µADS-B Flight Tests on Phantom 4 Unmanned Aircraft System

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Researchers at the National Aeronautics and Space Administration Armstrong Flight Research Center (Edwards, California) and Vigilant Aerospace Systems collaborated for the flight test demonstration of the Automatic Dependent Surveillance Broadcast (ADS-B) based collision avoidance technology with the uAvionix ADS-B Transponder (model Ping2020). The purpose of the testing is to demonstrate that NASA/Vigilant software and algorithms are compatible with uAvionix hardware systems and the DJI (Dà-Jiāng Innovations Science and Technology Co., Ltd, Shenzhen, Guangdong) Phantom 4 Unmanned Aerial System (UAS). The testing and demonstrations are necessary for both parties to further development and certification of the technology in three key areas: flights beyond line of sight, collision avoidance, and autonomous operations. NASA and Vigilant have developed and successfully flight-tested an Automatic Dependent Surveillance-Broadcast (ADS-B) Detect and Avoid system on the Phantom 4 DJI Quadrotor UAS. The ADS-B DAA system architecture is especially suited for UASs because it integrates: 1) commercial off-the-shelf ADS-B hardware; 2) radio data-link communications; 3) software algorithms for real-time ADS-B data integration, conflict detection, and alerting; and 4) a synthetic vision display using a fully-integrated NASA 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 Detect and Avoid Collision Avoidance Technology as installed on two UASs. In December 2016, four flights were conducted at Edwards Air Force Base (AFB) (Edwards, California). Researchers in the ground control station looking displays were able to verify the ADS-B target detection and collision avoidance resolutions. Further,

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an FAA representative witnessed the flight test execution of beyond line-of-sight encounter geometries and collision avoidance resolutions of small UAS.

Nomenclature

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 Service
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	=	Nastional Aeronautics and Space Administration
NextGen	=	Next Generation Air Transportation System
NIC	=	Navigation Integrity Category
RA	=	Resolution Advisory
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 Transciever
WAAS	=	Wide Area Augmentation System
WGS-84	=	World Geodetic System 1984

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 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 Phantom 4 DJI Quadrotor (Dà-Jiāng Innovations Science and Technology Co., Ltd, Shenzhen, Guangdong), 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[1]. This novel ADS-B DAA 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.

II. Systems Background

This research proposes an ADS-B DAA[2] system coupled to an unmanned aircraft system for detect and avoid capability to avoid accidents. The system utilizes a Ping ADS-B receiver and methods that allows a drone to sense surrounding aircraft and initiate collision avoidance maneuvers based on detected traffic information. The research further proposes 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 for autonomous operations (refer to figure 1).

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 autonomy such as advanced UAS operations. The outcomes of this technology transfer 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 exploitation 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.

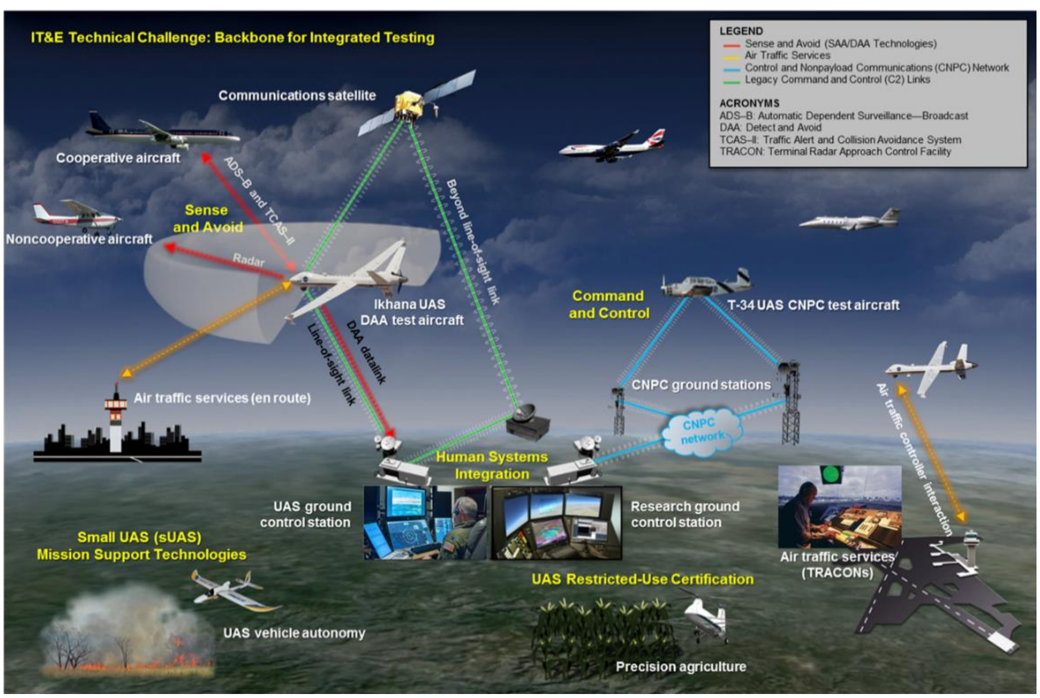

Fig. 1. ADS-B DAA Small UAS operational view

A. ADS-B DAA 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 DAA system architecture coupled to a UAS combines surveillance, communication data-links, and algorithms to generate traffic alerts 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 Phantom 4 ADS-B DAA system is Micro Avionics Ping 2020 (uAvionix), 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 Ping 2020 are a GPS Ping NAV and UAT antennas. The GPS Ping NAV receiver 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 Ping 2020 to the ground control station (GCS) ADS-B laptop computer, which contains the 3D synthetic display. The uAvionix line of "Ping" sensors are the smallest and lightest ADS-B based hardware available for unmanned aircraft. The Ping ADS-B receiver allows a drone to sense surrounding aircraft and the NASA/Vigilant developed software initiates the collision avoidance maneuvers based on that information. Ping 2020 system architecture[3]. Refer to Fig. 2.

