AUTOMATED AIRCRAFT TRACKING AND CONTROL IN CLASS G AIRSPACE

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Abstract

This paper presents results from a unique flight test concept that uses real-time flight test datalinks from Australia over existing commercial communication channels to a control center in North America for real-time automated tracking and control of manned and unmanned aircraft. The performance of this automated aircraft separation management architecture is presented for flight trials conducted in November 2009.

1 Introduction

The Smart Skies Project (Smart Skies) is a three-year collaborative research and flight test program exploring future technologies that support the safe and efficient utilization of shared airspace by both manned and unmanned aircraft. Smart Skies, which commenced in March 2008, brings together specialist researchers from Boeing Research & Technology (BR&T), Boeing Research & Technology Australia (BR&TA), and the Australian Research Centre for Aerospace Automation (ARCAA); a joint venture between the Commonwealth Scientific and Industrial Research Organization (CSIRO) ICT Centre, and Queensland University of Technology (QUT), to explore the development of three key Enabling Technologies for safe integration of UAVs into non-segregated airspace:

1) An Automated Separation Management System capable of providing separation assurance in complex and mixed usage airspace environments. The main component of this system is the Automated Dynamic Airspace Control (ADAC) Center, which contains the automated aircraft separation management software, the communications message handling software and the operator display tools necessary to achieve and visualize automated aircraft separation management. The ADAC exchanges custom messages designed for the Smart Skies project with a datalinked 'predictive' Flight Management System (pFMS) onboard Smart Skies flight assets.

2) Sense and Act (SA) systems for manned and unmanned aircraft capable of collision avoidance of dynamic and static obstacles.

3) A networked-enabled Mobile Aircraft Tracking System (MATS) comprising cost-effective Commercial Off The Shelf (COTS) radar and an integrated Automatic Dependent Surveillance - Broadcast (ADS-B) receiving ground station system.

The paper focuses on a flight test implementation of Enabling Technology 1 illustrated in Figure 1. Section 2 presents details of the flight test background, participating aircraft and an overview of the communications technologies. Key to the development of Enabling Technology 1 is the establishment of a reliable communications architecture between the test aircraft and the ADAC. Further details of the communications architecture, custom Smart Skies messages and the messaging system are presented in Section 3. Sample results of the ADAC and integrated flight assets during real-time flight trials are discussed in Section 4.

2 Flight Test Components

2.1 Background

Central to the Smart Skies Project are a series of integrated flight trials being conducted near the township of Kingaroy (Queensland, Australia). The objective of this flight test program is to characterize the performance of the developed technologies under realistic and stressing operating conditions.

As of February 2010, the Smart Skies program has completed three of six planned flight trials. Key Phase 1 and 2 flight trial results have been previously documented [1][2]. The real aircraft in each flight trial are flown at the Burrandowan Homestead test site in Queensland, Australia. In the Phase 1 flight trial the ADAC was located at a Boeing facility in Seattle, WA. Several scenarios involving up to three potentially conflicting aircraft, both real and simulated, were successfully executed and managed by the remote ADAC. In the Phase 2 and 3 flight trials the ADAC was located at a Boeing facility in Palmdale, CA. One of the goals of the Phase 2 and 3 flight trails was to increase the complexity of the Loss of Separation (LOS) scenarios and to include a maximum of six, simulated and real, aircraft. This paper will report on Phase 3 test results.

2.2 Flight Test Assets

The primary flight test aircraft used in the initial program include:

1) A Cessna 172R model aircraft referred to as the Airborne Systems Laboratory (ASL). The custom-modified aircraft is fitted with a GPS-INS truth data system, pFMS, custom flight display (for visualizing flight plans, safe flight plan updates, local situation awareness data and other information received from the ADAC) and a communications management system. The ASL is capable of conventional human piloted control, or optionally, a lateral auto-piloted mode (en-route).

2) A small autonomous fixed-wing UAS, referred to as the QUAS. The QUAS has a maximum take-off weight of 20kg, a payload capacity of 4kg and an endurance of approximately one hour (full fuel and payload). Onboard systems include a pFMS,

