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ADS-B Flight Tests on Ikhana Unmanned Aircraft System

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Abstract

Researchers at the National Aeronautics and Space Administration Dryden Flight Research Center (Edwards, California) have developed and flight-tested an Automatic Dependent Surveillance-Broadcast (ADS-B) system on the Ikhana (MQ-9 Predator) (General Atomics Aeronautical Systems Incorporated, San Diego, California) Unmanned Aircraft System (UAS). The present invention proposes a system architecture that integrates ADS-B surveillance technology to an unmanned aircraft system, with improved communications and sophisticated display capabilities to provide increased situational awareness and a self-separation assurance system to avoid accidents. In general, ADS-B Out refers to an appropriately equipped aircraft broadcasting ownship state information. ADS-B In refers to an appropriately equipped ability of the aircraft to receive and display ADS-B information from other aircraft. The ADS-B system architecture is especially suited for UASs because it integrates: 1) commercial off the shelf modified ADS-B hardware; 2) radio data-link communications; 3) redundancy of ADS-B data and hazardous weather data via secure internet communication; 4) software algorithms for real-time ADS-B data integration, conflict detection, and alerting; and 5) a synthetic vision display using a fully-integrated geobrowser for three dimensional graphical representations for ownship and air traffic situational awareness. The flight-test objectives of the proof-of-concept were to evaluate the performance of ADS-B Out as installed on the Ikhana MQ-9 and to demonstrate the ADS-B In functional capability. In March 2012, two ADS-B Out flights were conducted at Edwards Air Force Base (AFB) (Edwards, California) lasting over two hours. In May 2012, two

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ADS-B In flights were conducted in the local area airspace at Edwards AFB. A specially equipped mobile van generated ADS-B target messages on the ground while the Ikhana flew a mission profile. Researchers in the ground control station looking at the synthetic vision display were able to verify the ADS-B mobile target and other airborne local area traffic received by the onboard ADS-B system.

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Keywords: Air transportation and safety; Aircraft communications and navigation; Aircraft design; Testing and performance

1. Introduction

The National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (Edwards, California) has a long history of aeronautics research and more recently in the realm of unmanned aircraft systems (UASs). As a result, this research evaluates the ADS-B Out airworthiness certification standards applied for UASs, which are a prerequisite for commercial operations in the National Airspace System (NAS). This paper presents a system architecture that integrates Automatic Dependence Surveillance Broadcast (ADS-B) surveillance technology to an unmanned aircraft system (NASA Ikhana MQ-9 Predator B (General Atomics Aeronautical Systems Incorporated, San Diego, California)), with improved communications and sophisticated display capabilities to provide increased situational awareness and a self-separation assurance system. This increased situational and traffic awareness is a preeminent attribute for successful UAS operations and greatly improves safety for the UAS, other manned aircraft in the area, and nearby ground facilities and personnel.

ADS-B is a novel technology which promises to greatly improve air traffic safety and efficiency, especially in the realm of UASs. Current UASs provide only visual information to the pilot, depriving the crewmembers of seat of the pants sensory information. Due to the diminished (loss of four of the five senses) situational awareness capabilities of the UAS operators, a method for displaying relevant information pertaining to both vehicle ownship and the surrounding air traffic is highly desirable. By the year 2020, the Federal Aviation Administration (FAA) has mandated that aircraft operating within certain airspaces of the NAS be equipped with ADS-B Out technology. This novel ADS-B system is part of the Next Generation Air Transportation System (NextGen) and promises to significantly improve the safety and capacity of the NAS. ADS-B uses highly accurate Global Positioning System (GPS) signals to track aircraft, instead of relying on decades old radar technology. Perhaps one of the most exciting applications of ADS-B technology is in the realm of UASs. With the emergence of UASs, there is an increasing safety risk to these aircraft as well as others that may be operating in the same airspace. Due to the absence of an on-board pilot, these vehicles suffer from decreased situational awareness to their surroundings making proximate operations to manned vehicles oftentimes challenging. The integration of ADS-B technology into such UASs will undoubtedly change the existing flight operations paradigm for these vehicles within the NAS.

Nomenclature

The following is a list of acronyms used, which are used throughout the description of the ADS-B system:

AC	Advisory Circular (FAA)
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-R	Automatic Dependent Surveillance-Re-Broadcast
APM	Aircraft Personality Module
ARSB	Airworthiness and Safety Review Board
CDAT	Common Data Analysis Tool
COTS	commercial off the shelf
DGPS	Differential Global Positioning System
FAA	Federal Aviation Administration
FMS	Flight Monitor Server
GCS	ground control station

GPI	Generic Payload Interface
GPS	Global Positioning System
GVA	geometric vertical accuracy
HFOM	Horizontal Figure of Merit
HPL	Horizontal Protection Limit
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
ID	identification
MHz	megahertz
MOPS	Minimum Operation Performance Standards
NACp	Navigation Accuracy Category Position
NACv	Navigation Accuracy Category Velocity
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NIC	Navigation Integrity Category
RF	radio frequency
RTTS	Real-Time Tracking Surveillance
SIL	Surveillance Integrity Level
SDA	System Design Assurance
SDP	Surveillance Delivery Point
TIS-B	Traffic Information Services-Broadcast
TSO	Technical Standard Order
UAS	Unmanned Aircraft System
UAT	Universal Access Transceiver
WAAS	Wide Area Augmentation System
WGS-84	World Geodetic System 1984