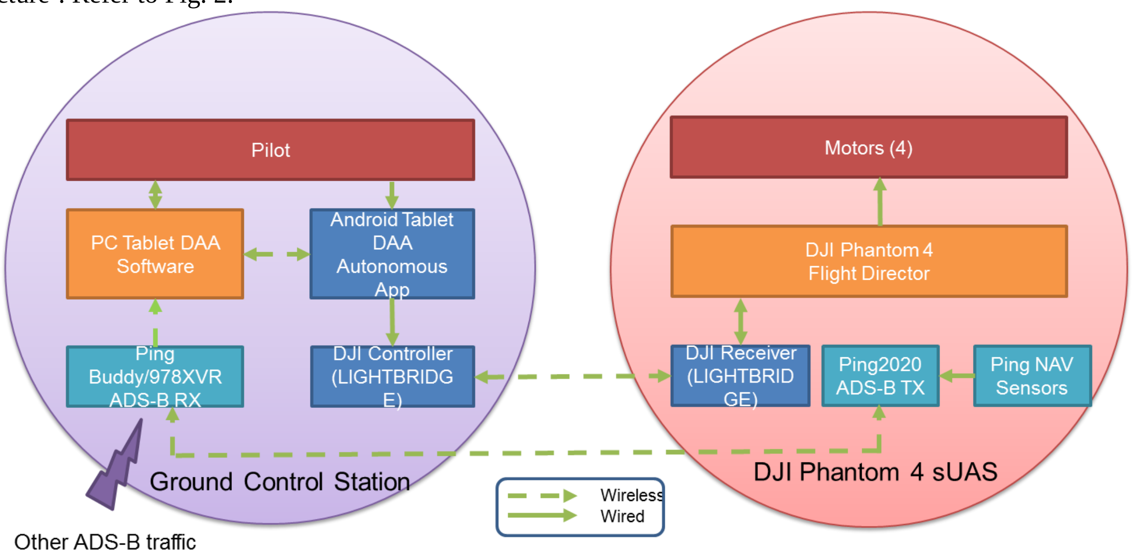

Fig. 2. ADS-B system architecture (Patent filed March 5, 2013; Serial No. 13/785,661).[4]

B. Display and Detect and Avoid Algorithm

The DAA display and Stratway[5] algorithm will be used during the flight test for the purpose of testing and evaluating detect and avoid concepts. During the flight test, the DAA display will act as the primary display for ADS-B traffic advisories (TAs). Resolution Advisory maneuvers will be conducted with the pilot-in-the-loop (i.e., actively controlling the aircraft) conducting maneuvers according to the following DAA display. Depending on the safety build up portion of the flight test, the pilot may fly the maneuvers manually, or the flight computer will automatically fly the RA after a period of time. In either case, the pilot will have 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, as shown in Table 2 below. 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 Resolution Advisories (RAs) are visual and vocalized 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 determined action to UAS
Execute:	Execute the determined action

C. Detect and Avoid Display

A key feature of the DAA display is to keep the pilot involved in conflict resolution before collision avoidance is necessary. 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, builds on Human Factors research and current display standards. The DAA display that 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.

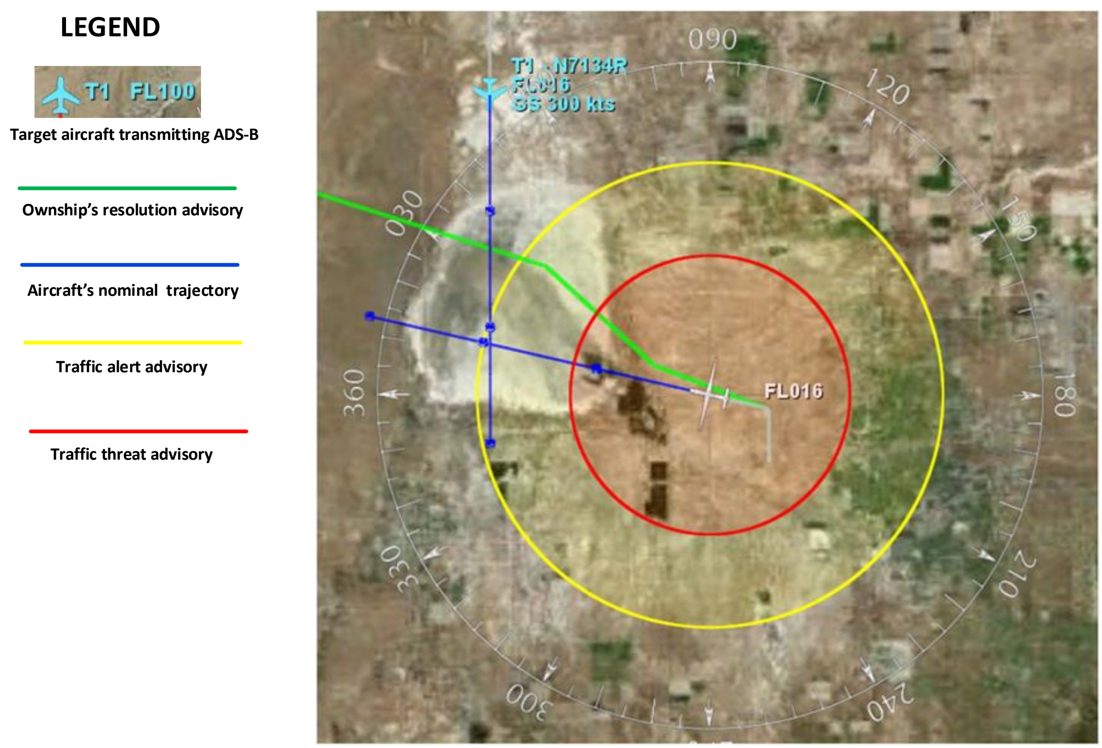

Fig. 3. NASA/Vigilant Aerospace Detect and Avoid and Display System

The Detect and Avoid Display System, shown in Figure 2, utilizes many features discussed in previous work:

- 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, 90 seconds.