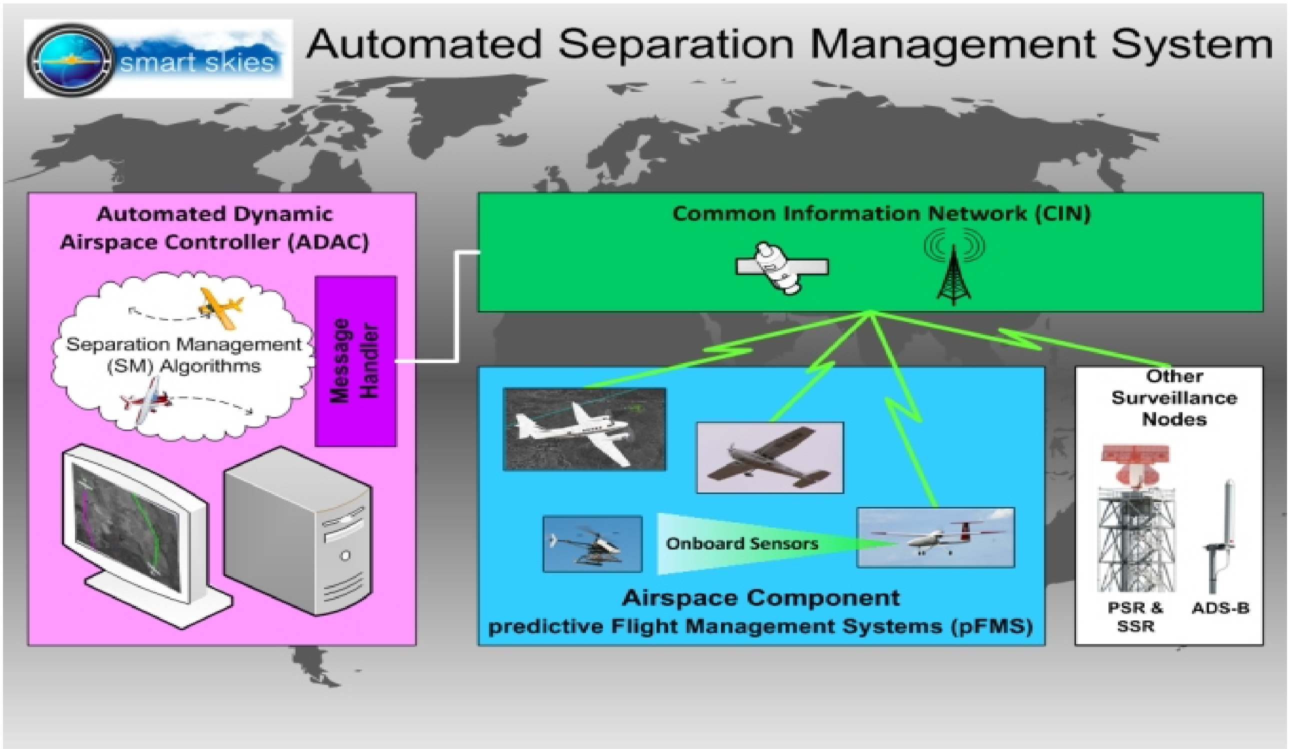

Figure 1: Automated separation management system architecture.

COTS autopilot, UHF, Iridium and 3G communications, and a vision-based sense and avoid payload.

3) A small autonomous helicopter, referred to as the CUAS. The CUAS has a maximum take-off weight of 13kg and endurance of approximately 45 minutes (full fuel and payload). Onboard systems include: a pFMS, custom-designed flight computer and autopilot, UHF communications, and an integrated LIght Detection And Ranging (LIDAR) and stereo vision based sense and avoid payload. Iridium and 3G communications systems are hosted within the CUAS ground control system to enable communication with the ADAC.

In addition to the aircraft described, the flight tests are augmented using multiple virtual aircraft. The virtual aircraft include fully automated Six Degrees-Of-Freedom (6DOF) simulation models and a manually piloted flight simulator at the University of Sheffield, UK [3]. Each of these flight simulation approaches can be networked to the ADAC either via the Internet or using an Iridium transceiver for satellite communications. The use of simulated aircraft in combination with real aircraft and real communications links provides a safe and efficient testing environment for the evaluation of complex Loss of Separation (LOS) scenarios.

2.3 Communications Overview

The communications capability used in Smart Skies is referred to as the Common Information Network (CIN). An overview of the communication components is illustrated in Figure 2. Two communication systems are currently being evaluated as part of the Smart Skies CIN: the Iridium [4] Router-Based Unrestricted Digital Internetworking Connectivity Solution (RUDICS) system and the Telstra Next G^{TM} cellular system (3G). Alternatives have been tested by other research groups [5][6]. RUDICS enables data calls from Iridium transceivers to be received at a ground-based gateway. Each connection is then relayed onto a ground-based network, providing end-to-end TCP/IP connections to the ADAC's message-handling service. All of the test aircraft