2. System Background

The present invention proposes an ADS-B system coupled to an unmanned aircraft system for increased situational awareness and self-separation assurance to avoid accidents. The invention proposes an ADS-B architecture and process, in which priority aircraft and ADS-B IN traffic information are included in the transmission of data through the telemetry communications to a remote ground control station. The invention further proposes methods for displaying general aviation traffic information in three and/or four dimension trajectories using an industry standard Earth browser for increased situation awareness and enhanced visual acquisition of traffic for conflict detection.

2.1. ADS-B Out System Architecture for Unmanned Vehicles

ADS-B is a surveillance technique which provides traffic surveillance and flight information by using air-to-air or air-to-ground data communications. The ADS-B system architecture coupled to a UAS combines surveillance, communication data-links, and algorithms to generate traffic alerting and displaying that information on a synthetic vision display. The ADS-B Out surveillance system provides automatic broadcasts of position, identity, altitude, and velocity information (ADS-B Out) on the 978 MHz frequency. The ADS-B universal access transceiver (UAT) functionality works on the 978 MHz frequency, which provides weather and traffic surveillance information to the UAS. In this specific application, the heart of the Ikhana ADS-B system is Garmin's GDL 90 (Garmin International Inc., Olathe, Kansas), which is an ADS-B transceiver that broadcasts ownship status information and receives traffic reports for up to thirty-two proximate targets. Connected to the GDL 90 are a GPS/Wide Area Augmentation System (WAAS) antenna and UAT antennas. The GPS/WAAS antenna is connected to the UAT built-in 15-channel GPS/WAAS receiver and enables the system to receive the ownship position and velocity state information, while the UAT antennas broadcast/receive ADS-B information on the 978 MHz frequency. ADS-B message packets are transmitted via telemetry from the GDL 90 to the ground control station (GCS) ADS-B laptop computer, which contains the 3D synthetic display, and the GSL 71 (Garmin International Inc., Olathe, Kansas), which provides simple system controls. The GSL 71 provides the pilot input to control the GDL 90 for squawk code transmission. Other system components include a barometric altitude encoder, which is connected to the GDL 90 and allows display of barometric altitude, and an Aircraft Personality Module (APM), which is accessed upon system initialization to instate pre-programmed aircraft configuration GDL 90 system settings.[1] Refer to Fig. 1.

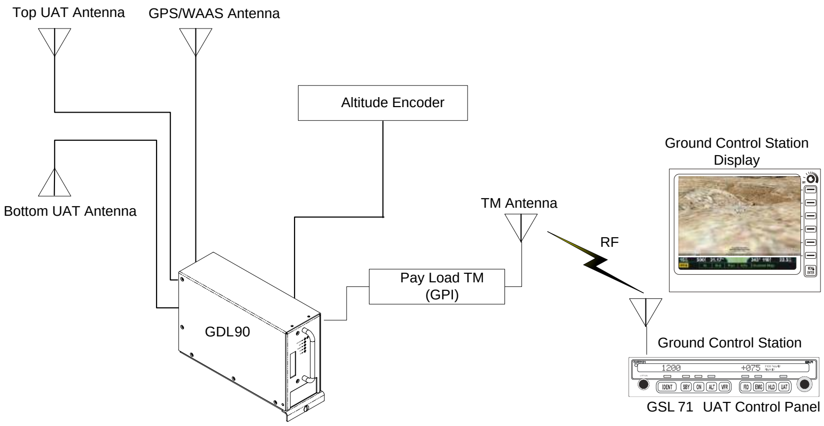

Fig. 1. ADS-B Out system architecture (Patent filed March 5, 2013; Serial No. 13/785,661).[2]

