µADS-B Detect and Avoid Flight Tests on Phantom 4 Unmanned Aircraft System

Ricardo Arteaga,[1] and Mike Dandachy[2]
NASA Armstrong Flight Research Center, Edwards, California 93523

Hong Truong[3]
University of California Davis, Davis, California 95616

Arun Aruljothi[4]
Stevens Institute of Technology, Hoboken, New Jersey 07030

Mihir Vedantam[5]
University of Kansas, Lawrence, Kansas 66045

Kraettli Epperson,[6] and Reed McCartney[7]
Vigilant Aerospace Systems, Inc., Oklahoma City, Oklahoma 73134

Researchers at the National Aeronautics and Space Administration Armstrong Flight Research Center in Edwards, California and Vigilant Aerospace Systems collaborated for the flight-test demonstration of an Automatic Dependent Surveillance-Broadcast based collision avoidance technology on a small unmanned aircraft system equipped with the uAvionix Automatic Dependent Surveillance-Broadcast transponder. The purpose of the testing was to demonstrate that National Aeronautics and Space Administration / Vigilant software and algorithms, commercialized as the FlightHorizon UAS™, are compatible with uAvionix hardware systems and the DJI Phantom 4 small unmanned aircraft system. The testing and demonstrations were necessary for both parties to further develop and certify the technology in three key areas: flights beyond visual line of sight, collision avoidance, and autonomous operations. The National Aeronautics and Space Administration and Vigilant Aerospace Systems have developed and successfully flight-tested an Automatic Dependent Surveillance-Broadcast Detect and Avoid system on the Phantom 4 small unmanned aircraft system. The Automatic Dependent Surveillance-Broadcast Detect and Avoid system architecture is especially suited for small unmanned aircraft systems because it integrates: 1) miniaturized Automatic Dependent Surveillance-Broadcast hardware; 2) radio data-link communications; 3) software algorithms for real-time Automatic Dependent Surveillance-Broadcast data integration, conflict detection, and alerting; and 4) a synthetic vision display using a fully-integrated National Aeronautics and Space Administration geobrowser for three dimensional graphical representations for ownship and air traffic situational awareness. The flight-test objectives were to evaluate the performance of Automatic Dependent Surveillance-Broadcast Detect and Avoid collision avoidance technology as installed on two small unmanned aircraft systems. In December 2016, four flight tests were conducted at Edwards Air Force Base. Researchers in the ground control station looking at displays were able to verify the Automatic Dependent Surveillance-Broadcast target detection and collision avoidance resolutions.

[1] Systems Engineer, Sensors & Systems Development Branch, non-member.
[2] Systems Engineer, Vehicle Integration & Test Branch, non-member.
[3] Intern, Sensors & Systems Development Branch, Student Member.
[4] Intern, Sensors & Systems Development Branch, Student Member.
[5] Intern, Sensors & Systems Development Branch, Student Member.
[6] Chief Exceutive Officer, Vigilant Aerospace Systems, Inc., non-member.
[7] Software Engineer, Vigilant Aerospace Systems, Inc., non-member.

U.S. Patent No. 9,405,005

Further, a Federal Aviation Administration representative witnessed the flight-test execution of beyond line-of-sight encounter geometries and collision avoidance resolutions of small unmanned aircraft sytems.

Nomenclature

AC	=	advisory circular (FAA)
ADS-B	=	Automatic Dependent Surveillance-Broadcast
AFSRB	=	Airworthiness and Flight Safety Review Board
API	=	application program interface
APP	=	application
BVLOS	=	beyond visual line of sight
CPA	=	closest point of approach
DAA	=	Detect and Avoid
DJI	=	Dà-Jiāng Innovations Science and Technology Co., Ltd., Shenzhen, China
FAA	=	Federal Aviation Administration
FEMA	=	Federal Emergency Management Agency
FPV	=	first-person view
GA	=	general aviation
GCS	=	ground control station
GPS	=	Global Positioning System
ICAO	=	International Civil Aviation Organization, Montreal, Quebec, Canada
ID	=	identification
IP	=	initial point
NAS	=	National Airspace System
NASA	=	National Aeronautics and Space Administration
NextGen	=	Next Generation Air Transportation System
NMAC	=	Near-Mid-Air-Collision
RAs	=	Resolution Advisories
RF	=	radio frequency
SDK	=	software development kit
SUAS	=	small unmanned aircraft system
TAs	=	traffic advisories
tCPA	=	time to closest point of approach
tL	=	look ahead time
UAS	=	unmanned aircraft system
UAT	=	universal access transceiver
UAVs	=	unmanned aircraft vehicles

I. Introduction

THE National Aeronautics and Space Administration (NASA) Armstrong 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 Automatic Dependent Surveillance-Broadcast (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 ADS-B and Detect and Avoid (DAA) technology into a small unmanned aircraft system (SUAS), with improved communications and display capabilities to provide increased situational awareness and a self-separation strategy during beyond visual line of sight (BVLOS) operations. This increased situational and traffic awareness is vital for successful SUAS operations and greatly improves safety for the SUAS, 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. The Federal Aviation Administration (FAA) has mandated by the year 2020 that aircraft operating within certain airspaces of the NAS be equipped with ADS-B Out technology [1]. This 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 SUASs. With the emergence of SUASs, 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 of their surroundings making proximate operations to manned vehicles oftentimes challenging. The integration of miniaturized ADS-B DAA technology into such SUASs will undoubtedly improve the existing flight operations paradigm for these vehicles within the NAS.

II. Systems Background

This research used an ADS-B DAA system coupled to a SUAS for detect and avoid capability to avoid accidents. The system utilized a Micro Avionics Ping2020 ADS-B transponder (uAvionix Corporation, Bigfork, Montana) and methods that allow a drone to sense surrounding aircraft and initiate collision avoidance maneuvers based on detected traffic information. The research further used methods for displaying general aviation traffic information in three and/or four dimensional trajectories using an industry standard Earth browser for increased situational awareness and enhanced visual acquisition of traffic for conflict detection and avoidance.

The evolution of autonomous systems will transform aviation operations, providing improvements in safety, efficiency, and flexibility of operations to increase the capacity, robustness, and flexibility of the NAS. Additional benefits will be realized through new uses of the airspace, enabled by advances in UAS operations such as full autonomy. The outcome of this technology will impact the initial autonomy applications in the near-term decade and will see initial integration of UAS capabilities into the NAS, as well as the proliferation of autonomous systems technologies within the aviation infrastructure. Operations of small, highly automated or autonomous vehicles within specially designated areas, as well as integration with more conventional aviation operations where appropriate, will address public, scientific, government, and commercial needs and maximize the benefits of aviation to society (refer to Fig. 1).

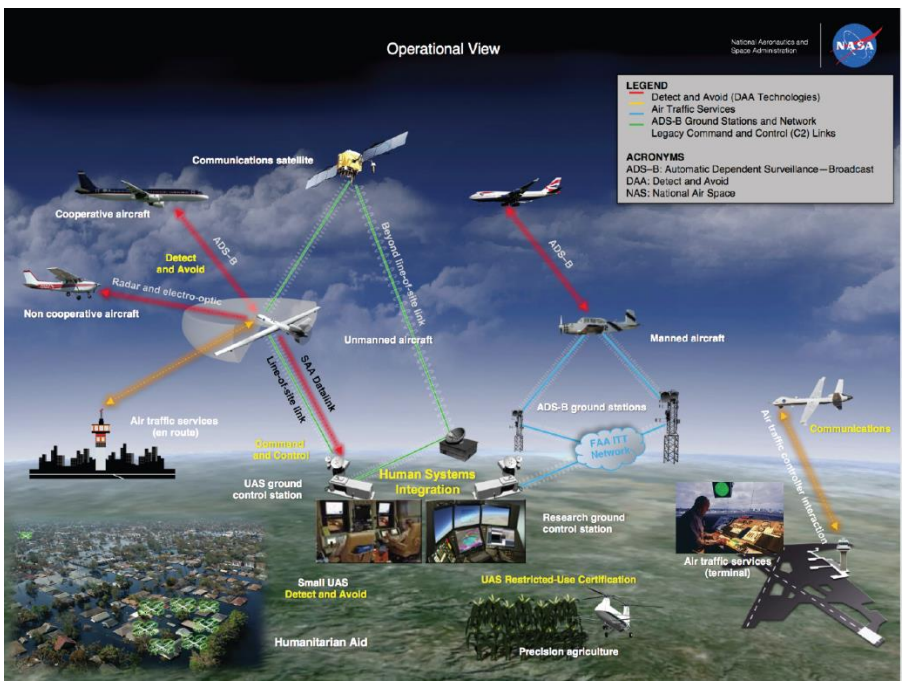

Fig. 1. ADS-B DAA SUAS operational view.

