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Flight Testing an ADS-B Equipped sUAS in GPS-Denied Environments

Christopher W. Lum,* Robert Larson,† Ward Handley,‡ Selina Lui,§ and Zachary Caratao¶

Autonomous Flight Systems Laboratory

University of Washington, Seattle, WA, 98195, USA

This paper details integration and flight testing of an automatic dependent surveillance-broadcast (ADS-B) transponder onto a small unmanned aerial system (sUAS). The sUAS broadcasts ADS-B packets on 1090 MHz and is visible to any aviation stakeholder with an ADS-B in receiver. In general, this provides a means for other observers such as air traffic control (ATC) or manned traffic to track the sUAS position. However, ADS-B relies heavily on availability of the global positioning system (GPS) and cannot function properly without reliable GPS. The work includes development of a secondary position estimation system that utilizes a local area multilateration system (LAMS) to interrogate the ADS-B transponder as a standard Mode S transponder and localize the sUAS in GPS-denied environments. The system consumes position information from both ADS-B and LAMS sources and fuses these reports into consistent estimates of the sUAS position. These fused estimates are then made available to aviation stakeholders so the situational awareness of the sUAS operator is not compromised. This allows the system to operate even if the sUAS enters into a GPS-denied environment. This paper describes the development of the fusion system as well as the flight testing and results of the integrated system.

Nomenclature

ADS-B	Automatic Dependent Surveillance-Broadcast
AFSL	Autonomous Flight Systems Laboratory
AHRS	Attitude Heading and Reference System
EMI	Electromagnetic Interference
FOB	Forward Operating Base
GA	General Aviation
GCS	Ground Control System
h_{AGL}	Altitude of aircraft above ground level
HDOP/VDOP	Horizontal/Vertical Dilution of Precision
HiL	Hardware-in-the-Loop
ILS	Instrument Landing System
INS	Inertial Navigation System
MFOC	Mobile Flight Operations Center
MOA	Military Operating Area
NAS	National Airspace
PIC	Pilot in Command

*Research Assistant Professor, William E. Boeing Department of Aeronautics and Astronautics, University of Washington; Guggenheim Hall Room 211, Box 352400, Seattle, WA 98195-2400, AIAA member.

†Research Assistant, William E. Boeing Department of Aeronautics and Astronautics, University of Washington; Guggenheim Hall Room 211, Box 352400, Seattle, WA 98195-2400, AIAA member.

‡Research Assistant, William E. Boeing Department of Aeronautics and Astronautics, University of Washington; Guggenheim Hall Room 211, Box 352400, Seattle, WA 98195-2400, AIAA member.

§Undergraduate Researcher, William E. Boeing Department of Aeronautics and Astronautics, University of Washington; Guggenheim Hall Room 211, Box 352400, Seattle, WA 98195-2400, AIAA member.

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PWM	Pulse Width Modulation
SSR	Secondary Surveillance Radar
TLS	Transponder Landing System
TRAPIS	TRAnsponder-based Positioning Information System (UW developed)
UA/UAS	Unmanned Aircraft/Unmanned Aerial System
UART	Universal Asynchronous Receiver/Transmitter
UW	University of Washington

I. Introduction

A. Problem Statement

The Federal Aviation Administration (FAA) Modernization and Reform Act of 2012[1] outlines steps forward on many aviation fronts to bring aerospace into the modern era. One major initiative from this act is the mandated safe integration of UAS into the National Airspace System (NAS).[2] Another related initiative is the FAA's Next Generation Air Transportation System (NextGen)[3] which showcases the ADS-B system as being a key component for both manned and unmanned traffic.[4] However, a recent investigation by the US Department of Transportation Inspector Generals Office[5] specifically identified these two areas behind schedule and in need of additional development. This paper focuses on developing technology that addresses these shortcomings and will therefore be vital to the progress of the anticipated $13.6 billion civilian UAS market.[6] ADS-B relies heavily on availability of the GPS and cannot function properly without reliable GPS. Further, several elements of the US Department of Defense have repeatedly requested systems and methods which enable UAS operations in GPS-denied situations. This work considers integration and flight testing of an ADS-B equipped sUAS in a GPS-denied environment. It will focus on technical issues associated with integrating a small form factor ADS-B unit with existing UAS avionics. Another major contribution of this paper is the documentation of the operational issues associated with coordinating GPS-denied UAS operations in conjunction with manned aviation within the current FAA regulatory environment.

B. Literature Review

1. Previous Work at the University of Washington

Work at the Autonomous Flight Systems Laboratory (AFSL) at the UW typically focuses on strategic algorithm development for UAS operation such as a search and rescue,[7,8] aerial mapping[9,10] and surveying.[11,12] The AFSL has also investigated situational awareness[13] and human-in-the-loop architectures for UAS operation.[14] Early flight testing work focused on indoor flight testing[15] by collaborating with industry partners, such as Boeing.[16]

2. Related Works

Although previous work in the area of ADS-B implementation on sUAS aircraft is limited, several major studies have been conducted in similar vein as the research presented in this paper. In 2009, researchers at the University of North Dakota presented software-in-the-loop simulations for an sUAS sense and avoid algorithm which made use of ADS-B information.[17] Another 2009 study involved an ADS-B based collision avoidance system to be used by sUAS in airspace with other unmanned and manned aircraft operating simultaneously.[18] A 2013 study investigated the possibility of incorporating ADS-B transponders on sUAS and presented a case study to include recommendations for ADS-B regulations regarding sUAS aircraft.[19] More recently, researchers investigated additional sense and avoid algorithms with access to multiple data streams to include traffic collision avoidance system (TCAS) and ADS-B information.[20] While studies such as these have largely focused on future regulations and algorithms for operating sUAS in airspace shared with other sUAS and manned aircraft, the research presented in this paper was focused on demonstrating the use of an ADS-B transponder on a commercially-available sUAS and tracking the aircraft in real time with ADS-B and secondary LAMS unit for GPS-degraded and GPS-denied operations.

II. Experimental Methods

This section describes the experimental hardware used in this research as well as the experimental methodology and planning used to execute flight tests.

A. ADS-B Payload

The ADS-B transponder used for this project was a Sagetech Corporation model XPS-TR, which is shown in Figure 1(a). The sUAS remote pilot in command (PIC) on the ground selects the appropriate ADS-B transponder mode (e.g. ALT, IDENT, etc.) using a commercial off-the-shelf (COTS) 2.4 GHz RC transmitter/receiver pair. Onboard the sUAS, an Arduino Mega 2560 was used to ingest and translate Universal Asynchronous Receiver/Transmitter (UART) telemetry messages from the Pixhawk autopilot, read pulse width modulation (PWM) signals from the receiver, and then send the appropriate proprietary Sagetech RS232 command messages to the XPS-TR. This architecture was based off of prior open source work published by Smart Project Holdings Ltd. available on `GitHub.com` with added features for simulating GPS-denied operations.[21,22] The wiring diagram[23] for the ADS-B payload is shown in Figure 2.

(a) Sagetech Corp. XPS-TR ADS-B out transponder.

(b) Sagetech Corp. Clarity ADS-B in receiver.

Figure 1. Sagetech ADS-B systems used.

The customized and integrated payload of ADS-B, RC receiver, and Arduino is the primary hardware described in this paper. These components are parts of the TRAnsponder-based Positioning System (TRAPIS) and is hereafter referred to as the TRAPIS payload. The overall TRAPIS system is described in Section II.C.2.

B. Local Area Multilateration System (LAMS)

The Local Area Multilateration System (LAMS), shown in Figure 3, is a compact surveillance radar developed by the Advanced Navigation and Positioning Corporation (ANPC). LAMS is a split-off portion of the ANPC Transponder Landing System (TLS),[24] which is used for IFR approaches at airports in difficult terrain where traditional instrument landing system (ILS) approaches are impossible.

As is typical of multilateration systems, the LAMS precisely measures the time delay between the Mode S interrogation response from an aircraft with an array of antennas (Figure 3(a)). The time for the signal to reach each antenna is slightly different due to the fact that the distance between the transponder and each antenna varies. Each antenna constrains the aircraft location to a point on a sphere centered at the antenna; by overlapping three or more antennas, a 3D solution for the aircraft location can be found. Additional information such as the Doppler shift of the signal can be used to determine the radial velocity of the aircraft. This information is ingested by the LAMS and relevant information is processed and displayed to users. For example, Figure 4(a) shows the local air traffic around a LAMS installation at the Columbia Gorge Regional Airport (KDLS).

The novelty of the LAMS lies in its small footprint, mobile design, short setup time (several hours), and low cost as compared to traditional airport infrastructure such as Secondary Surveillance Radar (SSR) or an

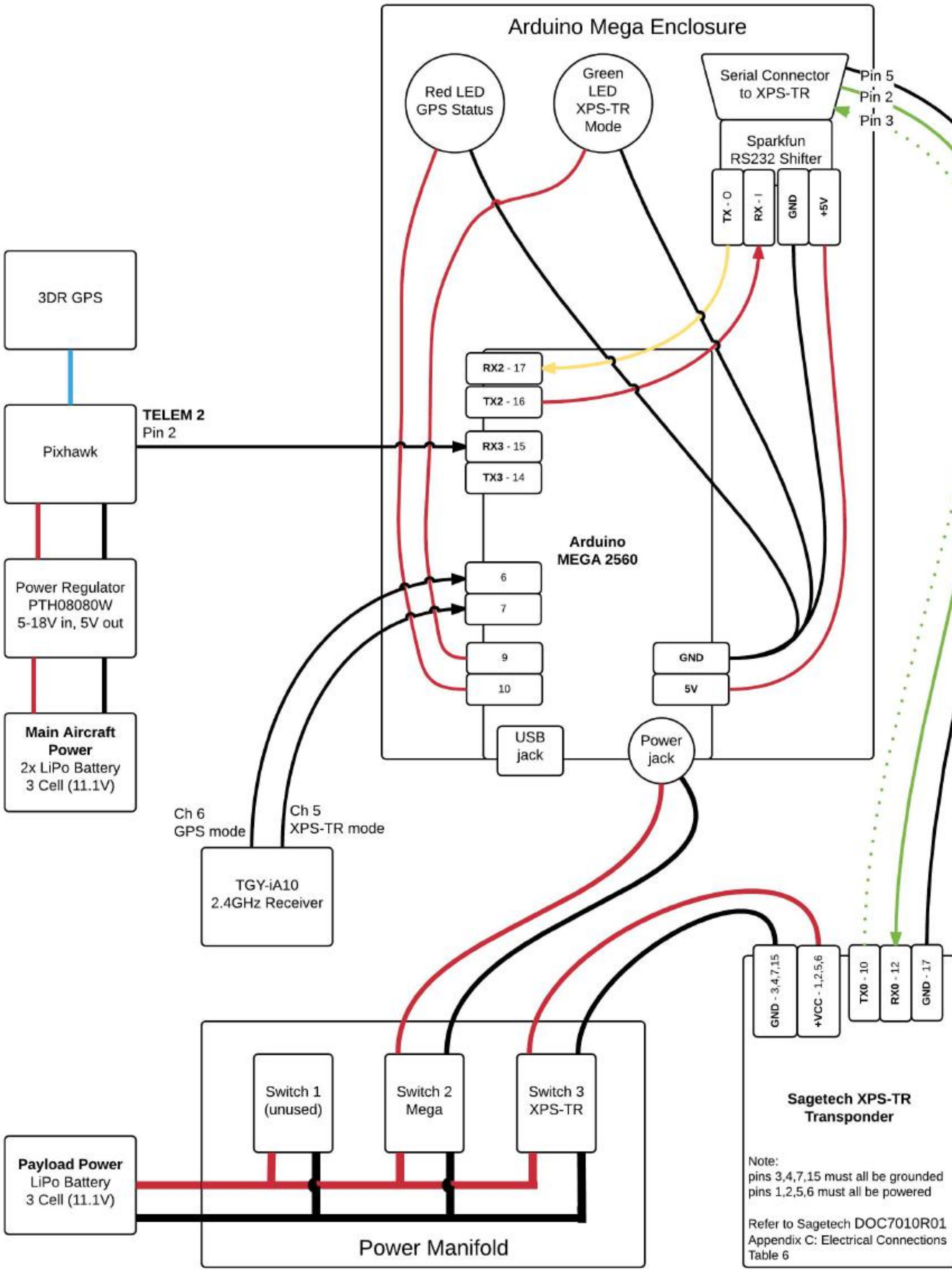
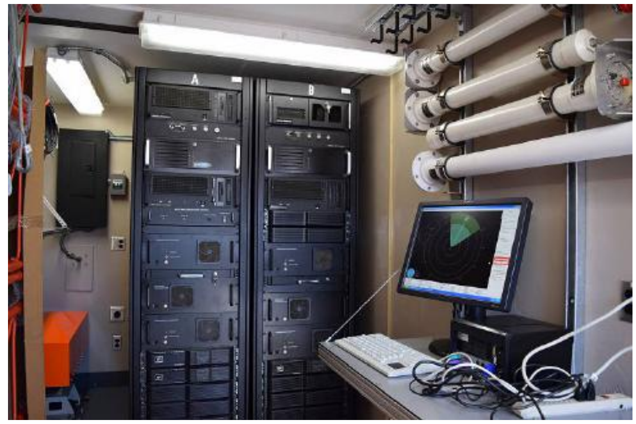


