ADS-B AIRBORNE MEASUREMENTS IN FRANKFURT

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Introduction

Automatic Dependent Surveillance-Broadcast (ADS-B) was the subject of airborne testing in Frankfurt, Germany in May 2000. ADS-B is a system in which latitude-longitude information is broadcast regularly by aircraft, so that receivers on the ground and in other aircraft can determine the presence and accurate locations of the transmitting aircraft. In addition to latitude and longitude, ADS-B transmissions include altitude, velocity, aircraft address, and a number of other items of optional information.

The tests in Germany were aimed at assessing the performance of Mode S Extended Squitter, which is one of several possible implementations of ADS-B. Extended Squitter uses a conventional Mode S signal format, specifically the 112-bit reply format at 1090 MHz, currently being used operationally for air-to-ground communications and air-to-air coordination in TCAS (Traffic Alert and Collision Avoidance System).

Objectives

The reason for testing in Frankfurt was to make measurements in a very high interference environment. The 1090 MHz band is actively being used for replies to secondary surveillance radars and for TCAS air-to-air surveillance. Because of the current operations, one of the issues in system development was to determine whether Extended Squitter can perform effectively in this environment. Prior to the testing in Frankfurt, similar testing was carried out in Los Angeles, which was considered to be the location of maximum 1090 MHz signal density in the United States [1].

The primary objective of the tests in Frankfurt was a direct measurement of Extended Squitter performance in the Frankfurt interference environment. Both air-to-air and air-to-ground receptions were to be tested. Also, it was important to use calibrated instrumentation so that received power levels could be measured as well as reception reliability. Another objective was to measure the interference environment, including the receptions rates and their power distributions. Also, the density and distribution of aircraft was to be measured during the testing periods.

Facilities and Flight Paths

As illustrated in Figure 1, the project included three instrumented aircraft and two project ground stations. It was realized during the tests that certain British Airways aircraft were also transmitting Extended Squitter signals. The receptions from these in-service aircraft provided additional data that was especially useful for system evaluation.

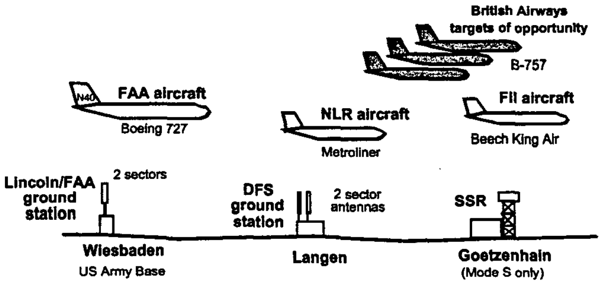

Figure 1. Airborne and Ground Based Facilities in the Tests.

This was an international project, including participation by Eurocontrol, the German DFS (Deutsche Flugsicherung), Thomson Airsys/Airsys Navigation Systems, NLR (Netherlands Lucht-en Ruimtevaartlaboratorium), the Federal Aviation Administration, and M.I.T. Lincoln Laboratory. The team of participants analyzed the data recorded during the tests and prepared a comprehensive final report [2]. The main elements of the tests and results are summarized in this paper.

The tests were conducted on five days. Figure 2 shows the flight paths most commonly used. Centered at Frankfurt, the tests included excursions about 200 nmi to the north and to the

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southeast. The figure shows the flight paths on 24 May 2000, in which all three-project aircraft participated. The three project aircraft are designated as follows.

"N40"	Boeing 727	FAA
"NLR"	Metroliner	Netherlands
"FII"	Beech King Air 300	Flight Inspection International

The FAA aircraft, N40 remained in the Frankfurt vicinity, in order to experience the maximum interference conditions (Figure 3). The NLR aircraft was contributed by the Netherlands, and is a twin-engine Metroliner. As shown in the figure, the NLR aircraft flew north 200 nmi to near Hamburg and back during this test. The Flight Inspection FII is also a twin-engine aircraft.

ADS-B transmitters, receivers, and recorders were installed on all three-project aircraft. LDPU receivers, which were made by UPS-AT, were used in all cases.