A. Automatic Dependent Surveillance-Broadcast Detect and Avoid System Architecture for a Small Unmanned Aircraft System

ADS-B is a surveillance technique which provides traffic and flight information by using air-to-air or air-to-ground data communications. The ADS-B DAA system architecture integrated into a SUAS combines surveillance, communication data-links, and algorithms to generate traffic alerts and displays that information on a synthetic vision display [2]. The SUAS is equipped with an ADS-B In / Out transponder and the ground control station (GCS) is equipped with an ADS-B In receiver. The ADS-B Out surveillance system provides automatic broadcasts of position, identity, altitude, and velocity information on the 978 MHz frequency. In this specific application, the heart of the

Phantom 4 ADS-B DAA system is a Micro Avionics Ping2020, which is an ADS-B In / Out transponder that broadcasts ownship position information and receives traffic reports for up to thirty-two proximate targets. Connected to the Ping2020 transponder are a GPS Ping NAV (uAvionix Corporation) and a universal access transceiver (UAT) antenna. The Ping NAV is a GPS receiver that enables the system to receive the ownship position and velocity state information, and the UAT omni directional antenna is designed to operate on 978 MHz. ADS-B position reports are transmitted via the ADS-B datalink from the airborne Ping2020 to the GCS ADS-B laptop computer, which contains the 3D synthetic display. The GCS ADS-B In (PingBuddy, uAvionix Corporation) receiver detects cooperative manned and unmanned surrounding aircraft within 100 miles, and the NASA / Vigilant Aerospace Systems Incorporated (Oklahoma City, Oklahoma) developed software initiates the collision avoidance maneuvers based on that information. The collision avoidance must activate when the separation layer has been compromised. Refer to Fig. 2 for the Ping2020 system architecture.

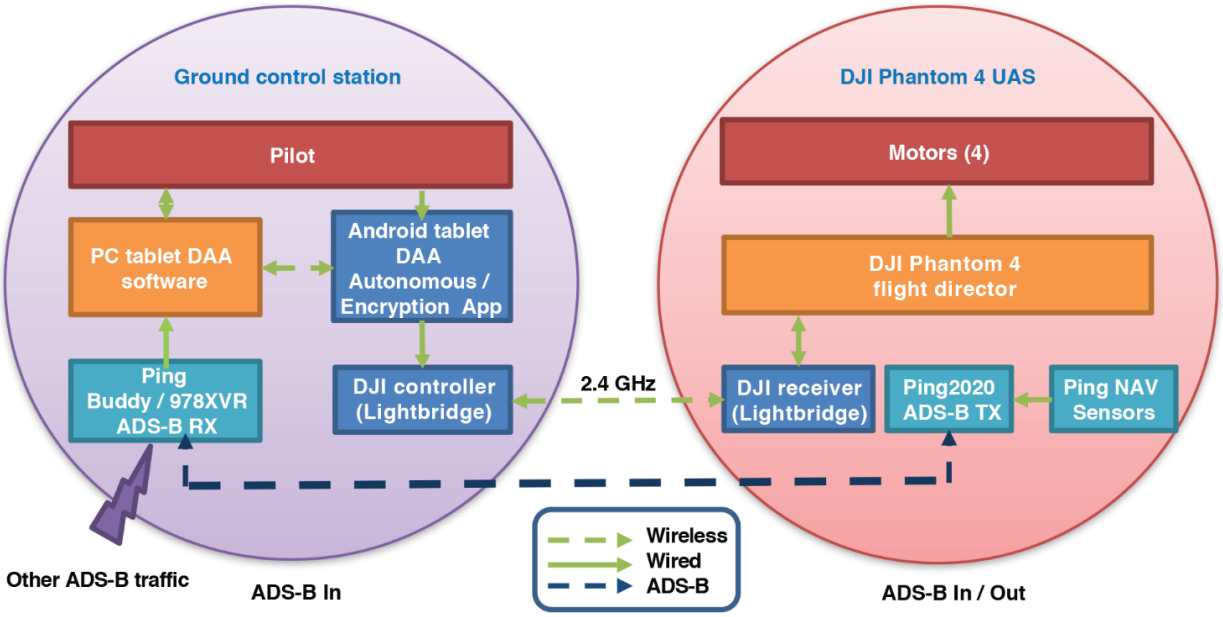

Fig. 2. ADS-B system architecture (U. S. Patent No. 9,405,005) [2].

B. Display and Detect and Avoid Algorithm

The DAA display and Stratway [3] algorithm was used during the flight test for the purpose of testing and evaluating detect and avoid concepts. During the flight test, the DAA display operated as the primary display for ADS-B traffic advisories (TAs). Resolution Advisory (RA) maneuvers conducted with the pilot-in-the-loop (i.e., actively controlling the aircraft) made maneuvers according to the guidance of the DAA display. Depending on the safety build up portion of the flight test, the pilot would fly the maneuvers manually, or the flight computer would automatically fly the RA after a period of time. In either case, the pilot had the ability to override any maneuver initiated by the flight computer.

A high-level progression of DAA functionality is included here as an example, from a flight-test perspective. The NASA developed DAA software performs real-time conflict detection and self-separation (i.e. remaining well clear of other air traffic) using the DAA sub-functions [4], as shown in Table 1. Basically, target detection is accomplished by the ADS-B transceiver, which can either be airborne or on the ground. The Stratway algorithm is then used for detecting conflicts as well as performing self-separation avoidance maneuvers. The RAs are visual and audible alerts that direct the pilot to increase separation.

Table 1. Detect and Avoid sub-functions.

Sub-functions	Explanation
Detect:	Detect presence of aircraft in vicinity of UAS
Track:	Estimate position and velocity (state) of intruders based on one or more surveillance reports
Evaluate:	Assess collision risk based on intruder and UAS states
Prioritize:	Prioritize intruder tracks based on a collision risk threshold
Declare:	Decide that action is needed
Determine:	Determine what action is required
Command:	Communicate the determined action to UAS (Resolution Advisories)
Execute:	Execute the determined action

C. Detect and Avoid Display

A key feature of the DAA display keeps the pilot-in-the-loop regarding threat aircraft and determines the conflict resolution maneuver before collision avoidance is necessary. The collision avoidance must activate when the separation threshold has been compromised. There are still many research and safety questions to be addressed in order to standardize displays for UAS pilot use, but the DAA display, developed by NASA and Vigilant Aerospace Systems [5], builds on human factors research and the current FAA Advisory Circular AC-20-172A [6], Airworthiness Approval for ADS-B In Systems and Applications display standards. The DAA display helps the pilot obtain sufficient situational awareness to anticipate and resolve potential conflicts before they become time-critical. Figure 3 shows a screen shot of the display with an example encounter that highlights many of the important features.

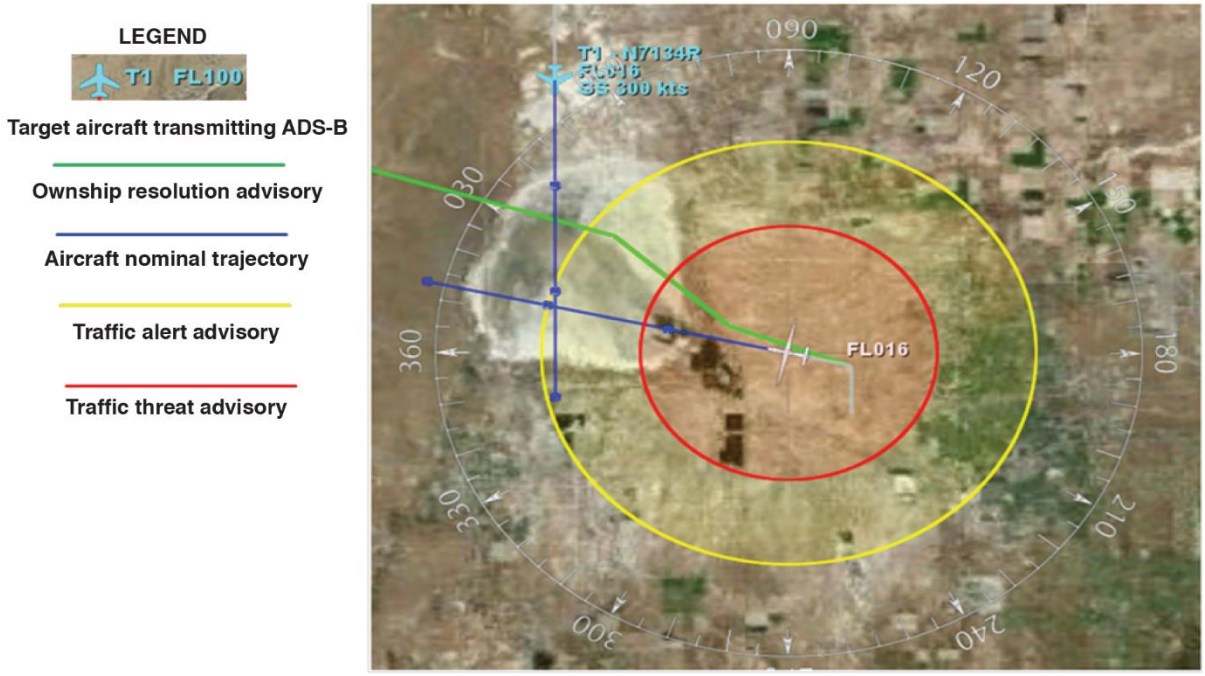

Fig. 3. NASA / Vigilant Aerospace DAA display system.