Figure 2. Wiring diagram for ADS-B transponder integrated with sUAS avionics.

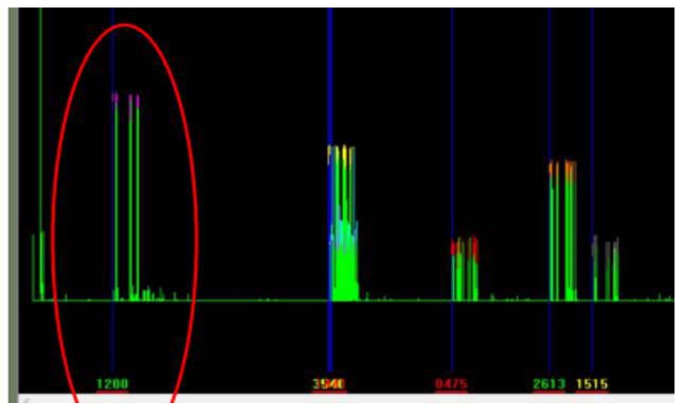
(a) LAMS installed at KDLS.



(b) Interior of a LAMS unit.

Figure 3. LAMS physical setup.

(a) LAMS surveillance display.



(b) Measurement of raw transponder measurements (squawk codes shown on bottom).

Figure 4. LAMS interface and measurements.

ILS. The LAMS is particularly valuable for deployment to remote areas or for temporary installations such as geographic surveys, fire fighting, search and rescue operations, polar research stations, or a military forward operating base (FOB). In these situations the LAMS operates as a valuable augmentation and backup to on-board positioning technologies such as GPS or inertial navigation systems (INS) in the event of equipment failure, obscured line of sight to GPS satellites, or GPS denial through jamming.

C. UAS Components

1. *Aircraft*

The sUAS flown in this experiment was a Skywalker 1900. This is a fixed wing aircraft with a 1.9 m wingspan that has a measured mass of 2.917 kg with all of the internal components. It carries a 5000 mAH 3S battery giving it an endurance of approximately 15 minutes. The center of gravity was placed 17.75" aft of the nose. The Skywalker 1900 was selected for testing because it has sufficient internal volume to integrate payload and it can safely and reliability be launched and recovered in a variety of environments. The sUAS used the Pixhawk[25] autopilot system to control the sUAS. The Pixhawk system contains components, such as the 3DR GPS + Compass module to gather position information, and the 3DR Telemetry radio to communicate with the ground control station (GCS).

The sUAS required modifications in order to install the TRAPIS payload within the fuselage of the aircraft. Removing a section from the bottom of fuselage provided not only more fuselage space, but also increased the ease of accessibility to TRAPIS payload housed inside of the aircraft. A removable 3D printed cover was manufactured to protect the exposed payload, support the structure of the aircraft, and conform to the sUAS's fuselage. Major components associated with the sUAS used for flight testing are shown in Table 1. At the time of this writing, to the best of the authors knowledge, this is the smallest, lightest ADS-B equipped aircraft in the world.

	Components	**Comment**
Guidance, navigation and control	Pixhawk with Arduplane firmware	See reference 25
Flight Control Surfaces	Aileron (2 servos on 1 channel)	Turnigy^{TM}TGY-50090M Analog Servo MG 1.6 kg/0.08 sec/9g
	Rudder (1 servo on 1 channel)	
	Elevator (1 servo on 1 channel	
Propulsion	Motor	Turnigy^{TM}D3542/6 1000 KV Brushless Outrunner Motor
	Propeller	APC LP09060E Thin Electric Propeller (9x6 in.)
	Battery	Turnigy^{TM}5000mAh 3S 25C LiPo Pack
	ESC	Turnigy^{TM}TRUST 45A SBEC Brushless Speed Controller
	Thrust	1260 g
Communication	Standard 2.4 GHz RC transmitter/receiver combination	Turnigy ^{TM}TGY-i10
TRAPIS Payload	Arduino Mega 2560	See Figures 1 and 6
	Sagetech Corp. XPS-TR ADS-B out transponder	
	Sagetech Corp. Clarity ADS-B in receiver	
N-number & ICAO	N632UW (A84701) w/ squawk code 1253	Original (bad) transponder was N6321VW (A84363)

Table 1. Major sUAS components used for experiment.

2. Ground Control Station

The UW utilizes a Mobile Flight Operations Center (MFOC) to conduct flight operations. The MFOC is a enclosed trailer that has been heavily modified by the AFSL. It is a comprehensive, stand-alone platform for sUAS flight operations in the field. It consists of the GCS and auxiliary utilities such as a 120 VAC generator, Kestrel 5500 weather meter, 4G LTE mobile hotspot, Sagetech Clarity ADS-B receiver (Figure 1(b)), an iPad running the WingX Pro application, a sUAS tracking platform, workbench, battery charging station, first person view (FPV) transmitter/receivers, and additional flight operations equipment.

The GCS is comprised of a desktop or laptop computer running Mission Planner and the custom built TRAPIS software. Mission Planner is a popular ground station application for planes, copters, and rovers that uses the Ardupilot family of controllers. Through the data telemetry link (3DR radios at 915 MHz), the GCS operator can monitor aircraft movement, controls, RC mode switching, battery levels, and GPS health. After a flight test, the GCS team can analyze and archive recorded flight test data.

TRAPIS is the software cornerstone of this project. It is a C# application with Windows Presentation Foundation (WPF) graphical user interface (GUI) (Figure 7). The essential functions of TRAPIS are manifold: ingesting aircraft surveillance data in the form of ADS-B and CAT48 packets, data handling (buffering, transfer, storage), data processing using a custom-built filters, and providing situational awareness to the operator. ADS-B data is collected via a Sagetech Corp. Clarity ADS-B in receiver on 978 and 1090 MHz (Figure 1(b)), which then relays these messages via WiFi to TRAPIS and WingXPro. LAMS data (CAT48 packets) are delivered over Ethernet to TRAPIS. Sagetech Corp. and ANPC provided realistic simulators to assist in the development and testing of TRAPIS. Additional simulation scenarios and tools such as data replay were developed in-house. The overall block diagram of TRAPIS is shown in Figure 6.

TRAPIS ingests both ADS-B and LAMS data and displays this to the operator. Both streams appear as separate position measurements and the operator must manually pair an ADS-B and LAMS stream corresponding to the same aircraft.

After pairing the two data streams TRAPIS instantiates unique estimators, such as Kalman filters, for each data stream. These two estimates are then fused together to provide a single, consistent estimate of the aircraft position. Specific details of this fusion and estimation process are beyond the scope of this paper and are discussed in a separate publication.[26]

Figure 5. The interior of the MFOC.

D. Manned Aircraft

In order to demonstrate sUAS transponder operations in a realistic general aviation (GA) airport environment, two manned aircraft were used during the flight demonstration. These aircraft operated in flight testing locations southeast and southwest of the KDLS airfield to ensure geographic separation from all sUAS operations. Manned aircraft support was provided by TacAero Inc., an aircraft training center located at the Ken Jernstedt Airfield (4S2) in Hood River, OR.

The two manned aircraft flown for the demonstration were a Vans RV-12 and a Cessna C172SP. These two aircraft were chosen in order to provide a comparison between disparate aircraft types equipped with different types of transponders.

The RV-12 owned by TacAero Inc. was factory-built at Synergy Air in Eugene, OR and utilized an ADS-B-compliant transponder. The Vans RV-12 shown in Figure 8(a) was flown during the flight demonstration. The tail number for the RV-12 was N484TA.

The Cessna is a high-wing, single engine general aviation aircraft that has remained a popular training aircraft since its inception in 1955. Unlike the Vans RV-12, the Cessna owned by TacAero Inc. does not use an ADS-B-compliant transponder, and instead operates a standard Mode C transponder with altitude encoding capability. A representative version of the Cessna is shown in Figure 8(b). The tail number of the Cessna that flew during the flight demonstration was N562AE. Within the scope of the FAA NextGen 2020 ADS-B transponder requirements, these two aircraft provided a direct comparison of aircraft tracking capabilities using ADS-B and non-ADS-B methods. Furthermore, the presence of manned aircraft during sUAS testing was intended to resemble scenarios in which sUAS and manned aircraft will operate simultaneously in nearby airspace. Based on the rapid and continued growth of the sUAS industry, such scenarios will occur with increasing frequency in the near future.

E. Hardware-in-the-Loop Units

The RV-12 and Cessna were instrumented with a flight data acquisition system to facilitate the capture of data during the experiment. These units contain all of the electrical components found in a fully functional sUAS, but are packaged in a form factor GA aircraft can easily carry. As such, these units are referred to as hardware-in-the-loop (HiL) units and called HiLPixhawk1 and HiLPixhawk3 (Figure 9). Since the HiLPixhawk units are equipped with the same avionics as the sUAS, they can also record data flash logs when placed in a manned aircraft. The data flash logs allow for a record of different flight characteristics, such as vibration, power consumption, altitude, and GPS position. The HiLPixhawk units are used to provide a secondary measurement of GPS position and altitude data that can be used to compare the LAMS and ADS-B data as recorded by TRAPIS and the LAMS for the manned aircraft.