- The heading circle shows both 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 traffic heading and could lead to more efficient heading change decisions.

- Traffic is displayed using directional symbols in accordance with DO-172A and DO-317. Additional information displayed with the traffic symbol is Traffic ID (received through ADS-B), altitude relative to ownship (calculated using ADS-B) and vertical rate sense indicator (calculated using ADS-B).

- Range rings support the operator in determining 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 1 nm from ownship and the red range ring corresponds 0.3 nm from ownship.

D. Autonomous detect and Avoid Android Application

The Autonomous Detect and Avoid Android application was designed to deliver waypoints and RAs from the DAA display to the DJI Phantom 4 UAS. The UAS was then able to fly the waypoints while resolving any conflicts that arose along the way. This application ran on the Android tablet connected the DJI remote controller. It utilized DJI's Mobile SDK. The SDK includes a Mission Manager that has the ability to fly waypoints, however this was not used. This is because the mission manager did not allow immediate reprogramming of waypoints in the case of a conflict resolution. Instead the Virtual Sticks API (Application Program Interface) was used to control the drone in real time, allowing us to provide corrections to flight as the DAA display found them. Figure 4 shows the main screen or activity of the application.

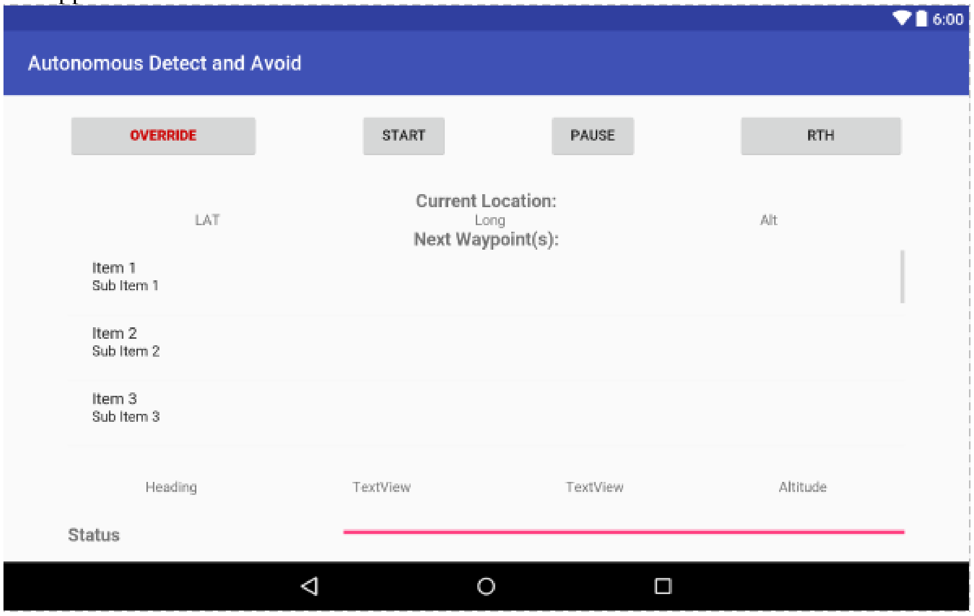

Fig. 4. NASA Autonomous Detect and Avoid

The Autonomous Detect and Avoid Android application allows the user to load the waypoints on the DAA Display in Figure 4 the button operations are as follows:

- The start button allows the aircraft to take off and fly the waypoints.
- The pause button pauses the current waypoint and will allow the user to resume it later.
- The RTH button returns the aircraft to the home location.
- The override button allows the pilot to disconnect the app from the controller so he may manually take back control.

The application was tested using a DJI Simulator that allowed each action to be completed as it would be if the aircraft was flying. The DAA Display was running its own simulation of the flight tests to provide the resolution advisories for autonomous operations.

III. Flight Test System

The following section outlines general (nonformatting) guidelines to follow, drawn from the original AIAA Manuscript Preparation Kit. These guidelines are applicable to all authors (except as noted), and include information on the policies and practices relevant to the publication of your manuscript.

A. Target Test Vehicle

To conduct flight tests the ADS-B DAA system was installed on a second Phantom 4 (Fig. 5). 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 ownship Phantom 4. The ADS-B parameter elements such as International Civil Aviation Organization (ICAO) 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 performed optimally for a stationary and moving target and was cleared for the first ADS-B DAA flight scheduled to take place December 7-9, 2016.

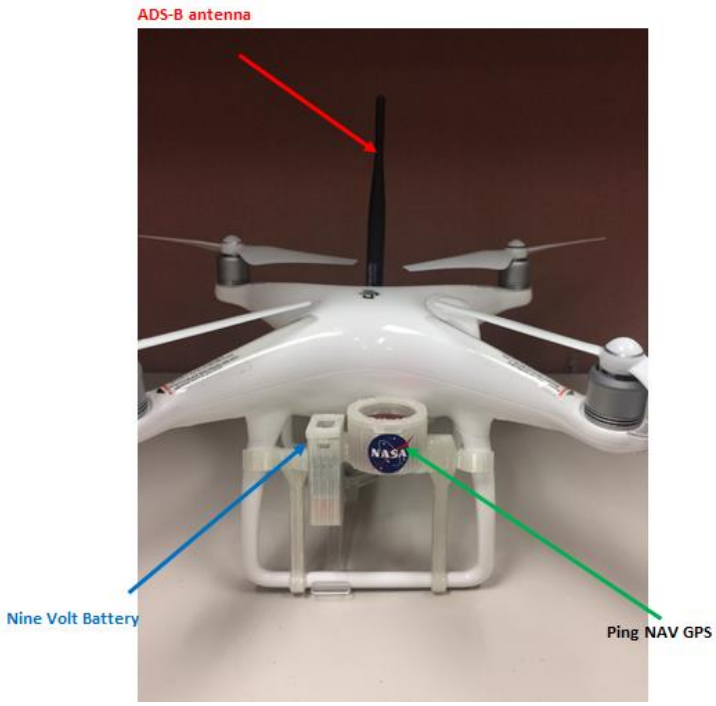

Fig. 5. ADS-B Phantom 4 intruder (Photo courtesy: NASA/Ricardo Arteaga).

