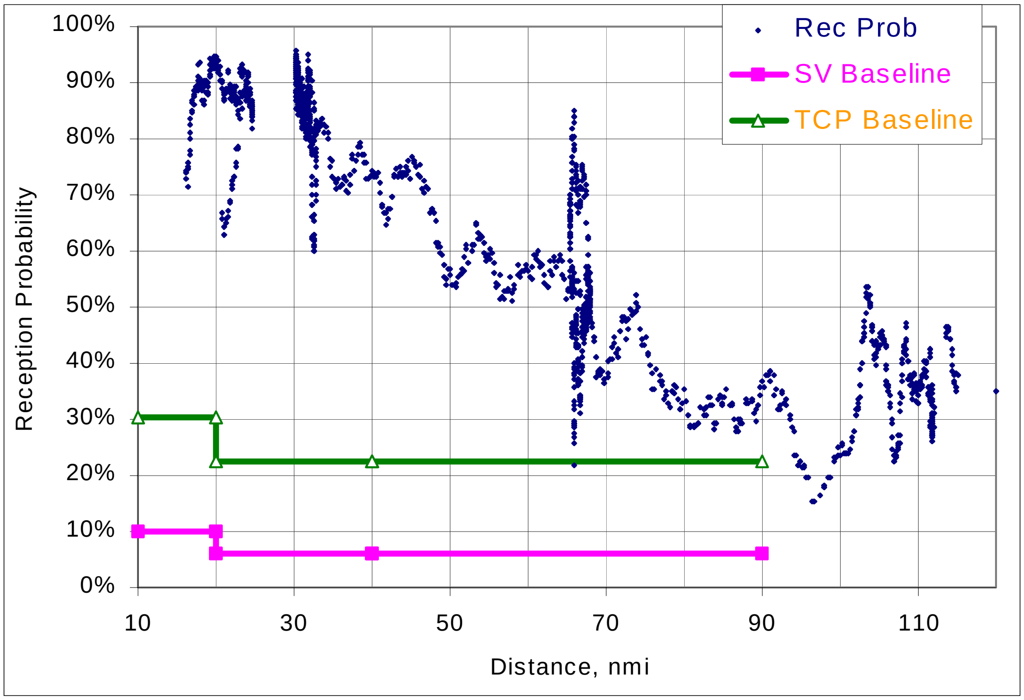


Figure 6.2.2-4a. Forward Quadrant reception by NLR LDPU, 20 May Comparison with DO-242 Performance Requirements

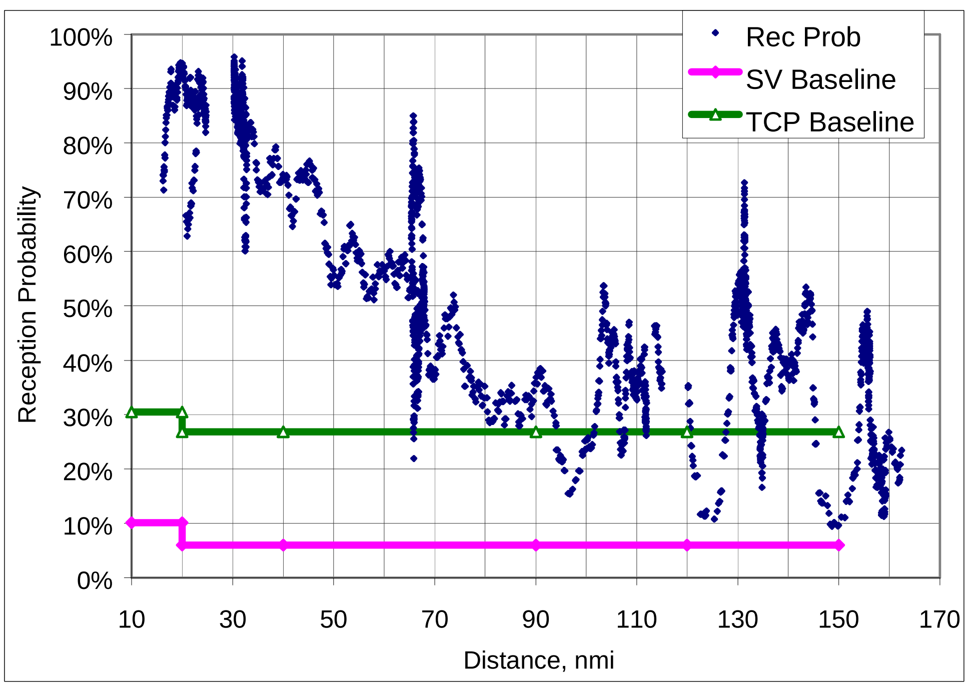


Figure 6.2.2-4b. Forward Quadrant Rec. Prob. by NLR LDPU, 20 May Comparison with Eurocontrol Performance Criteria

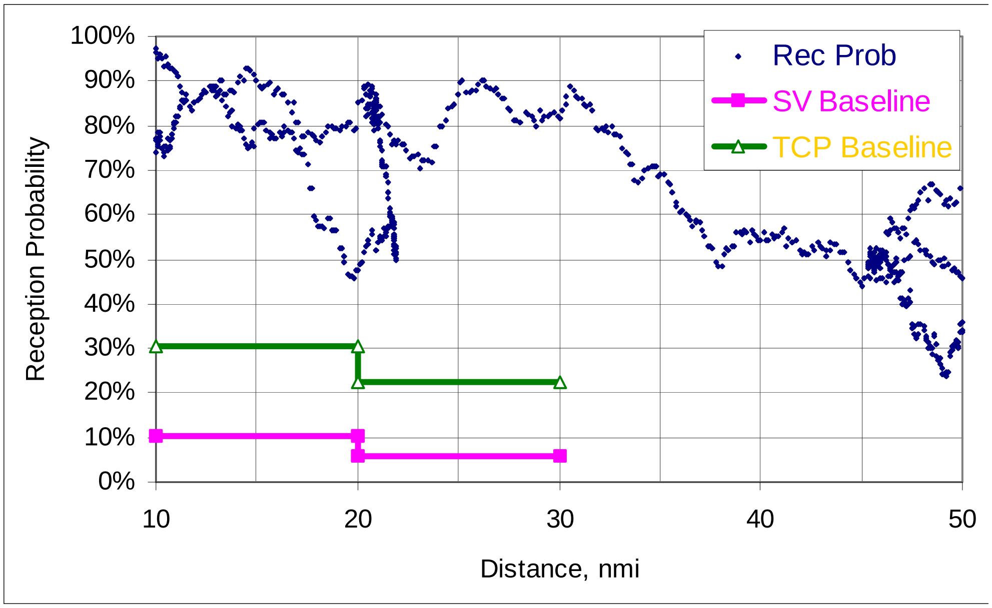


Figure 6.2.2-5a. Aft Quadrant Reception Probability by NLR LDPU, 20 May Comparison with DO-242 Performance Requirements

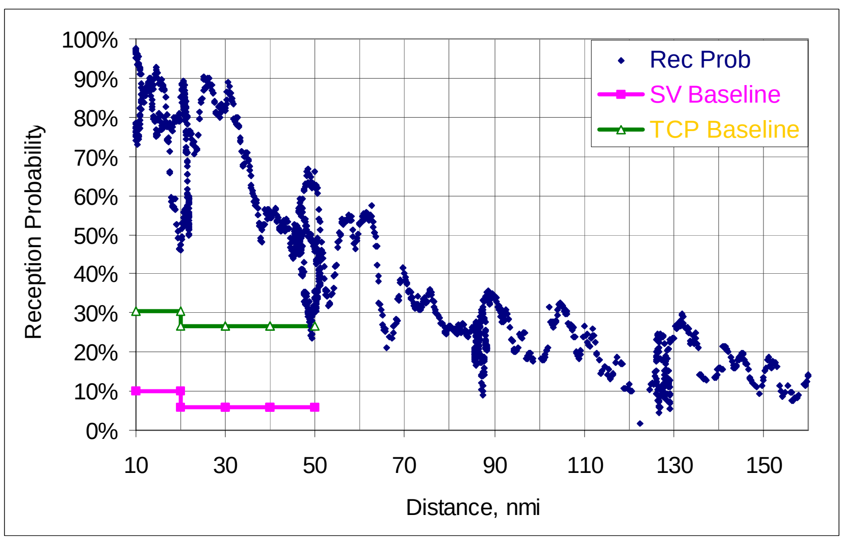


Figure 6.2.2-5b. Aft Quadrant Rec. Prob. by NLR LDPU, 20 May, Comparison with Eurocontrol Performance Criteria

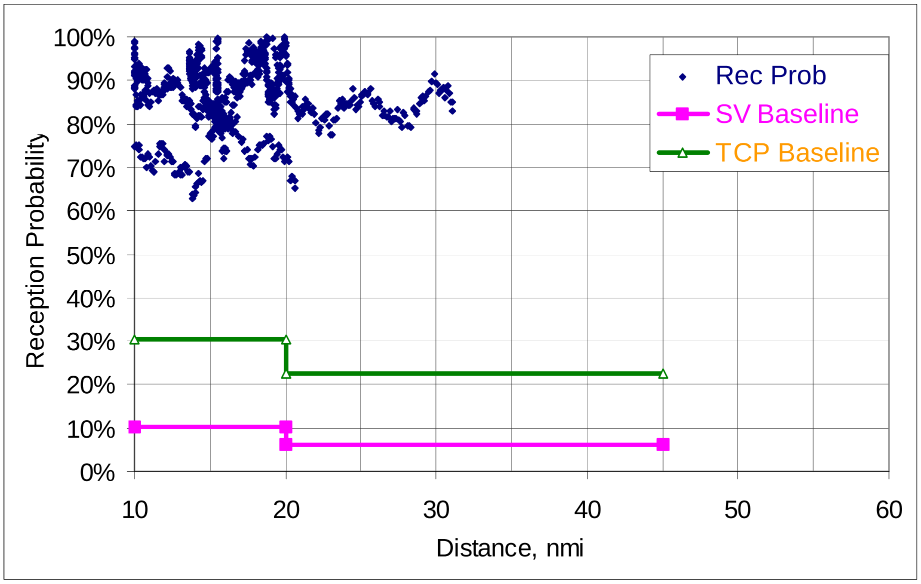


Figure 6.2.2-6a. Side Quadrants Rec. Prob. by NLR LDPU, 20 May Comparison with DO-242 Performance Requirements

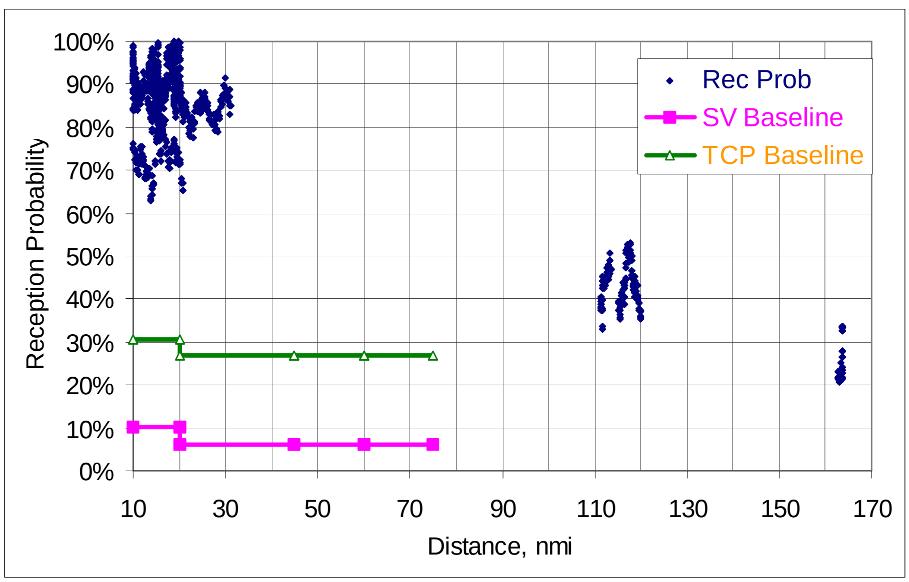


Figure 6.2.2-6b. Side Quadrants Rec. Prob. by NLR LDPU, 20 May Comparison with Eurocontrol Performance Criteria

6.2.3 Analysis of the Results from 22 May

An overview of the results for 22 May is provided in 4.4.1.2.3. FAA N40 and the FII project aircraft participated in the tests. The FII aircraft was in a holding pattern as FAA N40 flew a circuit as indicated in 4.4.1.2.3.1. A target of opportunity (BA-400664$_h$) was observed on a route from the northwest flying generally toward the southeast passing near Frankfurt and continuing on toward a destination beyond Munich.

An analysis of the data from the FII aircraft, that was previously summarized in Figure 4.4.1.2.3-4, indicates that the FII aircraft would have acquired the track (i.e., reception of both position and velocity information) on BA-400664$_h$ at range of approximately 113 nmi (with no subsequent update period exceeding 24 seconds) as BA-400664$_h$ approached the FII aircraft. On the outbound leg, FII would have maintained the track on BA-400664$_h$ to a range of beyond 85 nmi. The track would subsequently have been re-acquired and maintained out to a range of 164 nmi.

Analysis of the data collected onboard the FII aircraft on 22 May also indicates that it would have maintained the track on N40, as N40 departed the Frankfurt area, with state vector update periods not exceeding 24 seconds out to a range of beyond 126 nmi. Later in the same flight, as N40 was returning to Wiesbaden, the FII aircraft would have re-acquired the track (i.e., reception of both position and velocity information) on N40 at a range of approximately 92 nmi with no subsequent update period exceeding 24 seconds.

An analysis of the data from N40, that was previously summarized in Figure 4.4.1.2.3-5, indicates that N40 would have acquired the track (reception of both position and velocity information) on BA-400664$_h$ at range of approximately 139 nmi with no subsequent update period exceeding 24 seconds as BA-400665$_h$ approached N40. On the outbound leg, N40 would have maintained the track on BA-400664$_h$ to a range of beyond 111 nmi. The track would subsequently have been re-acquired and maintained out to a range of 143 nmi.

Analysis of the data collected onboard FAA N40 on 22 May also indicates that it would have maintained the track on the FII aircraft, with a state vector update period not exceeding 24 seconds, to a range of beyond 117 nmi as N40 departed the Frankfurt area. Later in the same flight, as N40 was returning to Wiesbaden, N40 would have re-acquired the track on the FII aircraft at a range of approximately 95 nmi with no subsequent update period exceeding 24 seconds. Note that the FII aircraft was not actually broadcasting velocity information and the 95 nmi range estimate represents the range within which position squitters were being reliably received.

6.2.3.1 Reception Probability as a Function of Target Bearing

Figures 6.2.3-1 to 6.2.3-3 present the reception probability of individual Extended Squitters versus range for each the FII and FAA N40 aircraft. The figures cover the forward quadrant (forward $\pm$ 45^{o}), the aft quadrant, and the port and starboard quadrants. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

6.2.3.1.1 Results from Measurements on the FII Aircraft, 22 May

Figure 6.2.3-1 plots the reception probability for the forward quadrant from data collected by the LDPU on the FII aircraft. Two target aircraft (FAA N40 and BA-400664$_h$) were each at a forward relative bearing from the FII aircraft during several separate time intervals. The reception probabilities for the Extended Squitters from BA-400664$_h$ and N40 were generally consistent. Only N40 appeared in the FII aircraft's forward quadrant at ranges of less than 40 nmi. Within this range Extended Squitters were received from N40 at ranges from 2 to 30 nmi with reception probabilities varying from approximately 61% to 89%. At ranges from 40 to 80 nmi Extended Squitter reception probabilities varied from approximately 53% at 40 nmi to approximately 23% at 80 nmi At the 80 nmi target range the reception probability varied from approximately 16% to 40%. At target ranges beyond 80 nmi the measured reception probabilities decreased to less than 20%, although little data was recorded for the forward quadrant at such ranges.

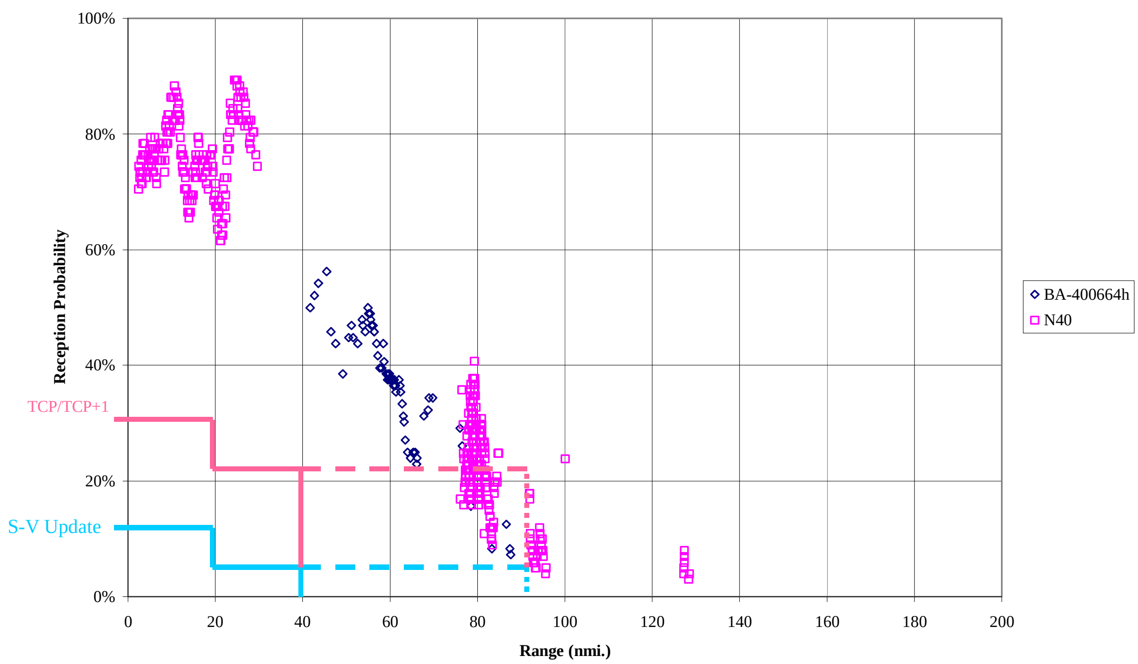


Figure 6.2.3-1. Forward Quadrant Reception Probability by FII, 22 May

Figure 6.2.3-2 plots the reception probability for the aft quadrant. The BA-400664$_h$ was at an aft relative bearing from the FII aircraft at several separate intervals.

N40 was at an aft relative bearing from the FII aircraft a significant amount of time at various ranges. The combination of the N40 and The BA-400664$_h$ results provide more or less continuous data on reception probability out to ranges of beyond 120 nmi. Extended squitter reception probability at ranges from 2 to 40 nmi varied from approximately 35% to 99% and except for a few very brief intervals was above 50%. For example the drop in reception probability for squitters being broadcast by N40 at a range of 18 nmi had a total duration of 25 seconds where the reception probability fell below 50%, but as a consequence of the sliding window approach used to produce plots in this section, even a brief event can impact multiple data point on the plots. In this particular case there was a state vector update produced for every one second interval (at least one position and/or velocity squitter was received during each second) during this 25 seconds of reduced reception probability. As for the cause of the degradation in this specific case, N40 was executing a turn during this time period with a 25-degree change in heading occurring during the 25-second interval. Thus an application using ADS-B reports that were output by the 1090 ADS-B system would have observed no degradation during this interval. At target ranges from 40 to 100 nmi the reception probably generally decreased from 50% to 20% with a few brief intervals recorded where the reception probability dropped below 20%, with a single sample at 14.5% being the lowest value.

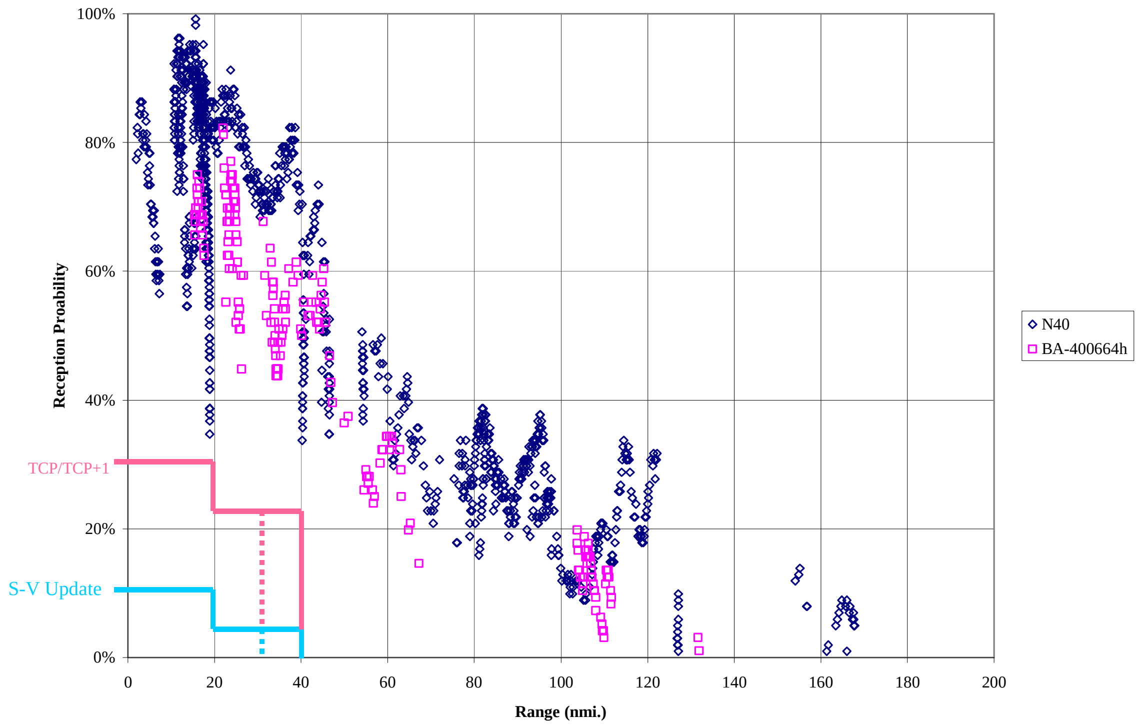


Figure 6.2.3-2. Aft Quadrant Reception Probability by FII, 22 May

Figure 6.2.3-3 plots the reception probability for port and starboard quadrants. The target aircraft (N40 and BA-400664$_h$) were each at a port or starboard relative bearing from the FII aircraft at a number of discrete times. The combined data provides a nearly continuous plot of reception probably out to ranges beyond 100 nmi. At target ranges of less than 40 nmi the probability of reception ranged from a low of 27% (at longer ranges) to a high of 92% at short ranges. At ranges between 40 and 75 nmi the reception probability for the broadcasts from the BA-400664$_h$ were 20% to 40% and the reception from N40 while generally above 20%, included very brief interval at approximately 60 nmi where the reception probability dropped to as low as 4%. This event, where the probability was less than 20%, spanned a time interval of 1 minute and occurred just after N40 had started it descent on its return to Wiesbaden near the end of the data collection exercise.

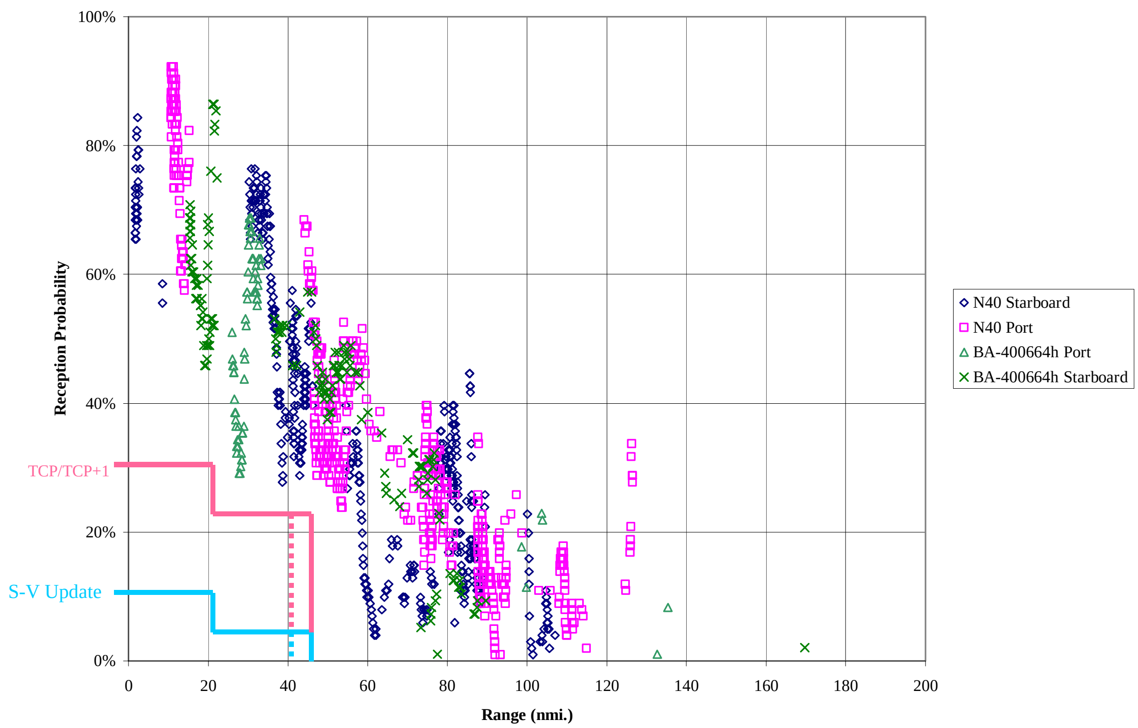


Figure 6.2.3-3. Port & Starboard Quadrants Reception Probability by FII, 22 May

6.2.3.1.2 Results from Measurements on the FAA N40 Aircraft, 22 May

Figure 6.2.3-4 plots the reception probability for the forward quadrant from data collected by the LDPU on the FAA N40 aircraft. The two target aircraft were FII and BA-400664$_h$. BA-400664$_h$ was at a forward relative bearing from N40 during several separate intervals. Substantial forward quadrant data at ranges to in excess of 100 nmi was collected from the FII aircraft. It should be noted that the FII aircraft was using a general aviation class transponder with a nominal transmitter power output level on the order of 2.5 dB less than for a typical air carrier transponder, such as used on BA-400664$_h$. There was not sufficient forward quadrant data collected from BA-400664$_h$ to verify if the higher transmitter power level resulted in higher probability of squitter reception by N40. For squitters received from the FII aircraft at target ranges out to 20 nmi the probability of squitter reception generally remained above 60% and at ranges between 20 nmi and 70 nmi the reception probability was generally above 40% with the lowest value being 28%. Beyond 70 nmi the reception probability dropped to 23% at 75 nmi then generally varying between 5% and 30% out to a range of 100 nmi. The limited data from BA-400664$_h$ shows reception probability varying between 52% and 90% at target ranges of 22 to 30 nmi. Longer-range data shows the probability of reception dropping below 23% at ranges beyond 83 nmi.

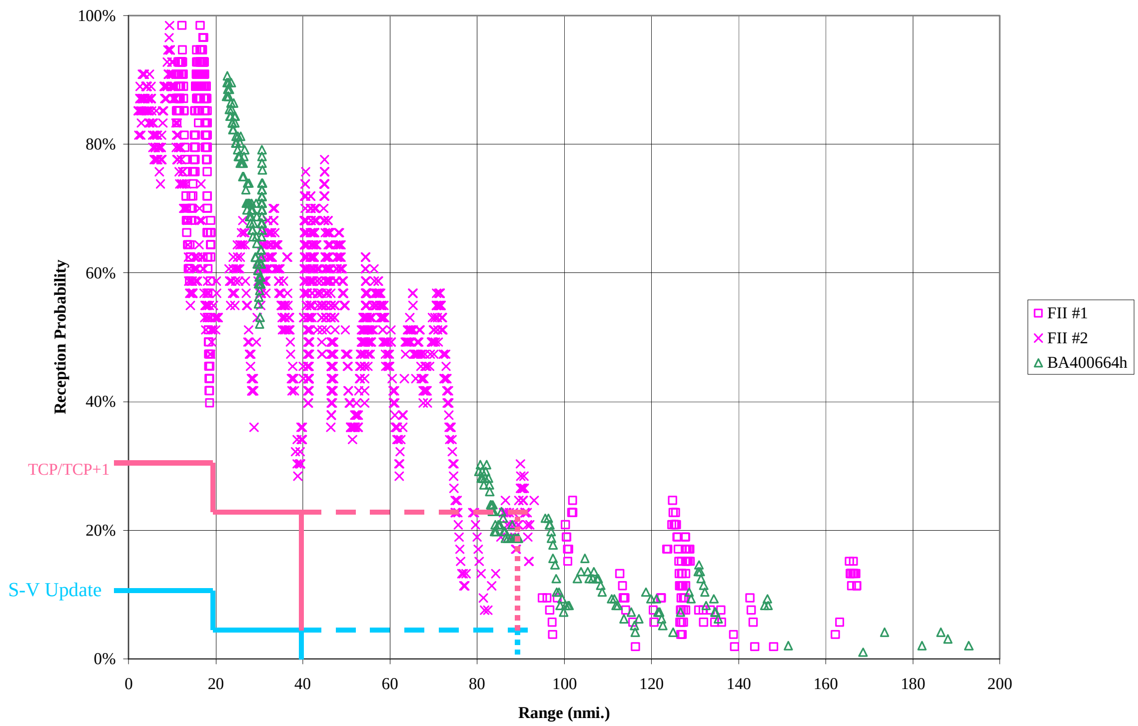


Figure 6.2.3-4. Forward Quadrant Reception Probability by N40, 22 May

Figure 6.2.3-5 plots the reception probability for the aft quadrant. BA-400664$_h$ was at an aft relative bearing from N40 only at ranges beyond 80 nmi and only for a limited time. The FII aircraft was at an aft relative bearing from N40 at several separate intervals where a modest amount of data was collected. The combination of the N40 and the BA-400664$_h$ results provide data to estimate the reception performance achieved in the aft quadrant on this flight. Extended squitter reception probability at ranges within 40 nmi varied from approximately 50% to 98% while reception probability at ranges between 40 nmi and 75 nmi were generally above 20% with only a very few data points dropping down to as low as 15%.

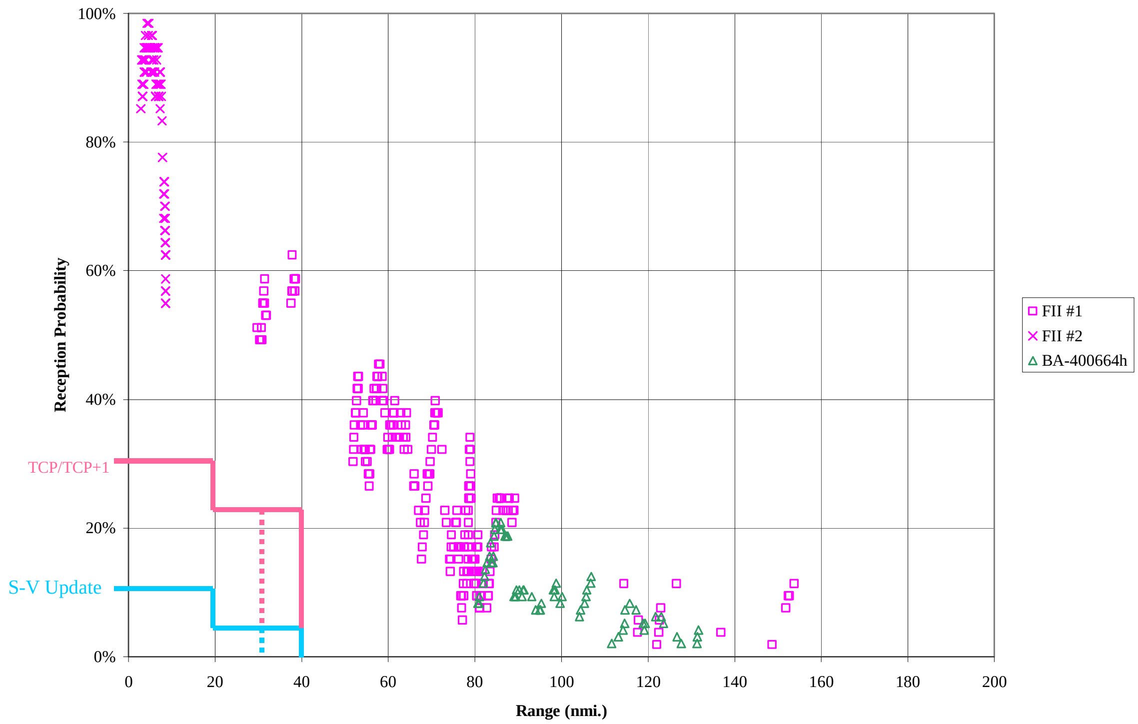


Figure 6.2.3-5. Aft Quadrant Reception Probability by N40, 22 May

Figure 6.2.3-6 plots the reception probability for port and starboard quadrants. The target aircraft (FII and BA-400664$_h$) were each at a port or starboard relative bearing from N40 at a number of discrete times. Combined the data provides a nearly continuous plot of reception probably out to ranges beyond 100 nmi. At target ranges of less than 20 nmi the probability of reception was generally above 60% with only a few lower data points dropping down to a minimum of 47%. At target ranges of between 20 nmi and 60 nmi the reception probabilities generally varied between 30% and 90% with a minimum value of 26% at a range of 50 nmi. Beyond 60 nmi the reception probability varied widely with the bulk of the data points remaining above 20% out to a range of 110 nmi. However, a few data points fell down into the 6% to 10% region at target ranges of approximately 76 nmi and greater.

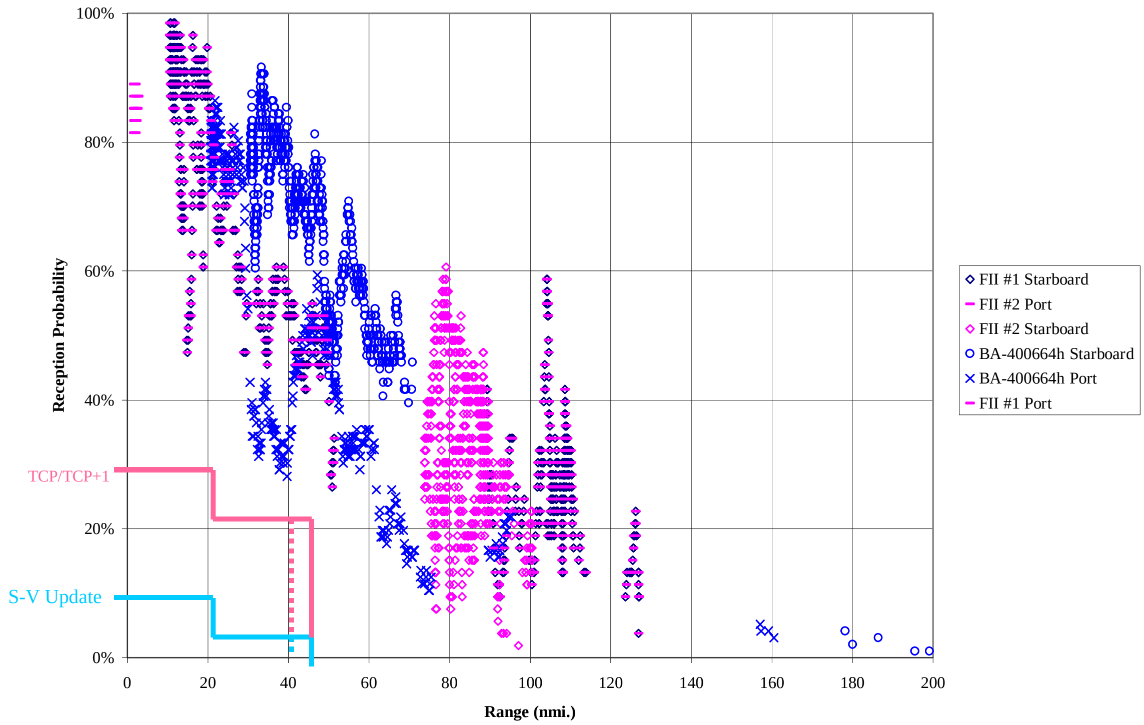


Figure 6.2.3-6. Port & Starboard Quadrants Reception Probability by N40, 22 May

6.2.3.2` Performance vs. Requirements

There was a modest amount of data collected for reception from the forward quadrant by the FII aircraft and substantially more data collected by FAA N40. Analysis of the results indicates that for the ranges up to 40 nmi (the limit of the MASPS requirements) the reception performance substantially exceeded that required by the ADS-B MASPS. At longer ranges the reception probability for TCP and TCP+1 squitters would exceed the desired 22.9% values out to target ranges of at least 75 nmi for both the FAA N40 and for the FII aircraft. The data indicates that tracking of the target aircraft, with state vector updates within the 12 seconds required by the MASPS (at 95% probability), should be possible at ranges of 100 nmi or greater. Reception performance in the aft and in the port and starboard quadrants substantially exceeded the reception performance required by the ADS-B MASPS.

6.2.4 Analysis of the Results from 24 May

An overview of the results for 24 May is provided in 4.4.1.1. FAA N40, NLR and the FII project aircraft participated in the tests on this day. The N40 was in a holding pattern as the FII and NLR aircraft flew a circuit as previously shown in Figure 4.4.1-1a. A target of opportunity (BA-400652_h) was observed on a route from northwest to southeast that overflew the Frankfurt area at the time the project aircraft were departing from Wiesbaden for the data collection flights. Data was presented in 4.4.1.1 that included Extended Squitters received from BA-400652_h by the project aircraft while they were still on the airport surface at Wiesbaden. However, the results presented below are limited to Extended Squitters received after the project aircraft was airborne (above 1000 ft altitude).

A summary of the data collected onboard the project aircraft was previously summarized in 4.4.1.1 and the figures contained therein. The following paragraphs present a further analysis of the results obtained from the evaluations on 24 May.

6.2.4.1 Reception Probability as a Function of Target Bearing

Figures 6.2.4-1 to 6.2.4-4 present the reception probability of individual Extended Squitters versus range received by the NLR Metroliner, the FII aircraft, and FAA N40. The figures cover the forward quadrant (i.e., forward $\pm 45^o$), the aft quadrant, and the port and starboard quadrants combined into a single figure. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. The additional Eurocontrol criteria for long autonomous operations are also indicated. For more information on the associated ADS-B MASPS and Eurocontrol requirements see 6.1 and specifically Table 6.1-4.

6.2.4.1.1 Results from Measurements on FII Aircraft. 24 May

Figure 6.2.4-1 plots the reception probability for the forward quadrant from data collected by the LDPU on the FII aircraft. Three target aircraft (FAA N40, NLR and BA-400652$_h$) were observer at a forward relative bearing from the FII aircraft. A moderate amount of forward quadrant data was collected from N40 and BA-400652$_h$. Only a very little, short range, forward quadrant data was collected from the NLR aircraft. The forward quadrant reception probabilities for the Extended Squitters received from both N40 and BA-400652$_h$ indicate reduced reception performance, compared to the performance achieved during other test periods. The target range within which the desired 22.9% probability of reception was achieved in the forward direction was approximately 50 nmi for BA-400652$_h$ and 40 nmi for N40. The results obtained for reception of the Extended Squitters from BA-400652$_h$ are not unexpected or of major concern since the degraded reception performance for this encounter occurred during the first few minutes after the FII aircraft departed from Wiesbaden and was climbing and maneuvering. During this interval BA-400652$_h$ was at a cruise altitude of FL370 and flying away from the FII aircraft. Although the probability of individual squitter reception dropped below the desired level of 22.9% at a range of approximately 50 nmi the FII aircraft would not have dropped the track on BA-400652$_h$ until approximately 23 minutes after FII departed Wiesbaden at which time the range to BA-400652$_h$ was approximately 70 nmi. At this time the FII aircraft had just reached a cruise altitude of FL220 and BA-400652$_h$ was descending through FL200. The track would subsequently have been re-acquired.

The results obtained for FII reception of Extended Squitters from N40 while the FII aircraft was outbound at the beginning of the tests (i.e., FII aft quadrant data) appear to be consistent with data collected on other days of the evaluation. However, the forward quadrant performance when the FII aircraft was returning toward Frankfurt/Wiesbaden near the end of this day's data collection showed degraded performance that required further investigation. The desired reception probability of 22.9% was not reached until the range to N40 was within approximately 40 nmi, as compared to the 70 to 80 nmi that was typically measured during the other days and time periods of the evaluation. During the time period in question N40 was in a holding pattern near Frankfurt while the FII aircraft was returning toward Frankfurt/Wiesbaden. Further investigation was undertaken to identify potential reasons for the degraded reception performance that occurred during this specific time period of this data set. Note that N40 experienced a similar level of degraded performance on 24 May during the same limited time period. The potential causes of this period of degraded reception performance are explored in 6.2.4.2.1.

There was insufficient forward quadrant data collected by the FII aircraft from the NLR aircraft to assess reception performance from this target other than the very short-range performance. The short-range performance was as expected and well exceeded the required level.

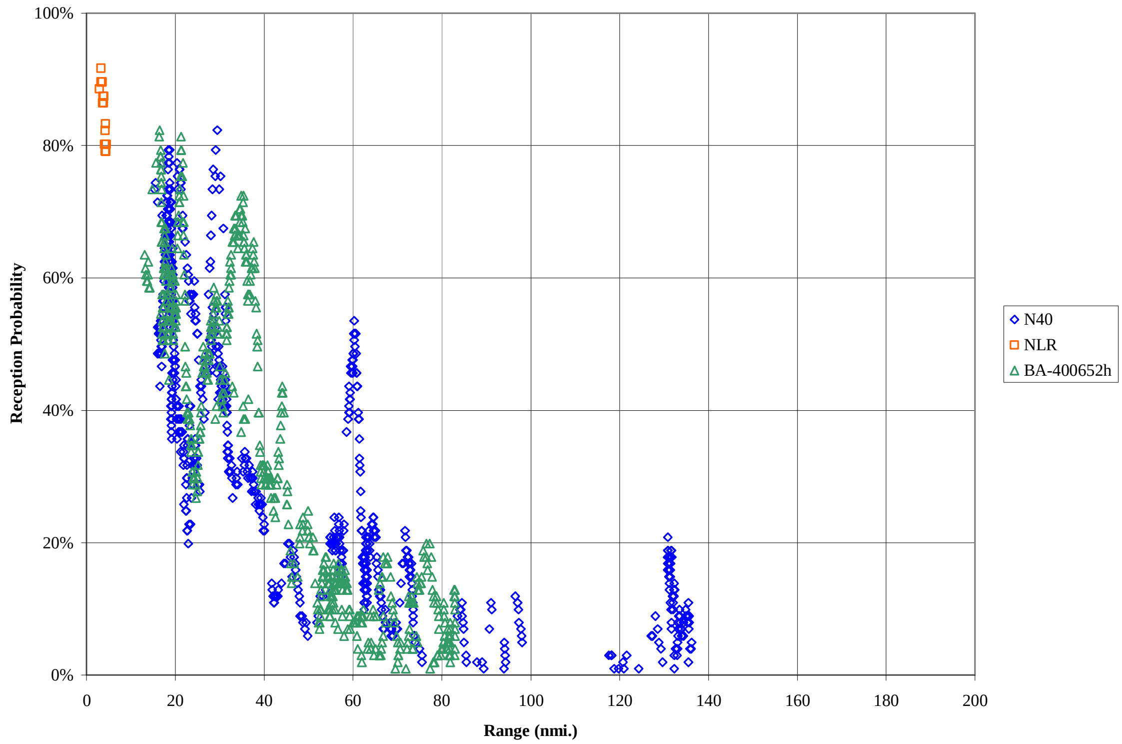


Figure 6.2.4-1. Forward Quadrant Reception Probability by FII, 24 May

Figure 6.2.4-2 plots the reception probability for the aft quadrant from data collected by the LDPU on the FII aircraft. Insufficient aft quadrant data was collected from BA-400652$_h$ to judge the reception performance for this target from this quadrant. A significant quantity of data was collected from N40 broadcasts as shown in Figure 6.2.4-2. This data from N40 was generally collected as the FII aircraft was outbound from Frankfurt/Wiesbaden and N40 was on its way to, and subsequently in, a holding pattern near Frankfurt. The Extended Squitter reception probability from N40 remained above the desired 22.9% level until the range to N40 was approximately 85 nmi. Note that the N40 data as shown in Figure 6.2.4-2 is presented as two data sets. This was done because N40 reset its LDPU to change flash memory cards, and thus briefly (approximately one minute) interrupting the transmission of valid Extended Squitters. This occurred while the range from the FII aircraft was approximately 77 nmi. Ignoring this brief intentional interruption in Extended Squitter broadcasts from N40, the FII aircraft would have maintained track on N40 until the target range reached approximately 106 nmi.