F. Experimental Setup

1. Initial Flight Testing

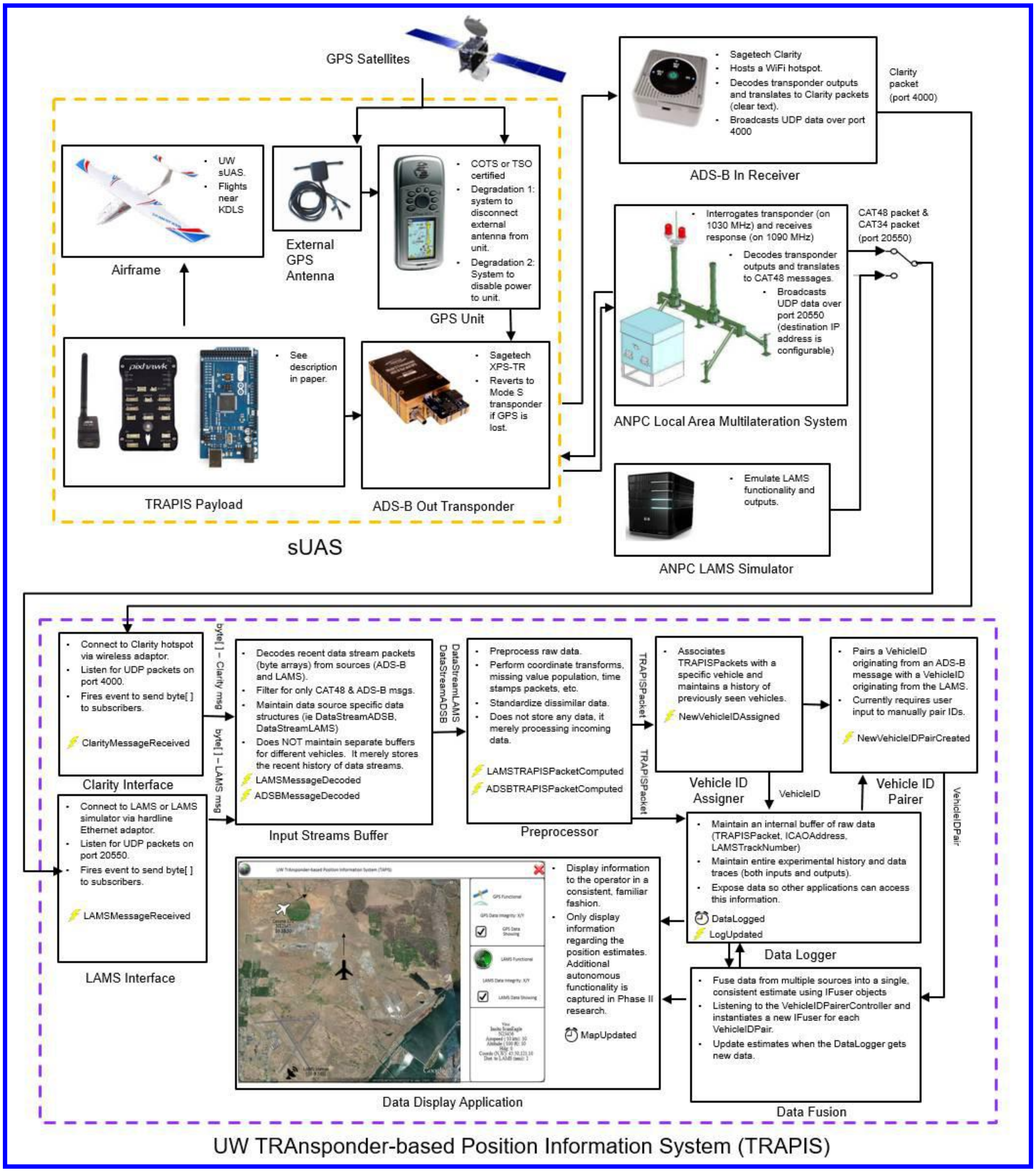


Figure 6. TRAPIS block diagram.

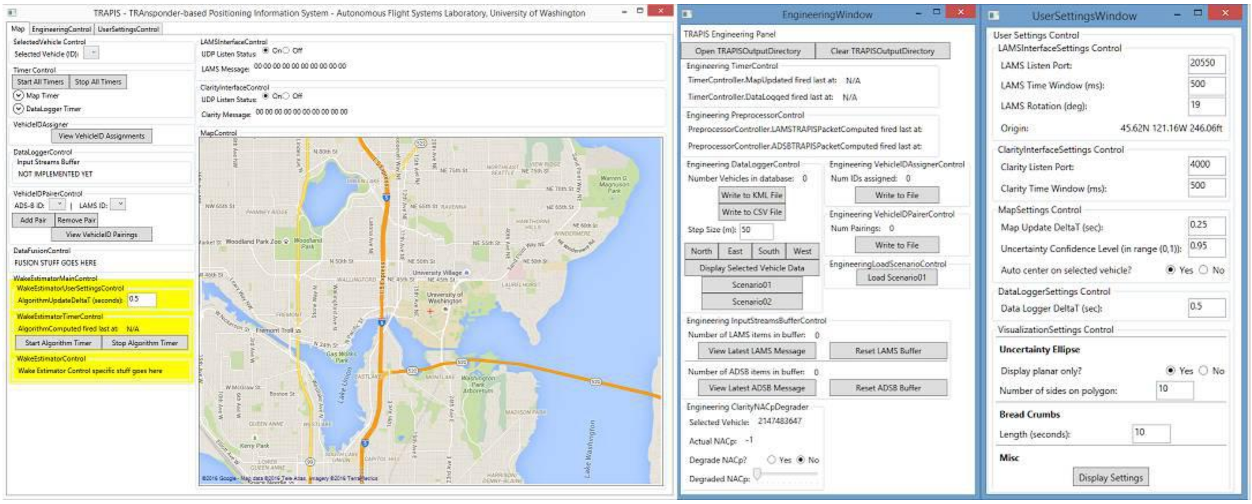


Figure 7. TRAPIS Graphical user interface.

(a) The Vans RV-12 (N484TA).

(b) A Cessna C172SP similar to the one used in the experiment.

Figure 8. The manned aircraft participating in the demonstration.

Before the flight demonstration at KDLS, several local flight tests were conducted with the sUAS carrying the TRAPIS payload. These initial flight tests were carried out in order to ensure that all test cards could be completed successfully while tracking the sUAS with an ADS-B in receiver. Additionally, these tests served to validate TRAPIS software performance in a real-world environment with manned aircraft operating at various altitudes near the test airspace. Note that these tests were not able to exercise consuming a stream from an actual LAMS system (the nearest system was located at KDLS) but a LAMS simulator software package was used to provide a high fidelity alternative.

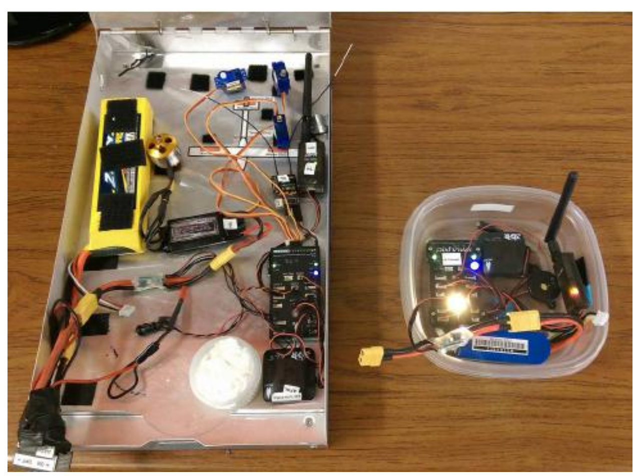


Figure 9. HilPixhawk1 (left) recorded the RV-12 flight and HiLPixhawk3 (right) recorded the Cessna flight path.

All preliminary flight testing was conducted at Meadowbrook Farm, a test airspace currently used for all AFSL local sUAS flight testing located in North Bend, WA. The test site is a 64 acre field located 25 miles east of downtown Seattle at 47.518868 N, 121.802444 W. The flight testing location can be reached from the UW in 40 minutes by car. The site was selected for additional reasons outside of proximity and travel time, and the location proved valuable for both sUAS flight testing and transponder testing considerations. Prior to the implementation of 14 CFR Part 107 on August 29, 2016, all AFSL flight operations were conducted under Certificate of Authorization (COA) 2016-WSA-23-COA. The terms of the COA required that all AFSL flight operations take place in Class G airspace below 400 feet AGL with aircraft weighing less than 55 lbs. Once these COA restrictions were accounted for, further precautions were taken to ensure that all transponder testing would not interfere with commercial and private aircraft operations. Since no previous test data had been gathered to ensure the validity of the transponder altitude reporting capabilities, the decision was made to conduct all transponder testing outside of the confines of the Seattle Class B airspace. Meadowbrook Farm is located outside of the Class B airspace shelf and allowed test crews to fly sUAS aircraft up to 400 feet AGL while remaining within Class G airspace.

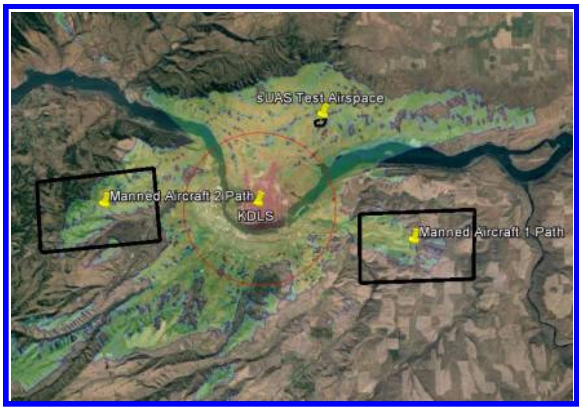
2. Test Site Selection

In order to ensure that all operations in the Columbia Gorge near KDLS were conducted in accordance with COA and FAA requirements, and in the interest safety for persons and equipment involved in the flight test, exhaustive site studies were conducted. The site studies led to the development of a detailed test plan which required coordination with multiple agencies and personnel.

After ground testing in Seattle was completed in the spring of 2016, preparations began for the final TRAPIS flight demonstration in the fall. Based on the results of the ground tests coupled with ADS-B and LAMS limitations, it was known that line-of-sight would be required between the sUAS and the KDLS ground station for all flight operations. Additionally, COA requirements stipulated that all flight operations would need to be conducted at altitudes less than 400 feet AGL. Furthermore, the COA required that all sUAS operations in Class G airspace near a non-towered airport with published instrument flight procedures must occur more than 3 nautical miles from the airport reference point. In order to determine suitable flight test locations subject to these criteria, an RF site survey was conducted. This survey was completed using Radio Mobile RF analysis freeware coupled with with guidance provided by ANPC personnel. The software allowed coverage maps to be created for the areas surrounding the KDLS airport subject to RF specifications of the LAMS unit and the XPS-TR transponder unit.

