National Air Traffic Services Ltd

Analysis & Research Department
Research & Innovation Group

Evaluation of ADS-B at Heathrow for The EUROCONTROL ADS Programme Report

EEC/ASTP/AIRP/003

	Signature	Name	Date
Prepared by:		Paul Askew	
Approved by: (For DAR)		Andy Price	

Abstract

This report represents the results of Automatic Dependent Surveillance Broadcast (ADS-B) Surface Surveillance Trials organised in April 2002 by National Air Traffic Services Ltd and EUROCONTROL Experimental Centre on behalf of the EUROCONTROL ADS Programme.

The objective of these trials was to compare the reception performance of four ground surveillance systems, these included, Multilateration, Mode S Extended Squitter, Universal Access Transceiver (UAT), and VHF Datalink Mode 4 (VDL-4), on the Heathrow Airport surface for a selected set of trajectories and receiving station positions. They therefore contribute to the implementation of a network for communication, navigation and surveillance in the provision of Air Traffic Management in Europe, and also provide information on link performance for ADS-B applications on the airport surface for the EUROCONTROL ADS Programme.

A large quantity and wide variety of data was recorded, as documented in this report. This document describes the equipment installation, the trials carried out, and presents analysis results of the data logs collected in the trials.

The results indicated that of the ADS-B technologies, the VDL4 link was least susceptible to reductions in performance caused by obstructions. The Mode S Extended Squitter showed some signs of co channel interference from aircraft, and possibly navigation aids.

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Abbreviations

ADS-B	Automatic Dependent Surveillance Broadcast
BAA plc	Company that owns Heathrow Airport
BER	Bit Error Rate
CPR	Compact Position Reporting
CTB	Control Tower Building
D-GPS	Differential Global Positioning System
DME	Distance Measuring Equipment
EEC	EUROCONTROL Experimental Centre
GPS	Global Positioning System
LDPU	Link Data Processing Unit
LET	Link Evaluation Team
MDS	Multistatic Dependent Surveillance ie multilateration
MLS	Microwave Landing System
Mode S	Mode Select
MTL	Minimum Trigger Level
NATS	National Air Traffic Services Ltd
SMR	Surface Movement Radar
TDOA	Time Difference of Arrival
TLAT	Technical Link Assessment Team
UAT	Universal Access Transceiver
VCR	Visual Control Room
VDL-4	VHF Digital Link Mode 4

Document History

Date	Status	Comments
July 02	Initial Draft for Comment	
October 02	Second Draft	Incorporation of comments from EUROCONTROL
Feb 03	Final Draft	Incorporation of final EUROCONTROL Comments and formatting changes required by NATS

1 Introduction

1.1 Document Objective

This document presents the results of performance analysis carried out on data collected in the Automatic Dependent Surveillance – Broadcast (ADS-B) Surface Surveillance Trial at Heathrow Airport, carried out by National Air Traffic Services Ltd (NATS) and EUROCONTROL Experimental Centre (EEC) in April 2002 on behalf of the EUROCONTROL ADS Programme.

It compares their performances in an airport surface environment free of co-channel interference (except for Mode S Extended Squitter and Multilateration). The ADS-B technologies are experimental and a single vehicle broadcasting messages is not representative of an operational environment in which many air and ground vehicles are operating with the same technology. The results presented in this will support the development of more realistic link models for the analysis of the ADS-B environment on the airport surface. The need for such data has been highlighted in previous reports on ADS-B technology assessment (see for example the LET and TLAT reports)

Furthermore, the determination of implementation costs for the technologies for both air and ground infrastructure is beyond the scope of this work. Neither are any issues regarding the introduction to service discussed. Therefore, any conclusions that the reader may draw from the data in this report may change when the technologies are considered in the context of a truly operational environment.

1.1 Background

NATS was awarded a contract by EEC to conduct and analyse airport surface trials of ADS-B equipment and the Multilateration system at Heathrow. The work was part of the Technology Link Assessment Task of the EUROCONTROL ADS Programme.

The trial compared and quantified the performance of the three ground surveillance technologies:

- ADS-B using Mode S Extended Squitter
- ADS-B using the Universal Access Transceiver (UAT)
- ADS-B using VHF Datalink Mode 4 (VDL-4)

This was conducted in a live trial where all three technologies transmitted information, which was received at a base station on the airport. The positional accuracy of each was determined by comparison with a reference GPS system that had an absolute accuracy of approximately 20cm.

The conduct of the trials at Heathrow provided a particularly challenging environment for the systems as the density of high buildings around the airports causes blocking and multipath problems to the ADS-B radio links.

1.2 Trial Objectives

The objectives of the ADS-B Surface Surveillance Trial were to:

- Determine and compare the reception performance of Mode S Extended Squitter, UAT, VDL-4 and Multilateration on the Heathrow airport surface for a selected set of mobile trajectories and receiving stations.

- Determine and compare the delivered position accuracy of the four systems.
- Evaluate the coverage provided by the four surveillance systems on airport surface.
- Evaluate GPS performance onboard the target vehicle, and explore potential Multipath problems.

The deliverables of the trials were:

- Data recordings in each phase.
- A Final Report presenting the results of ADS-B performance analysis on the logged data.

The trial was conducted in 4 phases

Installation of equipment on the target vehicle at Gatwick
Shakedown trials at Gatwick
Initial Test of equipment at Heathrow
Trial at Heathrow

2 Equipment Installation

The trial equipment comprised the mobile equipment installed in a NATS van, and a ground station. These are both described in further detail below.

2.1 Trials Vehicle

The vehicle was supplied by NATS and was equipped with a Honda 240V AC generator, equipment racks and an extending mast for mounting aerials. The mast was not extended during the trials although with the antenna plate attached, the vehicle had a height of 5m, which is consistent with the height of the bottom transponder on most aircraft. The vehicle, shown in Figure 2-1, is fully compliant with BAA plc [1] requirements and has a permit for airside use at Heathrow.

The van was originally used by NATS for the assessment of Microwave Landing Systems (MLS). The mast is hydraulically powered and can extend to a height of 18.5m. The onboard generator is capable of providing 4kVA at 240VAC and 50Hz, and offers the opportunity to provide regulated mains voltage when the vehicle is moving. Alternatively the van can be connected directly to the electricity grid for static work, if a local power supply is available. The power is distributed via a distribution board with circuit breakers to 12 Standard UK three pin sockets (BS1363) on two benches as well as to two 19-inch racks. Twelve Volts DC from the van battery is also available in the working area of the van.

Two sockets on the outside of the van and two blade antennae are connected to a patch panel on one of the equipment racks, allowing the respective antenna to be connected to different equipment. It is also equipped with two Airband VHF radios with two antennae on the roof.

Figure 2-1 NATS MLS Van

[1] The company that owns and operates Heathrow airport.

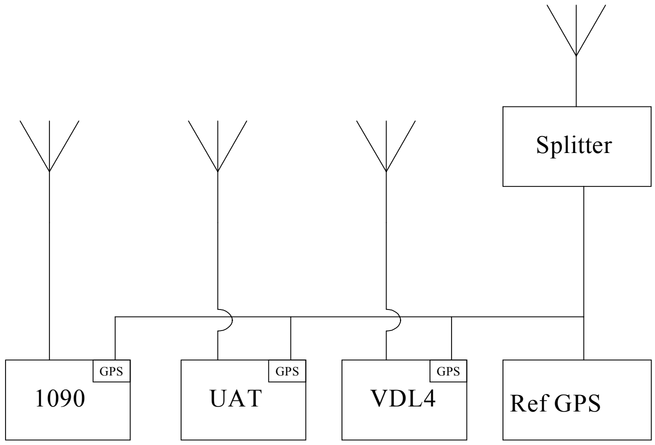


Figure 2-2 Block Diagram of Trials Equipment on Van

2.1.1 Global Positioning System (GPS)

A survey quality GPS (Ashtech) receiver was installed in the van, to work in conjunction with the base station described in 2.3.1, this had an accuracy of approximately 20cm. This was used as a 'Truth Track' that was used as the reference for all other position data during the trial.

A GPS receiver was also required by each of the link technologies to provide the position data for the ADS-B messages. The Mode S transponder was given GPS information by a Garmin 400 GPS receiver over an ARINC 429 link. The VDL-4 transceiver had an internal GPS receiver. The UAT had an internal GPS receiver and a linked GPS receiver, which was in accordance with its standard configuration.

The GPS receivers shared the same antenna, which was connected to a four-way splitter, to feed the VDL-4, UAT, Garmin & Ashtech. As it was an active antenna the power was provided by the Ashtech, with all the other receivers DC blocked. The layout can be seen in Figure 2-2 and a photograph of the splitter is shown in Figure 2-3.

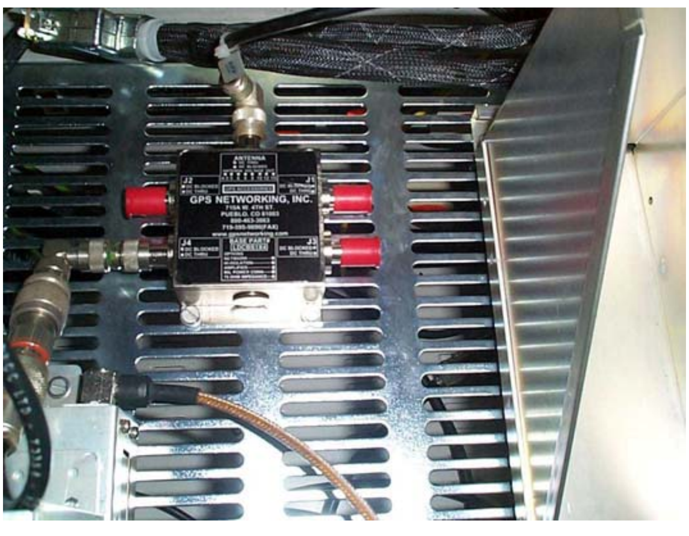


Figure 2-3 GPS 4 Way Splitter

2.1.2 Mode S Extended Squitter (1090 MHz)

EEC supplied and installed a Mode S Transponder (Honeywell XS 950) capable of extended squitter in the van. The installation was verified as functioning correctly during the mini shakedown trials at Gatwick. Figure 2-4 shows the installation of the transponder in the van. An attenuator is visible in this photograph, which was originally installed by EUROCONTROL as a precaution to protect operational systems at Heathrow from excessive power. However, given that these systems are designed to receive signals from aircraft, the attenuator was removed for the actual trials.

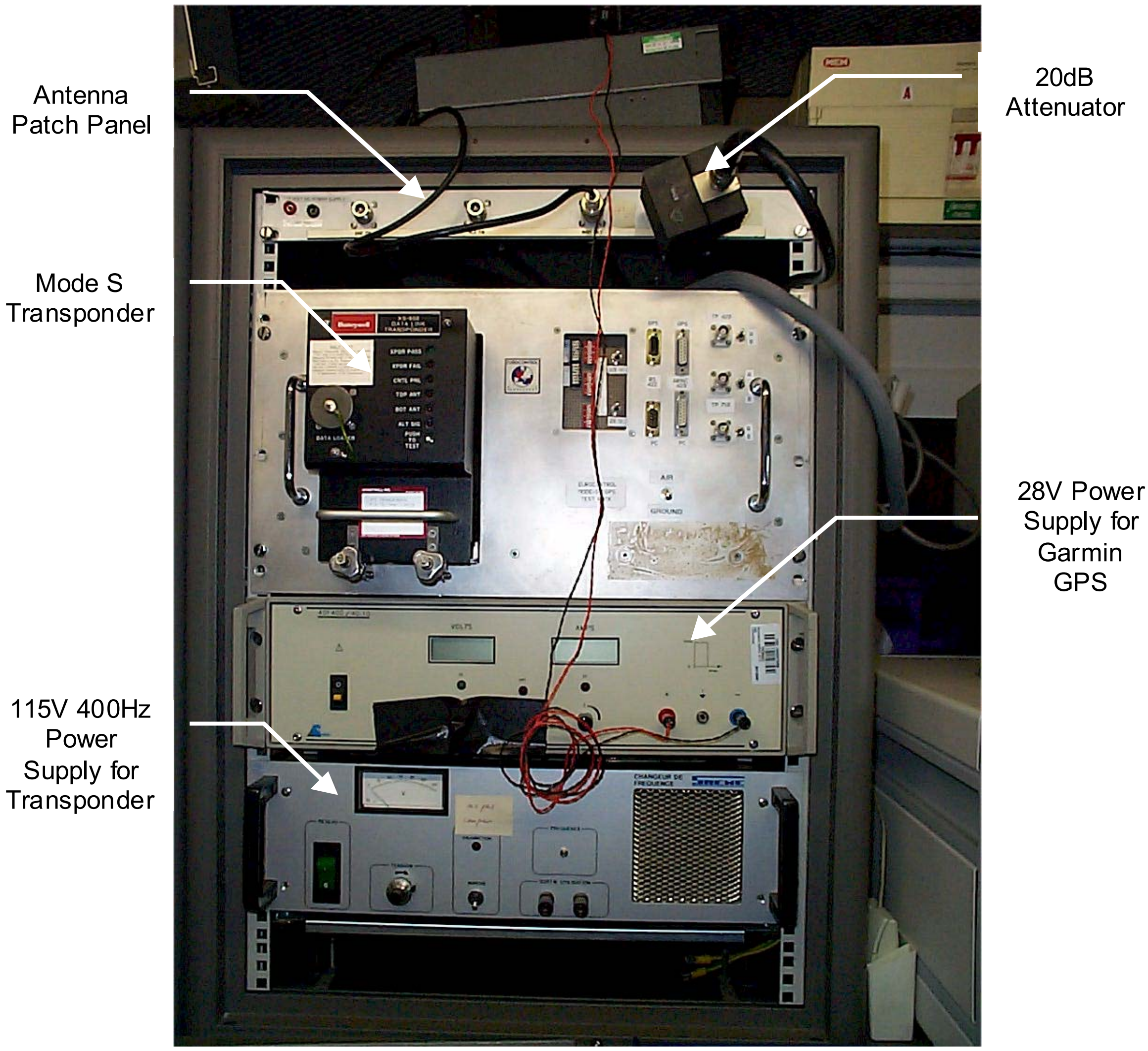


Figure 2-4 Mode S Transponder installation in van

2.1.3 Universal Access Transceiver (UAT)

EEC installed the UAT equipment, comprising Capstone equipment from UPS Aviation Technologies Incorporated (see details in Appendix D). This was powered by a 28V DC power supply. A blade antenna was attached to the antenna plate described below.