B. Test Aircraft Platform

The platform vehicle used for system testing was NASA's Phantom 4 (DJI Quadrotor) Quadrotor (Fig. 6). uAvionix's ADS-B capable Ping 2020 was installed inside the 3D printed mechanical support structure. As an autonomous UAS, all data from the Ping 2020 unit required radio frequency (RF) transmission to the ground control station via the ADS-B data link.

Fig. 6. Phantom 4 DJI Quadrotor Unmanned vehicle (NASA photo AFRC2016-0365-44).

C. 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. DAA Scenarios

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

The following descriptions outline the types of DAA Scenarios were planned to be flown to test specific modes of DAA system. Scenarios were planned to be flown such that both aircraft maintain constant heading and constant airspeed to arrive at a reference point which corresponds to the CPA – this is expected to produce an RA alert prior to CPA for most scenarios. Various geometries planned for each encounter type are shown in Figure 10 but not every type of geometry was actually flown in flight test for each configuration and vertical profile. Specific scenarios were identified and briefed prior to each day’s flight. These scenarios were decided 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.

2. DAA Vertical Profiles

The following encounter profiles are considered “cooperative surveillance encounters”. Vertical separation test setup consists of various encounter geometries for the vertical profile, with independent variables -- such as airspeed, altitude varying from scenario to scenario.

Series 10: 200 feet Level (No Alert) Profile

Both aircraft will fly level throughout the encounter with 200 feet of separation between them, whereby it is expected– no corrective resolution advisory is expected. Intruder were planned to be below ownship depending on the geometry. See Figure 7.

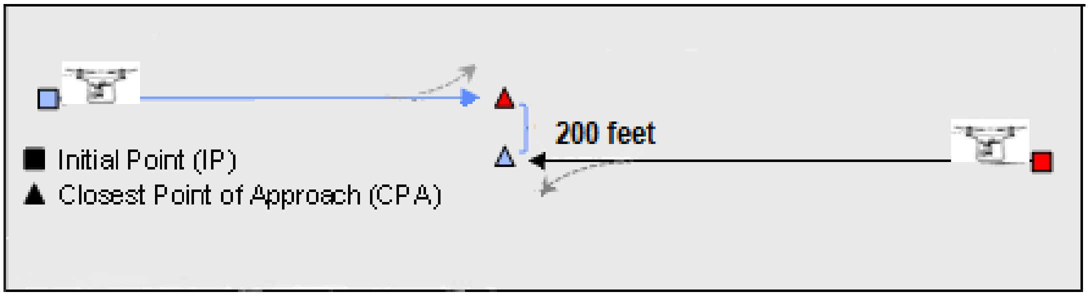

Fig. 7. Vertical Profile for Series 10 Encounters

Series 20: 100 feet Level Profile

Both aircraft will fly level throughout the encounter with 100 feet of separation between them, whereby it is expected that a corrective RA alert were planned to be issued prior to the CPA. Intruder were planned to be below ownship depending on the geometry. These scenarios were planned to be also be flown with autonomous enabled. See Figure 8.

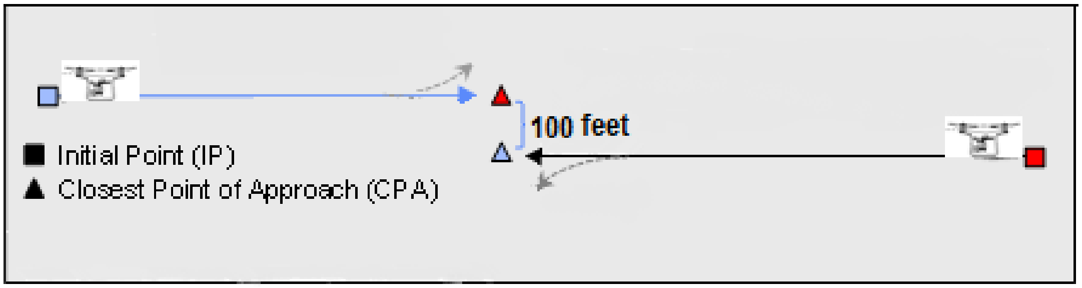

Fig. 8. Vertical Profile for Series 20 Encounters

Series 30: 50 feet Level Profile

Both aircraft will fly level throughout the encounter with 50 feet of separation between them, whereby it is expected that a corrective RA alert were planned to be issued prior to the CPA. Intruder were planned to be below ownship depending on the geometry. These scenarios were planned to be also be flown with autonomous enabled. See Figure 9.