After it was determined that flight testing would be conducted at altitudes ranging from 200 feet AGL to 400 feet AGL at least 3 NM from the airport to comply with COA restrictions, corresponding RF coverage plots were created. These coverage plots ensured that line-of-sight and adequate RF signal strength would be maintained between the sUAS transponder and the LAMS station at the distances and altitudes required for the flight test. Ultimately, potential flight test locations were determined by coverage maps generated for the 200 feet AGL condition, since this altitude proved to be the most restrictive when considering obstacles and ground clutter. RF signal strength estimates at possible test sites were determined by using a simulated stationary antenna located at the KDLS airfield to represent the LAMS station. The power and frequency specifications of the real LAMS station were modeled in order for this simulated antenna to accurately model the LAMS station. An additional antenna with power and frequency specifications matching those of the XPS-TR transponder was modeled. Terrain information was gathered from the data archives of the Space Shuttle Radar Topography Mission for the areas surrounding the KDLS airfield. Once this terrain data was gathered it was provided to the Radio Mobile software, and the transponder antenna elevation was set at 200 feet AGL. Based on these inputs, RF coverage maps were generated for the area surrounding KDLS.

The selected test sites are shown in Figure 10(a). The test location for the sUAS is shown in more detail in Figure 10(b). This area is a part of the Columbia Hills History State Park and as such, required approval from the Washington State Parks Department to utilize the area for research. A Right of Entry Permit (#P471004UNI1) was obtained for this activity. The test site was easily accessed through the use of Dalles Mountain Road, and was located approximately 20 minutes from the KDLS airport by car. The test location provided approximately 155 acres from which to carry out the sUAS operations and met all COA requirements necessary to conduct full testing of the TRAPIS system.



(a) Final flight test airspace with radio signal stregth predictions. The longitudinal width of the manned flight paths was 4.5 NM.

(b) KDLS planned and alternate test location for the sUAS. The longitudinal width of the sUAS flight path was 0.30 NM.

Figure 10. Airspace and test site location selection of all sUAS and manned aircrafts.

3. Test Planning

After the flight test location had been selected, the sUAS flight path was developed. Based on COA requirements and previous flight testing, a rectangular flight path was defined within the test airspace as shown in Figure 10(b). The rectangular pattern was designed to match the rectangular flight path used for the preliminary testing of the sUAS at Meadowbrook Farms. The flight path fit within the confines of the approved flight testing airspace with sufficient margins on all sides to prevent airspace breach in the event of diversion from the planned flight path. The long edges of the rectangular flight path were defined to be 0.30 NM, and the short edges were defined to be 0.15 NM for a total flight path distance of 0.90 NM and a total encompassed area of 38 acres.

The sUAS flight path in Figure 10(b) shows the flight path as defined using the Mission Planner software used on the GCS computer for autonomous operations. In consideration of the altitude restrictions imposed under the AFSL COA, the aircraft altitudes were set at 350 feet AGL between the first and second waypoints and 250 feet AGL between the third and fourth waypoints. The flight path was designed for the aircraft to climb between the fourth and first waypoint and descend between the second and third waypoints. Defining the flight path in this manner ensured that the initial flight testing at Meadowbrook Farms closely mirrored the KDLS flight testing.

Once the sUAS flight path was defined, the manned aircraft flight paths needed to be defined. At this stage of planning, flight safety considerations had to be taken into account to ensure that sUAS and manned aircraft operations could occur simultaneously while minimizing potential conflicts. In order to ensure adequate separation was maintained between manned and remote aircraft operations, the manned aircraft flight paths were defined to the west and to the southeast of the KDLS airfield, several miles from the sUAS test airspace as shown in Figure 10. Each manned aircraft flight path was defined in the same rectangular fashion as the sUAS flight path, with long side lengths of 4.5 NM and short side lengths of 2.7 NM for a total flight path distance of 14.5 NM and a total encompassed area of 1822 acres.

In order to ensure that proper vertical separation was maintained between all aircraft participating in the flight demonstration, altitudes were established for the manned aircraft flight paths. In keeping with the planned sUAS flight path, the manned aircraft flight paths included climbing and descending portions on the short legs with constant altitude portions on the long legs. Furthermore, the altitudes were selecting in order to comply with an FAA rule governing allowable VFR traffic altitudes. This rule requires that aircraft operating under VFR conditions above 3,000 feet AGL flying a heading between 000 degrees and 179 degrees must fly at odd-thousand foot altitudes plus 500 feet (e.g. 3,500 5,500), and aircraft flying a heading between 180 degrees and 359 degrees must fly at even-thousand foot altitudes plus 500 feet (e.g. 4,500 6,500). This rule ensures adequate separation is maintained between VFR aircraft traveling in separate directions, and the 500 foot addition ensures adequate separation is maintained between VFR and IFR traffic.

For the first manned aircraft flight path to the southeast of the KDLS airfield, the plan was for the aircraft to fly counter-clockwise around the flight path. The long leg on the north side of the path would be flown at 4,500 feet MSL, and the long leg on the south side of the path would be flown at 3,500 feet MSL. The climbing leg was the eastern short leg and the descending leg was the western short leg of the flight path. The second manned aircraft flight path to the west of the KDLS airfield required the aircraft to fly clockwise around the flight path. The long leg on the north side of the flight path would be flown at 5,500 feet MSL, and the long leg on the south side of the flight path would be flown at 6,500 feet MSL. The climbing leg was the eastern short leg and the descending leg was the western short leg.

A risk assessment[27,28] of the operation taking into account the location of the UAS and participating manned aircraft as well as the general density of non-participating aircraft in the area was performed.[29] It was determined that the spatial separation of the vehicles was sufficient to ensure sufficient safety during the operation. The chosen altitudes ensured that even at their closest, the manned aircraft would have 1,000 feet of altitude separation and 8 NM of lateral separation. Both of the manned aircraft had a minimum of 4 NM of lateral separation from the sUAS flight path and maintained vertical separation of over 1,000 feet. The final flight plan ensured that no unnecessary risks would be taken during the flight testing.

4. Logistics and Coordination

After all flight test locations and airspaces were finalized, coordination was required to ensure the flight test would proceed as planned on the day of the test. Due to the nature of the flight test with ground crews, sUAS flight crews, and manned aircraft operating in nearby airspace, it was imperative to ensure proper communication was maintained between all involved parties. In order to facilitate this communication, several protocols were developed.

The first problem to be addressed focused on maintaining communication between AFSL ground crew members located at the KDLS airfield and AFSL flight crew members located at the sUAS test site location. During normal AFSL flight testing operations at Meadowbrook Farms, ground station personnel and flight crew personnel are located in the same vicinity, and communications between required personnel are maintained through the use of a conference call on cell phones with hands-free devices. Ground testing conducted in the spring of 2016 indicated that cell phone reception at the sUAS test site would be inconsistent, and therefore other communications options were researched. The plan called for using the cell phone conference call as the primary means of communication between the AFSL ground crew at KDLS and the AFSL flight crew at the flight test location. If cell phone reception proved to be unreliable, the secondary means of communication involved using CB radio units on CB channel 12. Ultimately, cell coverage on the test day allowed for communications via the conference call.

Once a communications solution was devised for AFSL communications between the KDLS ground crew and the flight crew, communications between AFSL personnel and the manned aircraft were considered. During pre-test briefings, the pilots of the manned aircraft were informed of the test plans to include designated test airspace flight paths and altitude blocks. In order to facilitate communication between the manned aircraft pilots and the sUAS ground crew during testing, test crews communicated via the common air-to-ground frequency of 122.9 MHz. The sUAS remote pilot was able to communicate with the manned aircraft pilots from the sUAS ground station by using a Yaesu hand-held air band radio. Additionally, the manned aircraft pilots were able to report flight path progress to the sUAS ground crew, and the pilots were able to communicate with one another in order to avoid any potential aerial conflicts during the flight testing period.

G. Test Cards

1. Planned Test Cards

Considering the initial research goals and the overall scope of the project, several main tests were designed for the KDLS flight demonstration. These tests were intended to demonstrate the aircraft tracking capabilities of the TRAPIS code in GPS-degraded and GPS-denied environments while simultaneously demonstrating operation of a sUAS operating with an ADS-B out transponder in the same airspace as manned aircraft.

In order to demonstrate the full range of TRAPIS code and payload capabilities during a one-day flight demonstration, five test cards were created, each corresponding to a separate flight of the sUAS and are summarized in Table 2.

In each case, the planned flight involved the sUAS aircraft autonomously flying a rectangular path. Each of the test flights were designed so that the aircraft would navigate the flight path a total of five times before returning to loiter around the home point at an altitude of 250 feet AGL. After becoming established in

Test Card	Description	Summary
1	Normal	Full GPS and LAMS
2	GPS-degraded	Use LAMS with degraded ADS-B
3	GPS-denied	Use LAMS only, ADS-B fully denied
4	Intermittent GPS	Cycle between normal, degradation, denial
5	Evasive maneuvers	Full GPS and LAMS

Table 2. Planned test cards. Note that these cards were not able to be flow exactly according to this plan due to weather conditions.

the loiter, the aircraft would be returned to the ground station for a landing under manual control of the remote PIC. All test cards were planned to be conducted while the TacAero manned aircraft were flying in the separate designated flight test locations.

The first test card was designed to demonstrate the normal capabilities of the ADS-B Out transponder while operating in an environment without GPS degradation or denial. The test card called for the aircraft to be autonomously flown around the flight path for a total of five circuits while ensuring that the aircraft GPS signal was not being artificially degraded or denied. During the test, the AFSL ground crew located at the KDLS airport would monitor the TRAPIS software and make sure that both ADS-B and LAMS information were being received for aircraft tracking purposes. Additionally, both of the TacAero manned aircraft would be tracked by the AFSL ground station crew.

The second test card was designed to demonstrate the ability of the TRAPIS software to compensate for sUAS operations in degraded GPS environments by using LAMS information coupled with real-time filtered ADS-B estimates of aircraft position. The aircraft was intended to complete one full circuit of the flight path with a non-degraded GPS signal. Upon the start of the second circuit, the remote PIC was tasked with artificially degrading the GPS information being supplied to the ADS-B transponder, thereby corrupting the ADS-B position information being reported by the transponder. The GPS degradation was designed to remain in effect for the second, third, and fourth full laps of the flight path. Once the aircraft began the fifth lap of the flight path, the remote PIC was once again tasked with changing the GPS information back to a non-degraded state. By degrading the GPS information presented to the transponder during the middle three laps of the flight test, the contrast between normal and degraded GPS environment operations would be shown.

In order to show the operation of the TRAPIS software in GPS-denied environments, the third test card was designed in the same manner as the second test card. During the second, third, and fourth laps of the test, the remote PIC was tasked with artificially denying the GPS information provided to the transponder. By artificially denying the GPS signal, the position information displayed to the ground station user through the TRAPIS interface would only contain information from the LAMS system. During the first and final circuits of the planned flight path, the GPS information would not be denied to the transponder so that both the ADS-B and LAMS data streams would be seen by the TRAPIS operator located at the KDLS airport.