The aft reception performance from the NLR aircraft includes three separate range and time groupings of data. Both the short-range set of data (10 to 20 nmi) as well as the long-range set of data (> 70 nmi) are similar to the reception probabilities measured for reception of Extended Squitters from N40. However the mid-range (45 to 60 nmi) data shows notably lower probability of reception, even when compared to the reception at considerably longer ranges. Examination of the FII and NLR aircraft's flight profiles for the time interval in which this mid-range data was collected revealed that the FII was descending below 3000 ft on its way back to land at Wiesbaden and the NLR aircraft was also descending passing through 12,000 ft on its way back to land at Wiesbaden. Given the aircraft were engaged in these operations the reduced probability of reception at ranges greater than 40 nmi is not unexpected nor of significant operational concern.

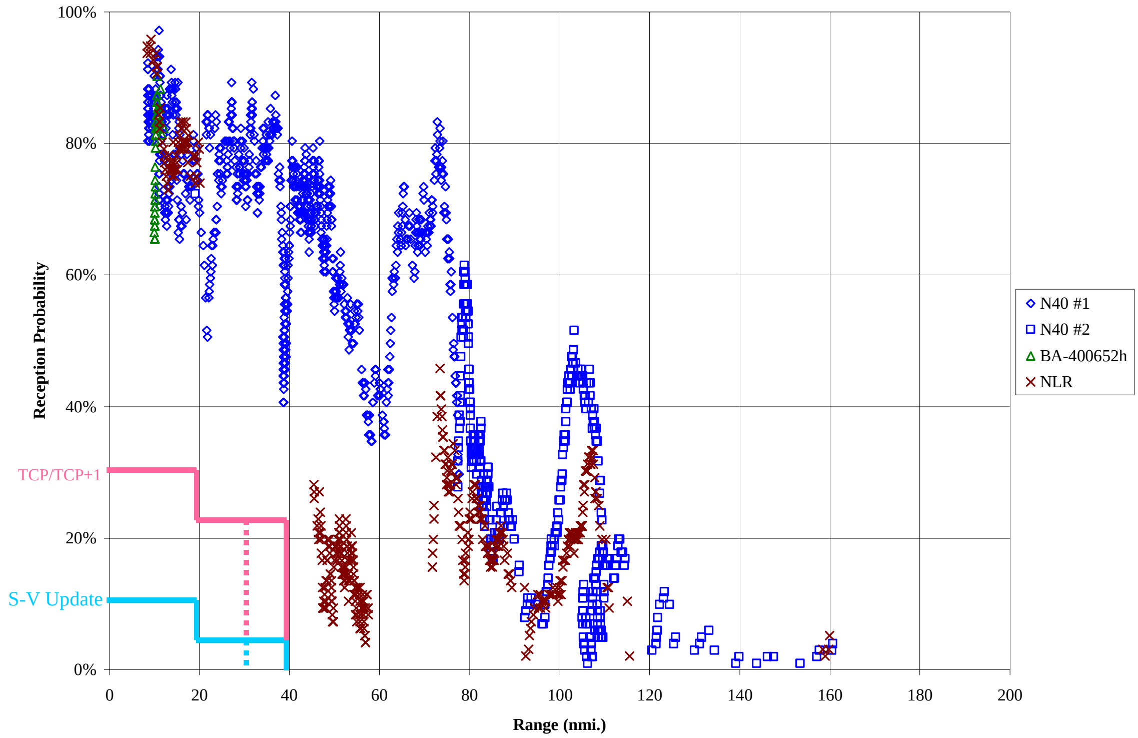


Figure 6.2.4-2. Aft Quadrant Reception Probability by FII, 24 May

Figure 6.2.4-3 plots the reception probability for port and starboard quadrants by the FII aircraft. Only limited port and starboard quadrant data was received from BA-400652$_h$ for which the reception probability remained above the desired 22.9% out to a range of approximately 45 nmi, except for a brief interval of 12 seconds at a target range of approximately 25 nmi. The other target aircraft (N40 and NLR) were each at a port or starboard relative bearing from N40 at varying ranges thus allowing for meaning analysis of reception results. The reception of squitters from N40 at these quadrants largely occurred at ranges within 32 nmi, with a few additional squitters received at long ranges (>120 nmi). Also the FII aircraft received Extended Squitters from the NLR aircraft out to ranges of approximately 75 nmi. Reception probabilities for Extended Squitters broadcast from both N40 and the NLR aircraft were typical for the measured target ranges with the probability of reception generally above the desired 22.9% value for ranges within 45 nmi.

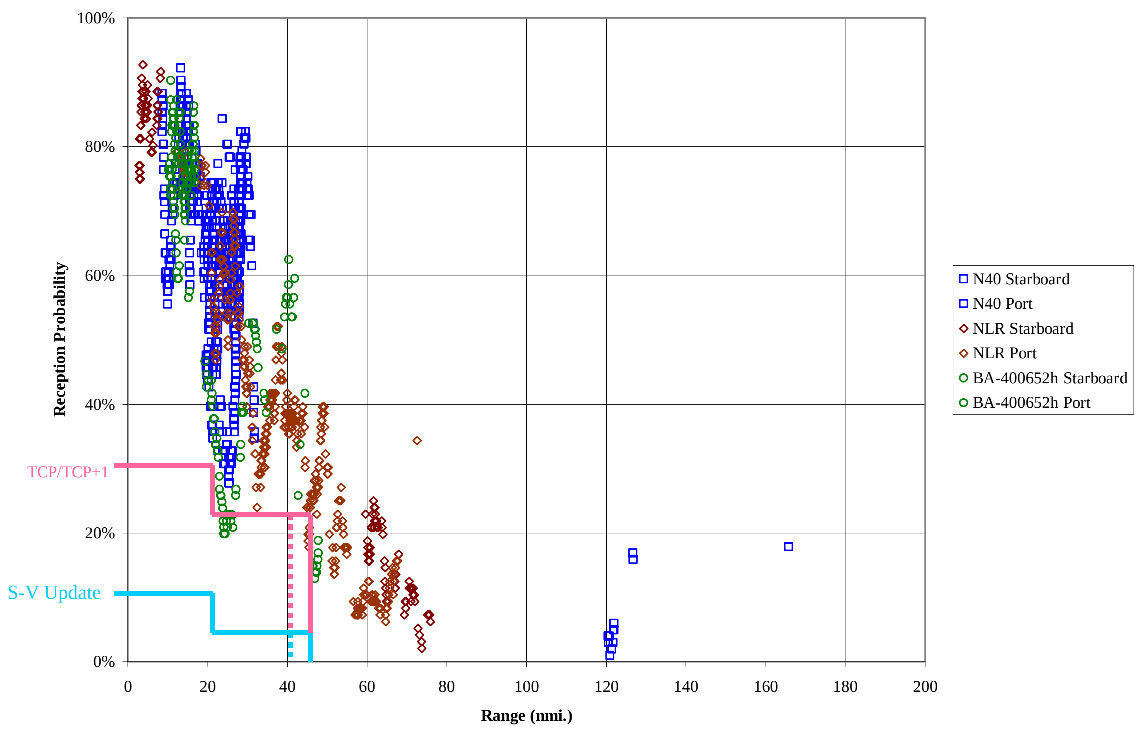


Figure 6.2.4-3. Port & Starboard Quadrants Reception Probability by FII, 24 May

6.2.4.1.2 Results from Measurements on N40 Aircraft, 24 May

Figure 6.2.4-4 plots the reception probability for the forward quadrant from data collected by the LDPU on FAA N40. Four target aircraft (FII, NLR, BA-400663$_h$ and BA-400664$_h$) were observed at a forward relative bearing from the N40 during the course of the flight tests on 24 May. The forward quadrant data for each of these aircraft was generally limited to a few brief time intervals. This was especially true for the British Airways aircraft, which were only briefly observed at long range (>130 nmi). The reception probability for Extended Squitters from the FII and NLR aircraft each included a case where the reception probability was lower than what was typically observed for the given target range. For the case of reception of Extended Squitters from the NLR and the FII aircraft there were specific situations where the desired 22.9% reception probability was only achieved when the target with within approximately 35 nmi. An examination of the NLR case showed that this data was collected while both N40 and the NLR aircraft were descending on their way to land at Wiesbaden at the end of the data collection exercise. At the beginning of this portion of the NLR data, its range to N40 was approximately 64 nmi and the NLR aircraft was descending through 11,000 ft and at this same time N40 was descending through 10,000 ft. By the time the range had reached 40 nmi the NLR aircraft had descended to approximately 7,000 ft and N40 had descended to approximately 8,000 ft. It should also be noted that the NLR aircraft ceased Extended Squitter transmissions for a period of time during its approach to Wiesbaden because of a warning indicator onboard that aircraft, which resulted in the flight crew declaring an emergency and shutting off the ADS-B system. Ignoring the period where NLR deliberately ceased ADS-B transmissions, N40 would have provided target tracking of the NLR aircraft at ranges within approximately 65 nmi. Earlier in the flight N40 observed the NLR aircraft in the forward quadrant. During this brief period the target range varied from approximately 53 nmi to 59 nmi and the reception probabilities varied from a low of 22% to a high of 48%. Generally this data set is consistent with the reception probabilities typical of other data sets.

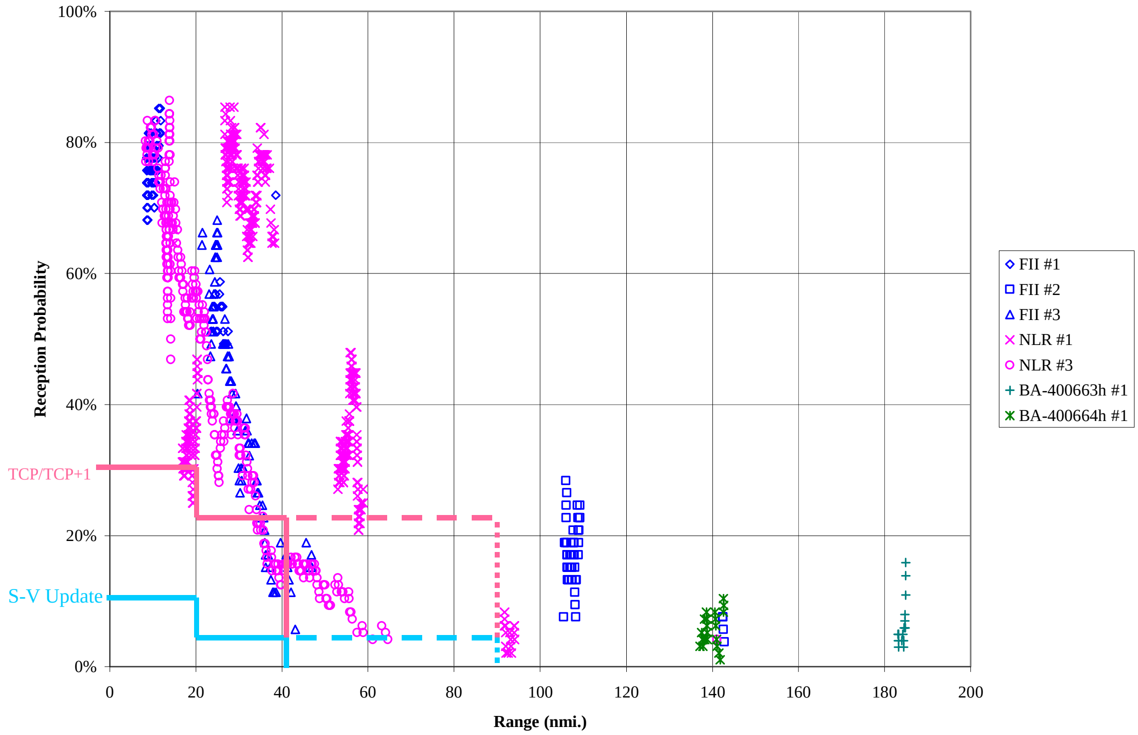


Figure 6.2.4-4. Forward Quadrant Reception Probability by N40, 24 May

Figure 6.2.4-5a plots the reception probability for the aft quadrant from data collected by the LDPU onboard N40. Only very little aft quadrant data was received from BA-400664$_h$ at a range of approximately 140 nmi. There was thus insufficient data to allow for further analysis of the aft quadrant reception performance from this target. Substantial aft quadrant data was received from the NLR aircraft. The reception performance for broadcasts from the NLR aircraft indicate that the desired 22.9% or greater reception probability would generally have been maintained until the target range reached approximately 65 nmi. More limited aft quadrant data was received from the FII aircraft mostly between the ranges of 14 nmi and 32 nmi where the reception probabilities varied between 17% and 89%. This data for the FII aircraft includes Extended Squitters received from early during the test flight as the FII aircraft was departing the Frankfurt/Wiesbaden area as well as data associated with the final few minutes of the test flight as the FII aircraft was returning to Wiesbaden. These data points below the desired 22.9% values all occurred during a single 28 second interval while the FII aircraft was descending through 2,800 ft as it prepared to land at Wiesbaden at a range from N40 of approximately 25 nmi. During this same time interval, N40 was also descending at approximately 12,000 ft on this way back to land at Wiesbaden. The lowest probability of reception recorded during the earlier phase of the flight, as the FII aircraft departed Frankfurt/Wiesbaden was approximately 33%. A few additional Extended Squitters from N40 were received from the FII aircraft at a range of approximately 90 nmi where the reception probability was in the range of 30% to 45%. A few additional Extended Squitters from N40 were received at long range (i.e., 115 nmi to 165 nmi) at reception probabilities of 15% and below.

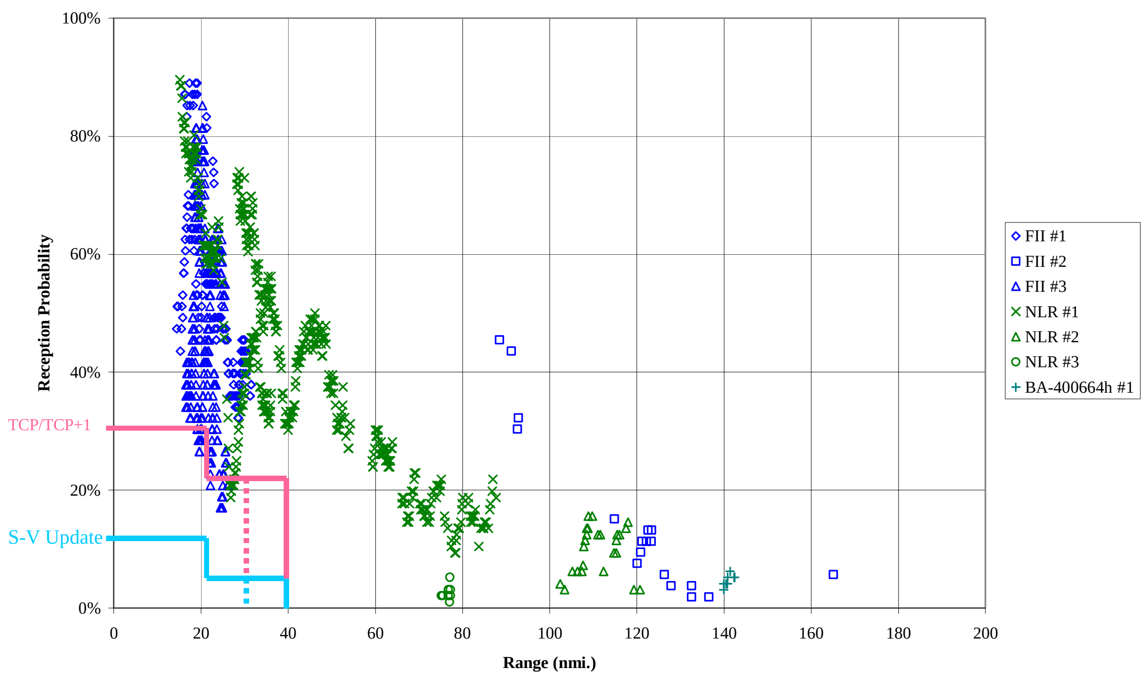


Figure 6.2.4-5a. Aft Quadrant Reception Probability by N40, 24 May

Figure 6.2.4-5b plots the reception probability for port and starboard quadrants by N40 on 24 May. Significant data from the FII and NLR project aircraft and from the BA-400652_h target of opportunity were recorded by N40 in the port and starboard quadrants. Considering all three target aircraft, the desired 22.9% probability of reception was exceed for all targets within 56 nmi and in most cases was exceed to ranges in excess of 75 nmi. There was one set of data points associated with the third data set from the FII aircraft at a ranges of 56 nmi to 73 nmi were the probability of reception was below 22.9%. This case was associated with the same encounter as discussed above for the forward quadrant where the overall probability of reception was unusually low. This case is further analyzed in 6.2.4.2.1.

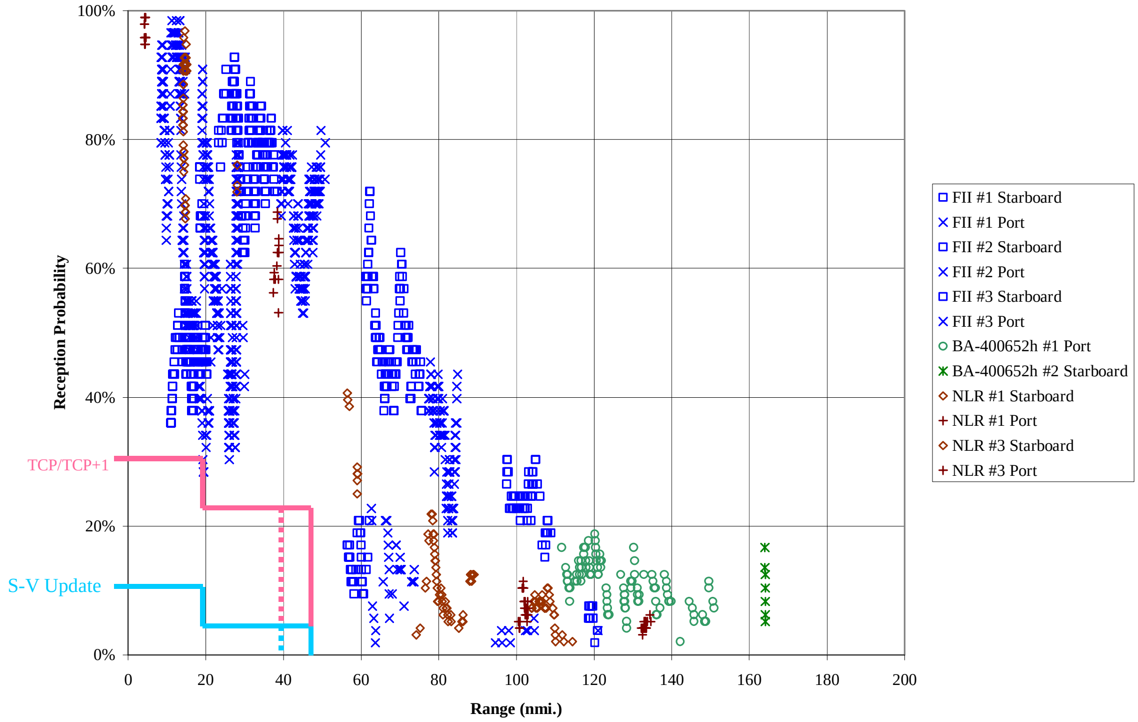


Figure 6.2.4-5b. Port & Starboard Quadrants Reception Probability by N40, 24 May

6.2.4.1.3 Results from measurements on NLR, 24 May

The NLR LDPU log of the 24 May was analyzed in 4.4.1.1. Figures 4.4.1-1a and 4.4.1-2a show the FII and N40 tracks recorded by the NLR LDPU during the trial session. Figures 4.4.1-1b and 2b plot the corresponding N40 and FII altitudes and range versus time. The NLR aircraft flew a two-leg flight from Wiesbaden. In the first leg NLR flew towards the north and therefore had the N40 mostly in the aft quadrant while FII (which was flying to the southeast) was found mostly in the aft and starboard quadrants. During the return leg the N40 was found mostly in the forward quadrant while the FII (which was also returning to Wiesbaden from a southeast direction) was found partly in the port quadrant and to a lesser extent in the forward quadrant.

The FII and N40 reception probability estimates from the NLR LDPU log have been shown in Figures 4.4.1-1e and 2e making a distinction between inbound and outbound flight phases. Figures 6.2.4-6a to 6.2.4-6c plot the same data separately for the forward, the aft and the side quadrants, respectively, of the receiver (NLR). Only the flight periods where both the transmitter and the receiver were airborne (altitude > 1000 ft) have been considered.

Figure 6.2.4-6a(1) plots the N40 and FII reception probabilities versus range for the forward quadrant of NLR and compares with the theoretical minima for meeting the D0-242 update interval requirements (SV and up to two TCPs) for ASAS and flight path deconfliction. Figure 6.2.4-6a(2) compares the same N40 and FII reception probabilities versus range for the forward quadrant of NLR with the theoretical minima for meeting the Eurocontrol criteria for autonomous operations (SV and four TCPs).

Figures 6.2.4-6(1) and 6.2.4-6a(2) indicate that FII Extended Squitter reception was better than that of N40 Extended Squitters at distances below 60 nmi and worse for distances above 60 nmi. Concerning state vector updates, both targets exceeded the theoretical reception probability minima up to 120 nmi (N40) and 80 nmi (FII). For TCP updates the observed reception probabilities fell below the RTCA minima at 50 nmi (N40) and 60 nmi (FII). It is noticeable that the NLR LDPU achieved better reception probabilities for N40 squitters than the FII LDPU during the 24 May trial session (compare with the FII results described in 6.2.4.1). FII and NLR flew similar flight profiles albeit in different directions. On the other hand NLR reception performance was not as good as its reception performance in the 20 May session (see Figure 6.2.2-4, N40 reception on NLR - forward quadrant).

Figure 6.2.4-6b(1) plots the N40 and FII reception probabilities versus range for the starboard and port quadrants of the receiver (NLR) and compares with the theoretical minima needed to meet DO-242 update interval requirements for ASAS and flight path deconfliction. Figure 6.2.4-6b(2) compares the same N40 and FII reception probabilities with the minima required to meet Eurocontrol autonomous operation update interval requirements. Both FII and N40 Extended Squitter reception probabilities were comfortably above the RTCA state vector minima and they also exceeded the minima for TCP updates (RTCA). The minima for reception of four TCPs (Eurocontrol) were exceeded up to 60 nmi (at least for the FII, there were no relevant samples for the N40).

Figure 6.2.4-6c(1) plots the N40 and FII reception probabilities versus range for the aft quadrant of the receiver (NLR) and compares with the minima that would meet DO-242 update interval requirements for ASAS and flight path deconfliction. Figure 6.2.4-6c(2) compares the same N40 and FII reception probabilities with the Eurocontrol criteria for autonomous operations. The reception probabilities of both targets exceeded the minima for state vector and TCP updates throughout the required range.

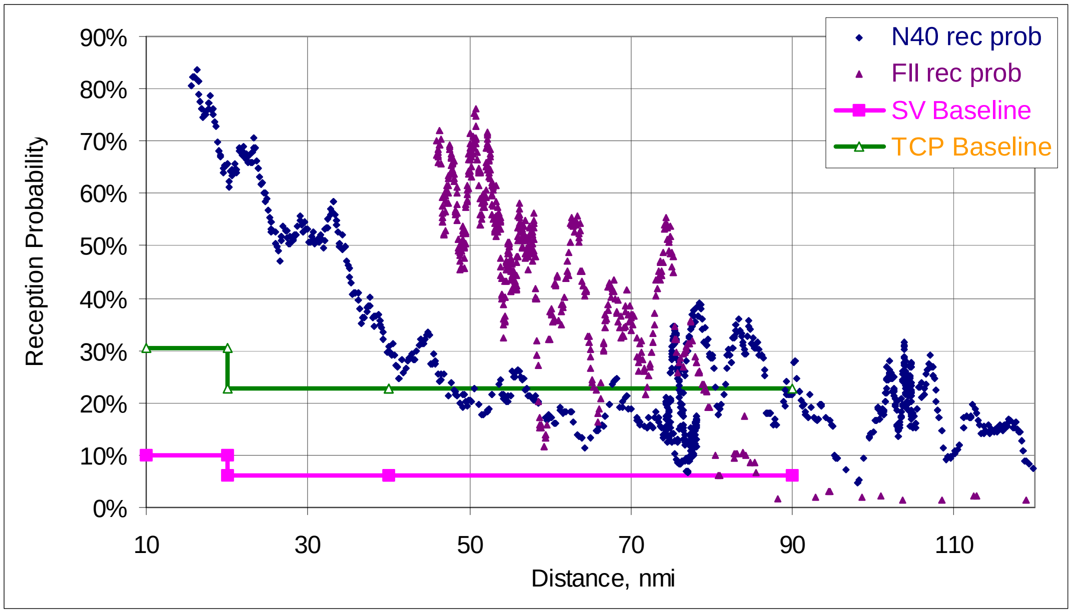


Figure 6.2.4-6a(1). Forward Quadrant Rec. Prob. by NLR LDPU, 24 May, Comparison with DO-242 requirements

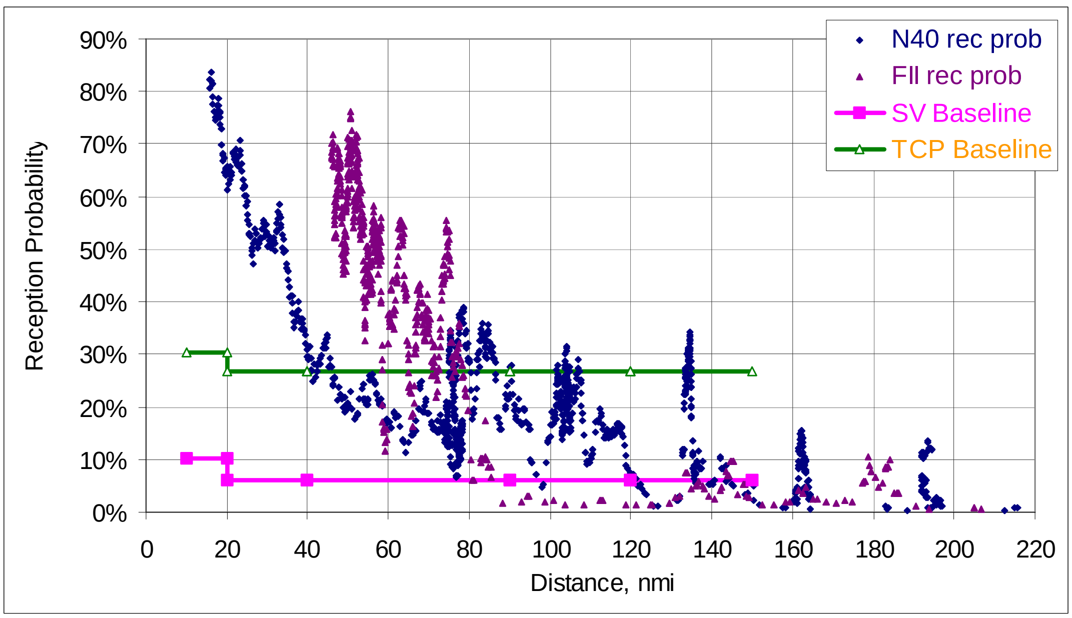


Figure 6.2.4-6a(2). Forward Quadrant Rec. Prob. by NLR LDPU, 24 May, Comparison with Eurocontrol Criteria

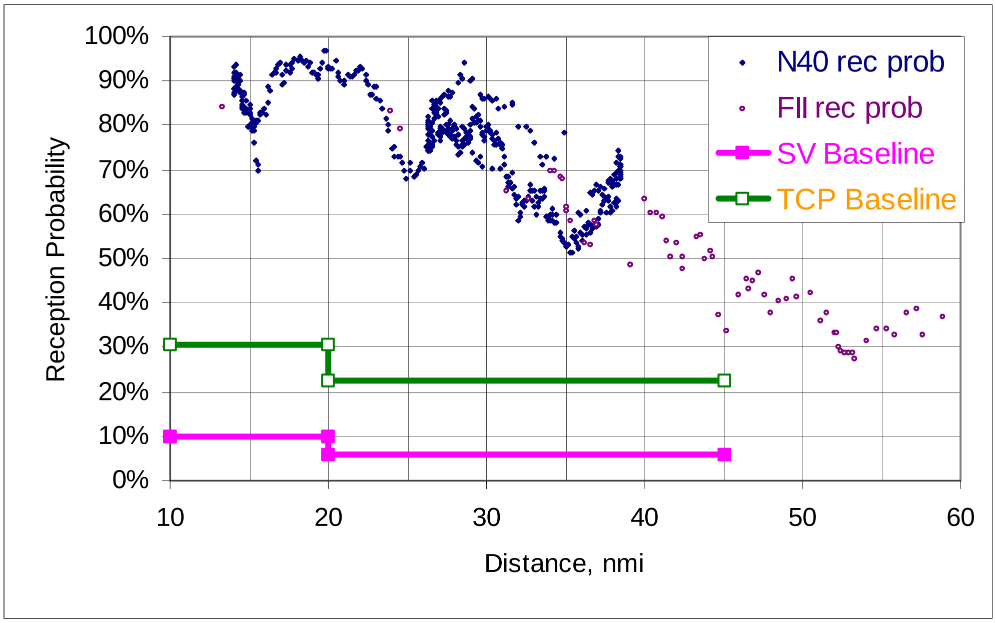


Figure 6.2.4-6b(1). Side Quadrants Rec. Prob. by NLR LDPU, 24 May Comparison with DO-242 Requirements

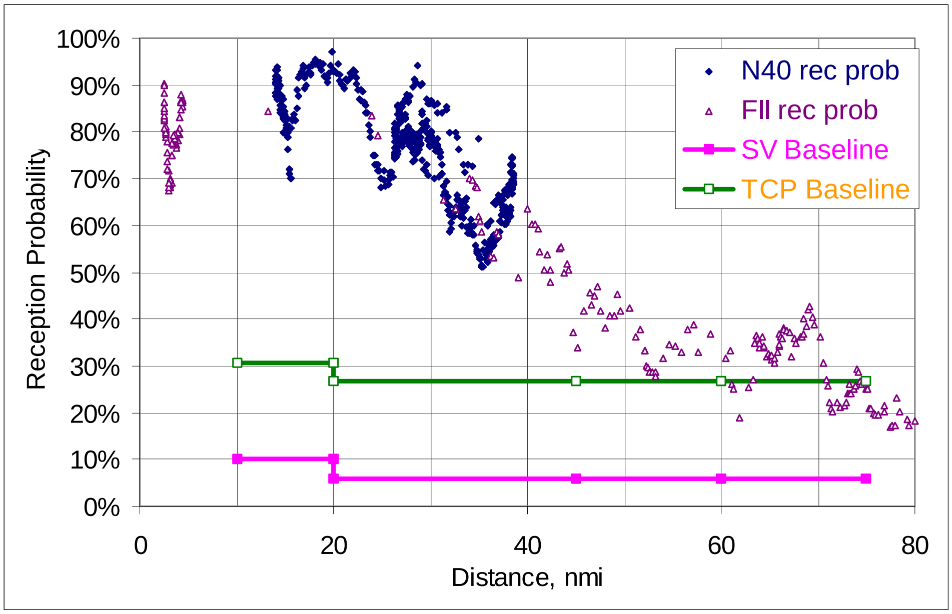


Figure 6.2.4-6b(2). Side Quadrants Rec. Prob. by NLR LDPU, 24 May Comparison with Eurocontrol Criteria

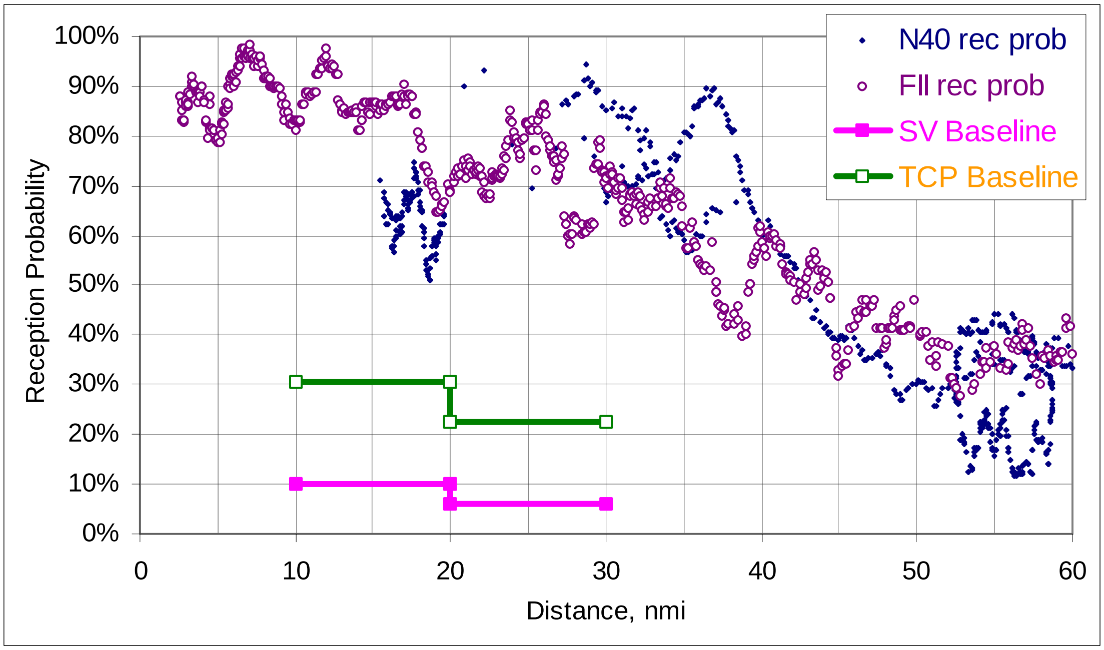


Figure 6.2.4-6c(1). Aft Quadrant Rec. Prob. by NLR LDPU, 20 May Comparison with DO-242 Requirements

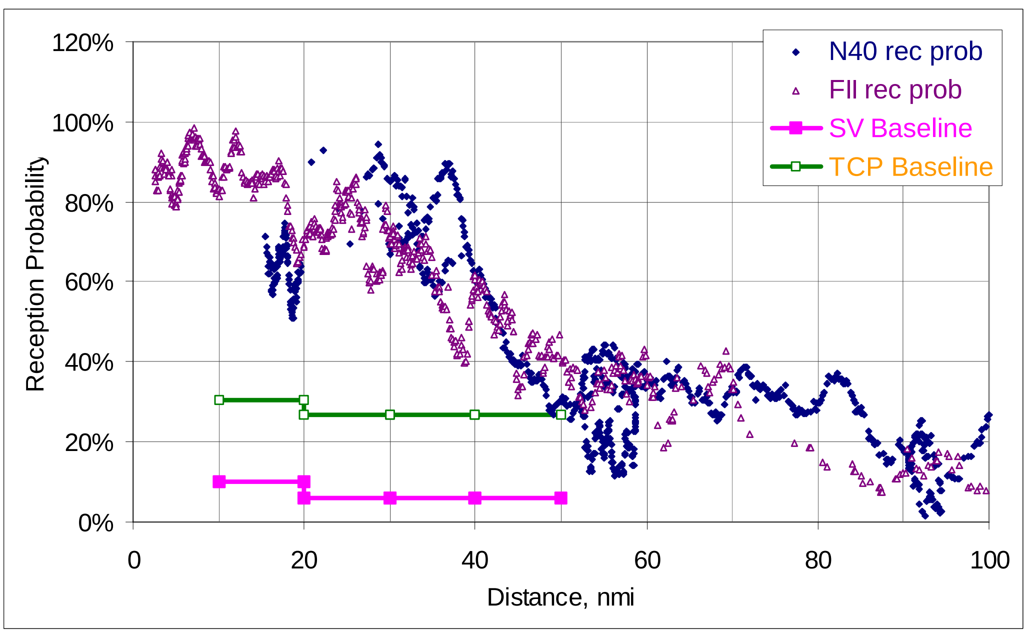


Figure 6.2.4-6c(2). Aft Quadrant Rec. Prob. by NLR LDPU, 20 May Comparison with Eurocontrol Criteria

6.2.4.2 Performance vs. Requirements

In considering the overall set of performance results reported above, there appeared to be anomalies in the performance results reported on 24 May that required further investigation. This involved analysis of data collected by the LDPUs onboard the FII aircraft and N40 associated with specific encounters between the project aircraft. Section 6.2.4.2.1 presents the results for this further investigation of the results.

6.2.4.2.1 Investigation of Factors for Periods of Degraded Performance

Both N40 and the FII aircraft experienced degraded reception performance on 24 May during the phase of the flight where the FII aircraft was returning to Wiesbaden and N40 was just completing its data collection while in the holding pattern near Frankfurt. The following material provides more details concerning the specific set of data associated with the encounter. The encounter in question involved the FII aircraft returning for a subsequent landing at Wiesbaden while N40 was in a holding pattern near Frankfurt. Both aircraft were flying at FL220 and both aircraft experienced lower than expected probability of squitter reception, for the given air-to-air target range. Figure 2.4.2-7a provides the ground tracks of the FII aircraft and N40 during the approximately 15 minute segment (12:24:13 to 12:39:16) of the encounter in question.

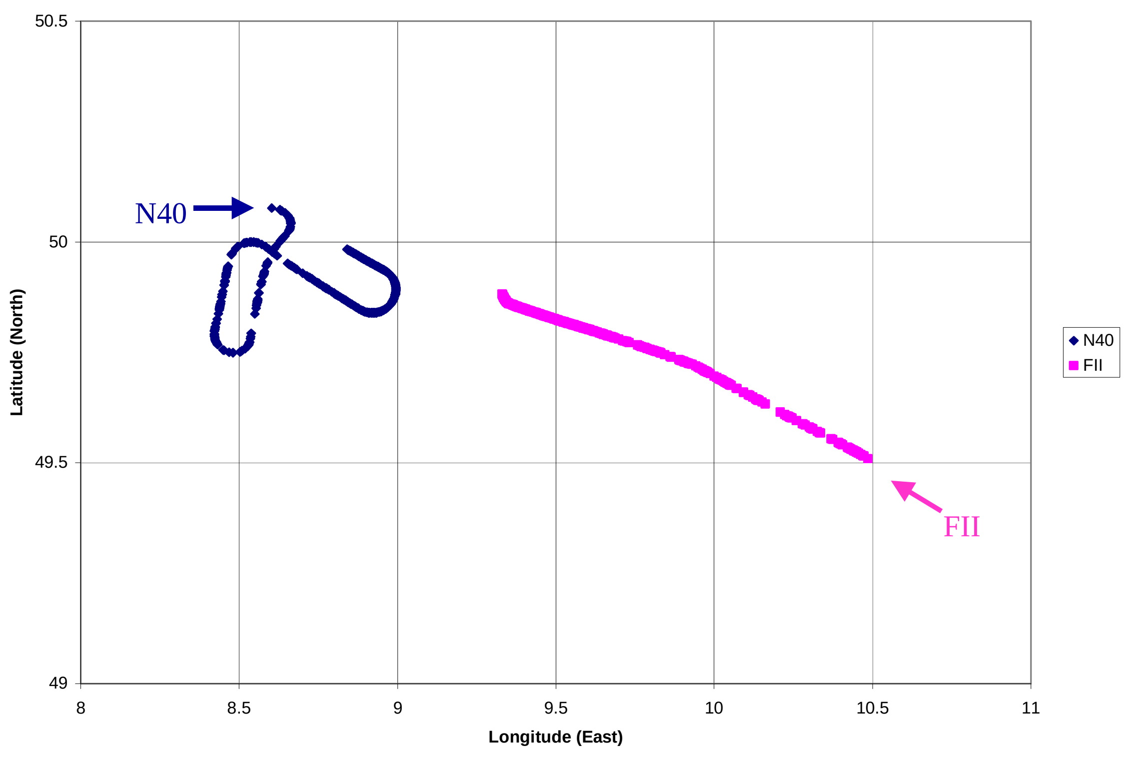


Figure 6.2.4-7a. Ground Track 12:24:13 to 12:39:16 on 24 May

As shown in Figure 6.2.4-7b, range between the FII aircraft and N40 decreased from 80 nmi to 19 nmi during this 15-minute interval.

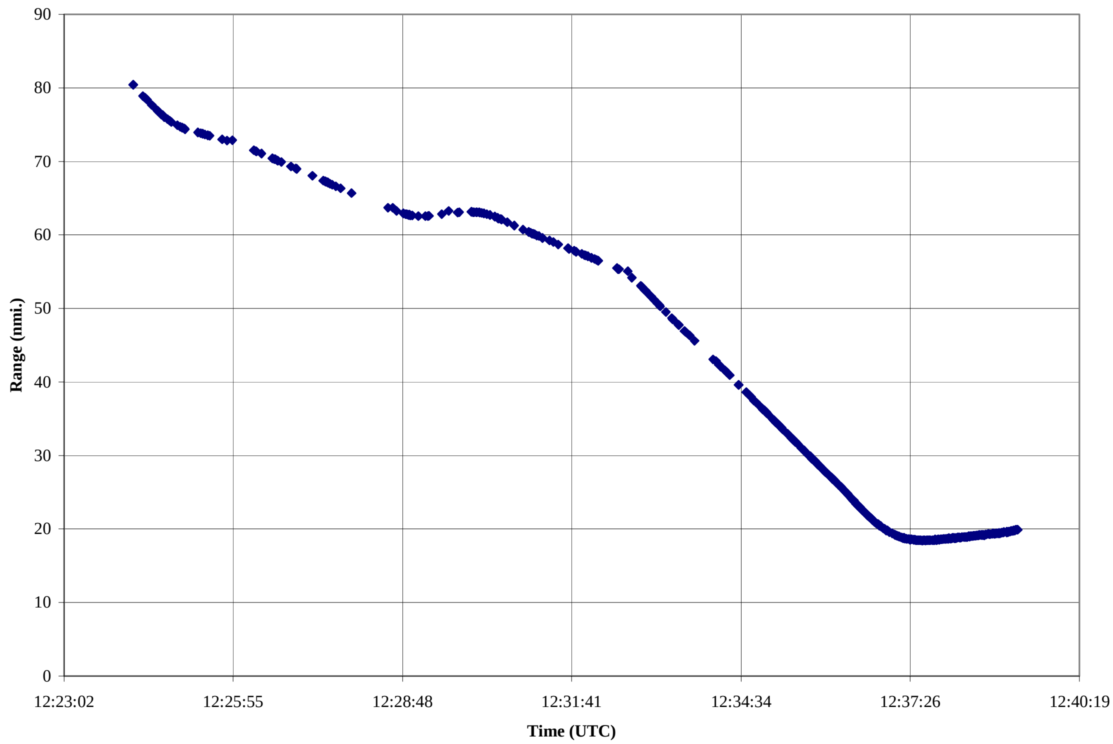


Figure 6.2.4-7b. FII-to-N40 Range vs. Time

During this 15-minute interval N40 completed a transition in the orientation of the racetrack holding pattern and as a result the relative bearing to the FII aircraft varied through the full 360 degrees. However, N40 appeared in the forward quadrant (to the left of centerline) as seen by the FII aircraft. Figure 6.2.4-7c shows the reception probability for each the FII aircraft and N40 during this 15 minute interval.