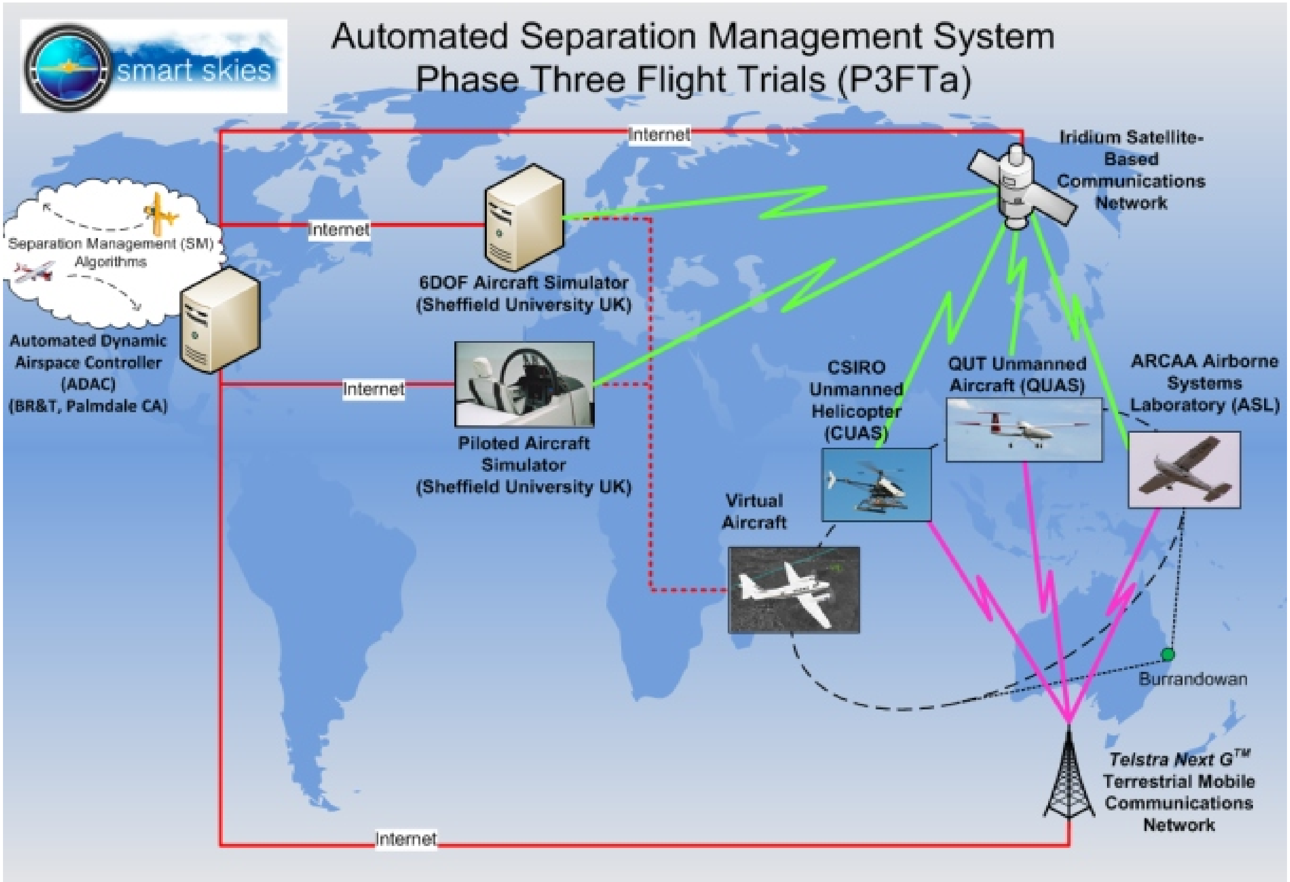

Figure 2: Phase 3 System Architecture

use both communication channels simultaneously to act as redundant data links; connecting aircraft to the automated aircraft separation management system control system. BR&T has implemented several Smart Skies ADAC Centers in North America and Australia to satisfy the Automated Separation Management System technology requirements.

3 Communications Architecture and Message Handling

3.1 Aircraft Connectivity

The Smart Skies Phase 3 Flight Trial Architecture is illustrated in Figure 2. Participating aircraft (fully equipped for two-way communication with the ADAC) may act cooperatively, sending tracking data to the ADAC and/or being tracked by an external source, such as a radar. Cooperative aircraft can also automatically receive short-term flight plan modifications as required from the ADAC to maintain safe aircraft separation, essentially placing suitable equipped aircraft under temporary high-level trajectory control by the ADAC. This architecture allows multiple aircraft to be continually tracked and controlled from an ADAC anywhere in the world with access to the Internet. The control cycle time goal for this system is approximately three seconds or less for all aircraft.

3.2 Message Types

Information exchanged with the aircraft pFMS on the CIN includes aircraft state variables, situational awareness and, if necessary, aircraft trajectory modification control messages. Communication between the aircraft and the ADAC utilize a set of custom Smart Skies messages defined in an Interface Control Document (ICD). Table 1 documents the set of messages exchanged during Phase 3 flight tests, with further details of the main messages

Message Type	Length[%] (Bytes)	TX Frequency (Hz)	Comments
TADS (aircraft state data)	**80**	**≥ 1**	
Proposed aircraft flight plan	**Variable, 160 for 10 waypoints**	**Once**	**Retransmitted if modified**
CTADS (commanded flight plan modifications)	**Variable, 128 for 5 waypoints**	**As needed**	**Transmitted by the ADAC to any cooperative aircraft requiring separation**
Ping	**30**	**0.1**	**Includes response message**
Acknowledgement	**28**	**As needed**	**Transmitted by ADAC or pFMS in response to receipt of a flight plan or CTADS respectively**
Situational Awareness	**Variable, 178 for 4 local aircraft**	**0.1**	**Transmitted by the ADAC to provide surveillance data to neighboring aircraft**

[%] All message lengths reported include 26 bytes of overhead inclusive of timestamps and aircraft identification.

Table 1: Phase 3 Message Types

detailed below.

The message type termed TADS (Trajectory Array Descriptive Data Set), contains the currently measured aircraft position, speed, attitude and the current flight plan leg identification. This message is transmitted periodically from the pFMS to the ADAC. The data transmission rate can be set according to the experimental requirements but typical TADS transmit rates were 1 Hz over Iridium and 2 Hz over the NextG cellular system.

Cooperative aircraft are expected to transmit basic flight intent information. This is encapsulated in a flight plan message that is transmitted by the onboard pFMS when the aircraft connects to the CIN, or updates are made to the flight plan. The ADAC uses this information for determining potential LOS events in the near future (up to 10 minutes in the future).

The aircraft Separation Management (SM) algorithm within the ADAC uses the received TADS data and flight intent information (information from other data streams are used to account for uncooperative aircraft), to determine if flight plans require modification to achieve safe aircraft separation.

If a LOS event occurs, the SM algorithm modifies the flight plans of cooperating aircraft and transmits the flight plan back to the aircraft. For these flight tests, there is no negotiation of flight plan modifications; it is assumed that the ADAC has sent a flyable and acceptable trajectory modification. The modified flight plan message is called Commanded TADS, or CTADS and is listed in Table 1. This message is sent only as required to maintain safe separation distances between the aircraft.

The system includes an additional ‘Ping’ message which is exchanged between the ADAC and each aircraft approximately every ten seconds. These pings satisfy multiple roles, including: Measuring network latency; determining clock offsets in the event of an uncoordinated clock; and active connection monitoring. This will be discussed further in Section 3.