Since the second and third test cards focused on testing TRAPIS's aircraft tracking capabilities during GPS-degraded and GPS-denied operations, the fourth test card was designed to test TRAPIS operations during periods of intermittent GPS availability. The method used for testing the payload with simulated intermittent GPS availability was similar to the methods used for the second and third test cards. The first and fifth circuits of the flight path were designed to be flown without GPS degradation or GPS denial. During the middle three circuits of the flight path, the remote PIC was tasked with cycling the transponder payload between non-degraded GPS information, artificially degraded GPS information, and artificially denied GPS information. By cycling the GPS information between these three options, the remote PIC was able to simulate an aircraft operating with an ADS-B transponder in an intermittent GPS environment.

The final test card was aimed at testing the abilities of the TRAPIS real-time state estimators to keep pace with position estimates for an aircraft that needed to perform evasive maneuvers. Many scenarios exist wherein an aircraft, manned or unmanned, would be required to perform evasive maneuvers in order to avoid an object to include a bird, another aircraft, terrain, or any variety of unplanned obstacle. In order to test for evasive maneuver tracking, the test card called for one circuit of the flight path to be flown autonomously. Once the circuit was complete, the remote PIC was tasked with taking manual control of the sUAS and performing evasive maneuvers to include sharp turns, climbs and descents. After the evasive maneuvers were completed, the pilot was tasked with placing the sUAS back into auto mode such that the aircraft would complete one final circuit of the flight path before landing.

Once all of the test cards were generated, the tests were run during initial flight testing excursions at Meadowbrook Farms. It was shown that all test cards could be completed successfully with the test aircraft and the TRAPIS payload, and that the TRAPIS user interface behaved as expected. These initial tests proved that all test cards were feasible and could be performed using the same type of rectangular flight path during the final KDLS flight demonstration.

2. *Modified Test Cards*

Flight test plans are drafted with the hope that test day conditions will allow all test cards to be completed as planned. In reality, unforeseen factors often prevent flight tests from proceeding according to the exact test plan, and this was the case with the actual flight test. On both September 22nd and September 23rd, 2016, weather conditions at the intended test site prevented the planned test cards from being completed and restricted flight options to manually-controlled flights in which the test sUAS would not have been able to autonomously complete the planned flight path. Additionally, unforeseen complications with the primary transponder unit and line-of-sight issues at the flight test site required alterations to the planned test cards. These challenges are described in greater detail in the later section of this paper.

During the first day of flight testing on September 22nd, it was determined that the original flight testing airspace would not suffice for the required flight tests. The LAMS system required line-of-sight with the transponder in order to successfully track the sUAS, and from the mobile GCS there was no line-of-sight between the sUAS and the LAMS station at the KDLS airfield. Accordingly, the aircraft needed to be launched reach the appropriate test altitudes before line-of-sight with the LAMS station could be achieved. In addition to the LAMS station, the ADS-B In receiver required line-of-sight with the transponder antenna in order to receive updates on aircraft position. This requirement further complicated matters with the use of the original test location, since both LAMS and ADS-B tracking required line-of-sight operation of the sUAS.

The team experienced connectivity problems and it was theorized that these issues stemmed from the lack of line-of-sight between the GCS at the test site and the ground station at the KDLS airport. Subsequent ground tests with a flight team member holding the test sUAS and walking near the test site showed improved transponder performance when the aircraft was moved to a hill 500 yards east of the original test location. The location of this hill in relation to the original GCS site in the proposed test airspace is shown in Figure 10(b). From the top of the hill there was line-of-sight between the KDLS ground station and the GCS, which allowed test personnel to troubleshoot connection issues between the sUAS, the LAMS, and the ADS-B In receiver before launching the aircraft.

After analyzing the results of the September 22nd ground tests at the original and alternate locations, it was determined that further tests on September 23rd should be conducted at the alternate test location on top of the hill. Strong winds continued to affect flight operations on the second day of testing, and COA requirements would have prevented the AFSL flight crew from maintaining line-of-sight with the sUAS during autonomous flight operations using the original flight path. In light of these factors, the plan changed from conducting autonomous flights around the original flight path to conducted manual flights near the alternate GCS location.

Since the test sUAS had never been flown in sustained 20-30 mph winds, there was potential for the aircraft to crash during flight testing. In order to ensure that all required data would be gathered during a successful flight, it was determined that all three GPS states would be tested during a successful flight. During manual operations, the remote PIC would fly the sUAS for several manually-controlled circuits around the test location with no artificial GPS degradation or denial before artificially degrading the GPS signal provided to the transponder for several additional circuits. The pilot would then artificially deny the GPS signal for several circuits before returning the GPS information to its non-degraded state for the final circuits of the test. This adjusted test plan was followed for the flight tests that were conducted from the alternate GCS location on September 23rd. Although the modified tests did not allow for each of the GPS degradation states to be tested on separate flights, it allowed the flight crew to test all required functionality while minimizing the risk of successive test flights in an extremely challenging flight environment.

III. Results

A. ADS-B and LAMS Data

1. Manned Aircraft Data

During flight testing, unforeseen environmental factors and issues with the sUAS ADS-B transponder prevented sUAS data from being gathered simultaneously with manned aircraft data as originally planned. These challenges are summarized in the subsection C. As a result of these issues, sUAS ADS-B and LAMS data was gathered on the second day of testing, while manned aircraft data was gathered on the first day of testing. Despite the fact that data was not gathered simultaneously for the manned aircraft and the sUAS, both data sets include all desired information from the test plan.

In addition to the difficulties faced in gathering the manned aircraft and sUAS data simultaneously, only one of the manned aircraft was successfully tracked via the LAMS during testing. Since the Vans RV-12 was fitted with an ADS-B Out transponder, it was tracked using both the ADS-B In receiver and the LAMS station. The Cessna did not have an ADS-B Out transponder, but it had a traditional Mode C transponder. Based on this difference in equipment between the two aircraft, it was planned that the Cessna would be tracked using only the LAMS station, which is capable of tracking aircraft with traditional Mode C transponders. During testing, it was found that the LAMS station did not track the Cessna, and as a result no data was gathered for the aircraft. It is speculated that the Cessna transponder might have suffered from the same issues as the original sUAS transponder unit detailed in subsection C.2. Transponder pulse widths outside of specified ranges could have contributed to the lack of LAMS tracking for the Cessna, but this hypothesis has not been verified.

The RV-12 pilot was tasked with flying the aircraft around the flight path to the southeast of the KDLS airport as shown in Figure 10. This flight path involved flying counterclockwise patterns with altitudes varying between 3,500 feet MSL and 4,500 feet MSL. The pilot remained on station with the aircraft for approximately one hour, and during that time flew continuous circuits of the designated flight path. All data gathered for the RV-12 during testing to include ADS-B, LAMS, and secondary GPS data is shown in Figure 11.

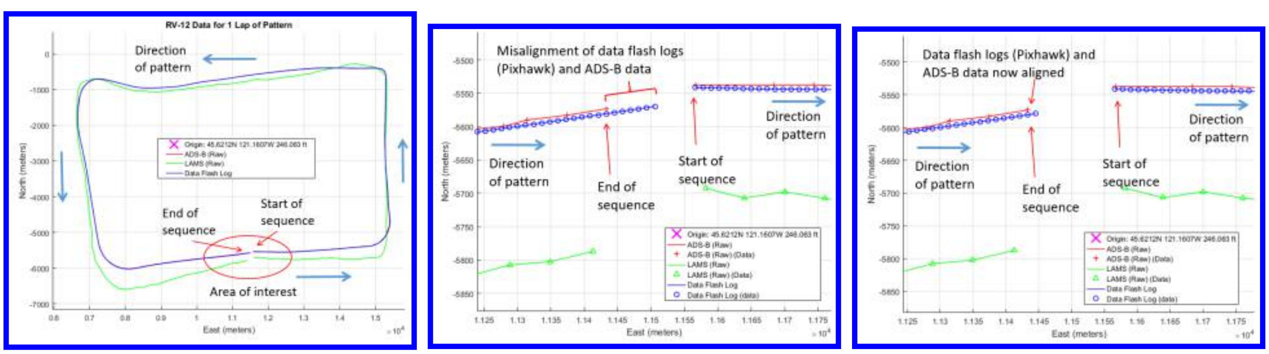
The data in Figure 11 shows all sources of aircraft positioning information for the RV-12 plotted simultaneously. The figure shows the ADS-B data represented as blue aircraft, the LAMS data represented as green circles, and the GPS data from the data flash log of HiLPixhawk1 is represented as yellow lines. The ADS-B and LAMS information plotted in the figure represents the information gathered over a 9 minute interval during the testing period, while the data flash log GPS data represents the entire time of flight for the RV-12. During testing, 30 to 40 mph winds out of the north were experienced. The effect of the high winds can be seen in the figure by the presence of flight path overshoots to the south when the aircraft turned from a southbound heading to an eastbound heading (the pilot was manually flying to predefined waypoints). Additionally, the rectangular flight path is visibly slanted due to the effect of the high winds on the overall ground track of the aircraft as it transited between the flight path coordinates.

The tracks presented in Figure 11 show strong agreement between the ADS-B position information and the LAMS position information, with a maximum difference of approximately 0.35 nautical miles at the southwest corner of the flight path. Additionally, the aircraft GPS tracks shown by the small blue aircraft symbols closely match the GPS tracks of HiLPixhawk1.

When examining this data set, it was noticed that HiLPixhawk1 and the TRAPIS system record time differently. This phenomenon can be witnessed by examining one lap of RV-in the previously described pattern. We first identify a starting point in both sources of data. We align the data so both TRAPIS (which records ADS-B and LAMS data) as well as the HiLPixhawk1 (data flash logs) start at the same time (labeled as 'Start of sequence' in Figure 12(a)). We then extract data for the next 515 seconds which yields an end point of both sets of data (labeled as 'End of sequence' in Figure 12(a)). If both TRAPIS and HiLPixhawk1 measured time consistently, after the 515 seconds, the end of the two sequences should line up spatially. However, by examining Figure 12(b) we see that the there is a misalignment of data. In this case, it appears that HiLPixhawk1 records time slower than TRAPIS. We consider TRAPIS to be correct and therefore scale the data flash log time to be consistent by stretching the HiLPixhawk1 recorded times by 0.2%. This correction yields Figure 12(c) that shows proper alignment of data.

In addition to comparison of the position information provided by the ADS-B and LAMS tracks, altitude information associated with the tracks was compared as shown in Figure 13.

Figure 11. RV-12 Data. Data flash logs (yellow), ADS-B (blue planes), LAMS (green circles). TRAPIS (ADS-B and LAMS) recorded approximately 11.5 minutes of data where as HiLPixhawk1 (data flash logs) record approximately 2 hours of data (observe the RV-12 entering and exiting pattern in the upper left).



(a) A single lap of the RV-12 pattern. Noticed that ADS-B and data flash logs are nearly coincident.

(b) Zoomed in data at the start and end of the pattern. Notice misalignment (extra data points) from the data flash logs. Each data flash data point is approximately 0.2 seconds apart.

(c) HiLPixhawk1 and TRAPIS times align after applying 0.2% time dilation.