2.2. ADS-B In System Architecture for Unmanned Vehicles

The ADS-B In system architecture is described by the block diagram in Fig. 2. The UAT is inherently capable of ADS-B-In reception of air-to-air ADS-B messages direct from aircraft nearby and air-to-ground ADS-B/Automatic Dependent Surveillance-Re-Broadcast (ADS-R)/Traffic Information Services-Broadcast (TIS-B) messages from ADS-B ground based transceiver(s), though it is not inherently configured to re-transmit them. In accordance with the present invention, the air-to-air ADS-B In messages from aircraft nearby, and air-to-ground ADS-R and TIS-B messages from ADS-B ground based transceiver(s) are received and processed from encoded ADS-B Out transmission of other aircraft. More specifically as seen in Fig. 2, the ADS-B In messages are received by the UAT via UAT antennas and are processed by the UAT as ADS-B/ ADS-R / TIS-B message reports. These ADS-B In message reports are temporarily stored by the UAT receiver, are encoded in the packet-based ADS-B messages, and are sent via serial asynchronous communications to the GCS. In general, the serial order sequence is ADS-B out ownship messages, which are sent and then followed by ADS-B In traffic message reports. The UAT is reprogrammed to do this for ADS-B Out/In by enabling both transmit and receive during initial setup installation using the provided instrument programming interface. Thus, the UAS ADS-B Out UAT transceiver effectively transmits not just the ownship UAS discretes, but also other surrounding priority aircraft and ADS-B In traffic information, all in “consolidated” ADS–B message reports. In this way the GCS has all the ADS-B data in one downlink. The UAS-to-GCS downlink message is designed to 1 Hz to provide enough information regarding the aircraft state and traffic data to give the GCS operator good situational awareness on the ADS-B In display. The ADS-B In synthetic vision display and software was developed in-house by NASA Dryden Flight Research Center for the visualization of the Ikhana ownship and surveillance traffic using the protocols of aircraft telemetry. A novel algorithm provides traffic situational awareness and alerting of potential collisions or hazardous traffic situations. Automatic traffic alerts are generated based on separation and collision zones surrounding the aircraft, respectively. This effort was necessary, since most ADS-B commercial displays are wired and operate only on manned aircraft, and therefore would not work using the limited bandwidth constraints and interface requirements of the UAS radio telemetry communications.

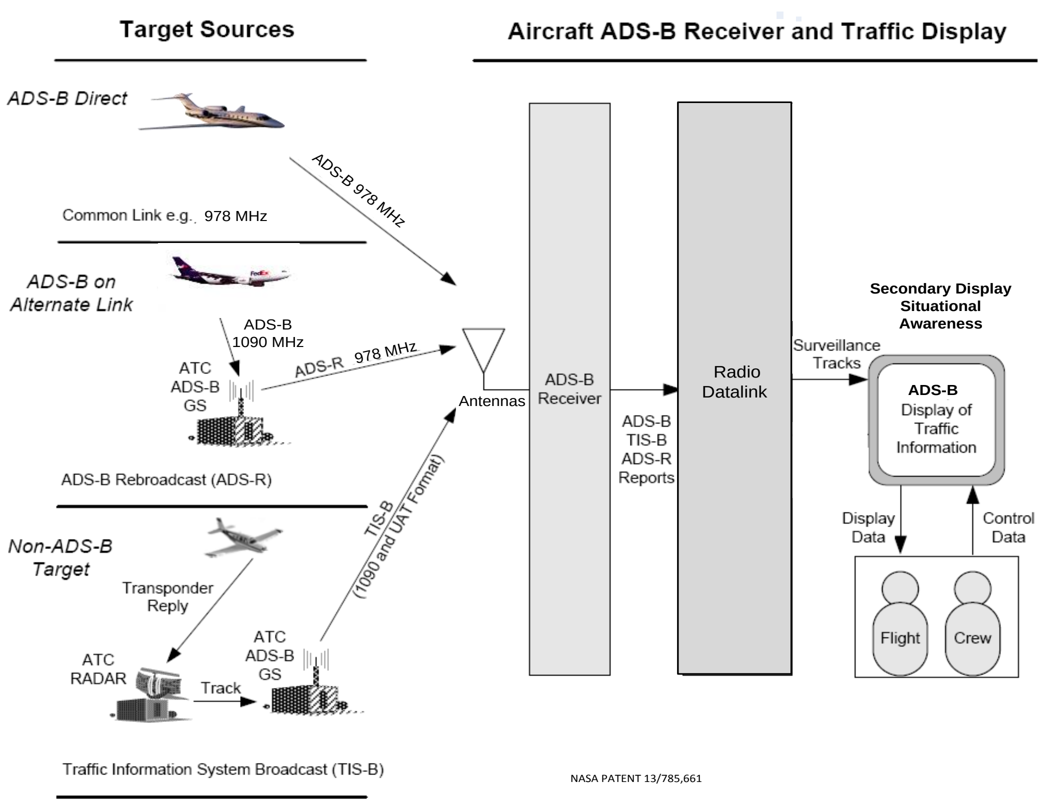

Fig. 2. ADS-B In system architecture (Patent filed March 5, 2013; Serial No. 13/785,661).[2]

3. Flight Test System

Due to the need for continuous software development, it was necessary to have a means of testing and debugging source code prior to flight testing to ensure nominal operation. To achieve this, both the NASA Research Instrumentation Laboratory (Dryden Flight Research Center, Edwards, California) and a mobile ADS-B test van were employed since they offered easy accessibility and a controlled environment at minimal cost. Accessibility to the Ikhana test aircraft was limited.

The Research Instrumentation Laboratory proved to be an excellent environment for testing and debugging source code; however, the absence of a UAT antenna severely limited ADS-B In testing capabilities. To overcome this deficiency, all ADS-B equipment was transferred into a NASA utility mobile van where both a GPS/WAAS and UAT antennas were installed on the roof of the vehicle. Power was supplied using a commercial inverter, which allowed for full system mobility. Furthermore, using local cell phone networks, a mobile hot spot was generated for allowing the Google Earth (Google Inc., Mountain View, California) browser unlimited internet access anywhere on the NASA site. Although several minor bugs were observed while the code was executing, which were later fixed, the traffic data was nevertheless received and successfully interpreted by the software. Ownship broadcast functionality (ADS-B Out) was also verified via direct contact with an employee at the FAA tech center in New Jersey. The FAA witnessed and supported all ground tests and collected data for post-data analysis using the Common Data Analysis Tool (CDAT).