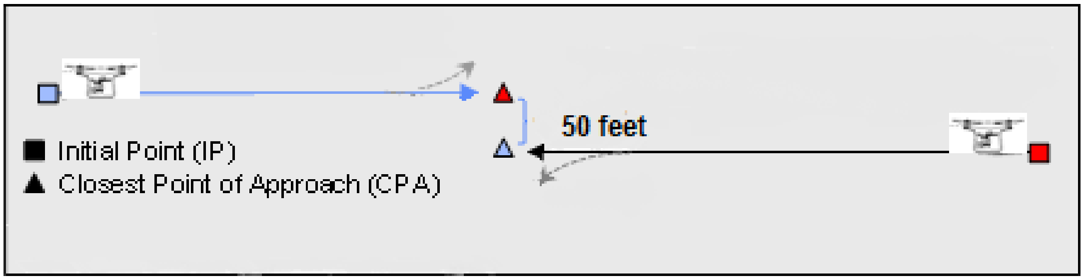

Fig. 9. Vertical Profile for Series 30 Encounters

3. DAA Horizontal Geometrics

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

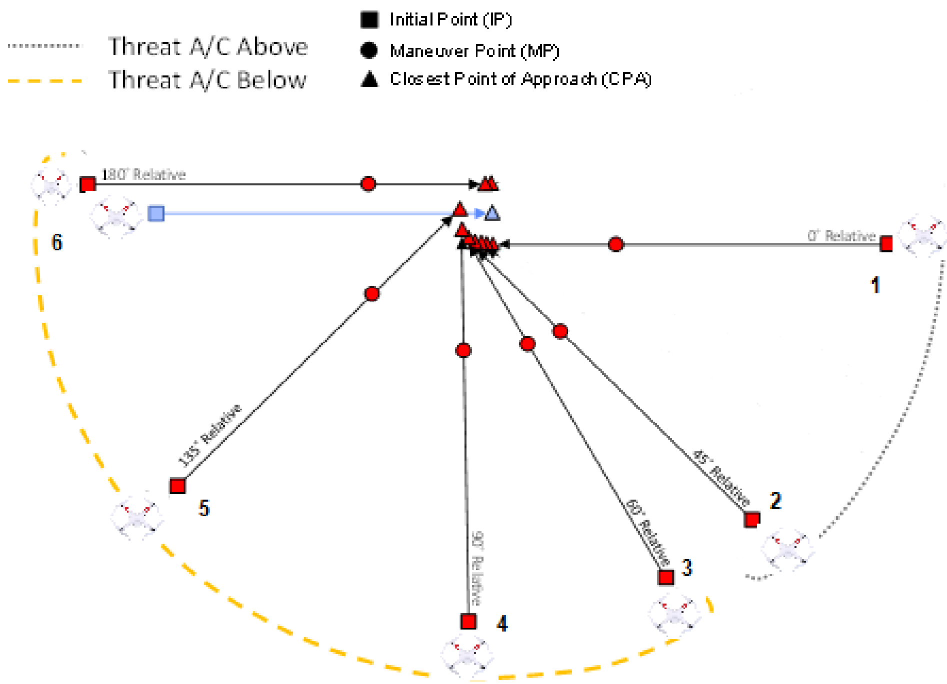

Fig. 10. ADS-B DAA Scenario Geometrics

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 **Error! Reference source not found.**. For Geometries 1 through 2 the intruder were planned to be above ownship, and for Geometries 3 through 6 the intruder were planned to be below ownship.

4. Detect and Avoid Scenario Requirements

Table 2 outlines the basic requirements for execution, safety mitigation, and prioritization for planned Detect and Avoid scenarios. Safety minimums calculated below 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

5. Flight Operating Area

The operating area for flight tests were conducted in the Muroc Model Master Complex. The airspace within the Muroc that was requested for each day of operation during this flight test are depicted within the magenta shaded area shown in breakout box in Figure 11.

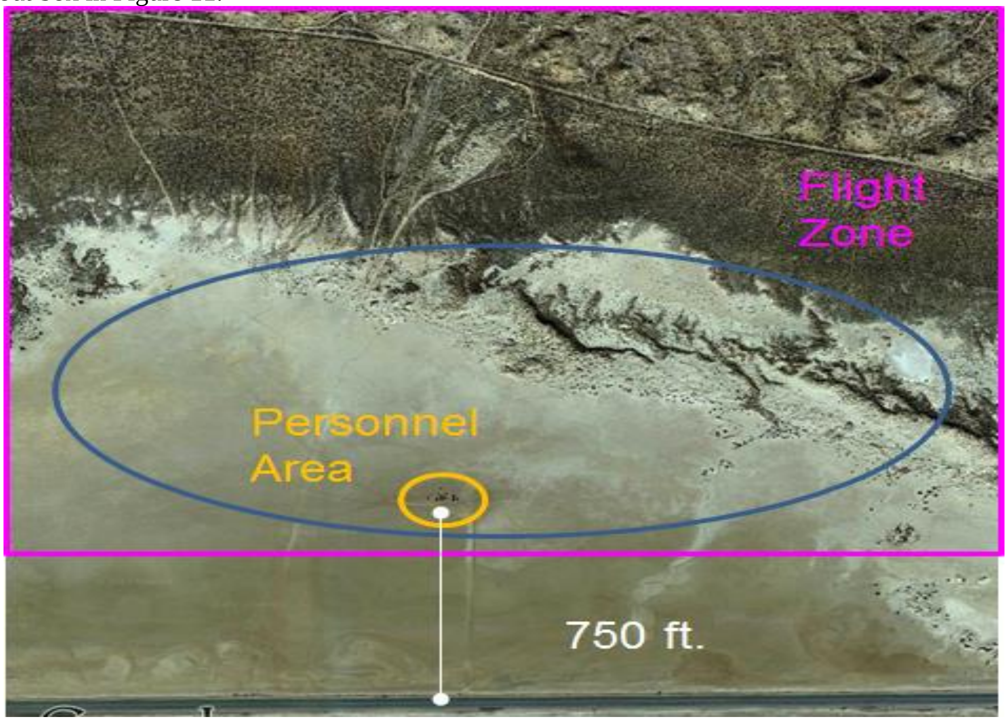

Fig. 11. Flight Operations Area

Scenarios began with both aircraft hovering at an IP with each aircraft flying toward a CPA, creating trajectories within the operating area outlined inside the Muroc flight zone as shown in Figure 12. In general, the test director requested an altitude block from 50 feet to 500 feet. Altitudes were adjusted per requirements for each scenario flown. Scenarios were planned so that they can be flown in altitude blocks other than requested so that the test can remain flexible to airspace usage.

