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Runway Incursion Prevention System ADS-B and DGPS Data Link Analysis Dallas – Ft. Worth International Airport

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November 2001

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Abstract

A runway incursion occurs whenever there is an event that creates a possible collision between an aircraft and another aircraft, vehicle, or object on the runway. The world's deadliest aviation accident was the result of a runway incursion. On March 27, 1977 a Pan Am 747 and a KLM 747 collided on Tenerife, Canary Islands, resulting in the death of 583 passengers. Several other fatal runway incursions have occurred since then, including the recent disaster at Chiang Kai-Shek International Airport in Taipei, Taiwan on Oct.31, 2000. On this day, a Singapore Airlines 747 attempted to take off on a closed runway, and struck construction equipment on the runway, killing 82 passengers. With airport traffic continuing to increase, reducing runway incursions is becoming an increasingly important and challenging task. In recent years, runway incursion incidents on airport runways, taxiways, and ramps have continued to steadily increase in number. The number of runway incursions has increased 60% in the previous five years, and a record number of incursions happened in 2000. [5] NASA Langley Research Center is developing technology to improve the safety of airport surface operations and to reduce the number of runway incursions. This technology development is part of the NASA Aviation Safety Program (AvSP). Three key components of AvSP include: Synthetic Vision Systems (SVS), Hold Short Advisory Landing Technology (HSALT), and the Runway Incursion Prevention System (RIPS). These systems were flight tested and demonstrated successfully at the Dallas – Fort Worth International Airport (DFW) during October 2000.

This report addresses the RIPS portion of the flight test at DFW. Specifically, this report documents the results of data analysis of performance data for the Automatic Dependent Surveillance – Broadcast (ADS-B) using 1090 MHz and Differential GPS (DGPS) prototype systems that Rockwell Collins supported on the NASA ARIES (Airborne Research Integrated Experiment System) research aircraft as part of the RIPS flight tests at DFW. ADS-B and DGPS are key enabling technologies of the NASA RIPS system. The RIPS system also includes an electronic moving map (EMM) which displays traffic on airport runways and taxiways on a head-down navigation display, a heads-up display (HUD) providing real time guidance, audible and visible incursion alerts, and several data links to provide a variety of information. [5]

This report describes the Rockwell Collins contributions to the RIPS demonstration system, summarizes the development process, and analyzes the data collected during the flight tests and demonstrations at DFW. This work was performed under the NASA AGATE (Advanced General Aviation Transport Experiments) contract NCA1-125 (WBS Task 5.3.2). Included in the flight test evaluation were interoperability tests between the NASA AGATE ADS-B flight test system and the NASA ARIES ADS-B system to assure that the "AGATE 1B" aircraft ADS-B avionics are compatible with those of high-end air transport aircraft such as the NASA ARIES 757.

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1.0 Introduction

The RIPS program goal is to reduce the number of runway incursions by integrating several technologies to improve the surface communication, navigation, and surveillance systems for flight crews and air traffic controllers (ATC). [5] Pilots need to know where they are, where other traffic and obstacles are located, and what path they need to take to their destination. Air traffic controllers need to know this information for each aircraft. [6] Today, confirmation of position and traffic is typically accomplished by visually scanning the airport surface and making references to paper maps. Radio communication may also be used to confirm position. This high reliance on visual methods for position and traffic monitoring makes situational awareness difficult in low-visibility weather, nighttime operations, or at unfamiliar airports. [6] In addition, pilots currently receive taxi routes via voice communications and must either write them down or memorize them. Misunderstandings or miscommunications can result in errors that could lead to dangerous incursion incidents. The RIPS system provides significant safety benefits by providing the flight crew with appropriate situational awareness of surface operations using cockpit displays, ADS-B and STIS-B for traffic information, DGPS for precision navigation and position reporting, and Controller Pilot Data Link Communications (CPDLC) for communications of taxi routes and taxi instructions.

2.0 RIPS System Description

The RIPS system uses the following technologies to achieve its operational objectives:

- Automated Dependent Surveillance – Broadcast (ADS-B), which provides vehicle-to-vehicle broadcast of traffic position information.
- Surface Traffic Information Services – Broadcast (STIS-B), which uses a ground-to-air data link to uplink surveillance reports to the aircraft. Traffic information is obtained from multilateration reception of transponder broadcasts or monitoring of ADS-B transmissions by the Airport Traffic Identification System (ATIDS) network, or can be obtained from Airport Surface Detection Equipment (ASDE-3) radar tracks. Traffic information is integrated into surveillance reports by the ground-based surveillance server system, which is part of the FAA Runway Incursion Reduction Program (RIRP) system.
- Local Area Augmentation System (LAAS), which provides a very accurate, high integrity position solution using Differential Global Positioning System (DGPS) augmented GPS receivers capable of receiving the LAAS broadcasts.
- Wide Area Augmentation System (WAAS), which provides increased positional accuracy to properly augmented Global Positioning System (GPS) receivers.
- Runway incursion alerting algorithms, used to provide aural and visual alerts in the flight deck.
- Cockpit Display of Traffic Information (CDTI) using STIS-B and ADS-B traffic information.
- Airport moving map retrofitted on a size B navigation display in the NASA ARIES aircraft, used to display taxi routes and traffic.
- Airport mapping database using a generic exchange format.
- Controller-Pilot Data Link Communications (CPDLC) via VHF Data Link (VDL) Mode 2, designed to reduce confusion in communications between the pilots and ATC.

Rockwell Collins was responsible for the airborne LAAS and ADS-B portions of the RIPS system, and these systems will be the focus of this document, and will be described in greater detail in the following sections.

2.1 LAAS System Description

The position of each aircraft/vehicle is very important in determining whether an incursion event is occurring. Thus, it is important that each aircraft/vehicle has accurate knowledge of its own-ship position. One way to achieve this capability is to use a Global Positioning System (GPS) receiver capable of receiving differential corrections broadcast by a Local Area Augmentation System (LAAS) ground station. The LAAS standard, which is in the process of being finalized by RTCA, is being developed to support precision approach and landing operations and other navigation and surveillance applications within a local area (about 20 nautical miles) including and surrounding an airport. [2] The operational goals of using LAAS to augment GPS include airport surface navigation and providing high accuracy position, velocity, and time (PVT) information to support ADS-B operations. [2] These are also two goals of the RIPS program, making LAAS a natural choice for incorporation into the RIPS system. This method of differential GPS (DGPS) operation can provide an accuracy of less than 3 meters for surface operations.

For the RIPS program, a prototype LAAS ground station was developed by Ohio University, and was located near the East Control Tower at DFW. This was a difficult location for the ground station to operate because the control tower was able to block a significant portion of the sky. Also, the area can be prone to multipath. However, this location was deliberately chosen to provide a difficult environment, to test the capability of the system. Typically, only one ground station per airport is required, and it is assigned a specific frequency and time slot to use for broadcast. For DFW, the frequency was 113.95 MHz using time slot A. The ground station uses several GPS receivers located at surveyed positions to compute errors present in the GPS signal. It computes the differential corrections for each GPS satellite, and broadcasts these corrections two times per second using a VHF data broadcast (VDB). A Collins GNLU-930 Multi-Mode Receiver (MMR) was used to receive these broadcast corrections and apply them to obtain a more accurate GPS PVT output. The MMR is able to receive GPS signals and LAAS corrections, and combine them to perform precision approaches in addition to being able to interact with VOR/ILS systems. In addition to differential corrections, the ground station also broadcasts airport runway information at intervals of a few seconds, which can be used to fly a precision approach. Unlike ILS, LAAS can support multiple runways using a single VDB frequency. Therefore, each runway is assigned a channel number that the MMR must tune to in order to receive the runway information and fly a precision approach. This channel number is determined according to a formula that utilizes the VDB frequency and a number assigned to each runway by the ground station. However, differential corrections from the ground station can be received and used by tuning the MMR to any of the runway channels. Precision approaches were not in the scope of RIPS, so this application of LAAS was not exercised.

2.2 ADS-B System Description

One key requirement to reducing incursions is for aircraft to be able to monitor traffic in the area. One method to accomplish this in the RIPS system is to equip aircraft with Automated Dependent Surveillance - Broadcast (ADS-B) systems. The ADS-B system is designed for use by aircraft and surface vehicles operating within the airport surface movement area. [3] It is automatic because no external stimulus is required for operation, and it is dependent because it relies on on-board equipment to provide surveillance information to other users. [3] Any user within broadcast range can receive and process ADS-B messages using an appropriate receiver. The RIPS system tested at DFW utilized ADS-B messages broadcast at 1090 MHz using the Mode-S extended squitters format. The messages contain a variety of information about the broadcasting vehicle, including: position, altitude, speed, heading, air/ground status, navigation uncertainty, aircraft ICAO address, aircraft type, and flight ID. The position information is obtained from a GPS receiver. The transmission of ADS-B messages can be performed in a Mode-S transponder transmitting at 1090 MHz, although a Mode-S transponder is not required for ADS-B transmission. Reception of ADS-B messages can be achieved in TCAS (Traffic Alerting and Collision Avoidance System) by using a 1090 MHz receiver, although TCAS is not required for ADS-B reception. Received ADS-B messages are used by RIPS for cockpit display of traffic information (CDTI) and as inputs to runway incursion alerting algorithms.

The ADS-B system developed for the RIPS program used a Collins TPR-901 transponder modified to send the required Mode-S extended squitters. The position information sent in the messages is obtained from a

Collins GNLU-930 Multi-Mode Receiver, operating in DGPS mode using corrections broadcast from the LAAS ground station. A Collins TTR-921 TCAS was modified to receive and process ADS-B messages. An ADS-B transmit pallet was installed in a FAA van, and an ADS-B transmit/receive system was installed on the NASA ARIES 757. In addition, a transmit-only ADS-B pallet developed for the Advanced General Aviation Transport Experiments (AGATE) program was used for interoperability testing. These installations will be described in greater detail in subsequent sections. The transmit-only pallets were utilized as surface vehicles, and only transmitted a "surface position" message and an "identification" message. Surface position messages were transmitted twice per second. The pallet used in the FAA van transmitted identification messages every 10 seconds, and the AGATE pallet transmitted identification messages every 5 seconds. These rates were fixed in software, at the 'high rates' specified by the ADS-B 1090 document, with the exception of the ID messages from the pallet in the FAA van, which were broadcast at the 'low rate'. [3]

2.3 Systems Development and Testing

Several months were spent by Rockwell Collins engineers on the design, integration, and testing of the ADS-B and DGPS systems prior to demonstrations at DFW. The RIPS project required new software to be written for the transponder, TCAS, and MMR. The transponder software required the most changes, and several software upgrades were performed throughout the testing, improving the software to near production quality. In addition, the ADS-B transmit pallet used in the FAA van and the AGATE ADS-B transmit pallet were built and tested. These pallets were tested in various configurations at Rockwell Collins facilities in Cedar Rapids, IA and Melbourne, FL. Pallet testing was also performed at the NASA LaRC in Hampton, Virginia. The LAAS DGPS ground station used at DFW was a new system developed by Ohio University for the RIPS program. Interoperability testing between the ground station and the Collins MMR was performed in Athens, Ohio prior to deployment of the ground station at DFW. Coverage testing of the LAAS data link was performed at DFW in August. System integration testing was performed on several occasions at DFW and at the NASA LaRC facility. The RIPS system was extensively tested during several weeks of research flights at DFW prior to the demonstrations. These research flights are discussed in more detail in Appendix D.

3.0 Rockwell Collins Equipment Installation

3.1 FAA Van Installation

3.1.1 Equipment

In a test van supplied by Trios Associates Inc. for the FAA, Rockwell Collins installed a transmit-only ADS-B pallet. This pallet contained the following Rockwell Collins equipment: a GNLU-930 Multi-Mode Receiver for GPS/LAAS reception, a modified TPR-901 transponder for broadcasting ADS-B messages over the Mode-S 1090 MHz data link, and a control head for changing the 4 digit transponder code. The transponder was used in the ARINC 718-A configuration, which is a newer configuration of the rear connector pins than the ARINC 718-4 definition. The 718-A specification has not yet been finalized by the industry. The pallet also contained a Datatrac 400H for supplying ARINC-429 labels to the transponder and MMR, and a ruggedized Fieldworks PC for monitoring transponder operation, and for recording the GPS/LAAS data from the MMR. The ADS-B transmit pallet used in the Trios/FAA van is shown in Figure 3.1

The transponder utilized two antennas, which were mounted on the top of the van near the back. The GPS antenna was mounted in the center of these two antennas, and the VHF antenna for receiving LAAS messages was located on a pole near the middle of the van. Figure 3-2 shows the location of these antennas as installed on the van.

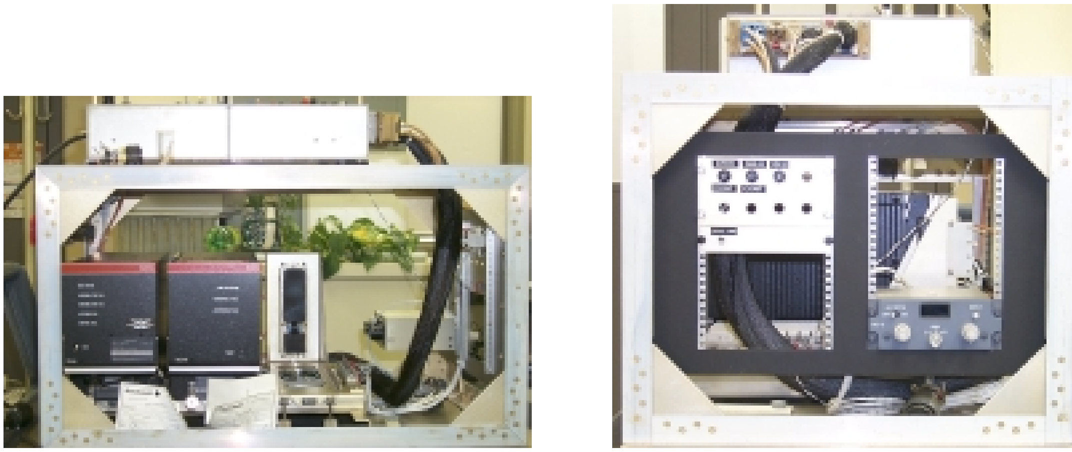


Figure 3-1 : ADS-B Transmit Pallet, Front and Side View

Figure 3-2: Antenna Locations on the FAA Test Van

3.1.2 ADS-B Transmit Pallet Operation

The pallet contained a breakout box (Figure 3-3) that interfaced with the transponder to provide easy access to ARINC-429 data buses and transponder configuration pins. This breakout box could be used with either a 718-4 or a 718-A transponder. Since a 718-A transponder was being used, ARINC-429 labels for altitude (Label 203) and Flight ID (Labels 233, 234, 235, and 236) were required as inputs. The label definitions can be found in reference [1]. In addition, in order to receive LAAS correction messages, a tuning label (Label 033) was required as an input to the GNLU-930. These labels were provided using the Datatrac 400H. The breakout box was also used to set the following transponder configurations: Mode S ICAO address, maximum airspeed, aircraft category, altitude type and source, and air/ground (weight on wheels) status. The control head was used to change the 4-digit transponder code, which was assigned by air traffic control on a nightly basis during the RIPS flight tests at DFW.