Typically, all messages are transmitted simultaneously over both communication links, if available. The ADAC logs incoming and outgoing data over each datalink and selects the data from what is judged the ‘best’ link for determining predicted aircraft states and for conflict resolution. During each flight test, determination of the preferred datalink is evaluated continually, using latency data

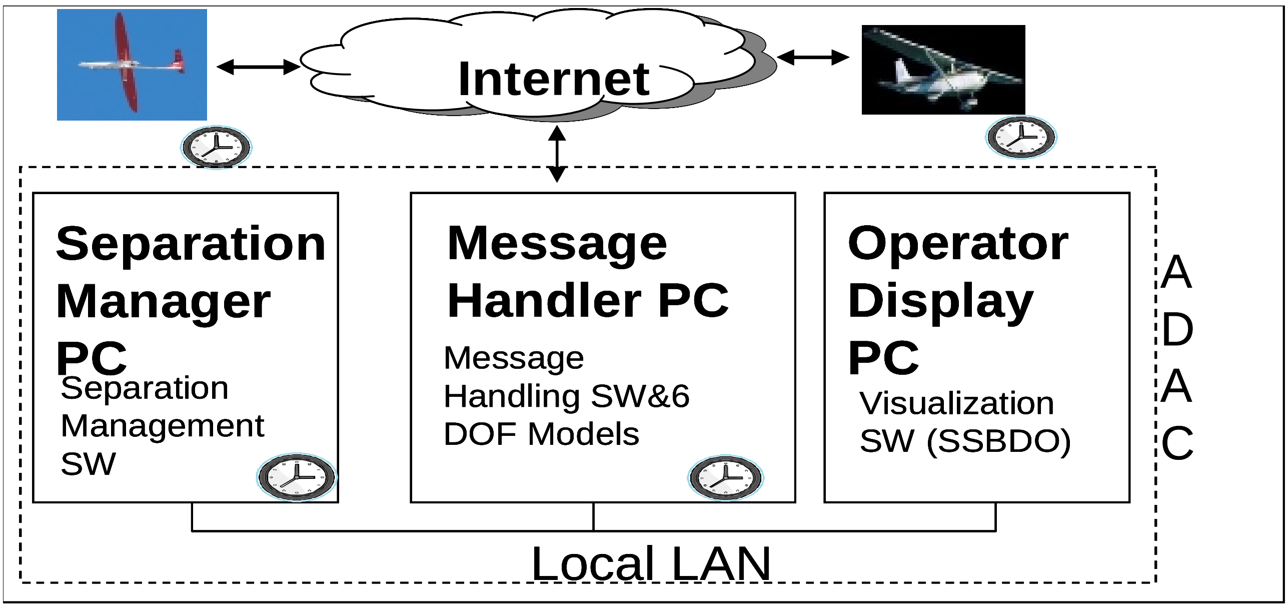

Figure 3: ADAC Phase 3 Architecture

derived from the ping messages. Sample results of the usage of each communication channel are presented in Appendix B.

3.3 Message Handling and ADAC Architecture

A more detailed illustration of the Phase 3 ADAC architecture is given in Figure 3. The ADAC currently consists of three computers on a Local Area Network (LAN). This LAN has a gateway to the Internet. The tasks of the ADAC (airspace management, message handling, operator displays) were distributed over several computers for Phase 3 due to the anticipated processor overloading if a single machine was used. One computer is dedicated to running the SM algorithm; another machine is dedicated to running operator visualization software; while a third computer hosts the message handling server, SM interface services and local 6DOF aircraft simulations.

Central to providing the connectivity to the SM algorithms is the message handling software. The implementation of the message handling server has been previously documented [7], so only a brief outline follows. The message handler acts as the server in a client-server architecture. Clients can either be aircraft separation software, individual aircraft or alternative streams of aircraft data. For example, client aircraft make connection-oriented TCP/IP data links with the messaging server and are responsible for establishing reconnections in the event of lost connectivity. Although the three ADAC computers are on a local LAN, the local ADAC client-server architecture could be implemented with the three computers each located at remote locations, each with a valid IP address. The partitioning of the separation algorithms from the messaging system enables the architecture to transparently trial different aircraft separation techniques. Future flight tests intend to integrate and test alternative algorithms for separation assurance [8].

Figure 3 also highlights where various clocks exist within the system, including: the SM; the message handler; and airborne flight computers. Clearly it is critical for the SM software to process a chronologically coordinated set of trajectories to apply safe separation thresholds. The agreed upon Smart Skies time reference is UTC. One method to accomplish this coordinated time reference is to have all clocks synchronized continually in real-time by deriving time from the Global Positioning System. This approach was not implemented in Smart Skies, namely because of the expense and logistics of adding GPS time services into all of the various ADAC installation locations. An alternative research approach investigated was to use the ping messages between the ADAC and each aircraft to determine any small individual clock offsets and network latencies. Clearly for an operational system a combination of both the GPS and the ping approach would appear to be fruitful.

To use the ping messages successfully, each aircraft's computer accesses a network time update service to update their respective clocks while on the ground prior to takeoff. The SM can internally adjust times of the incoming individual aircraft TADS messages by using ping messages which record the SM ping message transmit time, an aircrafts receive time of the ping message, the aircrafts ping response message time (ping messages from the server are expected to be responded to by the clients), and finally the SM software reception time of the ping response message. The time delta between the SM ping request and the aircraft receive ping request time is then the clock offset between the two clocks. The difference between the SM ping time and the SM ping response time then gives the total round trip latency for the relevant communication channel.