The DAA system utilizes many features discussed in previous work:

1) Ownship centric display with ownship displayed with a simple UAS icon. This feature is especially important for UAS where other maps and displays may be competing for the pilot's attention and resources. The UAS is at the apex of the icon, and the aircraft trajectory line helps the pilot understand where the UAS will be in 30, 60, and 90 seconds.
2) The heading circle shows both the current ownship heading and an abbreviation every 30 degrees. While this heading band does not replace traditional magnetic instruments for navigation, it does help the pilot quickly identify the traffic heading and could lead to more efficient heading change decisions.
3) Traffic is displayed using directional symbols in accordance with AC 20-172A and DO-317. Additional information displayed with the traffic symbol is flight identification (received through ADS-B), altitude relative to ownship (calculated using ADS-B), and a vertical rate sense indicator (calculated using ADS-B).
4) Range rings allow the operator to determine the proximity of the traffic relative to the separation requirements. The pilot can select the maximum forward display range, and the yellow range ring corresponds to 0.5 nmi from ownship, and the red range ring corresponds 0.3 nmi from ownship.

D. Autonomous Detect and Avoid Android Application

The NASA Autonomous Detect and Avoid Android application was designed to deliver 4D waypoints that can be designated in the horizontal, vertical, or time dimensions. This guidance set of points are called Resolution Advisories (RA) from the DAA display to the Dà-Jiāng Innovations Science and Technology Co, Ltd. (Shenzhen, China) (DJI) Phantom 4 SUAS. The SUAS was then able to fly the waypoints while resolving any conflicts that arose along the way. This application (APP) ran on an Android tablet connected to the DJI remote controller during autonomous mode operations. This DAA APP utilized DJI's mobile Software Development Kit (SDK). The SDK includes a mission manager that has the ability to fly waypoints, however, this flight control method was not used, because the mission manager did not allow immediate reprogramming of 4D waypoints in the case of a conflict resolution. Instead, the DJI Virtual Sticks application program interface (API) was used to control the drone in real time, allowing corrections to be provided during flight as the DAA display detected a loss of separation or airborne collision.

During semi-autonomous flight operations, the Litchi® Phantom 4 Pro Application (VC Technology Ltd., London, United Kingdom) running on an iPad™ mini (Apple Inc., Cupertino, California) was used to control the Phantom 4 SUAS to enable BVLOS operations. The Litchi® application provided pre-programmed flight missions, aircraft state information, and first-person view (FPV) video to enable BVLOS SUAS operations. The initial point (IP) waypoints and closest point of approach (CPA) waypoints for both the ownship and intruder unmanned aircraft vehicles (UAVs) were pre-loaded to match the respective flight card scenarios. Figure 4 shows the main screen or activity of the application.

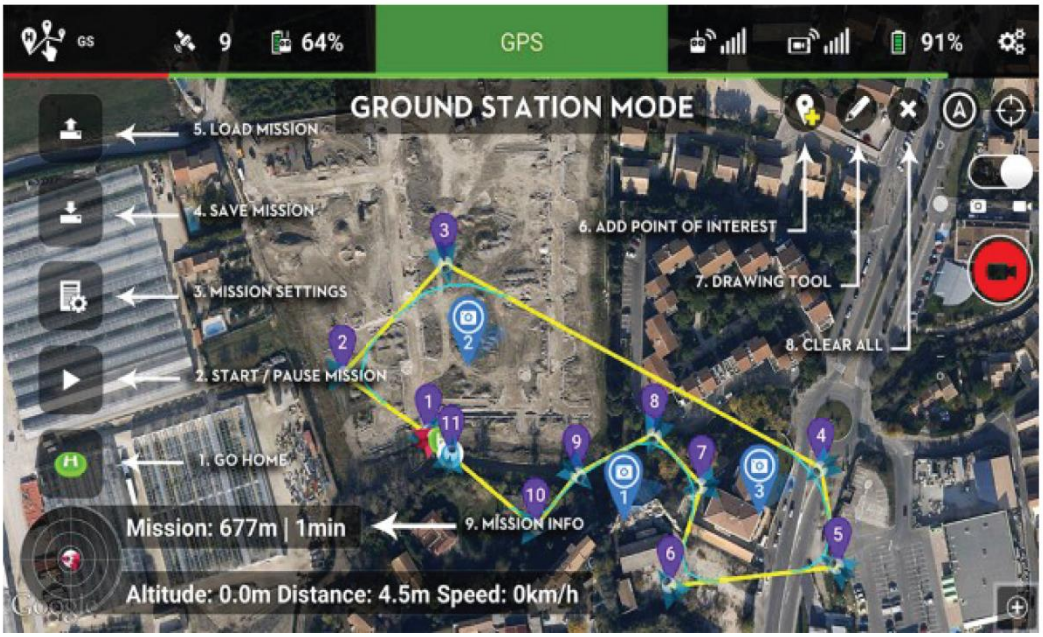

Fig. 4. Litchi® Phantom 4 Pro Application.

III. Flight-Test Planning

The following sections outline the flight-test system, flight-test planning, encounter scenarios, airspace constraints, and simulations to execute a safe and efficient flight-test campaign.

A. Test Aircraft Platform

The ownship platform used for system testing was the Phantom 4 Pro SUAS with obstacle avoidance. uAvionix's ADS-B capable UAT Ping2020 and Ping NAV GPS were installed inside the 3D printed mechanical support structure (Fig. 5). The ADS-B Ping2020 was used by the SUAS for air-to-air applications between two SUASs, between the SUAS and general aviation (GA) aircraft, and amongst the SUAS operators at the GCS via the ADS-B data link at 57,600 bits per second.

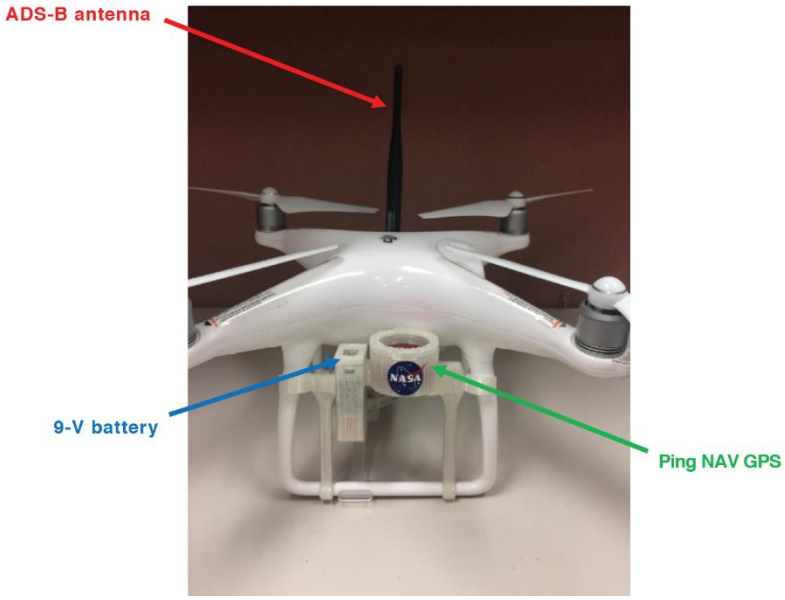

Fig. 5. Phantom 4 quadrotor unmanned vehicle.

B. Test Target Vehicle

To conduct flight tests, a second ADS-B Ping2020 and PingNAV GPS were installed on a second Phantom 4 Pro (Fig. 6) to act as the target and intruder vehicle during the tests. The ADS-B target vehicle served as an intruder for all the encounter geometries. The test target also served as an intruder aircraft when performing the combined system test procedure for the ownship Phantom 4. The ADS-B parameter elements such as the International Civil Aviation Organization (ICAO) (Montreal, Canada) address, emitter category, and call-sign were all changed to correspond to DAA001 for ownship and DAA002 as the transmitting test target. The ground system tests were successfully performed for the ownship and intruder target, which cleared the first ADS-B DAA flight that occurred on December 7-9, 2016.

Fig. 6. ADS-B Phantom 4 intruder.

C. Flight-Test Objectives

A flight-test plan for demonstrating ADS-B DAA was developed and approved by the NASA Armstrong Airworthiness and Flight Safety Review Board (AFSRB). The flight-test objectives for ADS-B DAA were to:

1) Demonstrate basic functionality of DAA capability.
2) Verify functionality of Phantom-4 autopilot with waypoint guidance commands for beyond-line-of-sight.
3) Obtain flight-test data to guide further development and certification.
4) Obtain video of the Phantom 4 accomplishing avoidance maneuvers.

D. Conduct of Flights and Profiles

Flight-test scenarios were divided into vertical and horizontal scenarios which are tailored to demonstrate surveillance and DAA avoidance techniques in an operational setting.

1. Detect and Avoid Scenario Requirements

Table 2 outlines the basic requirements for execution, safety mitigation, and prioritization for planned DAA scenarios. Safety minimums calculated in the vertical separation column of Table 2 take into consideration the planned offsets, as well as assumed standard deviation errors for timing, instrumentation, and pilot error.

Table 2. Detect and Avoid scenario requirements matrix.