Figure 12. Planar view of the RV-12 flying a single lap of the pattern to illustrate time dilation effect recorded in the data flash logs of HiLPixhawk1.

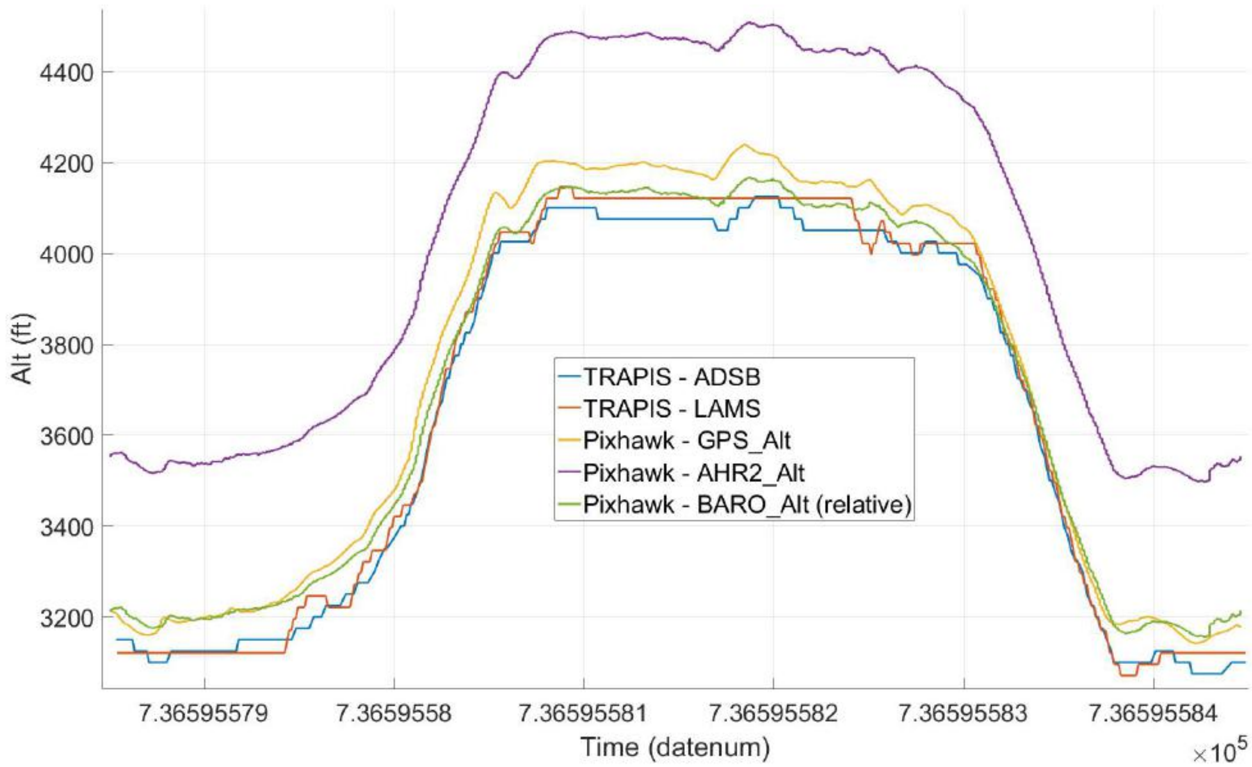


Figure 13. RV-12 altitude data during 515 second window (1 lap of pattern) on Sept. 22, 2016.

After comparing the data presented in Figure 13, it can be seen that several of the recorded altitudes closely match. In all traces, the altitude differences between flight path legs are clearly shown, with climbs and descents represented as well. Initially, the aircraft maintained an altitude of 3,100 feet before ascending to an altitude of 4,100 feet, and descending to an altitude of 3,100 feet. These altitudes correspond to the desired flight path altitudes of 4,500 feet MSL for the westbound leg and 3,500 feet MSL eastbound legs of the flight path. We can gain further insight into the system by comparing the various traces with each other

ADS-B (Blue) and LAMS (Red): The ADS-B out transponder (XPS-TR) is equipped with a pressure altimeter to provide mode C/S functionality. It is important to note that for the RV-12, this pressure port was correctly plumbed for aircraft static pressure and can therefore reliably report pressure altitude. This altitude is reported via both ADS-B and LAMS (Cat48) packets. The discrete nature of the altitude signal in Figure 13 can be attributed to fact that transponders encode pressure altitudes at 25 foot increments instead of a continuous spectrum. Of particular interest is the observation that it appears that the LAMS on the ground performs additional filtering on the input data and as such, the LAMS and ADS-B pressure altitudes are not identical. It appears that the LAMS provides some smoothing as the the raw altitude signal (ADS-B) has some high frequency oscillations removed. It is worth noting that both the ADS-B and LAMS signals appear in sync, implying that whatever filtering that is being done on the LAMS does not introduce any discernible time delay.

Notice that the ADS-B and LAMS data appear to have an approximately 50ft steady offset from one another. This variation in altitude can be explained by examining the local pressure corrections during the days of testing as shown in Table 3.

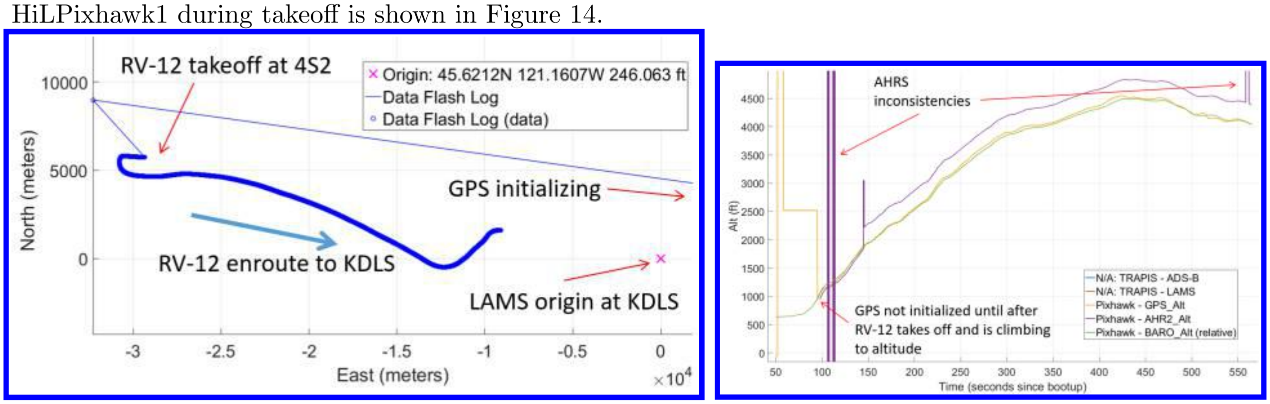
Table 3. Pressure corrections at KDLS during 2 days of testing.

Date	**Local Altimeter Setting**	**Altitude Deviation from Standard Day**
Sept. 22, 2016	29.97” Hg	50 ft
Sept. 23, 2016	30.09” Hg	170 ft

The data from the RV-12 (Figure 13) was acquired on Sept. 22 and as such, there was a 50ft deviation between standard day pressure and local conditions. While the ADS-B transponder did not make this local correction, The LAMS utilizes a Honeywell precision barometer (HPA200W2DA) to apply a local pressure on the ground before publishing to the Cat48 packet, thereby generating this difference.

HiLPixhawk1 GPS (Orange), AHRS (Purple), and Barometer (Green): HiLPixhawk1 provided additional altitude data to compare the TRAPIS (ADS-B and LAMS) results against. HiLPixhawk1 contains a barometric pressure sensor which is used to calculate a non-corrected pressure altitude. Note that HiLPixhawk1 records this as a relative altitude with a datum of 0 ft corresponding to wherever the system was turned on. The RV-12 in this experiment took off from Ken Jernstedt Airfield (4S2) in Hood River, OR where the elevation of the field is 628ft (4S2 and KDLS are nearly 16 nautical miles apart). Adding this field elevation to the relative data yields the green line in Figure 13. Based on the fact that this pressure altitude is uncorrected for local variation, we expect it to align closer with the ADS-B rather than LAMS data but this was not observed in the data (the opposite was true where HiLPixhawk1's uncorrected pressure altitude appears to align with the corrected LAMS pressure altitude). However, HiLPixhawk1 was simply placed in the cabin of the RV-12 and was therefore using cabin static pressure rather than properly plumbed static pressure which can account for this variation. This non-ideal placement of HiLPixhawk1 may also explain the variation in GPS altitude. The GPS receiver for HiLPixhawk1 was likely placed on the co-pilot seat without a completely unobstructed view of the sky.

The AHRS estimate of altitude by HiLPixhawk1 is consistently off by more than 300 feet. One can examine the start of the data flash log for one possible reason for this discrepancy. The data taken by HiLPixhawk1 during takeoff is shown in Figure 14.



(a) NE view of the data. Note that GPS errors are very large before initialization is complete.

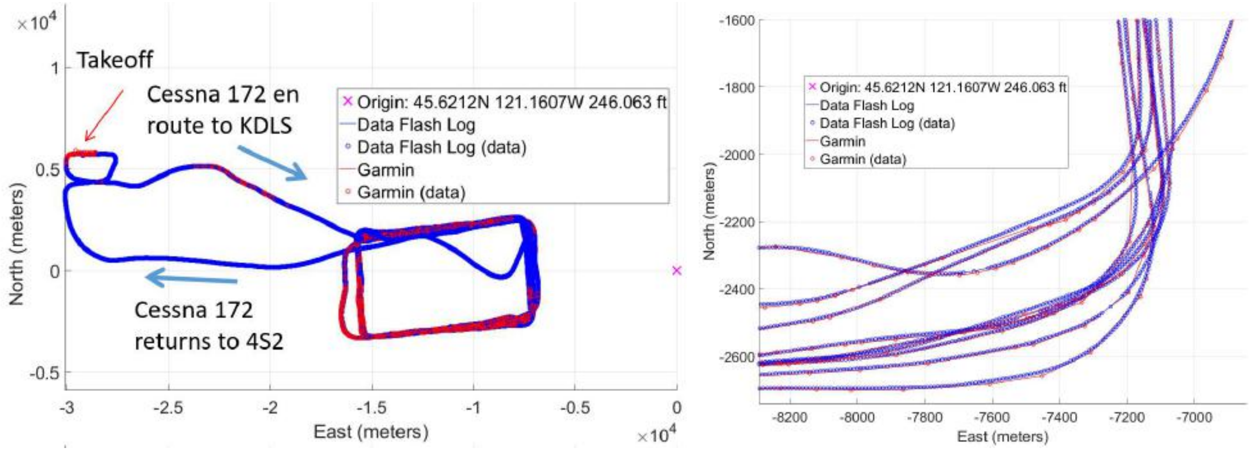
(b) Altitude measurements during takeoff. Note that GPS did not initialize before takeoff.

Figure 14. RV-12 takeoff data at 4S2.