The primary use of the ping messages is to allow the SM to estimate the round trip time latency for the particular channel chosen. This latency not only includes the communications channel latency, but also the message processing latency on both the individual aircraft and at the ADAC. As expected, the message processing latency on the aircraft, real or simulated, was negligible in comparison with the communications latency in Phase 3. However, the message processing latency at the ADAC within the message handler can add up to 100 ms delay on outgoing messages and up to 200ms on incoming messages. These delays exist due to a conservative throttling scheme used to prevent a large number of aircraft connections overloading the messaging server. Typically, each aircraft in a flight test maintains an end-to-end connection with the message handling server, with each connection being serviced by a dedicated thread. Although TCP/IP connections are maintained, the nature of the communications links (Iridium and 3G) means that losses in the connectivity of the wireless link will tear down the connection with the server. In such situations, the server can be left unaware that a datalink has been lost. For this reason, it is the responsibility of the pFMS on each participating aircraft to reconnect with the message server. For this reason, the transmission of the ping message by the ADAC also acts as a connection 'heartbeat', providing the ability to check for dead-connections, and indicating if the associated connection resources should be destroyed.

4 ADAC Performance and Flight Test Results

The Phase 3 test flight scenarios are listed in Appendix A and a sample of connectivity and separation results are in presented in Appendix B. Unfortunately due to a mechanical malfunction prior to the flight test number 3C, the CUAS autonomous helicopter was operated as a hardware-in-the-loop simulation, complete with the Iridium and 3G communications links working as if the CUAS had been fully operational. The round trip end-to-end latencies are plotted in Figure 4 for the first day of the Phase 3 flight trials. Note the latency data listed in Appendix B is the one-way latency, half of that shown in the figure. We typically observe that 3G latencies (including routing through a Network Address Translation server and the Internet) are only marginally less than Iridium latencies. However, the mean latencies of the Iridium communication channel are satisfactory

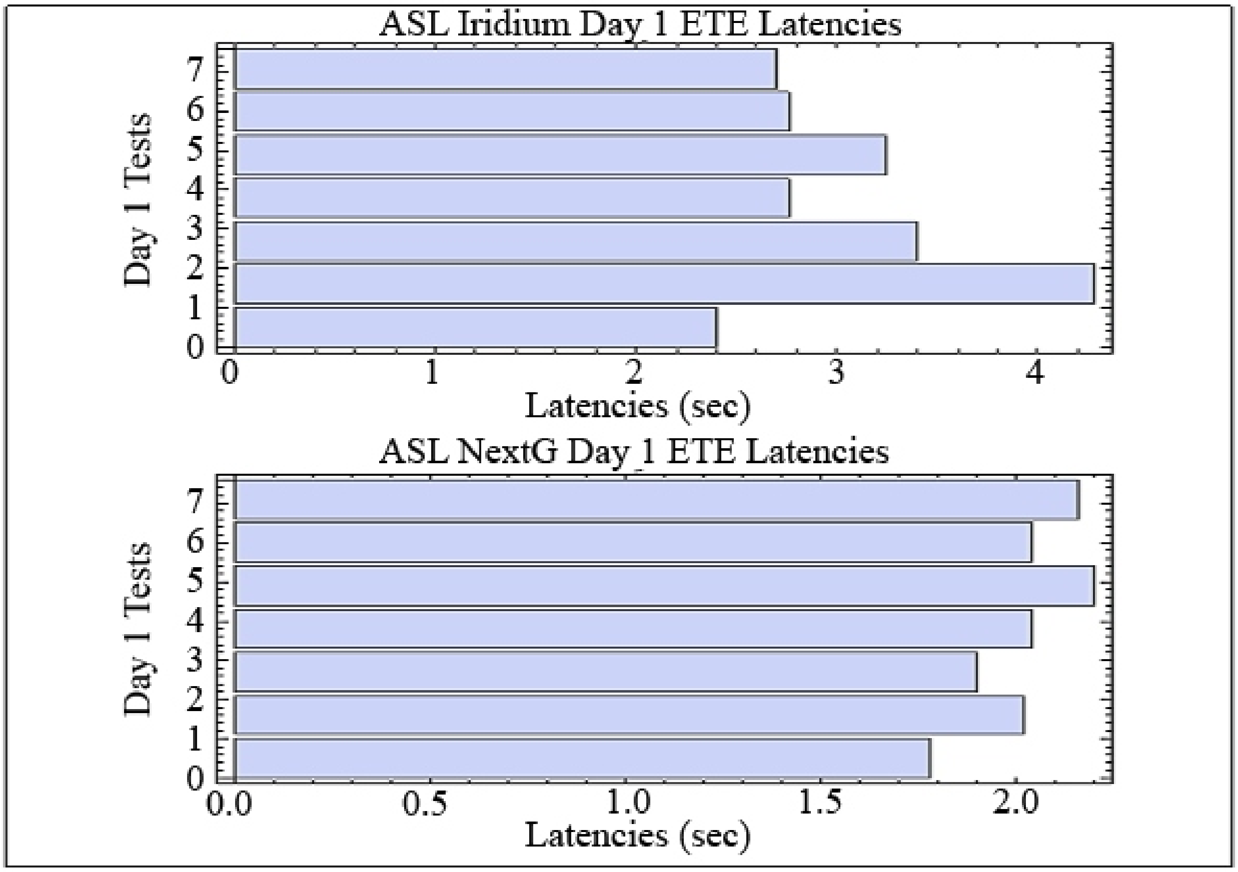

Fig. 4. Mean round trip end-to-end latencies from the first day of testing.

for the ADAC to successfully manage the airspace. Note that the time scale (order of minutes) for high-level trajectory control far exceeds the communications latencies. As previously mentioned, the latency includes aircraft and message handling overheads, so does not represent the best achievable latency of the 3G and Iridium communications systems.