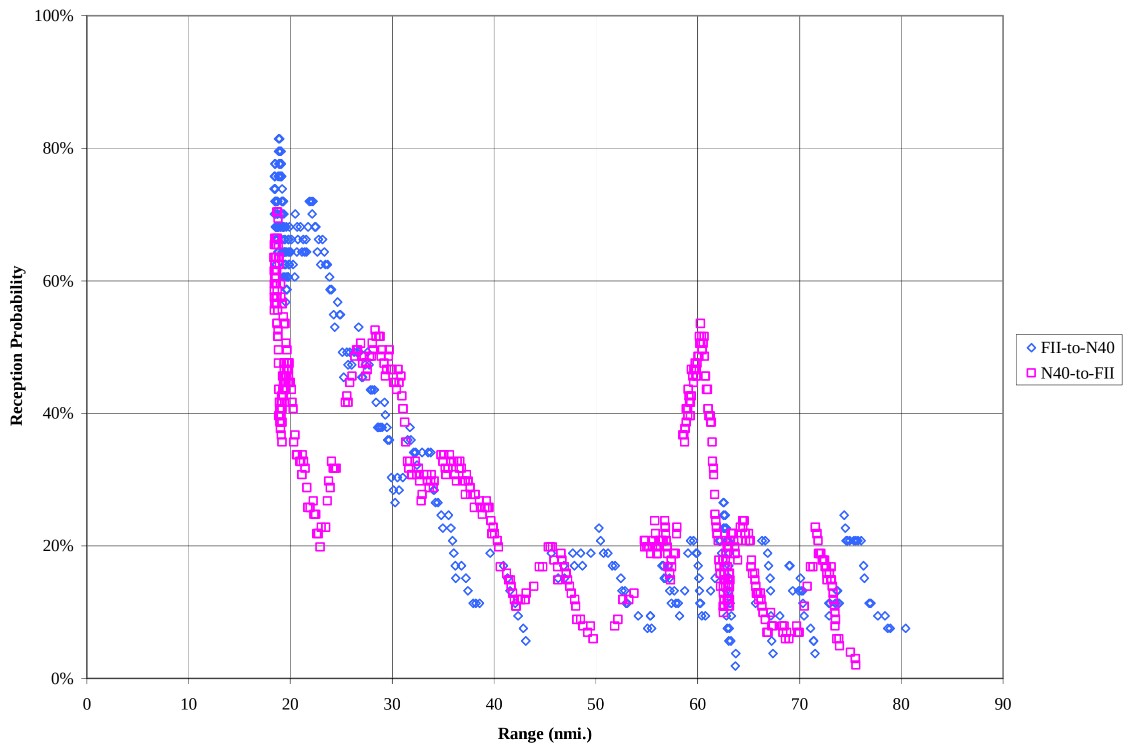


Figure 6.2.4-7c. Probability of Reception for FII and N40, 24 May

Certain of the specific areas of reduced reception performance, such as the sudden drop in reception probability onboard the FII aircraft at a range of approximately 23 nmi, can be directly attributed to N40 executing a turn. However, the overall reception probabilities at ranges of greater than 35 nmi is of concern and was the focus of the more detailed investigation. Note that the FII aircraft used a general aviation class transponder which had a transmitter output power of approximately 2.5 dB less than for N40 for the other aircraft involved in the evaluations. Therefore, at a given range it could be expected that the probability of receiving Extended Squitters from the FII aircraft would be generally lower than for the transmissions from the other aircraft.

The first step to better understand the cause(s) of the performance during the time interval in question on 24 May was to compare the 1090 MHz fruit rates measured onboard N40 for this time interval to other times during the flight evaluations. The ATCRBS fruit rates measured onboard N40 using the RMF were previously shown in Figure 4.3.1-1a and Figure 4.3.1-3. As shown in these figures and in the text of 4.3.1.1.1 the maximum ATCRBS fruit rates on 24 May were recorded during the sample at starting at 12:26:00. This period of maximum ATCRBS fruit rate occurs during the time internal of degraded Extended Squitter receptions discussed above. A maximum ATCRBS fruit rate of 29,000 per second was recorded from the bottom antenna on N40 at an MTL of -84dBm. Such a level of ATCRBS fruit may have contributed somewhat to degraded reception performance during the interval in question on 24 May. However, it does not appear to be sufficiently greater than the ATCRBS fruit rates experienced at other times intervals during the data collection, on 24 May or other days, to fully account for the reduced reception performance during the interval in question.

To further investigate the cause of the reduced reception performance for the interval in question on 24 May the received squitter power levels, as recorded by the LDPU were analyzed. Figure 6.2.4-7d plots the maximum power level for squitters received within the sample period (normally one second) vs. target range. The results from both the FII aircraft and N40 are included. A third set of data is provided as a reference (i.e., baseline) for comparison. This additional set of baseline data was recorded onboard the FII aircraft earlier on 24 May when the FII aircraft was departing the Frankfurt area and represents a typical case. A fixed 3.5 dB cable loss between the transponder and the antenna was assumed for this plot. Also recall that the FII transponder has a 2.5 dB lower transmitter power than N40.

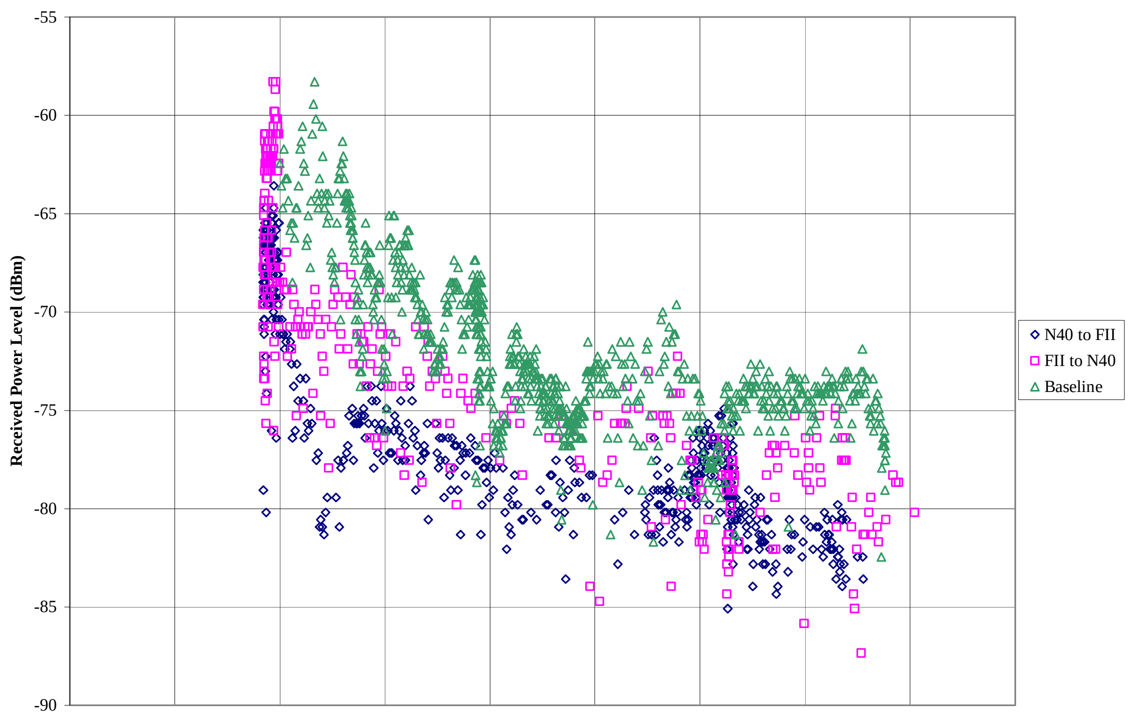


Figure 6.2.4-7d. Received Power Level vs. Range

The measurements for the power level of the received squitters appear to confirm that higher than typical (for Frankfurt) ATCRBS fruit rates was not the main factor in reduced reception performance. Rather, the lower than typical received signal levels appear to be a significant factor. Such a reduction in received signal levels could have been caused by either a problem with the avionics or an anomaly with the installed characteristics of the system. However, an avionics problem is unlikely to be responsible given that N40 and FII each used separate avionics for the transmission and for the reception of Extended Squitters (i.e., transponder and LDPU) and also since both aircraft experienced degraded reception performance during the same time interval. A possible cause for reduced received power levels could be related to the antenna pattern on one or both aircraft. As previously discussed in 2.2.1 for N40 and 2.2.2 for the FII aircraft, separate top and bottom transmit and receive antennas were used. No measurements for the installed antenna patterns were made, therefore anomalies in the antenna patterns can only be inferred from available data and by a review of the antenna mounting locations. During the course of the 15 minute interval being analyzed, N40 conducted several maneuvers including two 90 degree turns and two 180 degree turns. As a result any major azimuth dependent anomaly in either the transmission or reception antenna patterns could be expected to only appear for a small subset of the data. However, since the received signal levels appears to be generally lower than normal throughout most of the 15 minute interval, the overall reduced signal levels cannot be attributed specifically to an anomaly in the antenna patterns of N40. The relative bearing from the N40, as seen by the FII aircraft, was generally in the forward-left direction and varied only through a modest range of azimuth values during the 15-minute interval. If the FII aircraft's antenna pattern were to provide generally reduced co-altitude performance at relative bearings of approximately -10 degrees to -25 degrees this could be the primary cause of the degraded performance.

The antenna locations on the FII aircraft were previously shown in 2.2.2.5 and are repeated in Figure 6.2.4-7e. The 1090 MHz transmit antenna locations are indicated as A and B for the top and bottom antennas respectively. The 1090 MHz receive antennas are indicated as C and D for top and bottom respectively. None of the 1090 MHz antennas are located on the centerline of the airframe's fuselage, as they would be in an ideal/typical installation. Since all of the 1090 MHz antennas were located to the right of centerline this could very well have resulted in an anomaly to the overall antenna pattern in the horizontal plane toward the port side, where the degraded performance was noted during the tests. The resulting anomaly in the overall antenna pattern resulting from the off centerline antenna locations could be expected to be most severe for co-altitude targets.

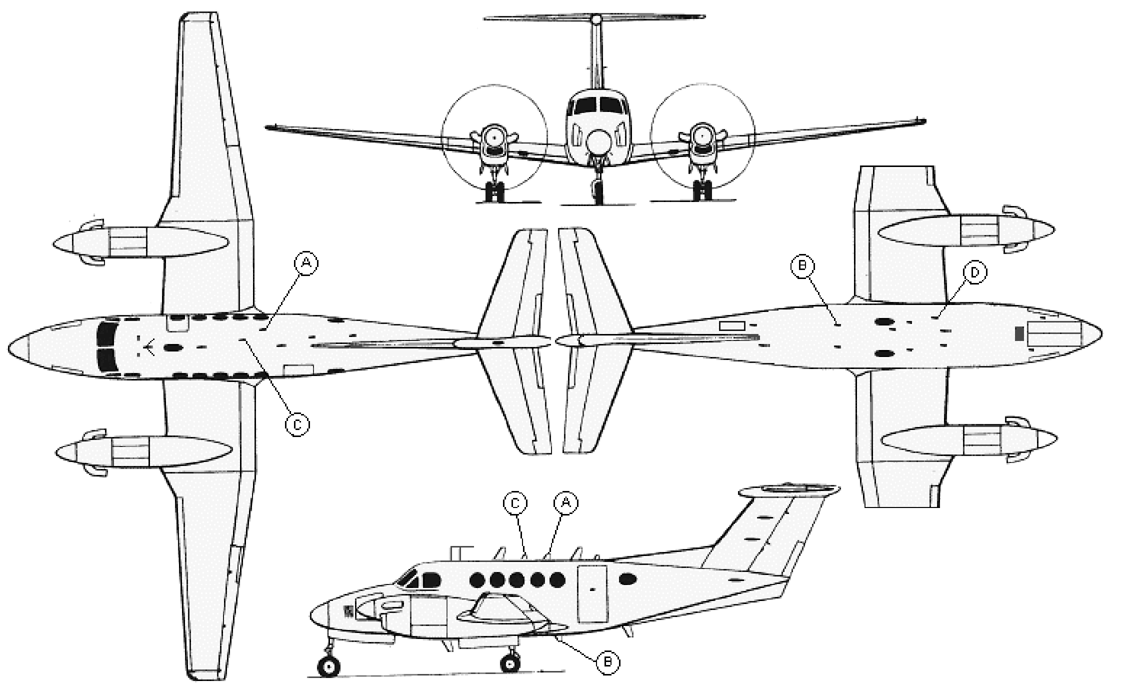


Figure 6.2.4-7e. Antenna Locations on FII Aircraft

While no definitive conclusions can be made at this time as to the what factor(s) have lead to the degraded reception performance during the final phase of the flight tests on 24 May, it appears that the antenna locations on the FII aircraft may have played a significant role. Also, increased ATCRBS 1090 MHz fruit rates may have played a minor role in the reduced reception performance.

6.2.4.2.2 Overview of Performance Results vs. Requirements

Analysis of the results indicate that for the ranges up to 40 nmi (the limit of the ADS-B MASPS Separation Assurance and Sequencing requirements) the reception performance measured on 24 May generally exceeded the minima that would theoretically be needed to meet the ADS-B MASPS requirements. A single period of degraded reception was noted during the final phase of the data collection exercise on 24 May where the probability of reception was somewhat worse than that required by the MASPS (range was 35 nmi vs. 40 nmi at 22.9% probability of reception). For the other cases analyzed, the measured performance exceeded the theoretical reception probability minima for state vector updates required by the separation assurance and flight path deconfliction planning MASPS applications. The range to which targets would have successfully been tracked was approximately 60 nmi in the worst case (associated with the same period of degraded reception performance noted above) and generally was 90 nmi or greater for the cases where the aircraft was in level flight.

Concerning the Eurocontrol proposed criteria for autonomous operations to 150 nmi range, which include the reception four TCPs, reception probability seemed generally adequate for ranges up to 80 nmi or greater except for the worst case period of the 24 May.

Additional analysis was performed on the RMF data collected during the critical time interval of 1230 to 1236 on 24 May where the degraded LDPU reception performance was noted. This analysis is described in 4.7 of this report. The "gold standard" enhanced decoding technique, as specified in the 1090 MHz ADS-B MOPS (draft 2nd version) was used and the results compared in Figure 4.7-1 to the LDPU and the TCAS decoder performance results. The results from the use of the enhanced decoding technique indicate that the reception probability would generally have been acceptable to a range of greater than 60 nmi as compared to approximately 40 nmi with the LDPU 1090 MHz receiver. This particular case clearly demonstrates the value of applying the enhanced decoding techniques to deal with unusual situations where otherwise the reception performance would be degraded below acceptable levels.

6.2.5 Analysis of the Results from 25 May

An overview of the results for 25 May is provided in 4.4.1.2.4. Only the N40 project aircraft participated in the flight tests on 25 May. A target of opportunity (BA-400663$_h$) was observed by N40 during the test flight. This is a case were the target aircraft was equipped with an air carrier class Mode S transponder providing the ADS-B transmissions. Data was collected on the FAA aircraft (N40) while outbound from Wiesbaden/Frankfurt on a flight path that went to a point just north of Stuttgart and then on toward Munich. ADS-B transmissions from BA-400663$_h$ were first received while BA-400663$_h$ was on the airport surface at Stuttgart at a range from N40 of approximately 23 nmi N40 was just passing about 13 nmi north of Stuttgart headed east at an altitude of approximately 23,000 ft as BA-400663$_h$ departed and headed west. The range between the two aircraft quickly increased as they headed generally in opposite directions

The target aircraft (BA-400663$_h$) was broadcasting position, velocity and Flight ID squitters. Therefore, it was possible to directly measure how quickly track acquisition occurred and when the Flight ID squitter was received. The time at which TCP and TCP+1 could be acquired with the required update rate has been estimated based on the measured probability of squitter reception (i.e., $\geq$22.9% probability of squitter reception as per Table 6.1-4). The target was acquired at short range where the acquisition time would be expected to be brief and this was confirmed. Starting with the first report after the aircraft became airborne (the squitter format switched from surface to airborne) both position and velocity squitters were received within the first two seconds and Flight ID and Type was received during the third second. Thus, the target track was established in two seconds. The probability of reception at this point was over 50% indicating that both TCP and TCP+1 squitters, if they had been supported, would have been received within less than 10 seconds.

Perhaps of greater interest for this particular data set is the performance as the range to the target increased while the two aircraft were flying on diverging flight paths. The probability of reception generally remained sufficient to satisfy the update rate for TCP and TCP+1 reception until the range reached just over 80 nmi. The target track would have been maintained (with no gaps in squitter reception exceeding 24 seconds) until the range exceeded 108 nmi. The target track would then have been re-established as the BA aircraft reached a range of approximately 120 nmi it would have been maintained until the target reached a range of 160 nmi where the track would have again been dropped. Intermittent reports were subsequently received from the target out to a range in excess of 200 nmi.

6.2.5.1 Reception Probability as a Function of Target Bearing

Figure 6.2.5-1 provides a plot of the reception probability of individual Extended Squitters versus range for the aft quadrant. The target aircraft did not appear in the forward quadrant as observed by N40 therefore no plot is provided for this quadrant. Also very little data was collected for the port and starboard quadrants and therefore no plots for reception probability for these quadrants is provided. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

Figure 6.2.5-1 plots the reception probability for the aft quadrant. BA-400663$_h$ was at an aft relative bearing from N40 during most of its flight at ranges beyond 24 nmi and the reception probability is plotted out to a maximum range of 160 nmi. The results provide adequate data to estimate the reception performance achieved in the aft quadrant on this flight. Extended squitter reception probability at ranges between 24 and 40 nmi varied from approximately 37% to 82% while reception probability generally deceased at ranges between 40 nmi and 80 nmi with a minimum reception probability of 16% at approximately 68 nmi but generally remaining above 20% out to 80 nmi. At ranges beyond 82 nmi the reception probability remained below 20%.

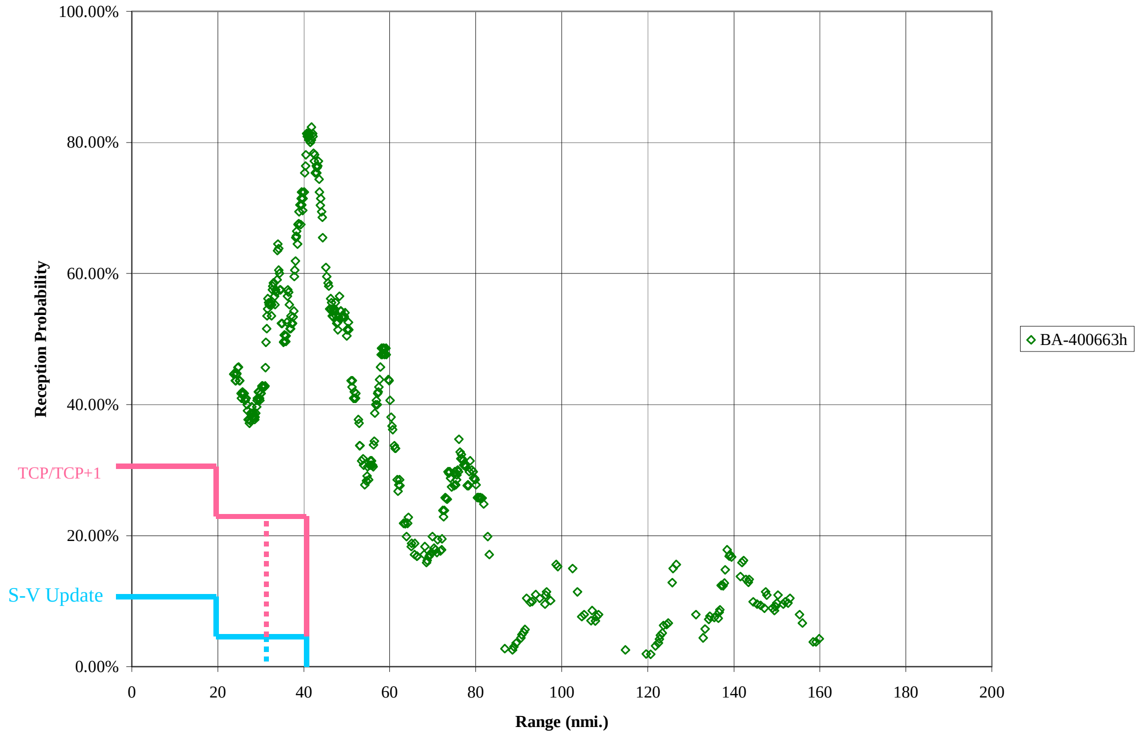


Figure 6.2.5-1. Aft Quadrant Reception Probability by N40, 25 May

6.2.5.2` Performance vs. Requirements

There was no data collected for reception from the forward quadrant by N40 on May 25 and only very little data for the port and starboard quadrants. Therefore, no analysis of reception performance from these quadrants was possible for this specific data collection flight. However, significant data was collection for the reception performance from the aft quadrant and analysis of the results for this quadrant indicate that reception performance substantially exceeded that required by the ADS-B MASPS.

6.3 COMPARISON OF THE TCAS AIR-TO-AIR RESULTS WITH SELECTED APPLICATION REQUIREMENTS

This section represents the results of the analysis of TCAS 2000 data for the air-to-air case and compares the measured performance against the requirements described in 6.1. Section 4.4.2 presented an overview of the air-to-air measurements and further analysis of the data. Specific emphasis has been given to cases where measured performance was less than expected or less than typical. This has been done in order to better understand if the cases were the performance was less than expected/typical indicate inherent limitations of the system that are consequences of specific limitations of the system or are the consequence of the specific limitations of the test environment (e.g. poor antenna locations, installation problems, etc.)

The following paragraphs include an analysis of the probability of Extended Squitter reception as a function of the relative bearing of the target aircraft, in the horizontal plane, from own aircraft. Target bearing has been sorted into four 90^o quadrants (forward, starboard, aft, port) for the purpose of this analysis. Two filters were applied to the specific reception probability data to be plotted. First all data collected when either own aircraft or the target aircraft was at an altitude of less than 1000 ft is not used for the plots. Second, if ownship is maneuvering with more than a modest turn rate (i.e., maneuvers in only horizontal plane) the data is not plotted. This latter filter was applied because the project aircraft were frequently following flight profiles that included very frequent changes in heading that would not be typical of a 'normal' flight profile.

The probability of reception for 1090 MHz Extended Squitters was analyzed using a 24-second window. A data point is produced, and included on the following plots, for each case where the TCAS logged the reception of at least one state vector squitter (i.e., position or velocity) during a 24-second window. It should be noted that for the case where the reception of state vector updates were being logged for each successive 1-second interval, even a very short term degradation in reception of squitters (such as 4 second gap in the reception) can produce many successive data points (e.g., up to 24) on the following plots showing a degraded reception probability. Such an event will appear as a sharp drop and rapid recovery in reception probability occurring within the span of a very few miles of target range. While such short duration events may produce a significant impact on the following plots, they are of little, or no operational consequence to most, or in most cases all applications that will utilize the ADS-B surveillance information.

6.3.1 Analysis of the Results from 19 May

An overview of the results for 19 May is provided in Section 4.4.2.2.1. During the shakedown flight for FAA N40, two targets of opportunity were encountered. The aircraft were British Airways aircraft with flight ids of: BA-400665$_h$ and BA-400652$_h$.

TCAS received only a few Extended squitters from BA-400652$_h$ and these results are summarized in Figure 4.4.2-12. The following results are only from BA-400665$_h$.

6.3.1.1 Reception Probability as a Function of Target Bearing

Figure 4.4.2-14 shows the track of BA-400665h with solid reports for a range to about 120 miles. Figure 6.3.1-1, plots the reception by N40 of the Extended Squitters versus range, by quadrant, for the BA aircraft. Sufficient data was only recorded from the aft, port, and starboard quadrants to b included in this plot. The target aircraft (BA-400665$_h$) was at an aft relative bearing from N40 on two separate occasions. The first occurrence for approximately 115 seconds at short range (approximately 15 nmi) and later for approximately 215 seconds at ranges from 47 to 87 nmi thus a modest amount of data was collected for reception performance in the aft quadrant on this flight. The target aircraft (BA-400665$_h$) was at a port or starboard relative bearing from N40 for much of the duration of the encounter. Data was collected at ranges from approximately 14 nmi out to 180 nmi, thus a significant amount of data was collected for reception performance in the port and starboard quadrants on this flight

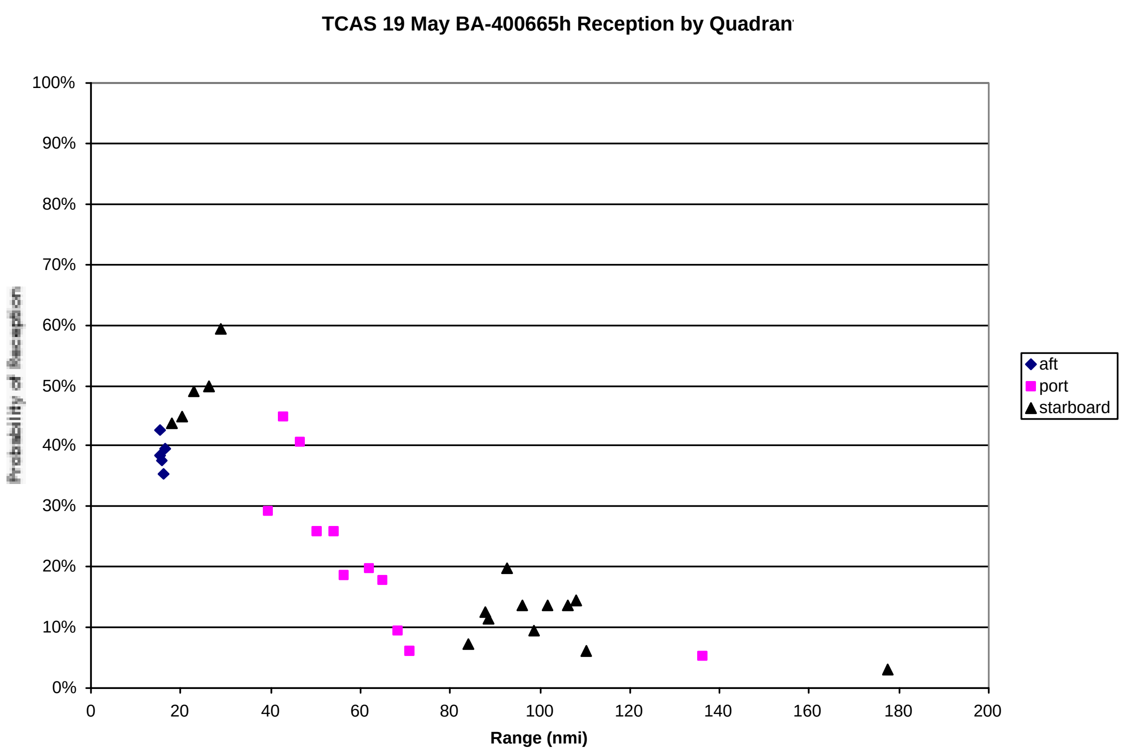


Figure 6.3.1-1. TCAS: BA-400665$_h$ Rec. Prob. vs. Range and Quadrant, 19 May

6.3.1.2 Performance vs. Requirements

There was insufficient data collected for reception from the forward quadrant to draw any firm conclusions on moderate to long range reception performance. However, the data analyzed for short-range reception performance is consistent with that required by the ADS-B MASPS. . Reception performance in the aft and in the port and starboard quadrants exceeds the reception performance required by the ADS-B MASPS.

6.3.2 Analysis of the Results from 20 May

An overview of the results for 20 May is provided in 4.4.2.2.2. All three project aircraft participated in the flight tests on 20 May. However, due to a GPS interface problem the FII aircraft was transmitting 'all zeros' for its latitude and longitude. Valid Extended Squitters from two target aircraft were recorded. These were the broadcasts from the NLR aircraft and broadcasts from a target of opportunity (i.e., BA-40066h_h). Note that the Extended Squitter broadcasts from the FII aircraft were also received but without that aircraft's latitude and longitude information. Analysis of the data previously shown in Figure 4.4.2-17 shows the probability of reception for both of these aircraft.

6.3.2.1 Reception Probability as a Function of Target Bearing

The following two figures plot the reception probability of individual Extended Squitters versus range. The figures cover the forward ,aft, port and starboard quadrants combined into a single figure. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

Figure 6.3.2-1 plots the reception probability for BA-400664$_h$ by quadrant. Figure 6.3.2-2 plots the reception probability for the NLR aircraft by quadrant. The two target aircraft (NLR and BA-400664$_h$) were each only at a forward relative bearing from N40 during several relatively brief intervals. The forward quadrant reception for the Extended Squitters from BA-400664$_h$ was generally superior to the reception of the broadcasts from the NLR aircraft for ranges of 40 -60 nmi

The NLR aircraft was at an aft relative bearing from N40 for a significant portion of the encounter with Extended Squitters received at ranges from approximately 15 to 98 nmi The BA-400664$_h$ aircraft was at an aft relative bearing at three separate instances at ranges of approximately 60, 90, and 160 nmi The aft quadrant reception probabilities for the NLR aircraft are generally consistent with the reception probabilities for the BA-400664$_h$.

The target aircraft (NLR and BA-400664$_h$) were each at a port or starboard relative bearing from N40 at separate discrete times. Data was collected at ranges from approximately 10 nmi out to 145 nmi, thus a moderate amount of data was collected for reception performance in the port and starboard quadrants on this flight. At target ranges of less than 80 nmi the probability of reception ranged from a low of 19% (at longer ranges) to a high of 91% at short ranges. At ranges between 80 and 105 nmi the reception probability for the broadcasts from the BA-400664$_h$ was 20% to 39%.

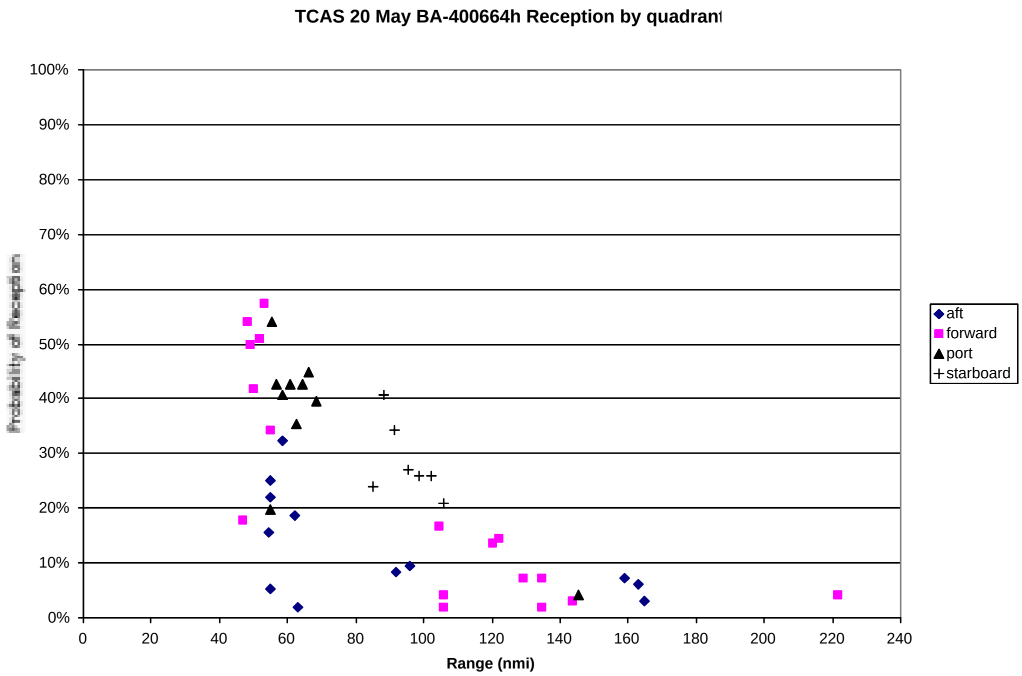


Figure 6.3.2-1. TCAS: BA-400664$_h$ Rec. Prob. vs. Range and Quadrant, 20 May

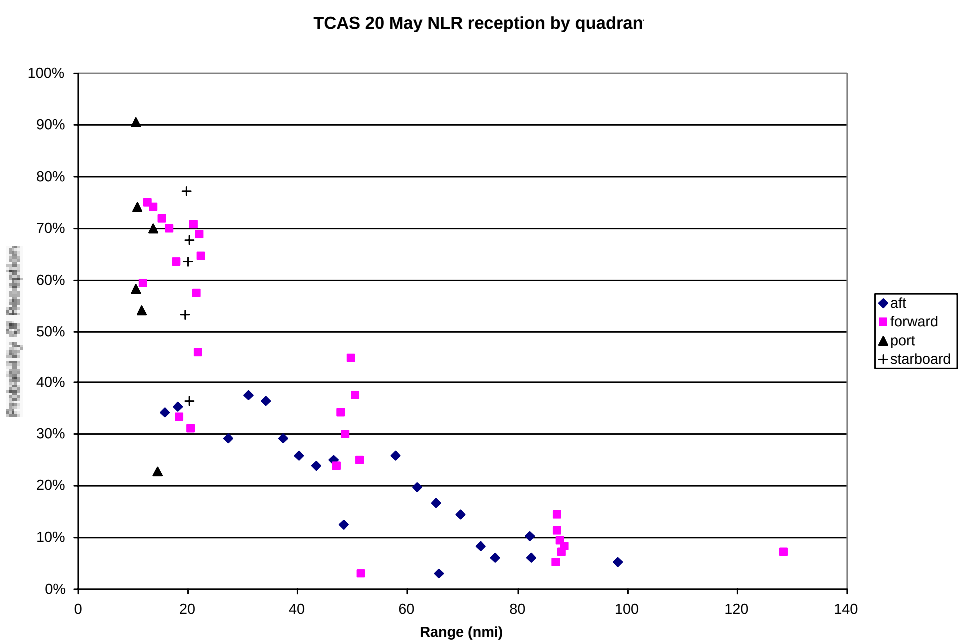


Figure 6.3.2-2. TCAS: NLR Rec. Prob. vs. Range and Quadrant, 20 May

6.3.2.2 Performance vs. Requirements

There was a modest amount of data collected for reception from the forward quadrant. Analysis of the results indicates that for the ranges up to 40 nmi (i.e., the limit of the MASPS requirements) the reception performance exceeded that required by the ADS-B MASPS. Generally the reception of the Extended Squitters broadcast from BA-400664_h was received with higher probability than were the broadcasts from the NLR aircraft at similar ranges. Reception performance in the aft and in the port and starboard quadrants substantially exceeded the reception performance required by the ADS-B MASPS.

6.3.3 Analysis of the Results from 22 May

An overview of the results for 22 May is provided in Section 4.4.2.2.3. FAA N40 and the FII project aircraft participated in the tests. The FII aircraft was in a holding pattern as FAA N40 flew a circuit as indicated in 4.4.1.2.3.1. A target of opportunity (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.

An analysis of the data from FAA N40 that was previously summarized in Figure 4.4.2-28 indicates that N40 would have acquired the track (i.e., reception of both position and velocity information) on BA-400664_h at range of approximately 125 nmi (i.e., with no subsequent update period exceeding 24 seconds as BA-400665_h approached N40.

6.3.3.1 Reception Probability as a Function of Target Bearing

The following figures plot the reception probability of individual Extended Squitters versus range for FAA N40. The figures cover the forward ,aft ,port and starboard quadrants combined into a single figure. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

There were two target aircraft FII and BA-400664_h. Figures 6.3.3-1 and 6.3.3-2, plot the reception probability for all quadrants from data collected by the TCAS on the FAA N40 aircraft. BA-400664_h was at a forward relative bearing from N40 during several separate intervals. Substantial forward quadrant data at ranges in excess of 100 nmi was collected from the FII aircraft. It should be noted that the FII aircraft was using a general aviation class transponder with a nominal transmitter power output level on the order of 2.5 dB less than for a typical air carrier transponder, such as used on BA-400664_h. There was not sufficient forward quadrant data collected from BA-400664_h to verify if the higher transmitter power level resulted in higher probability of squitter reception by N40. For squitters received from the FII aircraft at target ranges out to 20 nmi the probability of squitter reception generally averaged above 60%. and at ranges between 20 nmi and 70 nmi the reception probability was generally above 40% with the lowest value being 28%. Beyond 70 nmi the reception probability dropped to 23% at 75 nmi then generally varying between 5% and 25% out to a range of 100 nmi The limited data from BA-400664$_h$ shows reception probability varying between 34% and 56% at target ranges of 22 to 30 nmi. Longer range data shows the probability of reception dropping below 15% at ranges beyond 83 nmi.

The BA-400664$_h$ was at an aft relative bearing from N40 only at ranges beyond 80 nmi and only for a limited time. The FII aircraft was at an aft relative bearing from N40 at several separate intervals where a modest amount of data was collected. The combination of the N40 and The BA-400664$_h$ results provide data to estimate the reception performance achieved in the aft quadrant on this flight. Extended squitter reception probability at ranges within 40 nmi varied from approximately 25% to 70% while reception probability at ranges between 40 nmi and 75 nmi were generally above 20% with only a very few data points dropping down to as low as 15%.

The target aircraft (FII and BA-400664$_h$) were each at a port or starboard relative bearing from N40 at a number of discrete times. There was an insufficient amount of TCAS data for the starboard quadrant for the FII aircraft. Combined the data provides a nearly continuous plot of reception probably out to ranges beyond 100 nmi. At target ranges of less than 20 nmi the probability of reception was generally above 40% with only a few lower data points dropping down to a minimum of 25%.

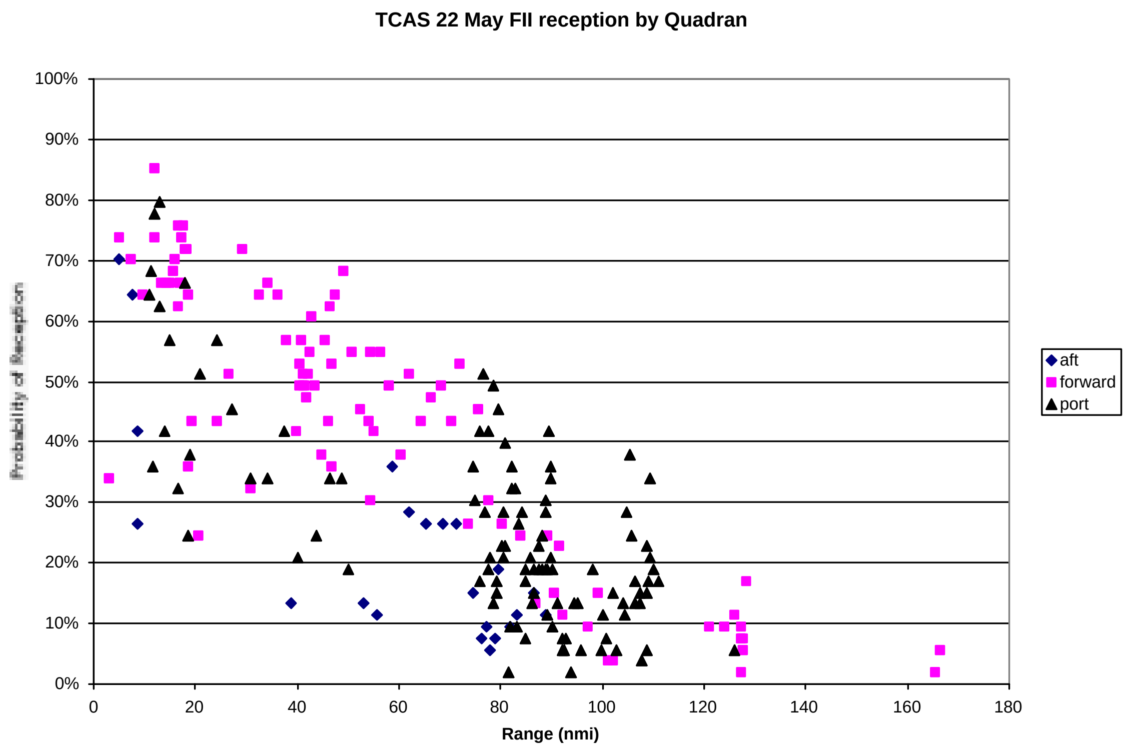


Figure 6.3.3-1. TCAS: FII Rec. Prob. vs. Range and Quadrant, 22 May

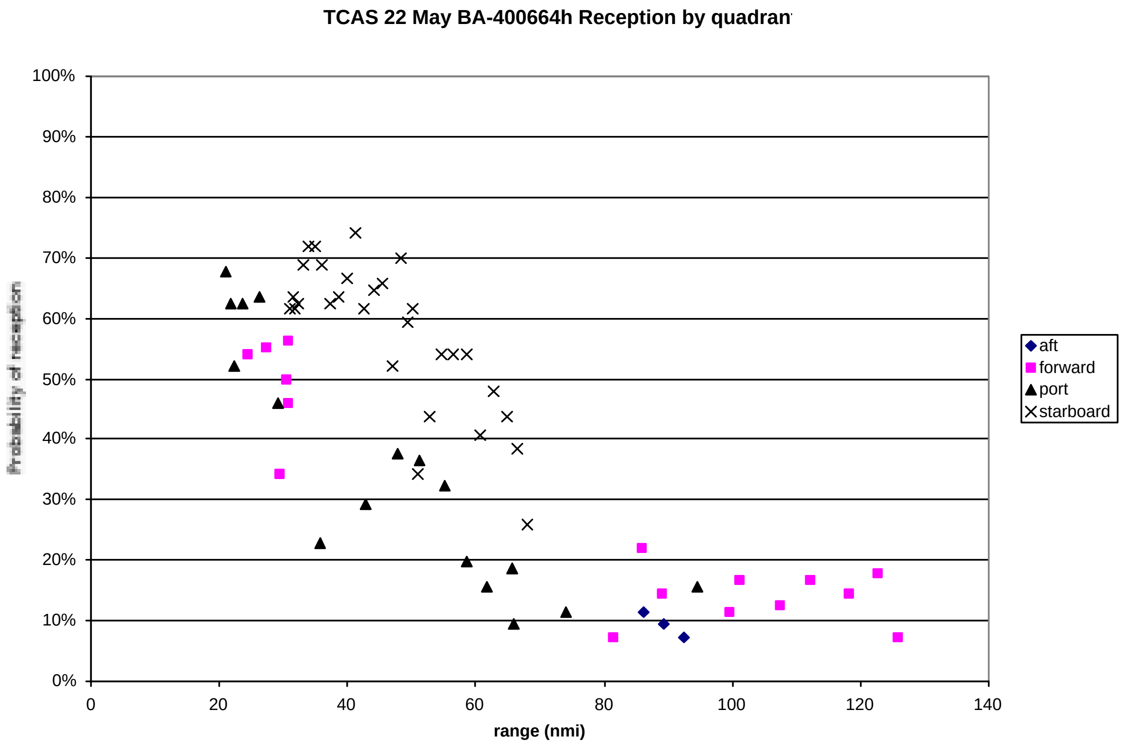


Figure 6.3.3-2. TCAS: BA-400664$_h$ Rec. Prob. vs. Range and Quadrant, 22 May

6.3.3.2 Performance vs. Requirements

There was a modest amount of data collected for reception from the forward quadrant by the FII aircraft and substantially more data collected by FAA N40. Analysis of the results indicates that for the ranges up to 40 nmi (i.e., the limit of the MASPS requirements) the reception performance substantially exceeded that required by the ADS-B MASPS. At longer ranges the reception probability for TCP and TCP+1 squitters would exceed the desired 22.9% values out to target ranges of at least 75 nmi for both the FAA N40 and for the FII aircraft. The data indicates that tracking of the target aircraft, with state vector updates within the 12 seconds required by the MASPS (at 95% probability), should be possible at ranges of 100 nmi or greater. Reception performance in the aft and in the port and starboard quadrants substantially exceeded the reception performance required by the ADS-B MASPS.

6.3.4 Analysis of the Results from 24 May

An overview of the results for 24 May is provided in 4.4.2.1. FAA N40, NLR, and the FII project aircraft participated in the tests on this day. The N40 was in a holding pattern as the FII and NLR aircraft flew a circuit as previously shown in Figure 4.4.1-1a A target of opportunity (BA-400652$_{h)}$ was observed on a route from Northwest to

Southeast the overflew the Frankfurt area at the time the project aircraft were departing from Wiesbaden for the data collection flights. An summary of the data collected onboard the project aircraft was previously summarized in section 4.4.2.1. and the figures contained therein. The following paragraphs present a further analysis of the results obtained from the evaluations on 24 May.