Figure 3-3: ADS-B Transmit Pallet Breakout Box

3.2 AGATE ADS-B Transmit Pallet

During RIPS tests at DFW, a second ADS-B source was used for interoperability testing. This source was an ADS-B pallet developed for the Advanced General Aviation Transport Experiment (AGATE) program. The pallet, shown in Figure 3-4, contained the following Rockwell Collins equipment: a GPS-4000A receiver, a TDR-94D transponder, and an RTU-4220. The pallet also contained an altitude encoder. The GPS receiver was not using the LAAS differential corrections broadcast from the Ohio University ground station. The RTU (Radio Tuning Unit) was used to control the transponder and display the altitude provided by the altitude encoder. This pallet was installed in a trailer located near the East control tower. Thus, it was a stationary target, and was not used in any incursion scenario tests or during the RIPS demonstrations. The purpose for testing with the AGATE ADS-B pallet was to validate interoperability of this pallet, intended for use on general aviation aircraft, e.g., the AGATE 1B aircraft, with the RIPS system and ADS-B installations on air transport category aircraft such as the NASA ARIES 757. Tests confirmed full interoperability of the AGATE ADS-B flight test system with the NASA ARIES 757. The NASA ARIES aircraft received approximately 60 to 70 percent of all messages broadcast by the AGATE ADS-B pallet. This reception rate is quite good considering the non-optimal antenna placement on the trailer located by the East control tower at DFW.

Figure 3-4: AGATE ADS-B Transmit Pallet

3.3 NASA ARIES 757 Installation

3.3.1 Hardware

A full transmit and receive ADS-B system was installed in the NASA ARIES 757. The equipment consisted of a GNLU-930 Multi-Mode receiver, a modified TPR-901 transponder operating in the ARINC 718-4 configuration, and a modified TTR-921 TCAS for receiving ADS-B messages. The transponder and TCAS were installed in the aircraft's electronics bay, and the MMR was installed in the flight management systems rack in the cabin. Conventional 757 TCAS (top and bottom omnidirectional) and GPS antennas were used for the TCAS and MMR, while the VOR antenna located on the tail of the 757 served as the VHF LAAS antenna. The MMR shared a GPS antenna with the # 2 Ashtech receiver and the Capstone MX-20 receiver through a RF splitter. The antenna configuration is illustrated in Figure 3-5.

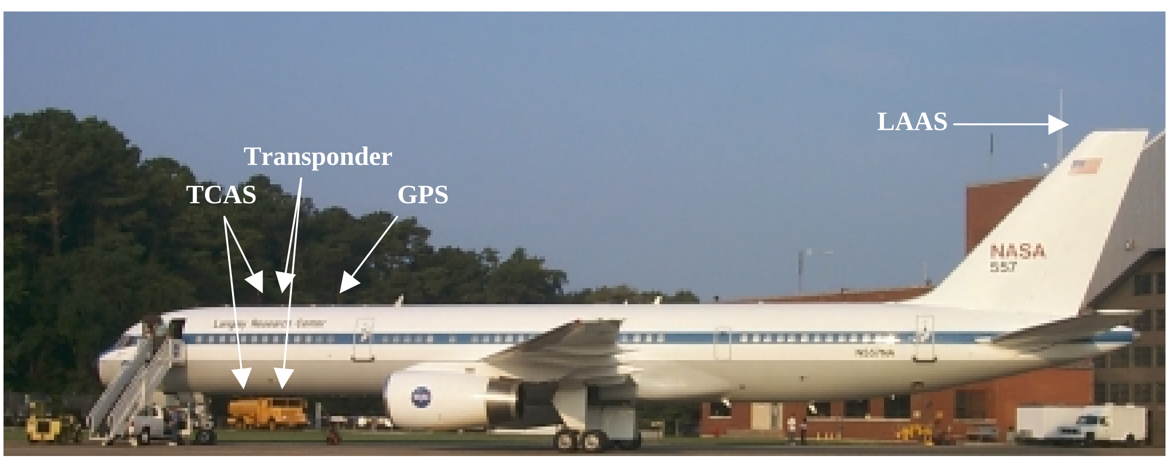


Figure 3-5: Antenna Locations on the NASA ARIES 757

3.3.2 Software

Two software programs were installed on a Fieldworks PC in the flight management systems rack of the NASA ARIES aircraft. One program recorded ARINC 429 output data from the GNLU-930 MMR. The other program used an RS-232 serial interface with the TTR-921 to capture received ADS-B messages. These messages were recorded, decoded, reformatted as ARINC-429 messages, and forwarded to the NASA I/O concentrator system for use by the RIPS application. The data recorded by these two programs was the primary data source used in the data analysis portion of this document.

4.0 Overview of RIPS Activities at DFW

4.1 Data Collection Period

Prior to the demonstrations at DFW, several weeks of research flights were performed at DFW. These research flights provided an opportunity to test the various components of RIPS in a controlled operating environment, and to collect and analyze the resulting data. In addition to RIPS testing, the Synthetic Vision System (SVS) and HSALT technologies were also extensively tested during the research flights.

During the demonstrations, only two RIPS scenarios (#1 and #3) were performed. However, two additional scenarios (#2 and #4) were evaluated during the data collection test period. The table below provides a description of each of the four RIPS scenarios. A map of the DFW airport that shows the taxiways and runways can be found in Appendix B.

RIPS Scenario	Description
1	The NASA ARIES aircraft is on final approach for a landing on 17C with the van holding short East of runway 17C at taxiway Y. When the aircraft is one mile out, the van travels West across the runway and creates an incursion.
2	A rejected take-off (RTO), where the NASA ARIES aircraft is departing on runway 17C or 35C, and the FAA van crosses the runway at the opposite end (ER or Z/Y) of the runway while the aircraft is on the take-off roll. The aircraft aborts the take-off by midfield and the van clears the runway.
3	The NASA ARIES aircraft holds short West of runway 17C/35C on taxiway Y, while the FAA van enters runway 17C/35C at taxiway ER and proceeds North down the runway as if performing a takeoff. The aircraft crosses the hold short bars as the van is moving down the runway, creating an incursion. The van reaches a speed of 70 miles per hour before exiting the runway to the East on taxiway EL.
4	The NASA ARIES aircraft is attempting to land on the same runway as the FAA van is ‘departing’ from. When the aircraft is on final approach, the FAA van proceeds down the runway from EL to ER (aircraft arriving on 17C) or Z (aircraft arriving on 35C) and exits the runway, while the aircraft does a go-around.

Table 4-1 : RIPS Scenario Descriptions

The research flights were extremely useful for making refinements and corrections to the implementations of each component of RIPS. The nature of the flights allowed the RIPS components to be tested in situations not easily duplicated in the lab or previous test environments. As a result, some hard to detect system anomalies were discovered and corrected. One of these anomalies was in the Collins ADS-B data recording software on the NASA ARIES. When the software received an ADS-B message of type “unknown” (not normally expected, and not previously encountered), it was not handled properly, and the previously received ADS-B message was recorded a second time. This error had the effect of corrupting the data file to the extent that the data was unable to be analyzed. The source of the “unknown” type ADS-

B messages was determined to be a ‘reference’ transponder for the ATIDS network. Unfortunately, the software bug was not corrected until shortly before the demonstrations, so only a small amount of data from the data collection period is available for analysis. The data that was analyzed is presented in section 5.2.

4.2 Industry Demonstrations

NASA conducted flight tests and demonstrations of the Runway Incursion Prevention System (RIPS) from October 24 – 26 at the Dallas - Fort Worth International Airport (DFW). In addition to the flight tests and demonstration of RIPS, NASA also conducted joint flight tests of the Synthetic Vision System (SVS) and the Hold Short Advisory Landing Technology (HSALT) system. While this report focuses on RIPS, description of the sorties and flight scenarios below includes reference to the flight test phases of the SVS and HSALT systems.

Research flights were conducted late each night to avoid high traffic loads in order to minimize impact on flight operations at DFW. Flight tests each night consisted of two sorties, with each sortie testing the same scenarios. Each sortie began with a RIPS scenario, followed by two synthetic vision approach scenarios, followed by another RIPS scenario, and finally concluding with an HSALT landing scenario. For each night of demonstrations, the industry audience was divided into two arbitrary groups. The first group would fly in the NASA ARIES 757 during the first sortie to observe the scenarios on NASA’s on-board flight test display systems, while the second group would remain in the Harvey hotel to observe events in a simulated control tower (i.e., actually a hotel room facing the airport) using data relayed from the aircraft via telemetry for depiction on display monitors. During the second sortie, the two groups would switch locations. The first sortie was performed from approximately 11:20 PM – 12:40 AM Central Daylight Time (CDT), and the second sortie was performed from approximately 1:40 AM – 3:00 AM CDT.

The first RIPS scenario performed (RIPS scenario #3) in the demonstrations involved the NASA ARIES aircraft holding short West of runway 17C/35C on taxiway Y, while the FAA van entered runway 17C/35C at taxiway ER and proceeded North down the runway as if performing a takeoff. The aircraft crossed the hold short bars as the van was moving down the runway, creating an incursion. The van reached a speed of 70 miles per hour before exiting the runway to the right on taxiway EL. A map of the DFW airport that shows the taxiways and runways can be found in Appendix B.

The second RIPS scenario performed (RIPS scenario #1) in the demonstrations involved the NASA ARIES aircraft coming in for a landing on 17C with the van holding short East of runway 17C at taxiway Y. When the aircraft was one mile out, the van crossed the runway, creating an incursion.

Using these RIPS scenarios, NASA tested several runway incursion alerting algorithms, two aircraft based alerting systems and one ground-based alerting system that uplinked the incursion alert via the STIS-B data link. In the analysis that follows, these scenarios will be referenced by their RIPS scenario number.

5.0 Performance Analysis

This section describes the ADS-B and DGPS performance results from both the data collection period and from the industry demonstrations. The results from the industry demonstrations are presented first in section 5.1. A more limited data analysis (due to the previously noted problems) for the data collection period is provided in section 5.2.

5.1 Industry Demonstration Results

Three nights of industry demonstrations were conducted, with two sorties flown each night. Section 5.1.1 describes the results of the DGPS data analysis, and section 5.1.2 describes the ADS-B data analysis results.

5.1.1 Differential GPS performance

Table 5-1 summarizes own-ship DGPS performance of the GNLU-930 MMR on both the NASA ARIES 757 aircraft and the FAA van for all six sorties.

	Demo 1 Sortie 1	**Demo 1 Sortie 2**	**Demo 2 Sortie 1**	**Demo 2 Sortie 2**	**Demo 3 Sortie 1**	**Demo 3 Sortie 2**
% of time in differential mode (MMR in the NASA ARIES 757)	99.81	99.86	99.92	100.00	99.33	95.42
% of time in differential mode (MMR in the FAA van)	99.51	98.02	99.73	99.36	99.38	97.40
Mean difference from Ashtech position (meters) (MMR in the NASA ARIES 757)	1.792	1.814	2.741	1.902	1.791	1.847
Standard Deviation of MMR-Ashtech difference (meters) (MMR in the NASA ARIES 757)	1.047	1.311	3.207	1.209	0.878	1.021

Table 5-1: MMR Performance Statistics

The MMR was operating in differential mode nearly 100% of the time, as can be seen in Table 5-1. Most of the time that it was not in differential mode was the result of the LAAS ground station not having differential corrections available for a sufficient number of satellites. This was due to poor satellite geometry, as seen by the ground station. During the demonstration, there were a number of cases where the control tower was blocking several satellites. This problem can be reduced in future efforts by locating the ground station so that a maximum amount of the sky is visible. CRC errors in the LAAS messages, likely due to RF errors, were another reason the MMR sometimes dropped out of differential mode. When the MMR was in differential mode, the positional accuracy of the MMR met the performance requirements specified by the LAAS system. [2] On the NASA ARIES aircraft, an Ashtech receiver was used as a "truth reference" to compute the accuracy of the MMR's position. Table 5-1 shows that the MMR position closely tracked the Ashtech's position. A similar "truth reference" comparison was not performed in the FAA van. The decrease in differential mode percentage during sortie 2 of Demo 3 was due to one specific event. During an approach to runway 17C, there was a period of several minutes where the satellite geometry seen by the aircraft and the LAAS ground station was too poor to support differential mode. The Ashtech receiver also experienced problems during this time. The FAA van was in a nearby location and also was affected by this situation, but for a shorter time period.

During coverage testing in August at DFW, the FAA van was used to test reception of the LAAS signal on all the runways and taxiways. The testing revealed that differential mode was maintained throughout the airport. There was one area of relatively weak signal reception on the West side of the airport near one of the American Airlines hangars. For all the main taxiways and runways, the LAAS signal was received sufficiently to maintain differential mode. The location of the LAAS ground station was not optimal (by design), so even better coverage could be achieved by choosing an optimal location.

5.1.2 ADS-B performance

5.1.2.1 Link Performance

Table 5-2 summarizes the message reception rates for the various ADS-B squitters transmitted by the FAA van, as received by the ADS-B receiver on the NASA ARIES aircraft.