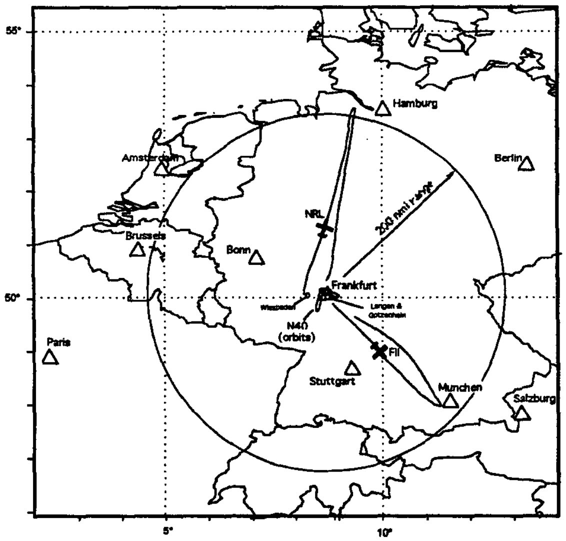

Figure 2. Illustration of the Test Locations Relative to Cities in Central Europe.

Note: The figure shows flight paths of the project aircraft on 24 May.

Two ground stations were installed specifically for these tests. They were instrumented for reception of Extended Squitter signals and data recording for later analysis. Their locations, Langen and Wiesbaden, are shown in Figure 3. At Langen, the receiving antenna was mounted on a rooftop at the German DFS building. The receiving antenna consisted of two 60-degree sectors, which provided partial coverage in azimuth. This configuration is intended to represent two of six sectors, which would cover all azimuth directions. At Wiesbaden, the receiving antenna also consisted of two 60-degree sector antennas, which were mounted on a small tower near the runway at the Wiesbaden US Army Base. In addition to coverage for terminal and enroute airspace, this siting also provided good views of the landing approach for that runway. Data recorded during landings of the project aircraft has been analyzed with respect to Extended Squitter application for runway approach monitoring. Radar ground stations were also used to monitor the aircraft during the tests. In particular, a Mode S Secondary Surveillance Radar (SSR) sited in Goetzenhain, near Langen, was used for Mode S surveillance of the project aircraft (Figure 3). Arrangements were also made to acquire recorded data from multiple in-service radars in order to make measurements of aircraft density.

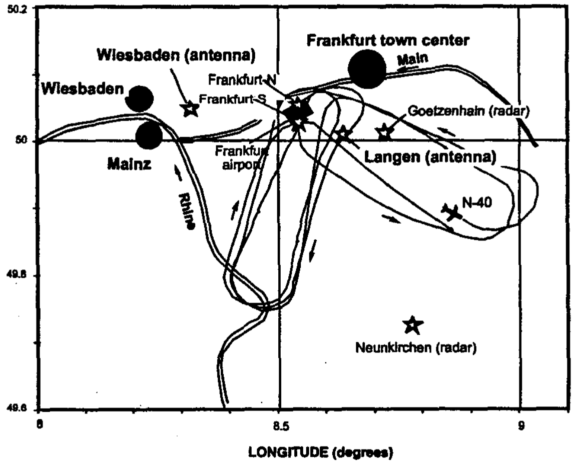

Figure 3. Oval Flight Path of N40, Staying in the Frankfurt High Density Area.

Tests were conducted on five days. The test activities can be summarized as follows.

19 May (Friday)	N40
20 May (Saturday)	N40 and NLR
22 May (Monday)	N40, FII
24 May (Wednesday)	N40, NLR, and FII
25 May (Thursday)	N40

Reception Performance

Air-to-Air Reception

Air-to-air reception performance was analyzed for a large number of cases. All three-project aircraft were equipped for both transmitting and receiving Extended Squitters, so when all three were participating, as was true on 24 May, there were a total of six air-to-air combinations. In addition, British Airways aircraft were included as transmitting aircraft on all of the test days.

On the first test day, 19 May, as N40 was flying in an oval pattern near Frankfurt, a British Airways (BA) aircraft flew directly over Frankfurt at 37,000 feet altitude. The flight paths are illustrated in Figure 4. Receptions on N40 supported a steady surveillance track as the BA aircraft approached from beyond 100 nmi to the west and continued through the point of closest approach (about 10 nmi range), then increasing in range to beyond 100 nmi to the east. The surveillance track was continuous during all of this time.