3.1. Test Van Vehicle

To conduct flight tests an ADS-B system was installed in a mobile van (Fig. 3). The ADS-B mobile test van served as a software development platform as well as ground surveillance traffic. The test van was used for several days which allowed sufficient time to debug all major run-time anomalies. The test van also served as a test target aircraft when performing the combined system test procedure for Ikhana. The ADS-B parameter elements such as International Civil Aviation Organization (ICAO) address, emitter category, and call-sign were all changed to correspond to a recently decommissioned NASA F/A-18 (McDonnell Douglass, now The Boeing Company, Chicago, Illinois) as the transmitting test target. The ADS-B telemetry data was monitored from the ADS-B laptop connected to the Ikhana GCS. The system performed optimally for a stationary and moving target and was cleared for the first ADS-B In flight scheduled to take place May 8, 2012.

Fig 3. ADS-B mobile van (Photo courtesy: NASA/Ricardo Arteaga).

3.2. Test Aircraft Platform

The platform vehicle used for system testing was NASA’s Ikhana (MQ-9) Predator-B (Fig. 4). Garmin’s ADS-B capable GDL 90 was installed in the forward avionics bay. As a semi-autonomous UAS, all data from the GDL 90 unit required radio frequency (RF) transmission to the ground control station via the Generic Payload Interface (GPI) communications link of the aircraft. The installation of additional NASA proprietary equipment was necessary to convert between the data communication protocols of the ADS-B UAT unit and the UAS serial telemetry protocols for proper RF communications. The installation of an onboard Ashtech (Ashtech OEM, Sunnyvale, California) Differential Global Positioning System (DGPS) unit served as a truth reference source for post flight data analysis. ADS-B was installed on the Ikhana per the Ikhana ADS-B Interface Control Document (ICD)[3] with the primary purpose of complying with the design requirements for ADS-B Out using Advisory Circular (AC-20-165)[4] and for ADS-B In using (AC-20-172A).[5] The AC-20-165 Airworthiness Approval of Automatic Dependent Surveillance-Broadcast (ADS-B) Out System requirements were tailored for unmanned aircraft systems.

Fig. 4. Ikhana MQ-9 unmanned vehicle (NASA photo ED12-0082-22).

4. Flight Testing

Although ground testing is essential for testing and debugging both hardware and software, flight testing is ultimately necessary for demonstrating the full ADS-B system functionality. A flight-test procedure for demonstrating ADS-B Out/In was developed and approved by the NASA Dryden Airworthiness and Safety Review Board (ASRB). The flight-test objective for ADS-B Out was to evaluate the performance of the ADS-B system as installed on the Ikhana MQ-9 UAS per the FAA airworthiness certification requirements. The flight-test objective for ADS-B Out/In was to demonstrate the ADS-B In functionality in addition to the ADS-B Out on the Ikhana MQ-9 UAS. Currently, two successful flight tests have been performed using the ADS-B Out configuration and two successful flights have been performed in the ADS-B Out/In configuration. Refer to Figs. 1 and 2 respectively.

The above-described ADS-B system coupled to an unmanned aircraft system was deployed and tested on an Ikhana Predator-B UAS. For flight testing all data-link transmission to the GCS took place over the GPI telemetry link. The FAA Flight Monitor Server (FMS) located at the William J. Hughes Technical Center (Atlantic City International Airport, New Jersey) monitored and recorded the flights. Further, the FMS multi-streamed ADS-B data were received during flight as backup by the Real-Time Tracking Surveillance (RTTS) client resident on the ADS-B laptop in the GCS. The FAA monitored all flights and collected data for post-flight analysis.

Prior to the first ADS-B Out flight, corrupted data over the data-link of the aircraft were occurring due to RS-422 wiring issues, which were finally resolved after the fifth re-wiring correction. The second data-link problem manifested in corrupted data over the radio telemetry, which occurred due to overloading the limited bandwidth with too much weather and traffic data. In order to simplify the problem, the ADS-B In functionality and the weather data were disabled. After the first two successful ADS-B Out flights, modifications were made to the GDL 90 to the passive configuration mode, which enabled ADS-B In and disabled weather data altogether with minor software modifications to the display the system finally worked. The real-time weather data were received by the display as network-link data stream over the internet.

4.1. Flight 1

NASA Dryden Flight Research Center flew its Ikhana MQ-9 unmanned aircraft with an ADS-B device on March 15, 2012. It was the first time an unmanned aircraft as large as Ikhana (with a 66-foot wingspan, a takeoff weight of more than 10,000 pounds, and a cruising altitude of 40,000 ft MSL) had successfully flown with ADS-B.[6]

Only the ADS-B Out functionality was enabled since ADS-B In traffic telemetry processing logic had not yet been incorporated into the software. The flight lasted approximately 2.5 hours with both hardware and software operating nominally. The aircraft performed several maneuvers designed to evaluate the performance and stability of the system. The flight profile from this test can be seen in Fig. 5.