2.1.4 VHF Digital Link Mode 4 (VDL4)

EEC installed a CNS Systems VDL-4 transceiver in the vehicle. A magnetic mount VHF aerial was attached to the antenna plate.

2.1.5 Vehicle Antenna Characteristics.

An antenna ground plane was produced, on which 4 antennae were attached. This is shown in Figure 2-5 below. This was fitted to the top of the mast on the van during the trial runs. The cables to the GPS and Mode S antenna were connected to sockets on the roof of the van, which were in turn connected to the patch panel shown in Figure 2-4. The cables for the UAT and VHF were passed through the van window during the trials and connected directly to their respective transmitters.

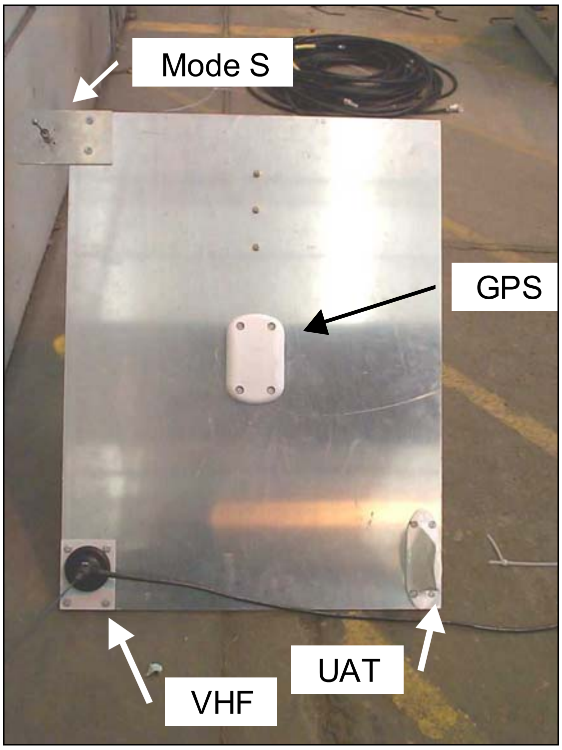


Figure 2-5 Configuration of antenna plate

On completion of the trial the antenna and transmitter characteristics for the van installation were measured. These are summarised in Table 2-1 below. A Bird SA-2000 Site Analyser (806-2000MHz) was used for the UAT and Mode S, and a Bird 400 antenna tester (65-520MHz) for the VDL-4.

Technology	Frequency (MHz)	Transmitter Power measured at antenna(W)	VSWR	Update Period
Mode S	1090	200	1.1	2 Hz
UAT	966	16	1.19	1 Hz
VDL 4	134.550	5 (Set as 37dBm on equipment)	1.21	1 Hz

Table 2-1 Summary of Link Characteristics.

2.2 Ground/Base Station at Gatwick

The equipment was initially installed at Gatwick, as a check to ensure functionality of the kit. EUROCONTROL staff were available during this time to eliminate any problems that were encountered. The configuration of the ground station is described in detail in the following section.

2.3 Ground/Base Station at Heathrow

Figure 2-6 and
Figure 2-7 illustrate the configuration of the ground station when it was installed at Heathrow. It was situated beneath the Visual Control Room at Heathrow Airport., which was approximately 25m from the edge of a balcony. Three masts were installed on the balcony for mounting the antenna. Cables were fed through a window from the ground station to the antenna. These are shown in Figure 2-8.

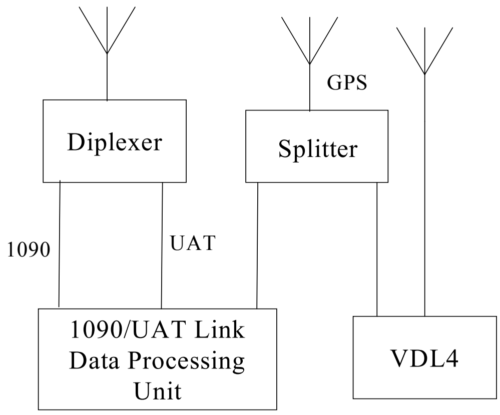


Figure 2-6 Block Diagram of Ground Station

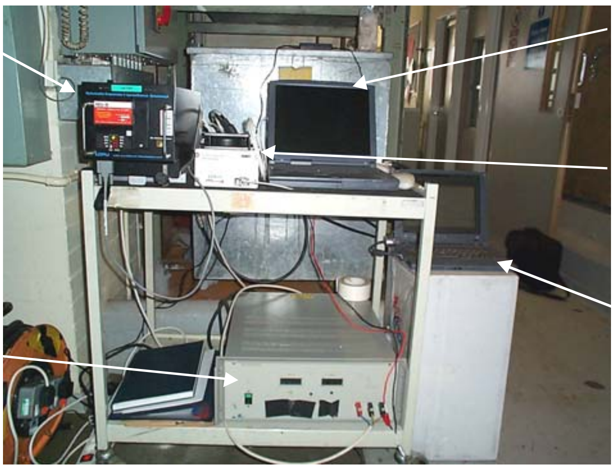


Figure 2-7 Ground Station at Heathrow

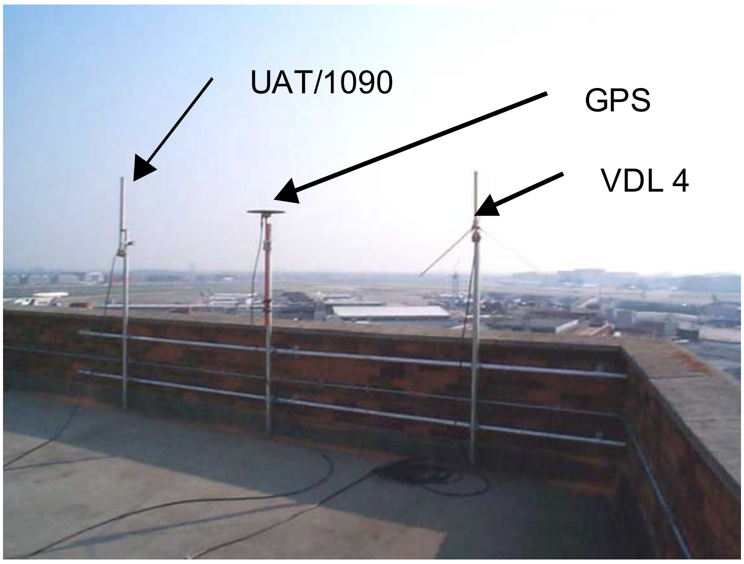


Figure 2-8 Antenna positions on Control Tower Balcony

Table 2-2 summarises the characteristics of the receivers and antennae that were used for each technology. Each technology is described in more detail in the section below.

Technology	Frequency (MHz)	VSWR	Receiver Sensitivity dBm
Mode S	1090	1.1	-79 dBm to –87dBm (MTL)
UAT	966	1.08	-93 dBm (MTL)
VDL 4	134.550	1.3	-110dBm at 10^{-4} BER

Table 2-2 Summary of Characteristics of Base Station.

2.3.1 Global Positioning System (GPS)

An Ashtech GPS antenna was mounted on a mast situated on the Control Tower balcony at Heathrow. This was used to provide both the Link Data Processing Unit (LDPU) and VDL-4 transceiver with a GPS signal, which was required to ensure their proper operation including the provision of a time source for the recordings. A splitter was used to share the signal between the two units with the VDL-4 transceiver providing the power for the active antenna.

A second survey quality Ashtech GPS with antenna was installed near the North side Far Field Monitor to enable the vehicle position to be the differential GPS data.

2.3.2 Mode S Extended Squitter & Universal Access Transceiver (UAT)

The signals for the UAT and the Mode S Extended Squitter were received by means of a single aerial mounted on a mast on the Heathrow Control Tower Balcony. The aerial was connected by 25m of cable to a diplexer in the plant room. This in turn split the Mode S signal (1090 MHz) and the UAT (966 MHz) and fed them to the Link Data Processing Unit for recording. The recordings were then used for the analysis described later in this report.

2.3.3 VHF Digital Link Mode 4 (VDL4)

A VDL-4 (CNS Systems) Transceiver was installed in the plant room, connected to a dedicated antenna on the balcony (see Figure 2-8). Again, the cable was required to reach 25m between the transceiver and the antenna. In order to monitor the VDL-4 link and to record the transmissions, a laptop was supplied by EUROCONTROL, which had Carmenta's MMCats software installed. MMCats is a software tool which records the VDL-4 data reported by the transceiver, and also provides displays of configuration and position.

2.3.4 Ground Antenna Position

Due to the short duration of the trial the antennas were situated on the balcony of the control tower, as this was readily accessible and required no specialist installation. Three masts were attached to the wall to allow the antennas to be mounted. The disadvantage of this installation was that the VCR and SMR obscured the western sector of the airport. Appendix A describes the antenna installation in more detail and gives views from the antenna positions around the airport.

3 Multilateration System Description

3.1 Background

NATS conducted research into the use of a multilateration system, or Multistatic Dependent Surveillance, at Heathrow in 1997. This eventually led to the award of a contract to install an operational system at Heathrow airport. The contract was awarded to Sensis Corporation, and a fully operational system entered service in late 2002.

3.2 Principle of operation

MDS relies upon measuring the difference of arrival times (TDOA) that transponder replies reach the receivers. These differences allow the system to triangulate on a particular transponder as the Mode S address is used by the system to identify targets. Figure 3-1 shows the principle of operation diagrammatically. As the position of each receiver is known exactly, differences in the times of arrival leads to the accurate determination of the target position. Further information can be found at http://www.sensis.com.

3.3 Heathrow Installation

The Heathrow installation of MDS has 15 receiving units and two reference transponders. This number is there to cope with the challenging topography of the airport. The position of several large buildings means that there are no areas of the airport visible from a single position.

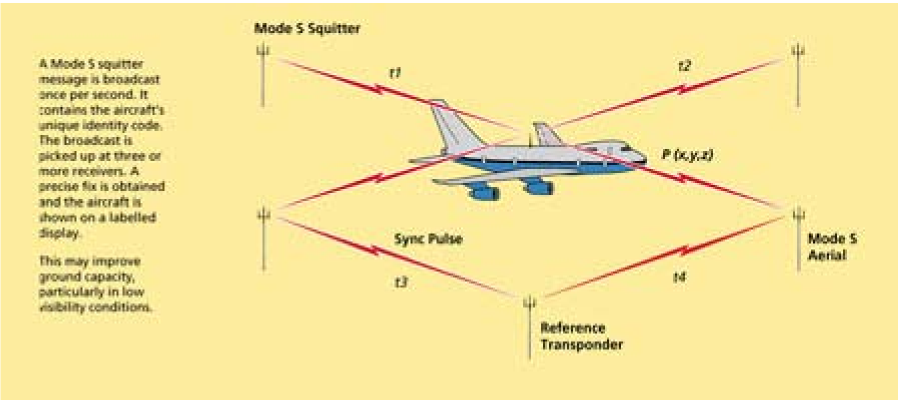


Figure 3-1 Outline of Multilateration Operation

4 Method of Analysis

The following section of the report describes how the analysis was performed. The reference GPS data was post processed at Gatwick, and then synchronised to the ADS-B reports. The ADS-B performance analysis was largely undertaken with macros that were supplied by EUROCONTROL.

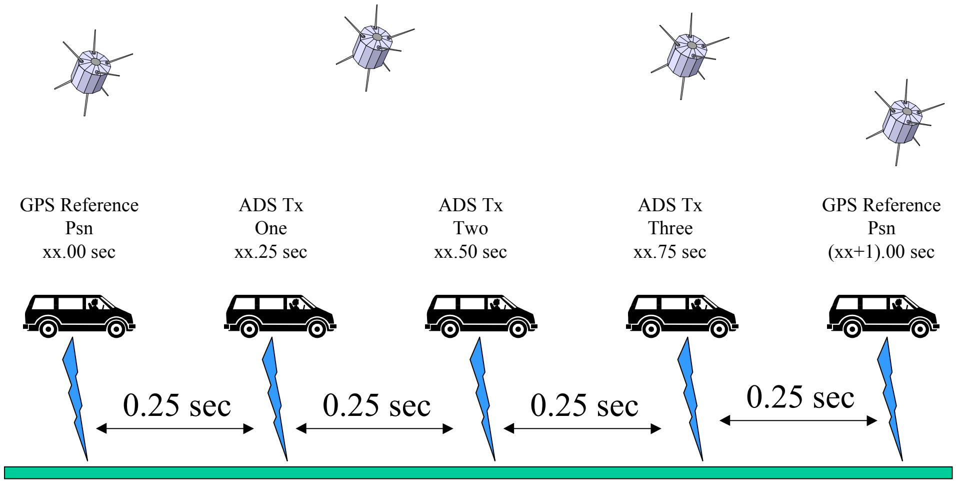
4.1 GPS Calculations

The GPS data from the Ashtech receivers on the vehicle and the master site was recorded during the trial and then post processed in conjunction with data from the United Kingdom Ordnance Survey to provide a truth track. The main concern was that all the position data provided by the ADS-B systems was in WGS84 latitude and longitude, rather than in a Cartesian Co Ordinate System. In terms of data collection and consistency this was advantageous, however, errors in position are usually expressed in terms of a distance measurement so the WGS84 latitude and longitude had to be converted into a WGS84 Cartesian co-ordinate system see Appendix C for details. The method used was that suggested in the Ordnance Survey Guide to Coordinate Systems [ref. 1]. Spot checks on the calculations used in this analysis, with a tool that the Ordnance Survey publish on the internet (www.gps.gov.uk) showed variations of approximately 3 cms which can be explained by rounding errors in the computations.

The most challenging aspect of the analysis was the synchronisation of the ADS-B data to the GPS truth track, as all of the data was recorded at different times. The GPS truth data was recorded at precisely the second (eg. 01.00, 02.00 etc), the Mode S at one second intervals that have been 'jittered'[2] and the UAT and VDL4 at other intervals of approximately one second. Given that the vehicle was travelling at speeds of up to 30 knots (approximately 15 metres per second) then leaving the data at its relative positions would potentially introduce large errors. This is illustrated in Figure 4-1 below. At 30 knots if the third ADS transmission were compared to the GPS position on the left then an error of 11.25m would be introduced. Even if the second transmission were compared to either, there would be a 7.5m error.