Note that it appears that the pilot of the RV-12 turned on HiLPixhawk1 while the aircraft was taxiing immediately before takeoff (acceleration consistent with full throttle takeoff was detected approximately 65 seconds after HiLPixhawk1 was powered on, this is consistent with altitude measurements). As such, the AHRS system did not have time to initialize the IMU and record proper zero offsets. Combine this with the fact that the GPS in HiLPixhawk1 did not fully initialize until after the RV-12 had taken off and was climbing to altitude yields an explanation why the AHRS becomes confused and reports an incorrect altitude. It is curious to note that the AHRS appears to provide reasonable estimates between approximately 115 and 145 seconds. After 145 seconds it picks up the 300 feet offset and is unable to recover for the remainder of the flight (approximately 2 hours of data).

Both the RV-12 and Cessna carried independent GPS measurement devices. The RV-12 flew a Garmin eTrex Venture and the Cessna flew a Garmin GPSMap76CSx unit. These units were used to record corroborating GPS data. However, the RV-12 data was lost and therefore cannot be used for comparison in Figure 11 or Figure 13. The hand-held GPS used by the Cessna only recorded a partial track (it is missing the last section of data). Furthermore, mode C transponder on board the Cessna was not functioning properly and, as such, LAMS was not able to track the vehicle. Therefore, the only comparison that can be made using the Cessna data is to compare the GPS data from HiLPixhawk3 with the hand-held GPS unit (Garmin GPSMap76CSx). This is shown in Figure 15.

Notice that both GPS sources are in good agreement in the horizontal plane (thereby implying a low



(a) NE view of the data. GPS was properly initialized before takeoff.
(b) Zoomed in view of south east corner of pattern.

Figure 15. Cessna data comparing the GPS data from HiLPixhawk3 to the Garmin GPSMap76CSx. Notice the HiLPixhawk3 data was acquired at a higher rate than the Garmin unit.

HDOP). To examine the GPS accuracy in the vertical dimension, the altitudes recorded by these two GPS sources as well as the other sensors on board the Cessna are shown in Figure 16.

Note that Figure 16 does not have the time dilation correction applied to the HiLPixhawk3 data. This shows that in this case, HiLPixhawk3 and the Garmin unit are in agreement with respect to measuring time. This possibly means that in the previous scenario, the TRAPIS system was responsible for introducing the 0.2% time dilation effect in the RV-12 data. Both HiLPixhawk3 and the Garmin GPS have good agreement in altitude (imply a low VDOP). Furthermore, notice that after accounting for the altitude of the field, when the aircraft is at mission altitude, the pressure altitude measured by HiLPixhawk3 appears to have a steady state error of approximately 300 ft. Again, 50 ft of this can be accounted for by the variation of local pressure from standard day conditions. The additional errors could arise from the fact that the Pixhawk system is designed for sUAS operations (400 ft AGL and below) and likely not calibrated for the higher pressure altitudes. This hypothesis is bolstered by the fact that the difference between pressure and geometric altitude are much smaller when the aircraft is at lower altitudes, such as during takeoff and landing.

2. sUAS Aircraft Data (Normal GPS Function)

All ADS-B and LAMS data for the sUAS aircraft was gathered on the second day of testing after the flight team ground station location had been moved to the secondary location. Two successful flights were conducted with the sUAS aircraft on the second day of testing, and all of the desired GPS scenarios were tested. The most complete data set was gathered during the second flight of the sUAS aircraft, after the ADS-B antenna was changed to a vertical orientation.

The ground tracks from an 80 second segment of the ADS-B and LAMS data associated with the second successful sUAS flight are shown in Figure 17. In the figure, it can be seen that the ADS-B data shown by the blue aircraft symbols does not directly align with the LAMS data shown by the red square symbols. This can be attributed to the fact that the LAMS does not directly output latitude and longitude of the transponder. Instead, it returns a radius and azimuth angle in a coordinate system local to the LAMS installation. This data needed to be rotated to obtain the equivalent latitude and longitude. It is possible that the rotation angle used by TRAPIS was slightly inaccurate, thereby rotating the LAMS data relative to the ADS-B/GPS data. Furthermore, the LAMS has some inherit uncertainty associated with its measurements. As stated by ANPC, a reasonable model of the error in azimuth angle measurement is a Gaussian distribution where 1.4 degrees from the mean captures 80% of the samples (a standard deviation of approximately 0.55 degrees). The equivalent error in the radial measurement has 300ft or 5% of the mean, whichever is worse to capture the same 80% of the samples.

Once position (lat/lon) information from TRAPIS (ADS-B and LAMS) and the sUAS on-board Pixhawk had been compared, the altitude information was examined. On the manned aircraft, ADS-B altitudes were

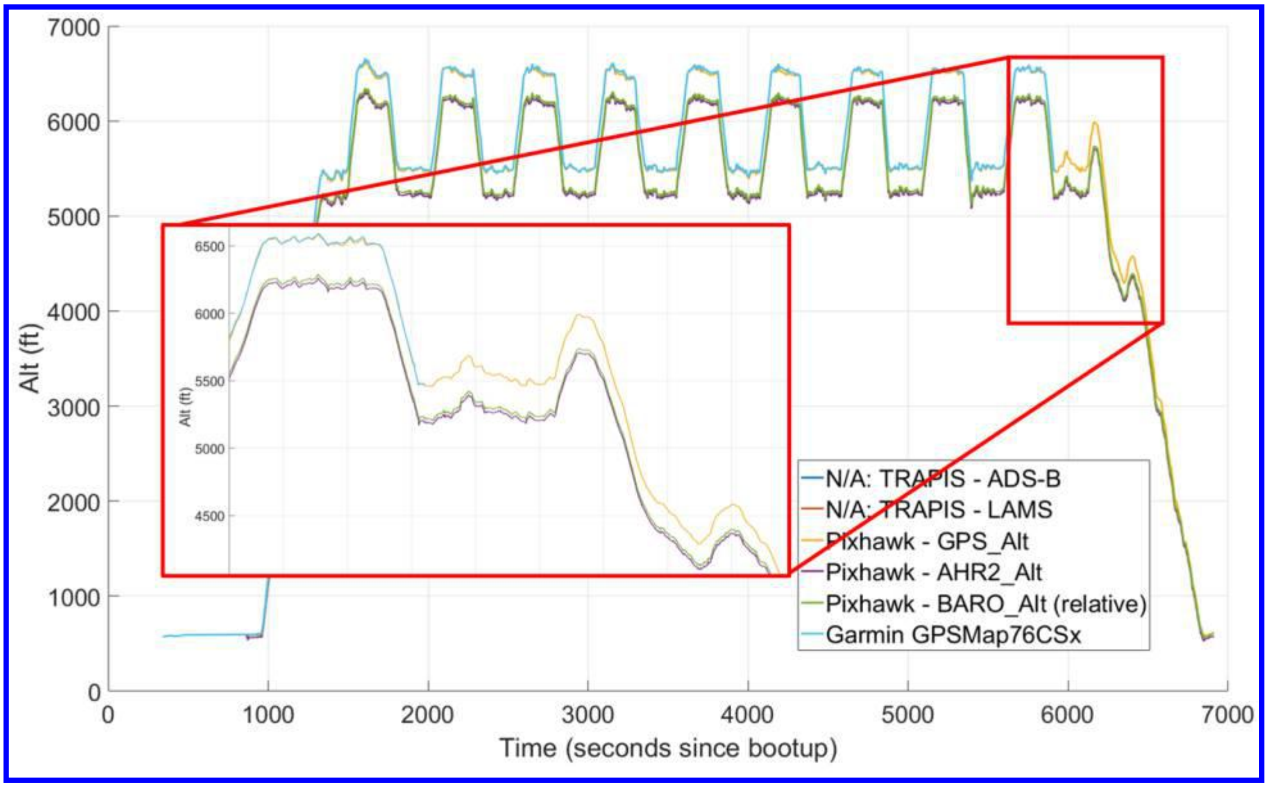


Figure 16. Cessna altitude data on Sept. 22, 2016. No time dilation is applied to HiLPixhawk3 data.

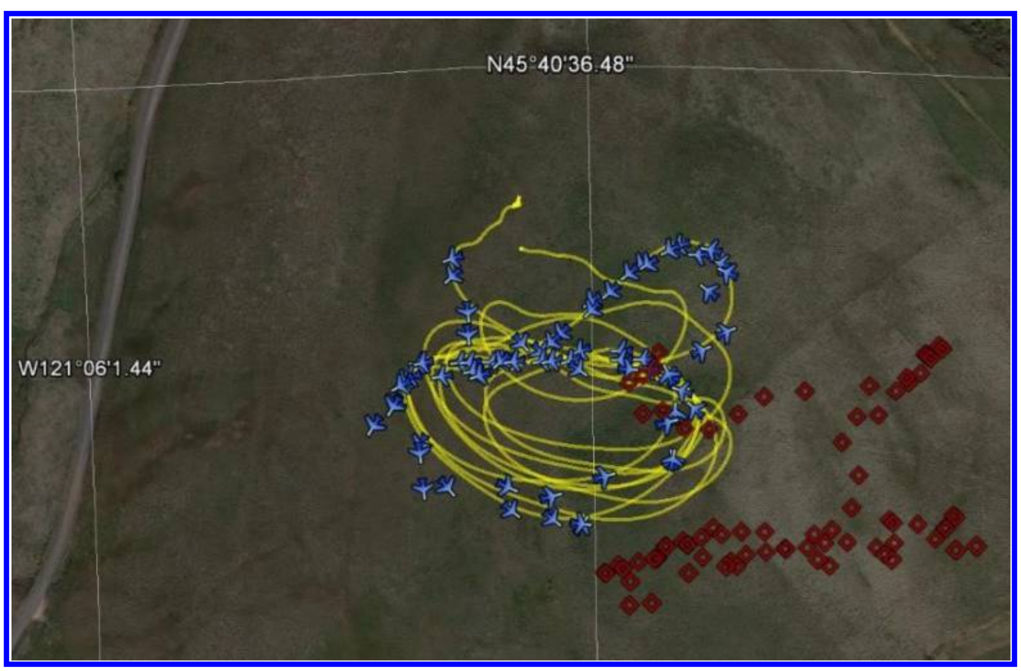


Figure 17. Data recorded for sUAS flight path 1. Data flash logs (yellow), ADS-B (blue planes), LAMS (red squares). Note the longitudinal width of the data flash log pattern is 700 feet.

reported as barometric altitudes gathered from the on-board, correctly plumbed static pressure port. The LAMS altitudes were reported as pressure altitudes from the transponder unit and corrected to true altitudes at the LAMS station. On the sUAS aircraft, these altitudes were gathered in a similar manner, however the GPS and transponder equipment used was much different. The GPS used on the sUAS reported geometric altitudes was a non-WAAS 3DR uBlox GPS unit. Additionally, the pressure altitude reported for ADS-B and LAMS packets was gathered directly from the Sagetech transponder which resided in the sUAS payload bay. Since investigation and placement of a static pressure port on the external surface of the sUAS airframe was outside the scope of this research, the static pressures reported to TRAPIS (ADS-B and LAMS) are subject to errors.