Vertical Profile	Scenario Desigation	Priority	Speed Knots	Aimpoint Offset CPA	Phantom 1 Altitude AGL	Phantom 2 Altitude AGL	Objective	Planned Vertical Seperation	Advisory RA Type	Automatic Response to RA	Loss Link Phantom 1	Loss Link Phantom 1
10 Series Scenarios 200 foot Level	Scenario X11	1	20	1 (200 ft Vert)	250	50	Ensure miss & safety pilot fam	200	No Advisory	No	LL1	LL2
	Scenario X12	1	20	1 (200 ft Vert)	250	50	No activation & safety pilot fam: No RA	200	No Advisory	No	LL1	LL2
	Scenario X13	1	30	1 (200 ft Vert)	250	50	No activation & safety pilot fam: No RA	200	No Advisory	No	LL1	LL2
	Scenario X14	1	30	1 (200 ft Vert)	250	50	No activation & safety pilot fam: No RA	200	No Advisory	No	LL1	LL2
20 Series Scenarios 100 foot Level	Scenario X21	1	20	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
	Scenario X22	2	20	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
	Scenario X23	2	30	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
	Scenario X24	2	30	2 (100 ft Vert)	150	50	Approach at head on, expect "Climb"	100	"Climb, Climb" 1000 fpm	Yes	LL1	LL2
30 Series Scenarios 50 foot Level	Scenario X31	2	20	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
	Scenario X32	1	20	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
	Scenario X33	1	30	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
	Scenario X34	1	30	3 (50 ft Vert)	125	75	Approach at head on, expect "Climb"	50	"Climb, Climb" 1000 fpm	No	LL1	LL2
50 Series Scenarios50\ foot Level	Scenario X51	3	20	4 (0 ft Horiz)	100	150	0 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	Yes	LL1	LL2
	Scenario X52	3	20	4 (0 ft Horiz)	100	150	45 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	Yes	LL1	LL2
	Scenario X53	3	30	4 (0 ft Horiz)	100	50	60 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	No	LL1	LL2
	Scenario X54	3	30	4 (0 ft Horiz)	100	50	90 Degree approach, expect "Turn Right"	50	"Turn Right, Turn Right"	Yes	LL1	LL2
	Scenario X55	3	30	4 (0 ft Horiz)	100	50	135 degree approach, expect "Turn Left"	50	"Turn Left, Turn Left"	No	LL1	LL2
	Scenario X56	3	30	4 (0 ft Horiz)	100	50	180 degree approach, expect "Turn Right"	50	"Turn Left, Turn Left"	No	LL1	LL2

2. Detect and Avoid Scenarios

The DAA scenarios began at a point that is approximately 36 seconds from the CPA, with an RA alert from DAA expected prior to the CPA. To mitigate the risk of a Near-Mid-Air-Collision (NMAC), vertical offsets of no less than 50 ft were used for all scenarios.

The following descriptions outline the types of DAA scenarios that were planned to be flown to test specific modes of the DAA system. Scenarios were planned to be flown such that both aircraft maintain a constant heading and constant airspeed to arrive at a reference point which corresponds to the CPA; which was expected to produce an RA alert prior to CPA for most scenarios. Various geometries were planned with over eighteen scripted encounter scenarios designed to stress the DAA algorithm in the horizontal and vertical profiles. Specific scenarios were identified and briefed prior to flight each day. These scenarios were chosen during the flight test and were dictated by data needs, conditions, airspace requirements, and other factors. The required scenarios for flight-test success are outlined in Table 2.

3. Detect and Avoid Vertical Profiles

The following encounter profiles are considered "cooperative surveillance encounters." Vertical separation test setup consisted of various encounter geometries for the vertical profile, with independent variables such as ground speed and altitude varying from scenario to scenario.

a. Series 10: 200-feet level (no alert) profile—Both aircraft fly level throughout the encounter with 200 ft of separation between them; no corrective resolution advisory is expected. Intruder initial condition was planned to be below ownship depending on the geometry (Fig. 7).

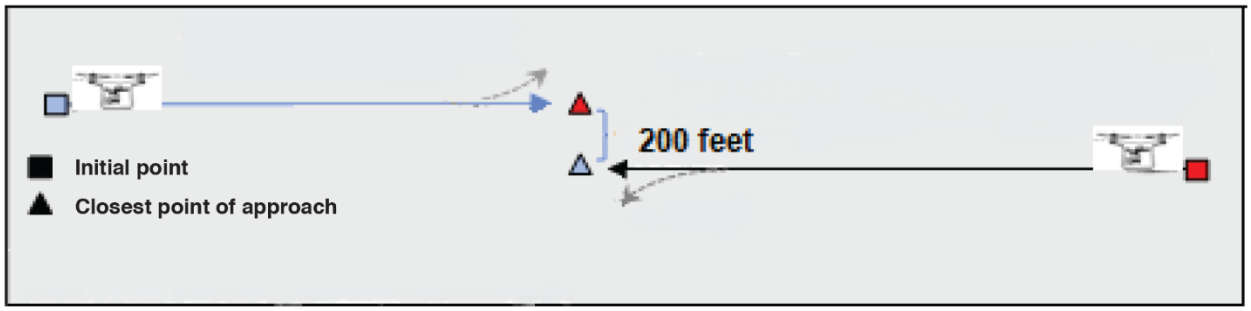

Fig. 7. Vertical profile for Series 10 encounters.

b. Series 20: 100-feet level profile—Both aircraft fly level throughout the encounter with 100 ft of separation between them, with a corrective RA alert expected to be issued prior to the CPA. Intruder initial condition was planned to be below ownship depending on the geometry. These scenarios were planned to also be flown with autonomous mode enabled (Fig. 8).

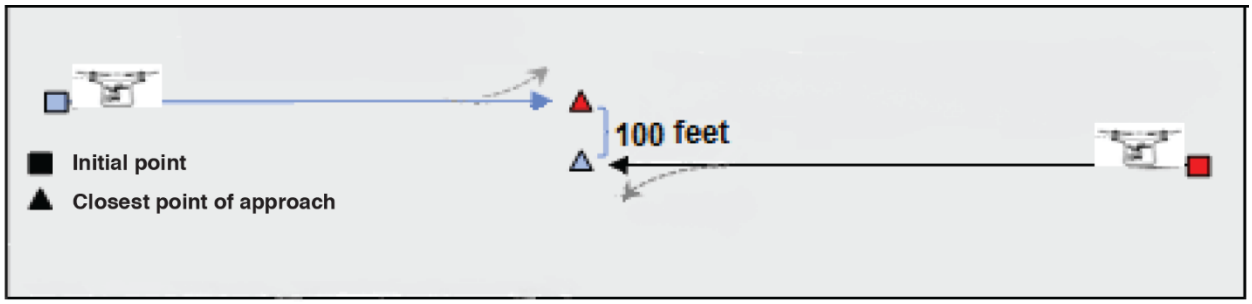

Fig. 8. Vertical profile for Series 20 encounters.

c. Series 30: 50-feet Level Profile—Both aircraft fly level throughout the encounter with 50 ft of separation between them; corrective RA alert expected to be issued prior to the CPA. Intruder planned to be below ownship depending on the geometry. These scenarios were planned to also be flown with autonomous mode enabled (Fig. 9).

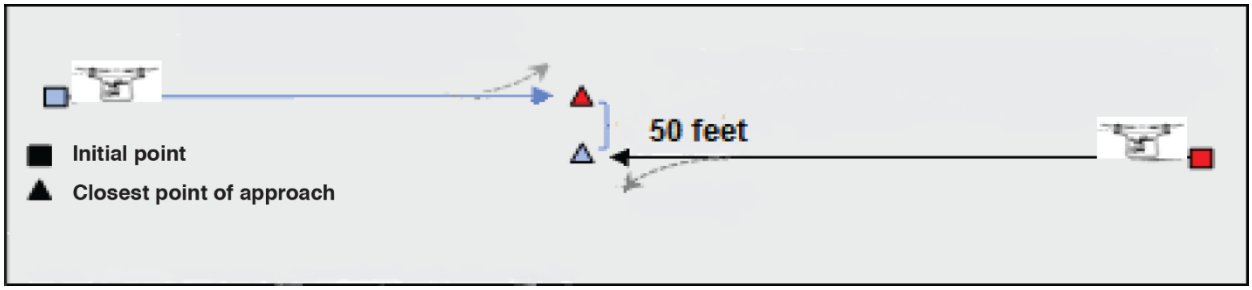

Fig. 9. Vertical profile for Series 30 encounters.

4. Detect and Avoid Horizontal Geometrics

There were six total horizontal geometries to be planned for Scenario Series 50, with a preplanned CPA. These geometries, and the relative altitudes (vertical profiles with intruder above or below) are depicted in Fig. 10 with relative heading offsets 0°, 45°, 60°, 90°, 135°, and 180° (ranging from head-on to overtaking).

For Series 50 encounters, only Geometries 1 through 6 were planned to be flown. For further information about the specific scenario types and geometries planned with the various equipment configuration builds, refer to Table 2. For Geometries 1 and 2, the intruder was planned to be above ownship; for Geometries 3 through 6, the intruder was planned to be below ownship.