To overcome this potential error it was decided to interpolate the positions on the truth track so that a 'true' position for each ADS transmission could be found. The interpolations were made linearly and hence do not take into account accelerations or the arc of a turn. For the vehicle concerned these are considered to be negligible over a 1 second period.

[2] The timing of a message is 'jittered' in the case of 1090 MHz Extended Squitter to allow multiple access of the channel by several users. The interval between consecutive messages is nominally one second, however a pseudorandom process is used to alter the timing by an interval of up to ± 100 ms.



Speed (knots & metres per second)	Cumulative Distance Travelled in 0.25s increments			
	00.25s	00.50s	00.75s	01.00s
30 kn (15m/s)	3.75m	7.5m	11.25m	15m
20 kn (10m/s)	2.5m	5m	7.5m	10m
10 kn (5m/s)	1.25m	2.5m	3.75m	5m

Figure 4-1 Illustration of potential GPS errors in calculations

4.2 Multilateration Data

The data from the MDS system was processed by the Sensis Corporation and made available to NATS in a text format. The data comprised an x-y position measured in metres from a local origin and the station time (which was not synchronised to GPS as the ADS-B systems were). The data given was exclusively for the van, and Sensis had filtered out all other targets.

4.3 ADS-B Performance assessment

The data from the trials is in a basic format with only simple processing performed. In an operational system it is expected that more processing would be done and erroneous data would be removed in real time. Each link transmitted an identifier, GPS time and a position given as WGS84 latitude and longitude. The receiver processed this data and hence events such as corrupt data or interference were not logged. The transmissions were not recorded, hence performance assessments were based on the expected transmission rates of the ADS-B equipment.

The ADS-B performance was assessed using macros supplied by the EUROCONTROL Experimental Centre. These macros first of all cleaned the data by removing messages with corrupt times or positions. They then enabled parameters such as the link integrity to be analysed. The detailed analysis is provided in Section 5.

Unlike the airborne trials, it was felt that measurements against distance were inappropriate due to the obstructions on the airport surface from buildings. An alternative measure was proposed which involved the plotting of parameters against bearing from the control tower. This would enable any anomalies in the results to be correlated with a nearby feature. The bearings were calculated with 0°, being at Grid North.

The results are essentially presented in three forms. First of all a plot is given showing the position of the van when it transmitted a position message. This basically gives a track of the van, and shows where transmissions were successfully received.

The second form presented are the plots of reception probability also referred to as decode probability. These allow the link performance to be assessed, high values mean that there is a good chance of a message being passed from the van to the base station. Low values mean that there is a potential problem, preventing a message being passed.

The final part of the analysis examines the update period, that is the time between position messages being received at the receiver. This is largely dependent upon the reception probability in any given area. The criterion adopted for comparison is the update periods for 95% of the messages received which corresponds to the value used in the airborne trials described in references 2 and 3 and are marked on the charts as lines. These values were measured because the airport does not give an ideal environment for measuring the true performance of the links because of such things as obstacles and multipath. For this reason, where it was possible, sections of data with high reception probabilities were taken to give an idealised view of what the update period would be, if the installation of the base station took proper account of the topography of the airport.

When messages were not received, the likely reason would be on of the following:

1. Obstacle
2. Interference
3. Transmitter stopped (e.g. when synchronisation with GPS is lost)

4.4 Conduct of Trial

The trial was conducted in two parts, a static trial and a mobile trial. The static trial was aimed at assessing the link reliability when aircraft were likely to pass between the vehicle and the receiver, as well as assessing the accuracy of the GPS receivers in the equipment. The mobile trial was aimed towards assessing the reliability of the link around the airport.

Planning and executing a trial on an operational airport proved challenging, however picking one of the world's busiest proved to be a learning experience. The trials were conducted mostly at night to avoid competition with aircraft and service vehicles for access to the runways and taxiways. Even so, the southern runway (27L/09R) was being resurfaced and was inaccessible, which meant the taxiway was used instead.

5 Results

5.1 Static Trial

The van was driven to an area known as grass area 13. This can be seen in Appendix A (Figure A-6). The main purpose of this part of the trial was to examine how aircraft moving past the van would affect the links, as well as trying to get an indication of the drift of the GPS. Effectively the constraints of the airport meant that less data than desired was collected The principal events that occurred during this trial can be seen in Table 5-1 below.

Approx. Time	Observed Event
18:32	Transponders switched on
18:34	UAT and VDL4 were received and processed at the ground station
18:36	Mode S ES received and processed at the ground station
18:40	Van waiting for aircraft to pass on its way to the static area
18:50	Van static and settled at site
18:55	All links being recorded
19:00	Aircraft passes between van and ground station (Boeing 767)
19:09	Aircraft passes between van and ground station (Boeing 737)
19:13	Boeing 747 towed past the van
19:27	Van had to move back because of potential interaction with Boeing 747 taxiing past
19:44	Transponders switched off.

Table 5-1 Breakdown of Events Observed During the Static Trial

Effectively the data above indicated that the most stable period for analysing static data was 18:55 to 19:25. The reports from each link were compared to the output from the reference GPS system. The reference GPS gave one report a second and with the differential corrections from the master station, the position reports were taken as being the 'truth track' against which the other links would be compared. The position of the van during the static period was taken as being the mean of all the reference GPS reports for the period in question.

5.1.1 Link Performance

5.1.1.1 Mode S Extended Squitter

The first result observed was that the data rate for the Mode S Extended Squitter dropped to one message every 5 seconds rather than the usual update rate of one message per second. This proved that the transponder was functioning correctly, as the Manual on Mode S Specific Services states that transponders can automatically adjust their message rate to one ever 5 seconds if the vehicle speed drops below 0.25 Kt.

For the time under consideration, the update period was 5 seconds throughout, meaning that 360 messages were expected. The number of messages that were actually received was 341, giving a reception probability of 94.7%. When the data is examined closely, a message is lost approximately once every 2 minutes. However there are four specific events in the data when two messages were lost during a one minute interval, and these are shown in the table below.

Time (UTC)	Observation	Event
19:00	Two consecutive messages lost in one minute	First aircraft starts to taxi past van on Runway 23
19:02	Two messages lost in a 15 second period	First aircraft finishes taxiing past van on Runway 23
19:08	Two messages lost in a 15 second period	Second aircraft finishes taxiing past van on Runway 23
19:16	Two messages lost in a 40 second period	Boeing 747 being towed along Runway 23

Table 5-2 Times at Which Two Extended Squitter Messages were Lost

5.1.1.2 Universal Access Transceiver

A period of 30 minutes meant that 1800 messages were expected from an update rate of 1 per second. Only two messages were lost for the whole period giving a decode probability of 99.9%. These two messages were consecutive and were lost at 19:18 UTC, which does not coincide with any particular observed event that may account for this anomaly.

5.1.1.3 VHF Digital Link Mode 4

No messages were lost so the reception probability during this period was 100%. In fact for the whole time that the VDL4 was being recorded during this part of the trial the reception probability remained at 100%.

5.1.2 Position

5.1.2.4 Mode S Extended Squitter

The data set for Mode S is smaller than UAT and VDL-4, due to the Mode S transponder automatically changing its squitter rate as described above. A GARMIN GPS receiver provided the position to the Transponder via an ARINC 429 bus, before encoding it for transmission in the Extended Squitter Message using the Compact Position Reporting (CPR) algorithm, which uses alternative methods for encoding latitude and longitude for odd and even seconds. The Extended Squitter Position relative to the Reference GPS is shown in Figure 5-1. It is noticeable that the error oscillated between four values, equating to the different algorithms used by the CPR for encoding the position in odd and even seconds. The difference only appears in the longitude, and comprises two position pairs. Each pair of points represents an oscillation between alternate positions, which is consistent with the CPR algorithm. Approximately halfway through the static period the error increased and the position reported by the Mode S Transponder moved eastward. The only event of significance is a drop in the number of satellites visible from 6 to 5, for a period of only 10 seconds. This can be seen in Figure 5-2. With this change in accuracy the 95% error is 10.97m.

5.1.2.5 Universal Access Transceiver

Again the plot of the position is given in Figure 5-1. The errors are much lower than in the Extended Squitter Messages, with a 95% error of 6.34 metres, and it can be seen that the value of the error is fairly constant throughout the static period.

5.1.2.6 VHF Digital Link Mode 4

The VDL4 link can provide up to nine different messages, known as ‘data bursts’, which are described in more detail in Reference 4. For the trial, two data bursts were used, the basic burst and the data burst which were transmitted in a ratio of 15 to 1. The basic burst contains position, velocity, accuracy figures, ground track, and height information. The data burst contains the callsign with a reduced accuracy position.

Over the period that the van was static the position remained largely stable, with a 95% error of 4.4 metres

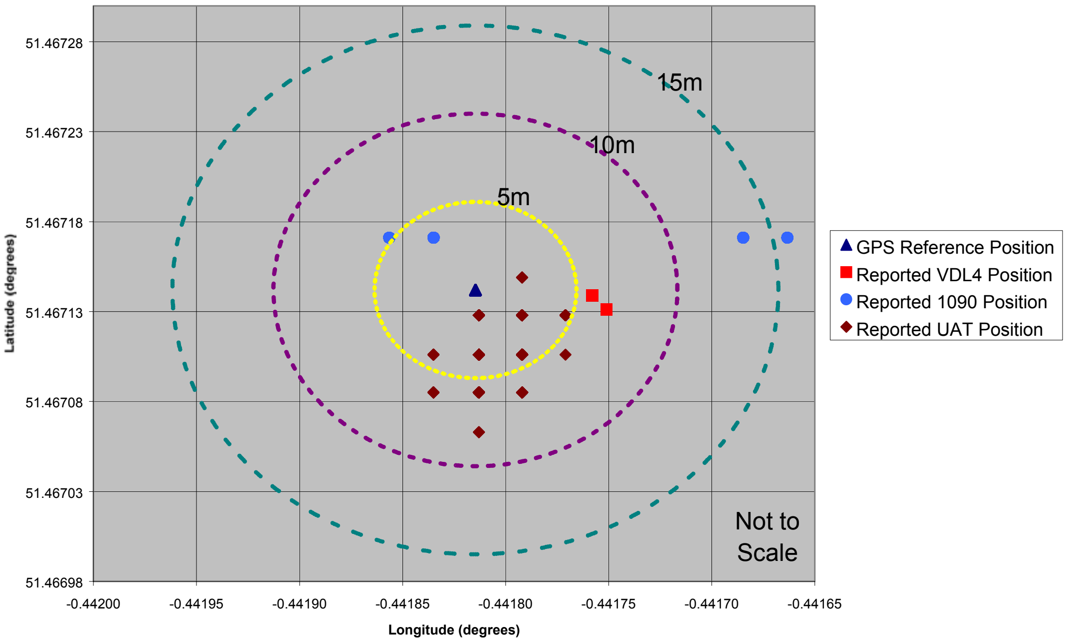


Figure 5-1 Plot of the Relative Positions Reported by the ADS-B Links

5.1.3 Multistatic Dependant Surveillance System

At the time of the trial, the MDS system still had not been accepted from the supplier, so was not fully validated. The system picked up many short squitters to supplement the extended squitter for the ADS-B messages. The system design is designed so that it has 100% coverage of the airfield. Furthermore, as the system picks up short squitters as well as extended squitters, the number of messages reported is far greater than was received through the ADS-B link. It was not possible to distinguish between short and extended squitters from the data that was supplied.

At the time of the trials the MDS took a Mode S Extended Squitter message in preference to its own calculated position, meaning that the position given would be its ADS-B position. When comparing the MDS output to the other links, absolute differences of several hundred metres were observed in the data. However the data processing system at the airport gave an accurate representation of where the van was on its display, indicating that the system resolved the differences that were observed. When the errors in position were calculated based on the MDS data alone, a 95 percentile error of no more than 1.55 metres was observed.

Figure 5-2 shows a plot of the errors calculated over time while the van was in a static position. Because of the difference in absolute position, the ADS-B errors are calculated from the mean position given by the reference GPS and the MDS errors are calculated from the mean position derived by the MDS system. This graph clearly shows very little variation in position for the MDS system, although there are three spikes towards the end of the data that are anomalous (at approximately 19:17, 19:21 and 19:25). The only observed events, were a Boeing 747 being towed past the van starting at 19:13 followed by another Boeing 747 taxiing past at 19:27. The positions of these aircraft may have been such that they caused multipath.

The ADS-B links each had their own GPS receiver. It is of interest to note that for the first half of this data set the errors are all relatively low, but a sudden jump occurs, particularly from the Mode S Extended Squitter link at approximately 19:10. The only events that may explain this are either the aircraft moving past 19:09, or the drop in the number of satellites visible. However, neither of these events, which were of relatively short duration, can explain why the error persisted so long.