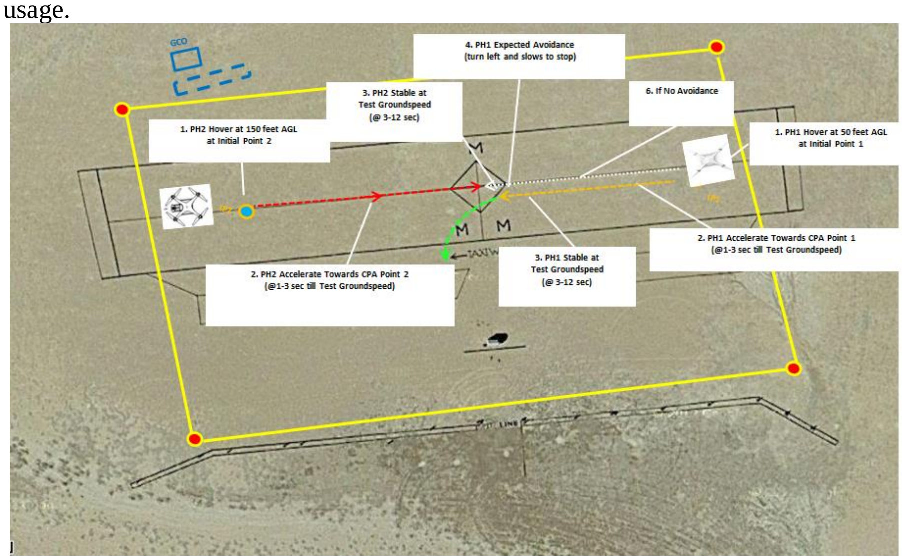

Fig. 12. Encounters Scenario Geometries

6. Simulations

The computational efficiency and performance of the ADS-B SAA 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[6] 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 nautical mile horizontal separation and 200 foot vertical separation for collision avoidance. All encounter geometries were simulated prior to the flight test execution. While executing simulations with different encounter geometries, the guidance and alerting performance is verified -- via testing different outcomes (Must Not Alert, Must Alert, Horizontal RAs, Vertical RAs) -- as well as guidance (Stratway+) algorithm proficiency with respect to numerous dependent variables or metrics such as whether it is well clear of traffic, CPA, and Alerting Time. It should be noted all the encounter geometries were verified for the DAA system performance (where an RA was expected) using the Phantom 4 aircraft performance capabilities. 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 figure 13.

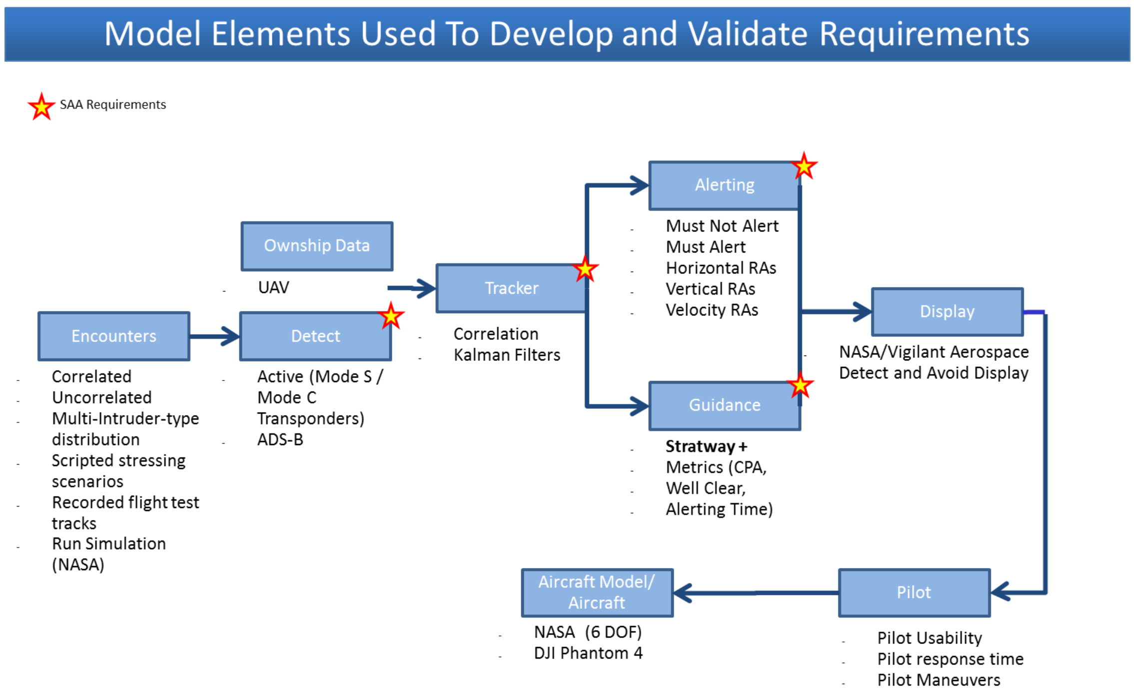

Fig. 13. Encounters Scenario Geometries

IV. 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 DAA system functionality. A flight-test procedure for demonstrating ADS-B Detect and Avoid was developed and approved by the NASA Armstrong Airworthiness and Safety Review Board (ASRB). The flight-test objective for ADS-B DAA was to:

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

D. Flight 1

The flight test objectives to validate a proof-of-concept functional flight for the UAVs and the DAA display system were successfully demonstrated. The playback of the flight data is shown in Fig. 14, indicates a total traffic count of two surveillance targets. Two targets (T1) including the DAA01 aircraft (T2) DAA02 were detected and tracked as real-time as surveillance targets. In general, the flight demonstration validated that the system receives and displays, as shown in Fig. 14, the following traffic information for targets of opportunity:

- 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) DAA001, DAA002
- Call signs DRONE1, DRONE2s

Fig. 14. ADS-B DAA Information from December 5, 2016.

The ADS-B SAA performance was evaluated for intruder aircrafts within a 0.6 nautical miles along track separation. The ADS-B SAA display is depicted in Fig. 13, 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 (i) intruder information for targets of opportunity. Motion data based on ADS-B trajectory models (blue) were generated and displayed.

E. Flight 2

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

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

Resolving these issues provided for better tracking of ADS-B targets and more accurate trajectories, as demonstrated in Figure 16, with additional traffic alert.