	Demo 1 Sortie 1	**Demo 1 Sortie 2**	**Demo 2 Sortie 1**	**Demo 2 Sortie 2**	**Demo 3 Sortie 1**	**Demo 3 Sortie 2**
Position messages Overall	78.30	82.64	79.05	82.24	71.10	78.14
Position Messages Aircraft in the air	91.51	90.09	87.85	88.31	88.44	89.13
Position Messages Aircraft on the ground	66.34	73.04	64.86	72.36	56.51	59.39
Position Messages Scenario 3	43.57	51.80	42.71	44.23	41.23	34.09
Position Messages Scenario 1	92.44	90.75	93.50	90.20	88.76	90.21
ID messages Overall	76.70	80.89	77.61	84.81	78.16	77.47

Table 5-2: Percentage of ADS-B messages received

In this table several trends can be observed. First, there is a notable difference between the link reliability when the NASA ARIES aircraft is in the air, and when the aircraft is on the ground. The reliability of the link when both the aircraft and the van are on the ground is anywhere from 16 to 30 percent less than the reliability of the link when the aircraft is airborne, for a given sortie. This is not totally unexpected, since maintaining line of sight and avoiding multipath is more difficult when both vehicles are on the ground.

A significant degradation in link performance occurs during RIPS scenario 3. The link performance is not very good while the van is driving North on the runway, but returns to the expected performance when the van exits the runway at taxiway EL. This anomaly can be seen in Figure 5-1 and 5-3, and in the other scenario 3 runs, which are shown in appendix C. This performance anomaly indicates poor ADS-B reception when the body of the van is positioned between the transmitting antennas on its roof and the receiving antennas on the aircraft. As shown in Figure 3-2, both ADS-B transmit antennas were located in the rear of the van. The roof of the van and the various objects on it could have altered the antenna radiation towards the front of the van. The alteration could be due to blockage, multipath, or raising of the radiation pattern away from the horizon. When the van turned onto taxiway EL, the NASA ARIES aircraft would see the radiation from the rear of the antennas, which was not subject to the influence of the van. More investigation into the nature of this problem is required.

For terminal area operation, the ADS-B MASPS requires a position message to be received within 5 seconds with a 98% probability. Scenario 1 involves terminal area operation, and the results show that this requirement is easily met. (10^{-9} probability of not meeting it). For surface operations, the requirement is for a position message to be received within one second with a 98% probability. Scenario 3 tests this requirement, and the results are not close to meeting the requirement. However, incursion alerts were still properly generated in five of the six scenario 3 runs.

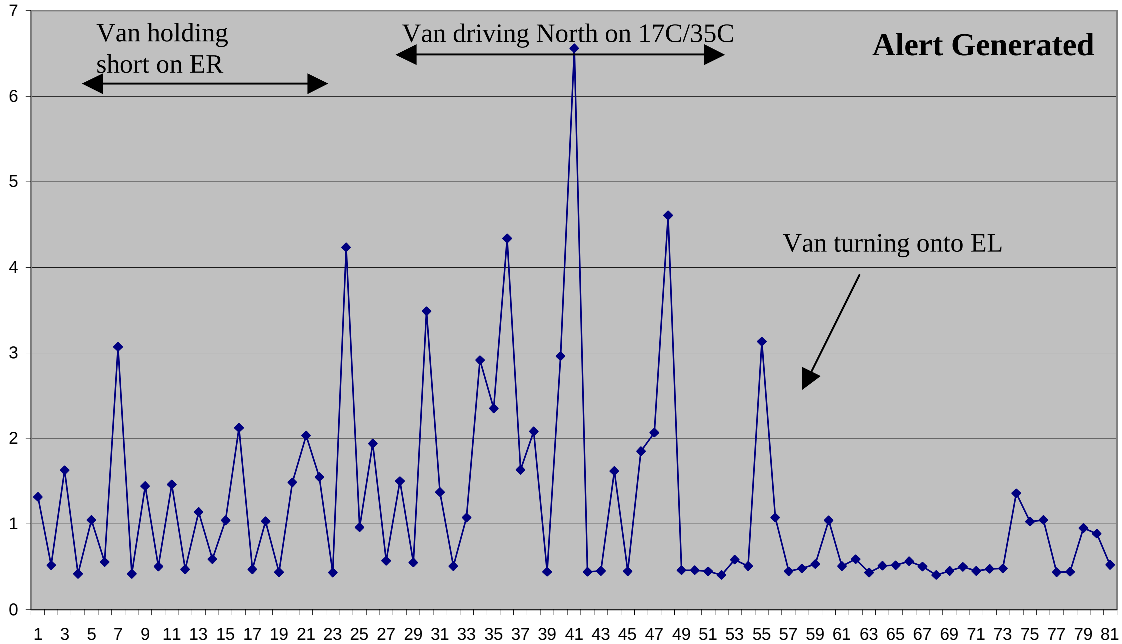


Figure 5-1: Time Between ADS-B Position Messages (Demo 1, Sortie 1, Scenario 3)

Figure 5-1 shows the performance of the ADS-B data link between the transmitter in the FAA van and the receiver on the NASA ARIES aircraft during the RIPS scenario 3. The Y-axis is the number of seconds between ADS-B "surface position" messages from the van as received by the NASA ARIES 757. The expected value is 0.5 seconds, as these messages are transmitted twice per second. The X-axis is a sequential numbering of each "surface position" message received during the scenario. The different portions of the scenario are identified by the arrows and corresponding text. Text has also been added on each graph to indicate whether an incursion alert was properly generated onboard the NASA ARIES aircraft. The position of the text does not correspond to when the alert was generated.

The improvement in link performance when the van exits runway 17C/35C onto taxiway EL is clearly illustrated in Figure 5-1. As mentioned previously, the position of the van relative to the aircraft seems to have a major effect on link performance. The only missed alert of the demonstrations was likely due to this anomaly, and can be seen in Figure C-13.

Figure 5-2 shows the performance of the ADS-B data link between the transmitter in the FAA van and the receiver on the NASA ARIES aircraft during RIPS scenario 1. The Y-axis is the number of seconds between ADS-B "surface position" messages from the van as received by the NASA ARIES 757. The expected value is 0.5 seconds, as these messages are transmitted twice per second. The X-axis is a sequential numbering of each "surface position" message received during the scenario. Text has also been added on each graph to indicate whether an incursion alert was properly generated onboard the NASA ARIES aircraft.

As shown in Figure 5-2, the performance of the data link during scenario 1 is excellent, especially when compared to the performance during scenario 3. The Y values of zero are due to duplicated messages in the recording process. Similar graphs for the data from this scenario in the other sorties can be found in Appendix C. Alerts were properly generated in all of the scenario 1 runs.

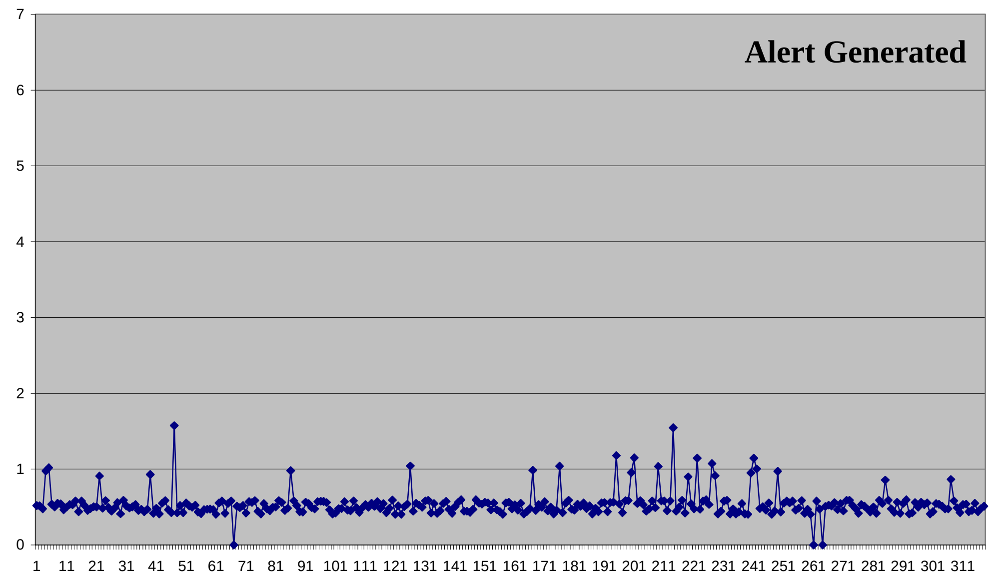


Figure 5-2: Time Between ADS-B Position Messages (Demo 1, Sortie 1, Scenario 1)

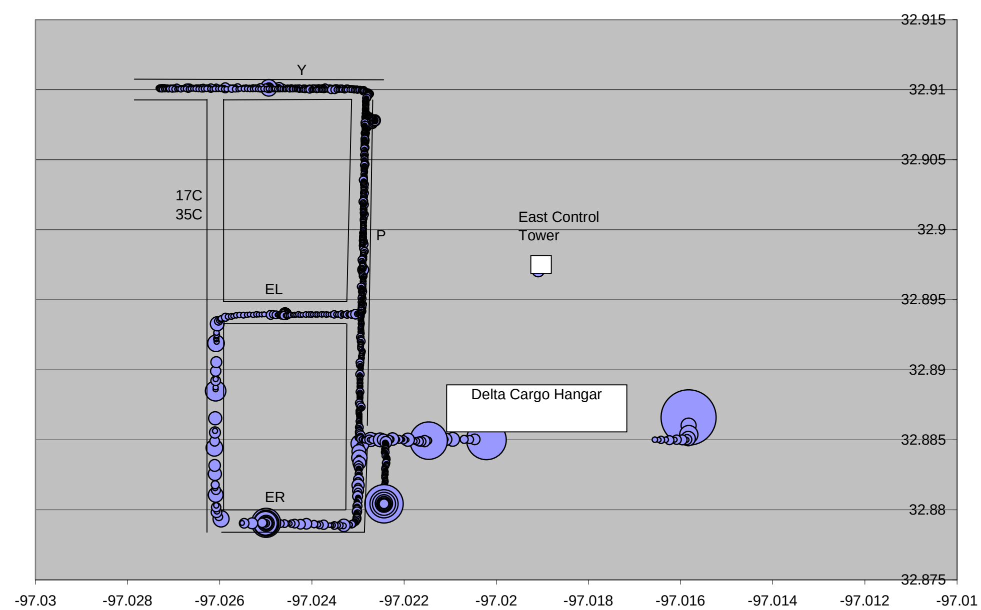


Figure 5-3: Time Between ADS-B Position Messages vs. Position (Demo 1, Sortie 1)

Figure 5-3 illustrates the performance of the ADS-B data link as a function of position for the entire sortie, which includes both RIPS incursion scenarios, and the time between scenarios. In addition, the position of the FAA van prior to the start of the sortie is included. All van positions East of taxiway P are the path of the van from the East Control Tower to taxiway ER prior to the start of the sortie. The Y-axis is Latitude and the X-axis is Longitude, both measured in degrees. The location of each circle on the graph represents the location of the FAA van as broadcast in an ADS-B message received by the NASA ARIES aircraft. The size of each circle represents the amount of time that had elapsed since the last time an ADS-B message was received by the aircraft. A larger circle indicates a longer time between messages. An outline of the relevant runways and taxiways and significant structures has been drawn on the graph to provide reference points.

This graph does not show the position of the NASA ARIES aircraft when each ADS-B message was received. However, the relative position of the aircraft can be inferred with knowledge of the sortie operation. The aircraft is airborne for the entire time, except prior to the start of the sortie, and during RIPS scenario 3. During RIPS scenario 3, the aircraft is on the ground just West of runway 17C/35C on taxiway Y. Prior to the start of RIPS scenario 3, the aircraft is taxiing to this position, and the FAA van is driving to its starting point for the scenario (taxiway ER short of runway 17C/35C). The position and direction of movement of the van during the sortie can be inferred from the scenario descriptions and the description of the sortie operation in section 4.0.

Several trouble spots can be observed from the graph. Not surprisingly, performance degrades near the Delta cargo hangar, due to signal blockage and multipath caused by the structure. In addition, the graph shows the larger gaps between messages when the van is heading North on runway 17C/35C during RIPS scenario 3. The improvement in reception as the van exits the runway onto taxiway EL can also be seen. Large gaps are also noticeable while the van is holding short of the runway on taxiway ER. This is an area that was known to exhibit poor RF transmission and reception. The ATIDS system also had trouble seeing the van in this location. Similar graphs for the remaining sorties, featuring similar trouble spots, can be found in Appendix C. Figure C-19 includes extra transmissions from the van (not shown in other graphs) after the last RIPS scenario, when the van was performing other tasks in the area around slant runway 13L/31R. The NASA ARIES aircraft was in the air during this time except as noted on the graph. When the aircraft did land, it continued South on runway 17C, exited West onto taxiway ER, proceeded North on taxiway L, and finally headed West on taxiway Y. The ADS-B data link was fairly reliable during this time, except for the two times when the Delta cargo hangar was directly between the aircraft and the van.

5.1.2.2 Positional Accuracy

Table 5-3 illustrates the Navigation Uncertainty Category (NUC) performance of ADS-B position messages from the FAA van, as recorded by the NASA ARIES aircraft. These NUC values provide an indication of the accuracy of the ADS-B position messages broadcast by the FAA Van. Table 5-4 shows the position accuracy ranges that correspond to each NUC value.

	Demo 1 Sortie 1	**Demo 1 Sortie 2**	**Demo 2 Sortie 1**	**Demo 2 Sortie 2**	**Demo 3 Sortie 1**	**Demo 3 Sortie 2**
NUC of 9	99.33	97.54	99.92	99.81	52.36	79.86
NUC of 8	0.00	1.88	0.05	0.14	47.64	15.20
NUC of 7	0.55	0.23	0.03	0.00	0.0	4.21
NUC of 6	0.10	0.35	0.00	0.04	0.0	0.73

Table 5-3: Percentage of Time FAA Van was operating in a given Navigation Uncertainty Category

The NUC value is a parameter implicitly provided in an ADS-B message that indicates the 95% containment radius in the error of the reported horizontal position (and vertical position for airborne messages). A higher NUC value indicates a smaller positional error. For the surface position messages broadcast by the FAA van, the accuracy ranges corresponding to each NUC value can be seen in Table 5-4. As illustrated in Table 5-3, the position of the van provided in the ADS-B broadcast usually had an error of less than three meters, which is expected when using a LAAS enhanced DGPS receiver as the position source. When the MMR in the van is operating in differential mode, a NUC of 8 or 9 is expected. A NUC of 7 usually indicates a normal (non-differential) mode for the MMR. Since the U.S. government turned off selective availability in the GPS system, a NUC of 6 should occur infrequently, and would indicate very poor satellite geometry or the presence of multipath.