Fig. 5. Flight profile from March 15, 2012 (Figure 5 is taken from the FAA flight analysis report and is not inserted because permission to publish is being sought from the Federal Aviation Administration).

According to an analysis report issued by the FAA, the ADS-B system on Ikhana performed exceptionally well, easily exceeding the mandated requirements. These ADS-B Out performance requirements can be seen in Table 1.

Table 1. FAA mandated accuracy and integrity requirements.[4]

Parameter	Requirement	Accuracy
NIC	≥ 7	Rc < 370.4 m (0.2 nm)
NAC_P	≥ 8	EPU < 92.6 m (0.05 nm)
NAC_V	≥ 1	< 10 m/s
SIL	≥ 3	≤ $1x10^{-7}$ per hour or sample
SDA	≥ 2	≤ $1x10^{-5}$ per hour

- Navigation Integrity Containment (NIC): express the integrity containment radius.
- Navigation Accuracy Category (NACp): express the position accuracy in levels.
- Navigation Accuracy Category (NACv): express the velocity accuracy in levels
- Surveillance Integrity Level (SIL): specify the probability of the true position lying outside that containment radius without alerting.
- System Design Assurance (SDA): indicates the probability of an ADS-B system malfunction causing false or misleading position information.

A summary of the pertinent results is found in Table 2. To view the raw data history, the reader is referenced to Appendix A (The Appendix is expected to be included in the final version of this paper. Permission to publish is being sought from the Federal Aviation Administration).

Table 2. Flight 1 ADS-B OUT performance data.

Total Messages Received: 9,089				
Parameter	Minimum	Maximum	Average	Standard Deviation
Horizontal Position Error (ft)	0.0000	98.2234	5.7353	3.1437
Horizontal Velocity Error (ft/s)	0.0000	4.5783	0.5301	0.4061
Geometric Altitude Error (ft)	0.0000	275.8803	11.3386	17.1549

Horizontal Figure of Merit (HFOM) denotes the accuracy of the horizontal position information from GPS. HFOM is an accuracy figure, which represents the radius of a circle that is centered on the GPS position solution, and is guaranteed to contain the true position of the receiver to within a certain probability (usually a 95% confidence level).

Horizontal Protection Limit (HPL) is the expression for the integrity of the horizontal position from GPS systems. HPL is an integrity figure which represents the radius of a circle that is centered on the GPS position solution, and is guaranteed to contain the true position of the receiver to within a certain probability (usually 10^{-7}), as shown in Fig. 6.

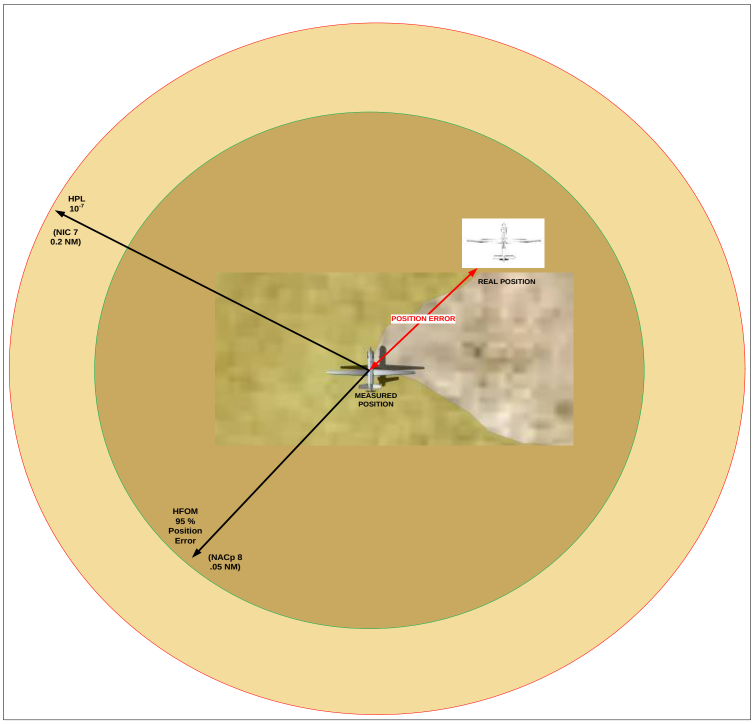

Fig. 6. HFOM and HPL.

From Table 2, it can be seen that the system performed exceptionally well. Referencing Table 1, it can be observed that the NAC_P output must have at least a value of 8, corresponding to a HFOM of less than 304 ft (0.05 nautical miles). Comparing this required value to those provided by the FAA in the (proposed) Appendix A, it can clearly be seen that the requirement is exceeded throughout the entire flight. Traditionally, the measurement errors are modeled as Gaussian distribution random variables. The results of horizontal position accuracy measured a $\mu = 5.7$ ft, $\sigma = 3.1$ ft, which in mathematical notation $\Pr(x \leq \mu+2\sigma) \approx .954$ ($x \leq 11.9$ ft) exceeds the required position accuracy of HFOM (304 ft with probability of 95%).