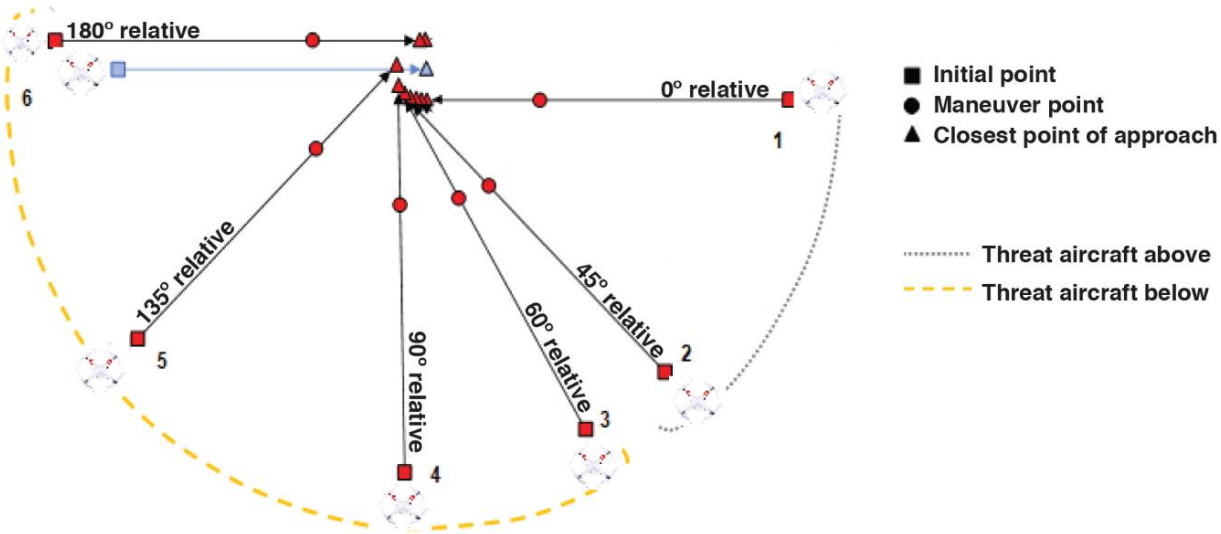

Fig. 10. ADS-B DAA scenario geometrics.

E. Flight Operating Area

The operating area for flight tests was the Muroc Model Master Complex (Edwards, California). The authorized airspace within the Muroc Complex requested for each day of operation during this flight test is outlined by the magenta colored box shown in the flight volume (Fig. 11). A geofence in the flight control software was used to contain the aircraft within the operating volume portrayed by the blue oval in Fig. 11.

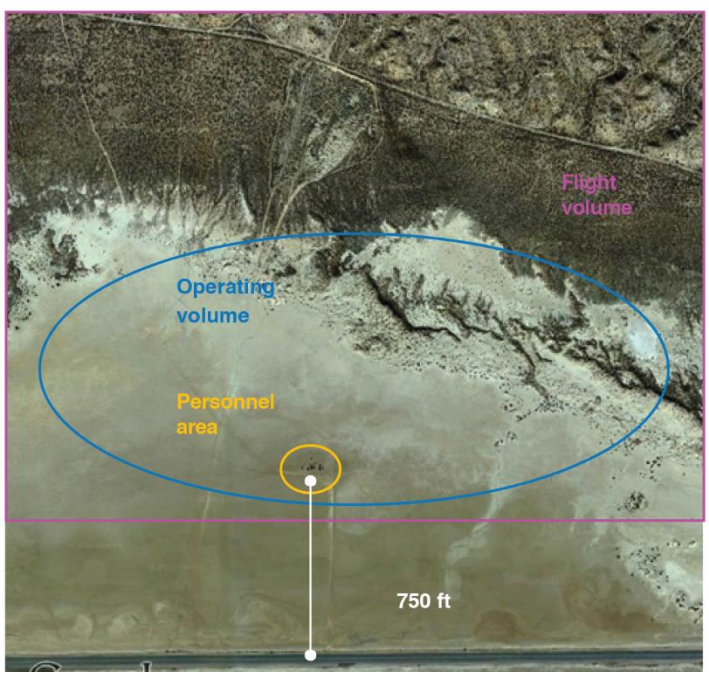

Fig. 11. Flight operations area.

Scenarios began with both aircraft hovering at an IP positioned BVLOS with each aircraft flying toward a CPA, creating (red and yellow) trajectories over the runway inside the Muroc operating volume as shown in Fig. 12. In general, the test director requested an altitude block from 50 ft to 500 ft. Altitudes were adjusted per requirements for

each scenario flown. Scenarios were planned so that they could be flown in altitude blocks other than requested so that the test could remain flexible to airspace usage.

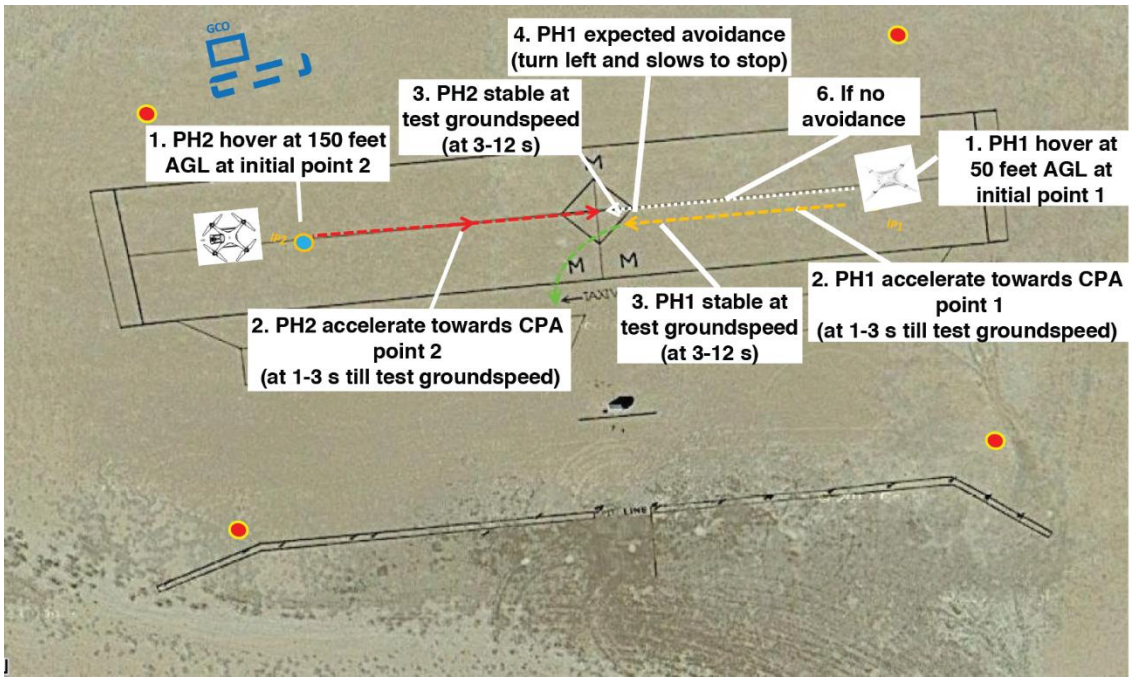

Fig. 12. Series 20 encounter geometry.

F. Simulations

The computational efficiency and performance of the ADS-B DAA algorithm is presented in this section. The goal of the simulation tool is to measure the CPA and the alerting time while following the RA. The simulation was developed in order to determine how the algorithm would resolve conflicts for the given scenarios over a broad range of encounter geometries. The DAA system used a 0.1 nmi horizontal separation and 200-ft vertical separation for the collision avoidance threshold. Critical to the performance of both the conflict detection and resolution is a model of the aircraft behavior [7]. The Phantom 4 SUAS aircraft performance behavior in terms of maximum climb rate, turn rate, altitude, and airspeed were applied to the DAA (Stratway+) algorithm and simulations. All encounter geometries in Table 2 were simulated prior to the flight-test execution. While executing simulations with different encounter geometries, the guidance and alerting performance was verified. The test outcomes (must not alert, must alert, horizontal RAs, and vertical RAs) as well as guidance (Stratway+) algorithm proficiency with respect to numerous dependent metrics were evaluated. It should be noted that all the encounter geometries were verified for the DAA system performance (where an RA was expected) using the Phantom 4 aircraft performance capabilities (Fig. 13). The simulations were tested with DAA software, allowing it to fly the waypoints and the resolutions. The DAA verification and validation methodology is shown in Fig. 14.

Fig. 13. X-33 simulation with a Resolution Advisory.