6.3.4.1 Reception Probability as a Function of Target Bearing

The following figures plot the reception probability of individual Extended Squitters versus range received by FAA N40. The figures cover the forward , aft , port and starboard quadrants combined into a single figure. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

Figures 6.3.4-1, (NLR), 6.3.4-2 (FII) and 6.3.4-3 (BA-400652$_h$) plot the reception probability for the all four quadrants from data collected by the TCAS on FAA N40. Three target aircraft (FII, NLR, and BA-400652$_h$) were observed at a forward relative bearing from the N40 during the course of the flight tests on 24 May. The forward quadrant data for each of these aircraft was generally limited to a few brief time intervals. The reception probability for Extended Squitters from the FII and NLR aircraft each included a case where the reception probability was lower than what was typically observed for the given target range. For the case of reception of Extended Squitters from the NLR and the FII aircraft there were specific situations where the desired 22.9% reception probability was only achieved when the target with within approximately 35 nmi. An examination of the NLR case showed that this data was collected while both N40 and the NLR aircraft were descending on their way to land at Wiesbaden at the end of the data collection exercise.

Only very little aft quadrant data was received from BA-400652h at a range of approximately 140 nmi. There was thus insufficient data to allow for further analysis of the aft quadrant reception performance from this target. Substantial aft quadrant data was received from the NLR aircraft. The reception performance for broadcasts from the NLR aircraft indicate that the desired 22.9% or greater reception probability would generally have been maintained until the target range reached approximately 50 nmi. More limited aft quadrant data was received from the FII aircraft mostly between the ranges of 14 nmi and 32 nmi where the reception probabilities varied between 40% and 80%.

Significant data from the FII and NLR project aircraft and from the BA-400652$_h$ target of opportunity was recorded by N40 in the port and starboard quadrants. Considering all three target aircraft, the desired 22.9% probability of reception was exceed for all targets within 56 nmi and in most cases was exceed to ranges in excess of 75 nmi.

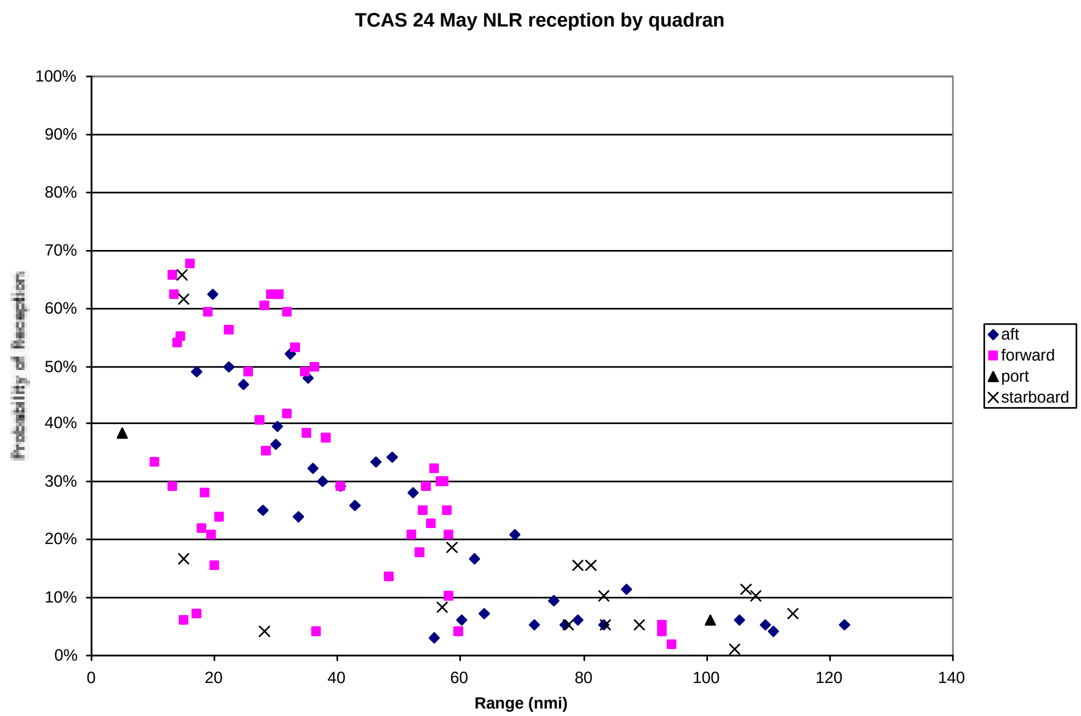


Figure 6.3.4-1. TCAS: NLR Rec. Prob. vs. Range and Quadrant, 24 May

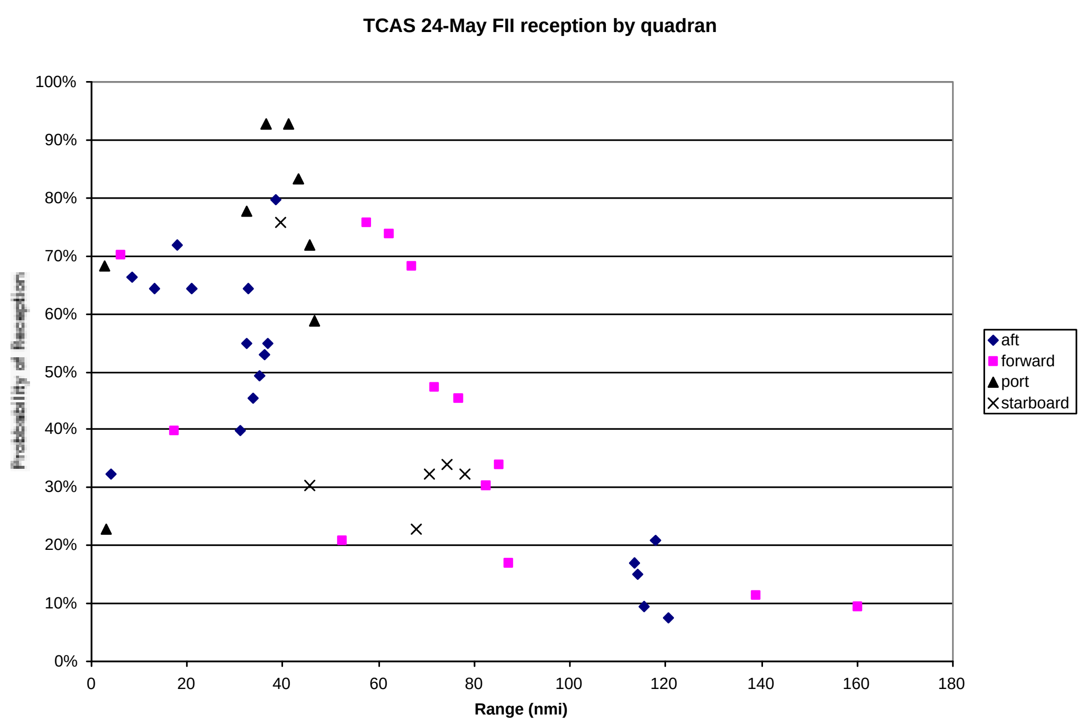


Figure 6.3.4-2. TCAS: FII Rec. Prob. vs. Range and Quadrant, 24 May

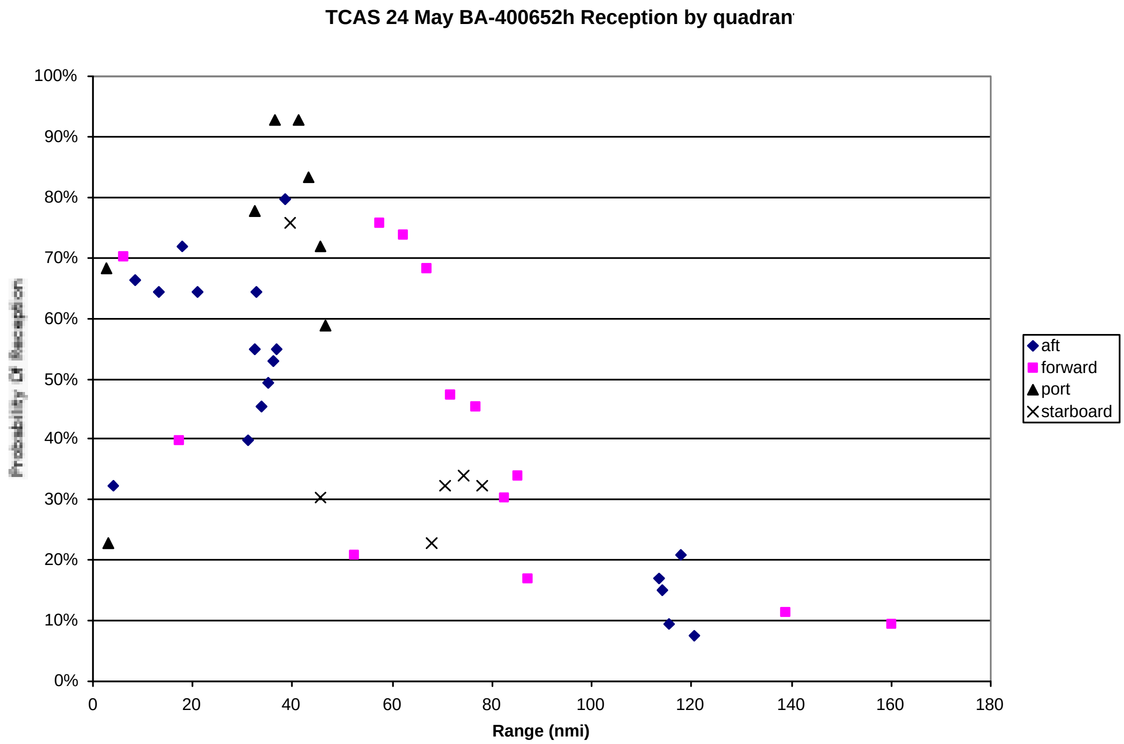


Figure 6.3.4-3. TCAS: BA-400652$_h$ Rec. Prob. vs. Range and Quadrant, 24 May

6.3.4.2 Performance vs. Requirements

In a comparison of all the days Extended Squitter reception, the 24 May exhibited anomalies in performance. A full discussion and the investigation are contained in Section 6.2.4.2.1, Investigation of Factors for Periods of Degraded Performance.

Analysis of the results indicates that for the ranges up to 40 nmi (i.e., the limit of the ADS-B MASPS requirements) the reception performance measured on 24 May generally exceeded that required by the ADS-B MASPS. A single period of degraded reception was noted during the final phase of the data collection exercise on 24 May were the probability of reception was somewhat worst than that required by the MASPS (range was 35 nmi vs. 40 nmi at 22.9% probability of reception). For the other cases analyzed, the measured performance exceeded the MASPS requirements. The range to which targets would have successfully been tracked was approximately 60 nmi in the worst case (associated with the same period of degraded reception performance noted above) and generally was 90 nmi or greater for the cases where the aircraft was in level flight.

6.3.5 Analysis of the Results from 25 May

An overview of the results for 25 May is provided in 4.4.2.2.4. Only the N40 project aircraft participated in the flight tests on 25 May. A target of opportunity (BA-400663h) was observed by N40 during the test flight. This is a case were the target aircraft was equipped with an air carrier class Mode S transponder providing the ADS-B transmissions. Data was collected on the FAA aircraft (N40) while outbound from Wiesbaden/Frankfurt on a flight path that went to a point just north of Stuttgart and then on toward Munich. ADS-B transmissions from BA-400663h were first received while BA-400663h was on the airport surface at Stuttgart at a range from N40 of approximately 23 nmi N40 was just passing about 13 nmi north of Stuttgart headed east at an altitude of approximately 23,000 ft as BA-400663h departed and headed west. The range between the two aircraft quickly increased as they headed generally in opposite directions

The target aircraft (BA-400663h) was broadcasting position, velocity, and Flight ID squitters. Therefore it was possible to directly measure how quickly track acquisition occurred and when the Flight ID squitter was received. The time at which Mode State and TCP+1 could be acquired with the required update rate has been estimated based on the measured probability of squitter reception (i.e., >22.9% probability of squitter reception as per Table 6.1-4). The target was acquired at short range where the acquisition time would be expected to be brief and this was confirmed. Starting with the first report after the aircraft became airborne (i.e., the type of squitters switched from surface to airborne) both position and velocity squitters were received within the first two seconds and Flight ID and Type was received during the third second. Thus, the target track was established in two seconds. The probability of reception at this point was over 50% indicating that both mode status and TCP+1 squitters would have been expected to be received within less than 10 seconds.

Perhaps of greater interest for this particular data set is the performance as the range to the target increased while the two aircraft were flying on diverging flight paths. The probability of reception generally remained sufficient to satisfy the update rate for mode status and TCP+1 reception until the range reached just over 80 nmi. The target track would have been maintained (i.e., with no gaps in squitter reception exceeding 24 seconds) until the range exceeded 108 nmi. The target track would then have been re-established as the BA aircraft reached a range of approximately 120 nmi it would have been maintained until the target reached a range of 160 nmi where the track would have again been dropped. Intermittent reports were subsequently received from the target out to a range in excess of 200 nmi.

6.3.5.1 Reception Probability as a Function of Target Bearing

Figure 6.3.5-1, provides a plot of the reception probability of individual Extended Squitters versus range for all quadrants for BA-400663$_h$. The majority of the data was received in the aft quadrant. The target aircraft did not appear in the forward quadrant as observed by N40. Therefore no plot is provided for this quadrant. Also very little data was collected for the port and starboard quadrants and therefore no plots for reception probability for these quadrants is provided. The Extended Squitter reception probability necessary to satisfy the RTCA ADS-B MASPS requirements for the Separation

Assurance & Sequencing application and the Flight Path Deconfliction Planning application are indicated on the figures. For more information on the associated ADS-B MASPS requirements see 6.1 and specifically Table 6.1-4.

Figure 6.2.10-1 plots the reception probability for the aft quadrant. BA-400663$_h$ was at an aft relative bearing from N40 during most of its flight at ranges beyond 24 nmi and the reception probability is plotted out to a maximum range of 156 nmi. The results provide adequate data to estimate the reception performance achieved in the aft quadrant on this flight. Extended squitter reception probability at ranges between 24 and 40 nmi varied from approximately 34% to 72% while reception probability generally deceased at ranges between 40 nmi and 80 nmi and varying between 15% and 30% in at target ranges between 60 and 80 nmi. At ranges beyond 82 nmi the reception probability remained at or below 10%.

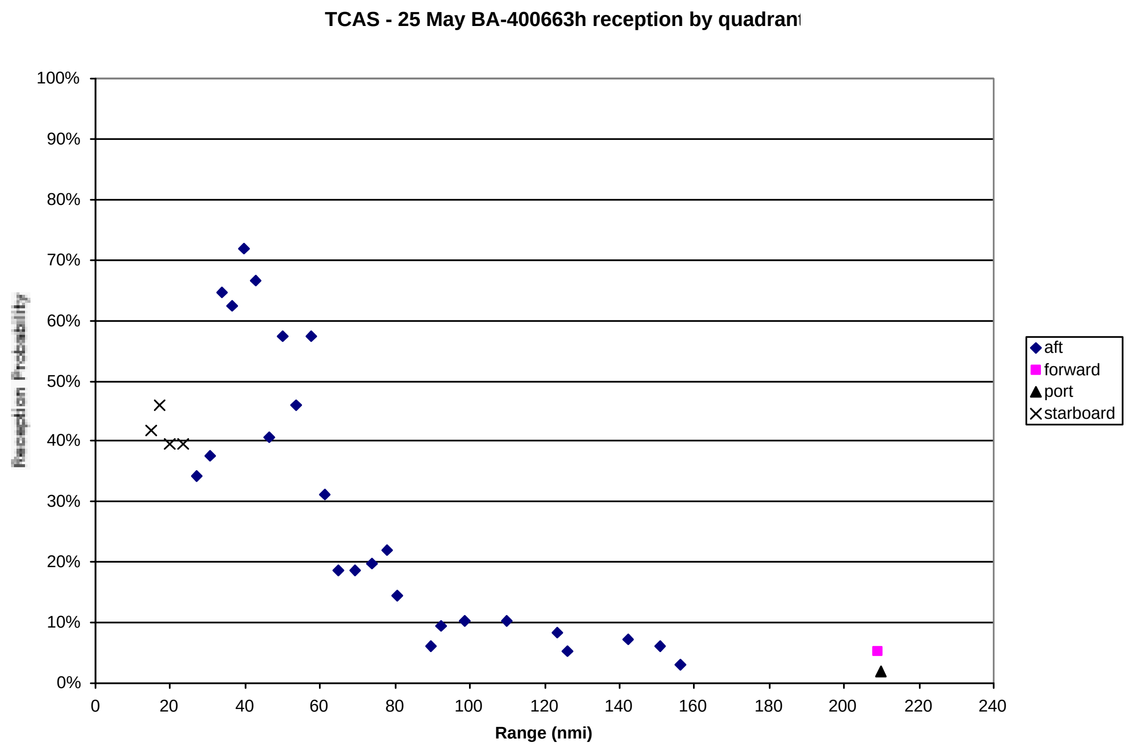


Figure 6.3.5-1. TCAS: BA-400663$_h$ Rec. Prob. vs. Range and Quadrant, 25 May

6.3.5.2 Performance vs. Requirements

There was no data collected for reception from the forward quadrant by N40 and only very little data for the port and starboard quadrants. Therefore no measurements of reception performance from these quadrants were possible for this specific data collection flight. However, significant data was collection for the reception performance from the aft quadrant and analysis of the results for this quadrant indicates that reception performance substantially exceeded that required by the ADS-B MASPS.

6.4 COMPARISON OF THE AIR-TO-GROUND RESULTS WITH SELECTED APPLICATION REQUIREMENTS

6.4.1 ANS-MAGS Ground Station Measurements

The following material makes a comparison between the results of the air-to-ground performance measured by the ANS-MAGS station and, as far as available, performance requirements imposed by ATS-Applications potentially utilizing ADS-B. As described in 6.1.4, performance requirements related to dedicated air-to-ground ADS-B applications are still in the definition phase. However, taking the values for the individual squitter reception probability calculated in Table 6.1-5 with respect to en route- and terminal ATC surveillance, the coverage of the sensor system used during the trials can be estimated. But it must be stated that the system was optimized for neither of the applications it is evaluated against. Furthermore, the ground station location was not optimal, so that the results that are presented here can be considered as the minimum available performance values of a Mode-S ADS-B ground station.

6.4.1.1 Air-To-Ground Measurements on 22 May 2000, N40 Aircraft

The data was collected at Langen on the 22 May 2000. This case shows a typical TMA situation and partly En-Route conditions.

N40 entered the north antenna sector of the Langen ground station coming back from the southeast flight approaching Wiesbaden. The complete flight profile is described in detail in 3.4. More information can be found in 4.5.3.1.2. The data presented in Figure 6.4.1.1-1 shows that N40 was flying mainly within the vertical antenna beam. The reception probability is increased while the range and altitude decreased. The aircraft remained in the coverage until 2500 ft altitude. Then it left the main beam to the west on the approach to Wiesbaden. The effect is a drop in the reception probability at about 10 nmi. This is caused by the loss of the vertical coverage below 2500 ft.

Taking into account the currently required minimum reception probability (position squitter only) of 15% for en-route and 32.3% for terminal applications, the measured values are higher and thus meet the minimum requirements. There is still a high potential for performance improvements by using more than one squitter type and enhanced hardware and software. After a technical optimization and an appropriate siting even the PRM requirement (85.8%) should be achievable with the ANS-MAGS ground station.

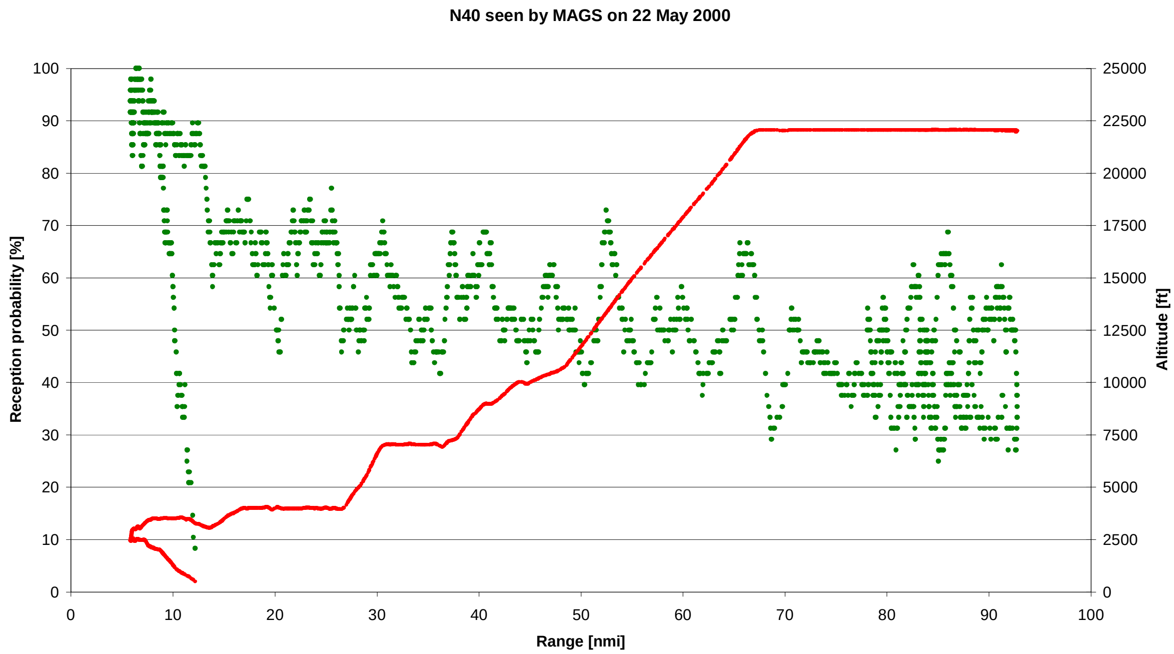


Figure 6.4.1.1-1. N40 Reception Probability and Altitude vs. Range

6.4.1.2 Air-To-Ground Measurement on 24 May 2000, NLR Aircraft

In this case the target aircraft flew on a northbound leg started at Wiesbaden (see 3.5). The duration of the flight was approximately 3 hours, the average flight level was 22000 ft. Due to a significant deviation between the measured results of the inbound and outbound flight, the performance figures have to be derived separately for either of the them.

6.4.1.2.1 Outbound

The aircraft entered the coverage of the main antenna beam at a range of 28 nmi still climbing, reached the cruising altitude of 22000 ft at a distance of 62 nmi. The probability of a single squitter reception exceeded the threshold of 36.9%, given by the ICAO and RTCA requirements for terminal and ATC surveillance application in Table 6.1-5, up to a distance of 73 nmi. The reception probability falls below 17.4% for the first time at the distance of 117 nmi. These values lead to the assumption that terminal surveillance could be served well by even a single sensor system, whereas en-route surveillance would demand a ground configuration utilizing more than one ground station for 150 nmi or even 200 nmi coverage.

6.4.1.2.2 Inbound

The values measured during the inbound flight were significantly lower than those measured outbound. Figure 4.5.2.1-9 shows that in the range from 80 nmi to 110 nmi the reception probability inbound was on average 20% lower than outbound. Possible reasons maybe the antenna installation on the fuselage of the aircraft as well as an increase of the RF interference level. Furthermore, an emergency occurred on board the aircraft that resulted in a shutdown of the transponder and consequently caused a gap of about 4 minutes in the squitter reception during the approach to Wiesbaden. The minimum reception probability for terminal surveillance given in Table 6.1-5 is violated at a range of 35 nmi, the value for en route surveillance at a range of 55 nmi. This special behavior needs further investigation. The RMF fruit measurement results could provide an explanation on the reduced Extended Squitter performance during the inbound flight.

6.4.1.3 Air-To-Ground Measurement on 24 May 2000, BA-400664$_h$ Aircraft

The following material presents a scenario that could be typical for an en-route application. The target aircraft was flying at a range of about 145 nmi at 39000 ft.

The first position squitter from the target of opportunity was received at a range of 155 nmi when the aircraft was climbing from 34000 ft to 39000 ft. During this phase, when the altitude was increasing, the reception probability was rather low, an average of 18%, and the update period exceeded the required value of 12 seconds for en-route applications several times. Short of reaching the cruising altitude of 39000 ft the average reception probability became 34%. This value was maintained until the aircraft left the main beam of the north antenna. During this phase of the flight the update interval for the reception of position squitters never exceeded 12 seconds, as illustrated in Figure 6.4.1.3-1. Figure 6.4.1.3-1 shows a variation from 10% up to 50% although the range was nearly constant and the aircraft was not maneuvering. The most probable reason for this behavior is that the system was working at its performance limit. However the required update period of 12 seconds for En-Route applications is met by the ANS-MAGS station within a range of approximately 143 nmi for a single sensor system.

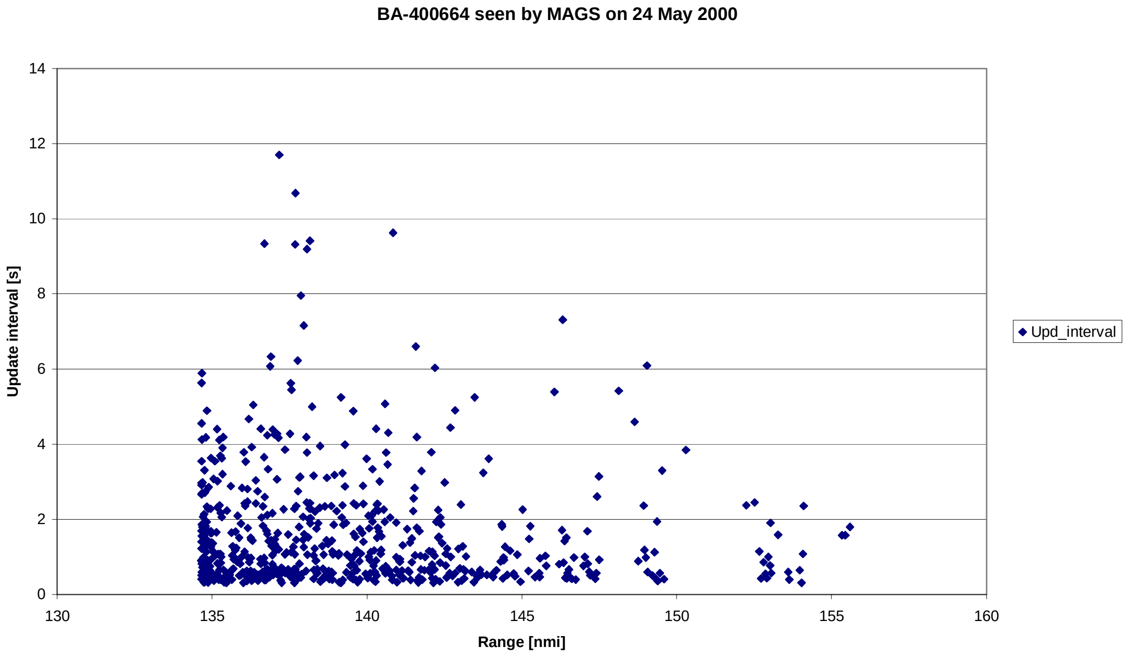


Figure 6.4.1.3-1. BA-400664$_h$ Update Interval vs. Range at 39000 ft

6.4.1.4 Air-To-Ground Measurement on 22 May 2000, BA-400664$_h$ Aircraft

The data was collected at Langen on the 22 May 2000. This case shows a target of opportunity - BA-400664$_h$ - on an en-route flight.

The aircraft entered the north antenna sector of the ANS-MAGS ground station from the west heading southeast at 37000 ft. The flight profile can be found in 4.5.3.1.2. In contrast to the N40 Wiesbaden approach on 22 May 2000 the BA-400664$_h$ stayed in level flight, was almost overflying the ground station and left the antenna main beam. Since the antenna does not have a strongly developed vertical pattern the reception of position squitter decreased as the aircraft approached the station. This effect starts at 40 nmi and its maximum is reached at 7.5 nmi when the BA-400664$_h$ left the main antenna beam. At this range the reception probability was 20% and thus sufficient for en-route surveillance (15% required). The required minimum reception probability for TMA surveillance (32.3%) is reached at a range of 11 nmi with 33.3% and continues above this level until a range of 97 nmi where the aircraft entered the north antenna sector. During the flight the squitter update interval exceeded the 5 seconds mark only one time (5.4 seconds).

The measured update intervals and corresponding reception probabilities are good for en-route applications until a range of approximately 100 nmi with that particular single ground station. An improvement to the antenna system and /or a multi-sensor environment should completely fulfill the currently specified requirements.

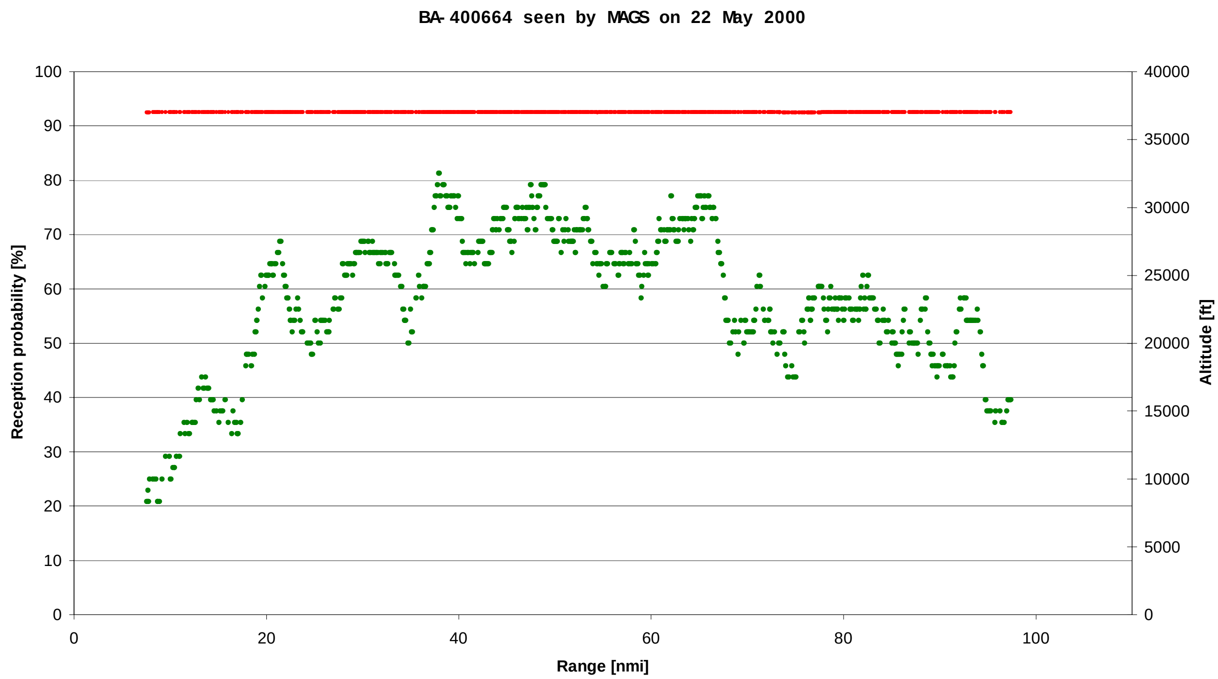


Figure 6.4.1.4-1. BA-400664$_h$ Reception Probability and Altitude vs. Range

6.4.1.3 Conclusions Related to the ANS-MAGS Station

The cases described in 6.4.1.1 to 6.4.1.4 cover three different surveillance applications, namely PRM, TMA and en-route.

PRM: the required reception probability of 85.8% has almost been met by the ANS-MAGS station as long as the target aircraft remained in the main beam of the antenna. Taking into account that the installation was far from optimal in terms of siting, it is expected that the performance of the ground station could be enhanced to serve this application.

TMA: based on a TMA range of 60 nmi the performance of the ANS-MAGS ground station was always better than required. With respect to a possible future extension of the required TMA range up to 100 nmi, the ANS-MAGS station nearly meets the required 60 nmi performance at 100nmi. With an improved system or a multi sensor environment such requirement could be met.

En-Route: the ANS-MAGS station used during the trials was not capable of supporting the single sensor requirement 150 nmi / 10 seconds for en-route applications. Taking into consideration the optimization potential with regard to the antenna, signal processing and siting aspects even the single sensor requirements probably could be met. The 200 nmi requirement could be satisfied by employing the ANS-MAGS station in a multi sensor configuration

6.4.2 Langen LDPU Ground Station Measurements

The following material compares the air-to-ground performance results derived from the log of the LDPU installed at Langen [see analysis presented in 4.5.3], with ATS application performance requirements which have been described in 6.1. The ATS applications under consideration are ATC surveillance in TMA and en-route airspaces. It should be remembered that performance requirements for air-ground ADS-B applications are still in the definition phase (see 6.1.4).

As it was explained in 4.4 and 4.5, the LDPU log allows estimation of two performance measures, namely state vector update intervals and the individual Extended Squitter reception probability. State vector updates can be approximated by the LDPU log record updates (which require reception of at least one velocity or position squitter within a 10-second period). Extended Squitter reception probability can be estimated by using the extended-squitter count in the LDPU log and the GPS UTC reception timestamps of the LDPU log records.

Table 6.2 defines the performance requirements for ATC surveillance en-route and TMA. Table 6-5 defines the minimum Extended Squitter reception probability values that would theoretically be needed to ensure that update intervals meet the air-to-ground performance requirements of Table 6.2. The trial aircraft did not transmit all the types of Extended Squitters that would be needed in an operational ADS-B system, but the calculated reception probabilities can be used to estimate the coverage of the Langen LDPU and sensor system under that level of reception reliability. It should be noted that the system was not optimized for either of the applications it is checked against and in particular the ground station location suffered from an elevated radio horizon (see Chap. 2).

6.4.2.1 Air-To-Ground Measurements on 20 May 2000, NLR Metroliner

The data collected by the Langen LDPU on 20 May 2000 has been analyzed in 4.5.3.1.1. The following paragraphs assess the air-to-ground performance of three flights from that test session, namely the two NLR Metroliner flights as well as the flight of a BA target of opportunity.

6.4.2.1.1 NLR Flight in the Southeast Sector

The track of this flight is shown in Figure 4.5.3.1.1-1b as captured by the Langen LDPU. The flight altitude and distance from Langen are shown in Figure 4.5.3.1.1-2b. This flight represents a typical TMA scenario and can be considered also as a low cruising altitude (~FL 200) en-route scenario.

Figure 4.5.3.1.1-1b and 4.5.3.1.1-2b show that the NLR aircraft entered the southeast antenna sector of the Langen ground station 16 nmi south of Langen at FL 130. It then flew towards the southeast cruising at FL 190 and staying within southeast beam coverage. On its return leg (cruising at FL 200) it exited the southeast beam 41 nmi to the east of Langen and while it was descending (FL 109). During the whole of this period, the NLR aircraft was clearly flying within the vertical Langen antenna pattern. It should be noted however that when the NLR aircraft approached its maximum distance from Langen (> 120 nmi) it may have gone very close to the elevated radio horizon (because of the obstacles described in Chap. 2) of the southeast sector beam.

Figure 6.4.2-1a plots the NLR Extended Squitter reception probability and altitude versus range separately for the inbound (NLR-a) and outbound (NLR-b) NLR flight legs, while the aircraft was within southeast beam coverage. This figure has been produced using the data presented in 4.5.2.1.1. The reception probability drops almost monotonically with range. Figure 6.4.2-1a also shows the theoretical minimum reception probability baseline (RTCA) from Table 5.5. It can be seen that the measured Extended Squitter reception probability exceeds the minimum for TMA throughout the required 60 nmi range and also satisfies the en-route minimum up to 100 nmi.

The Langen LDPU log can also be used to obtain estimates of the NLR state vector update intervals. Figure 6.4.2-1b compares the estimated 95th percentile containment values for NLR state vector updates (calculated as explained in 4.5.3.1.1) with the RTCA requirements for state vector updates stated in Table 6.2. The RTCA requirements assume that a state vector update requires either a position or velocity squitter, and this is implemented in the LDPU. Fig. 6.4.2-1b shows that the RTCA requirement would be met up to 107 nmi, which is in close agreement with the coverage estimate from the previous Extended Squitter reception probability considerations.

As shown in Table 6.5 the Eurocontrol draft surveillance standard has somewhat stricter requirements on state vector updates for air-ground ATS applications. For the classic surveillance case, the minimum reception probability is 36.9% for TMA and 20.1% for en route. Figure 6.4.2-1a shows that the NLR Extended Squitter reception probability meets the classic surveillance TMA minimum throughout the 60 nmi range and satisfies also the en route requirement up to 100 nmi. For the enhanced surveillance case, the minimum reception probability is 41.1% for TMA and 23.3% for en route. Figure 6.4.2-1a shows that the NLR Extended Squitter reception probability also meets the minimum for TMA enhanced surveillance throughout the 60 nmi and satisfies the minimum for en route up to 95 nmi.

Eurocontrol has also proposed a requirement for the reception of four TCPs within a 24-sec period and probability 95%. Assuming that these TCPs would be transmitted as individual squitters with a period of 1.7 sec, this would impose a minimum Extended Squitter reception probability of 26.8%. The NLR rec. probability would exceed this minimum up to 95 nmi.

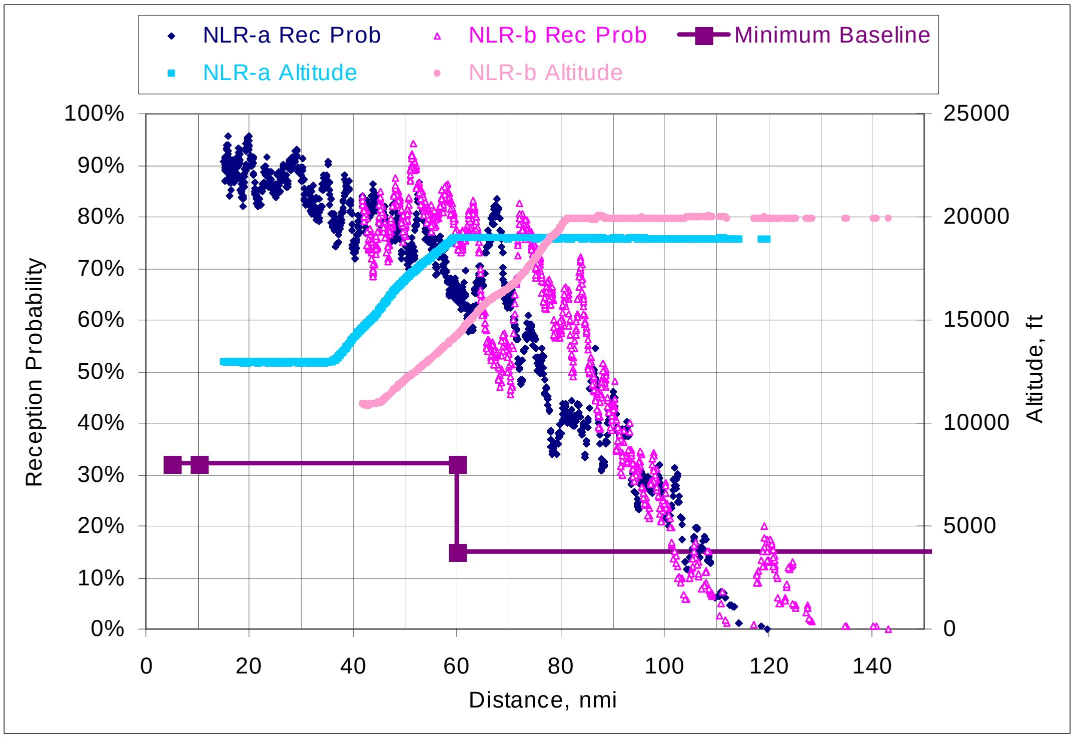


Figure 6.4.2-1a. NLR Ext. Squitter Rec. Prob. and Altitude vs. Range, Langen LDPU, 2nd Flight 20 May [NLR-a=outbound, NLR-b=inbound]

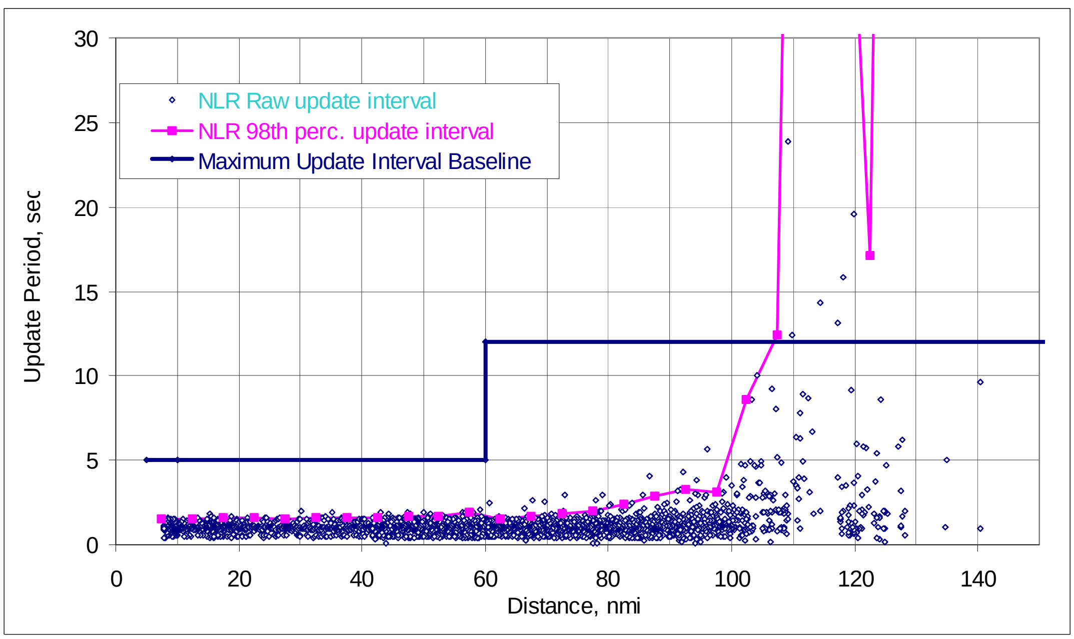


Figure 6.4.2-1b. NLR State Vector Update Interval vs. Range, Langen LDPU, 2nd Flight 20 May

6.4.2.1.2 NLR Flight in the North Sector

The track of this flight has been shown in Figure 4.5.3.1.1-1a as captured by the Langen LDPU. The NLR aircraft was first detected 102 nmi away from Langen at FL 150. It was within north antenna beam coverage of the Langen station and remained so until it arrived within 10 nmi of Langen at FL 30. Throughout this period NLR was also within the vertical Langen antenna pattern. This flight can be considered as another typical TMA scenario, while for en-route it is a rather extreme case given the low cruising altitude of the aircraft (FL 150). It should be noted that the Langen station had a lower radio horizon in the north sector compared with the southeast sector (see Chap. 2).

Figure 6.4.2-2a plots the NLR Extended Squitter reception probability and altitude versus range while NLR was within the north beam using the data presented in 4.5.3.1.1. As the aircraft flew towards Langen its reception probability rose rapidly at 90 nmi while its flight altitude was constant. This suggests a radio horizon effect limiting range beyond 90 nmi. In comparison, the other NLR flight (in the southeast sector) that was discussed in the previous subsection did not present such a sudden transition in reception probability values (compare with Figure 6.4.2-1a). Figure 6.4.2-2a also shows the theoretical minimum reception probability baseline (RTCA) from Table 6.5. It can be seen that the measured Extended Squitter reception probability comfortably exceeds the minimum for air-ground TMA throughout the required 60 nmi range. The en-route minimum is met up to 90 nmi presumably because of the radio horizon limitation of the Langen station.

Similar conclusions can be drawn from the NLR state vector update interval estimates. These are plotted in Figure 6.4.2-2b versus range from Langen. They comfortably exceed the RTCA requirements stated in Table 6.2 for TMA surveillance. For en-route surveillance NLR performance would meet the RTCA requirements up to 90 nmi, which again is in good agreement with the coverage estimate from the previous Extended Squitter reception probability considerations.

Concerning the Eurocontrol draft surveillance standard (see Tables 6.2 and 6.5), NLR performance comfortably meets both the classic and enhanced surveillance requirements for TMA (required range is 60 nmi). En-route range is limited to 88 nmi for classic and 86 nmi for enhanced surveillance.

The Eurocontrol proposed requirement for four TCPs within a 24-sec period with 95% confidence would also be satisfied up to 88 nmi.