NUC Value	**95% Containment Radius on Horizontal Position Error, μ**
9	$\mu < 3$ m
8	$3 \text{ m} \leq \mu < 10$ m
7	$10 \text{ m} \leq \mu < 92.6$ m
6	$\mu \geq 92.6$ m

Table 5-4 : Positional Error Range for Each NUC value

Figure 5-4 shows the ADS-B position of the FAA van received by the NASA ARIES overlaid on the GPS position of the FAA van as recorded in the van. The GPS position is the solid line, and the ADS-B position is indicated by crosshairs. The graph provides a qualitative view of ADS-B positional accuracy, showing that the position messages received by the NASA ARIES aircraft accurately reflect the position of the van. In addition, large gaps between crosshairs indicate a dropout in ADS-B message reception, which were discussed previously. Similar graphs for each sortie can be found in Appendix C. Note that Figure C-20 includes transmissions from the area around slant runway 13L/31R, which were received after the last RIPS scenario was finished and the FAA van was performing other tasks. The large sections of this graph with GPS position but no ADS-B position (other than the area near the Delta cargo hangar) are due to the termination of the ADS-B recording software on the NASA ARIES while the MMR was still collecting data.

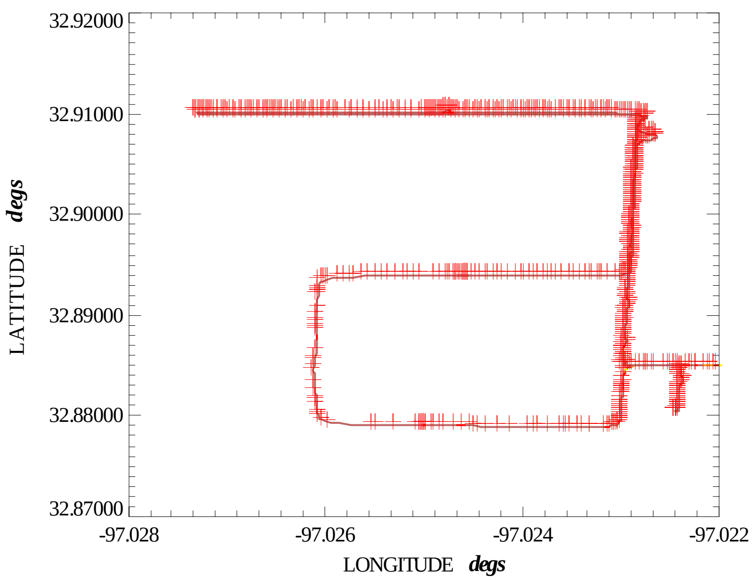


Figure 5-4: Overlay Plot of GPS and ADS-B Positions (Demo 1, Sortie 1)

5.2 Data Collection Period Results

As mentioned previously, a glitch in the ADS-B data recording software during the data collection period limited the amount of data that could be quantitatively analyzed. Because of this, only the last two nights of the data collection period will be analyzed. Differential GPS data from the data collection period was not further analyzed because the LAAS ground station was being modified throughout the data collection period and sufficient data was recorded and analyzed from the demonstrations to fully characterize the performance of the DGPS system.

The ADS-B performance for each of the four RIPS scenarios is illustrated in Figures 5-5 to 5-12. Each graph shows (on the Y-axis) the number of seconds between ADS-B "surface position" messages from the van as received by the NASA ARIES 757. The expected value is 0.5 seconds, as these messages are transmitted twice per second. The X-axis is a sequential numbering of each "surface position" message received during the scenario. Text has also been added on each graph to indicate whether an incursion alert was properly generated onboard the NASA ARIES aircraft.

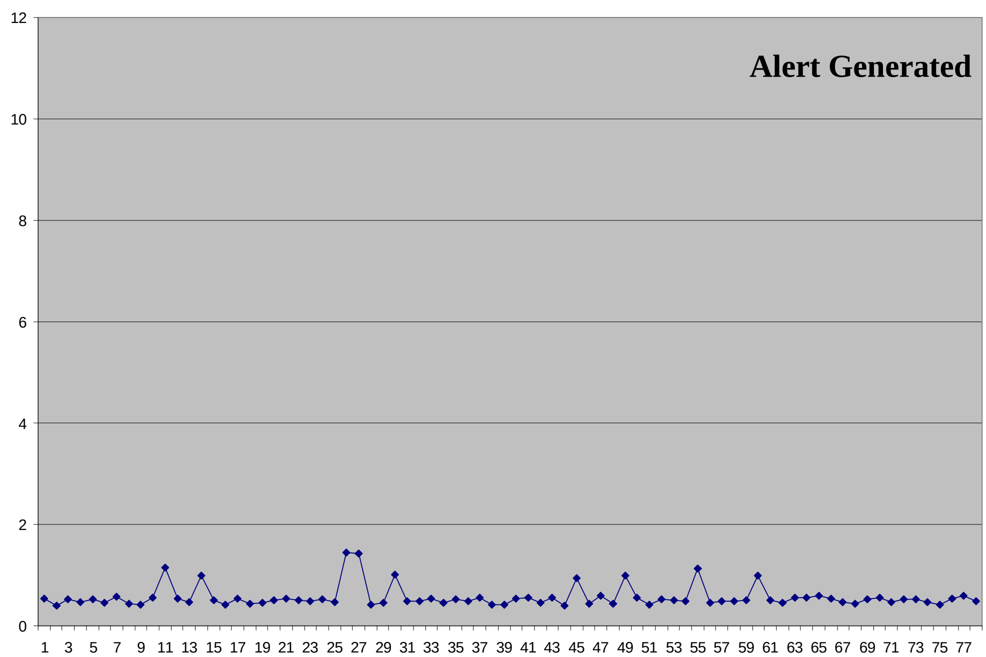


Figure 5-5: Time Between Received ADS-B Position Messages Research Flight 174, Flight Card 5, Scenario 1

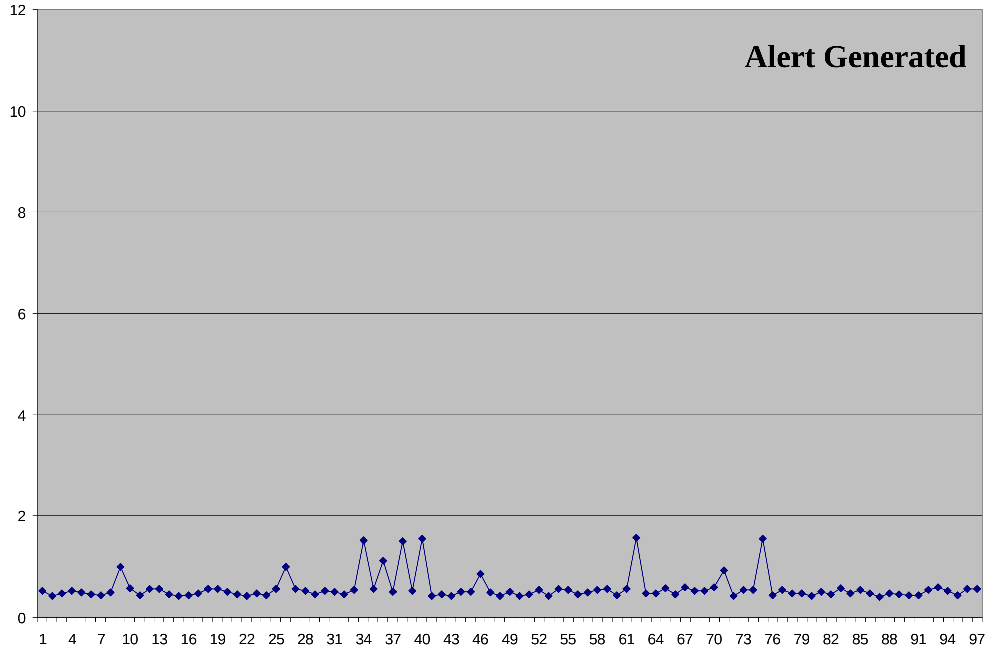


Figure 5-6: Time Between Received ADS-B Position Messages
Research Flight 174, Flight Card 9, Scenario 1

The ADS-B link performed well during both performances of scenario 1, as can be seen in Figures 5-5 and 5-6. These results are typical of those seen during the demonstrations for this scenario.

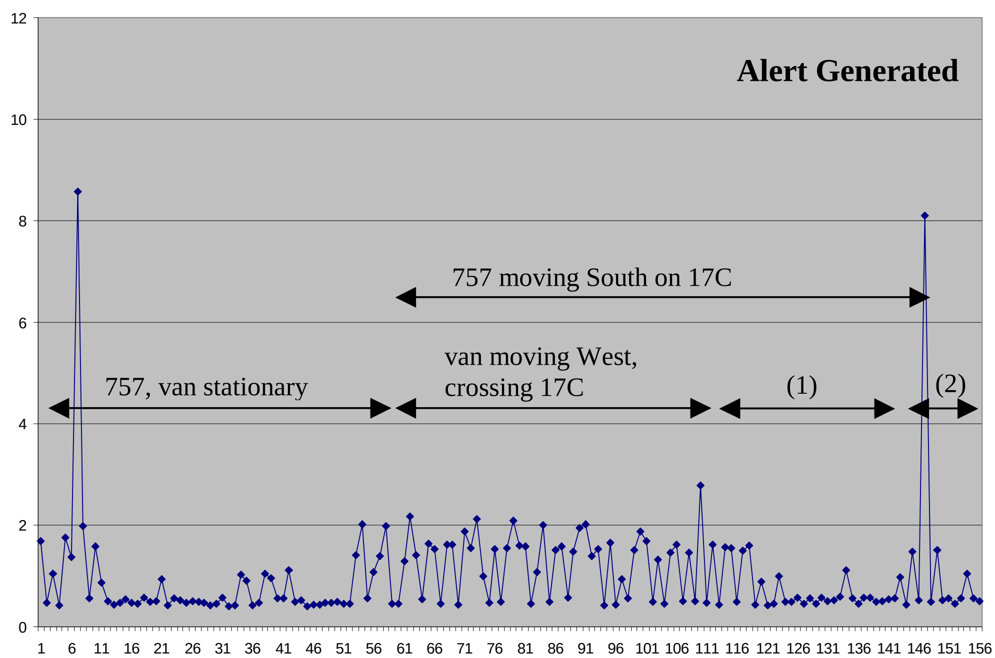


Figure 5-7: Time Between Received ADS-B Position Messages
Research Flight 173, Flight Card 24, Scenario 2

In Figure 5-7, the labeled arrows indicate specific portions of the scenario. During time period (1), the FAA van is stationary/slowly turning around, and during time period (2) it is moving East across runway 17C. The two worst gaps (over 8 seconds) in received messages happened before and after the actual scenario. This could be due to an unfavorable positioning of the FAA van antennas relative to the NASA ARIES antennas. Similar large gaps were observed during scenario 3 runs, as discussed previously in the report. When the van was moving across the runway, the performance was somewhat degraded, with several gaps of 1-3 messages. This could also be due to antenna positioning on the FAA van, as the back right transponder antenna is in a direct line between the back left transponder antenna (see Figure 3-2) and the NASA ARIES when the van is crossing the runway. Except for the two large gaps, the performance is better when the van is not on the runway.

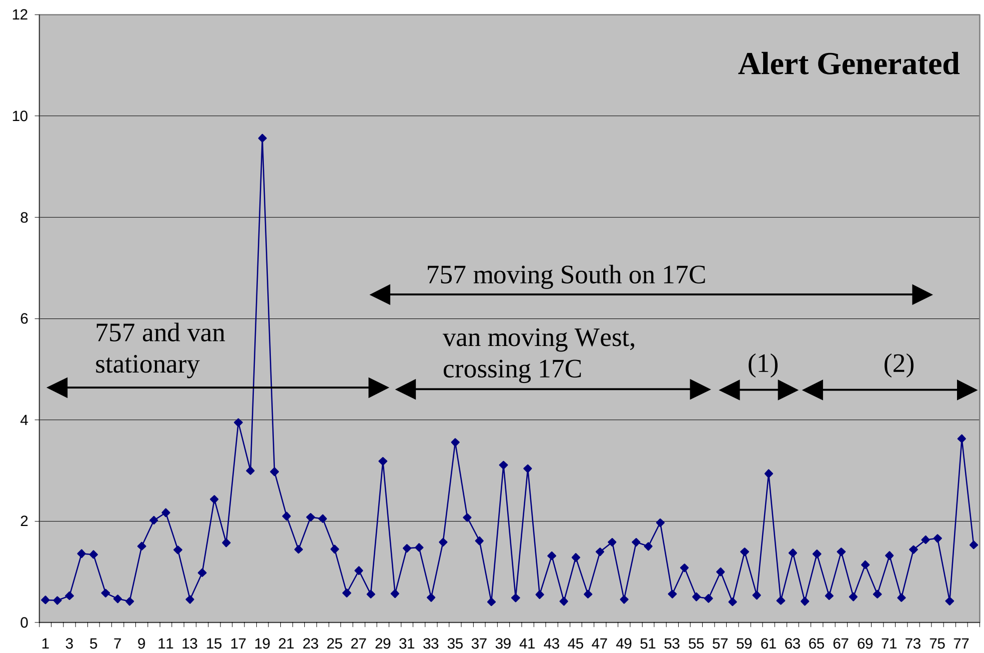


Figure 5-8: Time Between Received ADS-B Position Messages
Research Flight 174, Flight Card 12, Scenario 2

The performance of the ADS-B link during this performance of scenario 2 is similar to the one during research flight 173. There is again a large gap prior to the start of the scenario, and frequent gaps of 1-3 messages during the scenario. There are also 4 gaps of about 3 seconds each during the scenario. The van is turning around during time period (1) and moving east across 17C during time period (2).