Referencing Table 1, the NIC level of 7 corresponds to a HPL of less than 1,215 ft ($R_c \leq 0.2$ nautical miles). Upon examination of the raw flight data (maximum 98.2 ft), the system was well within mandated standards (maximum radius of containment) throughout the entirety of the flight. Similarly, for the required NAC_V of 1, the velocity error must be less than 32.81 ft/s (10 m/s). Again, observing the raw data history, it can be seen that this requirement was easily met throughout most of the flight.

The geometric altitude is a measure of height above the WGS-84 ellipsoid and is required to be transmitted by 14 CFR § 91.227.[4] In general, the geometric altitude error measured a $\mu = 11.3$ ft, $\sigma = 17.1$ ft or $\Pr(y \leq \mu+2\sigma) \approx .954$ ($y \leq 45$ ft). Although geometric vertical accuracy (GVA) is not required in DO-282A it will be required for DO-282B.[7] For example, DO-282B specifies a GVA with encoded value 2 corresponds to geometric vertical accuracy (95% accuracy bound) of 45 meters or less. Therefore, the geometric altitude error herein is provided as purely supplemental data.

Finally, the analysis must ensure that the Ikhana ADS-B transmitted position is within the allotted NAC_p accuracy limit. For example, if the aircraft reports a NACp =10 the ADS-B transmitted position should be within 10 meters. During flight the ADS-B transmitted parameters values of NACp= 10 and NIC=10 per the FAA Service Delivery Point (SDP) recorded CAT-33 data. Once more, the results illustrate (Fig. 7) the horizontal position accuracy was well within the reported NACp =10 (<10 meters 95% accuracy). Based on the aforementioned analysis, it is concluded that the ADS-B system as installed on the Ikhana MQ-9 and the requirements for indicating integrity and accuracy have been successfully met.

Fig. 7. Horizontal Position Accuracy (Figure 7 is taken from the FAA flight analysis report and is not inserted because permission to publish is being sought from the Federal Aviation Administration).

It should be noted that the proposed ADS-B architecture in Fig. 1 is a compliant architecture. ADS-B equipment meeting the minimum performance requirements of TSO-C154c[8] (i.e. GDL 90) that is directly connected to a position source that meets the minimum performance requirements of TSO-C145, is defined as a compliant architecture by AC20-165 and may set the SDA = 2 without further analysis.[4]

It should be noted that the proposed ADS-B hardware in Fig. 1 complies with TSOs C154c and C145a. Per the AC20-165 guidance, installations which derive SIL from GPS position sources compliant with any revision of TSO-C145, which output Horizontal Protection Level (HPL) or Horizontal Integrity Level (HIL), should set the SIL = 3 because HPL and HIL are based on a probability of $1x10^{-7}$ per hour.[4]

It is worth noting that several minor run-time anomalies were detected within the software. However, these anomalies were in no way critical to the system performance itself and did not degrade from the overall success of the mission. The errors were later addressed, thus fully preparing the software for the next flight.

4.2. Flight 2

The second ADS-B flight took place on March 20, 2012, and was once again highly successful. Again, only ADS-B Out functionality was enabled. The aircraft performed several maneuvers which differed from those executed in flight 1, and both hardware and software operated nominally, which was expected. The flight profile from this test can be seen in Fig. 8.

Fig. 8. Flight profile from March 20, 2012 (Figure 8 is taken from the FAA flight analysis report and is not inserted because permission to publish is being sought from the Federal Aviation Administration).

Much the same as the flight on March 15, 2012, the ADS-B system performed well above minimum requirements. The summarized data are presented in Table 3. From the analysis, it is clear that ADS-B performed exceptionally well throughout the entire flight and during the planned maneuvers.

Table 3. Flight 2 ADS-B performance data.

Total Messages Received: 8,262				
Parameter	Minimum	Maximum	Average	Standard Deviation
Horizontal Position Error (ft)	0.0000	54.0780	5.5933	3.4831
Horizontal Velocity Error (ft/s)	0.0000	6.4593	0.5568	0.5301
Geometric Altitude Error (ft)	0.0000	112.7048	11.8404	17.3622

Using the same analysis method as in Section 4.1, it can be seen that the system overall displayed similar performance to that of the first flight (Fig. 9). It is also noted that no run-time anomalies or hardware failures were observed, and the system performed optimally.

Fig. 9. Horizontal position accuracy (Figure 9 is taken from the FAA flight analysis report and is not inserted because permission to publish is being sought from the Federal Aviation Administration).