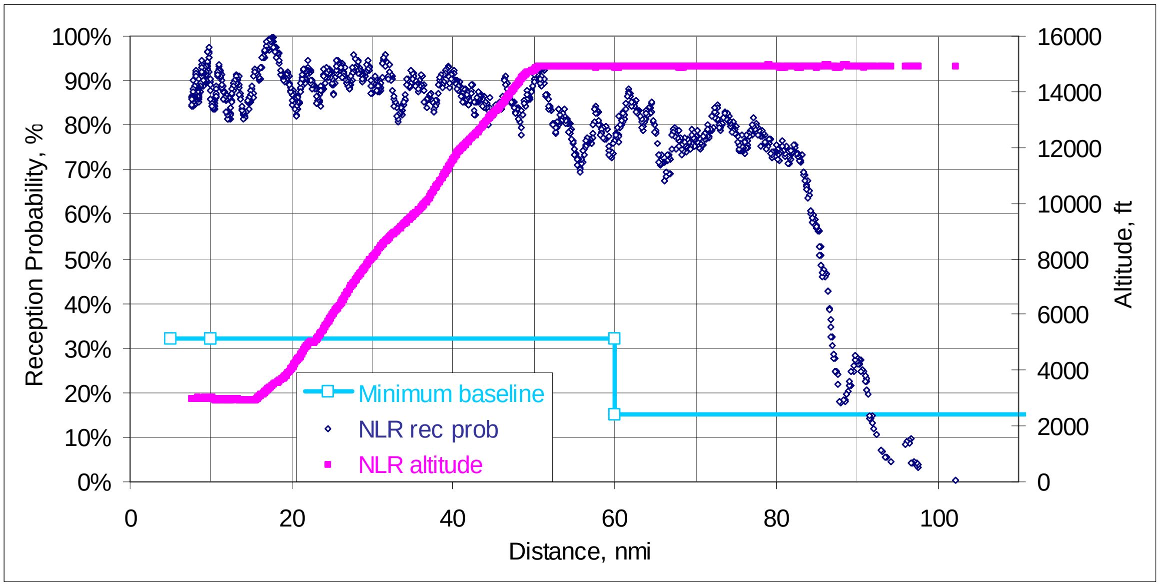


Figure 6.4.2-2a. NLR Ext. Squitter Rec. Prob. Vs. Range, Langen LDPU, 1st Flight 20 May

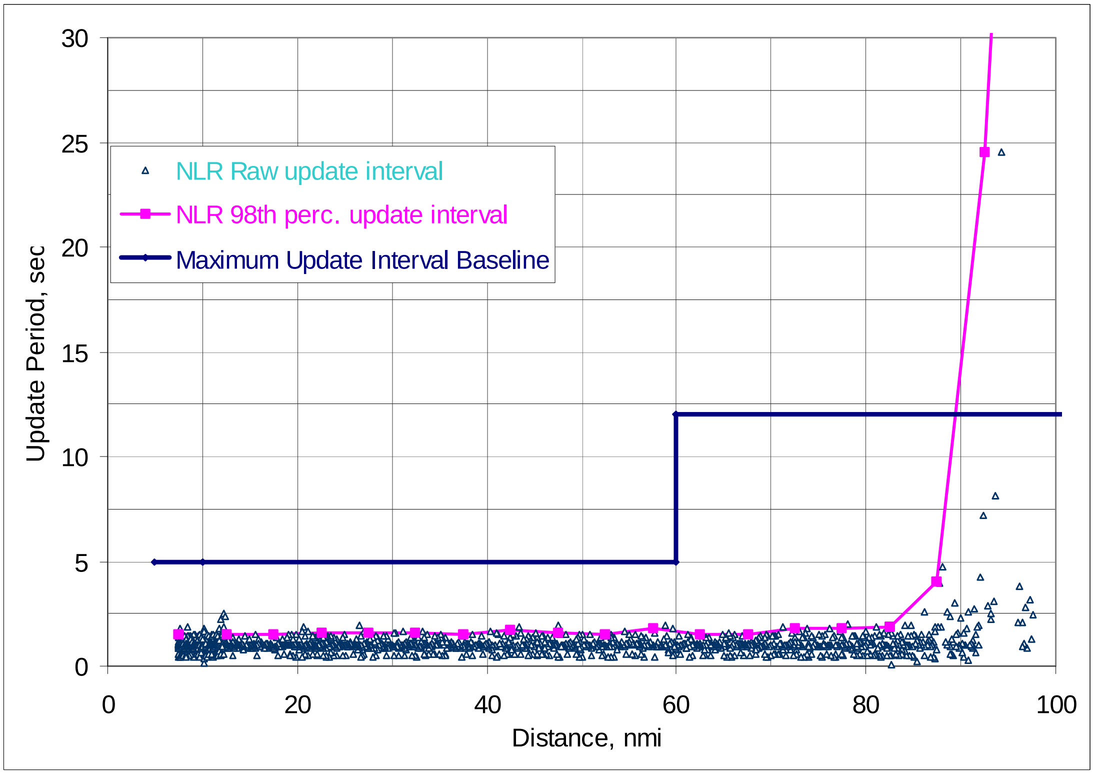


Figure 6.4.2-2b. NLR State Vector Update Interval vs. Range, Langen LDPU, 1st Flight 20 May

6.4.2.2 Air-to-Ground Measurements on 20 May, BA-400664$_h$

In this case, the target aircraft (see track in Figure 4.5.3.1.1-1b) flew on a west to southeast path at high cruising altitude (FL 330). It entered the Langen antenna southeast beam to the southeast of Langen at a distance of 94 nmi. Because of its high cruising altitude this flight represents a typical en-route scenario.

Figure 6.4.2-3a plots the BA-400664$_h$ Extended Squitter reception probability (by the Langen LDPU) and the flight altitude versus range while the aircraft traversed the southeast beam. This figure is derived from the data presented in 4.5.3.1.1. Clearly BA-400664$_h$ remained within the vertical antenna pattern of the Langen antenna until it approached its maximum detected distance from Langen (192 nmi), where it must have been very close to the Langen antenna radio horizon in the southeast sector. Figure 6.4.2-3a also shows the RTCA baseline of theoretical minimum reception probability values from Table 6.5. It can be seen that BA-400664$_h$ performance exceeded these minima up to 188 nmi.

Figure 6.4.2-3b plots the BA-400664$_h$ update intervals versus range from Langen. They comfortably exceed the RTCA air-ground requirements for state vector updates en-route throughout the flight.

Concerning the Eurocontrol draft surveillance standard, NLR performance would comfortably meet the theoretical reception probability minima (20.1%) for classic en-route surveillance up to 187 nmi. For enhanced surveillance (minimum reception probability. is 23.3%) the corresponding range would also be 187 nmi. The Eurocontrol proposed requirement for four TCPs within a 24-sec period with 95% confidence would be satisfied up to 186 nmi (required minimum probability is 26.8%).

In all the above cases the estimated coverage would exceed the required maximum range required per station (150 nmi).

It is also worth comparing BA-400664$_h$ performance with that of the NLR flight in the same sector (see 6.4.2.1). The former had far greater en-route surveillance coverage (> 180 nmi) than the latter (~ 100 nmi). This must have been due to their significantly different cruising altitudes (FL 330 versus 200), although it may have been augmented by differences in transmission power.

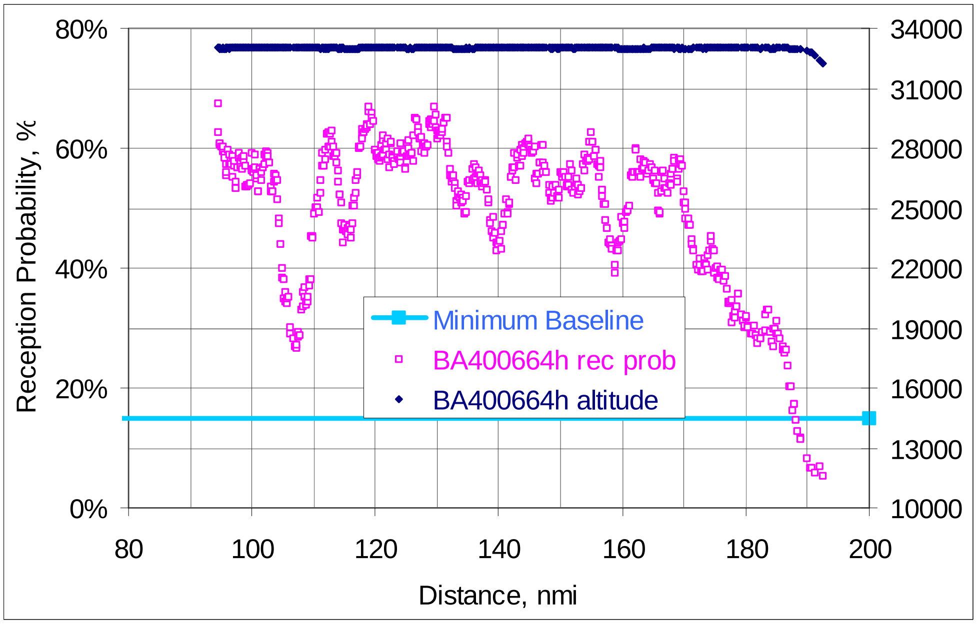


Figure 6.4.2-3a. BA-400664$_h$ Ext. Squitter Rec. Prob. and Altitude vs. Range, Langen LDPU, 20 May

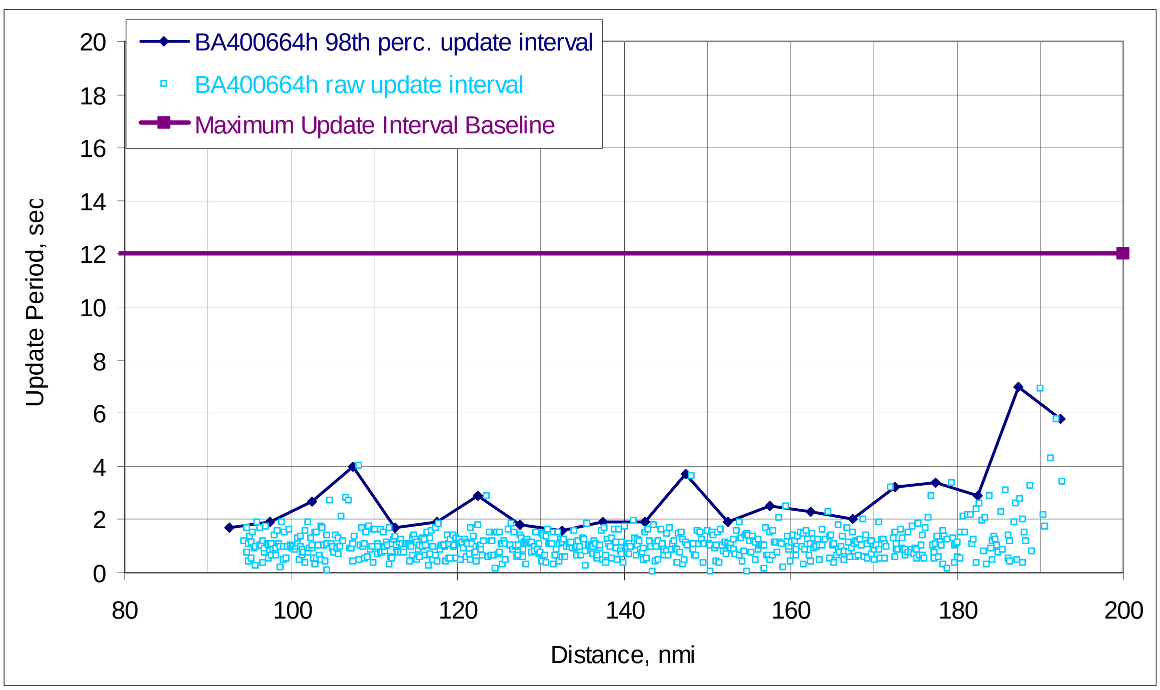


Figure 6.4.2-3b. BA-400664$_h$ SV Update Interval versus Range, Langen LDPU, 20 May

6.4.2.3 Air-To-Ground Measurements on 24 May 2000, NLR aircraft

In this case the target aircraft flew on a northbound leg started at Wiesbaden (see Figure 4.5.2.1-1a). The cruising altitude was at FL 200 (see Figure 4.5.2.1-2b). This flight can therefore be considered as a TMA and en route scenario similar to those discussed in 6.4.2.1 concerning the same aircraft but on a different date (5 May).

As discussed in 4.5.2.1, significant deviations were observed between the measured results of the inbound and outbound flight legs. Consequently performance figures will be discussed separately for each flight leg.

6.4.2.3.1 Outbound

NLR entered the coverage of the North antenna beam at a distance of 28 nmi still climbing (FL 126), and reached the cruising altitude of 20000 ft at a distance of 62 nmi. It was lost from the LDPU log when it reached the distance of 154 nmi from Langen.

Based on the results presented in 4.5.2.1, Figure 6.4.2-4 plots the individual Extended Squitter reception probability as well as the flight altitude versus range from Langen during this northbound flight leg (NLR-a). It can be seen that reception probability exceeded the RTCA minimum of 32.3% for TMA Surveillance (see Table 6.5) throughout the required range of 60 nmi. The reception probability fell below the RTCA en-route surveillance minimum of 15% for the first time at the distance of 144 nmi.

Concerning the Eurocontrol draft surveillance standard, NLR performance would meet the theoretical reception probability minima for classic en-route surveillance (20.1%) up to 136 nmi. For enhanced surveillance (minimum reception probability is 23.3%) the corresponding range would also be 136 nmi. The Eurocontrol proposed requirement for four TCPs within a 24-sec period with 95% confidence would be satisfied up to 135 nmi (required minimum probability is 26.8%). Classic surveillance TMA minimum reception probability (36.9%) would comfortably be met throughout the required range of 60 nmi. The same statement is true for enhanced TMA surveillance (requires 41.1% as minimum rec. prob.).

Performance is clearly better than what was seen in the NLR case of 20 May presented in 6.4.2.1.2 where the aircraft also flew in the north sector. However, in that case the NLR aircraft was inbound and flew at a lower altitude (FL 150 versus 200).

6.4.2.3.2 Inbound

Figure 6.4.2-4[3] also shows (NLR-b) the reception probability results for the return leg of the NLR flight. The values measured during the inbound flight were lower than those measured outbound. Figure 6.4.2-4 shows that in the range from 80 nmi to 110 nmi the reception probability inbound was in average 20% lower than outbound. Possible reasons might be the antenna installation on the fuselage of the aircraft and/or an increase of the RF interference level.

Comparison with the requirements given in Table 6.5 shows that the requested RTCA minimum reception probability for Terminal Surveillance (32.3%) is violated at the range of 42 nmi, and the value for En Route Surveillance at the range of 135 nmi. This coverage is considerably shorter than that of the outbound flight leg. It is also shorter that what was observed (see 6.4.2.1.2) for the same aircraft on the 5 May, where NLR also flew towards Langen in the north sector and at a lower flight altitude (FL 150).

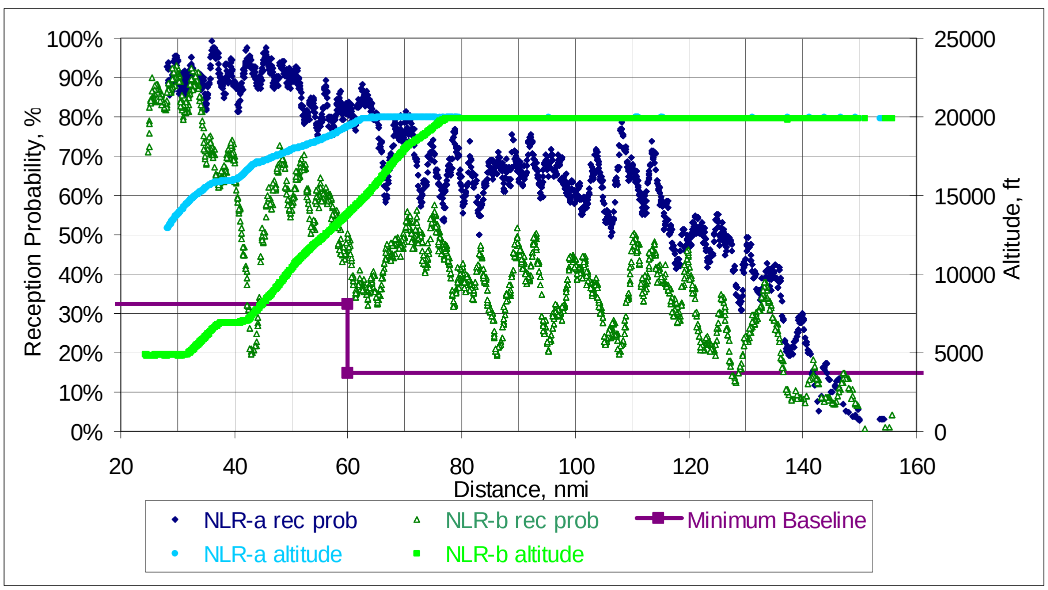


Figure 6.4.2-4. NLR Ext. Squitter Rec. Prob. and Altitude vs. Range, Langen LDPU, 24 May,
[NLR-a = Northbound leg, NLR-b= Inbound leg]

[3] It should be noted that an emergency incident onboard the NLR aircraft caused a shutdown of its transponder for about 4 minutes (see Sec. 4.5.2.1) while it was approaching Langen. The performance results shown in Fig. 6.4.2-4 do not include this final time period.

6.4.2.4 Air-To-Ground Measurements on 24 May 2000, BA-400664$_h$

This BA target of opportunity (see Fig. 4.5.2.1-1a, target BA-400664$_h$-b) traversed the north sector antenna beam from east to west at a long range (> 135 nmi) from Langen. The aircraft was flying at FL 390 and therefore this flight represents another typical en-route scenario.

The first position squitter from this target was received at a range of 173 nmi while the aircraft was at the edge of the eastern boundary of the North beam. The BA aircraft was climbing from FL 280 towards the cruising altitude of FL 390. Figure 6.4.2-5 plots the individual Extended Squitter reception probability and altitude versus range using the data presented in 4.5.2.1. During the climbing phase the reception probability increased gradually as the distance was reduced (see also Fig. 4.5.2.1-2b), albeit with significant variations. After the cruising altitude of 39000 ft was reached, reception probability stabilized in the range 40 to 70% and it stayed within this range until the aircraft left the North beam, although distance from Langen was increasing.

Comparison with the minima specified in Table 6.5 shows that during the cruising phase at FL 390 reception probability stayed well above the RTCA and Eurocontrol minima for en-route surveillance (15% for RTCA, 20.1% for Eurocontrol classic surveillance and 23.3% for Eurocontrol enhanced surveillance). The Eurocontrol proposed requirement for four TCPs within a 24-sec period with 95% confidence would also be satisfied (required minimum probability is 26.8%).

During the climbing phase, the BA-400664h reception probability exceeded the RTCA minimum for en-route surveillance up to 145 nmi (altitude FL 380). The Eurocontrol classic surveillance minimum for en-route was exceeded reliably up to 144 nmi and that for enhanced en-route surveillance up to 143 nmi.

The results of the cruising phase are equivalent to those presented in 6.4.2.2 for the same aircraft in an en-route scenario in the southeast sector (FL 330). The climbing phase provided lesser performance than the cruising phase but better than the en-route scenarios for NLR in 6.4.2.1 that were at lower cruising altitudes (FL 150 and FL 220).

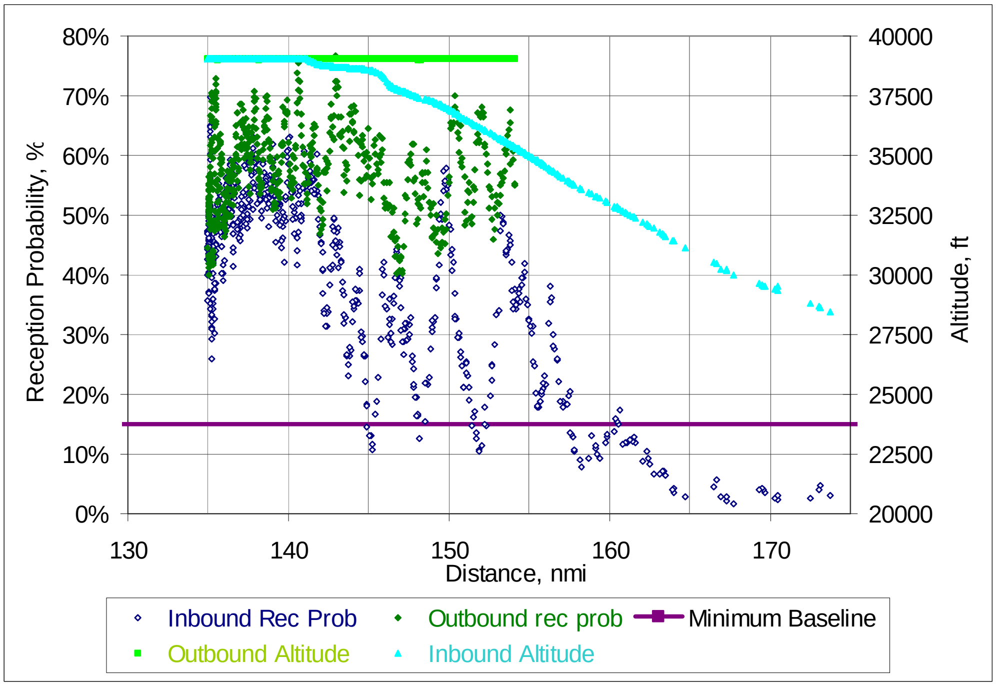


Figure 6.4.2-5. BA-400664$_h$ Ext. Squitter Rec. Prob. and Altitude versus Range, Langen LDPU, 20 May

6.4.2.5 Air-To-Ground Measurements on 24 May 2000, BA-400652$_h$ Aircraft

This case shows a target of opportunity (BA-400652$_h$) on a flight through the southeast sector passing over Langen. Its track can be seen in Fig. 4.5.2.1-1a (target BA-400652$_h$-b). The BA aircraft was first detected within the southeast beam at 122 nmi from Langen and FL 178 while it was still climbing to its cruising level of FL 350. It then flew towards Langen where it exited from main antenna coverage. This BA flight represents an en-route scenario and demonstrates a cone of silence limitation of the antenna sectors used at Langen.

Figure 6.4.2-6 shows the BA-400652$_h$ individual Extended Squitter reception probability and altitude versus distance while it was within southeast beam coverage. In this case maximum range was clearly limited by the Langen southeast Beam radio horizon. It is also noticeable that reception probability starts to drop as the BA aircraft gets close to Langen. This effect effectively starts at ~40 nmi from Langen and its maximum is reached at 7.5 nmi while the aircraft is over Langen. It is presumably due to the Langen antenna cone of silence in the vertical plane. In an operational system such limitations are overcome by adding appropriate antennas enhancing the vertical plane gain pattern.

Comparison with the minima specified in Table 6.5 shows that BA-400652$_h$ reception probability exceeded the minimum for en route surveillance required by RTCA (15%) for distances up to 114 nmi at which point the aircraft altitude had reached FL 200. The RTCA minimum reception probability for TMA surveillance (32.3%) was exceeded for ranges above 17 nmi. Eurocontrol minima for en-route classic surveillance (20.1%) were exceeded for distances below 114 nmi and those for en-route enhanced surveillance (23.3%) were exceeded for distances below 110 nmi. Eurocontrol minima for TMA classic surveillance (36.9%) were exceeded for distances above 17 nmi, while those for TMA enhanced surveillance (41.1%) were exceeded for distances above 19 nmi. The requirement for four TCPs imposes a minimum reception probability of 26.8% that was exceeded for distances below 110 nmi and above 17 nmi.

The BA-400652$_h$ flight can be compared with the NLR flight discussed in 6.4.2.1.1 which also took place in the southeast sector and had a cruising altitude of FL 200. The coverage obtained in that flight was quite similar to that of the BA-400652$_h$ flight that supports the proposition that the main range-limiting factor in these flights was the elevated radio horizon of the Langen station.

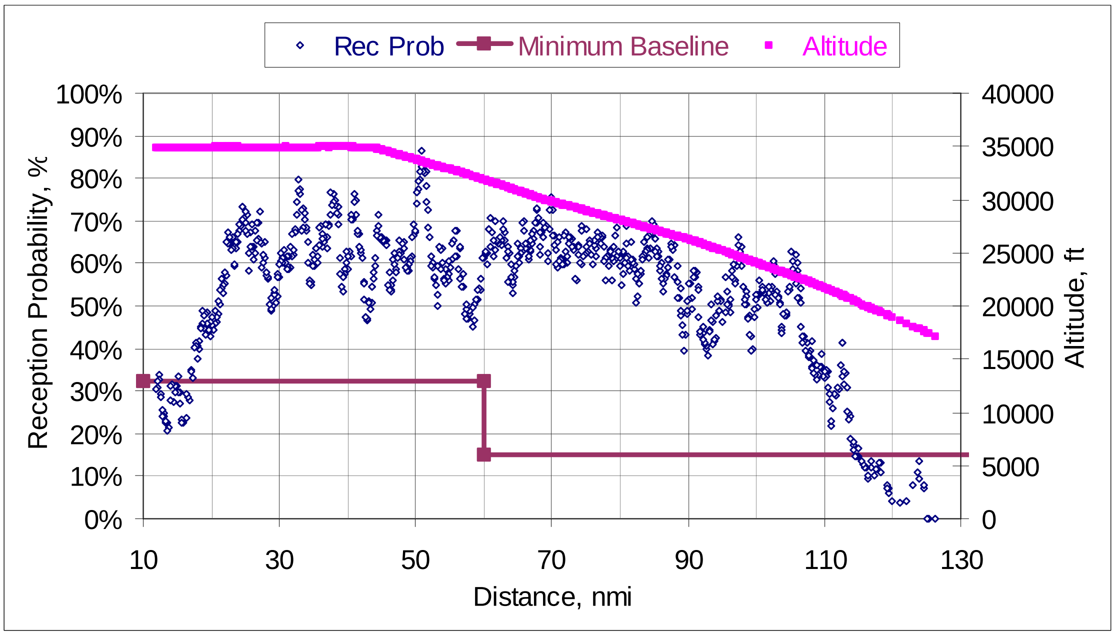


Figure 6.4.2-6. BA-400652$_h$ Ext. Squitter Rec. Prob. and Altitude vs. Range, Langen LDPU, 24 May

6.4.2.6 Conclusions on Langen LDPU Station Air-Ground Performance

The flights described in sections 6.4.2.1 through 5 above, provided TMA and en route air-ground surveillance scenarios.

Concerning TMA, where the maximum coverage required is 60 nmi, the Langen LDPU ground station met this requirement for state vector updates under both RTCA and Eurocontrol requirements except for flights passing very close to Langen. For the latter scenarios, the Langen station clearly lacked an antenna providing overhead coverage. The Langen LDPU should also be capable of receiving four TCPs within TMA coverage per the proposed Eurocontrol requirement.

Concerning en-route the maximum required coverage per station is 150 nmi (at least under the draft Eurocontrol requirements). Langen LDPU station met the required 150 nmi coverage for state vector updates (under both RTCA and Eurocontrol requirements) but only on flights above FL 300. The requirement for four TCPs should also be met for high altitude flights. It is thought that the siting of the station negatively affected long-range performance at lower altitudes because of the elevated radio horizons in both main-beam sectors.

There were some cases of degraded performance, which call for further analysis. Antenna positioning on the aircraft may have played a role, but variations in TX power and/or RF environment might also be a factor.

6.4.3 Wiesbaden LDPU Measurements

As discussed in section 2.1 of this report, the FAA ground test configuration at Wiesbaden included an LDPU connected to two adjacent sectors of a six sector antenna. This configuration provided a primary coverage area at azimuths from -15 degrees to +105 degrees. It was realized that the antenna siting would not have been acceptable for an operational system as full 360 degrees coverage would not have been possible. Also the antenna siting was not ideal for providing long-range en route coverage because of line-on-sight limitations, especially toward the north. The flight paths of the project aircraft, as well as the paths flown by several of the observed targets of opportunity frequently included operations beyond the -3dB contour of the eastern sector antenna beam. Although Extended Squitter reception would be expected to be somewhat degraded beyond the -3dB coverage contour, it was decided to not fully exclude consideration of the out-of-beam data. Specifically, the en route performance results presented in the following sub-paragraphs include Extended Squitter reception performance from targets within an extended coverage area. This extended coverage area being a 30 degree wedge at azimuths from +105 to +135 degrees.

The summary of the overall reception performance, in terms of reception probability, has been presented in Chapter 4 of this report. The following paragraphs take a more detailed look at the performance achieved for specific air-ground surveillance applications/operational domains and compares the results obtained against the required performance levels described in Table 6.1-2 and Table 6.1-5.

The results from each day of the evaluation were analyzed for following three air-to-ground surveillance applications:

1. En Route ATC surveillance
2. Terminal ATC surveillance
3. Parallel Runway Monitoring (PRM)

Note that in an operational Extended Squitter ground system, separate antennas each with optimized siting would typically be used for these three distinct applications. The Wiesbaden ground antenna siting would be most representative of the siting used in support of terminal surveillance applications, but limited to the azimuth coverage as noted above.

Note that the window size used for the reception probability analysis for the PRM application has been reduced to 6 seconds, as compared to the 24 seconds used for the en route and terminal ATC surveillance applications. This was done to reflect the much faster state vector update rate requirement associated with the PRM application.

6.4.3.1 Air-to-Ground Measurements on May 19

Of the project aircraft only N40 participated in the data collection on May 19. 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.

6.4.3.1.1 En Route Surveillance

The flight profile for N40 resulted in only short-range data (i.e., <31 nmi) being collected by the Wiesbaden ground station for this target. Also some short-range data was collected from BA-400652$_h$ as it briefly passed thought the ground station antenna's primary coverage area. A longer range target, BA-400665$_h$ was observed to the north of Wiesbaden, which allowed for the collection of long-range performance data off of the north sector of the ground station antenna. Figure 6.4.3-1a plots the reception probability vs. range for targets within the ground station's primary coverage area. Only data collected from targets at altitudes above 18,000 ft is included in the en route data set. The drop in reception probability at short-range (approximately 7 nmi) can be attributed to the target aircraft transitioning the ground station antenna's cone of silence. This effect is exaggerated on the plot by the 24 second sliding (trailing) window technique used to calculate the reception probability. Figure 6.4.3-1b includes additional Extended Squitter reception results for targets in the extended coverage area. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the en route air-to-ground surveillance requirements varies between 15% (U.S. MASPS and ICAO SARPs requirements) to 23.3% (Eurocontrol enhanced ATS requirements). Although the mid-to-long range data collected within the ground station's primary coverage area on May 19 is not extensive, the results obtained indicate that the requirements were satisfied to a range of 150 nmi (the maximum range for which data was collected was 153 nmi).

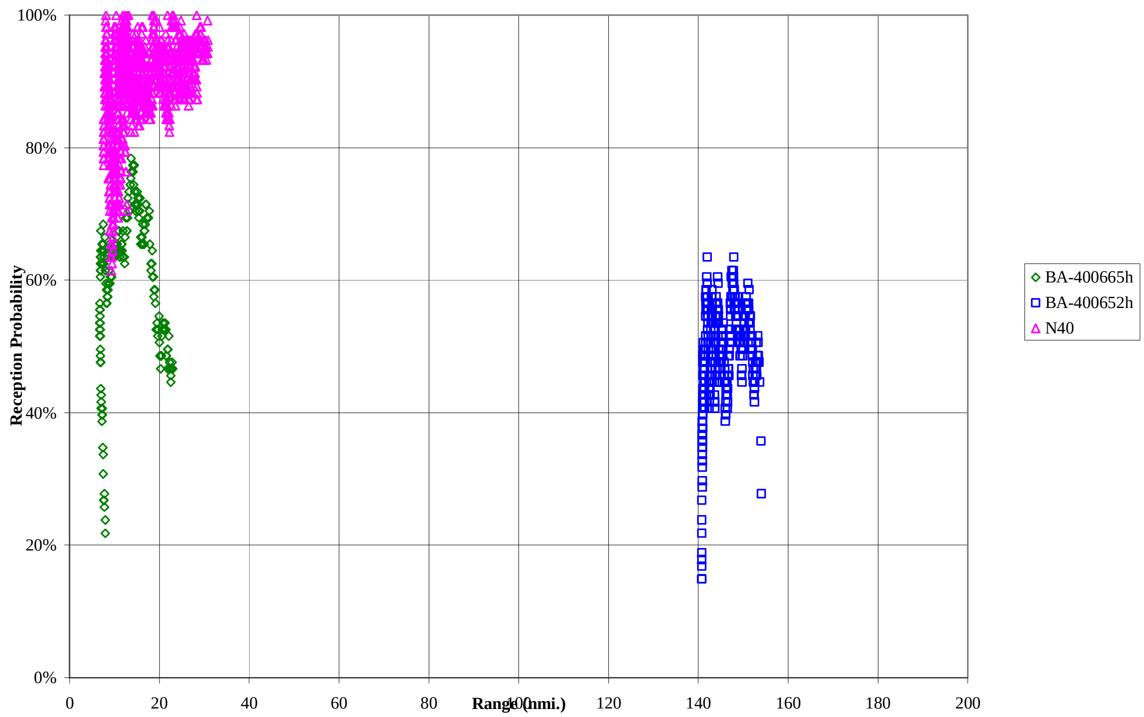


Figure 6.4.3-1a. En Route Reception Probability for Primary Coverage Area,19 May

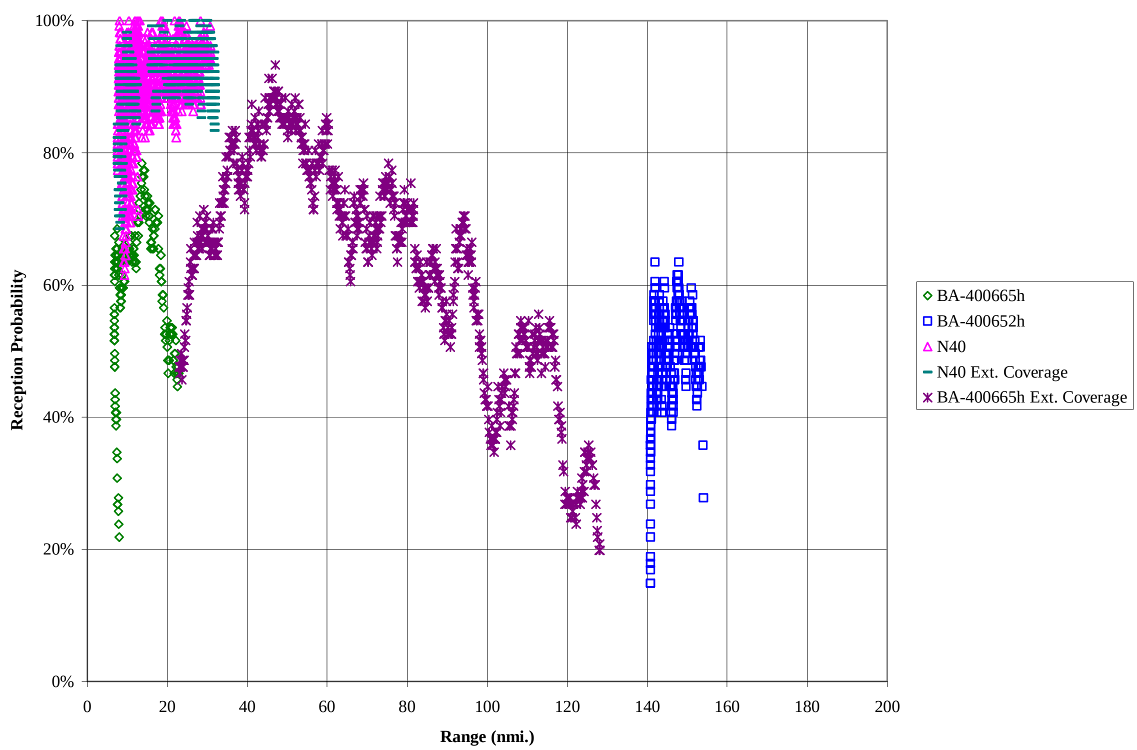


Figure 6.4.3-1b. En Route Reception Probability for Primary & Extended Coverage Areas, 19 May

6.4.3.1.2 Terminal Surveillance

The flight profile for N40 resulted in only short-range data (i.e., <31 nmi) being collected by the Wiesbaden ground station for this target. Also some short-range data was collected from BA-400652$_h$ as it briefly passed thought the ground station antenna's primary coverage area. No data was collected within the ground station's primary coverage area beyond 31 nmi. Figure 6.4.3-2 plots the reception probability vs. range. Only data collected from targets within the ground station's primary coverage area and at altitudes between 1000 ft and 18,000 ft is included. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the terminal air-to-ground surveillance requirements varies between 32.3% (U.S. MASPS and ICAO SARPs requirements) to 36.9% (Eurocontrol enhanced ATS requirements). During this data collection N40 flight profile consisted of flying 'racetrack' holding patterns at altitudes of 10,000 ft, 15,000 ft and 22,000 ft. The data considered in the terminal surveillance data set included N40 operations during the lower two altitude holding patterns as well as data from N40 departure from Wiesbaden and its subsequent return to Wiesbaden. Thus the N40 data set includes more extensive aircraft maneuvering than would be typical for a typical operational flight profile. Even with this, the required performance levels for terminal air-to-ground surveillance were exceeded, limited to the maximum range of the data set.

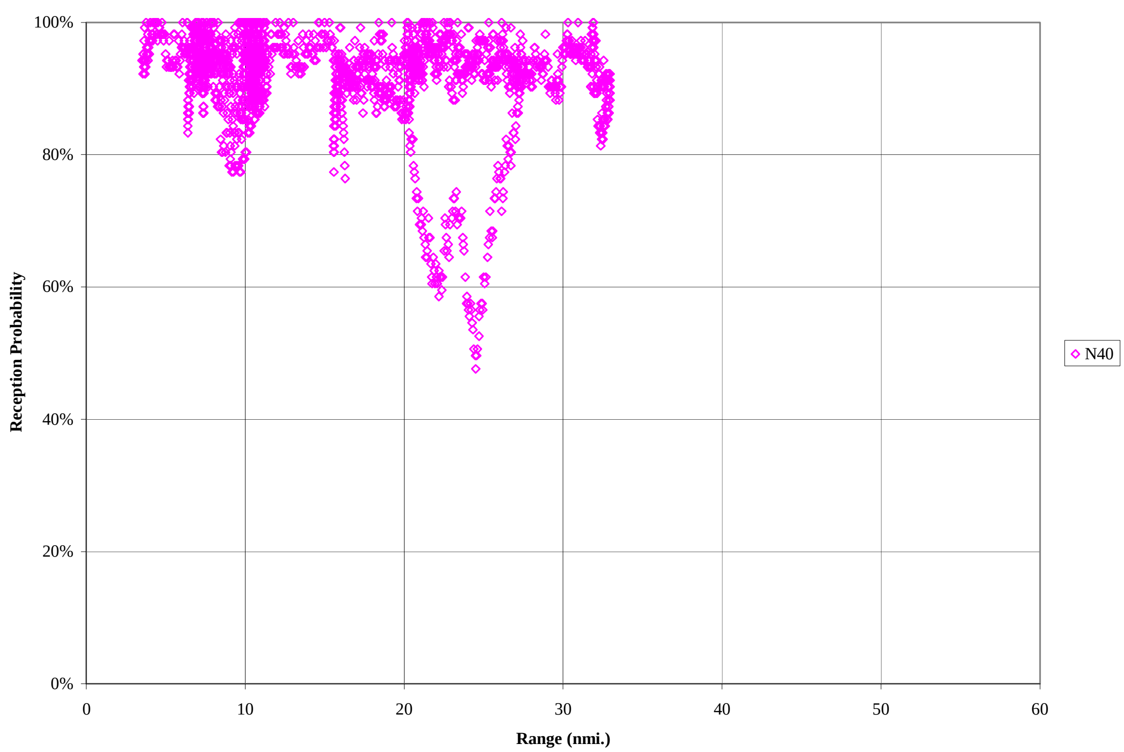


Figure 6.4.3-2. Terminal Reception Probability,19 May

6.3.3.1.3 PRM Surveillance

The data collected by the Wiesbaden ground station was analyzed in order to understand if the level of performance that could be provided by a single ground station could satisfy the PRM application requirement. The PRM application has the shortest air-to-ground range requirements but imposes the most demanding requirements for reception probability. For the PRM performance analysis, a maximum range of 30 nmi or the point at which the aircraft turned onto its final approach was considered. Note that as indicated in Table 6.1-2 the RTCA ADS-B MASPS only specifies the PRM reception performance to a range of 10 nmi. Figure 6.3.3-3 plots the project aircraft flight segment considered for this analysis. Figure 6.3.3-4a plots the Extended Squitter reception probability for data collected during the approach and landing flight segment of N40 at Wiesbaden.

As shown in Table 6.1-5 the required probability of reception within 10 nmi varies from 48.8% (i.e., Eurocontrol requirement for 2500 ft runway separation) to 90% (i.e., RTCA MASPS requirement for 1000 ft runway separation) in order to insure the PRM state-vector update rate requirements are satisfied . The measured reception performance generally exceeded 80% probability of reception at ranges within 20 nmi.

The Wiesbaden measurements were analyzed in more detail focusing on the reports generated by the LDPU rather than individual squitters. The LDPU generates reports at a nominal rate of once per second, with exceptions when no data was received during a one second period. Figure 6.3.3-4b summarizes the performance at the report level.