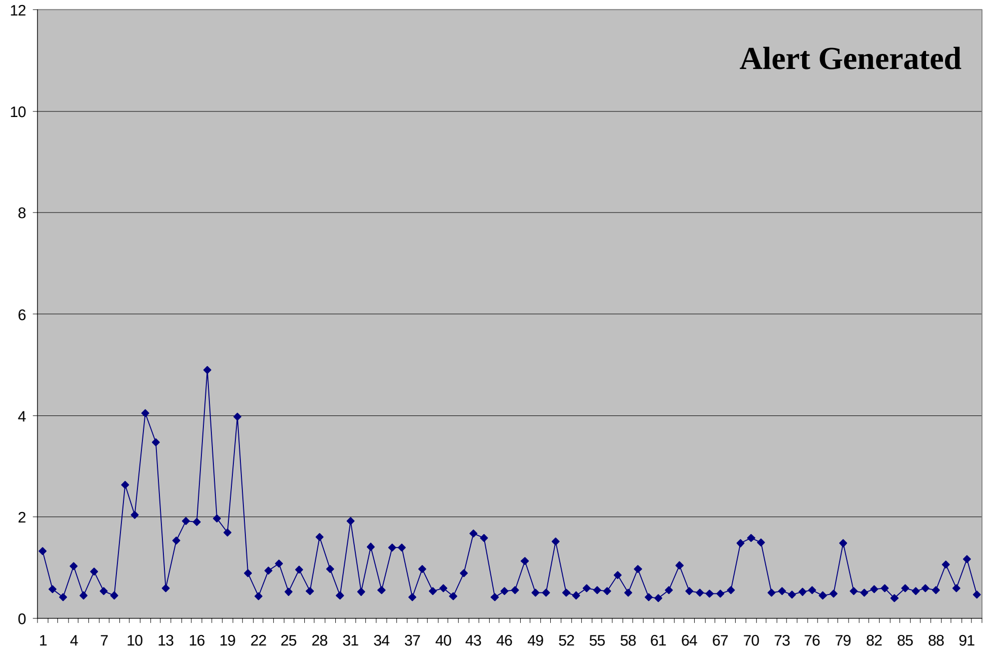


Figure 5-9: Time Between Received ADS-B Position Messages
Research Flight 174, Flight Card 1, Scenario 3

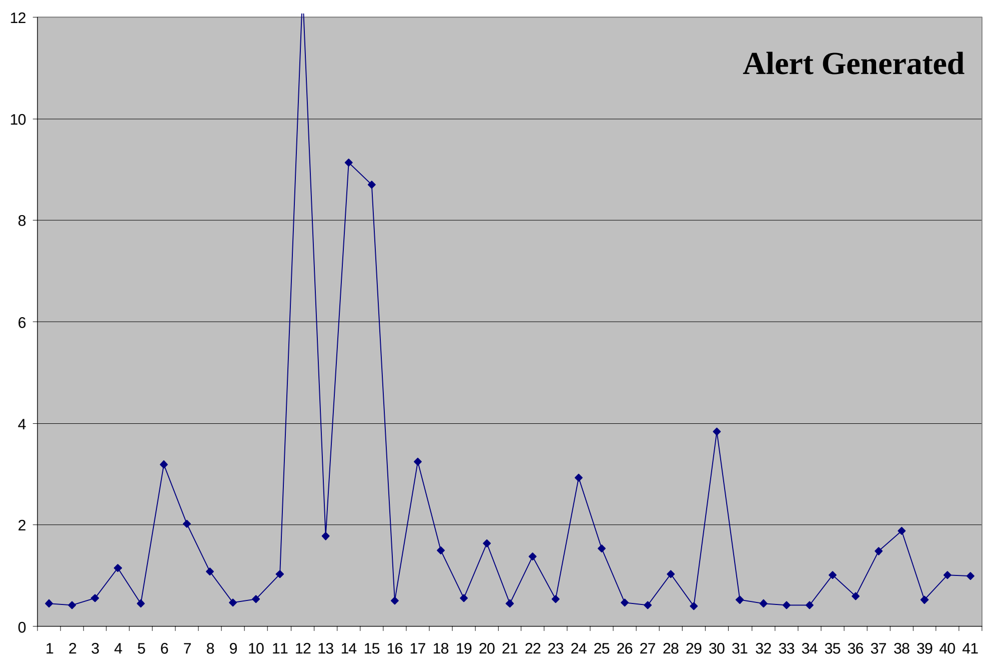


Figure 5-10: Time Between Received ADS-B Position Messages
Research Flight 174, Flight Card 4, Scenario 3

Scenario 3 was the most problematic scenario during the demonstrations, and was also erratic during research flight 174. The behavior during the flight card 4 run was very similar to that observed in the demonstrations. The link was very good during the flight card 1, and there was nothing unusual about this run to account for the difference.

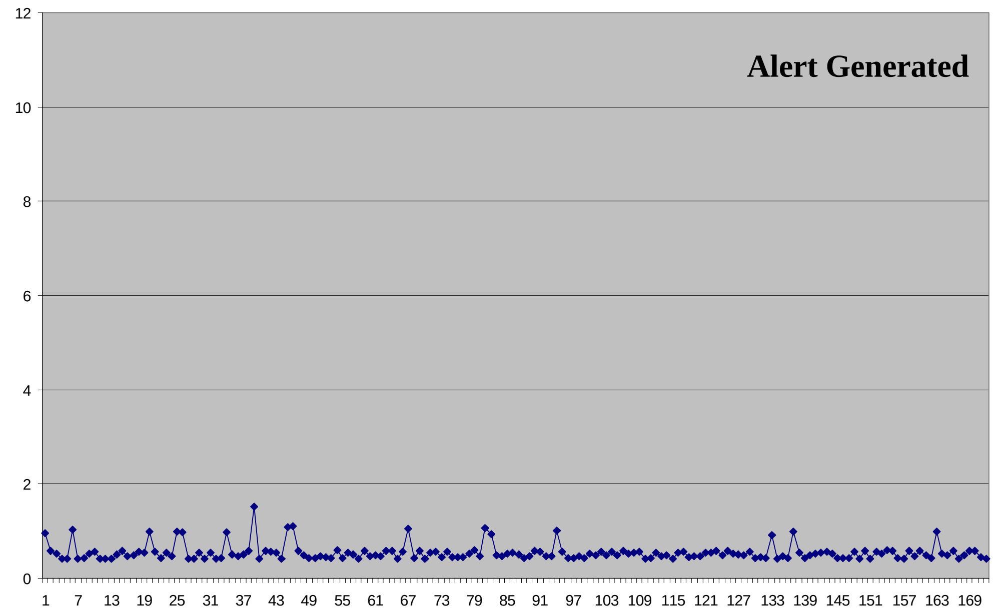


Figure 5-11: Time Between Received ADS-B Position Messages
Research Flight 174, Flight Card 2, Scenario 4

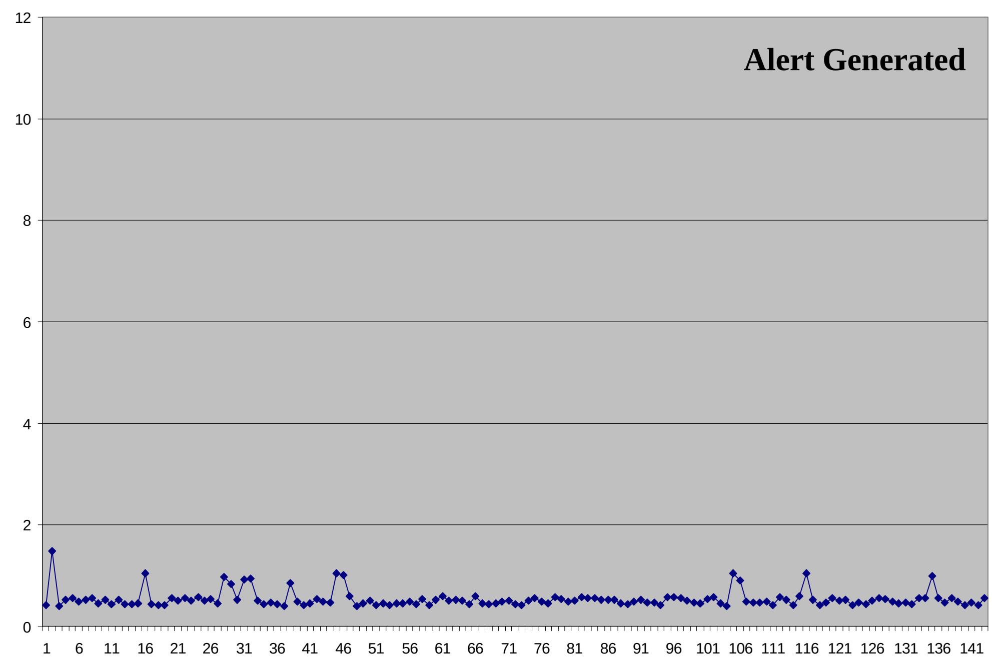


Figure 5-12: Time Between Received ADS-B Position Messages
Research Flight 174, Flight Card 6, Scenario 4

The results for the scenario 4 runs are very good, as expected. The NASA ARIES is airborne during this scenario, and the ADS-B link was very reliable during the demonstrations when the NASA ARIES aircraft was in the air.

6.0 Summary

The prototype ADS-B and LAAS systems developed for the RIPS program successfully demonstrated the feasibility and value of utilizing these technologies to reduce runway incursion events. During the demonstrations, incursion alerts were properly generated in 11 of the 12 RIPS scenarios performed. Throughout the testing of these systems at DFW and elsewhere, many improvements were made to the systems, and much insight was gained on their performance characteristics. Although the systems were only prototypes, with a few improvements they could become production quality systems. LAAS reception was very reliable, and the availability of corrections from the ground station could be improved by placing the ground station in a location less susceptible to multipath and satellite line of sight blockage. The position solution of the MMR was also very accurate and reliable. The link reliability of the ADS-B system was excellent when the NASA ARIES aircraft was airborne, but was very dependent on line of sight and multipath effects when both the aircraft and the FAA van were on the ground. When there was a good line of sight between the aircraft and the van with no multipath effects, the reliability was very good. However, there were several cases (such as RIPS scenario 3) where the reliability of message reception was greatly reduced by poor line of sight and/or multipath. These cases could be avoided or reduced by a more careful selection of antennas and antenna locations. For example, placing one transponder antenna near the front of the FAA van and one near the back would greatly improve the ADS-B performance of scenario 3 by eliminating the null pattern in front of the van. However, meeting the ADS- B MASPS requirement of receiving position messages at a one second update rate for surface operations will be difficult, even with the best antenna configurations.

Reference Documents

[1] "Mark 3 Air Traffic Control Transponder (ATCRBS/MODE-S)", ARINC Characteristic 718-4, ARINC, December, 1989.

[2] " Minimum Aviation Performance Standards for The Local Area Augmentation System (LAAS) ", Document No. RTCA/DO-246, RTCA, September 28, 1998.

[3] " Minimum Operational Performance Standards for 1090 MHz Automatic Dependent Surveillance Broadcast (ADS-B)", RTCA Paper No. 145-00/SC186-152, RTCA, May 12, 2000.

[4] Koczo, S. "Integrated Airport Surface Operations ", NASA/CR-1998-208441, July 1998.

[5] Runway Incursion Prevention Fact Sheet, NASA, FS-2000-09-53-LaRC.

[6] Young, S.D., and Jones, D.R., "Flight Testing of an Airport Surface Guidance, Navigation, and Control System", Proceedings of Institute of Navigation 2000 Conference, 1998.

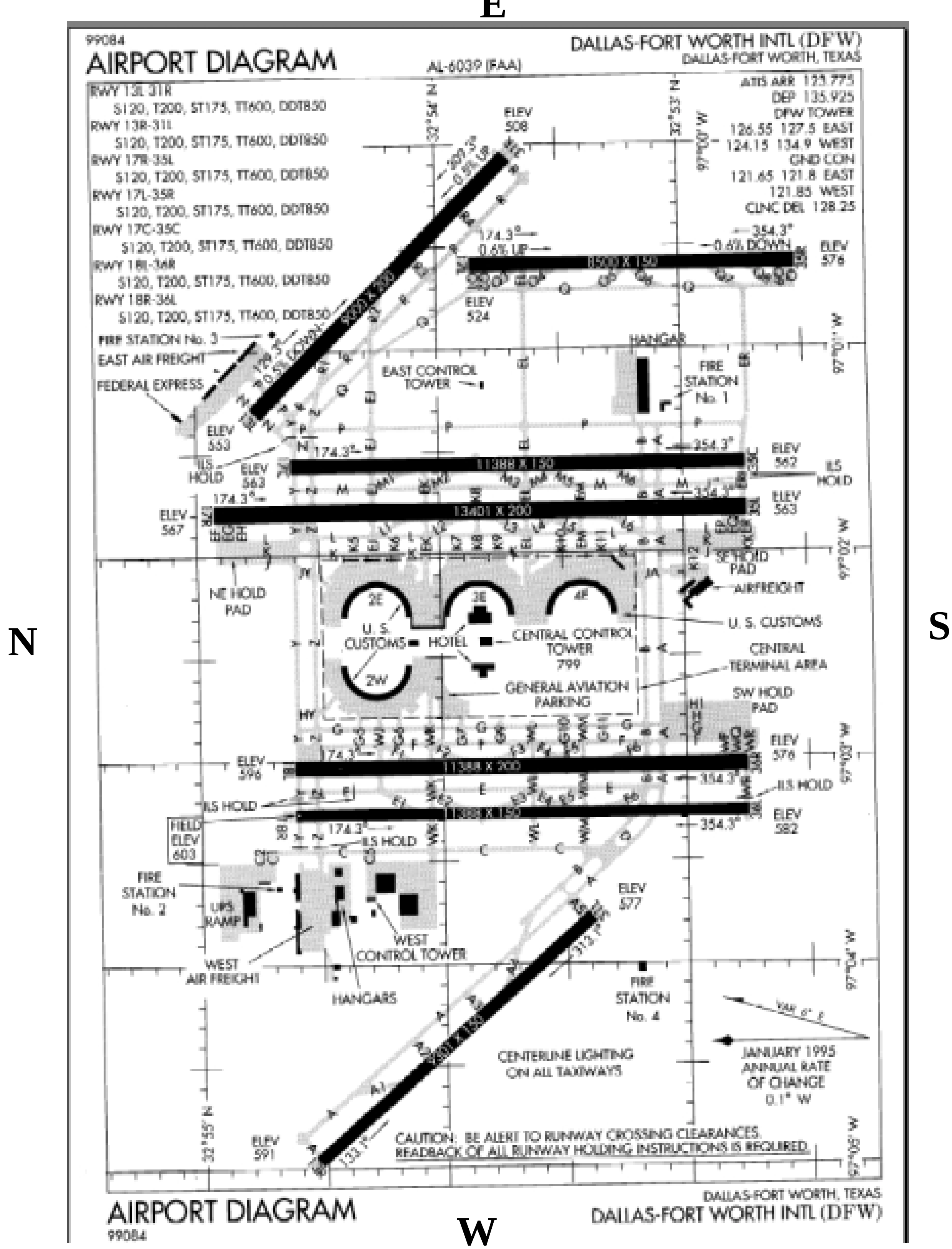
[7] "Demonstration and Testing at the Dallas-Ft. Worth International Airport Requirements Document", version 2.1, NASA LaRC Requirements Document, June 6, 2000.