When determining potential future LOS conditions, the ADAC separation management software uses two methods to predict future aircraft positions: Firstly, a long term trajectory predictor, which assumes that aircraft will maintain a track close to their filed flight plan; Secondly, a short term predictor, which uses received aircraft state data to estimate future aircraft positions. This two-tier approach provides fallback functionality for aircraft that do not maintain flight along their intended flight plan, or when the long-term trajectory prediction doesn't match actual behavior. During the Phase 3 flight trials, the SM assumed the safe aircraft separation thresholds presented in Table 2. Note that the 3C test scenario, using the two unmanned aircraft (QUAS and CUAS hardware-in-the-loop simulator), was carried out over a smaller test area than the flight tests involving the Cessna 172R ASL. Rather than applying an overly large safe separation distance, the ADAC in the 3C tests (UAV only scenario) applied a common aircraft separation threshold of 50 meters for both long-term and short-term predictions. The sample results in Appendix B show that the separation algorithm performed quite well over nearly all test cases.

Test Identification	Long-Term Separation Threshold	Short-Term Separation Threshold
2B1, 2B2, 2B3	*1000 m*	*200 m*
3C	*50 m*	*50 m*
2D1, 2D2	*1000 m*	*200 m*

Table 2. Safe separation thresholds used in Phase 3 flight trials.

Figure 5 shows the ground tracks from test case 3B1. As shown in Appendix A, this case involved the Cessna attempting to fly a figure-eight flight plan while four Flamingo UAV simulations (QUAS 6DOF simulation) attempted to fly intersecting and repeating orbits at the same altitude. The ground tracks show that whilst the ADAC was able to manage the airspace, the workload of the piloted aircraft was significant (dark, solid line in Fig. 5). Although an unlikely scenario, such cases present challenges to the separation algorithms.

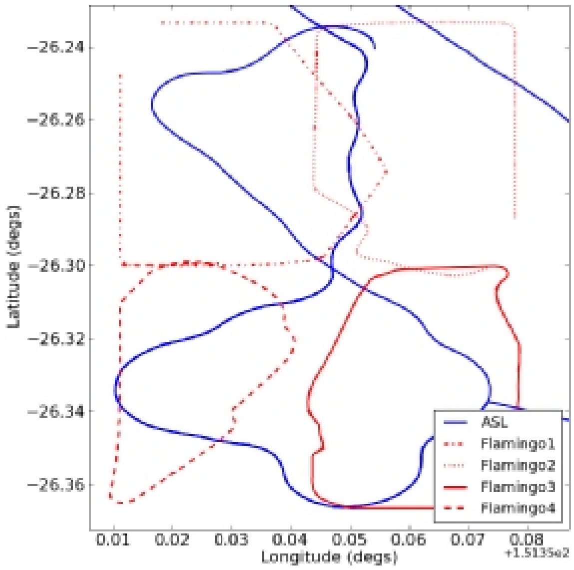

Fig. 5. Ground tracks recorded during flight test 3B1.

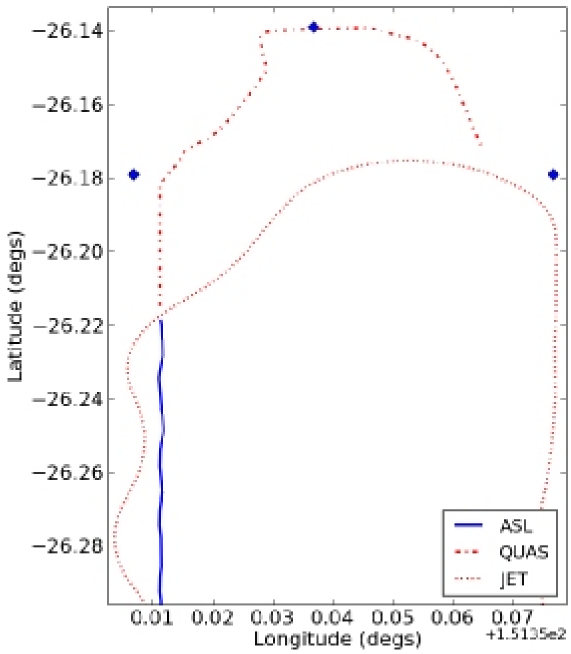

Fig. 6. Subset of ground tracks recorded during flight test 3D1.

Figure 6 shows the tracks of a test (3D1) designed to test the separation management software in overtaking situations. Three aircraft (the ASL, the QUAS and a piloted simulation of a Jetstream) were initially staggered around an oval flight plan (with the faster Jetstream aircraft at the back) and all flew in a clockwise direction. The tracks show that the SM commanded the Jetstream to initially overtake the ASL (bottom-left of Fig. 6), followed by a command to cut the oval corner to avoid the QUAS. Note that in this case, all aircraft were assigned equal priority so the SM algorithm did not account for the size and speed of each aircraft.