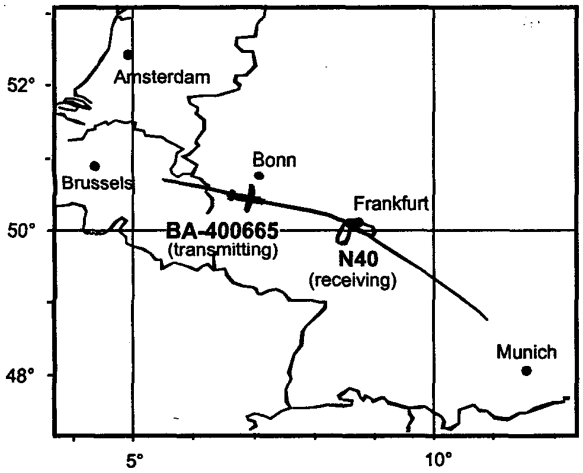

Figure 4. British Airways Aircraft Flying Over Frankfurt on 19 May.

While the surveillance track was continuous during this encounter, the receptions were analyzed in more detail to determine whether the standards for surveillance update rate were satisfied. The ADS-B standards for reception performance [3] require surveillance reception within 7 seconds (95% reliability) for ranges between 10 and 20 nmi and reception within 12 seconds (95% reliability) for longer ranges. The performance results are shown in Figure 5. Surveillance update-rate standards were satisfied beginning at a range of 130 nmi, and were continually satisfied throughout the inbound portion and the outbound portion until reaching a range of 109 nmi.

The recorded receptions were also analyzed in more detail to determine whether they would have supported intent communications, although intent messages were not actually transmitted during these tests. The results (Figure 5) indicate that the intent standards would be satisfied within 63 nmi during the inbound leg and within 50 nmi during the outbound leg.

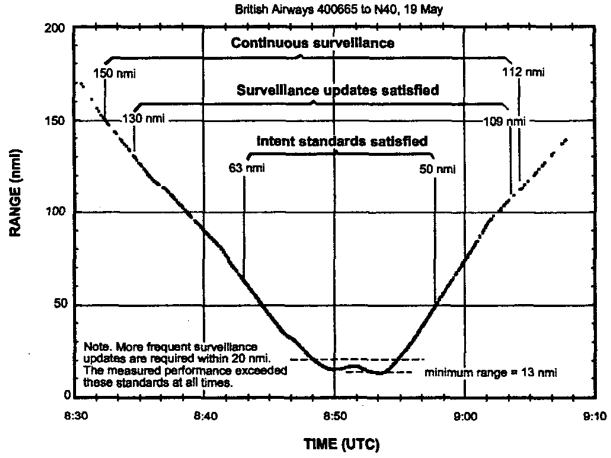

Figure 5. Receptions From British Airways Aircraft

These results apply to the LDPU receiver, which was used during the tests. The recorded data was analyzed further to determine the performance that would be achieved using the enhanced reception techniques, which are planned to be standardized for Extended Squitter reception [4]. The results of this analysis are summarized in Table 1.

Performance was found to be continuously provided at all times within the ranges shown in this table.

Table 1. Performance in the First Encounter (British Airways)

	LDPU receiver	Enhanced Receiver
Surveillance update standards		
Inbound	beyond 100 nmi	beyond 100 nmi
Outbound	beyond 100 nmi	beyond 100 nmi
Intent communication		
Inbound	within 63 nmi	within 112 nmi
Outbound	within 50 nmi	within 57 nmi

This is the first case that occurred in the Frankfurt tests. A large number of other cases were analyzed, and the results shown in the above case is typical. The final report [2] documents the results in all of the cases.

Air-to-Ground Reception

Air-to-ground reception was also analyzed. This was done for many individual cases, for receptions at both ground stations. Performance was also assessed using a special technique developed at Lincoln Laboratory called a "spaghetti plot".

The spaghetti plot shown in Figure 6 provides a way of assessing Mode S reception performance at Langen based on a large number of operational aircraft flying at the time of the test. This technique uses the short squitters, which are transmitted by all Mode S transponders once per second. As these are received at the Langen ground station, they indicate the reception reliability. In assessing performance, it is necessary also to determine the location of the aircraft, although latitude-longitude information is not included in these short squitters. To provide the needed information, the Mode S radar at Goetzenhain was used. The recorded radar data indicates the location of each Mode S aircraft and its 24 bit address. The 24 bit address, which is included in each short squitter, provides the connection so the two forms of data can be merged to show system performance as a function of aircraft location.