Analysis of the ADS-B transmitted barometric altitude met the required performance accuracy of ±125 ft from the Mode C transponder altitude. The FAA airworthiness guidelines, however, state that the barometric altitude source should be the same for a transponder and an ADS-B unit,[4] so using the same static port was justified. It should be noted that the functional requirement derived from the using same source guideline for the Mode C transponder was not feasible because of the proprietary interfaces of General Atomics. The added altitude encoder was therefore calibrated to match the existing Mode C transponder. Results computed from 583 radar reports are shown in Fig. 10 with altitude errors centered around zero.

Fig. 10. Barometric altitude accuracy (Figure 10 is taken from the FAA flight analysis report and is not inserted because permission to publish is being sought from the Federal Aviation Administration).

4.3. Flight 3

On May 8, 2012, the team was the first to install and fly an ADS-B system on a large unmanned aircraft and downlink its output, including both ownship information and surrounding live air traffic, to a ground control station. The flight-test objective was to demonstrate the ADS-B In functionality in addition to the ADS-B Out on an unmanned aircraft system. A secondary objective was to complete a proof-of-concept flight of the display system. The ADS-B surveillance sensor information flows to the ADS-B laptop display via radio frequency telemetry to the GCS. This ADS-B display is a unique traffic display configuration for aviation, and is applicable to depicting traffic on an exocentric (God's-Eye) or egocentric (forward looking) synthetic vision display. The ADS-B display design provides traffic information in three and four dimensions at the GCS using an industry standard Earth browser for the visual acquisition of traffic and situational awareness; and for consolidating the above-mentioned display with weather, restricted airspace, and satellite imagery information for hazard avoidance. The ADS-B display application is designed to support basic situational awareness. The ADS-B display design has the capability to track and identify in real time various aircraft up to a maximum of thirty-two surveillance targets, using the guidelines set forth in AC 20-172A.[5]

The ADS-B In reception performance was evaluated by the ability to track the ADS-B mobile van throughout the entire flight. The capacity to track ADS-B and TIS-B targets were evaluated as targets of opportunity, which were correlated with an FAA RTTS display. The mobile van system was transmitting state parameters (position, velocity, and heading) and supplying them to the ADS-B data link. The surveyed position and state parameters of the FAA van target were known *a priori*, which properly correlated with the positional information as well as other surveillance identification information displayed during flight. A scenario for moving the two mobile ADS-B vehicles on the ground was also evaluated during flight for track correlation and identification. Both targets were successfully identified and tracked from altitudes of 30,000 ft MSL. Researchers found the situational awareness of the display to be more useful in tracking air traffic when using the exocentric (God's-Eye) view. During the flight demonstration, the ADS-B display was able to track as many as seventeen real-time ADS-B and TIS-B targets. The validation of the ADS-B In system receiving ADS-B/TIS-B traffic state data was successfully demonstrated. As stated above, the FAA monitored all flights and collected data for post-flight analysis.

4.4. Flight 4

On May 11, 2012, the Ikhana flew a training flight with FAA pilots, and the ADS-B In surveillance data were recorded. The playback of the flight data is shown in Fig. 11, indicating a total traffic count of seventeen surveillance targets. The stationary mobile van over a surveyed geodetic point was the only known ADS-B target. The state parameters of the FAA van target were known *a priori*, which properly correlated with the positional information as well as other surveillance information displayed. During UAS operations it is necessary to convey information regarding the aircraft that pose traffic threats as well as the information necessary to navigate the ownship. This research effort combined an ADS-B system adapted for use in a UAS with a prototype display designed for ADS-B traffic information and alerting to provide increased situational awareness. The secondary objective to complete a proof-of-concept flight of the display system was successfully demonstrated. In general, the flight evaluations verified that the system receives and displays the following traffic information for targets of opportunity (Fig. 11):

- Relative horizontal position
- Ground speed
- Directionality (Heading or Track Angle)
- Pressure altitude of airborne traffic relative to ownship
- Vertical trend of airborne traffic

- Air/Ground status of other aircraft
- Flight ID (ICAO code)