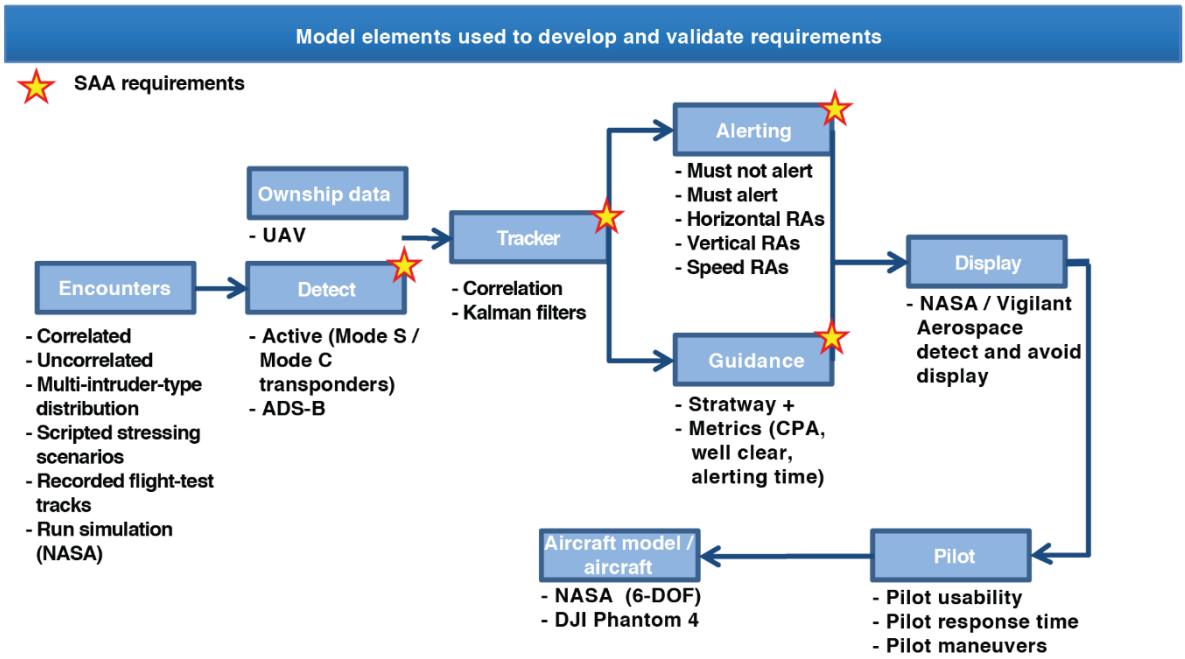

Fig. 14. DAA verification and validation methodology.

IV. Flight Testing

Although ground tests and simulations are essential for testing and debugging both hardware and software, flight testing is ultimately necessary for demonstrating the full ADS-B DAA system functionality. The flight-test separation challenges for airborne, airspace, and ground hazards were mitigated, clearing the authorization for the flight tests. These mitigations included ground surveillance using a visual observer and an ADS-B ground station to detect manned and unmanned aircraft.

A. Flight 1

The flight-test objective to demonstrate the basic functionality of the DAA capability for the SUAS was successfully demonstrated. The playback of the flight data shows a total traffic count of two surveillance targets. Two targets (T1) including the DAA01 aircraft and (T2) including the DAA02 aircraft were detected and tracked in real-time as surveillance targets. In general, the flight demonstration validated that the system received and displayed, as shown in Fig. 15, the following traffic information for targets of opportunity:

1) Relative horizontal position
2) Ground speed
3) Directionality (heading or track angle)
4) Pressure altitude of airborne traffic relative to ownship
5) Vertical trend of airborne traffic
6) Air / ground status of other aircraft
7) Flight ID (ICAO code) DAA001 and DAA002
8) Call signs DRONE1 and DRONE2

Fig. 15. ADS-B DAA Flight 1on December 5, 2016; detect and track intruders.

The ADS-B DAA performance was evaluated for intruder aircraft within a 0.6 nmi along track separation. The ADS-B DAA display is depicted in Fig. 15 with runways and taxiways, and ADS-B traffic on a plan view (God's-eye view) relative to ownship. In general, the flight demonstration validated that the system receives and displays the following intruder information for targets of opportunity. Motion data based on ADS-B trajectory models applying a look-ahead time (tL) prediction of 30, 60, and 90 seconds (blue circles) were generated and displayed.

B. Flight 2

The second ADS-B flight took place on December 7, 2016 and was once again successful. The aircraft performed several maneuvers which differed from those executed in flight 1, and the software performed well. The DAA display consistently tracked the targets, displayed their ADS-B data, and removed targets when the data were stale (> 24-second update), just as it did during flight 1. Electromagnetic interference and hardware problems were detected and quickly resolved:

1) Moving the UAVs farther apart resolved the problem with UAVs imposing an altitude limit of 15 ft and delivering suboptimal camera feed when within close proximity to each other.
2) Positioning the ADS-B In receiver antenna to have unblocked line-of-sight of the SUAS ensured the SUAS was being tracked throughout the scenarios.

3) Resolving these problems provided for better tracking of ADS-B targets and more accurate trajectories, as demonstrated in Fig. 16, with additional traffic alerts.

Fig. 16. ADS-B DAA Flight 2 on December 7, 2016; determine if intruder is a collision threat.

Scenarios X11 through X14 defined in Table 2, did not alert as expected. Motion data based on ADS-B trajectory models (blue circles) were generated, and a collision advisory alert was displayed.

C. Flight 3

On December 8, 2016, the team successfully flew all the flight-test encounter geometries with ADS-B Out. Throughout the flight test, trajectories were mostly on track; however, the software did not update them quickly enough to project a resolution. Problems with bad antennas and reception slowed the development of the flight test, since one UAV would not appear until it was within the detect and avoid horizontal separation of 0.1 nmi due to limited transmission range. As a result, the software did not have enough time to calculate a corrective resolution advisory.

1) Replacement of the ADS-B Ping2020 transponder updating at only 4 seconds and a UAT antenna resolved the transmission problem of one of the drones (Fig. 17).
2) Replacement of the 9-V batteries every 1.5 hours and testing the voltage to verify greater than 6 V resolved the transmission range problem.

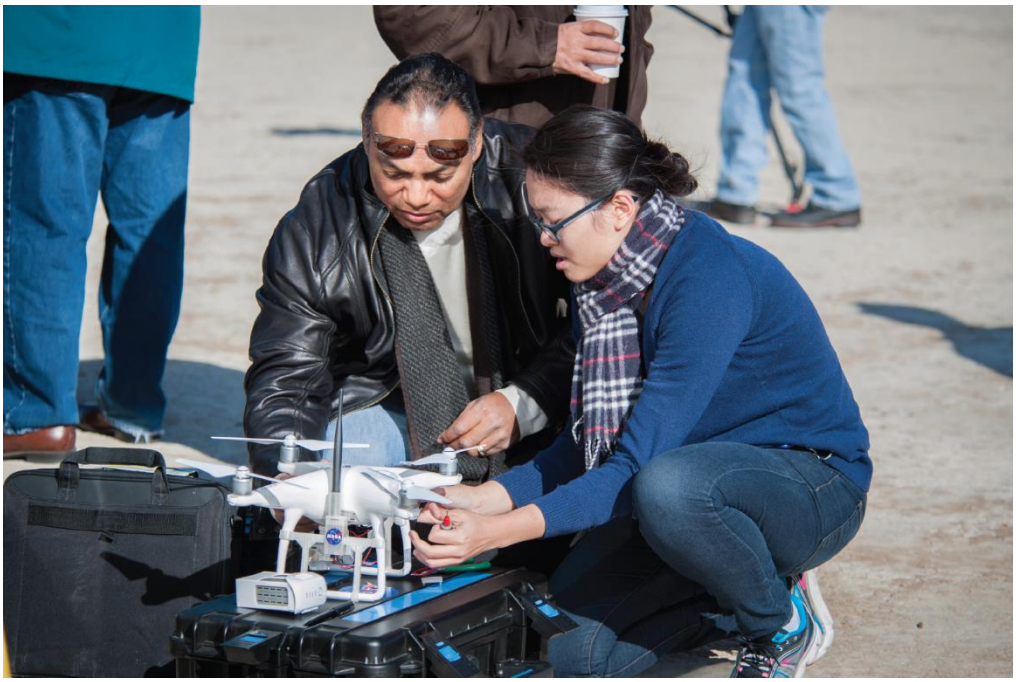

Fig. 17. ADS-B DAA Flight 3 on December 8, 2016; transmission problems with ADS-B hardware addressed.

The DAA software did not account for the quadcopter maneuvering as a non-linear time invariant system. The simulations assumed the aircraft behavior model was linear; therefore, the trajectory prediction models were designed to use ADS-B state-based nominal trajectories with 30 seconds of historical state information. However, the Phantom 4 SUAS is capable of hovering and moving in any of the three dimensions instantaneously and making very rapid turns. Changing the software to account for this nonlinearity would update the trajectories faster, giving the software more time to create resolutions. One method would be for the software to reset the trajectory prediction models during hover operations, since the ground tracks are unstable at very slow ground speeds.

D. Flight 4

On December 9, 2016, the team successfully flew all the flight-test encounter geometries with the ADS-B DAA capability to enable BVLOS UAS operations. Throughout the flight test, trajectories were mostly on track, flying outbound to the IP. However, the software did not update them quickly enough on the inbound to provide a conflict resolution. Although the transmission problems were resolved, the reception sensitivity of the PingBuddy receiver manifested in the intermittent reception of one drone based on the direction of the PingBuddy antenna affected the timing of the conflict resolution. The ADS-B receiver and antenna sensitivity is paramount for BVLOS and low altitude SUAS operations. The DAA algorithm accurately detected that a predicted trajectory would create a loss of safe separation with the ownship and generated an alert prompting that a collision was possible within time to close point of approach (tCPA) of 0 seconds with a Desend RA shown in green (Fig. 18). The research flight-test team at NASA Armstrong Flight Research Center is shown in Fig. 19.