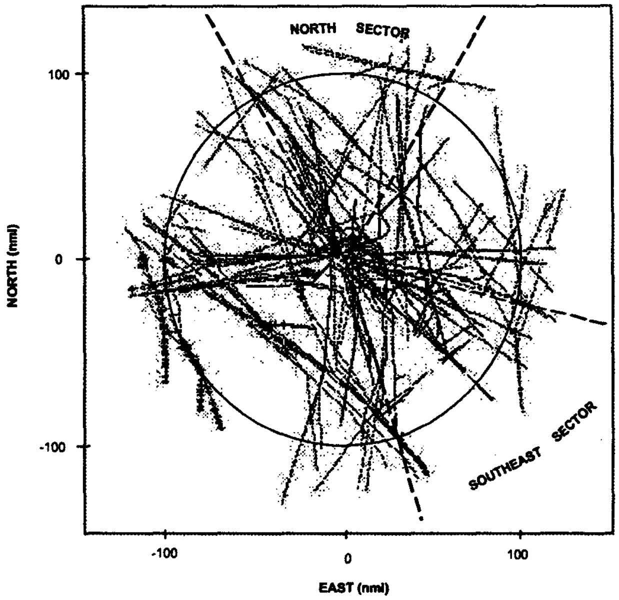

Figure 6. Langen LDPU Short Squitter Plot, 24 May

The spaghetti plot is constructed as follows. For each scan of the radar (Goetzenhain Mode S radar used here), a small point is plotted showing the current aircraft location. The Langen receptions are then examined to determine whether short squitters were received from that aircraft during the scan. If not the plotted point is changed to a larger red symbol, to indicate a flaw in LDPU reception. Where the resulting plot shows clean aircraft tracks without the larger red symbols, this indicates that the Mode S signals were consistently being received during that time. By examining the plot one can judge whether Mode S reception was successful or not for a large number of aircraft and their locations.

Note that only two antenna sectors were being used at Langen, so reception quality should be judged only within these two sectors, as marked in the figure. The data analysis leading to the results in Figure 6 took horizon obstructions into account. Because the two project ground stations were sited in convenient locations rather than prominent hilltop operational sites, it was found that significant horizon obstructions by nearby buildings existed in certain directions. Measurements were made of the heights and directions of these obstructions so that the tracks included in the spaghetti plots did not include aircraft behind these buildings.

The spaghetti-plot results in Figure 6 indicate very good reception quality for nearly every aircraft in the airspace during the time of the test. We consider this to be a particularly significant result because of the technique, which includes a large number of operational aircraft, which are on normal flight paths (not selected for test purposes), and includes the actual transponder characteristics such as transmitter power, antenna cable loss, and antenna mounting locations.

Runway Approach Surveillance

The Wiesbaden ground station was near the runway at Wiesbaden, and was well sited for runway approach surveillance. The data recorded at this site was analyzed to assess the surveillance performance for the landings of the project aircraft at Wiesbaden.

The runway approach measurements on the first day are plotted in Figure 7. This is the landing of N40 at the end of the day's testing. This plot includes all of the time in which the aircraft was within the two receiving antenna sectors, and within 30 nmi range of the receiving station. During the time period plotted here (924 seconds), the aircraft was under surveillance and in-track the whole time. Also, the Wiesbaden receiving station generated reports consistently once per second with the 3 exceptions shown here. The overall report reliability was therefore 924/927 = 99.7 percent. This is excellent performance. The photo in Figure 8 shows the view from the receiving antenna of the aircraft, N40, during a landing.

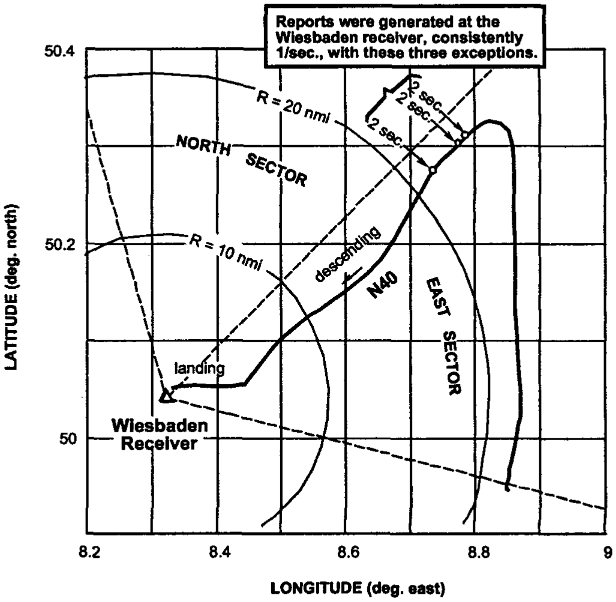

Figure 7. Air-to-Ground Surveillance During N40Landing Approach, 19 May

There were a total of eight landings at Wiesbaden during the test series, and all eight have been analyzed in this manner. The analysis considered ranges out to 30 nmi or the point at which the aircraft turned onto final approach, and in which the aircraft was within the two antenna sectors.