[8] "GNSS Based Precision Approach Local Area Augmentation System (LAAS) – Signal in space Interface Control Document (ICD) ", Document No. RTCA/DO-246, RTCA, September 28, 1998.

Appendix A Acronyms

ADS-B	Automated Dependent Surveillance Broadcast
AGATE	Advanced General Aviation Transport Experiments
ARIES	Airborne Research Integrated Experiment System
ATC	Air Traffic Control (Air Traffic Controller)
ATIDS	Airport Traffic Identification System
AVSP	Aviation Safety Program
CDTI	Cockpit Display of Traffic Information
CPDLC	Controller-Pilot Data Link Communications
DFW	Dallas-Ft. Worth International Airport
DGPS	Differential Global Positioning System
EMM	Electronic Moving Map
FAA	Federal Aviation Administration
GNLU	Global Navigation and Landing Unit
GPS	Global Positioning System
HSALT	Hold Short Advisory Landing Technology
ILS	Instrument Landing System
LaRC	Langley Research Center
LAAS	Local Area Augmentation System
MASPS	Minimum Aviation System Performance Standards
MMR	Multi-Mode Receiver
NASA	National Aeronautics and Space Administration
PVT	Position, Velocity, Time
RIAAS	Runway Incursion Advisory and Alerting System
RIPS	Runway Incursion Prevention System
RIRP	Runway Incursion Reduction Program
R/T	Receiver/Transmitter
RTU	Radio Tuning Unit
STIS-B	Surface Traffic Information Services - Broadcast
SVS	Synthetic Vision System
TCAS	Traffic Alerting and Collision Avoidance System
UAT	Universal Access Transceiver
VDB	VHF Data Broadcast
VDL	VHF Data Link
VHF	Very High Frequency
VOR	VHF Omnidirectional Range
WAAS	Wide Area Augmentation System

Appendix B DFW Airport Surface Map



Airport Diagram as Published by the National Ocean Service

Appendix C Additional ADS-B Data Plots

C.1 First Night of Demonstrations

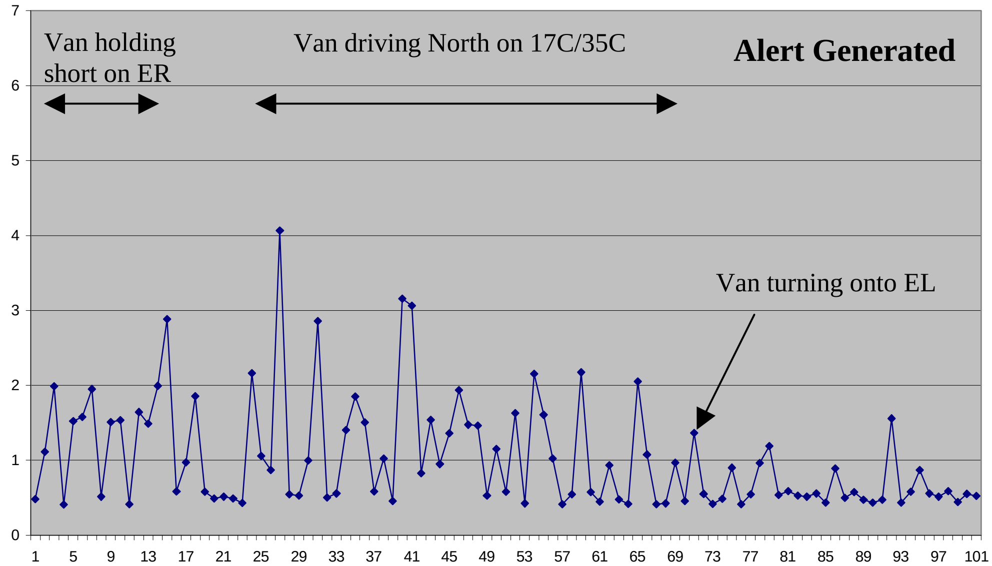


Figure C-1: Time Between Received ADS-B Position Messages (Demo 1, Sortie 2, Scenario 3)

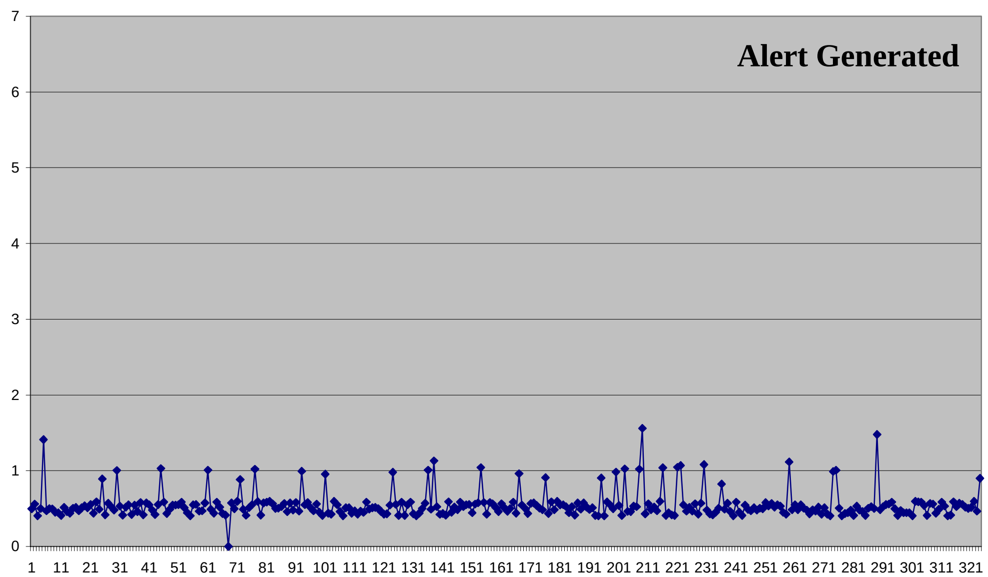


Figure C-2: Time Between Received ADS-B Position Messages (Demo 1, Sortie 2, Scenario 1)

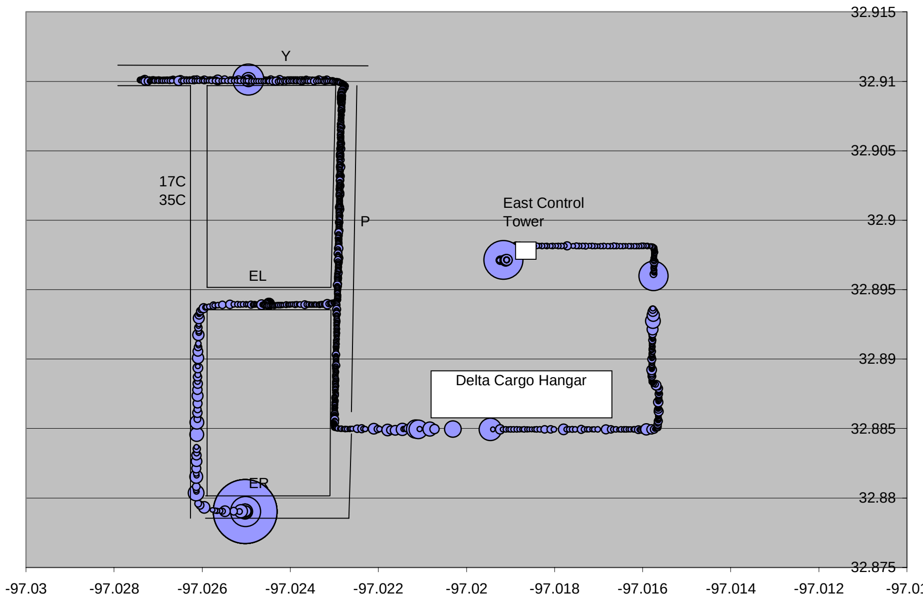


Figure C-3: Time Between ADS-B Position Messages vs. Position (Demo 1, Sortie 2)

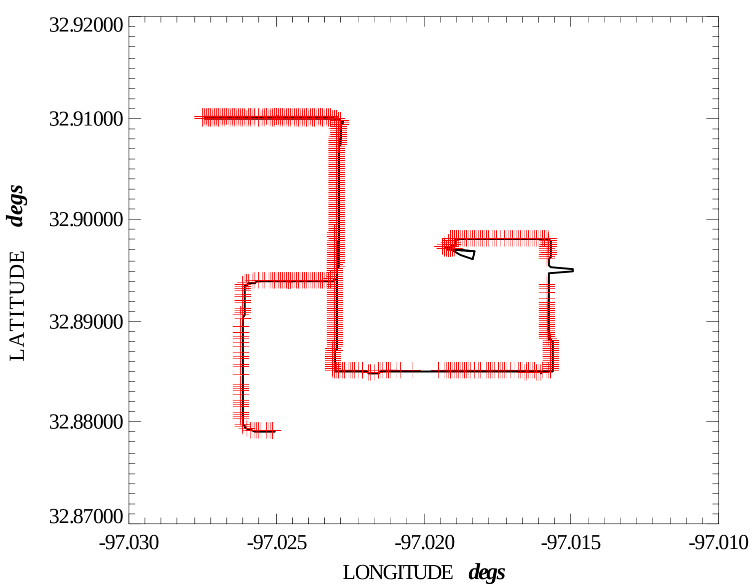


Figure C-4: Overlay Plot of GPS and ADS-B positions (Demo 1, Sortie 2)

C.2 Second Night of Demonstrations

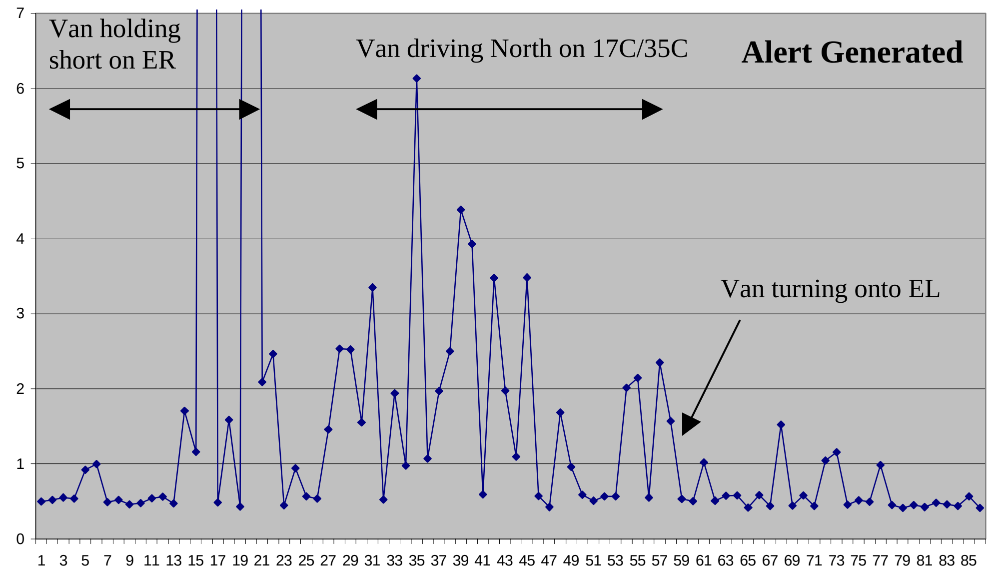


Figure C-5: Time Between Received ADS-B Position Messages (Demo 2, Sortie 1, Scenario 3)

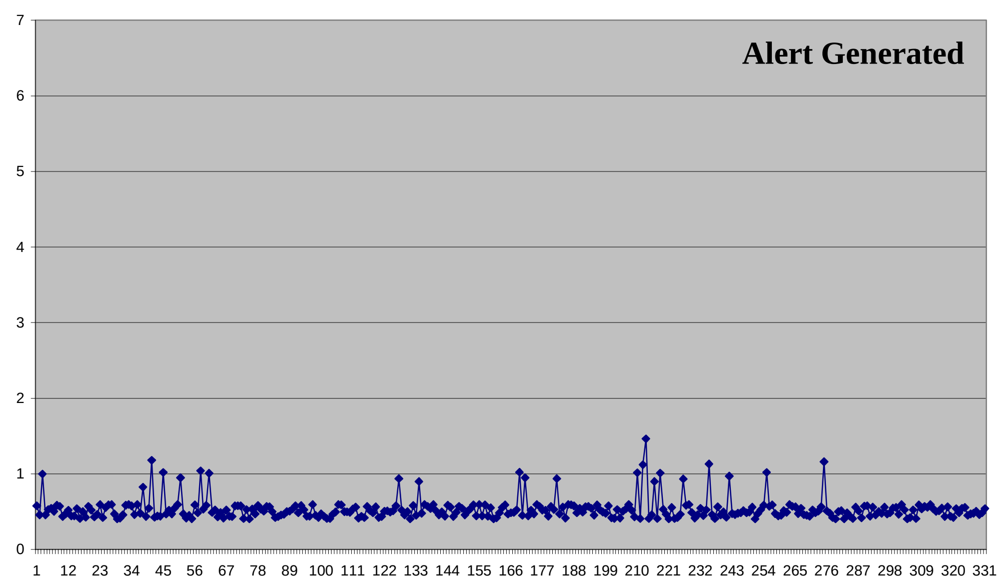


Figure C-6: Time Between Received ADS-B Position Messages (Demo 2, Sortie 1, Scenario 1)