5 Final Remarks

This paper has outlined the architecture of a flight test concept that allows a datalinked control center to autonomously track and control (in the event of a loss of safe separation) the trajectory of manned and unmanned aircraft from a geographically distant location. The Smart Skies project is investigating many future automation technologies, some of which are aligned with the goals of NextGen [9], such as trajectory control and higher levels of automation for conflict detection and resolution. The Phase 3 flight-testing, conducted in November of 2009, included several program 'firsts' including:

- Flying and controlling the QUAS UAV beyond visual range;
- Flying uncooperative aircraft which sent tracking data but which did not accept commands from the ADAC;
- A 'rogue' piloted simulator operated at the University of Sheffield. The pilot of this simulated aircraft intentionally failed to follow its transmitted flight plan, but instead attempted to intercept other aircraft in the flight test region, thus testing the Separation Manager in non-planned scenarios.

The Smart Skies project continues into 2011, with flight tests planned for Enabling Technologies 2 and 3 (dynamic sense and act, and networked mobile aircraft tracking system, respectively). The separation management software and the messaging system are constantly evolving with future enhancements (to be tested in Spring 2010) to the ADAC and new flight test capabilities, including:

- Enabling the message handler to receive a data feed from the MATS ground station, including aircraft data sourced from radar and ADS-B transmissions.
- Allowing the ADAC to receive and utilize target data derived from airborne sensors to enhance the airspace management.
- Reduced message processing latency within the message handler.
- Testing the system with up to 10 aircraft in close proximity, potentially creating many secondary and cascading potential collisions.

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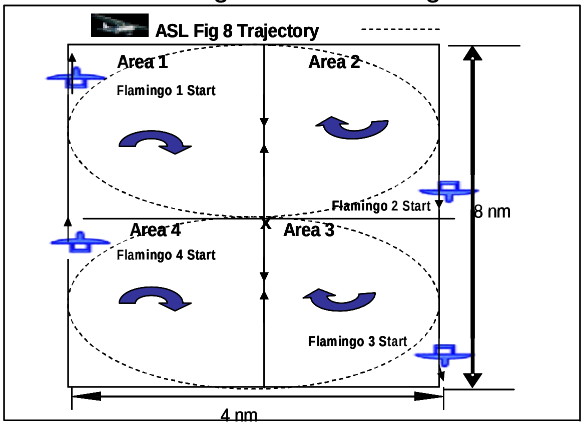
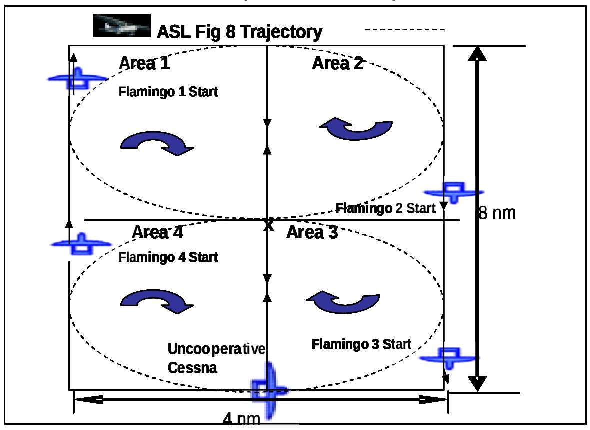
Appendix A : Phase 3 Test Scenarios

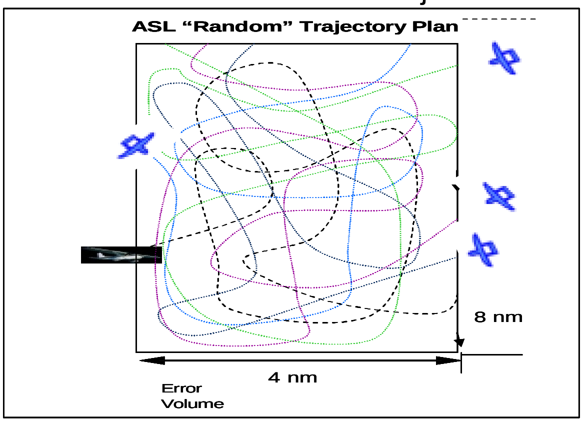
Test 2B1: Orbiting 6-DOF Flamingos and ASL