The results in this figure indicate that performance was excellent during this approach and landing. This plot includes the entire track of N40 while the aircraft was within the receiving sectors, a total of 924 seconds. During this time, reports were consistently generated at the nominal rate with only three exceptions, as noted in the figure. Therefore the reliability at the report level was

Report reliability = (921 reports) / (927 sec.) = 99.7 percent

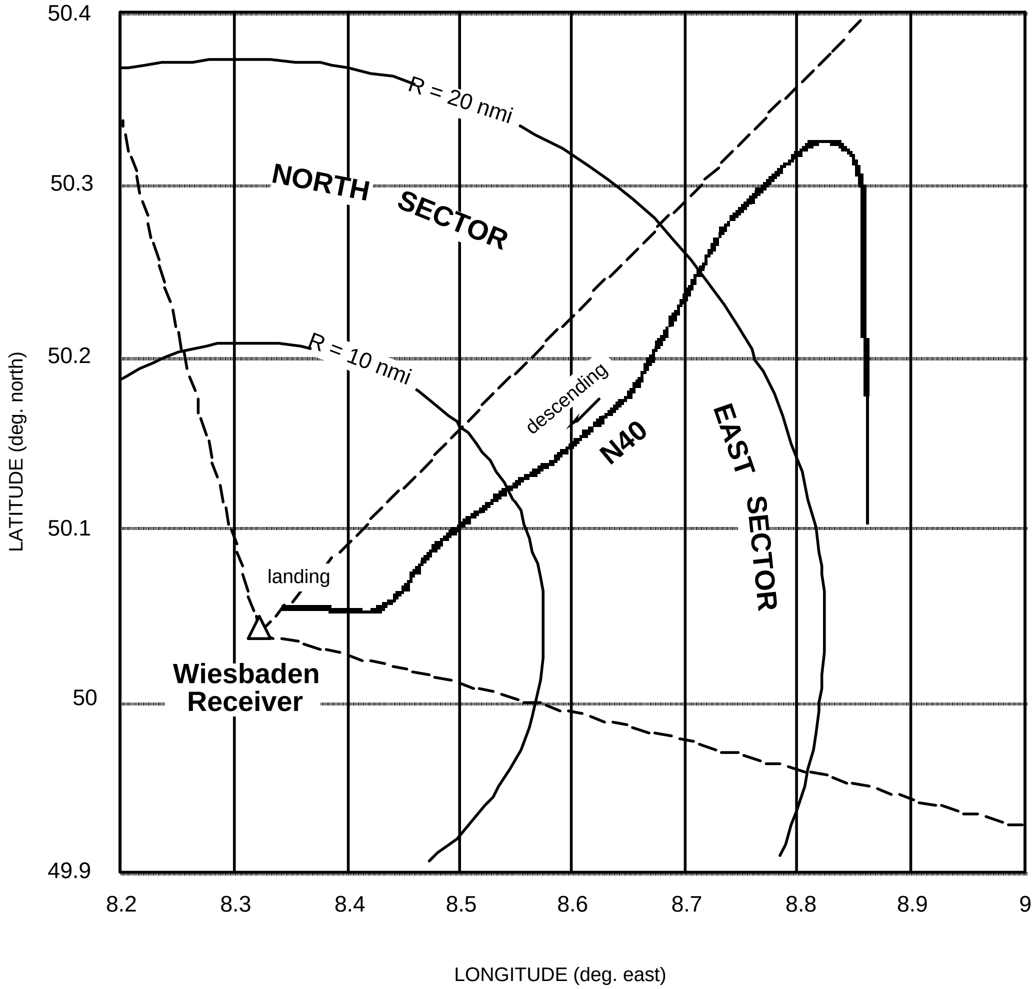


Figure 6.3.3-3. Approach and Landing Ground Track, 19 May

In summary, for the landing approach of N40, surveillance was excellent. The aircraft was under surveillance and in track 100 percent of the time, and once/sec. surveillance updates were generated 99.7 percent of the time. Similar excellent performance was seen on all five days of testing, as is summarized in 6.4.3.5.3

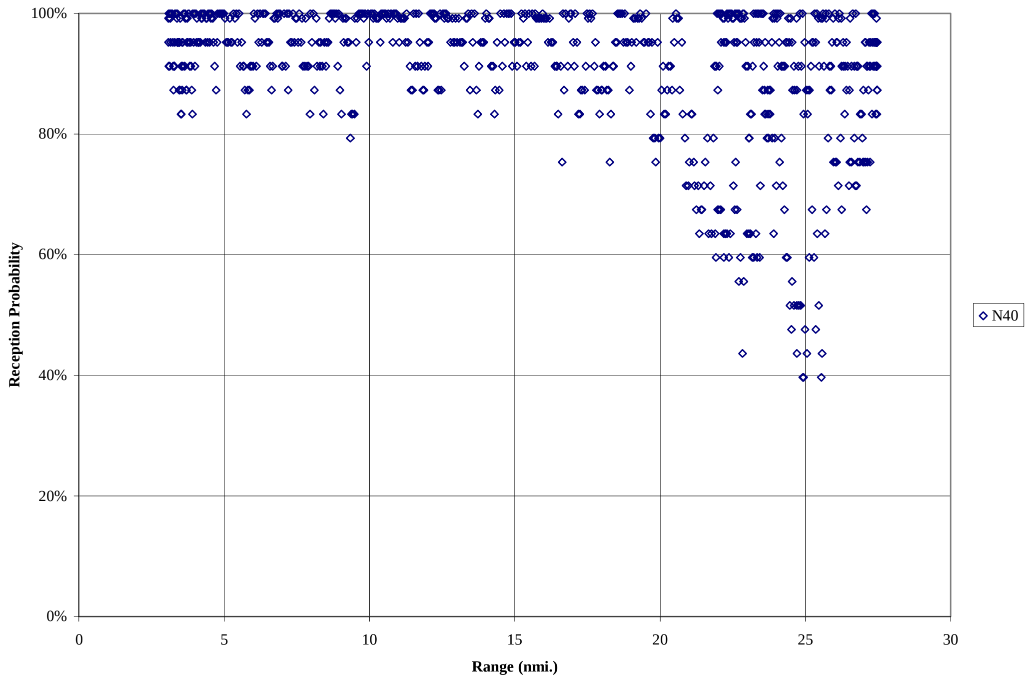


Figure 6.3.3-4a. Reception Probability for PRM Application, 19 May

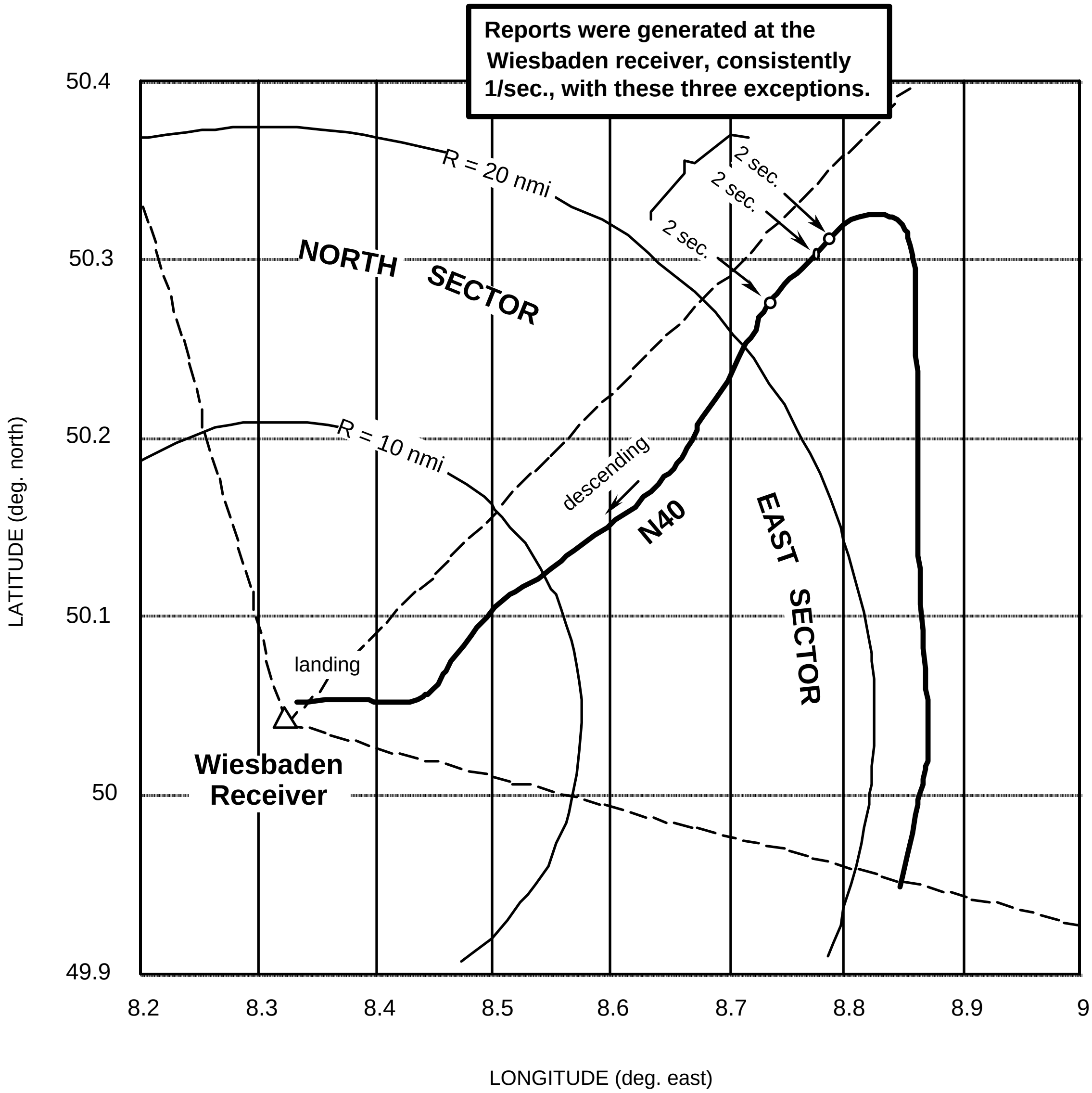


Figure 4.3.3-4b. Air-to-Ground Surveillance During N40Landing Approach, 29 May

Note. This plot includes N40's landing and approach and the preceding track while the aircraft was within the receiving antenna sectors. During this time (924 sec.), the Wiesbaden receiving station generated reports consistently 1/sec. with 3 exceptions shown here. Overall report reliability = 99.7 percent.

6.4.3.2 Air-to-Ground Measurements on 20 May

All three project aircraft participated in the data collection on May 20. 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 three British Airways targets of opportunity were also observed. A plot of the ground tracks of N40, NLR aircraft and the targets of opportunity observed during the data collection are presented in Chapter 4 of this report.

6.4.3.2.1 En Route Surveillance

The flight profile for N40 resulted in only short-range data (i.e., <29 nmi) being collected by the Wiesbaden ground station for this target. Figure 6.4.3-5a plots the reception probability vs. range for targets with the ground station's primary coverage area. Only data collected from targets at altitudes above 18,000 ft is included in the en route data set. These constraints resulted in not reporting any en route data from the NLR project aircraft nor the two British Airways targets of opportunity as a part of this en route air-ground surveillance data set. Figure 6.4.3-5b includes additional Extended Squitter reception results for targets in the extended coverage area. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the en route air-to-ground surveillance requirements varies between 15% (U.S. MASPS and ICAO SARPs requirements) to 23.3% (Eurocontrol enhanced ATS requirements). Although there is no mid-range or long range data available for target with the ground station's primary coverage area as part of the en route data set for May 20, the results obtained at short-range exceed the requirements. Data collected for targets with the ground station's extended coverage area indicates generally adequate performance out to a range of approximately 150 nmi.

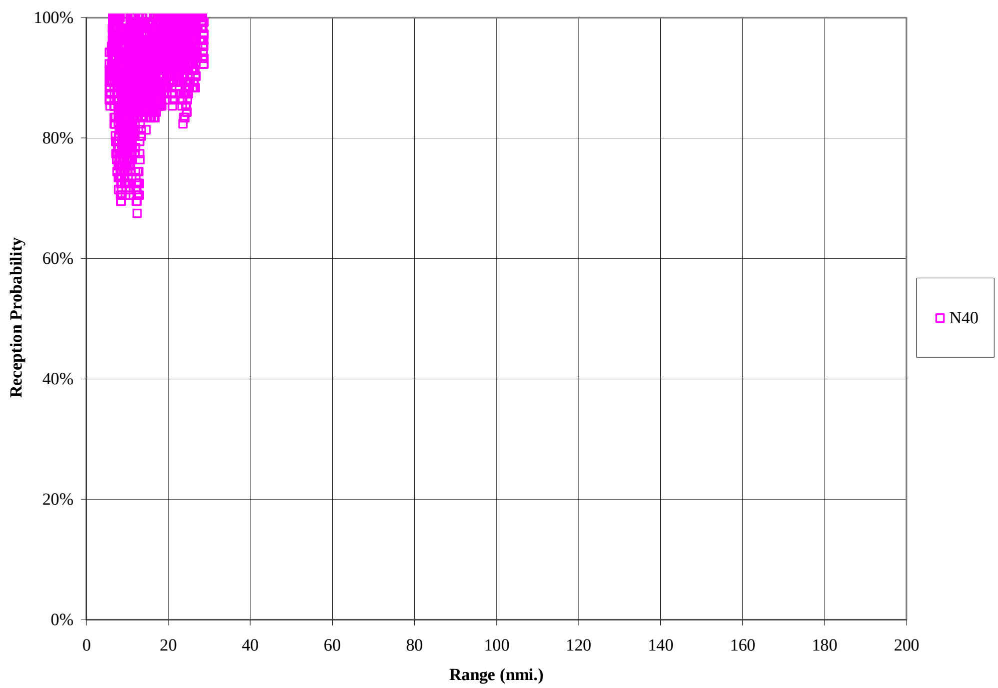


Figure 6.4.3-5a. En Route Reception Probability for Primary Coverage Area, 20 May

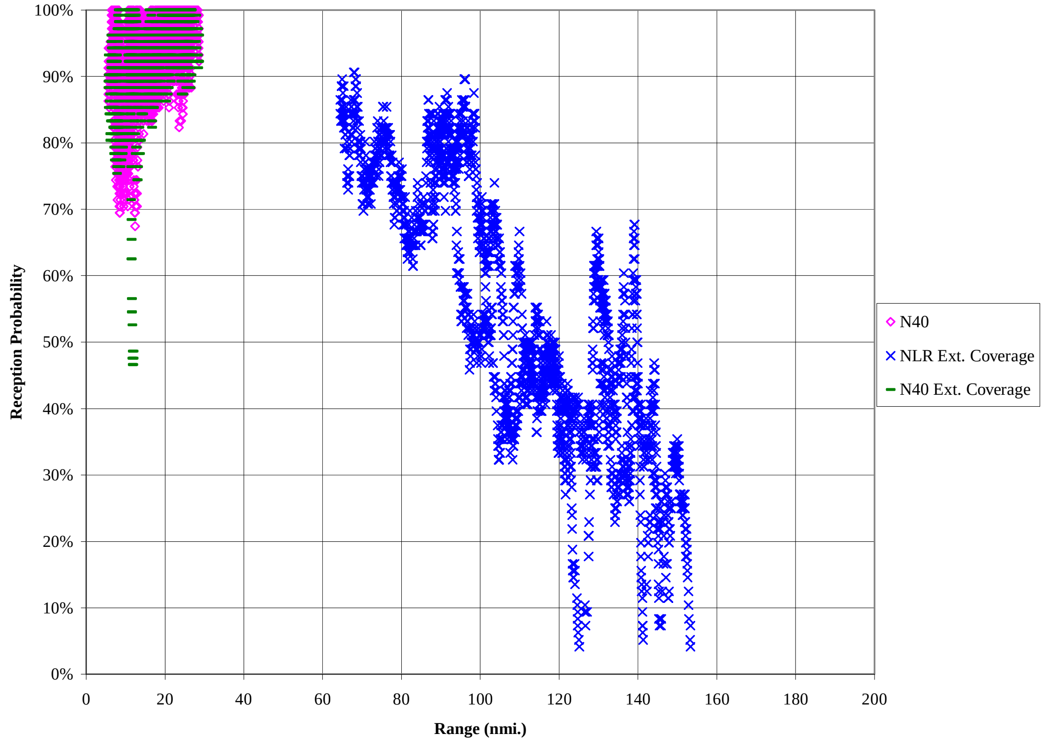


Figure 6.4.3-5b. En Route Reception Probability for Primary & Extended Coverage Areas, 20 May

6.4.3.2.2 Terminal Surveillance

The flight profile for N40 resulted in only short-range terminal data (i.e., <30 nmi) being collected by the Wiesbaden ground station for this target. Also short and mid-range data was collected from the NLR project aircraft as it returned to Wiesbaden. Figure 6.4.3-6 plots the reception probability vs. range. Only data collected from targets within the ground station's primary coverage area and at altitudes between 1000 ft and 18,000 ft is included. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the terminal air-to-ground surveillance requirements varies between 32.3% (U.S. MASPS and ICAO SARPs requirements) to 36.9% (Eurocontrol enhanced ATS requirements). The sharp drop in reception probability at short-range (approximately 3 nmi) can be attributed to the target aircraft transitioning the ground station antenna's cone of silence. This occurred as N40 over flew Wiesbaden at an altitude of approximately 10,000 ft as just at the aircraft entered the ground station's coverage area. This effect is exaggerated on the plot by the 24 second sliding (trailing) window approach used to calculate the reception probability.

The results from the data analyzed for May 20 indicate that the terminal air-to-ground surveillance requirements are well exceeded with the measured Extended Squitter reception probability always exceeding 80% out to 60 nmi, except at very short-ranges (<6 nmi) where the effects of the ground station antenna's cone of silence resulted in reduced reception probabilities for targets over flying Wiesbaden.

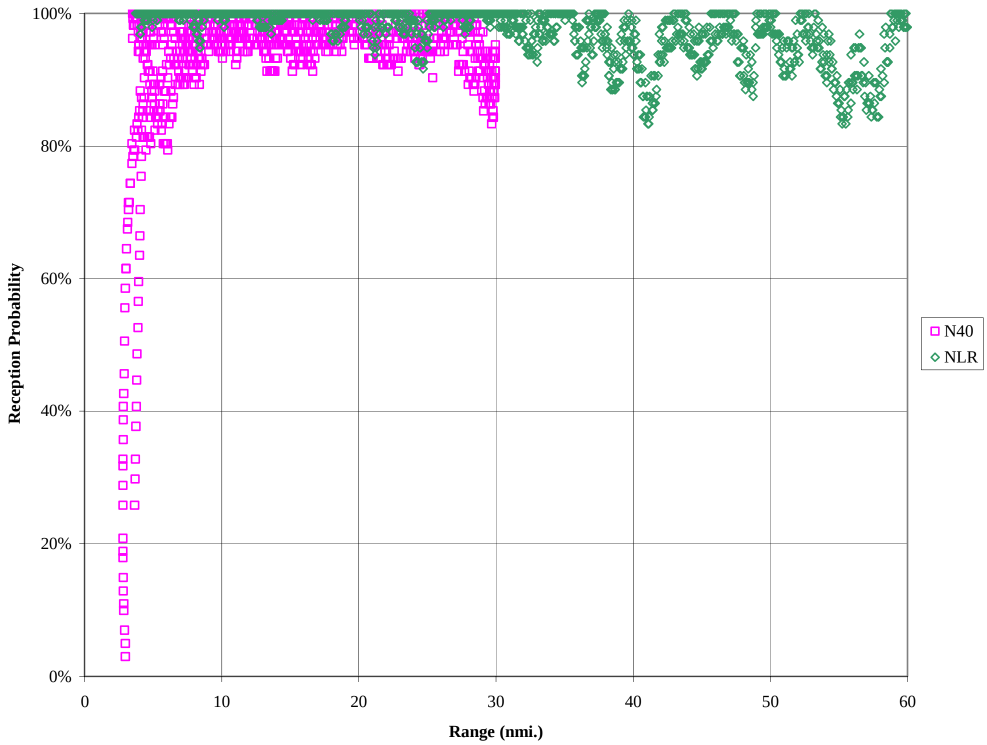


Figure 6.4.3-6. Terminal Reception Probability, 20 May

6.4.3.2.3 PRM Surveillance

The data collected by the Wiesbaden ground station was analyzed in order to understand if the level of performance that could be provided by a single ground station could satisfy the PRM application requirement. The PRM application has the shortest air-to-ground range requirements but imposes the most demanding requirements for reception probability. For the PRM performance analysis, a maximum range of 30 nmi or the point at which the aircraft turned onto its final approach was considered. Note that as indicated in Table 6.1-2 the RTCA ADS-B MASPS only specifies the PRM reception performance to a range of 10 nmi. Figure 6.4.3-7 plots the project aircraft flight segment considered for this analysis. Figure 6.4.3-8 plots the Extended Squitter reception probability for data collected during the approach and landing flight segment of N40 and the NLR aircraft at Wiesbaden.

As shown in Table 6.1-5 the required probability of reception within 10 nmi varies from 48.8% (i.e., Eurocontrol requirement for 2500 ft runway separation) to 90% (i.e., RTCA MASPS requirement for 1000 ft runway separation) in order to insure the PRM state-vector update rate requirements are satisfied . The measured reception performance generally exceeded 80% probability of reception for all ranges within 30 nmi. An examination of the update period for each the NLR aircraft and N40 revealed that the ADS-B reports were consistently output by the ground station's LDPU from both targets at 1 second intervals with no exceptions.

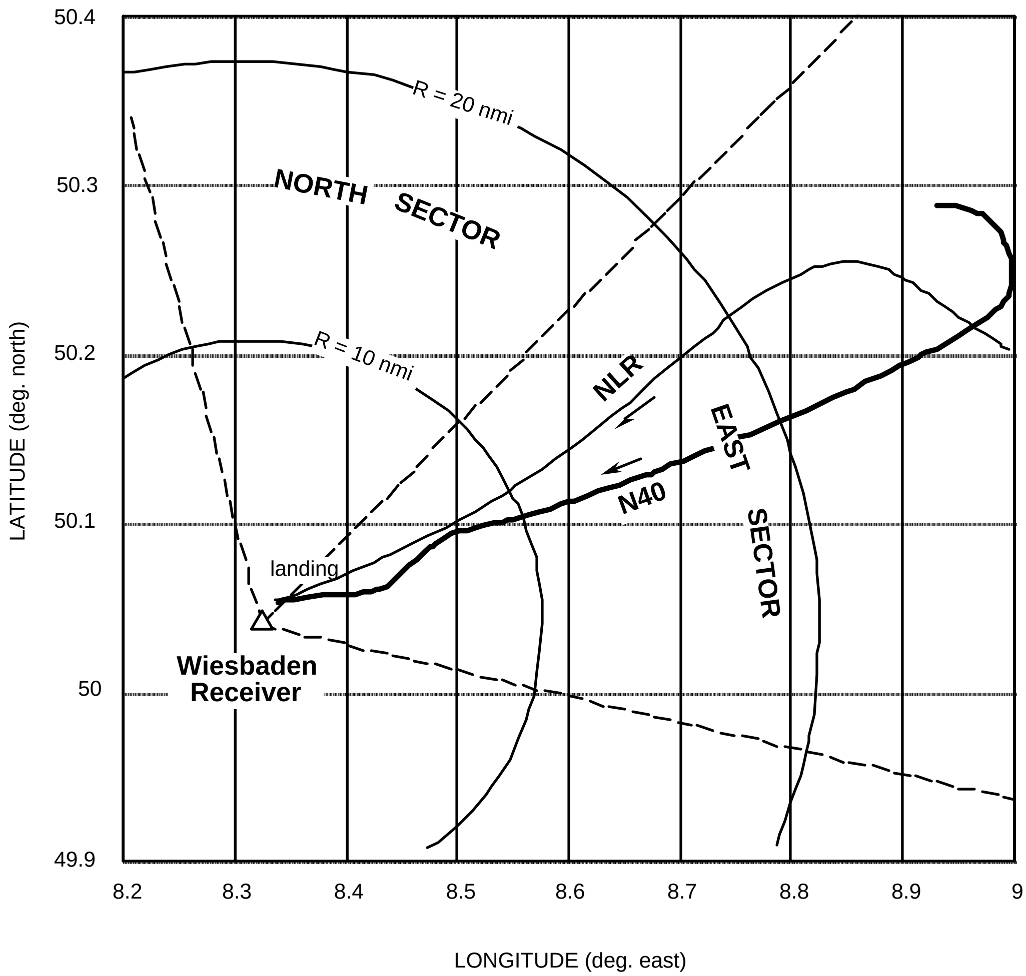


Figure 6.4.3-7. Approach and Landing Ground Track, 20 May

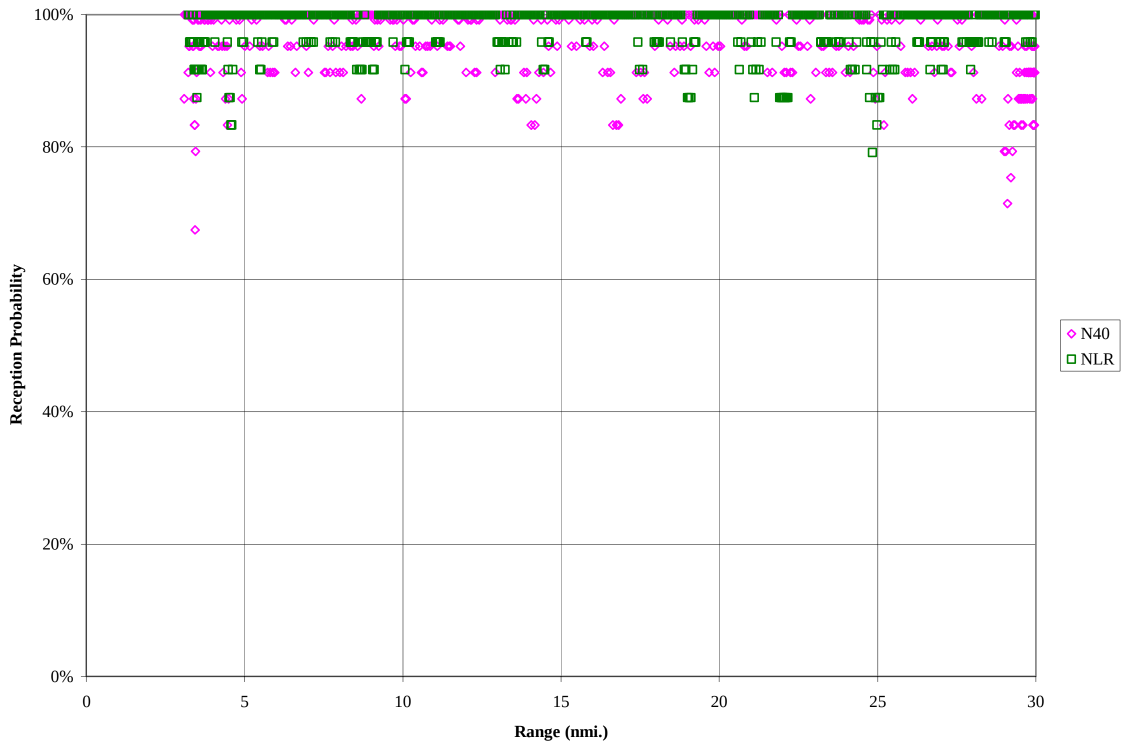


Figure 6.4.3-8. Reception Probability for PRM Application, 20 May

6.4.3.3 Air-to-Ground Measurements on 22 May

The FII and N40 project aircraft participated in the data collection on May 22. During the data collection at the Wiesbaden ground station a British Airways target of opportunity was also observed. A plot of the ground tracks of N40, FII aircraft and the target of opportunity observed during the data collection is presented in Chapter 4 of this report.

6.4.3.3.1 En Route Surveillance

The flight profile for the FII resulted in only short-range data (i.e., <29 nmi) being collected by the Wiesbaden ground station for this target. Data was collected from N40 within the ground station's primary coverage area at ranges between approximately 66 nmi and 114 nmi. Extensive data was collected from BA-400664h at ranges from approximately 18 nmi to 185 nmi. Figure 6.4.3-9a plots the reception probability vs. range for targets within the ground station's primary coverage area. Only data collected from targets at altitudes above 18,000 ft is included in the en route data set. These constraints resulted in not reporting much of the data from N40 as a part of this en route air-ground surveillance data set for the ground station's primary coverage area. Figure 6.4.3-9b includes additional Extended Squitter reception results for targets in the extended coverage area. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the en route air-to-ground surveillance requirements varies between

15% (U.S. MASPS and ICAO SARPs requirements) to 23.3% (Eurocontrol enhanced ATS requirements). The results obtained from the data collected within the ground stations's primary coverage area on May 22 indicate the reception probability was consistently above 40% for at all ranges out to over 150 nmi and generally remained above 20% out to 185 nmi (i.e., the range limit of the available data). Although the results for data collected for the extended coverage area shows somewhat lower performance, the results are generally consistent with providing acceptable performance at a 150 nmi air-to-ground range.

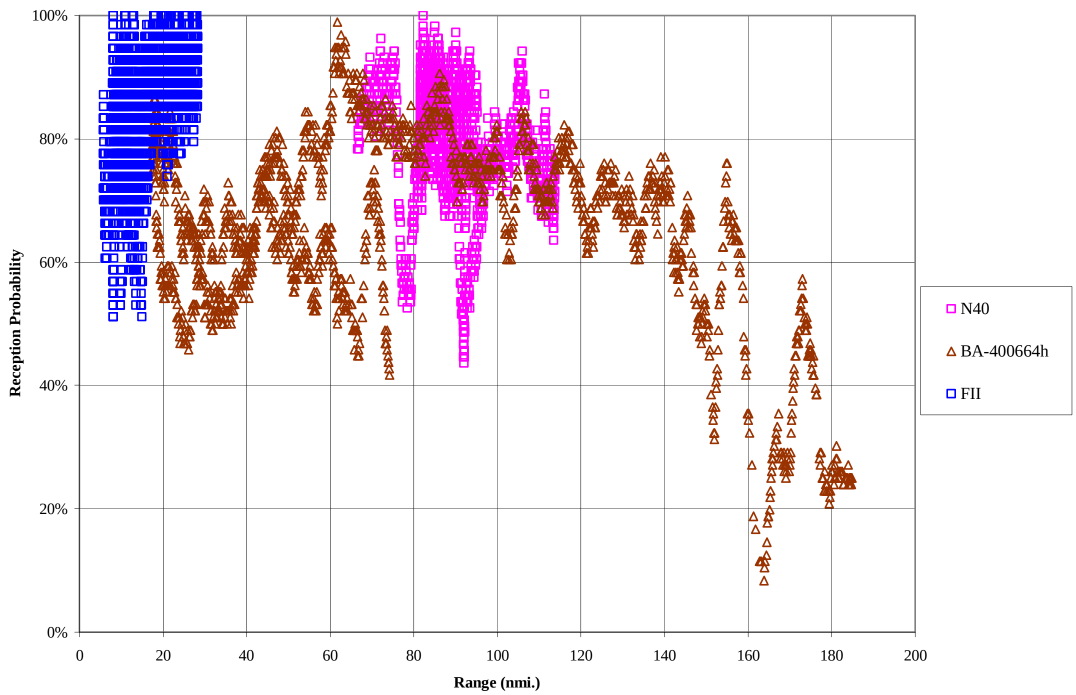


Figure 6.4.3-9a. En Route Reception Probability for Primary Coverage Area, 22 May

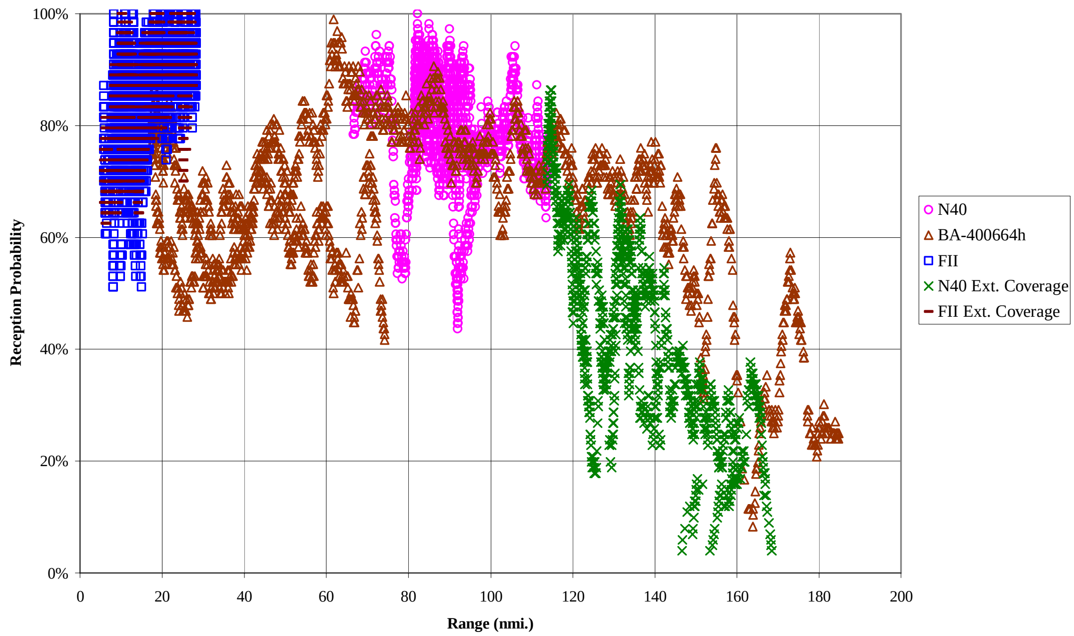


Figure 6.4.3-9b. En Route Reception Probability for Primary & Extended Coverage Areas, 22 May

6.4.3.3.2 Terminal Surveillance

The flight profile for the FII aircraft resulted in only short-range data (i.e., <14 nmi) being collected by the Wiesbaden ground station for this target as part of the terminal data set. Short and mid-range data was collected from N40 as it returned to Wiesbaden. Figure 6.4.3-10 plots the reception probability vs. range. Only data collected from targets within the ground station's primary coverage area and at altitudes between 1000 ft and 18,000 ft is included. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the terminal air-to-ground surveillance requirements varies between 32.3% (U.S. MASPS and ICAO SARPs requirements) to 36.9% (Eurocontrol enhanced ATS requirements). The sharp drop in reception probability at short-range (approximately 3 nmi) can be attributed to the target aircraft transitioning the ground station antenna's cone of silence. This occurred as the FII aircraft over flew Wiesbaden at an altitude of approximately 7,000 ft and just at the aircraft entered the ground station's coverage area. This effect is exaggerated on the plot by the 24 second sliding (trailing) window approach used to calculate the reception probability.

The results from the data analyzed for May 22 indicates that the terminal air-to-ground surveillance requirements are well exceeded with the measured Extended Squitter reception probability generally exceeding 60% out to 60 nmi, except for a brief drop to a minimum value of 42% that occurred at a range of approximately 35 nmi as N40 was returning to Wiesbaden. N40 was at a altitude of 4,000 ft at this point in is flight profile.

The measured results for May 22 well exceed the requirements for terminal air-to-ground surveillance.

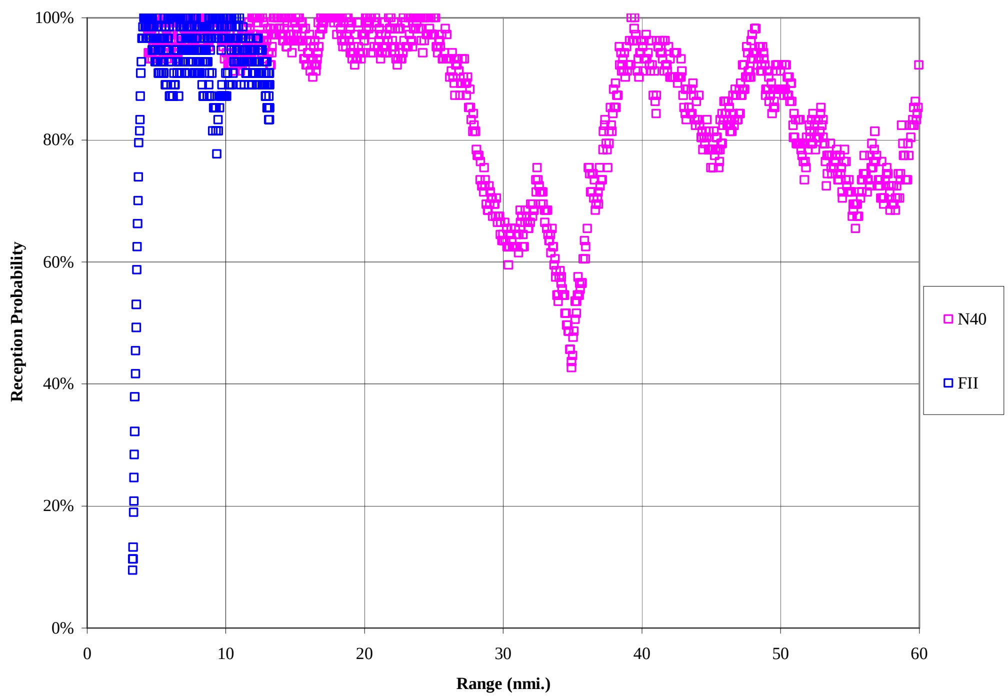


Figure 6.4.3-10. Terminal Reception Probability, 22 May

6.4.3.3.3 PRM Surveillance

The data collected by the Wiesbaden ground station was analyzed in order to understand if the level of performance that could be provided by a single ground station could satisfy the PRM application requirement. The PRM application has the shortest air-to-ground range requirements but imposes the most demanding requirements for reception probability. For the PRM performance analysis, a maximum range of 30 nmi or the point at which the aircraft turned onto its final approach was considered. Note that as indicated in Table 6.1-2 the RTCA ADS-B MASPS only specifies the PRM reception performance to a range of 10 nmi. Figure 6.4.3-11 plots the project aircraft flight segment considered for this analysis. Figure 6.4.3-12 plots the Extended Squitter reception probability for data collected during the approach and landing flight segment of N40 and the FII aircraft at Wiesbaden.

As shown in Table 6.1-5 the required probability of reception within 10 nmi varies from 48.8% (i.e., Eurocontrol requirement for 2500 ft runway separation) to 90% (i.e., RTCA MASPS requirement for 1000 ft runway separation) in order to insure the PRM state-vector update rate requirements are satisfied . The measured reception performance generally exceeded 80% for all ranges within approximately 28 nmi. The short range reception probability was generally lower for Extended Squitters broadcast by the FII aircraft as compared to broadcasts from N40. An examination of the update period revealed that the ADS-B reports were consistently output by the ground station's LDPU for N40 at 1 second intervals with no exceptions and for the FII aircraft at 1 second intervals with the exception of a single case where the update period was 2 seconds. This exception for the FII aircraft occurred 5 seconds before the ADS-B reports indicated the FII aircraft was on the surface and may have been the result of line-of-sight limitations of the ground station location.

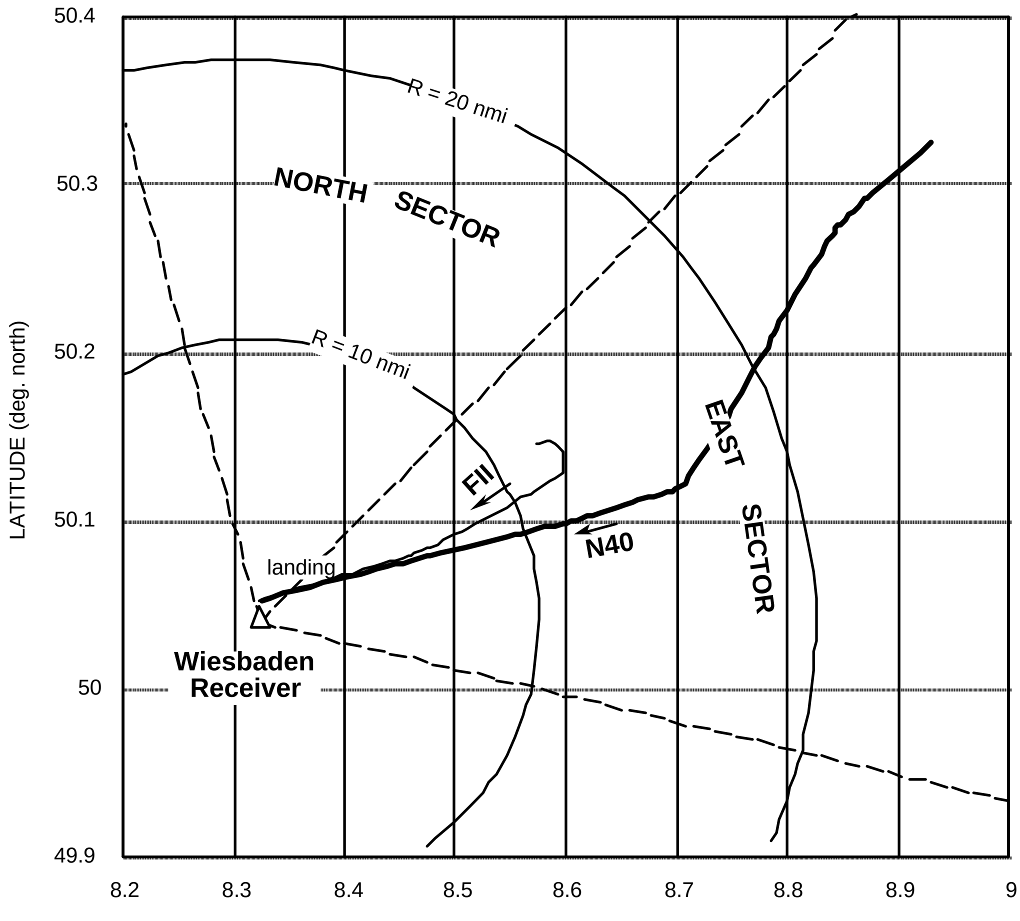


Figure 6.4.3-11. Approach and Landing Ground Track, 22 May

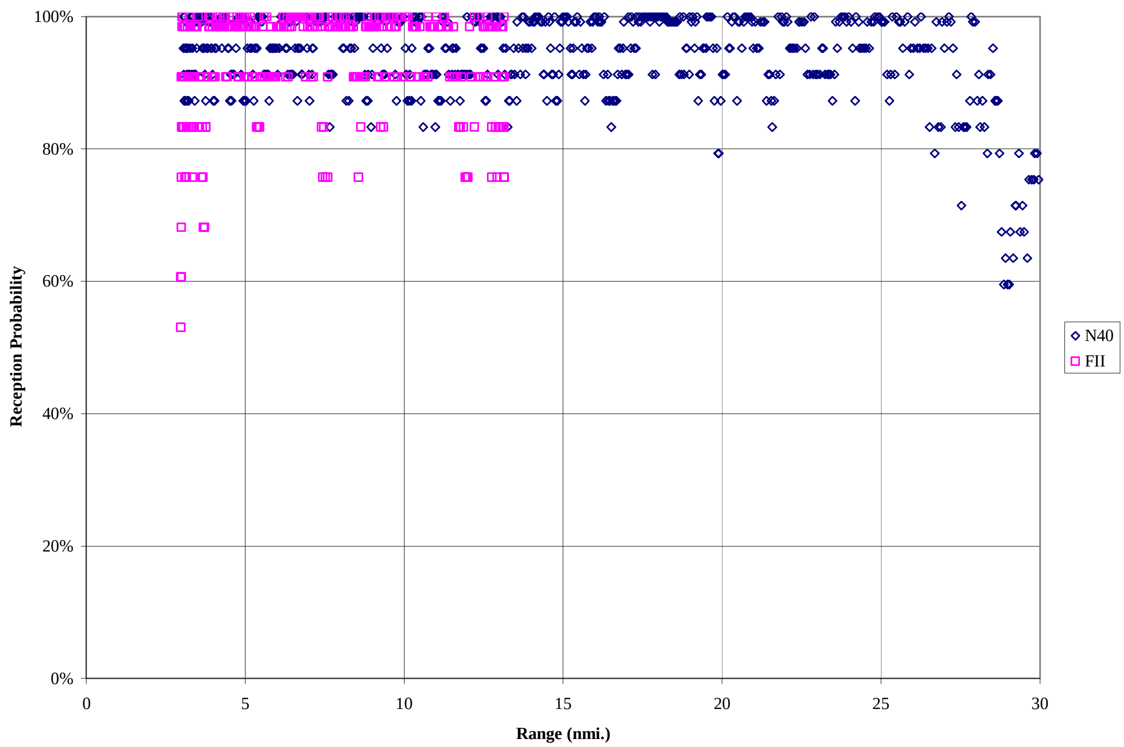


Figure 6.4.3-12. Reception Probability for PRM Application, 22 May

6.4.3.4 Air-to-Ground Measurements on 24 May

All three project aircraft participated in the data collection on May 24. During the data collection at the Wiesbaden ground station a British Airways target of opportunity was also observed. A plot of the ground tracks of N40, NLR aircraft and the target of opportunity observed during the data collection is presented in Chapter 4 of this report.

6.4.3.4.1 En Route Surveillance

The flight profile for the N40 resulted in only short-range data (i.e., <28 nmi) being collected by the Wiesbaden ground station for this target. Data was collected from FII aircraft at ranges between approximately 37 nmi and 53 nmi while in the ground station's primary coverage area. For the NLR aircraft data was collected on its outbound leg at ranges between 53 nmi and 97 nmi and for the inbound leg at ranges between 75 nmi and 101 nmi while in the ground station's primary coverage area. Limited data was collected from BA-400652$_h$ at ranges from approximately 5 nmi to 21 nmi as it quickly passed into then out of the ground station's primary coverage area. Figure 6.4.3-13a plots the reception probability vs. range for targets in the ground station's primary coverage area. Figure 6.4.3-13b includes additional Extended Squitter reception results for targets in the extended coverage area. Only data collected from targets at altitudes above 18,000 ft is included in the en route data set.

Appling the constraints for en route targets in the ground station's primary coverage area resulted in not reporting much of the longer range data from the FII aircraft and from BA-400652$_h$ as a part of this en route air-ground surveillance data set. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the en route air-to-ground surveillance requirements varies between 15% (U.S. MASPS and ICAO SARPs requirements) to 23.3% (Eurocontrol enhanced ATS requirements). The results obtained from the data collected on May 24 for targets within the ground station's primary coverage area did not include any data for ranges beyond 101 nmi. The only data for ranges beyond 53 nmi was for the NLR aircraft. Generally the results for all aircraft at ranges within 80 nmi indicates a probability reception exceeding 50%. The single exception is the sharp drop in reception probability at short-range (approximately 3 nmi) which can be attributed to the target aircraft transitioning the ground station antenna's cone of silence. This occurred as BA-400652$_h$ over flew Wiesbaden at an altitude of approximately 37,000 ft and just as the aircraft entered the ground station's coverage area. This effect is exaggerated on the plot by the 24 second sliding (trailing) window technique used to calculate the reception probability.