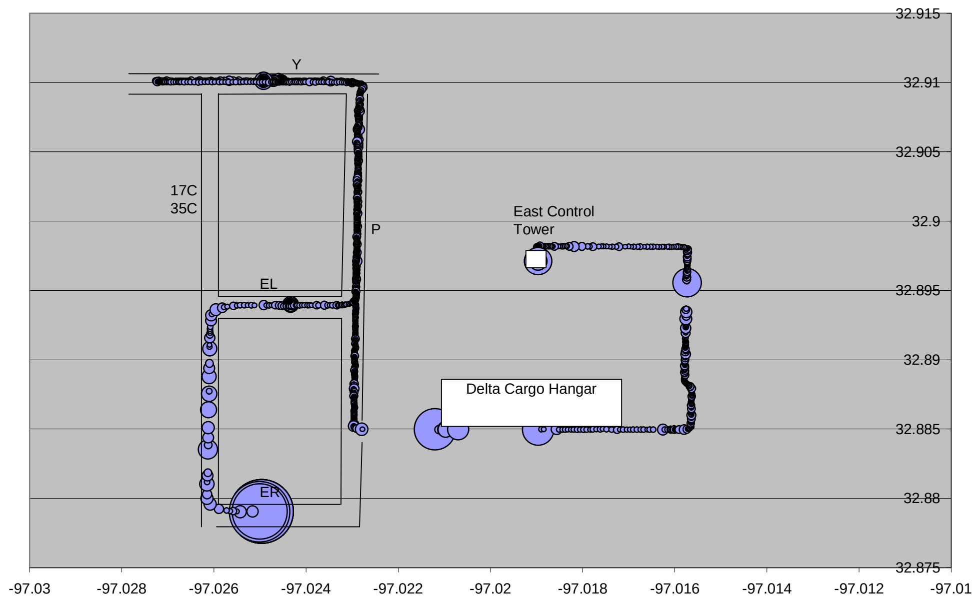


Figure C-7: Time Between ADS-B Position Messages vs. Position (Demo 2, Sortie 1)

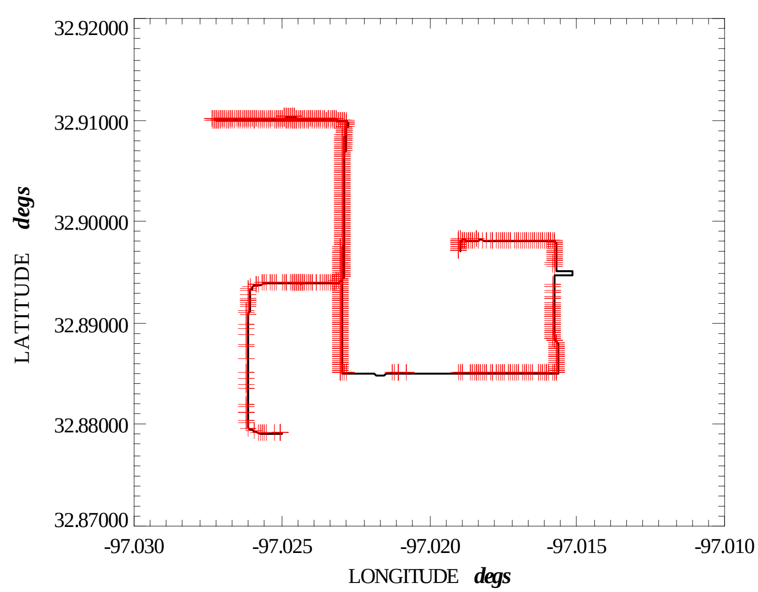


Figure C-8: Overlay Plot of GPS and ADS-B positions (Demo 2, Sortie 1)

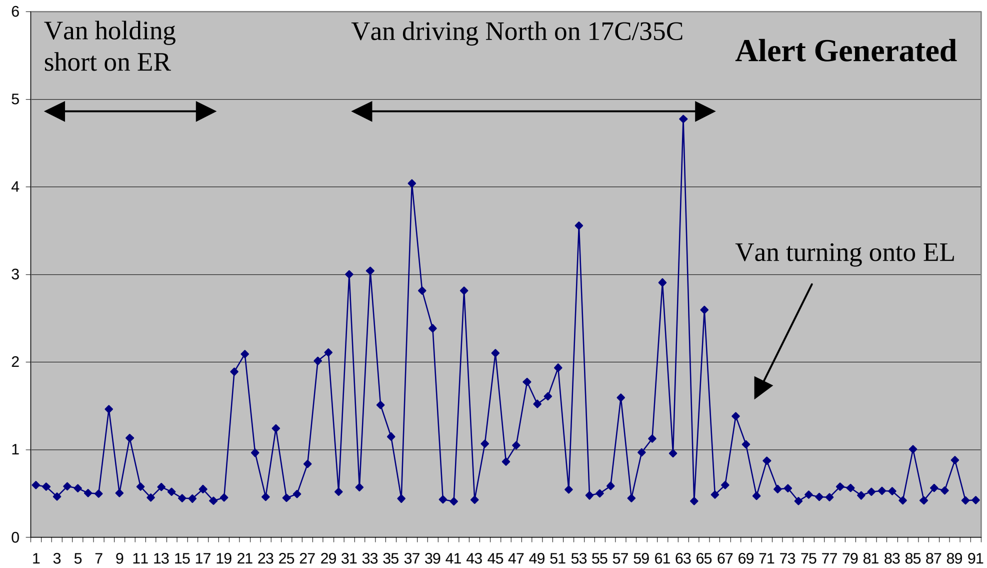


Figure C-9: Time Between Received ADS-B Position Messages (Demo 2, Sortie 2, Scenario 3)

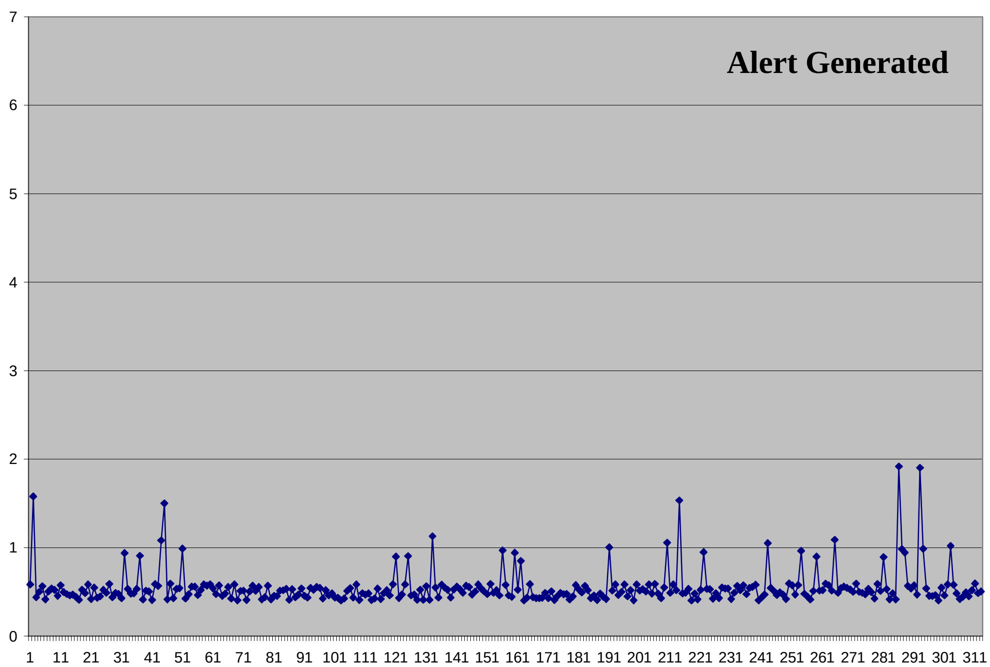


Figure C-10: Time Between Received ADS-B Position Messages (Demo 2, Sortie 2, Scenario 1)

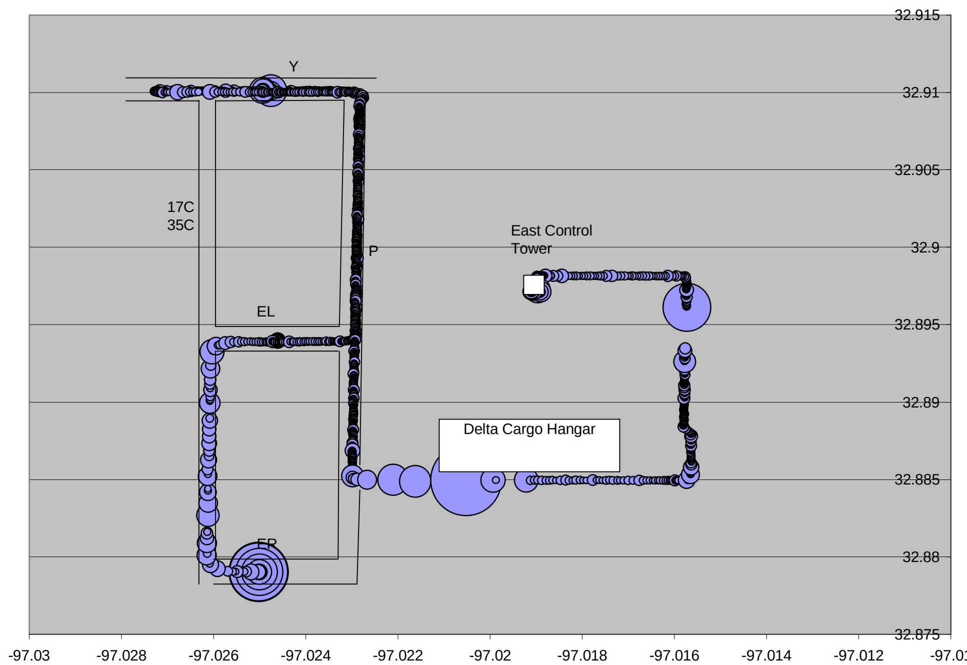


Figure C-11: Time Between ADS-B Position Messages vs. Position (Demo 2, Sortie 2)

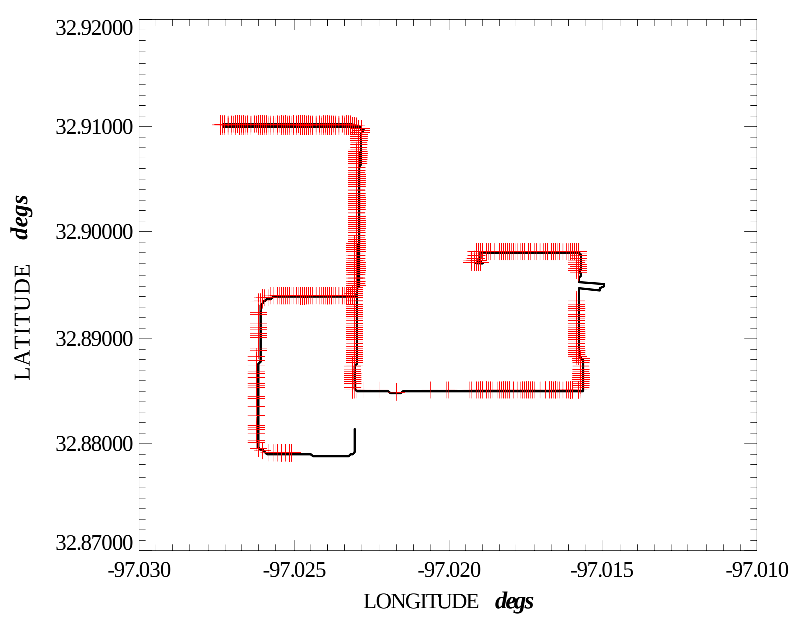


Figure C-12: Overlay Plot of GPS and ADS-B positions (Demo 2, Sortie 2)

C.3 Third Night of Demonstrations

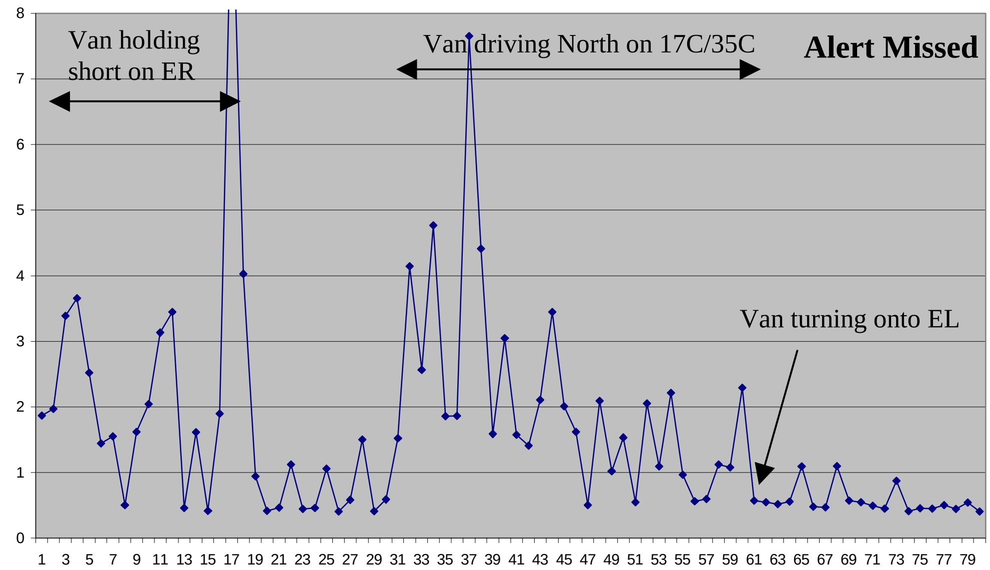


Figure C-13: Time Between Received ADS-B Position Messages (Demo 3, Sortie 1, Scenario 3)