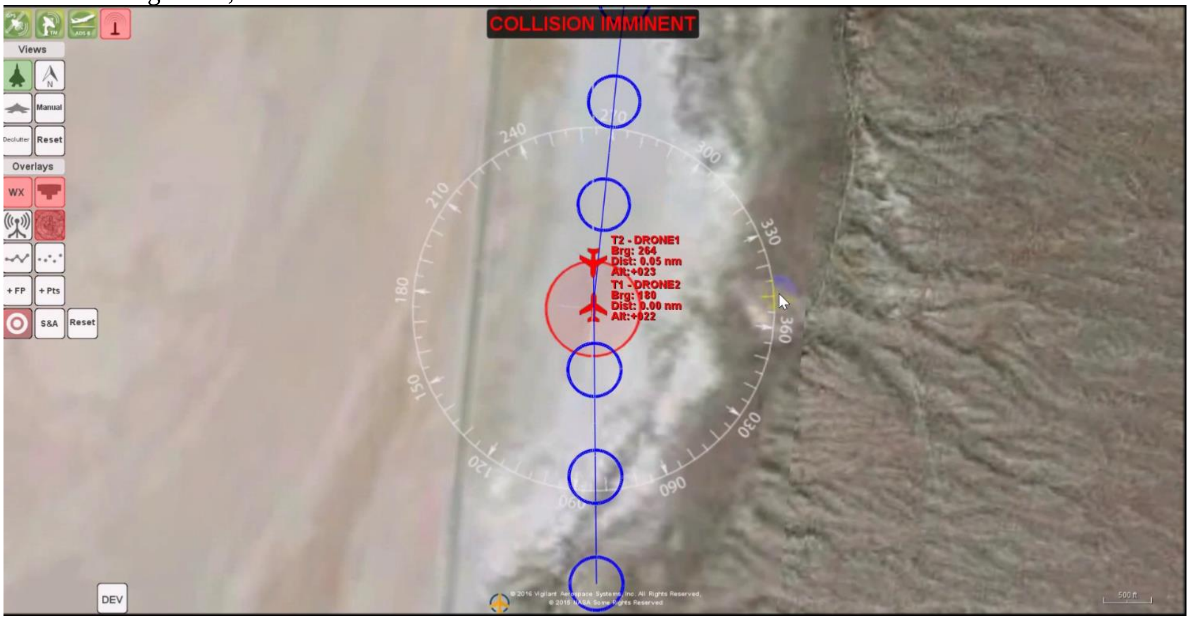

Fig. 15. ADS-B DAA traffic from December 7, 2016.

Scenarios X11 through X14 did not alert as expected. Motion data based on ADS-B trajectory models (blue circles) were generated and a collision advisory alert was displayed. The SAA algorithm accurately detected that a predicted trajectory would create a loss of safe separation with the ownship (see Fig. 15 below) and generated an alert prompting that a collision imminent was possible within (time to close point of approach) TCPA of 0 seconds.

F. 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. Issues with bad antennas and reception also slowed the development of the flight test, since one UAV would not appear until it was within the sense and avoid horizontal separation of 0.1NM due to limited transmission range; as a result, the software did not have enough time to calculate a corrective resolution advisory.

- Replacement of ADS-B transponder updating at only 4 seconds and a UAT antenna resolve the transmission issue one of the Drones (figure 16, 17).
- Replacement of the 9 volt batteries every 1.5 hours and testing the voltage to verify greater than 6 volts resolved the transmission issue.

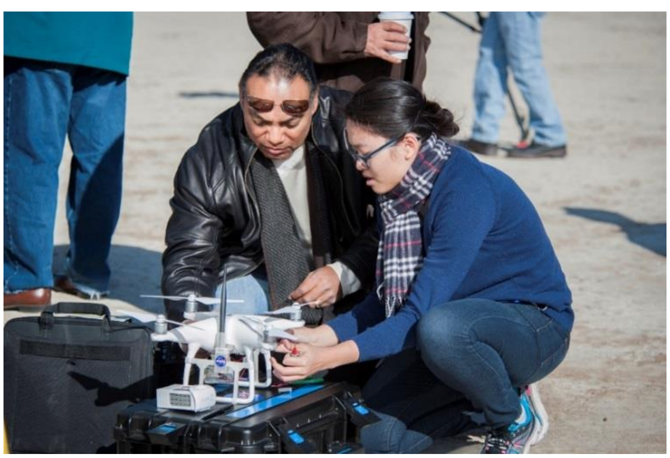

Fig. 16. ADS-B DAA tests from December 8, 2016 (NASA photo AFRC2016-0365-09)

Fig. 17. ADS-B DAA tests from December 8, 2016 (NASA photo AFRC2016-0365-09)

The DAA software did not account for quadcopter being non-linear time invariant systems; the simulations assumed the aircrafts behaviour were linear; therefore, the trajectory models use ADS-B state-based nominal trajectories. However, the Phantom 4 UAVs are capable of moving in any of the four lateral directions 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 model predictions during hover operations, since the ground tracks are unstable at very slow ground speeds.

G. Flight 4

On December 9, 2016, the team successfully flew all the flight test encounter geometries with ADS-B Out. 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 issues were resolved, the reception sensitivity of the Ping buddy antenna manifested in spotty reception of one of drone based on the direction of the Ping Buddy antenna and therefore affected the timing of the conflict resolution. The ADS-B receiver and antenna sensitivity is paramount for beyond-line-of-sight low altitude operations.