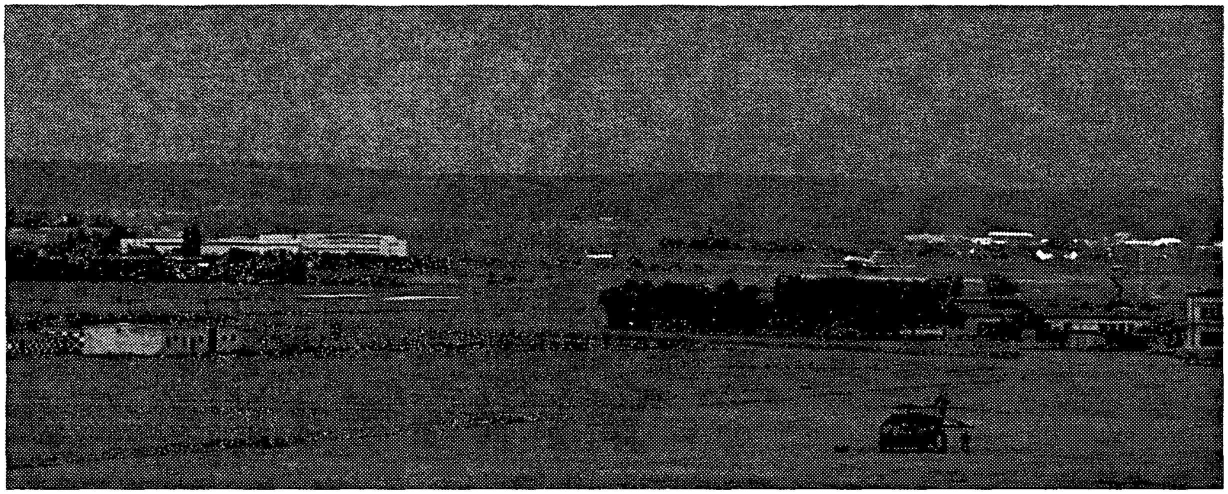

Figure 8. A View Of N40 While Landing At Wiesbaden.

The analysis results for all eight landings are summarized in the following table. Excellent performance was observed in all cases. The most demanding performance standards for monitoring approaches to parallel runways require surveillance updates every 1.5 seconds or more frequently with 95 percent reliability [3]. In every case, the measured performance exceeded the surveillance standards for approach monitoring.

Table 2. Measured Performance During Eight Landings

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

Measurements of the Interference Environment

In addition to direct measurements of surveillance performance, a large number of measurements were made to characterize the interference environment. Before the tests, Frankfurt was considered to be the highest interference environment in the world, so it was planned to make quantitative and repeated measurements, and to make comparisons with similar measurements in the United States.

Measurements were made of the signal density in the 1090 MHz band, which is the band in which Extended Squitters are transmitted. Measurements were also made in the 1030 MHz band, which includes the radar interrogations that trigger replies at 1090 MHz. Aircraft density was also measured, and this data was analyzed to determine the distribution in range and the distribution in altitude of the aircraft in this airspace.

Interference at 1090 MHz

Measurements were made of Mode A, C and Mode S receptions in the 1090 MHz band. These are replies to interrogations in Mode A, Mode C, and Mode S, including interrogations from ground based radars and from TCAS aircraft. Figure 9 shows the received rate of Mode A, C signals, plotted as a function of received power level. This is a cumulative distribution, in which the rate plotted at a given power level is the total received rate of all signals received at that power level or stronger.

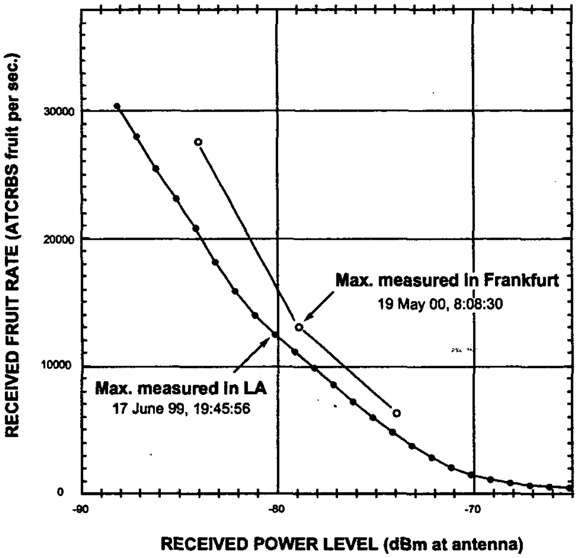

Figure 9. Comparison Between Frankfurt and Los Angeles (1090 MHz).