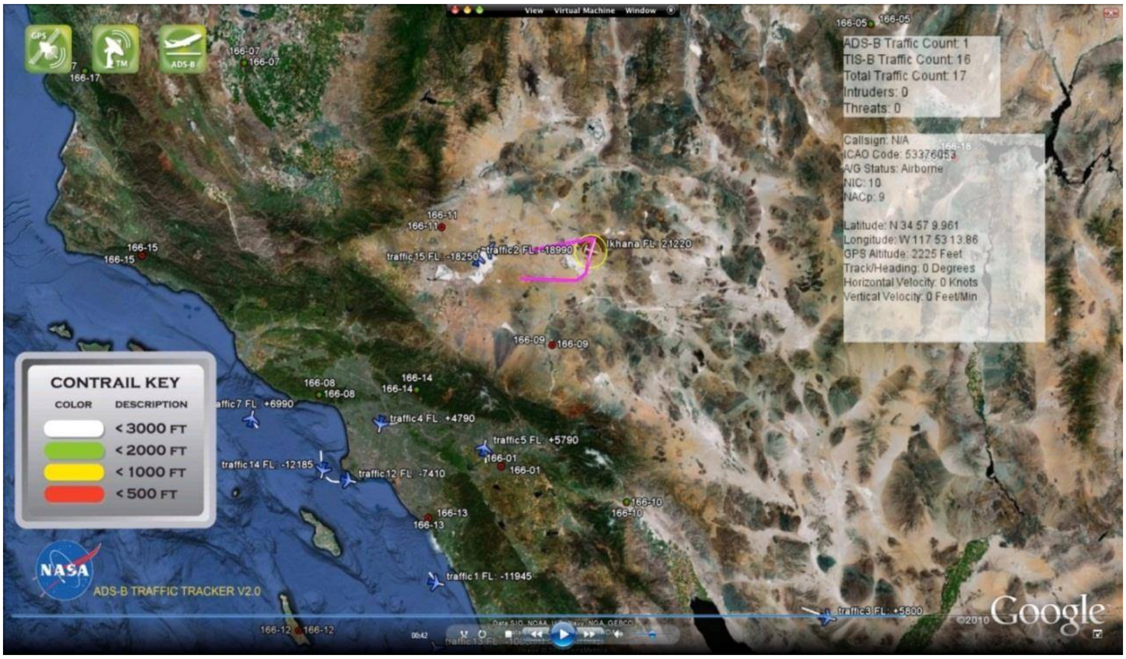

Fig. 11. ADS-B In traffic from May 11, 2012 (Patent filed March 5, 2013; Serial No. 13/785,661).[2]

The ADS-B display is depicted in Fig. 11, with runways and taxiways, and ADS-B/TIS-B traffic on a plan view (God's-Eye view) relative to ownship. The ADS-B ground stations (red dots) symbology and real time weather (NEXRAD Doppler) fit seamlessly with the display. UAS operators can control the zoom from ground-level to suborbital views and spatially orient to any three-dimensional view using pan/tilt.

4.5. Lessons Learned

The lessons learned from the ADS-B flight tests (Fig. 12) is that integrating with a UAS proprietary radio data-link is challenging. Lessons learned include:

- Simplify, simplify, simplify, don’t try to get it totally right the first time.
- Incrementally integrate the ADS-B Out and ADS-B In capability.
- The use of a mobile ADS-B van for software and hardware integration significantly reduces risk and was used as a mitigation strategy.

Fig. 12. Ikhana MQ-9 prior to first ADS-B flight (NASA photo ED12-0082-17).

5. Conclusion

The UAS in the NAS project has demonstrated that an adapted ADS-B system coupled to a UAS has successfully met the ADS-B Out airworthiness certification requirements, which are a prerequisite for commercial operations in the NAS. It has also been shown that an adapted ADS-B system suitable for use on a UAS with ADS-B In capability can increase situational awareness for self-separation assurance. To increase situational awareness of UAS pilots, a novel system for displaying ownship and ADS-B traffic information has been developed. Increased situational and traffic awareness is a preeminent attribute for successful UAS operations and greatly improves safety for the UAS.[9]

The platform used for system testing was NASA's Ikhana Predator-B with Garmin's ADS-B capable GDL 90 installed in the forward avionics bay. Due to the absence of an on-board pilot, all data from the unit required RF transmission to the ground station via the aircraft's GPI link. A series of hardware and software ground tests were performed for system validation. For ADS-B Out testing, the instrumentation laboratory was used due to the availability of a GPS connection. A mobile test van was later used for ADS-B In testing since it enabled the use of a UAT antenna for the reception of real-time traffic. During this ADS-B integration on a UAS development, considerable time and effort went into solving problems with radio data-link, and the lesson learned was to incrementally integrate the ADS-B Out and In capability.

Currently, the system has undergone two highly successful flights, one on March 15, 2012, and the other on March 20, 2012. It was the first time an unmanned aircraft as large as Ikhana has flown while equipped with ADS-B. Only ADS-B Out functionality was enabled, and the system performed nominally in both cases. Further, the FAA monitored both flights and collected data for post-flight analysis. After viewing the results, it was found that the hardware performed exceptionally well, with error rates and magnitudes far below the mandated requirements.

Furthermore, the system has undergone two additional successful follow-up flights, one on May 8, 2012, and the other on May 11, 2012. Both flights validated successful operation of ADS-B In and ultimately the system as a whole. These results have demonstrated that UAS integration into the NAS can be efficiently accomplished when equipped with an integrated ADS-B system.

In conclusion, this flight-test report introduced the fundamentals of ADS-B, designed an innovative ADS-B system based on UAT 978MHz, analyzed the airworthiness requirements and industry standards which guided the design and development unique to Unmanned Aircraft Systems, and presented the flight-test results. With the emergence of unmanned aircraft systems (UASs), there is an increasing safety risk to these aircraft as well as others that may be operating in the same airspace. NASA will continue further research with flight tests and operational demonstrations on one or more UAS aircraft equipped with ADS-B technology to determine its suitability to provide aircraft separation assurance.

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Appendix A. FAA-NASA Dryden Flight Test Report

(The Appendix is expected to be included in the final version of this paper. Permission to publish is being sought from the Federal Aviation Administration)

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APPENDIX A

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