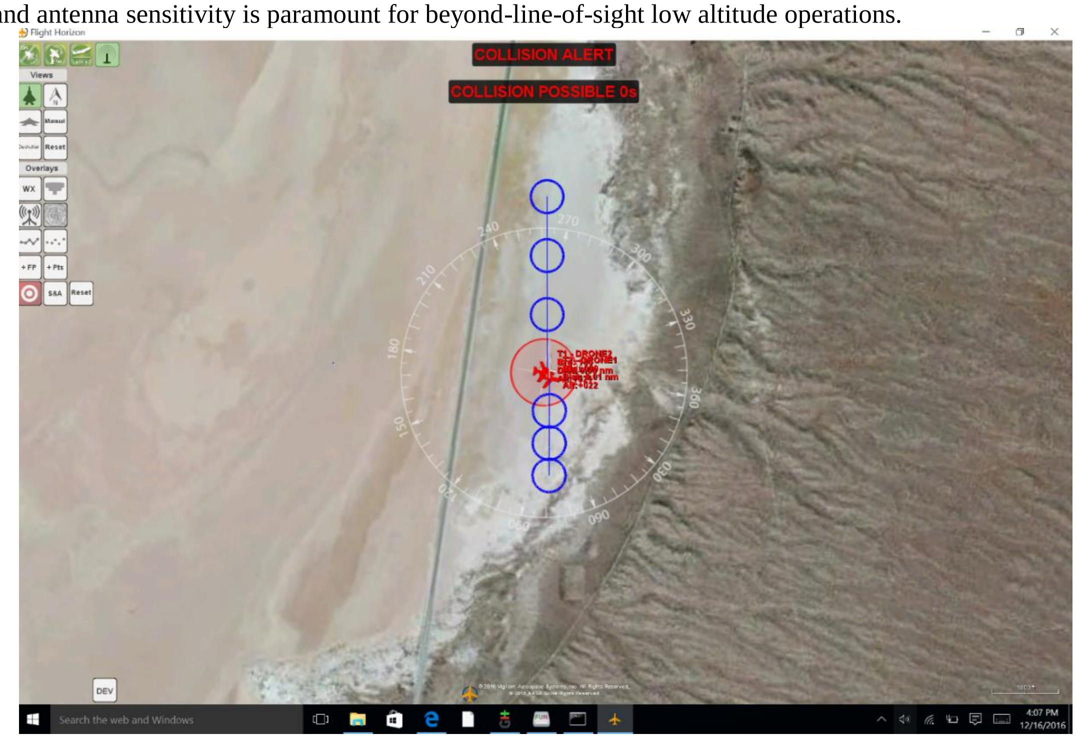

Fig. 18. ADS-B DAA flights from December 9th 2016 (Patent filed March 5, 2013; Serial No. 13/785,661).[4]

During these scenarios a conflict detection and a conflict resolution (no resolution available vocalized alert) was successfully provided to the user. No resolution alert and vocalized advisory means the operator has to manually maneuver to avoid the conflict based on the information presented. Overall the traffic detection and conflict detection and alerting of airborne traffic operated during the entire flights.

H. Lessons Learned

The lessons learned from the ADS-B DAA flight tests (Fig. 12) is that flight testing with a UAS ADS-B Detect and Avoid technology is challenging. Lessons learned include:

- Simplify, simplify, simplify, don't try to get it totally right the first time.
- Incrementally integrate the ADS-B hardware and ADS-B DAA software capability.
- Simulation of linear models are not reality.
- Timing is everything (for resolution advisories)
- Utilize plenty of 9 volt and DJI batteries during flight tests.
- Use a better ADS-B receiver antenna to increase range reception for beyond line-of-sight operations at low altitudes.
- Quadrotor UAVs are not linear time invariant systems.
- Reset the trajectories when the drone performs a hover (ground speed <3 knots).
- Ownship selection using needs to be fixed using an ICAO code for Ownship.

V. Conclusion

NASA and Vigilant Aerospace has successfully demonstrated an ADS-B DAA system coupled to a UAS to maintain safe and efficient low altitude flight operations. This novel ADS-B based collision avoidance technology enables growth in commercial application of UAS 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 line of sight, collision avoidance, and autonomous operations. The first flight phase focused on the performance needed for minimal separation provisions of multiple sUAS conducting expanded operations beyond-line-of sight. The DAA sense and avoid configuration parameter used for conflict detection and resolution included a horizontal separation of 0.1 NM and 200 feet vertical separation The ADS-B DAA alerting mechanism for conflict situation awareness for all users of the airspace, separation requirements were successfully tested between UAS operational areas, and for reporting loss of separation and mechanisms for corrective resolution advisories. Analysis, simulations, and flight tests were conducted to validate assumptions for assurance of collision avoidance in low risk environments.

The platform used for system testing was DJIs Phantom 4 Quadrotor with uAvionix's ADS-B capable Ping 2020 installed inside the mechanical support structure. All data from the unit required RF transmission to the ground station via the aircraft's ADS-B 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 antennas, transmitter, and replacing batteries. A major lesson learned was DAA design assumption was for linear time invariant systems; however, the small UAV Quadrotor behaviour is nonlinear so the trajectories did account for the non-linearity. A further improvement to the DAA algorithm would reset the trajectories during hover operations (ground speed <3 knots).

Currently, the system has undergone two highly successful flights on Dec 5 and 7th, 2016. The DAA system successfully detects conflict and provides alerting to the operator. Furthermore, the system has undergone two additional successful follow-up flights, one on Dec 8, 2016, and the other on Dec 9, 2016. Although some improvements can be made in the ADA-B receiver antenna and the nonlinear behaviour of small UAVs, both flights validated successful operation of ADS-B DAA and ultimately the system as a whole. The FAA witnessed the flight test execution of small UAS and these results have demonstrated that sUAS integration into the NAS can be efficiently accomplished when equipped with an integrated ADS-B DAA system. However, there are still several tasks to complete for future research. The DAA system's conflict resolution advisory can be completed autonomously by the UAS. In the case of the DJI 4, this would require the conflict advisory to generate and feed waypoints serially to the fligh controls. The DAA system also needs to be placed on board the system instead of requiring a ground control system. This would allow the UAS to operate outside the range of the ground control station allowing the system to tackle more complex missions.

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. NASA in collaboration with Vigilant Aerospace is testing technologies to increase drone safety and for assuring collision avoidance for sUAS in the NAS.

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