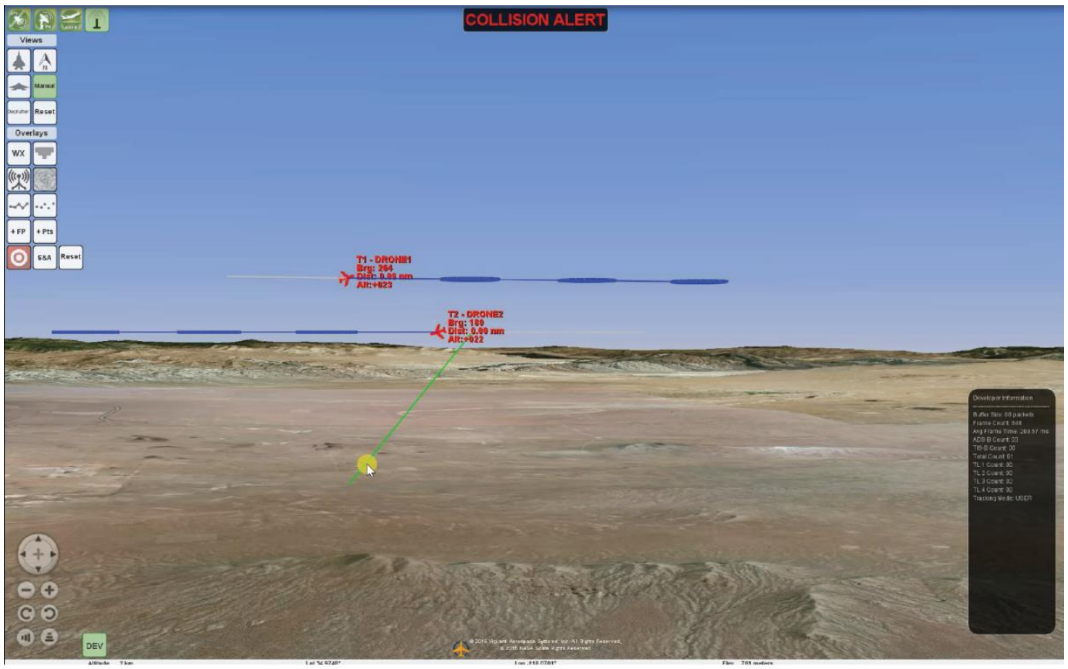

Fig. 18. ADS-B DAA Flight 4 on December 9, 2016; commands maneuver to avoid the collision.

Fig. 19. NASA Armstrong research flight-test team.

E. Flight 5

After corrective actions were taken, the team was not able to verify that the software reliably generated RAs (ascend and turn right) during previous flight tests as compared to simulations. One hypothesis was that the software was not generating RAs (ascend and turn right) because the PingBuddy ADS-B receiver was not receiving signals reliably enough and at a sufficient distance to build up sufficient trajectories (continuously updating 30 seconds of track information) to trigger a timely RA. Three significant changes were made to address this problem: 1) the

PingBuddy was replaced by the PingEFB (uAvionix), which is a USB ADS-B In dual-band (978 and 1090 MHz) receiver with improved receive sensitivity (-93 dBmW) [8]; 2) the software was upgraded to use the ADS-B parser for the PingEFB; and 3) the battery was replaced with a 12-V rechargeable lithium-ion polymer battery with an eight-hour capacity to minimize frequent batteries changes.

Vigilant Aerospace Systems completed live flight demonstrations of FlightHorizon UAS™ using two unmanned aircraft to demonstrate and document the full safety lifecycle of detect, track, predict, avoid, and recovery functions during multiple flight encounters [9]. These flight demonstrations were carried out in late May 2017 at the Oklahoma State University (OSU) Unmanned Aircraft Flight Station (Glencoe, Oklahoma) with the help of both Vigilant Aerospace Systems and OSU licensed unmanned aircraft pilots. The demonstrations resulted in the short video (test objective #4) demonstrating the flight advisories and resolution advisory (green) commands issued by FlightHorizon UAS™ side-by-side with actual footage of the flight maneuvers [9] (Fig. 20). The flight tests demonstrated that the system was able to consistently generate correct and usable RAs multiple times and reliably, under realistic SUAS flying conditions over relatively short distances.

Fig. 20. ADS-B DAA Flight 5 on May 2017; commands maneuver to safely avoid the collision.

F. Flight 6

Flight testing was conducted at NASA Armstrong Flight Research Center in July 2017, using manned and unmanned aircraft to demonstrate and document the full safety lifecycle of detect, track, predict, avoid, and recovery functions during multiple flight encounters. An illustrative flight-test scenario, an ADS-B 1090ES equipped MQ-9 unmanned aircraft (General Atomics Aeronautical Systems, Inc., Poway, California) flew at Fight Level 100 at 151 knots in realistic flight conditions. The FlightHorizon UAS™ surveillance and DAA algorithm was executed on a laptop at a remote ground station. A King Air (Beechcraft, Wichita, Kansas) ADS-B 1090ES equipped intruder aircraft flew at Fight Level 097 at 168 knots and was on a 30-degree cross-track collision path towards the first aircraft. The two aircraft were flying level without aircraft maneuvers. The DAA system used a 1.0-nmi horizontal separation and 400-ft vertical separation for the collision avoidance threshold. The FlightHorizon UAS™ surveillance and DAA algorithm adapted to the UAS MQ-9 aircraft capabilities had been monitoring and continuously updating 90 seconds of track information about the King Air aircraft and applying a (tL) look ahead prediction of 30, 60, and 90 seconds to the King Air track. At the given aircraft speeds, the DAA algorithm was sensing at a range of 4.69 nmi and tCPA alerting time of 90 seconds before issuing a “Climb” RA. The Airborne Surveillance and DAA processing algorithm detected the required position reports for accuracy inside of 30 nmi, and the alerting logic reported a valid traffic alert (yellow) and RA (green) corrective climb command to avoid the collision (Fig. 21). These flights validated CPA predictions and DAA alerting logic in realistic flight conditions.

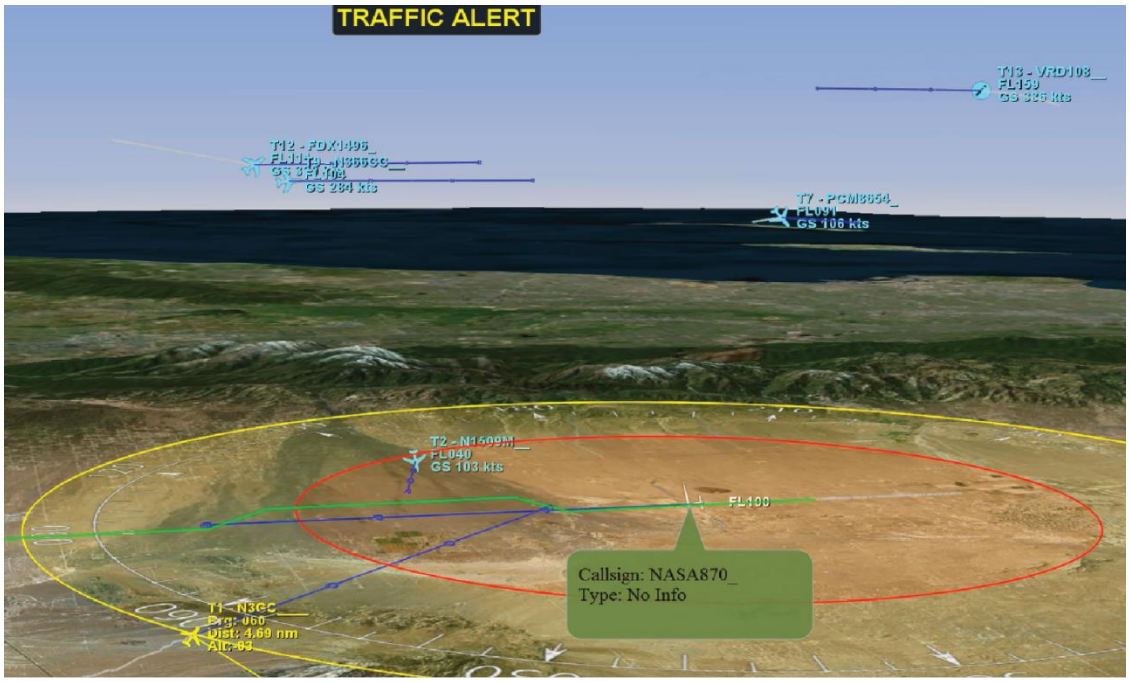

Fig. 21. ADS-B DAA flights from July 2017 (U.S. Patent No. 9,405,005) [2].

G. Flight Operations Harvey

The integrated DAA system for SUAS developed and flight-tested at NASA was deployed in August 2017 for Hurricane Harvey humanitarian aid and recovery. The NASA commercialized technology enabled vital bird's-eye views of the Houston disaster areas left in the wake of Hurricane Harvey that helped first in the search and rescue mission, and then in damage assessment [10]. Vigilant Aerospace Systems provided a FlightHorizon UAS™ system to members of the Humanitarian Drones team and operational training of this technology during the early stages of the Hurricane Harvey disaster recovery. The team provided damage assessment and data collection services to the Federal Emergency Management Agency, who are working to collect data in the Gulf Coast region for flood damage assessment and humanitarian aid [11, 12].