For comparison, corresponding measurements from the Los Angeles Basin are also plotted in Figure 9 [1]. It was found in both Frankfurt and LA that the received rates varied during the tests, and in this respect the data plotted in this figure shows the maximum rates observed.

Note that these interference rates are very high. For example, for power levels of -84 dBm and higher, the rate is nearly 30,000 per second. The duration of each Mode A, C signal is 22 microseconds, so the rate-time product is greater than 50 percent.

The Frankfurt-LA comparison in Figure 9 shows that Frankfurt does have more interference than LA, although not by a large factor.

Measurements were also made of the Mode S reception rate. The results generally show that the Mode S rates are lower than Mode A, C by about a factor of 10. Measurements of this kind were made on all days, and are all presented in the final report [2].

Interference at 1030 MHz

Interrogation rate measurements revealed a high interrogation rate, especially in the immediate Frankfurt area. It was also seen that ATCRBS interrogation rate is a function of altitude, exhibiting a significant increase as altitude increases. Measurement results are given in Figure 10, showing the effects of altitude, and of the difference between top and bottom mounted antennas.

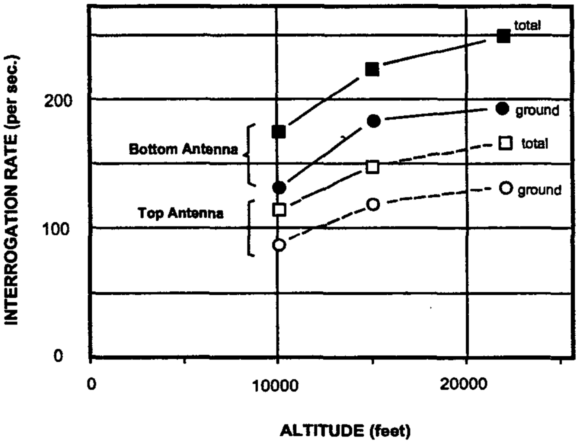

Figure 10. Interrogation Rate as a Function of Altitude

Aircraft Density

Radar data was recorded in order to monitor aircraft traffic during the tests. The recordings were made of Secondary Surveillance Radar (SSR) data; primary radar was not used. The radar at Goetzenhain was used for surveillance in Mode S and a number of other radars were used for surveillance in Modes A and C.

Figure 11 shows the number of aircraft and the range distribution relative to Frankfurt. To obtain these results, which extend out to 200 nmi from Frankfurt, multiple radars were used to avoid the line-of-sight limit for a single radar. An analysis was carried out to combine the multiple-radar data so that each aircraft is counted once. Measurements are shown here for three times, intended to be the maximum, the minimum, and a typical average density condition.

For comparison, Figure 11 also shows corresponding aircraft measurements made in the LA Basin [1], using LAX airport as the center point. This comparison indicates that LA has higher aircraft density near the center relative to Frankfurt. Beyond about 50 nmi, the aircraft density in LA is reduced, whereas the density surrounding Frankfurt remains high extending to much longer ranges.