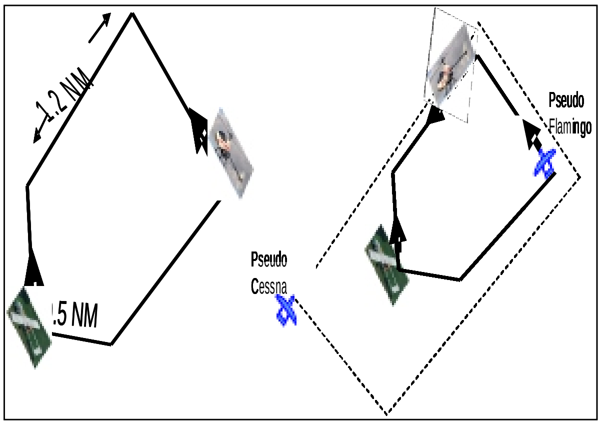
Test 2B2 : 2B1 plus Uncooperative AC



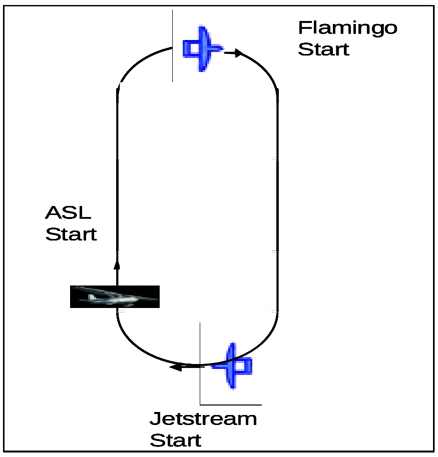
Test 2B3: Random Cessna Trajectories



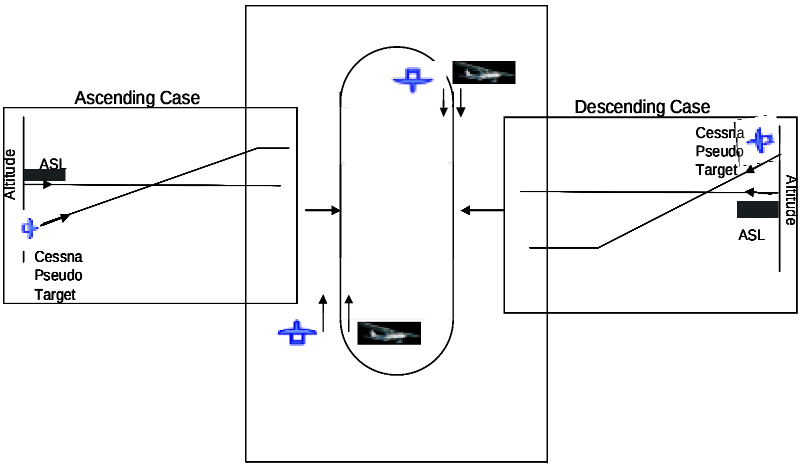
Test 3C: UAV Test Cases



Test 2D1:Slow-Medium-Fast



Test 2D2:Test Climbing-Descending



Appendix B. Phase 3 Flight Trial Results

Test #	CUAS/QUAS Iridium 1 Way Latencies	CUAS/QUAS NextG 1 Way Latencies	SM usage of CUAS/QUAS Comm. Channels(Irid/NextG)	Computer Clock Offsets (QUAS-CUAS unless otherwise noted)	SM Performance
3C1-1 run 1	CUAS :1.89 Sec QUAS :Bad link	CUAS :0.72 Sec QUAS :1.25 Sec	CUAS 60.2%/17.5% QUAS: 39.6%/60.4%	Approx 20 sec	Separations > 50 m
3C1-1Run 5	CUAS :1.40 Sec QUAS 2.03	CUAS :0.87 Sec QUAS :1.08Sec	CUAS 16.8%/83.2% QUAS: 15.5%/84.5%	Approx 20.5 sec	Separations > 50 m
3C1-1 Run 6	CUAS :1.46 Sec QUAS :1.42 Sec	CUAS :0.84 Sec QUAS :1.36Sec	CUAS 28.7%/71.3% QUAS: 42.5%/57.5%	Approx 37sec/Clock Reset	One Violation
3C1-1 Run 7	CUAS :1.31 Sec QUAS :Bad link	CUAS :0.88 Sec QUAS :1.19 Sec	CUAS 54.8%/48.2% QUAS:18%/82%	Approx 13sec	Separations > 50 m
3C5-Run 1	CUAS :1.24 Sec QUAS :Bad link	CUAS :0.68 Sec QUAS :1.24 Sec	CUAS 69.6%/30.4% QUAS:17.2%/82.8%	Approx 13 sec	One violation
3C5-Run 2	CUAS :1.23 Sec QUAS :1.88 Sec	CUAS :0.76 Sec QUAS :1.36 Sec	CUAS 37.4% / 62.6% QUAS:77.9% / 22.1%	Approx -14 sec QUAS, Approx 21 Sec MH Fla	Separations > 50 m
3C7-Run 2	CUAS :1.32 Sec QUAS :2.36 Sec	CUAS :0.67 Sec QUAS :1.02 Sec	CUAS 19.9% / 80.1% QUAS:20.3% / 79.7%	Approx -14 sec QUAS, Approx 22 Sec MH Fla	One violation

Fig. B1. Iridium/3G connectivity and separation results from Nov 11th 2009.

Test #	ASL Iridium 1 Way Latency	ASL NextG 1 Way Latency	SM usage of ASL Comm. Channels	MH Computer Clock Offsets	SM Performance
3B3-1 run2	1.20 Sec	0.89 sec	Iridium: 60.2% NextG: 39.8%	Approx 18 sec	One long term violation, ASL-Cessna DCA 0.4 km
3B3-2 run2	2.14 sec	1.01 sec	Iridium:0 % NextG: 100 %	Approx 18 sec	Two long term violations Sheffield Sim-Cessna 1: 0.47 ASL-Cessna s2: 0.25 km
3B3-1 run4	1.70 sec	0.95 sec	Iridium:0 % NextG: 100 %	Approx 18 sec	One Long term violation Sim ASL 0.5 km* One Short Term violation Sim-Ces2: 0.18 km* * Sim was “Rogue”
3B1-1 run 1	1.38 sec	1.02 sec	Iridium:10.1% NextG: 89.9 %	Approx 20 sec	Two Long Term Violations: Fla2: 0.30 km Fla4:0.47 km
3B1-2 run 1	1.62 sec	1.10 sec	Iridium: 0 % Next G: 100 %	Approx 20 sec	Two Long Term Violations: Fla2: 0.32 km Fla4: 0.55 km
3B1-3 run1	1.38 sec	1.02 sec	Iridium: 0 % Next G: 100 %	Approx 20 sec	Two Long Term Violations: Fla2: 0.64 km Fla3: 0.74 km
3B2-1 run1	1.35 sec	1.08 sec	Iridium: 0 % Next G: 100 %	Approx 20 sec	One Long Term: Uncooperative: Fla 2: 0.52 km One Short Term: Uncooperative: Fla4 :.008 km

Fig. B2. Iridium/3G connectivity and separation results from Nov 9th 2009.