H. Lessons Learned

Flight testing with an ADS-B Detect and Avoid technology for BVLOS SUAS operations is challenging. Lessons learned include:

1) Fly, Fix, Fly; do not try to get it totally right the first time, as success comes only after overcoming many technical challenges.
2) Incrementally integrate the ADS-B hardware and ADS-B DAA software capability. Once the ADS-B hardware is selected, a spiral series of software upgrades is necessary to improve system functionality and performance [13].
3) 3D printing saves time and money, and allows testing of new designs during the integration phase.
4) Simulation of linear models are not reality. Simulations did not include the effects of winds and non-linear (fly-hover-fly) aircraft behavior.
5) Timing is everything for RAs. In order to meet the time constraint at the CPA, and thus a timely resolution advisory, timing tolerances were used for both aircraft.
6) Use rechargeable LiPo 12-V batteries with at least 2200 mAh for ADS-B transponders during flight tests.
7) Use a better (sensitivity minimum triggering level -93 dBmW) ADS-B receiver antenna to increase range reception for beyond line-of-sight operations at very low altitudes.
8) Reset the trajectories when the drone performs a hover (ground speed < 3 knots). Thus, halt and hover can be an avoidance maneuver.

9) The ownship selection in the software should default to the ICAO code for ownship to ensure tracking during signal dropouts. Signal drop outs can occur during RF line-of-sight terrain obstruction and aircraft maneuvers.

V. Conclusion and Future Work

The National Aeronautics and Space Administration and Vigilant Aerospace Systems have successfully demonstrated an Automatic Dependent Surveillance-Broadcast Detect and Avoid system coupled to a small unmanned aircraft system to enable beyond visual line of sight low altitude flight operations. This patented Automatic Dependent Surveillance-Broadcast based collision avoidance technology enables growth in commercial application of small unmanned aircraft system operations at lower altitudes. The testing and demonstrations are necessary for both parties to further the development and certification of the technology in three key areas: flights beyond-visual-line-of sight, collision avoidance, and autonomous operations. The first flight phase focused on the performance required for minimal separation provisions of two small unmanned aircraft systems conducting operations beyond-visual-line-of sight. The Detect and Avoid algorithm configuration parameters used for conflict detection and resolution included a horizontal separation threshold of 0.1 nmi and 200-ft vertical separation. The Automatic Dependent Surveillance-Broadcast Detect and Avoid alerting mechanism for conflict detection and separation requirements was successfully tested between two small unmanned aircraft systems for reporting loss of separation and alerting logic for timely corrective resolution advisories. Analysis, simulations, and flight tests were conducted to validate assumptions for collision avoidance in low risk environments.

The platform used for system testing was DJI's Phantom 4 small unmanned aircraft system with uAvionix's Automatic Dependent Surveillance-Broadcast capable Ping2020 installed inside a mechanical support structure. All data from the unit required radio frequency transmission to the ground station via the aircraft Automatic Dependent Surveillance-Broadcast link. A series of hardware and software ground tests were performed for system validation.

Pragmatic lessons were learned during the flight tests of a small unmanned aircraft system integrated with Automatic Dependent Surveillance-Broadcast Detect and Avoid for beyond visual line of sight operations. During this Automatic Dependent Surveillance-Broadcast Detect and Avoid integration on a small unmanned aircraft system development, considerable time and effort went into solving problems with antennas, transmitter, receivers, and replacing batteries. The Automatic Dependent Surveillance-Broadcast receiver and antenna sensitivity is paramount for the performance of Automatic Dependent Surveillance-Broadcast Detect and Avoid during beyond visual line of sight operations. A software lesson learned was the Detect and Avoid design assumption for large unmanned aircraft systems as being linear time invariant systems; however, the small unmanned aircraft system aircraft behavior is nonlinear, thus the trajectories are inaccurate at very low ground speeds. A further improvement to the Detect and Avoid algorithm would reset the trajectories during hover operation (ground speed < 3 knots), because the Stratway conflict detection relies on accurate trajectories of the ownship and traffic aircraft.

Currently, the system has undergone four successful flights in December 2016 and included approximately 100 scripted encounters. Furthermore, the system has undergone additional successful follow-up flights in May and July 2017. The Detect and Avoid system successfully detects conflicts and provides alerting to the small unmanned aircraft system operator, and combined with obstacle avoidance sensors increases safety. After significant improvements to performance were made by using the PingEFB Automatic Dependent Surveillance-Broadcast receiver and the nonlinear behavior of small unmanned aircraft systems, subsequent flight testing validated successful operation of Automatic Dependent Surveillance-Broadcast Detect and Avoid and ultimately the system as a whole. The Federal Aviation Administration witnessed the flight-test execution of two small unmanned aircraft systems, and these results have demonstrated that small unmanned aircraft system integration into the National Airspace System can be efficiently accomplished when equipped with an integrated Automatic Dependent Surveillance-Broadcast Detect and Avoid system. However, there are still several tasks to complete for future research. Our current research is focused on the development of a state-of-the-art miniaturized radar system suitable for small unmanned aircraft systems for detecting non-cooperative objects. Future research is required to address the separation challenges of multiple small unmanned aircraft systems for airborne, airspace, and ground terrain hazards including the effects of Automatic Dependent Surveillance-Broadcast interference and delays.

In conclusion, operations of small, highly autonomous vehicles within specially designated areas, as well as integration within the National Airspace, will address public, scientific, government, and commercial needs and maximize the benefits of aviation to society. Recently, Vigilant Aerospace Systems provided a FlightHorizon UAS™ system to members of the Humanitarian Drones team and operational training of this technology during the early stages of the Hurricane Harvey disaster recovery. The team provided damage assessment and data collection services to Federal Emergency Management Agency, who are working to collect data in the Gulf Coast region for flood damage

assessment and humanitarian aid. To this end, this National Aeronautics and Space Administration patented unmanned aircraft system detect and avoid technology was deployed for Federal Emergency Management Agency damage and aid assessment missions to help our fellow American's in need.

Acknowledgments

This research was supported and funded by the NASA Technology Transfer Office (Laura Fobel). The team thanks the FAA technical representative (Sean Kavaeny) for their collaboration on this research. The interns were supported and funded by National Aeronautics and Space Administration Headquarters and Vigilant Aerospace Systems. The team thanks Humanitarian Drones for their voluntary service during Hurricane Harvey disaster recovery (http://humanitariandrones.org/).

References

[1] U.S. Department of Transportation Federal Aviation Administration, "Advisory Circular–Airworthiness Approval of Automatic Dependent Surveillance–Broadcast (ADS-B) Out Systems," AC No. 20-165, 2010.

[2] Arteaga, R. A., "Automatic Dependent Surveillance Broadcast (ADS-B) System for Ownship and Traffic Situational Awareness," U.S. Patent No. 9,405,005, issued August 2, 2016.

[3] Hagen, G., Butler, R., and Maddalon, J., "Stratway: A Modular Approach to Strategic Conflict Resolution," AIAA-2011-6892, 2011.
doi: 10.2514/6.2011-6892

[4] U.S. Department of Transportation Federal Aviation Administration Sponsored Sense and Avoid Workshop, "Sense and Avoid (SAA) for Unmanned Aircraft Systems (UAS)," January 2013.

[5] Arteaga, R. A., Kotcher, R., Cavalin, M., and Dandachy, M., "Application of an ADS-B Sense and Avoid Algorithm," AIAA-2016-3651, 2016.
doi: 10.2514/6.2016-3651

[6] U.S. Department of Transportation Federal Aviation Administration, "Advisory Circular-Airworthiness Approval for ADS-B In Systems and Applications," AC No. 20-172A, 2012.

[7] Kuchar, J. K., and Lee, C. Y., "Survey of Conflict Detection and Resolution Modeling Methods," AIAA-97-3732, 1997.
doi: 10.2514/6.1997-3732

[8] Guterres, R. M., Jones, S. R., Orrell, G. L., and Strain, R. C., "ADS-B Surveillance System Performance with Small UAS at Low Altitudes" AIAA-2017-1154, 2017.
doi: 10.2514/6.2017-1154

[9] Vigilant Aerospace Systems, Inc., "Vigilant Aerospace Completes Demonstration Flights at OSU Unmanned Aircraft Flight Station, URL: https://vigilantaerospace.com/vigilant-aerospace-completes-demonstration-flight-encounters-osu-uafs/ [retrieved 10 October 2017].

[10] NASA, "NASA Commercialized Technology, Assists Hurricane Harvey Recovery Efforts," URL: https://www.nasa.gov/centers/armstrong/features/drones_assist_harvey_recovery_efforts.html [retrieved 10 October 2017].

[11] DroneLife, "Drone Industry Aids Red Cross in Hurricane Harvey Response," URL: https://dronelife.com/2017/08/31/drone-industry-aids-red-cross-hurricane-harvey-response/ [retrieved 10 Octorber 2017].

[12] Humanitarian Drones, "Thank You," YouTube video, URL: https://www.youtube.com/watch?v=2CdkQJ01OSg [retrieved 10 October 2017].

[13] Rechtin, E., and Maier, M. W., *The Art of Systems Architecting*, 2nd ed., CRC Press, Boca Raton, Florida, 2002.