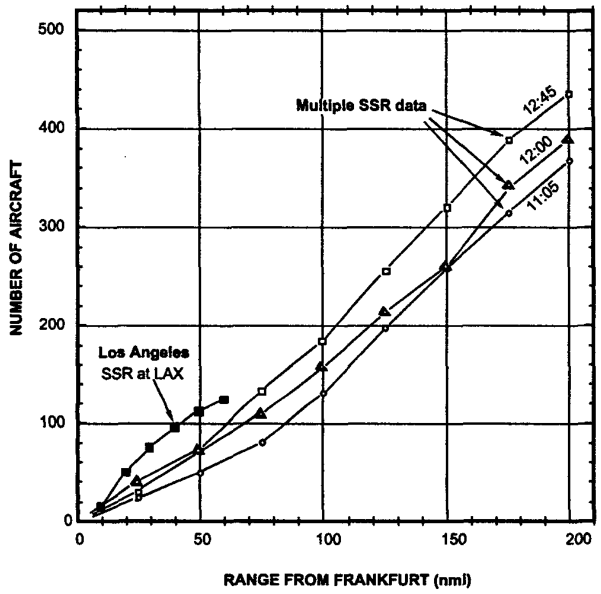

Figure 11. Aircraft Count and Distribution in Range, 24 May

The aircraft surveillance data was also analyzed to determine the distribution in altitude. The results in Figure 12 show the altitude distribution of aircraft within 100 nmi of Frankfurt. The distribution is shown in both histogram and cumulative forms.

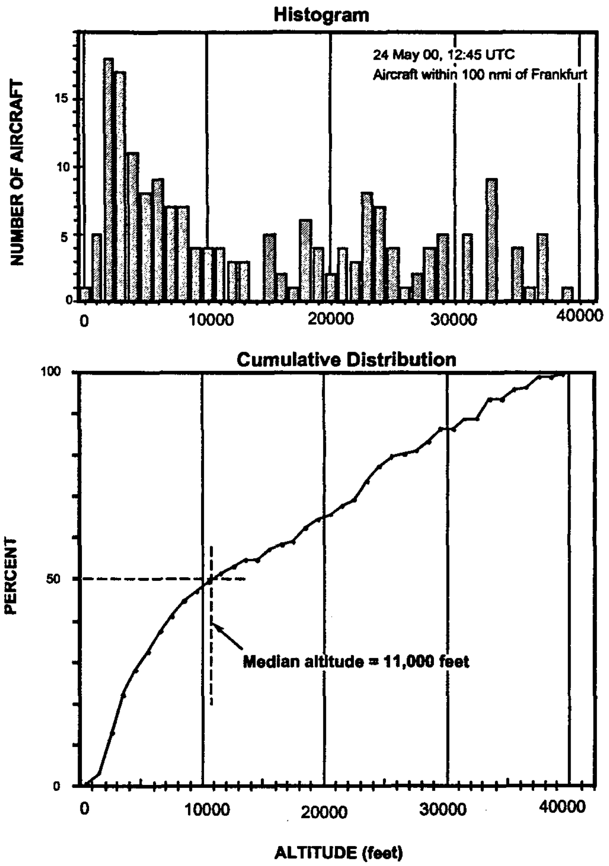

Figure 12. Aircraft Altitude Distribution

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

Table 3. Individual Radars Identified in the Frankfurt Receptions.

	Inter. Rate (per sec.)	Scan Period (sec.)	Mode Interlace	Military or Civilian	Beamwidth (degrees)	Notes
1	125	9.92	A-C-	experimental	2.9	Goetzenhain
2	151	11.797	A-C-	civilian	2.216	
3	155.3	10.054	A-C-	civilian	2.538	
4	157	10.047	A-C-	civilian	2.471	
5	159	10.045	A-C-	civilian	2.488	
6	162	8.162	A-C-	civilian	2.474	
7	163	10.049	A-C-	civilian	2.339	
8	211.4	11.63	A-A-C-	civilian	2.398	
9	234	4.7576	A-C-	civilian	2.86	near Frankfurt-south
10	235	4.772	A-C-	civilian	2.38	
11	248	9.99001	1AC then 2AC	military	2.236	
12	248.9	10.0816	1CA then 2CA	military	2.128	
13	250	9.36	12AC	military		
14	250.1	9.947	1AC then 2AC	military	1.77	
15	250.1	10.0099	1AC then 2AC	military	2.695	
16	250.1	9.9641	1AC then 2AC	military	2.2	
17	252	10.006	1CA then 2CA	military	1.718	
18	254	10.035	1AC then 2AC	military	2.15	
19	260	10.163	1CA then 2CA	military	2.43	
20	263	4.7563	A-C-	civilian	2.305	
21	266.6	4.7647	A-C-	civilian	2.458	
22	270.9	4.756	A-C-	civilian	2.33	
23	272	9.793	1AC then 2AC	military	2.49	
24	272.9	4.768	A-C-	civilian	2.38	
25	274	9.79699	1AC then 2AC	military	2.386	
26	276.9	4.758	A-C-	civilian	2.28	
27	289.9	4.75634	A-C-	civilian	2.56	
28	294	4.08224	A-A-C-	civilian	2.29	
29	300	11.905	1AC then 2AC	military	2.203	
30	300.2	11.88	1AC then 2AC	military	2.106	
31	304.9	5.06395	A-C-	civilian	2.31	
32	341.6	4.737	A-A-C-	civilian		Frankfurt-south
33	346.8	4.41906	A-C-	civilian	2.37	
34	350	4.302	A-	peculiar	4	
35	350	4.1614	A-	peculiar	4.62	
36	350	4.1636	A-	peculiar	3.96	
37	350	4.1636	A-	peculiar	4.108	
38	350	4.302	A-	peculiar	4	
39	364.2	3.76641	A-A-C-	civilian	2.16	
40	364.2	3.76641	A-A-C-	civilian	2.16	
41	365.7	4.988	A-C	civilian	4.69	
42	365.9	3.8459	A-C-	civilian	3.66	
43	375	4.785	22AACC	military	4.85	
44	426.3	11.629	A-A-C-	civilian	2.42	
45	455	11.837	A-C-	civilian	2.47	
46	460.6	11.837	A-C-	civilian	2.33	