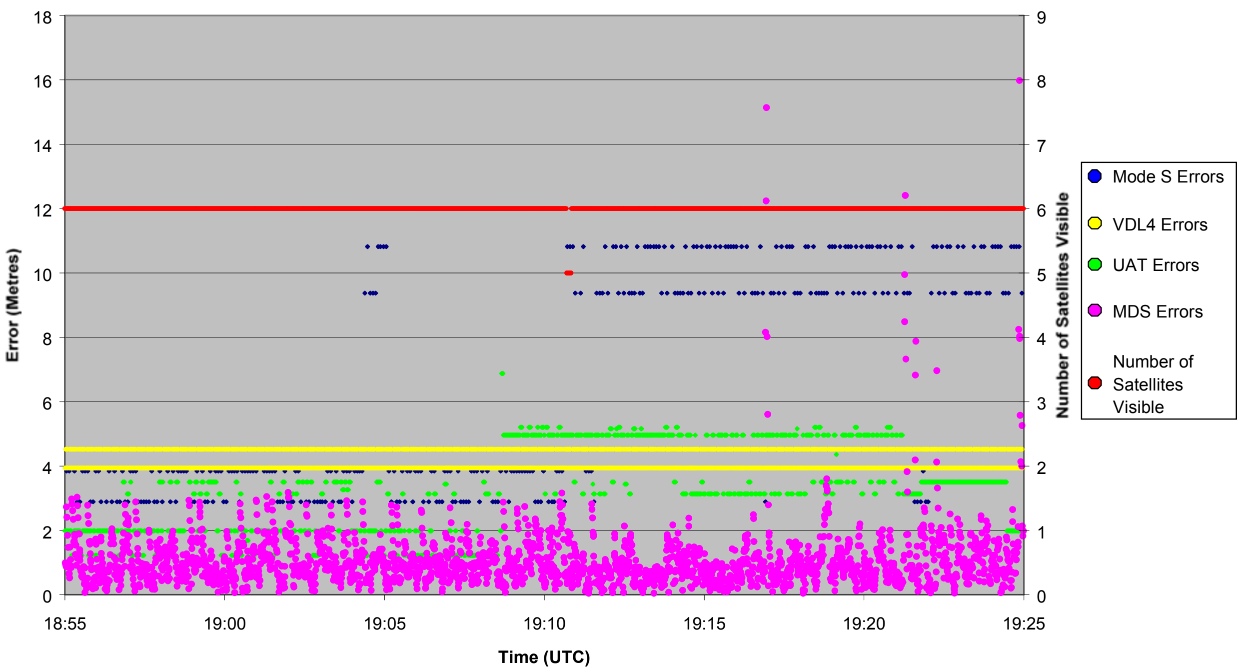


Figure 5-2 Plot of the Errors of the ADS-B Links and MDS System Over Time

5.2 Mobile Trial

The mobile trial took place over four hours, with the subsequent data analysis being broken down into 12 separate test runs, covering specific areas of the airport. These are listed in the table below. A full page plan of Heathrow is available at Appendix E.

Test	Description	Start Point	End Point	Start Time	End Time
1	Inner Circuit of Taxiways clockwise	23(I)	23(I)	22:20	22:29
2	Approach to runway 23	115	134	22:40	22:46
3	Runway 23	40	78	22:49	22:51
4	Approach to 09L	77(O)	115	22:54	23:01
5	09L – 27R 27R – 09L	09L 27R	27R 09L	23:02 23:07	23:06 23:12
6	Fire Station Run	115	89	23:12	23:19
7	Parallel run to 09R	100	88	23:25	23:31
8	Terminal 4 Loop	118	106	23:35	23:43
9	126 – Maintenance Area	126	47	23:44	23:49
10	Maintenance Area Hangers			23:50	23:58
11	Maintenance Area Taxiways	44	76	00:12	00:16
12	Stands/Hangers In – turn - out			00:17	

Table 5-3 Breakdown of Tests for the Mobile Trial

5.2.1 Overall Link Performance

A comparison of all three ADS-B technologies for the whole of the trial, reveals the different propagation characteristics of VHF and UHF signals. The three figures below show the reported positions from each of the three ADS-B for the whole. It can be seen that the Mode S Extended Squitter (Figure 5-3) and the Universal Access Transceiver (Figure 5-4), provided reports from the eastern side of the airport, but as the van moved towards the part of the airport that was obscured by the control tower, reception of messages became less frequent. The Mode S Extended Squitter showed a definite cut off, whereas the UAT signal was available for longer with messages occasionally being available from the western side of the airport. Figure 5-6 shows the reports form the VHF Digital Link Mode 4 Transceiver. The position reports that are offset came from the data burst, which is briefly described in 5.1.1.3.

For all the links, the north western corner of the airport, particularly near the threshold of runway 09L, posed a problem, although for VDL4 it was the only significant problem area. Given the position of the VCR and SMR relative to the antennae, these obstructions can explain the blindspots to the north west of the airport. The UAT and Mode S Extended Squitter were far more susceptible to obstructions, and these will be discussed in some of the tests described below.

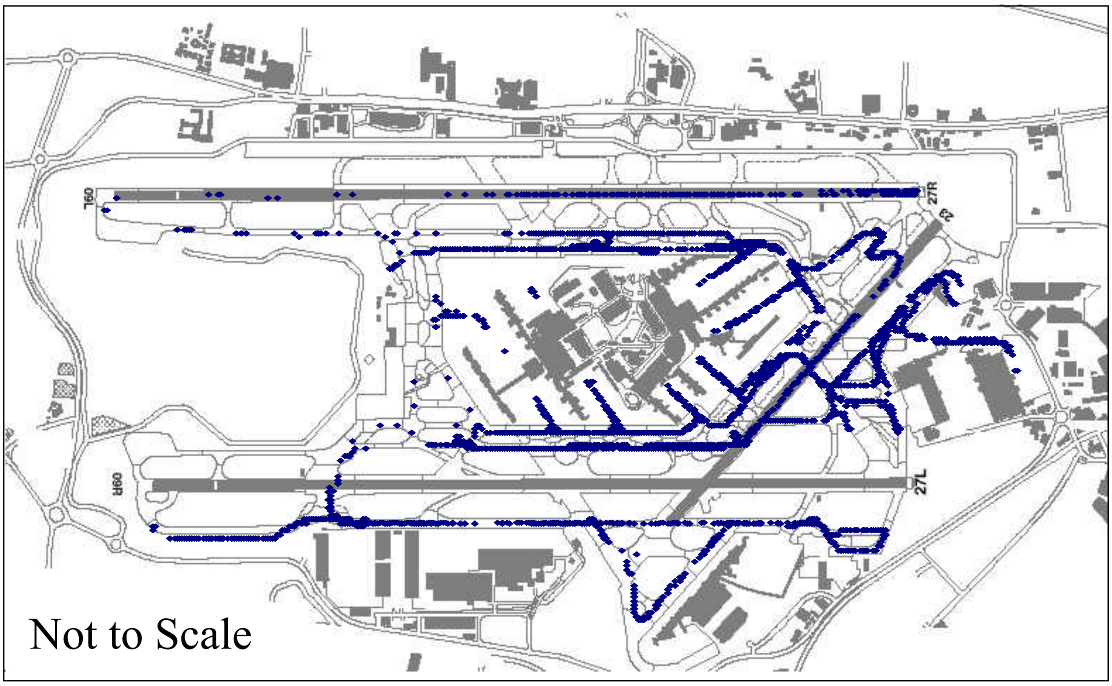


Figure 5-3 Position Reports from Mode S Extended Squitter

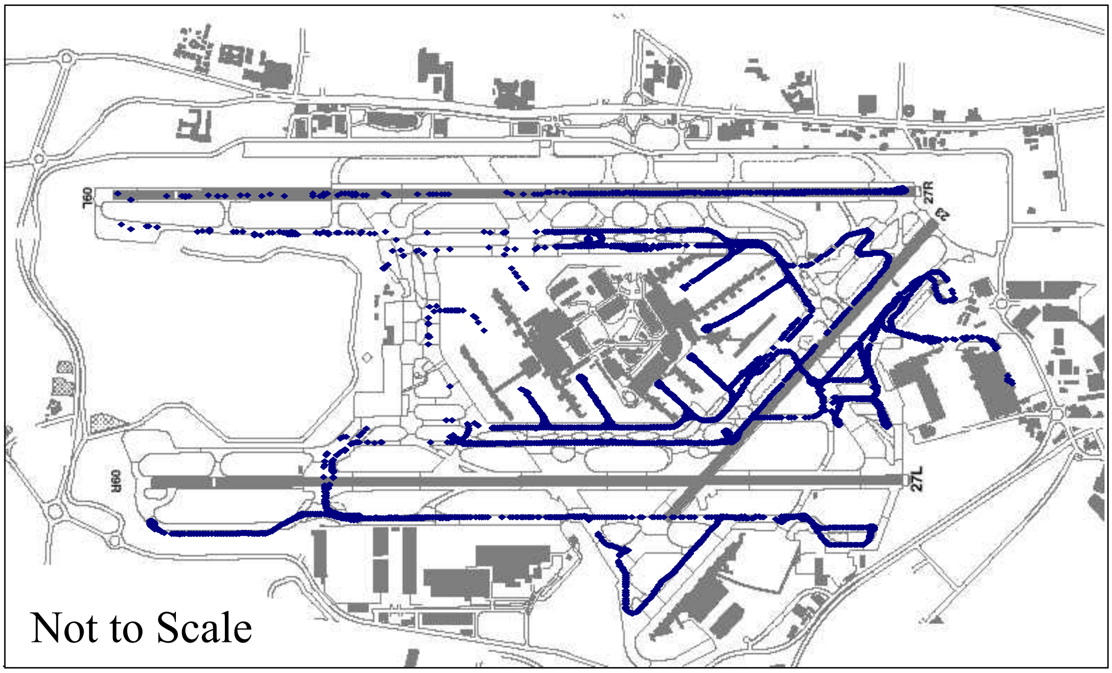


Figure 5-4 Position Reports from Universal Access Transceiver

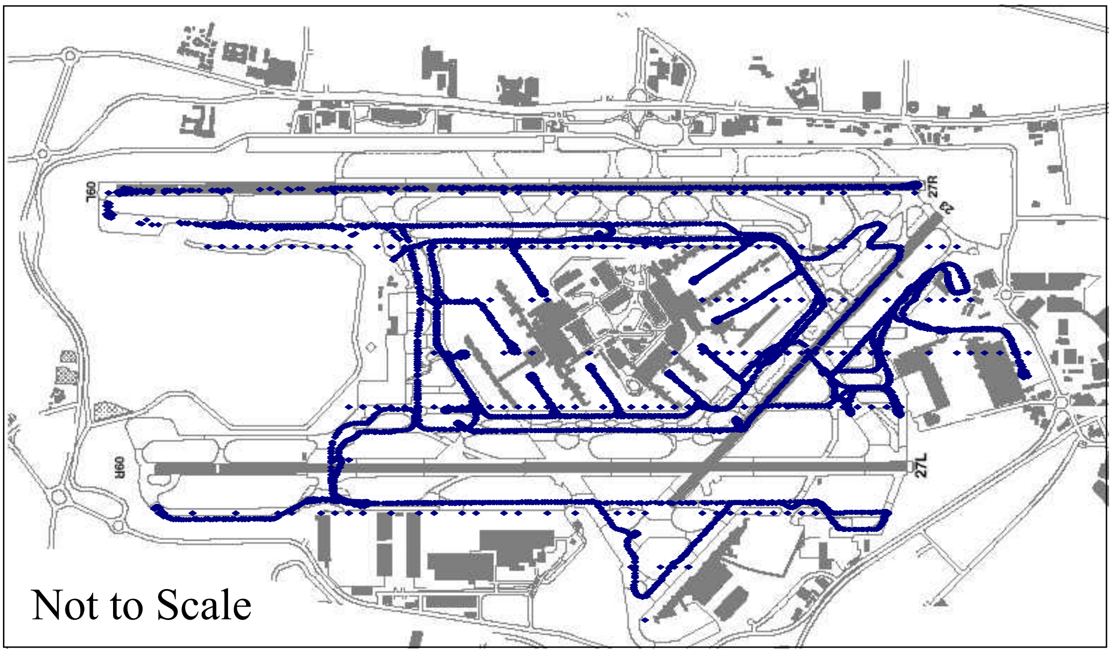


Figure 5-5 Position Reports from VHF Digital Link Mode 4

5.2.2 Mode S Extended Squitter

The areas of the airport that were obscured by the Control Tower had a low reception probability. As an overall proportion of the trial the Extended Squitter was available for approximately 55% of the time, which is representative of the amount of time that the van was obscured from the base station antenna by the Control Tower.

Test 3, the run along runway 23, represents a relatively clear view of the control tower from the trials van. The following diagrams show the performance of the link during this run with a duration of just over 2 minutes. Figure 5-6 shows where the vehicle turned onto the threshold of Runway 23 and proceeded along its length. The gap in the data appears to be in a direct line between the Control Tower the DME and the Europier (which is one of the aircraft piers to the west of the terminal buildings). Comparing this plan view with the photographs in Appendix A shows that the runway is in clear view of the Control Tower.

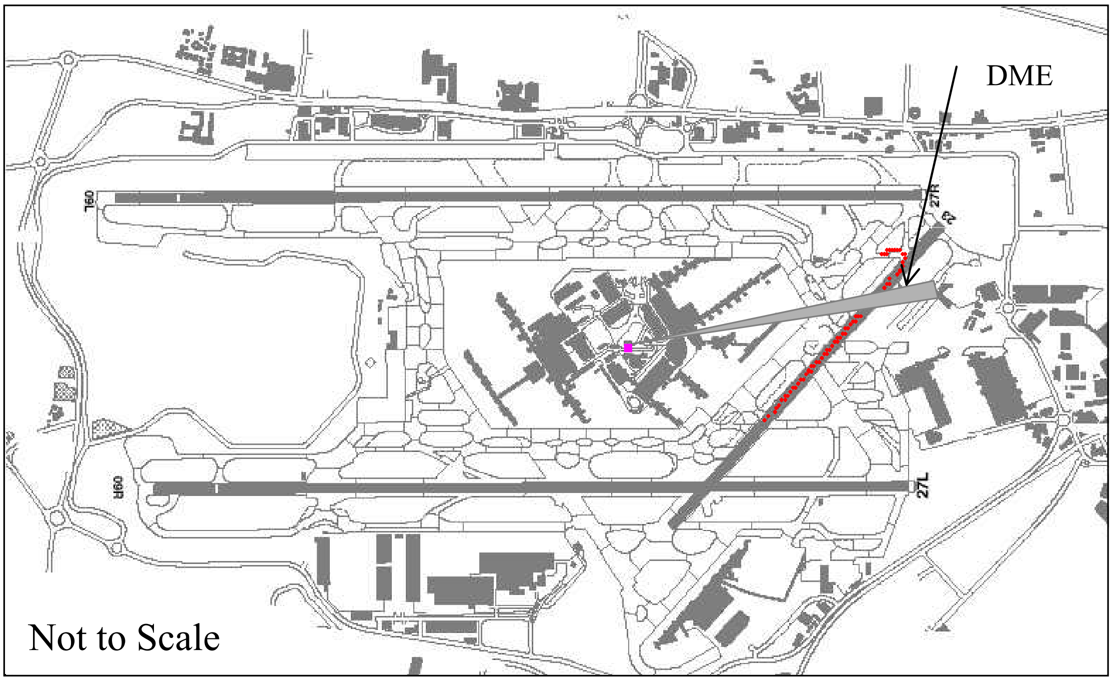


Figure 5-6 Test Run 3 Showing Where Mode S Extended Squitter was Received.