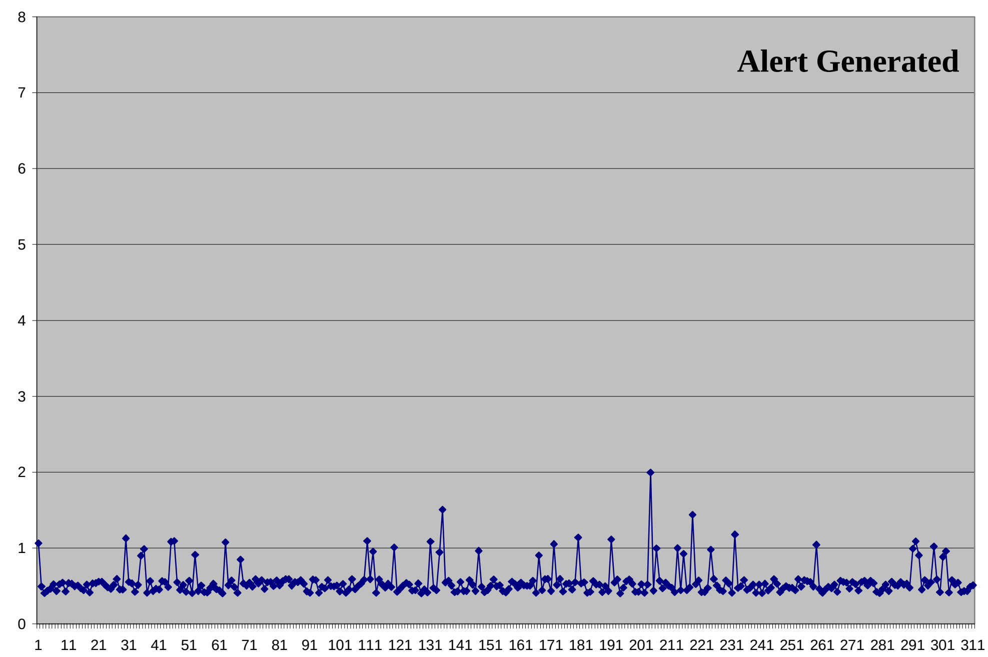


Figure C-14: Time Between Received ADS-B Position Messages (Demo 3, Sortie 1, Scenario 1)

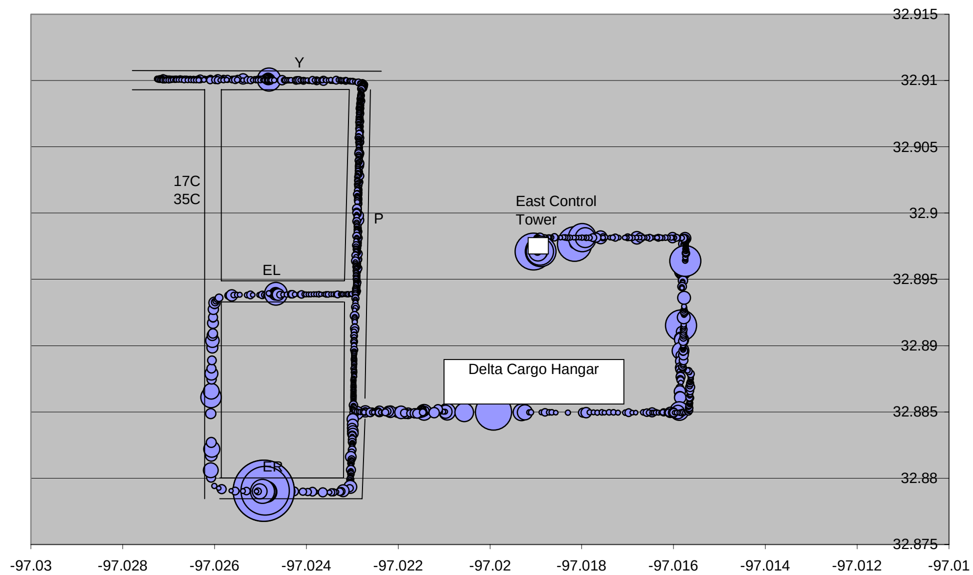


Figure C-15: Time Between ADS-B Position Messages vs. Position (Demo 3, Sortie 1)

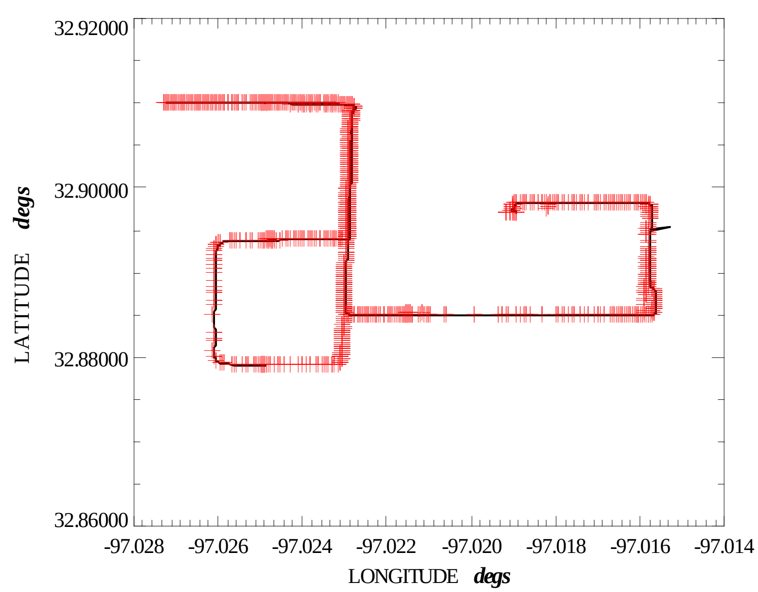


Figure C-16: Overlay Plot of GPS and ADS-B positions (Demo 3, Sortie 1)

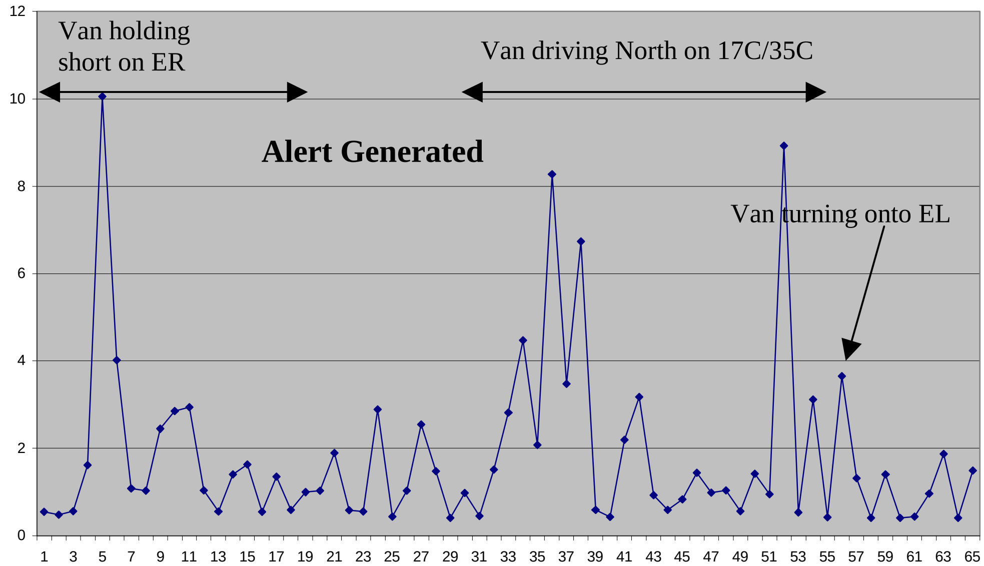


Figure C-17: Time Between Received ADS-B Position Messages (Demo 3, Sortie 2, Scenario 3)

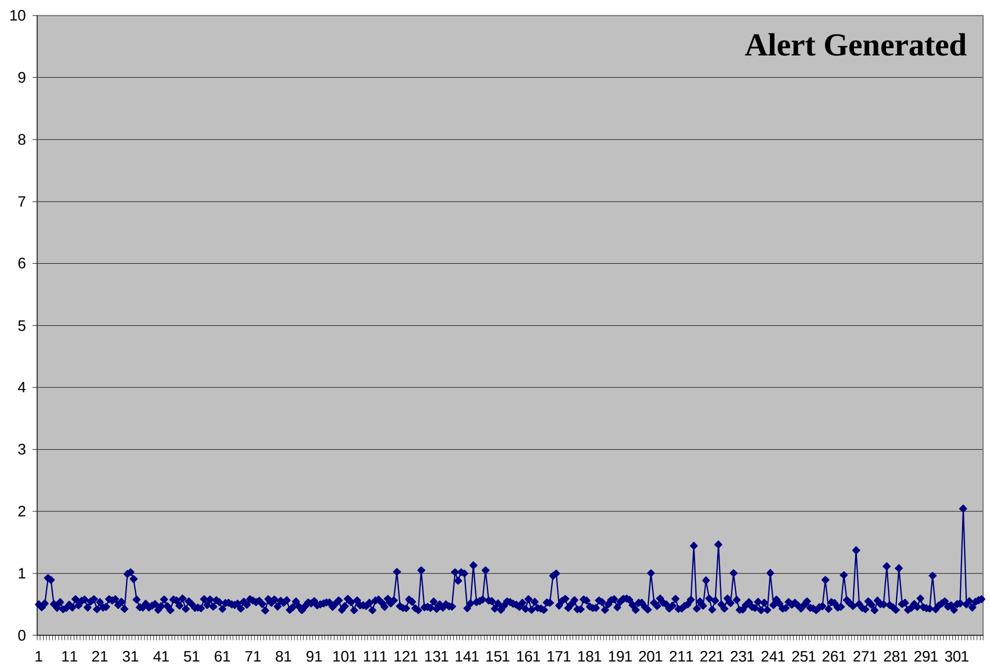


Figure C-18: Time Between Received ADS-B Position Messages (Demo 3, Sortie 2, Scenario 1)

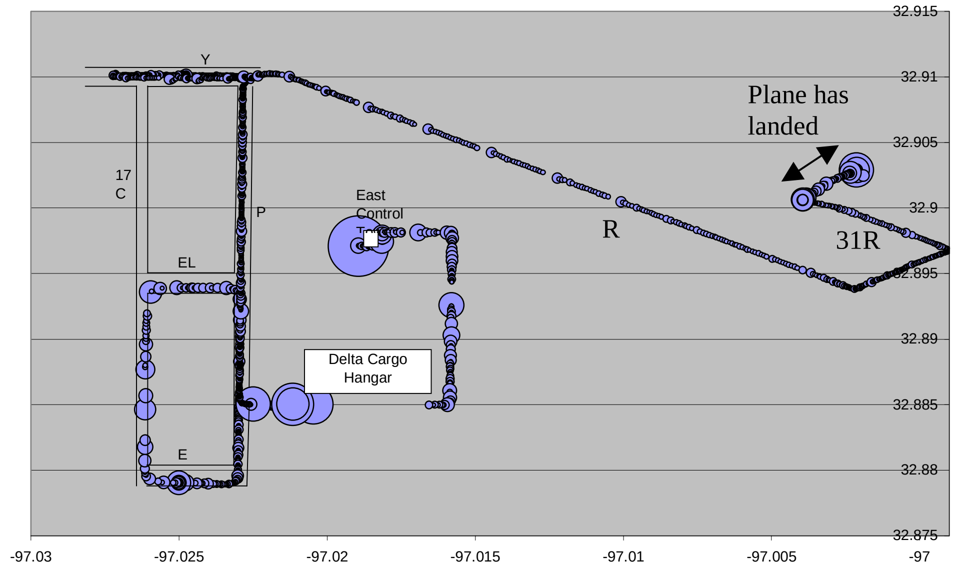


Figure C-19: Time Between ADS-B Position Messages vs. Position (Demo 3, Sortie 2)

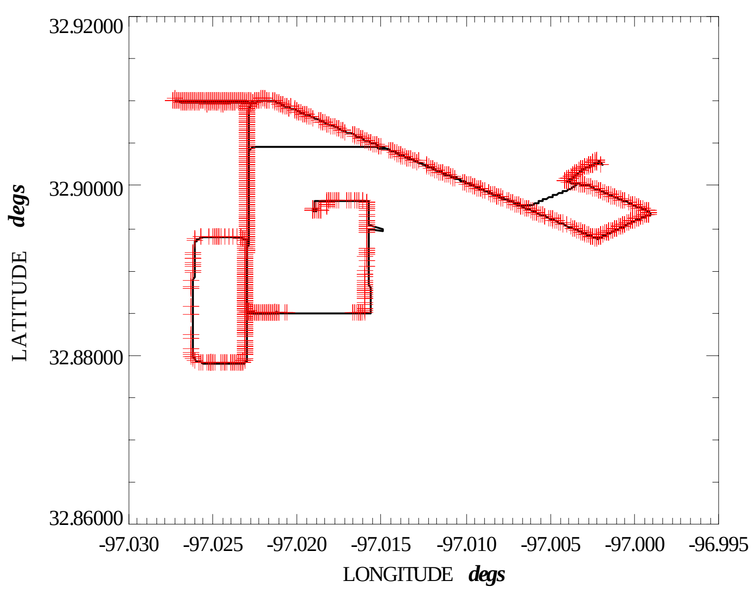


Figure C-20: Overlay Plot of GPS and ADS-B positions (Demo 3, Sortie 2)

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13. ABSTRACT *(Maximum 200 words)*
A Runway Incursion Prevention System (RIPS) was tested at the Dallas - Ft. Worth International Airport in October 2000. The system integrated airborne and ground components to provide both pilots and controllers with enhanced situational awareness, supplemental guidance cues, a real-time display of traffic information, and warning of runway incursions in order to prevent runway incidents while also improving operational capability. Rockwell Collins provided and supported a prototype Automatic Dependent Surveillance - Broadcast (ADS-B) system using 1090 MHz and a prototype Differential GPS (DGPS) system onboard the NASA Boeing 757 research aircraft. This report describes the Rockwell Collins contributions to the RIPS flight test, summarizes the development process, and analyzes both ADS-B and DGPS data collected during the flight test. In addition, results are report on interoperability tests conducted between the NASA Advanced General Aviation Transport Experiments (AGATE) ADS-B flight test system and the NASA Boeing 757 ADS-B system.

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