Reception from the NLR aircraft was erratic at ranges of greater than 80 nmi. This was especially the case during the aircraft inbound leg toward Wiesbaden. This may indicate equipment problems on the NLR aircraft or perhaps was the effect of having a less than ideal aircraft antenna placement that resulted in an sub-optimal antenna pattern. This same effect was noted in the reception of transmissions from the NLR aircraft by the Langen ground station and by other project aircraft. All data within the en route data set for May 24 is consistent with the en route air-to-ground surveillance requirements for ranges within 85 nmi. Only data from the NLR aircraft was available for ranges greater than 53 nmi and the results for the NLR aircraft indicated erratic reception performance levels as noted above.

For this specific date, the bulk of the available performance data for ranges beyond 90 nmi came from targets within the ground station's extended coverage area. Data collected from these targets shows generally good performance, with reception probabilities generally above 20%, out to ranges on the order of 150 nmi.

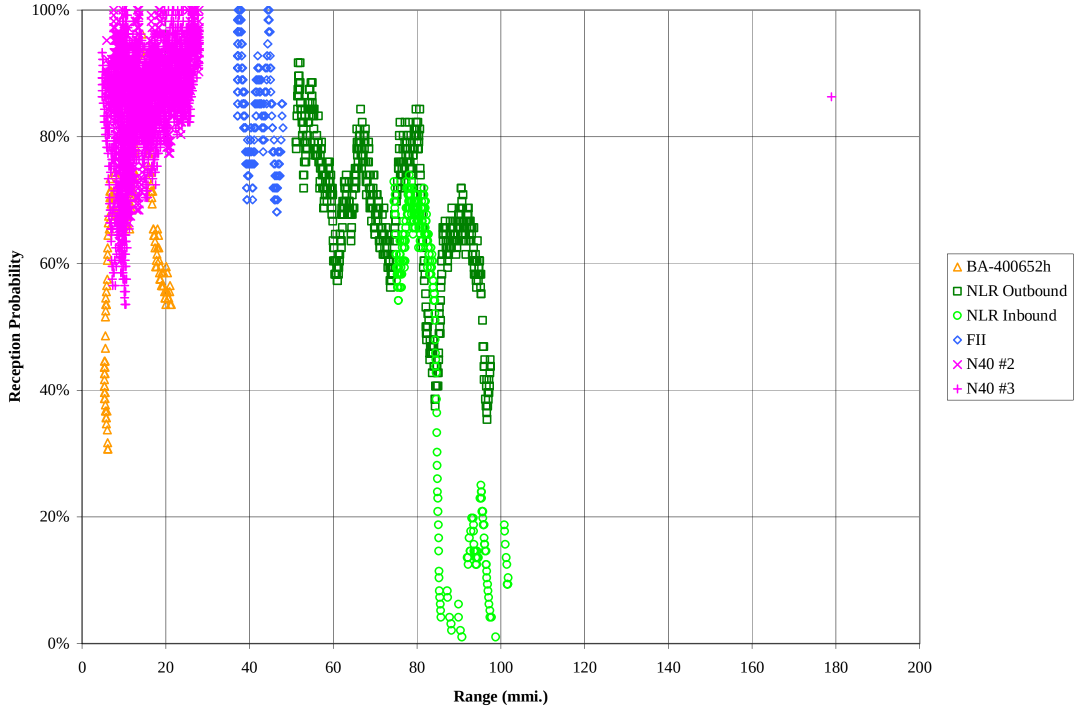


Figure 6.4.3-13a. En Route Reception Probability for Primary Coverage Area, 24 May

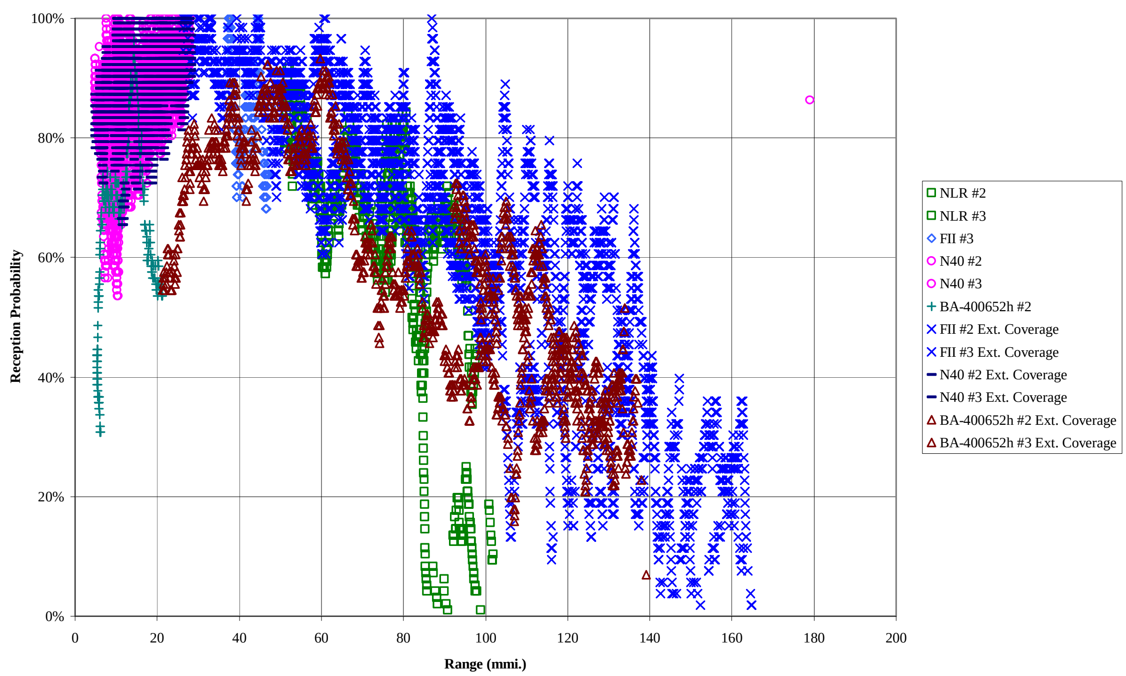


Figure 6.4.3-13b. En Route Reception Probability for Primary & Extended Coverage Areas, 24 May

6.4.3.4.2 Terminal Surveillance

The flight profile for N40 resulted in only short-range data (i.e., <28 nmi) being collected by the Wiesbaden ground station for this target as part of the terminal data set. Data was collected from the FII aircraft at ranges between approximately 3 nmi and 38 nmi Date from the NLR aircraft was collected at ranges between 19 nmi and 60 nmi (the terminal range limit). Figure 6.4.3-14 plots the reception probability vs. range. Only data collected from targets within the ground station's primary coverage area and at altitudes between 1000 ft and 18,000 ft is included. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the terminal air-to-ground surveillance requirements varies between 32.3% (U.S. MASPS and ICAO SARPs requirements) to 36.9% (Eurocontrol enhanced ATS requirements).

The results from the data analyzed for May 24 indicates that with one exception the measured performance well exceeded the terminal air-to-ground surveillance requirements with the Extended Squitter reception probability generally exceeding 53% out to the 60 nmi terminal coverage limit. As with the en route case the reception of Extended Squitter transmissions from the NLR aircraft on its inbound leg showed erratic performance. As noted for the en route case this may have results from issues with the NLR aircraft avionics or antenna pattern. The NLR data for this inbound leg is incomplete as a result of the aircraft reporting an emergency situation after which time the onboard ADS-B transmissions were halted.

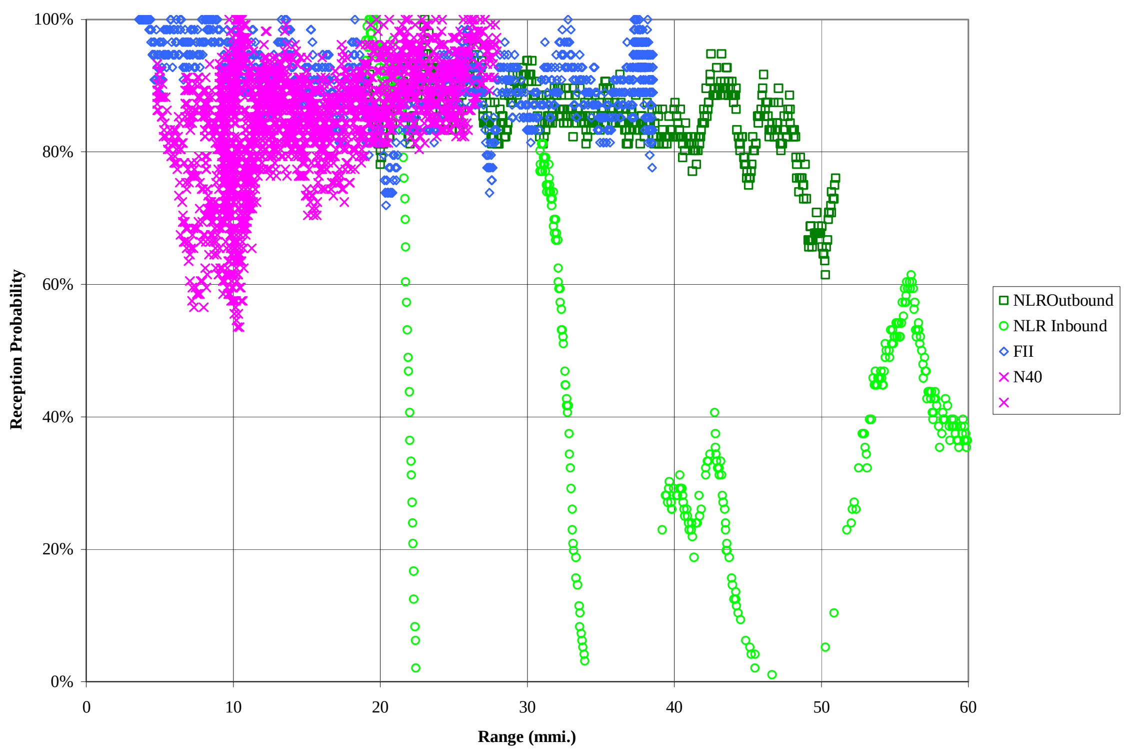


Figure 6.4.3-14. Terminal Reception Probability, 24 May

6.4.3.4.3 PRM Surveillance

The data collected by the Wiesbaden ground station was analyzed in order to understand if the level of performance that could be provided by a single ground station could satisfy the PRM application requirement. The PRM application has the shortest air-to-ground range requirements but imposes the most demanding requirements for reception probability. For the PRM performance analysis, a maximum range of 30 nmi or the point at which the aircraft turned onto its final approach was considered. Note that as indicated in Table 6.1-2 the RTCA ADS-B MASPS only specifies the PRM reception performance to a range of 10 nmi. Figure 6.4.3-15 plots the project aircraft flight segment considered for this analysis. Figure 6.4.3-16 plots the Extended Squitter reception probability for data collected during the approach and landing flight segment of N40, FII and the NLR aircraft at Wiesbaden. Due to an emergency on the NLR aircraft experienced on its approach to Wiesbaden, the ADS-B was shut down and as a result only a very modest amount of data applicable to the PRM application is available from the NLR aircraft. The available NLR data was while the aircraft was approximately 20 nmi range from Wiesbaden.

As shown in Table 6.1-5 the required probability of reception within 10 nmi varies from 48.8% (i.e., Eurocontrol requirement for 2500 ft runway separation) to 90% (i.e., RTCA MASPS requirement for 1000 ft runway separation) in order to insure the PRM state-vector update rate requirements are satisfied . The measured reception performance for the FII aircraft and N40 generally exceeded 80% probability of reception for ranges out to approximately 20 nmi. The reception probability was generally lower for Extended Squitters broadcast by the FII aircraft as compared to broadcasts from N40. An examination of the update period for the FII aircraft revealed that the ADS-B reports were consistently output by the ground station's LDPU at 1 second intervals with the exception of a single 2 second interval occurring just 2 seconds before the aircraft reported being on the surface which may have resulted from line-of-sight limitations of the ground station location. An examination of the update period for N40 revealed that the ADS-B reports were consistently output by the ground station's LDPU at 1 second intervals with no exceptions.

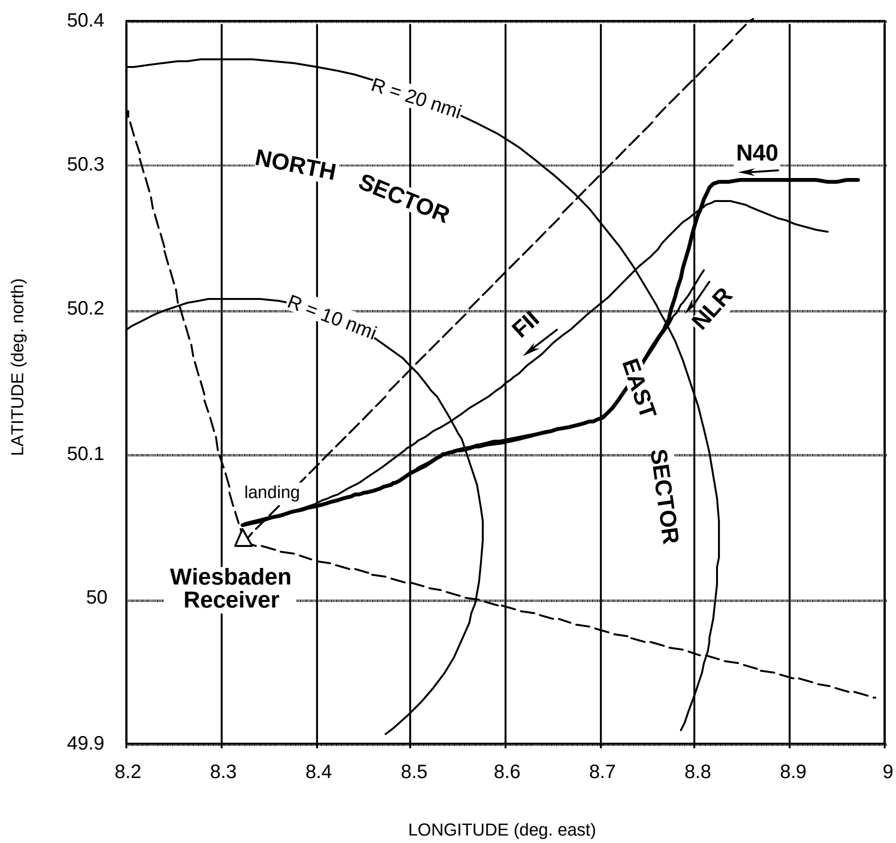


Figure 6.4.3-15. Approach and Landing Ground Track, 24 May

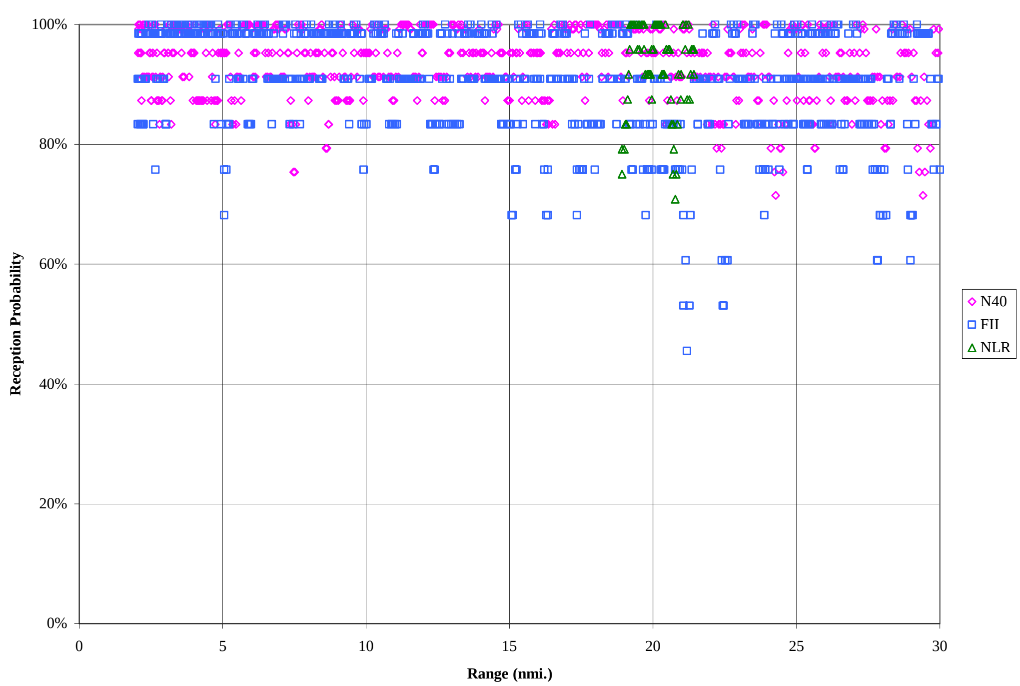


Figure 6.4.3-16. Reception Probability for PRM Application, 24 May

6.4.3.5 Air-to-Ground Measurements on 25 May

Of the project aircraft only N40 participated in the data collection on May 25. This was the final data collection flight. During the data collection at the Wiesbaden ground station, one British Airways target of opportunity were also observed. However, this target of opportunity did not pass through the ground station's primary coverage area and thus is in included in the results reported below.

6.4.3.1.1 En Route Surveillance

Figure 6.4.3-17a plots the reception probability vs. range for targets within the ground station's primary coverage area. Figure 6.4.3-17b includes additional Extended Squitter reception results for targets in the extended coverage area. Only data collected from N40 while at altitudes above 18,000 ft is included in this en route data set. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the en route air-to-ground surveillance requirements varies between 15% (U.S. MASPS and ICAO SARPs requirements) to 23.3% (Eurocontrol enhanced ATS requirements). Although no long-range data beyond 118 nmi was collected on May 25 for targets with the ground station's primary coverage area. The results obtained indicate that the requirements were readily satisfied at out to this range. The probability of reception was greater than 65% out to the maximum range of the data set (i.e., 118 nmi) for the primary coverage area except for a single brief interval occurring at a range of approximately 83 nmi. At this point the reception probability briefly dropped to a minimum value of approximately 38% as N40 was executing a maneuver on it inbound flight path returning toward Wiesbaden. The additional data collected from the extended coverage area shows generally acceptable performance out to ranges in excess of 150 nmi.

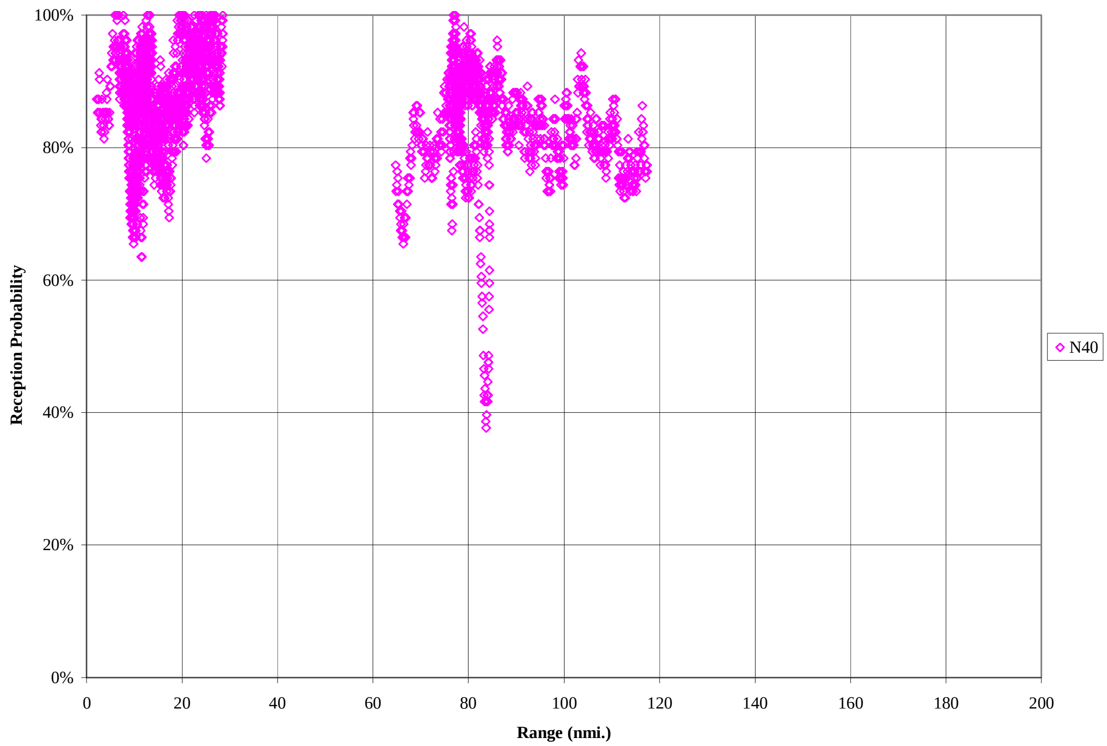


Figure 6.4.3-17a. En Route Reception Probability for Primary Coverage Area, 25 May

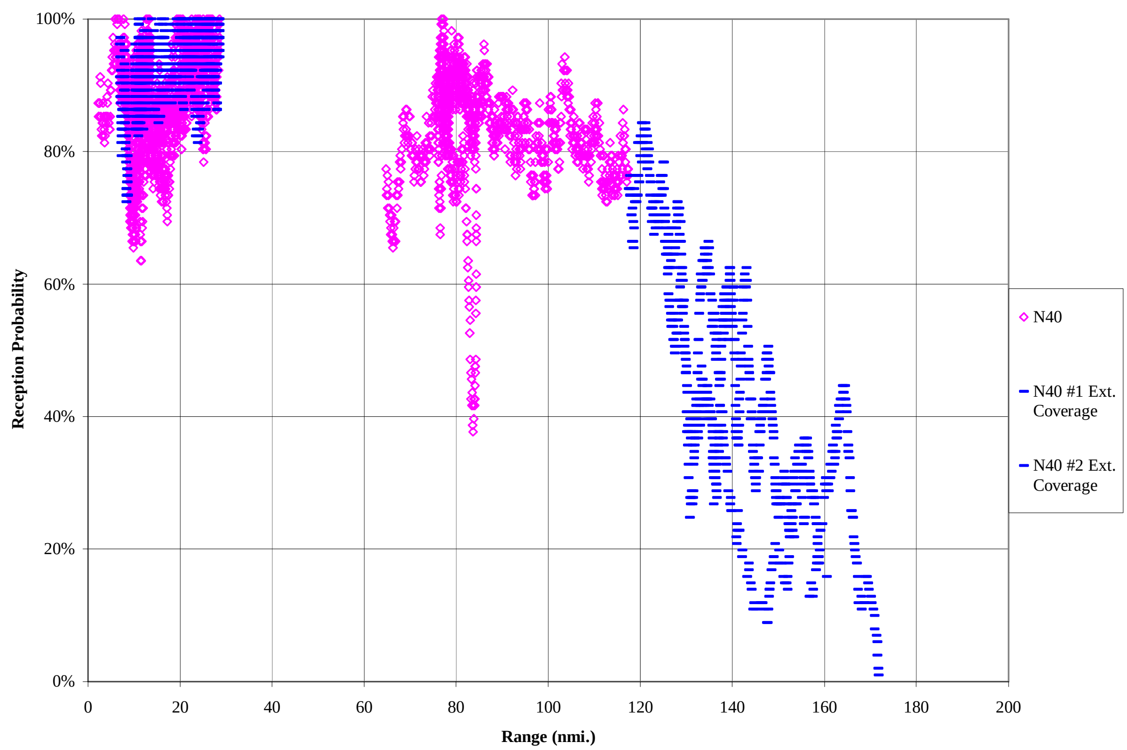


Figure 6.4.3-17b. En Route Reception Probability for Primary & Extended Coverage Areas, 25 May

6.4.3.5.2 Terminal Surveillance

The flight profile for N40 resulted in data being collected by the Wiesbaden ground station for this target on its inbound flight leg. Figure 6.4.3-18 plots the reception probability vs. range. Only data collected from N40 while within the ground station's primary coverage area and at altitudes between 1000 ft and 18,000 ft is included. As listed in Table 6.1-5 the probability of squitter reception necessary to satisfy the terminal air-to-ground surveillance requirements varies between 32.3% (U.S. MASPS and ICAO SARPs requirements) to 36.9% (Eurocontrol enhanced ATS requirements. The measured reception probability shown in the plot exceeds 70% for all ranges out to the terminal airspace coverage limit of 60 nmi. This well exceeds the required performance levels for terminal air-to-ground surveillance.

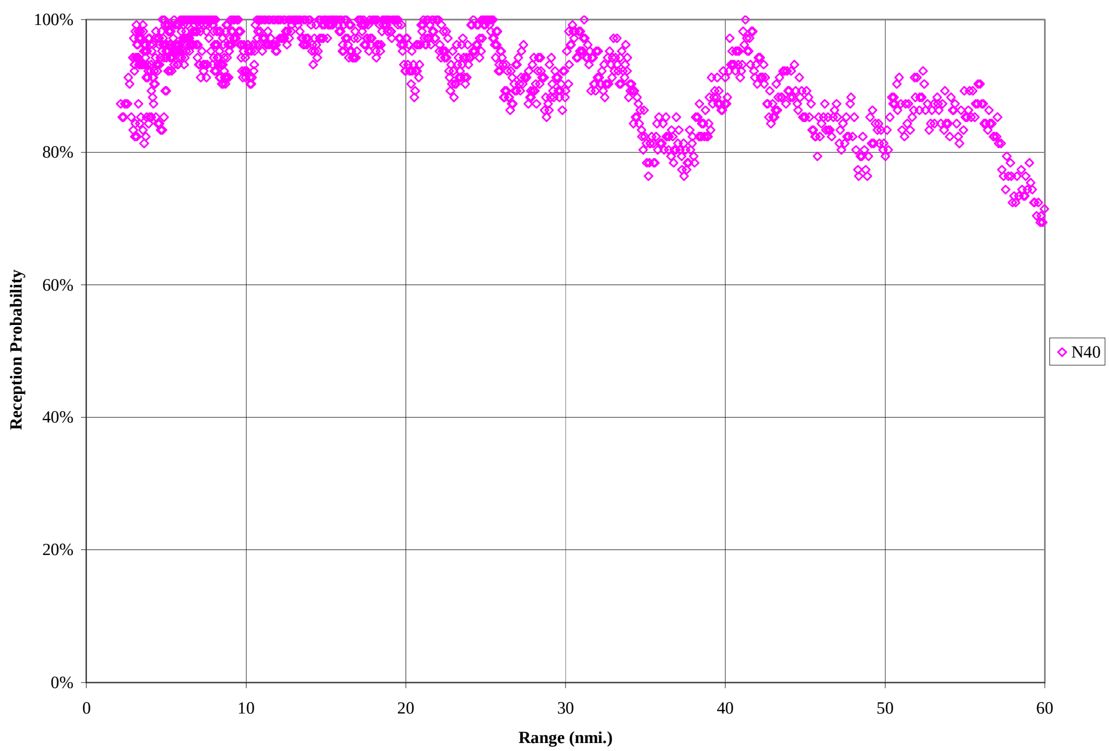


Figure 6.4.3-18. Terminal Reception Probability, 25 May

6.4.3.5.3 PRM Surveillance

The data collected by the Wiesbaden ground station was analyzed in order to understand if the level of performance that could be provided by a single ground station could satisfy the PRM application requirement. The PRM application has the shortest air-to-ground range requirements but imposes the most demanding requirements for reception probability. For the PRM performance analysis, a maximum range of 30 nmi <u>or</u> the point at which the aircraft turned onto its final approach was considered. Note that as indicated in Table 6.1-2 the RTCA ADS-B MASPS only specifies the PRM reception performance to a range of 10 nmi. Figure 6.4.3-19 plots the N40 flight segment considered for this analysis. Figure 6.4.3-20 plots the Extended Squitter reception probability for data collected during the approach and landing flight segment of N40 at Wiesbaden.

As shown in Table 6.1-5 the required probability of reception within 10 nmi varies from 48.8% (i.e., Eurocontrol requirement for 2500 ft runway separation) to 90% (i.e., RTCA MASPS requirement for 1000 ft runway separation) in order to insure the PRM state-vector update rate requirements are satisfied. The measured reception performance for N40 generally exceeded 80% probability of reception out to the 30 nmi range. An examination of the update period for N40 revealed that the ADS-B reports were consistently output by the ground station's LDPU at 1 second intervals with no exceptions.

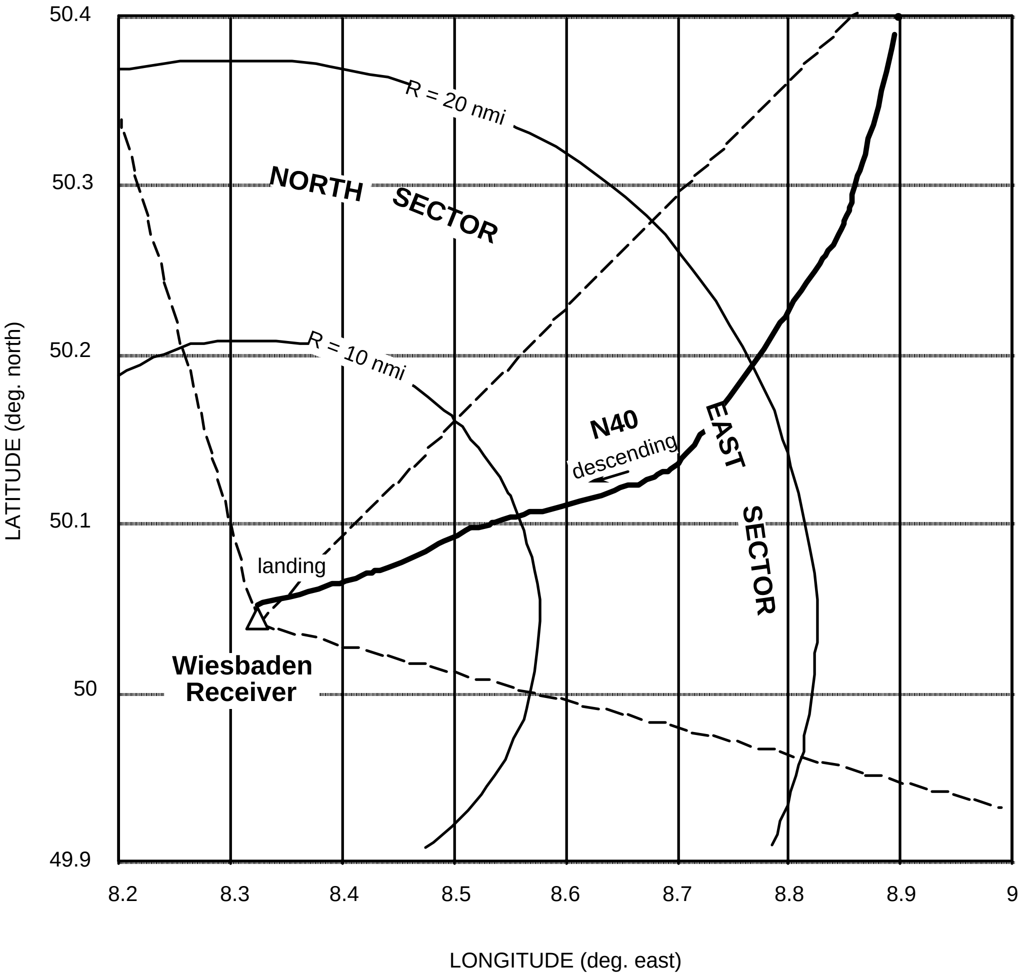


Figure 6.4.3-19. Approach and Landing Ground Track, 25 May

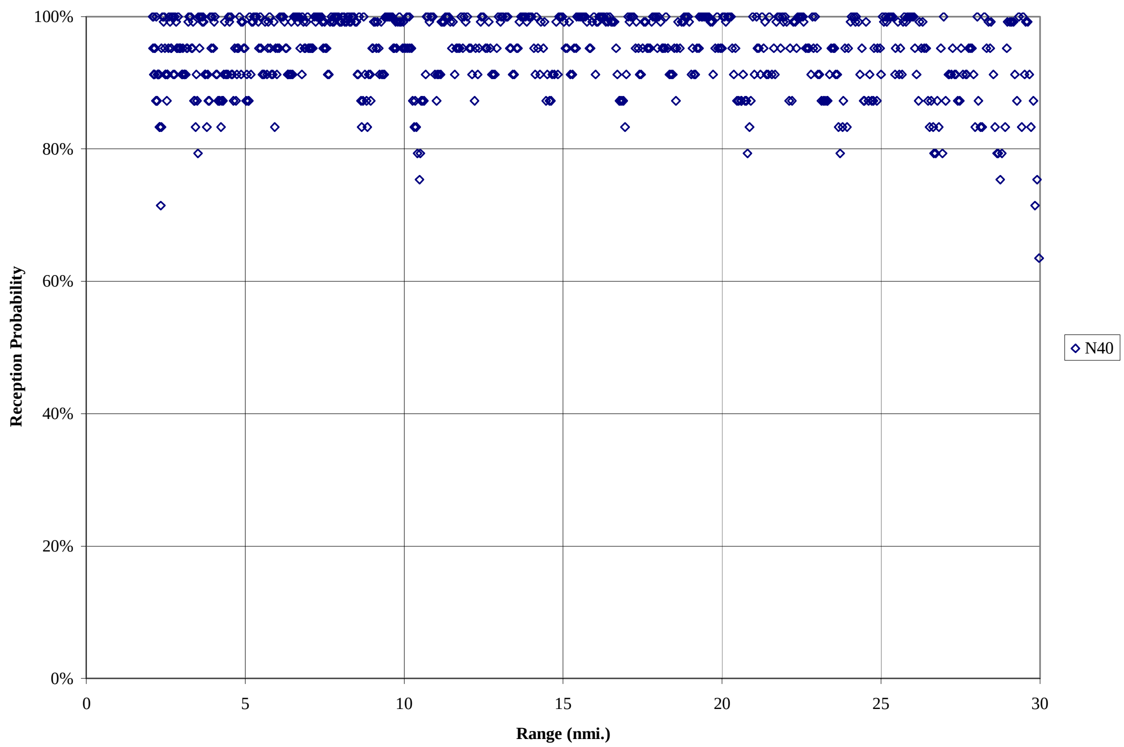


Figure 6.4.3-20. Reception Probability for PRM Application, 25 May

In summary, measured reception performance associated with PRM was excellent on all five test days, including a total of 8 landings. The measurements can be summarized as shown below. In every case, reception performance satisfied the most demanding PRM surveillance standards (1000 foot runway spacing).

Date	Landing Aircraft	Time in track (%)	No. of Missed Reports	Report Reliability (%)
19 May	N40	100	3	99.7
20 May	N40	100	0	100
20 May	NLR	100	0	100
22 May	N40	100	0	100
22 May	FII	100	1	99.8
24 May	N40	100	0	100
24 May	FII	100	1	99.8
25 May	N40	100	0	100

7. SUMMARY AND CONCLUSIONS

In May 2000, DFS, FAA and Eurocontrol, in collaboration with several industry organizations, performed Automatic Dependent Surveillance-Broadcast (ADS-B) flight trials using Mode S Extended Squitter in German airspace. A large quantity and wide variety of data were recorded. After analyzing the data it was concluded that these measurements were very successful. Measurements of interference environments and reception performance have been made in a variety of conditions, involving three project aircraft and several in-service, British Airways aircraft. Both airborne and ground-based receptions were analyzed, and several receiving systems were evaluated. Equipment failures occurred in a few cases, but these have been isolated, and a large amount of valid data has been extracted, as documented in this report.

7.1 TEST CONFIGURATION

Airborne and ground facilities were assembled to make detailed measurements of the Radio Frequency (RF) Secondary Surveillance Radar (SSR) channel utilization and the air-to-air and air-to-ground performance of Extended Squitter.

Ground stations were installed at DFS facilities at Langen and at the U.S. Army Air Base at Wiesbaden. The Langen station included three separate Extended Squitter receivers, connected such that measurements were made through a pair of sectorized, directional antennas. The Wiesbaden ground station was configured with an Extended Squitter receiver, connected to a sectorized, directional antenna, and a digitizing, video recorder (the FAA RF Measurement Facility) connected to an omnidirectional antenna. The Wiesbaden and Langen ground stations also included a test transponder transmitting Extended Squitter messages through an omni directional antenna to enable evaluation of the uplink (ground-to-air) Extended Squitter performance.

Three project aircraft participated in the Frankfurt trials. An NLR Metroliner was configured with an Extended Squitter receiver/transmitter unit. A Beech King Air, equipped and flown by Flight Inspection International personnel, was also configured with an Extended Squitter receiver/transmitter unit. An FAA Boeing B-727, was configured with an Extended Squitter receiver/transmitter, a separate TCAS-integrated Extended Squitter receiver, and several receivers designed to record the RF channel utilization at 1030 MHz and 1090 MHz. The FAA B-727 was the principal environmental measurement platform for the Frankfurt trial. In addition to the project aircraft, several Extended Squitter targets of opportunity were observed. British Airways has equipped several in-service Boeing B757 aircraft with Extended Squitter transmitter installations (integrated with their TCAS installations) and these targets of opportunity served as valuable examples of an early commercial Extended Squitter implementation.

The focus of the ADS-B evaluations described in this report was on terminal and en route operations. The flight test profiles were appropriate for the assessment of longer range air-to-air ADS-B performance, i.e., separation assurance and sequencing, flight path deconfliction, and autonomous operations. Most of the flight profiles were flown within existing high density terminal and en route airspace. At the end of some flight profiles the approaches flown by project aircraft to Wiesbaden approximated parallel approach conditions. In addition, data was gathered using the TCAS 2000 receiver to enable the future assessment of TCAS II Hybrid Surveillance performance.

Test facilities were also configured to allow the assessment of air-to-ground performance. The ADS-B ground stations used for the evaluation were representative of units configured to provide ATC surveillance services in high traffic density terminal and en route environments. Unfortunately the constraints of available ground sites limited the evaluation of longer range air-to-ground performance to relatively high elevation targets in certain preferred directions covered by the ground directional antennas. The data gathered support validation of ADS-B operation in terminal operations, but do not provide as complete a basis for evaluating very long range (greater than 120 nmi) en route air-to-ground surveillance. The results of these studies contribute to a better understanding of the ability of the 1090 MHz Extended Squitter technology to satisfy certain of the other requirements for which the test configuration was not optimal.

Additional data were collected from radar sites throughout Germany during the flight test intervals. Such data served to document the aircraft density and distribution present during the flight tests.

7.2 ENVIRONMENTAL CONDITIONS

Extensive measurements were made of the RF environment in the airspace surrounding Frankfurt. ADS-B air-to-air and air-to-ground performance within this same airspace was also characterized. The RF environmental measurements were compared to measurements conducted previously in Frankfurt and at other locations in U.S. airspace.

The results confirm that Germany continues to have very high channel occupancy on the SSR interrogation (1030 MHz) and reply (1090 MHz) channels, relative to measurements made at other sites throughout the world. The ATCRBS fruit rate measured in Frankfurt was 30 to 50 % higher than that measured in Los Angeles in 1999. Mode A and Mode C interrogation rates remain at the same level as 1995 while Mode S and Airborne Collision Avoidance Systems (ACAS) intermode interrogation rates increased significantly with the European ACAS II mandate. Traffic counts indicate a traffic increase of about 50% over Germany since 1994. Although comparable fruit measurements were not made in 1995 and 2000, and thus a direct comparison of airborne fruit rates is not possible, it appears that increases in fruit that would correspond to increases in traffic were offset to some extent by a reduction in the number of active radar sites in southern Germany.

The measured Mode S fruit rate was less than 10% of the ATCRBS fruit rate. Seventy-three percent of Mode S 1090 MHz transmissions were replies to TCAS surveillance interrogations and 23% were acquisition squitters. Extended squitter transmissions account for about 1% of the Mode S fruit rate, while replies to the single Mode S ground sensor account for less than 3%.

Fruit rates depend on both the interrogation rates seen by each aircraft and the distribution of aircraft within reception range of the affected receiver. Therefore it was an essential part of the Frankfurt trials that detailed measurements be made of the number and distribution of all aircraft that could be a source of interference to the ADS-B receivers located in the Frankfurt area. It was estimated that at least 520 aircraft were in view of the sensitive receiver installed on the FAA aircraft.

Analysis of multiple ground radar recordings reveals most aircraft were below 10,000 feet. Higher altitude aircraft were approximately uniformly distributed between 10,000 and 40,000 ft. Above 30,000 ft, the distribution was seen to be concentrated at the odd thousands, which is consistent with air traffic control practices in Europe. The median altitude Frankfurt was observed to be about 11,000 ft on work days. On the weekend this value decreased to some extent. However, this was still significantly higher than the altitude distribution in Los Angeles, where the median altitude was measured to be about 4000 ft. It was also observed that the fruit rates did not vary with altitude in general as much as interrogation rates.

Interrogation rates vary with location, time and altitude. A significant difference was observed in the altitude dependence of ATCRBS and Mode S interrogation rates. While ATCRBS interrogation rates increased with altitude, Mode S interrogation rates were observed to peak at an intermediate altitude in the Frankfurt area.

ATCRBS interrogations rates have decreased in southern Germany since 1995, but remain at the same level in the Frankfurt area. An increase in Mode S interrogations was observed, which likely arose from the European ACAS mandate.

Germany, like other States in core Europe, mandated Mode S equipage for IFR traffic from 2003 onwards and for VFR traffic from 2005. This was done to mitigate the current Mode A code shortage and to be able to cope with the increasing air traffic in a safe manner (reduce RF load). Currently most of the aircraft flying in Germany are Mode S equipped and an increase in the Mode S equipage is to be expected. In the near future about half the DFS radar sensors will transition from ATCRBS to Mode S. This will reduce the fruit load under the same traffic density conditions.

More specific results are listed below:

(a) The RF environment surrounding the Frankfurt area continues to exhibit very high rates of SSR interrogations and reply rates. The measured ATCRBS interrogation rates in the immediate Frankfurt area peaked at well over 300 interrogations per second (probably in part due to a local radar with sub-optimum sidelobe suppression); the interrogation rates within approximately 30 nmi of Frankfurt averaged 250-300 interrogations/second, which is nearly a factor of two higher than rates measured in the LA Basin airspace in June 1999. These interrogation rates reflect the high density of ground military interrogators, many of which are configured with relatively high pulse repetition frequencies, as well as the high density of airborne TCAS interrogators. TCAS equipage in particular has increased dramatically since the previous measurements made in the Frankfurt area (1995).

(b) Mode S interrogation rates averaged between 150-200/second throughout the measurement period. Note that because of the point-to-point nature of Mode S protocols, each Mode S interrogation elicits a single reply rather than the many replies that an ATCRBS interrogation reply may elicit.

(c) The combination of high interrogation rates with moderate to high traffic density produces very high ATCRBS reply rates. ATCRBS reply rates of 35-40K/second (cumulative rate of replies whose power at the receive antenna exceeded –87 dBm) were observed in the immediate Frankfurt area; these rates are approximately 30-50% higher than ATCRBS reply rates measured in the Los Angeles Basin in 1999. These reply rates in southern Germany (near Munich) dropped to less than half the rates measured over Frankfurt.

(d) Mode S reply rates were a modest fraction of the ATCRBS reply rates. Even with the substantial increase in the number airborne TCAS-equipped aircraft near Frankfurt, Mode S reply rates were under 1000/second throughout the measurement period. The May 2000 interference environment for the 1090 MHz channel in the Frankfurt area is dominated by ATCRBS replies.

7.3 EXTENDED SQUITTER PERFORMANCE

Three sources for the ADS-B performance requirements have been considered for this study. Currently the most comprehensive source for ADS-B performance requirements is the RTCA Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B), DO-242 [Ref. 6]. The second source of ADS-B requirements considered was the ICAO Manual of Air Traffic Services Data Link Applications, ICAO Document 9694 [Ref. 18], and the third source of requirements considered were preliminary European requirements for ADS-B (Tamvaclis et al) provided by the Eurocontrol ADS Programme, which still require harmonization at the time of this report (May 2001).

The performance evaluation focuses on requirements concerning the maximum acceptable state vector and intent (Trajectory Change Points – TCP) update intervals (to a specific confidence level =95%) as well as initial acquisition range and tracking range. Performance requirements are taken from the RTCA ADS-B MASPS (DO-242) and a draft proposition from the Eurocontrol ADS Programme referring to air-to-ground surveillance and air-to-air autonomous operations[1]. Analysis took into account the bearing of the target aircraft since MASPS performance requirements for flight path deconfliction specify the required range per target quadrant (forward, aft, side).