The true bearing of the reported position of the van from the control tower was calculated from GPS positions. When the Reception Probability is plotted against bearing as in Figure 5-7, it is seen to fall dramatically from approximately 87% at a bearing of 68°, to a minimum of 26% at a bearing of 76°, before climbing past 87% again at a bearing of 88°. It is interesting to not that although the Europier covers a sector between 68° and 104°, the DME is at a bearing of 75° and the drop begins 7° before and finishes 13° after the position of the DME. The close proximity of the van to the DME and the clustering of the performance degradation around it indicate that co channel interference from the DME is the more likely cause of the drop in reception probability rather than multipath effects from the more distant Europier.

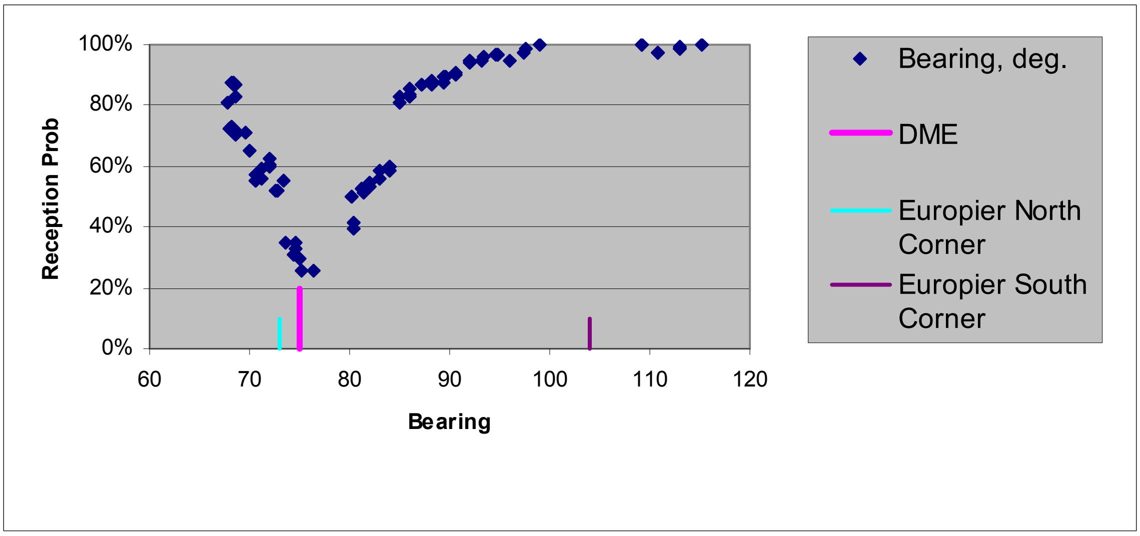


Figure 5-7 Plot of Reception Probability Against Bearing for Test 3

Figure 5-8 shows that during this test the reception probability only exceeded 80% for a relatively short period.

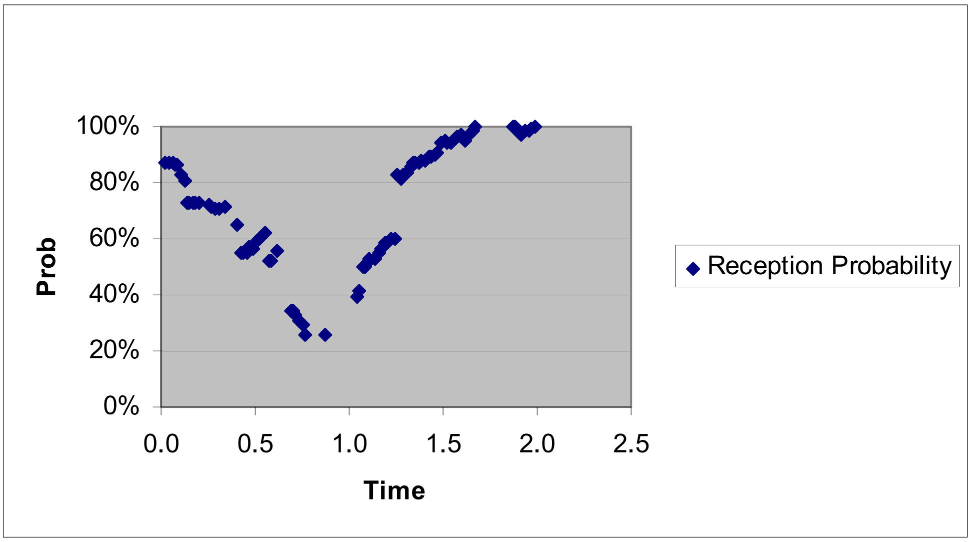


Figure 5-8 Reception Probability Against Time

Figure 5-9 shows that 95% of the messages were received in under 2.2 seconds. Furthermore, when obstructions are considered such as piers and beacons, the update rate at the receiver is always going to be less than the transmission rate. Clearly this means that aspirations for update periods of 1.5 seconds or less will be difficult to achieve. Obviously, one method is to increase the number of receivers ensuring clear line of sight between the receiver and all areas to be surveyed, so that the apparent losses due to obstructions are minimised. Knowledge of the true update rate, without any obstructions, will give an idea of how effective this solution will be.

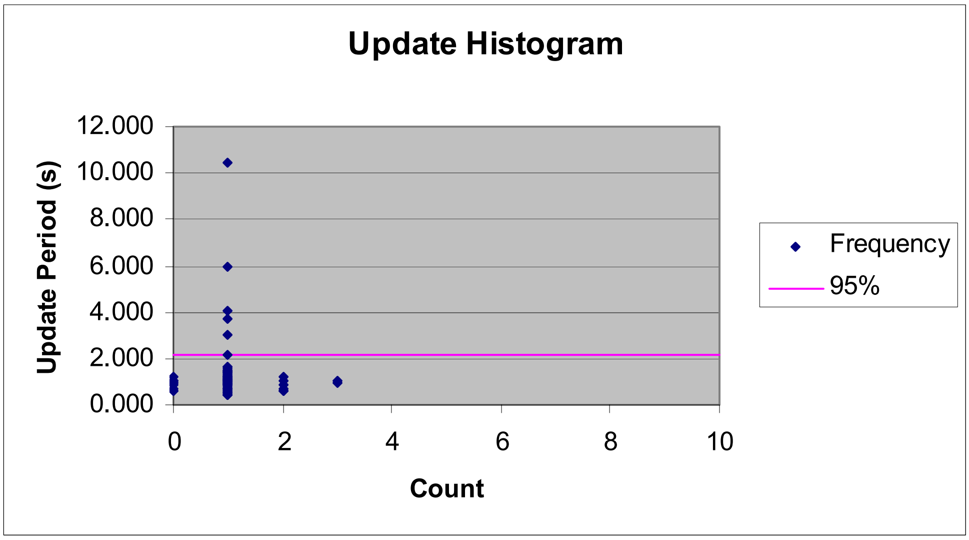


Figure 5-9 A Histogram of Update Periods for Test 3

In order to get a view of a true update rate, the data was searched for periods during which the reception probability was at 100% for a relatively long period of time. This was impossible for the extended squitter, and so the data was searched for a period during which the reception probability was over 90%. A period of approximately one minute was identified in Test 9, which was the run north of and parallel to runway 09R.

Figure 5-10 shows the track of the van along the outer taxiway to the north of runway 09R/27L. Comparing the reception Probabilities against bearing and against time in Figure 5-11 and Figure 5-12, it can be seen that reception probability is above 80% for most of the run over a period of about 2 minutes.

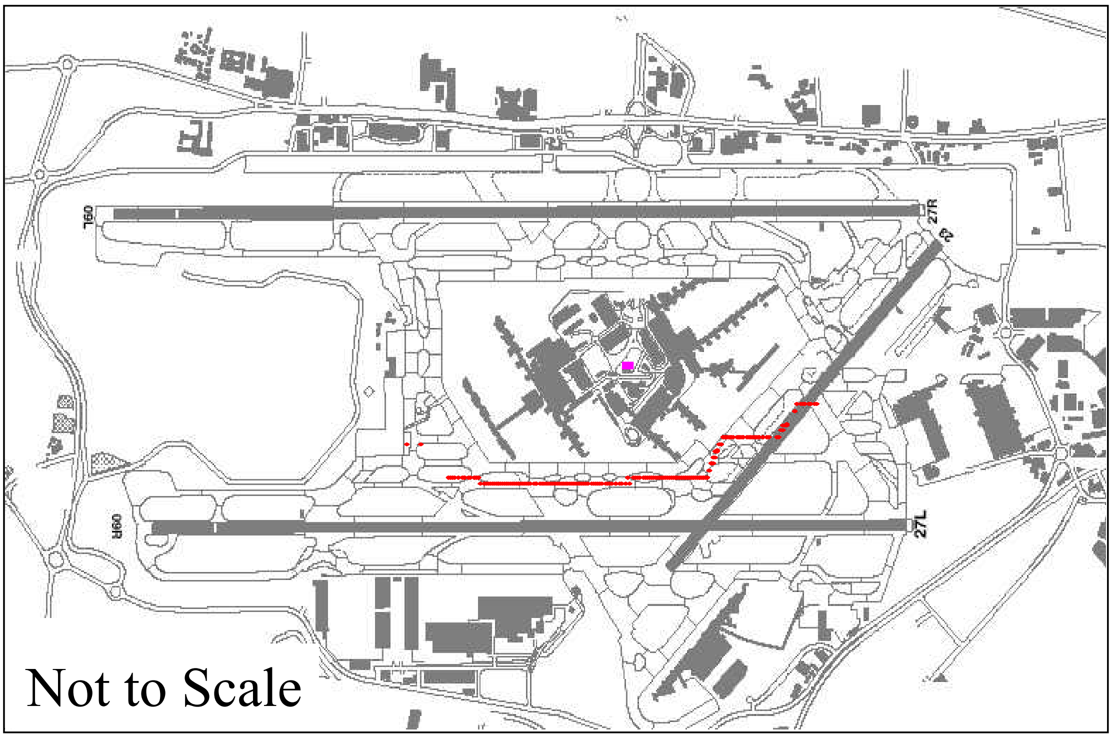


Figure 5-10 Plot of Track Updates During Test 9

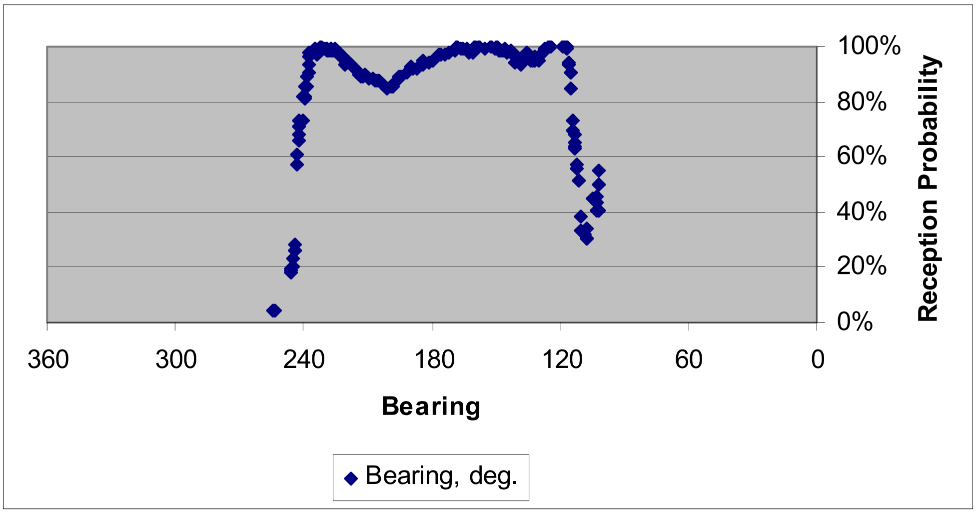


Figure 5-11 Reception Probability Against Bearing For Test 9

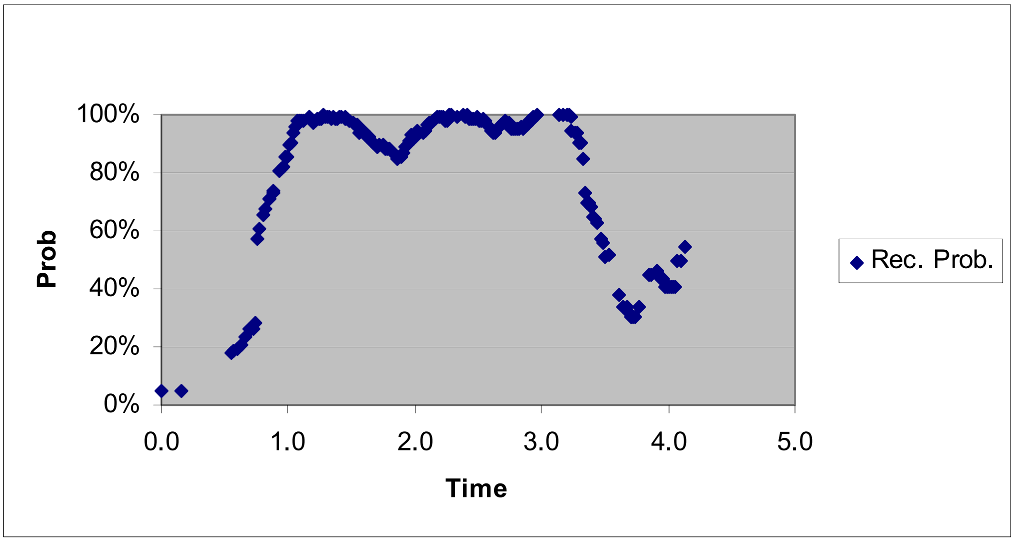


Figure 5-12 Reception Probability Against Time for Test 9

Figure 5-13 and Figure 5-14 show the calculated update period for this test run. Ninety five per cent of the update periods for test 9 are below 1.9 seconds when the entire test is considered, which is similar to the 2.1 seconds found in test 3. However, when the data is reduced to only those data points that are above 90%, to approximate an unobstructed view of the area under surveillance, then 95% of the update periods are lower than 1.4 seconds. This indicates that it is possible for an update period of less than 1.5 seconds to be achieved 95% of the time if enough receivers are suitable sited around the airport.