Percent Mode S and TCAS

The recorded radar was also used to estimate the percentage of aircraft that are equipped with Mode S transponders, and the TCAS percentage. The results indicate that of all transponder equipped aircraft, approximately 53 percent had Mode S transponders while the remaining 47 percent had ATCRBS transponders. Also, among Mode S aircraft, approximately 81 percent were equipped with TCAS.

Individual Radars

It was also possible, using detailed analysis of recorded interrogation data, to focus on individual radars and determine their scan rates and other characteristics. The recorded data gives the arrival time and power level of each received pulse. The first analysis step was to identify interrogations, which are pulse combinations having the appropriate spacing. This was done for Mode A, Mode C, Mode S (both long and short formats). The next step was to look for repeating patterns of interrogation rate. It was observed that many of the radars used multiple interrogation periods. After filtering the data to a single period or a group of periods, the next step was to look for a repeating scan period. This process makes it possible to identify each radar separately, even in cases in which two radars have nearly the same interrogation rate and scan rate.

Table 3 shows the main radars that were identified in this way. Blank indicates an item that has not been determined. The list should not be considered to be complete, because of the time consuming manual steps required in the analysis. Nevertheless we believe the list includes most of the radars, and is useful for indicating the variety of radar characteristics in this environment. These results can be compared with a similar study, done after measurements in Frankfurt in 1995 [5]. Many of the same radars were identified in both measurements.

Summary

The measurements in Frankfurt confirm the expectation that the interference conditions there are very high. Nevertheless, performance in receiving Extended Squitter signals was good for both air-to-air and air-to-ground links. For example, in the first encounter, which was with an in-service British Airways aircraft, air-to-air surveillance was continuous and satisfied the MASPS standards for update rate to beyond 100 nmi both inbound and outbound. In this case and in several other encounters with British Airways aircraft, the data was particularly valuable to this test program because it included normal flight paths as well as normal aircraft antennas, cables, and transponders. For assessing air-to-ground performance, a "spaghetti plot" technique was used, which made it possible to assess performance for a large number of operational aircraft, again using their normal flight paths, antennas, cables, and transponders. One part of the test and analysis focused on landing aircraft whose landing approaches were under ADS-B surveillance as received at a ground station on the airport. Performance was found to be excellent in all of the landings that occurred during the test series. In summary, the tests were successful in assessing the interference environment and in assessing Extended Squitter performance in this environment.

References

[1] "Measurement of 1090 MHz Extended Squitter Performance In the Los Angeles Basin," FAA report DOT/FAA/ND-00/7, May 2000.

[2] "Measurement of 1090 MHz Extended Squitter Performance and the 1030/1090 MHz Environment In Frankfurt, Germany," FAA report DOT/FAA/ND-01/1, 4 May 2001. Available electronically from http://adsb.tc.faa.gov/.

[3] "Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B)," RTCA/DO-242, Feb. 1998. A revised version, DO-242A, has been issued since this study was completed. The results in this paper reply to DO-242.

[4] "Minimum Operational Performance Standards for 1090 MHz Automatic Dependent Surveillance-Broadcast (ADS-B), RTCA/DO-260, Sept. 2000. Revision A is currently being developed to provide standards for enhanced reception.

[5] "1030/1090 Megahertz Signal Analysis, Frankfurt, Germany," FAA Technical Center Report DOT/FAA/CT-TN95/20, July 1996.

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