The flight tests took place in a high-density terminal and en-route airspace. It can be argued that the most demanding air-to-air range DO-242 requirements for flight path deconfliction were not specified for such an environment. Nevertheless, one of the

[1] Both the RTCA and Eurocontrol requirements are undergoing further development. It is therefore possible that new or revised requirements may emerge from these ongoing activities

desired goals of the evaluation was to determine the range at which such an application might be feasible over extended squitter in a high traffic density and high RF interference environment.

The three project aircraft and the British Airways (BA) targets of opportunity broadcasted position, velocity and in most cases Flight ID squitters but not TCP or mode/status squitters. None of the 1090 MHz receivers were fully MOPS compliant. Consequently update interval and tracking/acquisition range performance was estimated from the per message reception probability measurements using a theoretical model described in Chapter 6.

In all cases analyzed in more detail, the airborne receivers were either LDPUs or TCAS 2000 avionics, while the ground receivers were the ANS-MAGS station and the ERA station at Langen and two LDPUs (one at Langen and one at Wiesbaden). All ground stations at Langen shared the same sector antenna. However, only the dual-channel LDPUs were connected to both sector beam antennas, while the ANS -MAGS and ERA receivers were connected to a single sector beam antenna.

No errors were observed that would have appeared in the report of ADS-B MOPS compliant avionics. A few errors were observed only in the LDPU logs in both air-to-air and air-to-ground reception (described in 4.4). The frequency of such errors was lesser in the air-to-ground case and regardless such errors did not affect the performance measurements.

It should be noted however that the Frankfurt 1090 MHz Extended Squitter trials involved a small number of Extended Squitter equipped aircraft, and hence they cannot show how the 1090 MHz system would perform with a large number of aircraft. These trials were performed in a real environment with many sources of TCAS acquisition squitters and severe ATCRBS interference. However, additional investigations including simulations will be necessary to address other issues like self interference.

7.3.1 Air-to-Air Performance

In the Frankfurt environment the measurements are consistent with the state vector and intent requirements and 40 nmi range requirements for the separation assurance application. At ranges beyond 40 nmi, as required to support a long range deconfliction application, the measured update rates would typically support the MASPS application requirements (state vector and intent information) up to a range of 75 nmi, and state vector information alone to 90 nmi reliably, in most cases.

Concerning the Eurocontrol proposed criteria for autonomous operations to 150 nmi range, which include the reception four TCPs, reception probability was observed to be generally adequate for ranges up to 75 nmi.

Performance measurements with the TCAS based receiver were generally similar to that measured with the LDPUs. However, the ranges were consistently shorter due to the less sensitive receiver and time sharing with TCAS surveillance functions.

There were certain exceptions to the effective air-to-air reception range observed showing both shorter and longer range performance. The worst case performance observed during the evaluation was an effective air-to-air range on the order of 40 nmi. However, it was subsequently demonstrated that by applying the advanced reception techniques the effective reception range in this worst case situation would have been extended to approximately 60 nmi.

The air-to-air data and performance evaluations indicate the following more specific conclusions:

(a) Update requirements for intent information dominate long range performance.

(b) The observed reception probabilities would be adequate to meet State Vector tracking MASPS requirements up to 80 to more than100 nmi.

(c) The observed reception probabilities would be adequate to meet TCP and TCP+1 update MASPS requirements, as applicable to long range deconfliction in the forward quadrant, up to 60 to 90 nmi.

(d) The observed reception probabilities would be adequate to meet four-TCP update[2] Eurocontrol requirements, applicable to autonomous operations in the forward quadrant, up to 50 to 90 nmi.

(e) Update rate and range requirements for long range deconfliction were supported for side and aft quadrants.

(f) Generally Extended Squitters broadcast from BA targets of opportunity were received with higher probability than were the broadcasts from project aircraft at similar ranges. This is probably because the BA aircraft flew essentially high altitude, level, straight trajectories and the BA aircraft antenna installations are expected to have fewer antenna gain variations than the installations on the smaller project aircraft.

(g) There were some short periods, notably on the 24 May, where significant performance drops were observed (35 versus 60 nmi range for two TCP and 60 versus 90 nmi range for state vector tracking). These degradations were linked to reductions in the received signal level. Experimental 1090 MHz antenna placements on the FII and NLR aircraft and possible intermittent connections may have contributed to the observed signal level reductions.

[2] A requirement for four TCPs has been proposed by the Eurocontrol ADS Programme and is not supported by the current 1090 MOPS. For the calculations, it has been assumed that each of the four TCP is broadcast as a separate squitter every 1.7 sec.

7.3.2 Air-to-Ground Performance

Air-to-ground reception capabilities were generally line-of-sight limited and an air-to-ground effective reception range in the Frankfurt environment of at least 150 nmi appears feasible with a properly sited, sectorized ground antenna.

Air-to-ground reception performance while the aircraft were on final approach to land at Wiesbaden, based on measurements from the 1090 MHz ADS-B ground station at Wiesbaden, indicate that 1090 MHz ADS-B is capable of satisfying the requirements for a PRM application.

(a) Three different receivers were evaluated at two sites. Differences were observed in the performance of the LDPU, ANS-MAGS and ERA receivers, with the LDPU the most capable and the ERA receiver the least. This is believed to be due the fact that the LDPU was the only receiver that implemented error correction. All three receivers demonstrated performance adequate for terminal operations; the differences were most apparent in long range, en route scenarios. The air-to-ground performance evaluation indicates the following more specific conclusions. .

(a) Terminal Surveillance

1. On both Langen and Wiesbaden LDPUs as well as on the ANS-MAGS station, the observed reception probabilities would be adequate to meet the Eurocontrol classical and enhanced ATS surveillance state vector and four-TCP update interval maxima up to more than the required 60 nmi.

2. The only exception observed may have resulted from issues with the NLR aircraft avionics or its antenna patterns. Even under those circumstances 35 to 40 nmi coverage were achieved.

(b) En-Route surveillance:

1. Performance of the LDPU stations at Langen and Wiesbaden would be adequate to meet Eurocontrol requirements up to 150 nmi, including the four TCPs.
2. The observed reception performance of the ANS-MAGS station would be adequate to meet ICAO and Eurocontrol state vector update requirements up to 100-140 nmi. It would also be adequate to meet Eurocontrol four TCP requirements up to more than 100 nmi.

3. The only exceptions observed concerned low altitude flights, which were affected by the elevated radio horizon of the ground stations, and the return flight of NLR on the 24 May, which has been mentioned earlier.

4. Note that the Eurocontrol classical and enhanced ATS surveillance performance requirements are stricter than those specified in ICAO 9694, and they are dominated by the range requirement for four TCPs[2].

(c) Parallel Runway Monitoring (PRM)

1. The location of the Langen station was not suitable as a PRM site (not situated with appropriate visibility to a runway end). The Wiesbaden station, which was near the Wiesbaden runway, was sited appropriately for PRM.

2. The data recorded at Wiesbaden was analyzed with respect to the ADS-B standards for supporting PRM. The analysis considered ranges out to 30 nmi or the point at which aircraft turned onto final approach. The five days of testing included a total of 8 landings at Wiesbaden.

3. In every case analysed air-to-ground surveillance was 100 percent, in the sense that the aircraft was always in track. LDPU state vector updates were generated by the LDPU at a steady rate of 1/second with very few exceptions. The standards for update reliability were satisfied in every case.

7.3.3 Factors Affecting Extended Squitter Reception

Successful reception of Extended Squitters is fundamentally dependent on the signal-to-interference (S/I) ratio and on the type of decoding algorithm used within the Extended Squitter receiver. Examination of the measured ADS-B reception performance generally demonstrated that factors that affected the S/I ratio had corresponding effects on the squitter reception probability. Either decreasing the received power level at the receiver antenna or increasing the interference level reduced the probability of reception of the particular squitter. This is particularly important in assessing the factors likely to affect the air-to-air Extended Squitter reception performance.

The received power referred to the receiving antenna is directly affected by all the elements included in any link budget calculation, which include transmitter power at the Extended Squitter source, transmit antenna gain, and receive antenna gain. In particular, antenna gain variations may substantially degrade and ultimately limit the long range squitter reception performance. Data from the Frankfurt measurements demonstrated variability in squitter reception probability that varied directly with received power at constant range against a single target. Where this variability is substantial (as in the NLR and FII transponder installations) the range at which acceptable squitter reception probability is observed is reduced.

Conversely, the interference environment effectively raises the minimum threshold at which Extended Squitters may be received reliably. An example of this was demonstrated by examining the reception of squitters from a British Airways target of opportunity using the LDPU on N40 on two different days. N40 was orbiting over Frankfurt on both days, but the measured interference environment was substantially (20-30%) higher on May 24 than on May 20. Correspondingly, the minimum power level at which squitters were successfully received from a common target was increased by 2-3 dB.

Receiver architecture and the implementation of the decoding algorithm also affect squitter reception. Comparisons between the various ground-based receivers at the Langen ground station demonstrated that while performance was enhanced when more sophisticated error detection and correction algorithms were used, surprisingly good performance was obtained even with a ground-based receiver with very limited error detection and correction. In the airborne environment a similar comparison was made between the TCAS-integrated squitter receiver and the stand alone LDPU where the advantages (in the LDPU) of greater sensitivity, an antenna with an integral preamplifier, and no sharing of the listening window with whisper-shout TCAS interrogations, resulted in substantial improvement in the long range squitter reception performance.

Although useful performance was obtained from both the LDPU and the TCAS-based squitter receivers in the Frankfurt trials, additional analysis was performed to assess whether these as-built units represented the best performance possible. In fact, offline analysis of Frankfurt data (specifically the digitized 1090 MHz video recordings) demonstrated that the enhanced reception techniques (as described in Appendix B and as defined in the Appendix I of the 1090 MHz ADS-B MOPS and beyond the algorithms implemented in the trials equipment) appear to be capable offering a significant performance gain, in terms of the effective air-to-air reception range of extended squitters. Based on the Frankfurt measurements such algorithms would not be necessary to support separation assurance applications in current interference environments, but would be necessary to meet the longest range application (long range deconfliction) should those applications be implemented in current and future high interference environments.

Factors which affect the S/I interference ratio may be exploited to improve squitter reception performance. For instance, shaping antenna patterns to provide azimuth dependent gain can reduce the effective interference environment while maintaining constant link margin in a preferred direction. This is particularly useful for ground installations where the use of sectorized antennas have been demonstrated to provide long range reception performance even in a high interference environment such as Frankfurt. The use of directional airborne antennas is also under consideration within RTCA SC-186 to enhance airborne, long range reception.

7.4 RECOMMENDED FOLLOW-ON ACTIVITIES

The use of aircraft derived data for surveillance and traffic management will improve the overall system. ADS-B is an opportunity for improvements with additional challenges. Any surveillance technique that is intended as a future replacement for the current secondary surveillance radar system in support of ATC activities must provide at least the same level of performance as the existing system. In addition, a safe implementation of new techniques is required.

In high density European airspace, it is expected that near term benefits will result from the use of ADS-B in terminal and ground movement areas, where applications like precision runway monitoring or advanced surface guidance and control systems may be considered. Depending on the geographical environment it is assumed that at least four sensors would be required to cover an airport or terminal area. In a similar way it is assumed that ADS-B en route applications in core Europe would be based on a multi-sensor system. Any requirement for a specific surveillance application would have to be considered under several conditions including the assumption of an appropriate sensor configuration.

In U.S. airspace ADS-B is expected to play a key role in supporting near term improvements in airborne terminal operations and for increasing situational awareness in surface operations.

The Frankfurt measurement activity was a very successful effort that provided detailed characterization of a very high interference RF environment and documented Extended Squitter performance in that environment. However, some of the original detailed questions have not been fully answered, and the results from the trials have suggested additional research areas that were not apparent at the outset.

The environmental measurements from the Frankfurt trials represent a valuable source of validation for simulations that will extend the limited Extended Squitter performance measurements to future ADS-B aircraft and ground equipage scenarios. In collaboration with FAA- and European-sponsored simulation efforts, the trials data may be used as a basis for modeling the 1090 MHz interference environments and as a benchmark for estimating Extended Squitter reception performance. Such simulations should include an accurate model of radar/transponder interactions, including realistic transponder suppression effects. The recorded environmental data will also serve as the basis for development of test procedures for advanced squitter decoding algorithms included in the 1090 MHz MOPS (Rev. A). Other work sponsored by FAA and Eurocontrol is in progress to address concerns regarding the impact of full fleet equipage with Extended Squitter and the deployment of TIS-B. The measurements recorded in the Frankfurt trials are a valuable source of validation for those simulations and analyses.

Data was collected at Wiesbaden that would enable estimates to be made of the fruit rate seen by a ground, omnidirectional antenna. These data have not yet been analyzed, and the task of completing this assessment is another valuable follow-up area. Data were also collected during over flight of Paris and London by the FAA aircraft. Analysis of this data could yield estimates of fruit rates at these additional sites.

Further ground station development is necessary to support various air-to-ground applications proposed for ADS-B. Development of angle-of-arrival techniques for sectorized antennas may allow ground stations to provide independent azimuth estimates for received squitters. Integration of Mode S interrogation and data link protocols can provide a combination of range validation and support for Downlink of Aircraft Parameters. Investigations of a means by which such ground stations may provide backup surveillance capabilities are another area of fruitful ground station development. The output of such activities may be guidance material for inclusion and update to existing ICAO and other standards.

Various detailed analyses may be performed using the Frankfurt trials data and follow-on flight data to assess the effects of antenna pattern variations on air-to-air squitter reception performance. Quantifying the observed antenna gain effects in the trials data will assist the 1090 MOPS effort in determining the criteria for antenna installation in Extended Squitter installations. The development of a broad database of such effects will also assist in developing appropriate link budgets used in estimating Extended Squitter reception performance given a distribution of transmitter power and antenna installations that accompany fleet-wide Extended Squitter equipage.

Measurement of squitter reception on the airport surface remains necessary. Quantification of the effects of multipath and local blockage is crucial to understanding of how to site ground receiver stations and what airport coverage may be expected.

Analysis of Extended Squitter reception performance in airborne, short range, high update rate geometries was not conducted. The review of existing Los Angeles and Frankfurt data, and augmentation of simulation tools to assess the performance of Extended Squitter in such applications will be necessary prior to their deployment.

Detailed analysis of the interrogator characteristics and their effects should be conducted to identify the causes of interrogation rate “hotspots”. This may also include an investigation of the general effects of various radar operational parameters on the resulting fruit environment and a more detailed look at specific effects related to the military radar shutdown conducted during a portion of the Frankfurt trials

ABBREVIATIONS

AB	Air Base
A/D	Analog / Digital
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance Broadcast
AMCP	Aeronautical Mobile Communications Panel
AMF	Airborne Measurement Facility
ANS	Airsys Navigation Systems
ASAS	Airborne Separation Assurance System
A-SMGCS	Advanced Surface Movement Guidance and Control System
ASTERIX	All purpose STandard for Enhanced Radar Information eXchange
ATC	Air Traffic Control
ATCRBS	ATC Radar Beacon System (=SSR)
BA	British Airways
CAA	Civil Aviation Authority
dB	Decibel
dBm	Decibels relative to a milliwatt
DFS	DFS Deutsche Flugsicherung GmbH
DME	Distance Measuring Equipment
Doc	Document
DOT	Department of Transport
E	East
EUROCAE	The European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FII	Flight Inspection International
FL	Flight Level
FMC	Flight Management Computer
FTP	File Transfer Protocol
GE	German
GPS	Global Positioning System
Hz	Hertz
HQ	Headquarter
ICAO	International Civil Aviation Organization
IRF	Interrogation Repetition Frequency
LAX	Los Angeles International Airport
LDPU	Link Data Processing Unit
LL	Lincoln Laboratory
MAGS	Mode S Airport Ground Sensor
MASPS	Minimum Aviation System Performance Standards
MATS	Military Air Traffic Services
MET	meteorological
MIT	Massachusetts Institute of Technology
MHz	Megahertz
Mode A, C	Conventional SSR modes
Mode S	Selective SSR mode
MOPS	Minimum Operational Performance Standards

MRSD	Military Radar Shutdown
MTL	Minimum Trigger Level
N40	FAA aircraft
NLR	The Netherlands National Lucht- en Ruimtevaartlaboratorium
nmi	nautical miles
N	North
OPS	Operations
PC	Personal Computer
PEGASUS	Performance Experiments in Germany on ADS-B Using Mode S Extended Squitter
R.Collins	Rockwell Collins
R&D	Research & Development
RF	radio frequency
RMF	RF Measurement Facility
S	South
SICASP	SSR Improvements and Collision Avoidance Systems Panel
SSR	Secondary Surveillance Radar
TB	Test bed
TC	Technical Center
TCAS	Traffic Alert and Collision Avoidance System
UAT	Universal Access Transceiver
UK	United Kingdom
UPS AT	UPS Aviation Technology
US	United States
UTC	Coordinated Universal Time
VDL	VHF Data Link
VHF	Very High Frequency
W	West
WG	Working Group
WJHTC	William J. Hughes Technical Center
WP	Working Paper

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APPENDIX A

Extended Squitter Message Reception Waveforms

A.1 Example Extended Squitter Message Receptions

The following figures show examples of 1090 MHz raw video signal data recorded with the RMF. The signals were recorded on May 24 at 10:56:25 UTC using the RMF installed on N40. At the time, N40 was reporting an altitude of 22075 feet positioned at latitude 49.98999 and longitude 8.871388 flying in a westerly direction. Each of the messages is extended squitters that were successfully decoded using an enhanced decoding technique. The messages shown were arbitrarily chosen to represent varying yet typical degrees of interference encountered in the Frankfurt environment.

Figure A-1 shows an Identification message received on the bottom antenna from ICAO address $A6F486_h$. This was a Lincoln Laboratory transponder configured to broadcast extended squitters located at the Wiesbaden ground site. Adjacent position messages from A6F486 indicate an altitude of 100 feet at a range of just over 21 nautical miles. This message shows no significant interference.

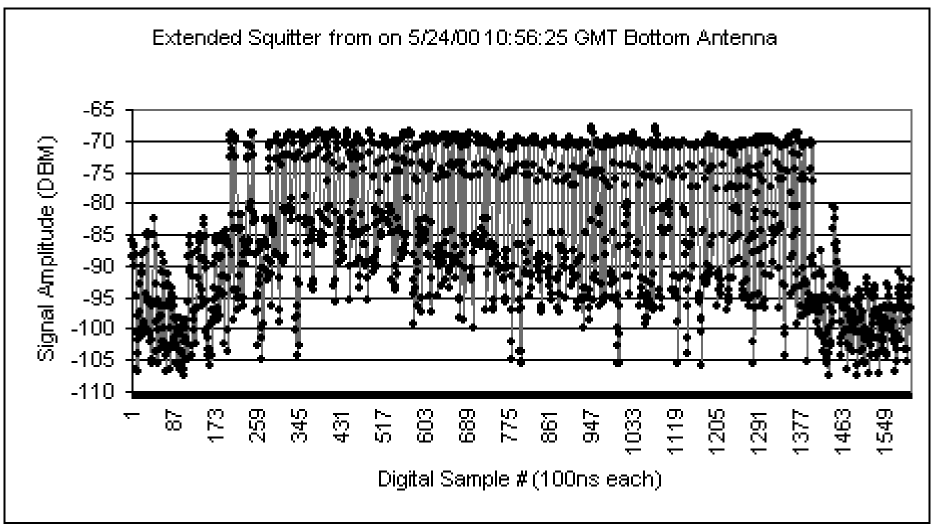

Figure A.1. Identification Message Reception - Bottom Antenna

Figure A-2 shows an Airborne Position message received on the top antenna from A6F486. Markers were added to the figure to identify the start and end of the message. Because A6F486 was located on the ground, most of the messages that were successfully decoded from A6F486 were received on the bottom antenna. The amplitude is significantly lower on the top antenna.

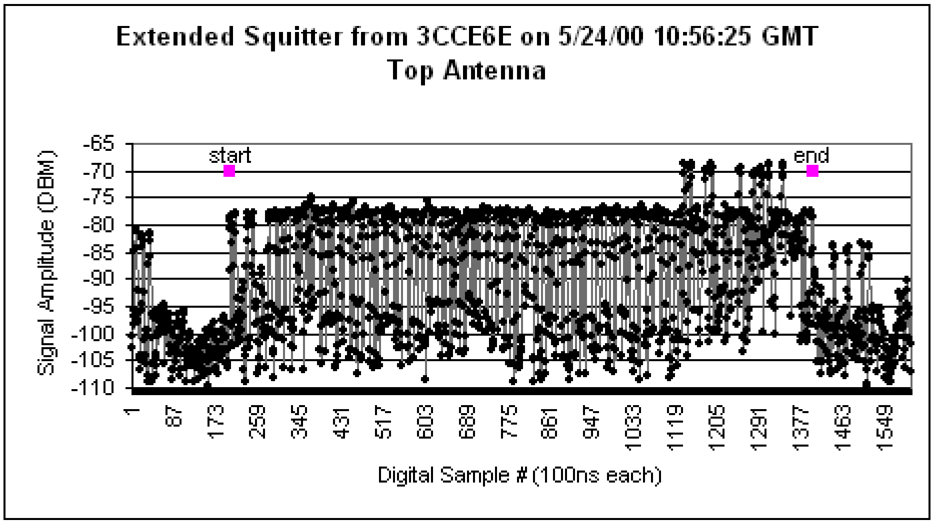

Figure A-2. Airborne Position Message Reception - Top Antenna

Figure A-3 shows an Aircraft Identification message received on the top antenna from the FII aircraft, ICAO address $3CCE6E_h$. The FII aircraft was on the ground at a distance of just under 21 nautical miles from N40 at the time. There is clearly a stronger ATCRBS reply overlapping near the end of the message.

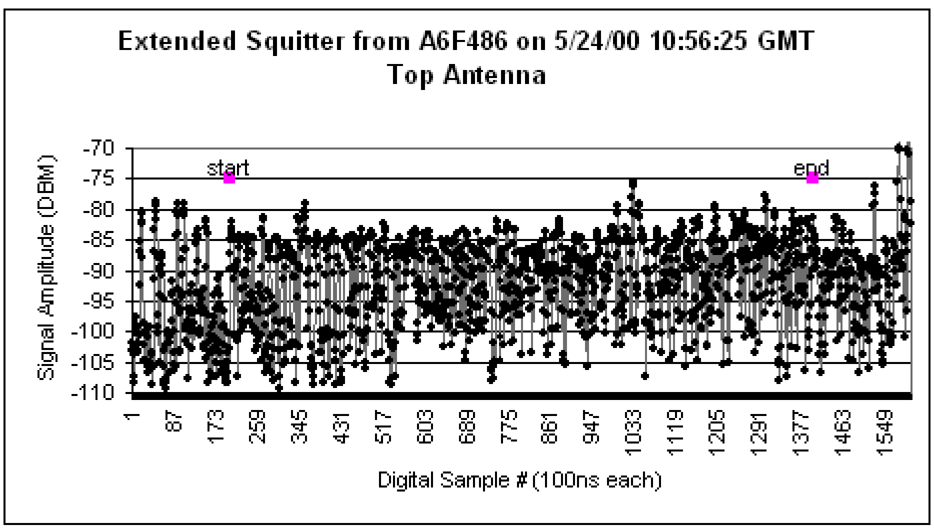

Figure A-3. Aircraft Identification Message Reception - Top Antenna

Figure A-4 shows a Surface Position message received on the bottom antenna from the FII aircraft. There is interference near the middle of the message.

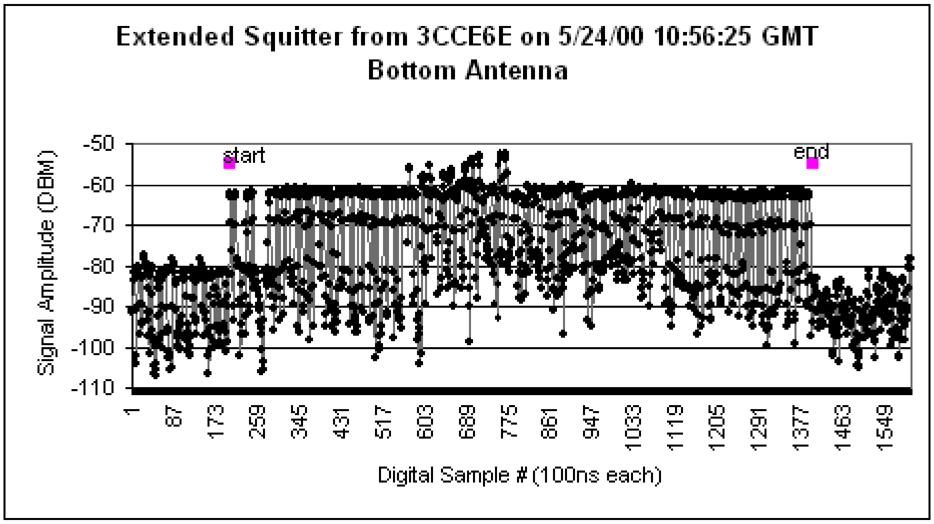

Figure A-4. Surface Position Message Reception - Bottom Antenna

Figure A-5 shows an Airborne Position message received on the top antenna from a BA target of opportunity with an ICAO address of 400652_h. The decoded position data from the extended squitter messages indicate that the aircraft was at an altitude of 36950 feet and latitude 50.36563 and longitude 6.854457. Its range from N40 at the time was over 81 nautical miles.

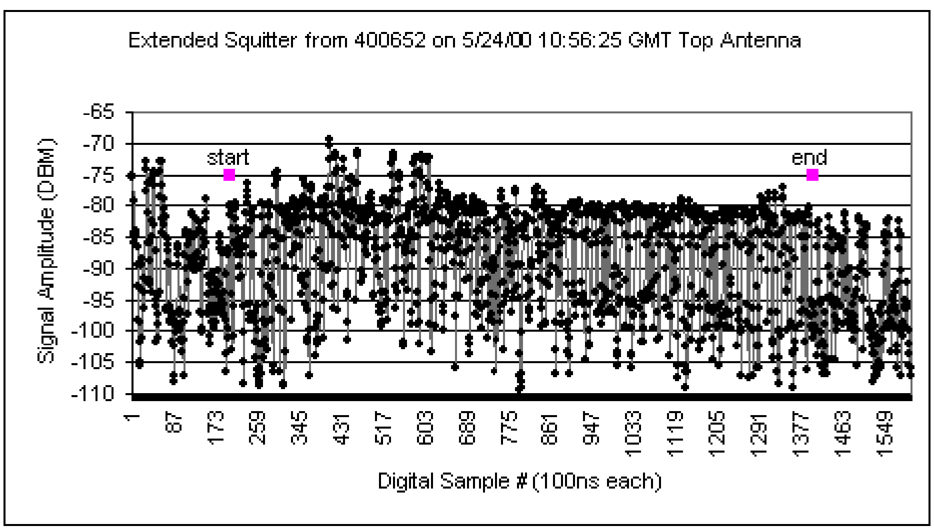

Figure A-5. Airborne Position Message Reception - Top Antenna

Figure 4A-6 shows an Airborne Velocity message received on the top antenna from the BA aircraft with overlapping interference.

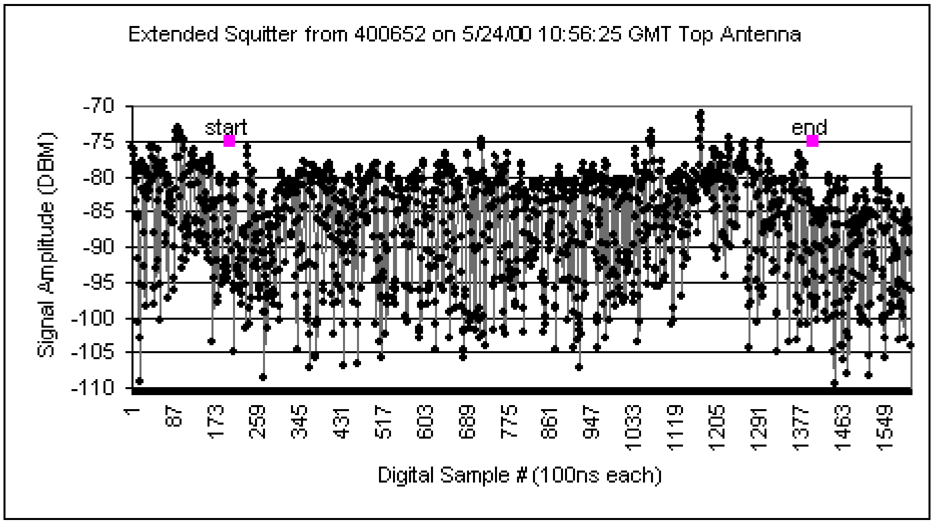

Figure A-6. Airborne Velocity Message Reception - Top Antenna

APPENDIX B

1090 Radio Frequency Measurement Facility (RMF) Reception Techniques

B.1 Introduction

B.1.1 Background

The 1090 Radio Frequency Measurement Facility (RMF) was developed as a means to analyze the 1090 RF environment. The RMF hardware consists of dual channel A/D converters that sample an incoming analog video signal at a 10 MHz rate and store the digitized data on high-density digital tape recorders. The video signal is provided from a receiver external to the RMF. In Frankfurt, the receiver video signal was provided by the Link-Display Processing Unit (LDPU) from both the top and bottom antennas. RMF software was developed to analyze the recorded data to characterize the 1090 MHz RF environment, measure the extended squitter performance in high fruit rate environments, and evaluate the performance of the improved Mode S processing techniques. The RMF data is processed off-line to detect extended squitter messages and other Mode S messages. The software processes the data using an enhanced reception technique like those defined in the RTCA DO-260, Appendix I. The software is also capable of processing the data using the TCAS reception method. The details of the RMF reception software are contained below.

B.1.2 Pulse Positions and Leading Edge Positions

The RMF samples at a rate of 10 samples per microsecond, therefore each preamble pulse and each data chip is nominally seen by 5 data samples. Each data sample has a digitized amplitude value ranging from the receiver noise level to the maximum signal level expected, precise to a fraction of a dB.

Of fundamental importance to the message decoding process is the location of pulses and their leading edges. With the RMF software implementation, a pulse consists of 4 or more successive samples above threshold. A valid pulse position is any sample that is above threshold and is followed by 3 other samples above threshold. Since the RMF samples at a 10 MHz rate, each sample is 100 nanoseconds apart. A minimum pulse is at least 300 nanoseconds in duration.

A leading edge is a valid pulse position that is 4.8 dB or more greater than its preceding sample and less than 4.8 dB lower than its succeeding sample**.**

B.1.3 Threshold

The software allows the user to select either a fixed threshold at specified level in dBm or an adaptive threshold at a specified level (dBm) above noise. The adaptive threshold method uses a process to monitor and track the current noise level, the threshold will maintain a user-defined level in dBm above the noise. The adaptive threshold was developed to provide a stable threshold when DC fluctuations in the signal level from the receiver are present.

B.2. Enhanced Reception Techniques

B.2.1 Preamble Detection

All pulses above the receiver threshold are detected. The preamble detection logic advances through the digitized data one sample at a time until a pulse position or lead edge is found. The pulse position or lead edge establishes a potential preamble reference position. For a preamble to be declared, there must be at least one lead edge or pulse position located within +/- one sample period of the nominal position of each of the three remaining preamble pulses.

The pulse sample timing tolerance is limited to either one sample plus or one sample minus but not both in the same preamble. If one pulse of a preamble set is present only in the - 1 clock position and another pulse is only present in the + 1 clock position then the preamble is not declared.

Timing offset is limited to one direction during preamble detection. If there are 2 or more lead edges in either the +1 clock offset or -1 clock offset direction, then the reference position will be shifted in that direction. Otherwise the center position will be used. However, if the center position is selected and there are no lead edges declared in the center position a preamble is not declared.

It is required that there is at least 2 lead edges declared within the + or - 1 sample tolerance range of the four pulses with at least one of them in the reference position.

B.2.2 Reference Level Generation

The reference level generation process determines the amplitude of the incoming message from the preamble pulses, and then sets a dynamic threshold 6 dB below the reference. The reference level generation process begins by selecting amplitude samples from each of the preamble pulses that are considered appropriate candidates, namely only those that have leading edges declared in their reference positions.

The three amplitude samples after each valid lead edge position are entered into the reference level declaration algorithm (up to 12 samples are possible).

For each qualified sample amplitude, the amplitude is compared to all other qualified amplitude samples and the number that lies within plus or minus 2 dB is counted. If the highest count is unique, then the reference level is set to the amplitude of that sample. If there is a tie, it is resolved by removing all amplitudes from the tied set that are greater than 2 dB above the lowest amplitude in the tied set. The reference level is set to the average of all remaining samples.

B.2.3 Preamble Validation

The reference level generation step is performed prior to preamble validation so that the dynamic threshold determined by the reference level process can be applied during preamble validation. It is required that there is a pulse position or lead edge declared within + or - one sample period of the start of the 1 chip or the start of the 0 chip for each of the first five data pulses of the message. In addition, it is required that the peak amplitude of the pulses found must exceed the dynamic threshold. The dynamic threshold is set to 6 dB below the amplitude of the preamble.

B.2.4 Enhanced Bit and Confidence Declaration

The RMF enhanced reception technique uses a multiple sample method that is a variation of the 4-4 multiple amplitude approach defined in appendix I of the ADS-B MOPS. Since there are 10 samples per bit with the RMF data, a 5-5 multiple amplitude method was implemented. Each of the 10 samples per bit are quantized into four levels:

0: below threshold (-6 dB relative to the preamble)
1: above threshold but below the +/- dB preamble window
2: within the +/- 3 dB preamble window
3: above the +/- 3 dB preamble window

The 5-5 method forms two estimates of the bit data and confidence values, one using the odd samples (1-3-5-7-9) and the other using the even samples (2-4-6-8-10). The lookup value for the odd and even patterns are built from the five 2 bit quantized values. Therefore, there is a lookup table of size 1024 for both the odd and even patterns. The lookup tables provide one of the following values:

H1: the pattern occurred 90% or more when the bit was a "1"
M1: the pattern occurred 70% - 90% when the bit was a "1"
L1: the pattern occurred 50% - 70% when the bit was a "1"
L0: the pattern occurred 30% - 50% when the bit was a "1"
M0: the pattern occurred 10% - 30% when the bit was a "1"
H0: the pattern occurred 10% when the bit was a "1"

The lookup tables were generated by recording millions of bit patterns from Mode S messages in at least a 40,000 fruit per second environment. The odd and even values resulting from the lookup tables are used to index another table that provides the bit and confidence value. The odd / even pattern combining table is as follows:

Odd and Even Sample Combination Table

Odd (1,3,5,7,9) **Even (2,4,6,8,10)**

	H1	**M1**	**L1**	**H0**	**M0**	**L0**
H1	H1	H1	H1	L0	H1	H1
M1	H1	H1	L1	H0	L0	L1
L1	H1	L1	L1	H0	L0	L0
H0	L0	H0	H0	H0	H0	H0
M0	H1	L0	L0	H0	H0	L0
L0	H1	L1	L0	H0	L0	L0

B.2.5 Enhanced Error Detection and Correction Techniques

The RMF enhanced reception implementation utilizes both the conservative and the Brute Force error detection and correction techniques. The method applied follows that recommended in Appendix I.

B.2.5.1 Conservative Technique

This technique is attempted only if the span of all low confidence bits in a message is no more than 24 bits. There must also be a limit of 12 low confidence bits total. Error correction is successful when a conversion of some or all of the low confidence bits results in a zero error syndrome.

B.2.5.2 Brute Force Technique

The brute force technique is applied only when the conservative technique has failed. The brute force technique is applied only if there are 5 or less low confidence bits in the message, but the low confidence bits are not limited to a 24 bit span. Error correction is successful when a conversion of some or all of the low confidence bits results in a zero error syndrome.

B.2.6 Re-triggerable Preamble Detection

The decoder will only re-trigger when a signal is already being processed if the determined reference level and the amplitude of all 5 data pulses of the new signal is at least 3 dB above the declared level of the existing signal. When in a re-trigger situation, the preamble validation step will require that there exists not only a pulse position or lead edge in the start of either the 1 chip or 0 chip, but that the amplitude resulting from the average of the three amplitude samples following the lead edge or pulse position found must exceed the amplitude of the reply in progress by at least 3 dB. This is required of all five pulses and all lead edges or pulse positions within + or - 1 clock of the start of both the one chip and the zero chip will be tested until a valid pulse amplitude is found or determined not to exist.

B.2.7 The RMF "Gold Standard"

The RMF 1090 environment analysis software was developed using the enhanced reception techniques to measure the Mode S fruit rate in high-density fruit environments such as Frankfurt Germany. When utilizing any of the methods described above, there are a high number of false triggers especially when using a low threshold. To counteract this effect, modifications to the technique and a number of filters were applied. The filter settings are selectable via a user menu and were optimized to reduce triggering to occur only on real Mode S signals with as little false trigger rate as possible. This was critical in order to provide accurate Mode S fruit rate data.

Data analysis has shown that the filters that reduce false triggers for environment analysis also enhance extended squitter reception. A new version of the reception algorithm was developed to simulate a detection process that could be implemented by emulating the reception limitations of a real-time application. With some of these filters incorporated into the real-time emulation, the recovery time from false triggers can be reduced, therefore maximizing message reception performance.

A real-time emulation is required to determine reception performance that is realistically achievable. The term "RMF Gold Standard" applies to this optimized yet real-time simulated reception technique. The RMF gold standard modifications and real-time simulation method are described below:

B.2.8 Real-time Design Approach

In order to emulate a reception process that could be applied to a real-time application, a basic design philosophy had to be developed. Figure B-1 illustrates the design approach used for the RMF Gold Standard.

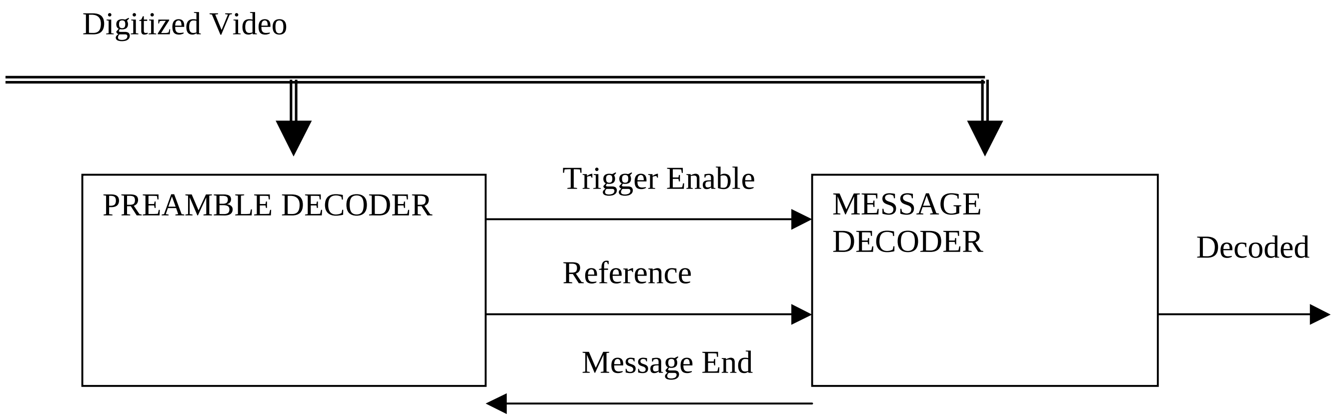

Figure B-1. The RMF Gold Standard Design Approach

Since the RMF Gold Standard reception is used to set a standard for extended squitter reception, it is important that the technique applied is able to maximize its capability to trigger on valid messages and to minimize the time required to recover from false triggers. To achieve this, the digitized video is continuously clocked into a preamble decoder and a message decoder in parallel. The preamble decoder contains parallel circuitry that compares delayed versions of the incoming signal in order to trigger when pulses align properly in the 4 preamble pulse positions and the first 5 data bit positions. At the same time the reference level is determined from the 4 preamble pulses. When the preamble decoder triggers, it triggers the message decoder and provides the reference level. Once the preamble decoder triggers, it continues to operate but in a re-trigger mode. When in re-trigger mode the preamble decoder will only trigger again if the new set of pulses exceed the previous trigger by at least 3 dB. After triggering, the preamble decoder will operate in re-trigger mode until the message end signal is received from the message decoder, at which time, it will return to normal trigger mode.

When enabled, the message decoder will continue to decode the message until the end of the message or one of the early termination filters determines that the message is not valid, at which time, the message decoder will signal the preamble decoder to return to normal trigger mode. There are four early termination filters and are described below.

Low Confidence Limit Filter - Message decoding is terminated if more than 12 low confidence bits are declared.

Indeterminate Bit Limit Filter - Message decoding is terminated if 3 consecutive data bits contain a sample pattern of all zero's (all 10 of each bit samples are more than 6 dB below the reference level).

Pulse Position Gap Filter - Message decoding is terminated if within the data block portion of a message there is greater than 30 consecutive samples without a pulse position declared.

DF Code Filter - Message decoding is terminated if it is determined that the message cannot produce a DF code between 16 and 23. This is accomplished by testing the first two data bit and confidence values. If any or all of these bits that are declared high confidence can not produce a value of 10 (binary) then message decoding is cancelled.

With this design approach, the preamble detector provides continuous triggering capability that is only desensitized by the occurrence of a preamble in combination with preamble validation. With the feedback from the message decoder, the amount of time that the preamble detector is desensitized is minimized when the trigger is determined to be false or a message type that is not wanted.

B.3 RMF TCAS Reception Technique

Software has also been developed that performs 1090 MHz signal analysis using the current TCAS reception technique as defined in DO-185A. The system calibration, receiver threshold, and the definition of pulses and their leading edges are performed the same as for the enhanced reception method described above.

B.3.1 Receiver Desensitization and DMTL

For the TCAS reception technique, in accordance with the ADS-B MOPS section 2.2.4.3.4.1 a DMTL is implemented that will desensitize the system due to pulse events or preamble decode events. When a pulse is detected (at least 300 nanoseconds in duration) with an amplitude at least 8 dB above threshold, the DMTL is set to the amplitude of the pulse -6 dB for a duration of 5 microseconds. If a valid preamble is detected, the DMTL is held for 115 microseconds.

NOTE: The DMTL that results from a single pulse is held for 5 microseconds unless, before it recovers, it is re-triggered by a stronger pulse. In which case the new DMTL is set and held for 5 microseconds. If a subsequent pulse occurs within 5 microseconds that is above DMTL but of lower amplitude than the preceding pulse, the DMTL continues to be held at the level determined by the original pulse until it expires. At which time, the DMTL adjusts to the level determined by the subsequent pulse. This secondary DMTL will expire 5 microseconds after the lead edge of the subsequent pulse. However, if the subsequent pulse turns out to be a P1 pulse of a valid preamble, the resulting DMTL that is held for 115 microseconds is set to 6 dB below the subsequent pulse amplitude

B.3.2 Preamble Detection

The software locates each preamble by treating all pulses above the receiver threshold as a potential P1 pulse. Therefore, each sample that is determined to be a pulse position or lead edge is tested to have a corresponding P2, P3 and P4 pulse. These subsequent pulses must have at least 1 pulse position or lead edge within 100 nanoseconds of its nominal position with respect to the current P1 reference position. To be declared valid pulse positions, each of the P2, P3, and P4 pulses must have at least 4 consecutive samples above the DMTL set by the P1 pulse. There must be at least 2 leading edges declared within the P1 pulse center reference position and within + or - 100 nanoseconds of the nominal position of the remaining preamble pulse positions.

B.3.3 Bit and Confidence Declaration

Once a preamble has been detected, the data is declared for each bit by awarding the bit value according to which chip center sample has the highest amplitude. The confidence value for each bit is declared by counting the number of samples in each half that are above DMTL. If the count differs by at least 3 and it agrees with the bit value, high confidence is declared, otherwise low confidence is declared. If there are more than 7 consecutive low confidence bits, the message is discarded. If the first bit is a 1, the message is processed as a long reply, otherwise it is processed as a short reply.

B.3.4 Message Re-Triggering

The message reply processor will re-trigger if a reply that is at least 3 dB stronger than the reply in progress is detected. The amplitude of the first pulse of each reply is used for comparison.