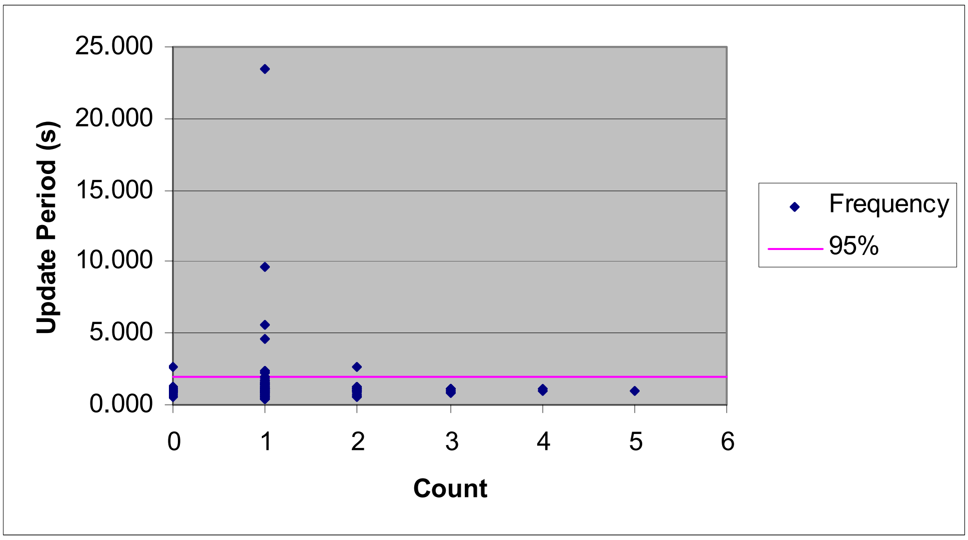


Figure 5-13 Update Period for Test 9

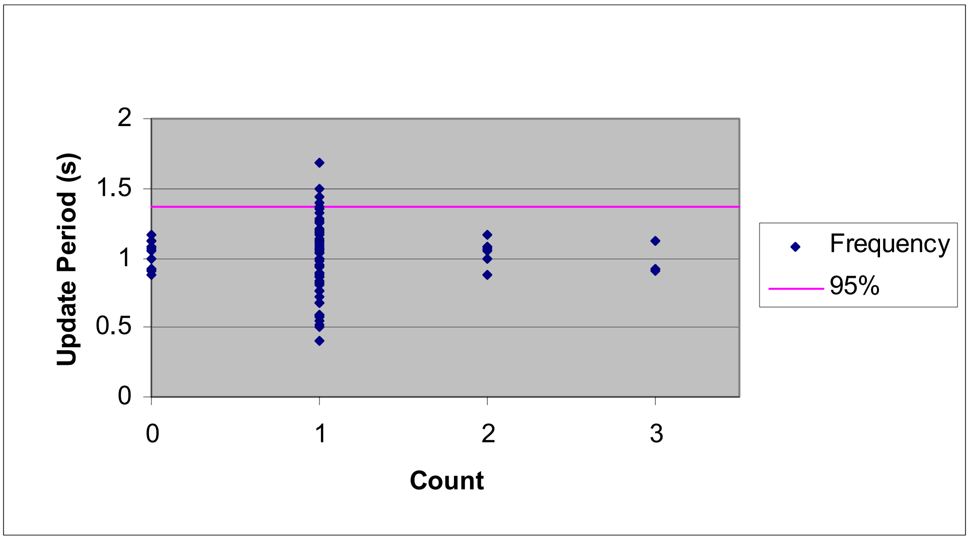


Figure 5-14 Update Period for Test 9 With the Obstacles Removed

5.2.3 Universal Access Transceiver

The UAT suffered from the effect of obstructions, and those parts of the airport that were blocked by buildings showed poor receptions. In particular the north-western sector of the airport is hidden from view by the Visual Control Room.

Perhaps the test with the best overall reception was test 7, involving a run along the taxiway to the south of runway 09R/27L, for the full length of the runway. Figure 5-15 shows the positions from which messages were received by the base station. It shows the taxiway is visible to the base station for almost its entire length apart from two areas. These areas are in line with the ends of Pier 1 and Pier 6, although the gap that is in line with Pier 6 is next to the Cargo Area and the DME. The gap may therefore be due to one of three effects;

- Corruption from the DME
- Signal blocked by the pier
- Reflections or multipath due to the buildings in the cargo area.

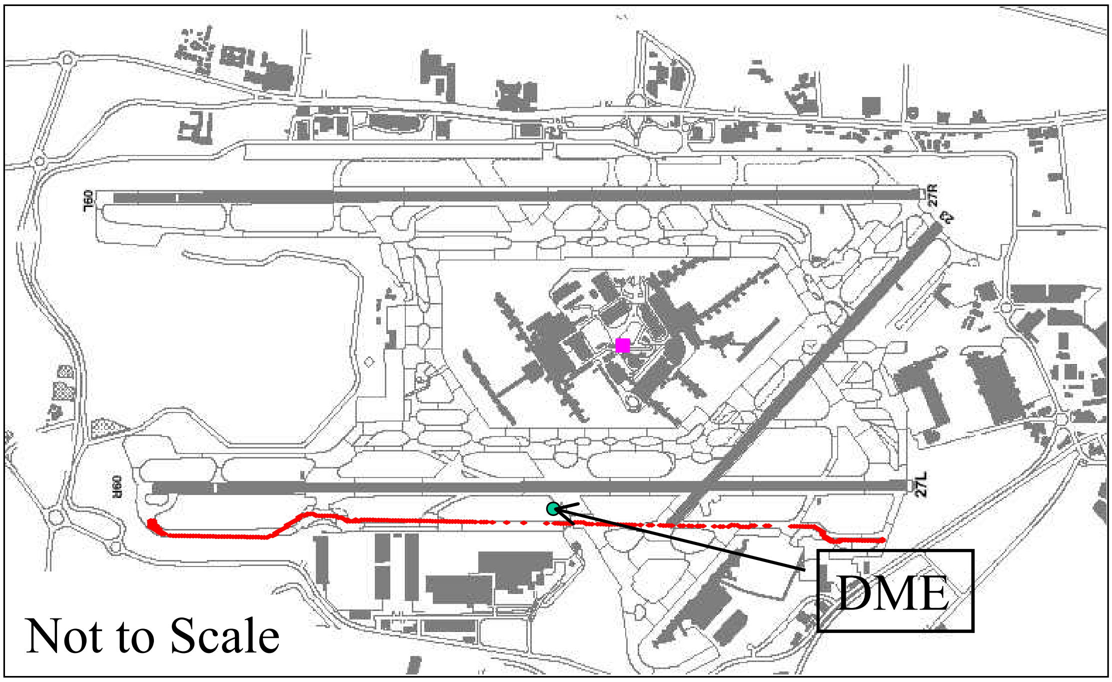


Figure 5-15 Plot of Messages Received from the UAT During Test 7

When the reception probability is plotted against bearing as in Figure 5-16, four distinct drops in reception probability are observed. The final one at approximately 249º represents the end of the run when the corner of the VCR starts to impede the view from the antenna to the threshold area.

At bearings of 138º and 166º the reception probability drops to 58%. Given that the ends of the pier of Terminal 4 lie between bearings of 133º and 177º, and that the end of pier 1 is at 141º, it is likely that these obstructions are the cause of the drop in reception.

Perhaps of more interest is that at a bearing of 214º the reception probability drops to a minimum of 30%. The DME beacon for the southern runway (09R/27L) is adjacent to the taxiway and is at a bearing of 207º from the Control Tower, which is close to the bearing

(206º) when the reception probability starts to drop below 60%. The drop in reception probability begins at 191º, although with the buildings in that sector of the airport, as described above, it is difficult to isolate one cause without performing analysis of the radio frequency environment.

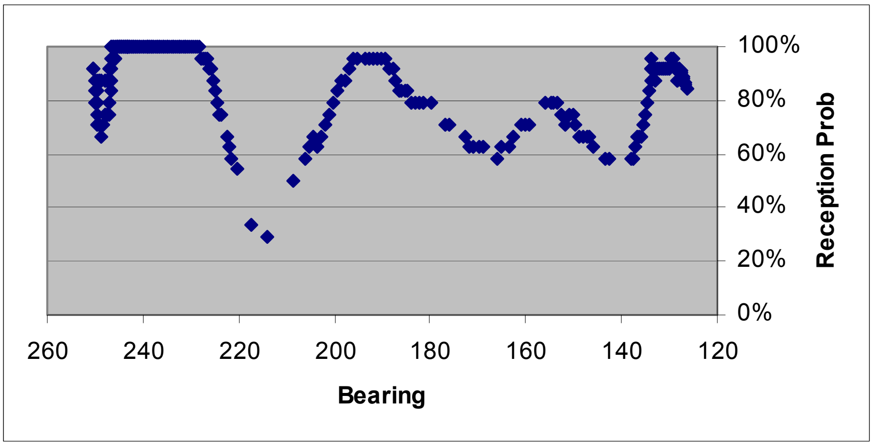


Figure 5-16 Plot of Reception Probability Against Bearing for Test 7

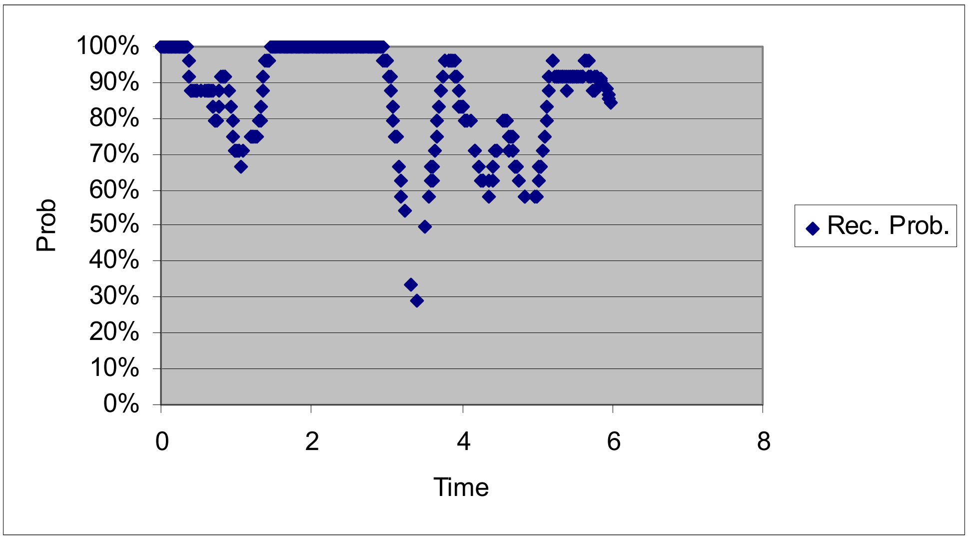


Figure 5-17 Plot of Reception Probability Against Time

Figure 5-17 shows that the reception probability was 100% for a period of approximately 2 minutes allowing a good sample to be obtained for comparing the update period for this trial and an idealised environment. These are shown in Figure 5-18 and Figure 5-19. Taking the entire data set for the test run, including those areas where the reception probability was low, 95% of the update periods were below 2.1 seconds. When the poorer areas were discounted the update periods improved with 95% of updates occurring in less than 1.5 seconds.

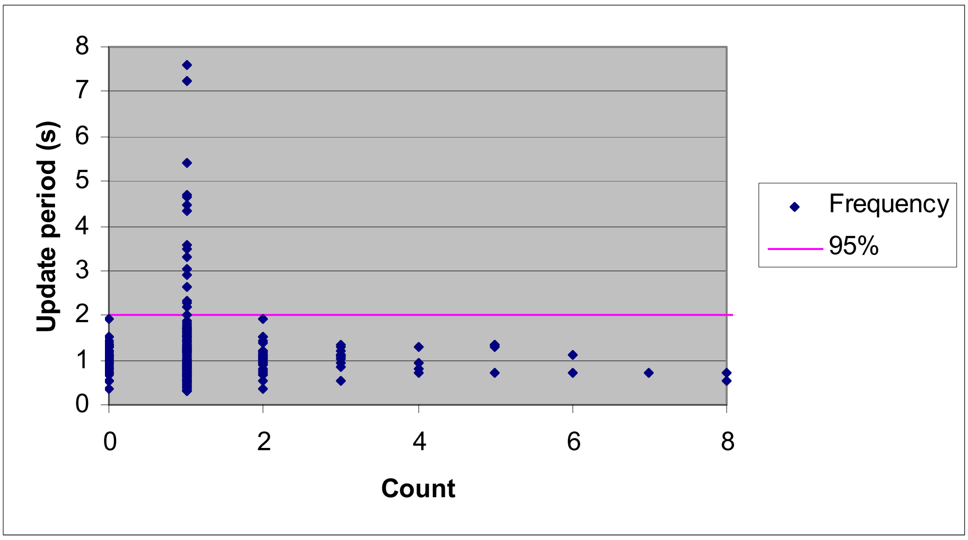


Figure 5-18 Update Period for Test 7

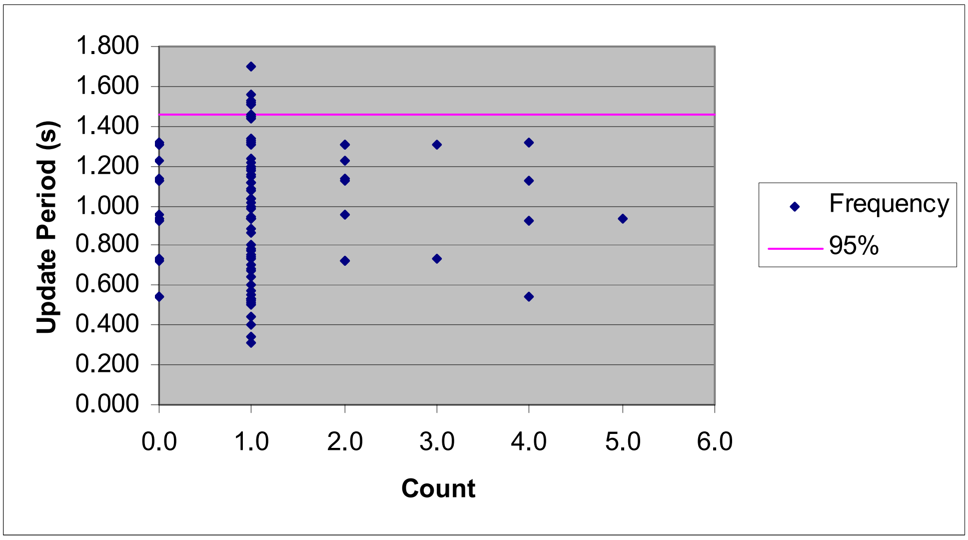


Figure 5-19 UAT Update Period when reception Probability is 100%

5.2.4 VHF Datalink Mode 4

The VDL4 gave good coverage over the airport, which is due to the propagation characteristics of VHF.

When the transceivers were set up, it was possible to set the sequence of messages that would be transmitted. In the case of this trial, it was one Data Burst Message followed by 15 Basic Burst Messages. This was discussed in 5.1.2.6. The data burst can be seen as the offset reports in Figure 5-20.

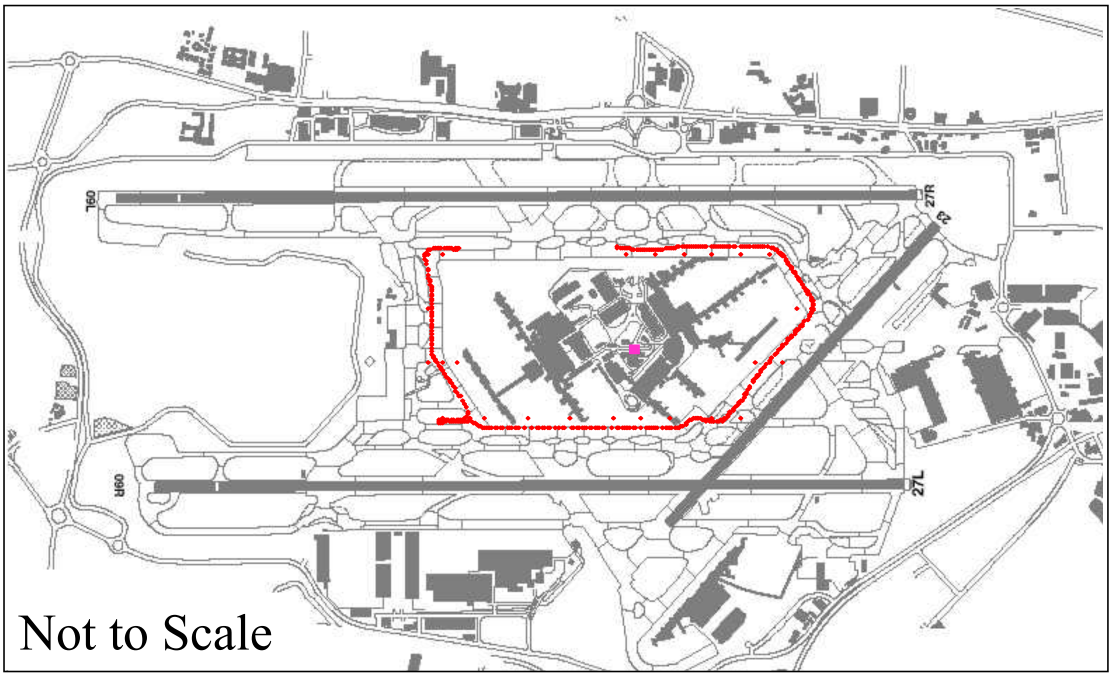


Figure 5-20 Position Messages Received from the VDL4 Transceiver

Analysis of the update periods and reception probability was modified to take account of the Flight ID messages. For reception probability the flight ID message was included, as the reliability of the link was the main criteria, ie was a message received from a particular place on the airport surface. The Data Burst was not used for calculating the update period, so the update periods below refer to the intervals between receiving an actual position update.

The reception probability for the VDL4 was quite high as seen in Figure 5-21. Apart from a region between 250º and 300º, which is consistent with the obstruction of the VCR and SMR, it is above 95%.

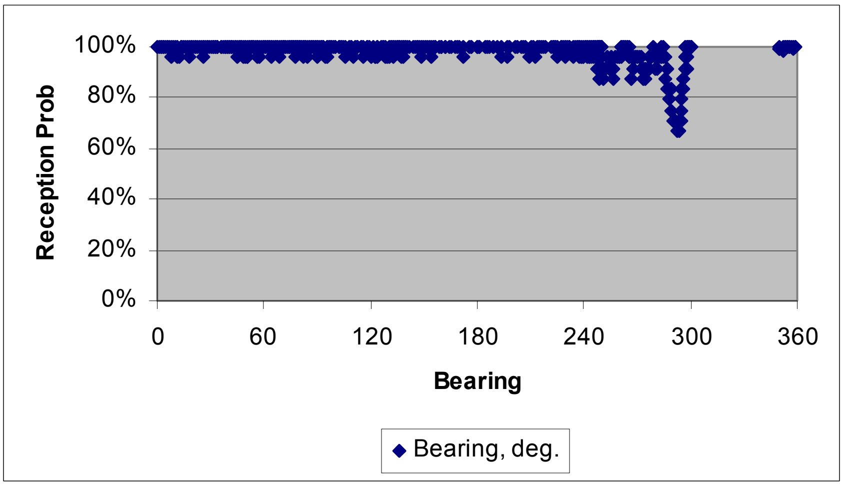


Figure 5-21 Reception Probability Against Bearing for Test Run 1

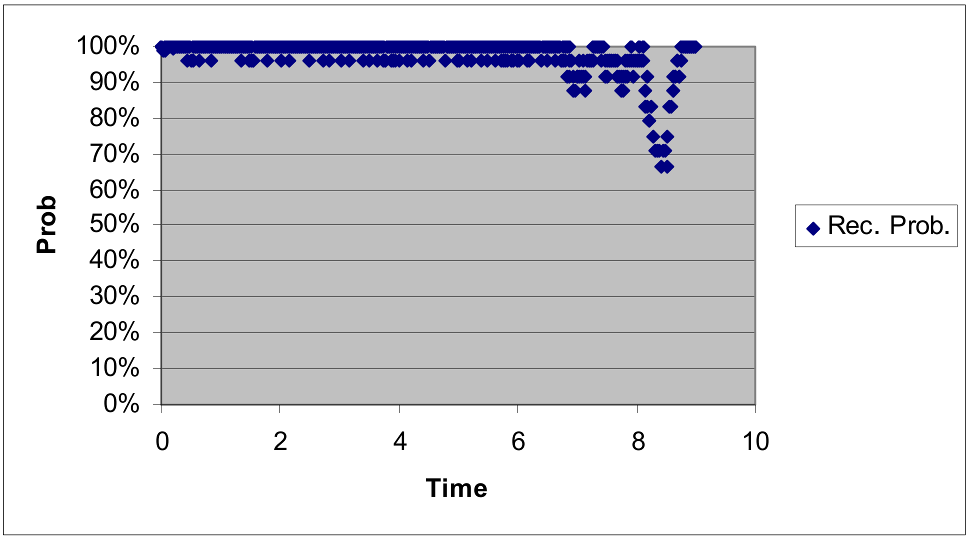


Figure 5-22 Reception Probability Against Time for Test Run 1

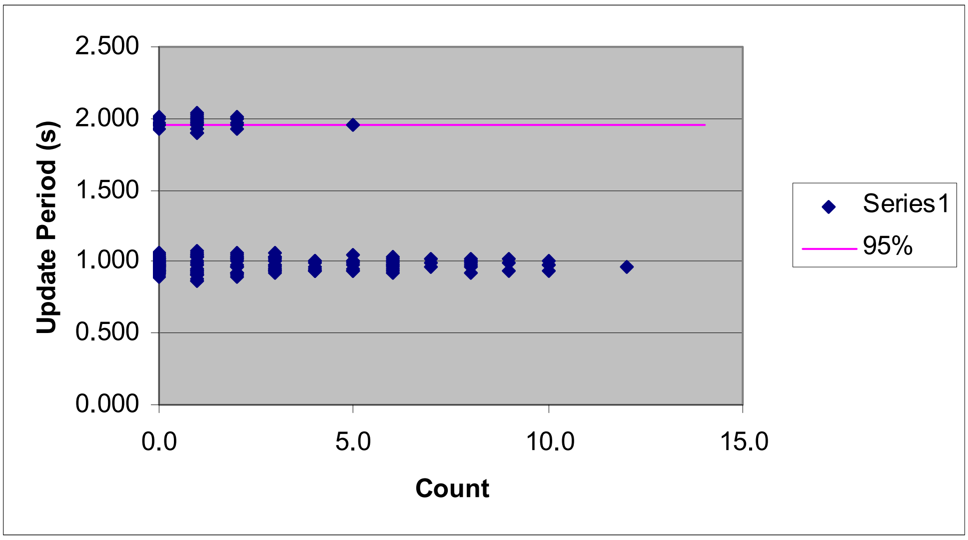


Figure 5-23 A Histogram of Update Periods for Test Run 1

The update period for the VDL4 was 1.95 seconds, although it should be noted that the configuration of the transceivers was such that 1 message in 16 did not include a high precision position and as such were not included in the calculations. In fact for all the runs, the update period for VDL4 was between 1.90 seconds and 1.98 seconds, for areas where the reception probability was above 90% (to take account of obstructions).

5.2.5 Comparison to MDS

The original intention of the project was to perform the ADS-B trial after the acceptance of the multilateration system into service. However, circumstances meant that the two projects could not maintain their synchronisation and the ADS trials occurred before the Site Acceptance of the multilateration system. Therefore no comparison has been made, although it is believed that the system was close to an operationally acceptable standard at the time of the trials.

5.2.5.1 Link Performance

The data received consisted solely of the X-Y position and station time. Several position reports were received for each one second period indicating the coverage of the airport was satisfactory. However, it was not possible to distinguish between short squitters and extended squitters from the supplied data making an in depth analysis impossible.

5.2.5.2 Position Accuracy

The position accuracy is of particular interest as it is derived from a time difference of arrival approach so it provides an independent means of calculating the position of a vehicle. Secondly the MDS takes ADS-B reports in preference to a multilaterated position. A comparison of the relative accuracy of the two methods is of particular interest.

Unfortunately, errors found in the data were substantial with the MDS giving a position several hundred metres different to the ADS-B positions, making it impossible to compare the data sets directly. As the MDS system has since been accepted the only explanation can be a difference in the data processing used by the MDS system.

6 Conclusions

The trial was successful in gathering a large amount of data in a live airport environment, which is available for further analysis.

During the static trial messages were lost from the Mode S Transponder (1090 MHz Extended Squitter) when aircraft passed close to the van. The UAT was not affected in this way. As these two technologies are on a similar frequency, this indicates that the likely cause is co-channel interference from the aircraft transponder rather than a temporary obstruction by the aircraft structure.

The trial has indicated a potential interaction between the ADS-B technologies (Mode S, UAT) and Navigation Aids, namely Distance Measuring Equipment. Although the geometry of this particular trial meant that the ends of piers that were on a similar bearing to the DMEs, introducing some uncertainty, the reductions in reception probability were more pronounced close to the DMEs. This should be investigated further. VDL-4 did not suffer from any degradation of performance at these same points.

The Mode S Extended Squitter and Universal Access Transceiver links were not available in certain sectors of the airport, particularly where there was an obstruction between the base station and the van. The VHF Digital Link Mode 4 was not affected to the same degree by these obstructions. This is as expected given the relative propagation characteristics of VHF and UHF signals.

The Mode S Extended Squitter showed a lower performance than the other links, but this may be due to other users of the same frequency. Analysis of the use of the 1090 MHz Channel should help clarify whether other uses of the same frequency potentially interact with the ADS-B message.

The UAT had a better link reliability than the Mode S Extended Squitter but still suffered from line of sight problems.

The VDL4 had the highest link reliability, as would be expected given the lower frequency of the link compared to UAT and Mode S Extended Squitter.

Investigation into any areas of interest should be conducted in a more controlled environment, allowing any observed effects to be studied without risk of interference from operational activities. It would also be advisable to try and select a site was arranged so that potential interactions could be easily identified e.g. ends of piers and DME beacons. When these effects are better understood, they could be re-examined in an operational context on an airport.

7 Acknowledgements

Conducting the trial at Heathrow posed unique challenges, which at times appeared to overwhelm other aspects of the trial. Without the help of Airports Engineering the trial would have been impossible. Particular thanks are due to the following people.

Graeme Henderson	NATS
Mike Quansah	NATS
Damian Mills	NATS
Gérard Rambaud	EUROCONTROL Experimental Centre

Appendix A Antenna Installation at Heathrow Airport.

Three 2 metre high masts were installed on the Southeast-facing wall on level 8 of the Heathrow Control Tower Building.

Figure A-1 – Antenna Masts

Figure A-2 – View Northwest from the Antennae

The view from the VDL4 antenna looking north west shows the obstruction from VCR and the SMR as well as plant being a potential source of obstruction or reflections. Ideally the antennae would have been sited on the roof of the VCR or on a mast above the SMR, to provide an unobscured view of most of the airport. However, such an installation would have required a lot of co-ordination together with more design work, and a higher standard of installation. This was deemed to be beyond the needs of these trials, as their short duration did not justify the disruption.

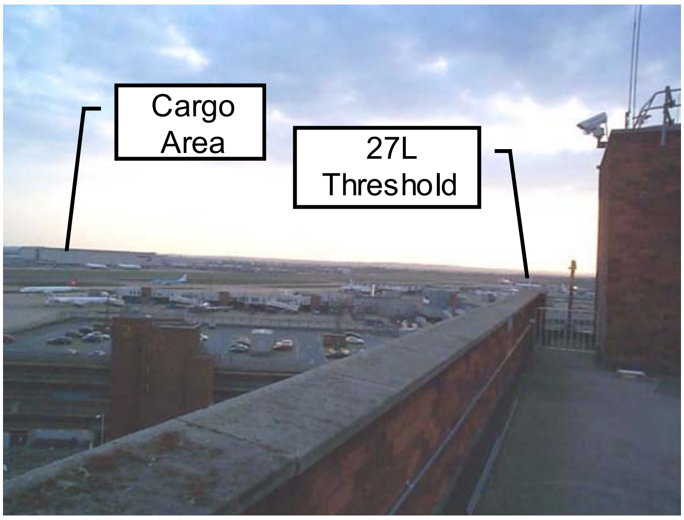


Figure A-3 – View to South West from Antennae

Figure A-3 picture shows the view from the VDL4 antenna past the VCR towards the cargo area and the end of runway 27L.

Figure A-4 – View North from Masts

Figure A-4 shows the view looking north from the VDL4 antenna with the Heathrow 23cm radar visible form the site and the plant on the roof obscuring the north western sector of the airport.

Figure A-5 – View South East

The view south shows the unobscured view from the antennae towards the south eastern sector of the airport. Terminal 2 is visible in the foreground and the maintenance area is visible in the background.

Figure A-6 – Static Trial Position

This final photograph was taken late in the evening during the static trial showing the unobstructed view to the trials van.

Appendix B DME Data for London Heathrow

There are 3 DME located on each runway at Heathrow airport. The characteristics of each DME are described in the following table.

Location	Type	Power	Frequency
Northern Runway	Fernau 2020	100W Peak	1001 MHz
Southern Runway	Fernau 2020	100W Peak	933 MHz
Runway 23	Fernau 2020	100W Peak	1005 MHz

Appendix C Co-ordinate Transformation

The subject of geographic co-ordinates is vast and prone to error when comparing different co-ordinate systems. In the case of these trials the transformation was simply from latitude and longitude to a Cartesian based system. This was to enable the relative positions of tracks to be compared in terms of metres rather than degrees.

The method used was as follows.

In mapping the surface of earth, an alternative is to limit the information to horizontal position only, and express it as angular co-ordinates latitude and longitude. For a point above or below the surface of the earth, we could include its height, defined appropriately. The surface of the earth, however, is irregular and changeable. What is needed to calculate the co-ordinate Cartesian is a model. The figure of the earth is approximated as an ellipsoid of revolution generated by revolving an ellipse about its minor axis see **Figure C-1**. This figure is also referred to as an *oblate ellipsoid*.

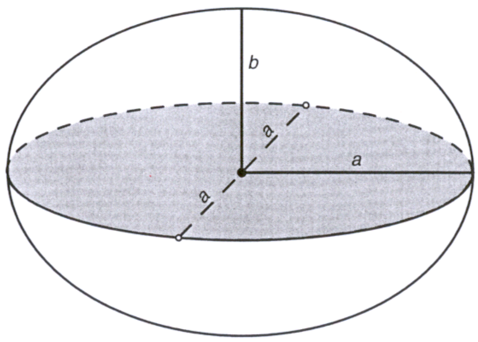


Figure C-1 : Ellipsoid of revolution (oblate ellipsoid)

For a global reference system it makes sense to define an ellipsoid in conjunction with an Earth-Centred, Earth-Fixed (ECEF) Cartesian co-ordinate system, with a common origin at the centre of mass of the earth and the axis of revolution of the ellipsoid coincident with the z axis.

Having specified the origin and the orientation of the ellipsoid, there are only two parameters left for full characterisation : the lengths of the semi-major and semi-minor axes, denoted as *a* (see **Table 1** for value) and *b*, receptively.

The **e**ccentricity is defined as $e^2 = \frac{a^2 - b^2}{a^2}$

In geodesy, it is more common to characterise the ellipsoid by specifying the semi-major axis and **f**lattening, denoted as *f* and defined as $f = \frac{a - b}{a}$. The flattening and the eccentricity are related by $e^2 = 2f - f^2$

Now we can define the geodetic co-ordinates (also called geographic or ellipsoidal co-ordinates) of a point P as follows see .

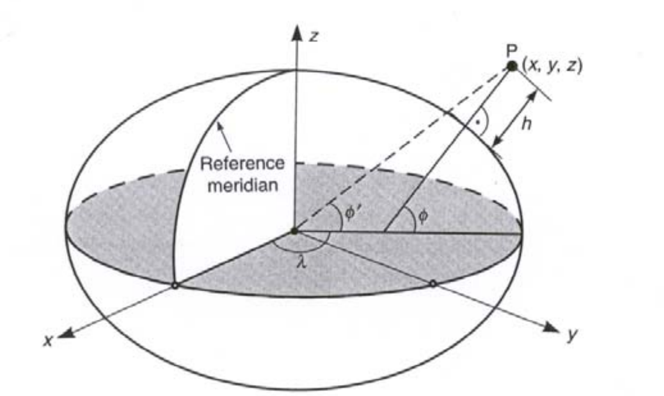


Figure C-2 : Cartesian (x, y, z) and ellipsoidal (ϕ, λ, h) co-ordinates.

Geocentric latitude is denoted as *ϕ'*. We denote a right angle as

geodetic latitude (*ϕ*) : the angle measured in the meridian plane through the point P between the equatorial (x-y) plane of the ellipsoid and the line perpendicular to the surface of the ellipsoid at **P** (measured positive north from the equator, negative south)

geodetic longitude (*λ*) : the angle measured in the equatorial plane between the reference meridian and the meridian plane through **P** (measured positive east from the zero meridian)

geodetic height (*h*) : measured along the normal to the ellipsoid through **P**

A geocentric ellipsoid specifies a global datum or a reference surface to be used in defining 3-D co-ordinates of a point anywhere. Parameters *a* and *f* have been refined over the years. The International Ellipsoid (1924) was defined as : *a* = 6378388 m, *f* =1/297. The best available values today are only slightly different.

The ephemerides of the GPS satellites are expressed in WGS 84. The user positions, therefore, are obtained as WGS 84 co-ordinates. The definition of WGS 84 itself has undergone refinements resulting in adjustment to the values of the fundamental constant see **Table 1**.

Table 1 WGS 84 fundamental parameters (revised in 1997)

Parameter	Value
Ellipsoid	
Semi-Major axis (*a*)	6378137.0 m
Reciprocal flattening (*1/f*)	298.257223563
Earth's angular velocity (ω_E)	7292115.0 x 10^{-11} rad/sec
Earth's gravitational constant (*GM*)	3986004.418 x 10^{8} m^3/s^2
Speed of light in a vacuum (*c*)	2.99792458 x 10^{8} m/s

- Conversion between Geodetic and Cartesian Co-ordinates

We consider below the transformation of the co-ordinates of a point **P** from the Earth-Centred, Earth-Fixed (ECEF) Cartesian co-ordinate frame (x, y, z) to the ellipsoidal co-ordinates (ϕ, λ, h), and vice versa. The centre of the ellipsoid coincides with the origin of the ECEF Cartesian co-ordinate frame, and the minor axis (the axis of revolution) is coincident with the z-axis see **Figure C-3**.

The transformations are made easier by defining distance ***N*** along the normal from ***P*** to the meridian ellipse between ***P'*** and the z axis see **Figure C-3**.

$$N = \frac{a^2}{\sqrt{a^2 \cos^2 \phi + b^2 \sin^2 \phi}} = \frac{a}{\sqrt{1 - e^2 \sin^2 \phi}}$$

Ellipsoidal to Cartesian : from **Figure C-3**, the Cartesian Co-ordinates (x, y, z) of a point with ellipsoidal co-ordinates (ϕ, λ, h) are given by :

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (N+h)\cos\phi\cos\lambda \\ (N+h)\cos\phi\sin\lambda \\ (N(1-e^2)+h)\sin\phi \end{bmatrix}$$

The ellipsoid height was not always available from the ADS-B messages, so in these cases the heights from the reference GPS were used.

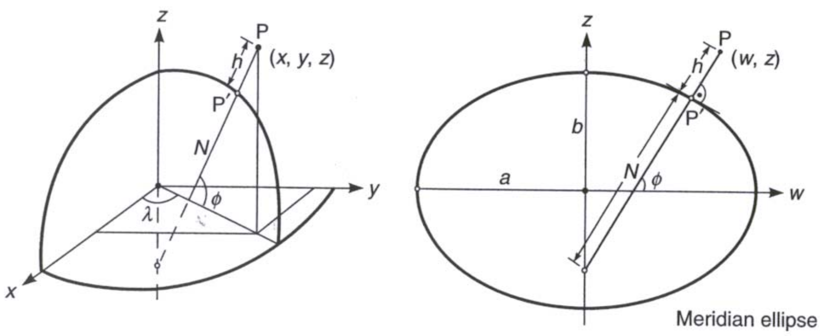


Figure C-3 : Cartesian and Geodetic Co-ordinates

Appendix D Equipment Used

The equipment that was used for the trials is shown below:

D.1 Ground/Base Station

The installation equipment for the Ground Base stations of the 3 ADS-B technologies, namely Mode-S extended Squitter, UAT and VDL-4 are described in the following chapter.

D.1.1 Global Positioning System (GPS)

- Ashtech Z12 GPS Receiver and Antenna mounted on a mast situated on the Control Tower balcony.
- Ashtech Z12 differential GPS situated near the North side Far Field Monitor.

D.1.2. ADS-B using Mode S & Universal Access Transceiver (UAT)

The following equipment was used for the installation of the Ground Base Transceiver 2000 at Heathrow control tower.

- Omni-directional Mode S antenna mounted on a mast situated on the control Tower balcony see Figure 2-8.

    Type : Gigawave

- Power Supply ASF 1000 / 40.25

    S/N 510645

- Diplexer SODHY T/R at 966 MHz and R at 1090 MHz

    Reference DXC 9611-66
    S/N 01/52-1

- SODHY DC block for 1090

    S/N 20/29

- UPS Aviation Technologies GBT 2000 for UAT and Mode S datalink.

    P/N 435-6076-100 GBT 2000
    S/N 6017645

D.1.3. ADS-B using VHF Datalink Mode 4 (VDL4)

The following equipment was used for the installation of the VDL Mode 4 equipment as Ground Station at Heathrow control tower.

- VDL4 transceiver provided by CNS Systems (Operating on 134.550MHz)

    Part Number 4000-10-10
    Serial N° 1018
    Application Software P/N 4000-10-3.0

Omnidirectional VHF antenna

    Type N° K 51 26 31 (KATHREIM)

- Splitter Aero Antenna Technology Inc - 2 Outputs - for GPS

    S/N 5207
    UPS AT P/N 115-0008-00

- Laptop with MultiMode CATS software version 1.1 from CARMENTA used to record and display VDL 4 data.

Control Tower Equipment

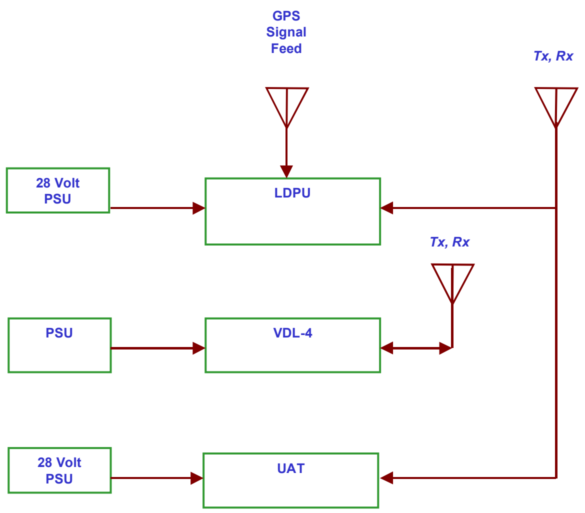


Figure D-1 – Schematic of the Ground Station Equipment

D.2 Van

The equipment in the Van of the 3 ADS-B technologies, namely Mode-S extended Squitter, UAT and VDL-4 is described below.

D.2.1. Generator

A Honda 220V Surge projected generator

D.2.2. Global Positioning System (GPS)

- Ashtech GPS receiver
- Splitter GPS Networking - 4 Outputs -

  S/N 6021
- Splitter Aero Antenna Technology Inc - 2 Outputs - for GPS

  S/N 5191
  UPS AT P/N 115-0008-00

D.2.3. ADS-B using Mode S Extended Squitter

Honeywell Mode S transponder XS-950 :

Transponder Honeywell Level IV   P/N : 7517800-10002R
S/W P/N : 200F-00042
S/N : 97020353

Power Supply 115v/400 SAEME

Garmin GPS 4000 receiver

P/N 011-00504-00
S/N 96700314

Omni-directional 1090 antenna provided by EEC.

D.2.4. Universal Access Transceiver (UAT)

The ADS-B Capstone system is composed of three UPS Aviation Technologies namely :

Apollo GX50 GPS

P/N 430-6050-402
TSO-C129a, Class A1
DO-178B Software level C
UPS Aviation Technologies, Inc.
S/N 6033444
S/W version 3.3

CDTI Apollo MX20 multi-function cockpit display

P/N 430-0270-000
S/N 6031619
S/W version 2.3

UAT datalink radio

P/N 430-6075-000
FAA-PMA
DO-178B Software Level D
UPS Aviation Technologies, Inc.
S/N 6028410
S/W version 2.0

Power supply Convergie ASF 400/40V 10A

P/N 190

966 MHz UAT antenna AT130-1

P/N 590-0016
S/N 5011

D.2.5. ADS-B using VHF Datalink Mode 4 (VDL-4)

VDL4 transceiver provided by CNS Systems (Operating on 134.550MHz)

CNS Systems

Part Number 4000-10-10
Serial N° 1019
Application Software P/N 4000-10-3.0

Power supply Convergie ASF 400/40V 10A
P/N 247

Magnetic VHF antenna ALLGON

D.2.6 28 Volt Power Supply

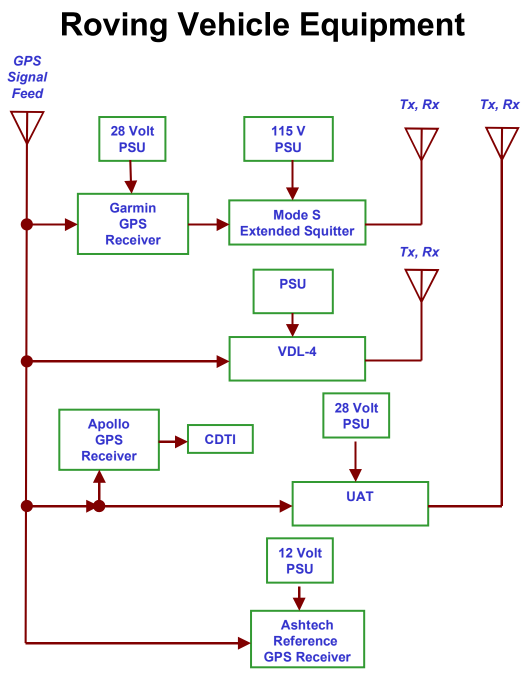


Figure D-2 – Schematic of the van equipment

Appendix E Plan of Heathrow Airport