The altitudes recorded for the sUAS are shown in Figure 18 for a 355 second period of the test flight. Since all flight operations had to be conducted below 400 feet AGL, the range of allowable altitudes for the sUAS was much lower than the range of allowable altitudes for the manned aircraft. This exacerbates the 25ft resolution of the ADS-B and LAMS repoted altitudes. Also note that this data was taken on Sept. 23, 2016 and referring to Table 3, the correction for local pressure this day can account for 170ft of the observed 121ft difference between the ADS-B (uncorrected) and LAMS (corrected) pressure altitudes. After correcting the relative barometric pressure for the elevation of the launch point (1348ft) all of the sUAS Pixhawk altitudes line up well. Notice that unlike the RV-12 data, the sUAS was allowed to initialize properly and as such, the AHRS provides a consistent altitude measurement.

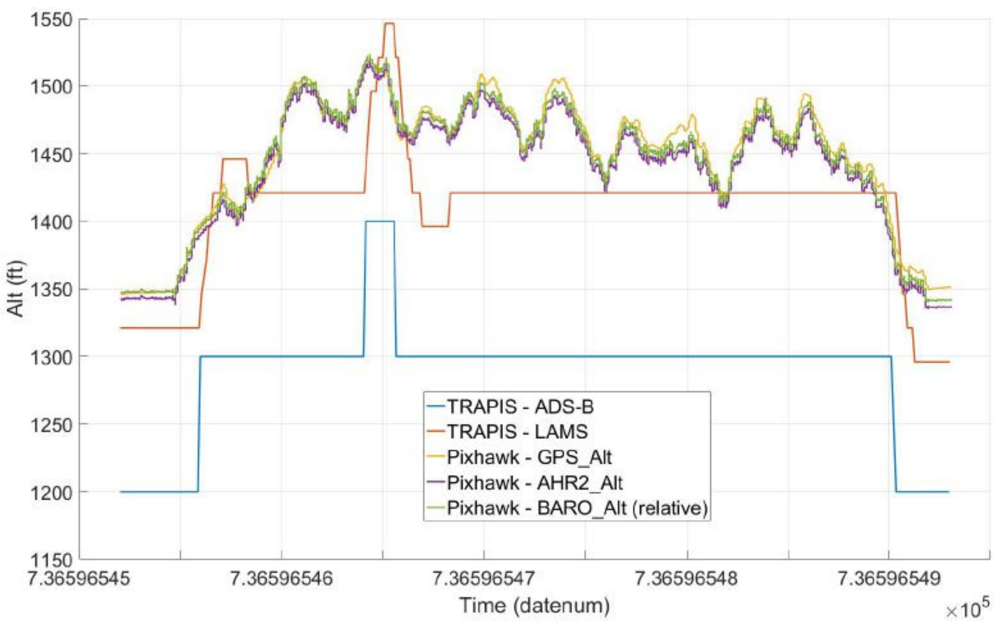


Figure 18. Altitude output from TRAPIS and sUAS Pixhawk for the sUAS flight on Sept. 23, 2016 for a 355 second period.

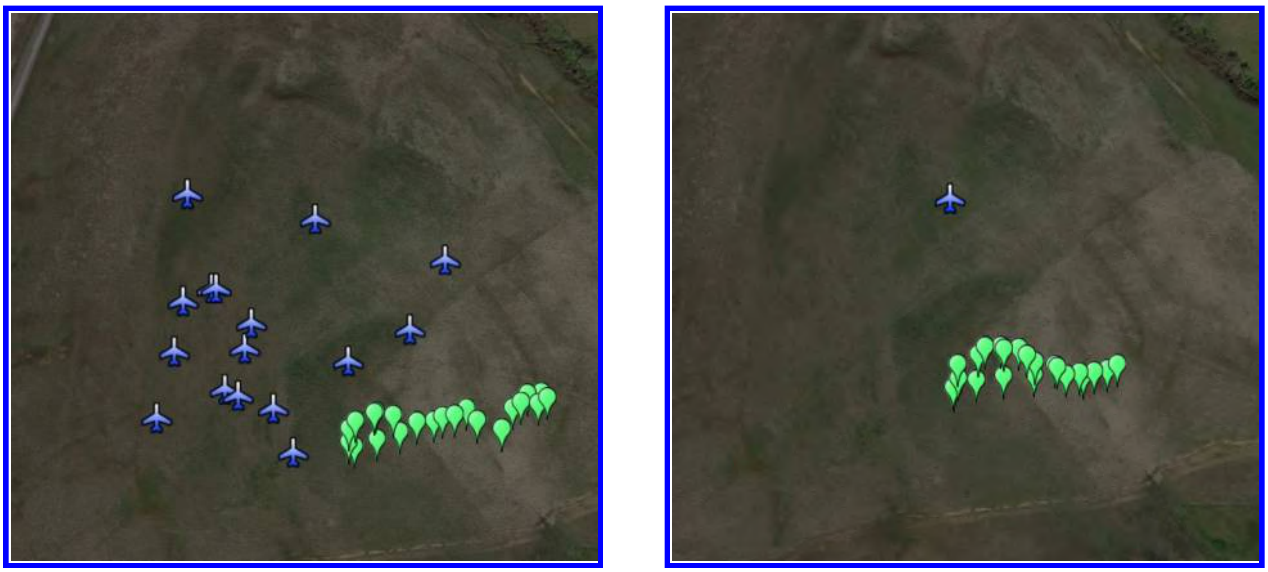
3. *sUAS Aircraft Data (GPS Degraded)*

After several rectangular laps were flown with the sUAS in manual mode and the GPS operating in a non-degraded state, the GPS information provided to the transponder was artificially degraded. By artificially degrading the GPS information being provided to the transponder the ADS-B position measurements were corrupted and the LAMS position measurements served as the primary means of tracking the aircraft. The results of the testing with the GPS information being artificially degraded are shown in Figure 19(a).

Based on the aircraft position information shown in the figure, it can be seen that the GPS information provided to the transponder was artificially degraded. Based on the Arduino code, the positions, headings, and velocities associated with the GPS information were degraded in such a manner that the GPS information was unreliable for sUAS tracking on a small flight path. Although the degraded GPS information proved unreliable for tracking the sUAS during testing, the LAMS position information continued to be reliable, though slightly offset from the actual vehicle ground track. From the figure it can be seen that the LAMS position information continued to be received by the TRAPIS software during GPS-degraded operations, and the LAMS station sufficiently tracked the sUAS movements on the east-west flight path. The offset between the ADS-B track and the LAMS track was consistent with the offset for the tracks during normal GPS operations. Overall, the LAMS track showed that the LAMS could be reliably used as a secondary sUAS tracking system during GPS-degraded operations.

4. sUAS Aircraft Data (GPS Denied)

Once several additional laps were flown with artificial GPS degradation, the GPS signal provided to the ADS-B transponder was artificially denied. As with the GPS degradation, during GPS-denied operations the LAMS served as the primary means of sUAS tracking. The LAMS data associated with the GPS-denied testing is shown in Figure 19(b).



(a) sUAS GPS degraded scenario. Notice that ADS-B packets become noisy but LAMS remains clean.

(b) sUAS GPS Denied scenario. Notice that last ADS-B packet is held in memory but no subsequent packets are received.

Figure 19. ADS-B data (blue planes) and LAMS data (green pointers) for a GPS degraded and denied scenario.

By looking at the figure, it can be seen that during GPS-denied operations the ADS-B information stopped being provided to the TRAPIS software. Once GPS information stopped being provided to the transponder, a single blue aircraft symbol remained to indicate the last reported GPS position. Although ADS-B information was not provided to the TRAPIS software during the GPS-denied operations, LAMS information continued to be provided. The LAMS track shown in the figure closely matches the LAMS track generated during GPS-degraded operations. Based on the information gathered from the LAMS during GPS-denied operations, it was shown that the LAMS could be used as a primary tracking method during GPS-denied operations, whether those conditions were caused by GPS outages or active GPS jamming.

B. Comparison Data

1. sUAS Aircraft

The Pixhawk system is able to record two data sets. One set is the communication between the telemetry radio installed on the aircraft and the telemetry radio connected to the Ground Control Station (GCS). The second data set is collected by the 3DR GPS and Pixhawk as data flash logs.

Flight path data was collected from the data flash logs, ADS-B, and LAMS tracking systems. Figure 17 displays the second flight path of the sUAS during a 79 second flight segment recorded by the ADS-B (shown as blue airplanes) and LAMS (shown as red diamonds). Figure 17 also displays the entire flight path collected from the data flash logs (shown as the yellow path). By comparison, it can be seen that the yellow path of positions gathered from the data flash log matches the positions reported in the ADS-B data stream. This was expected since the GPS information used to generate the ADS-B packets for the sUAS during testing was the same GPS used to generate the data flash logs. Although the information from the data flash logs show that the aircraft path matched the path shown in the ADS-B data, inconsistent data was gathered from the telemetry log due to connection issues. During the sUAS test flight, the GCS lost communication to the sUAS Pixhawk. This is the reason there is not a complete data sample from the telemetry log compared to the data gathered from the data flash logs, ADS-B, and LAMS data.

Overall, the data gathered from the sUAS data flash logs after flight testing was completed showed agreement with the ADS-B and LAMS position and altitude data gathered at the KDLS ground station. This additional data served to validate the results of testing, and served as a quality measure of comparison.

2. Manned Aircraft

Each manned aircraft was equipped with a HiLPixhawk unit (Figure 9). The HiLPixhawk units were installed in the manned aircraft to record the flight paths and altitude information during the manned aircraft test cards.

HiLPixhawk1 recorded the GPS track gathered for the RV-12 flight path, which can be seen as the yellow line in Figure 11. From the figure, the ADS-B and LAMS data streams recorded aircraft positions that aligned with the aircraft positions gathered by the GPS unit installed on HiLPixhawk1. This secondary data set allowed for verification of the LAMS and ADS-B position information reported in the data streams for the RV-12 during flight testing. The Garmin eTrex Venture also collected GPS data, but this data was lost before it could be processed for comparison between HiLPixhawk1, the ADS-B, and LAMS GPS tracks.

HiLPixhawk3 recorded the flight path for the Cessna. Since the ADS-B and LAMS data was not recorded for the Cessna, the comparison offered here is between the Garmin GPSMap76CS and the data flash log from HiLPixhawk3. While both sets of GPS data agreed with each other, HiLPixhawk3 gathered a more complete flight path flown than the Garmin GPSMap76CS due to the Garmin GPSMap76CS running out of battery.

C. Challenges Encountered

1. Environmental Factors

At the site location, the ground team experienced 15-20 mph winds with gusts up to 37 mph. High wind caused noise interference with communications systems, and required extra time to secure base infrastructure. For the sUAS, the winds provided extra lift which benefited the launch by hand, but hindered safe, accurate landing.

Light drizzles of rain prompted covering electrical equipment to ensure protection in the event of heavier showers. Aside from time consumption, the drizzle added extra risk to the hardware components and operating electrical devices.

2. Hardware Problems

Various hardware issues caused extra stress on time and affected flight test recordings and flight monitoring using Mission Planner.

While flying, the signal from the GCS operating Mission Planner and the sUAS was dropping or intermittent. This caused a delay in communicating any important deviations from pilot control and resulted in intermittent coverage in flight track recordings.

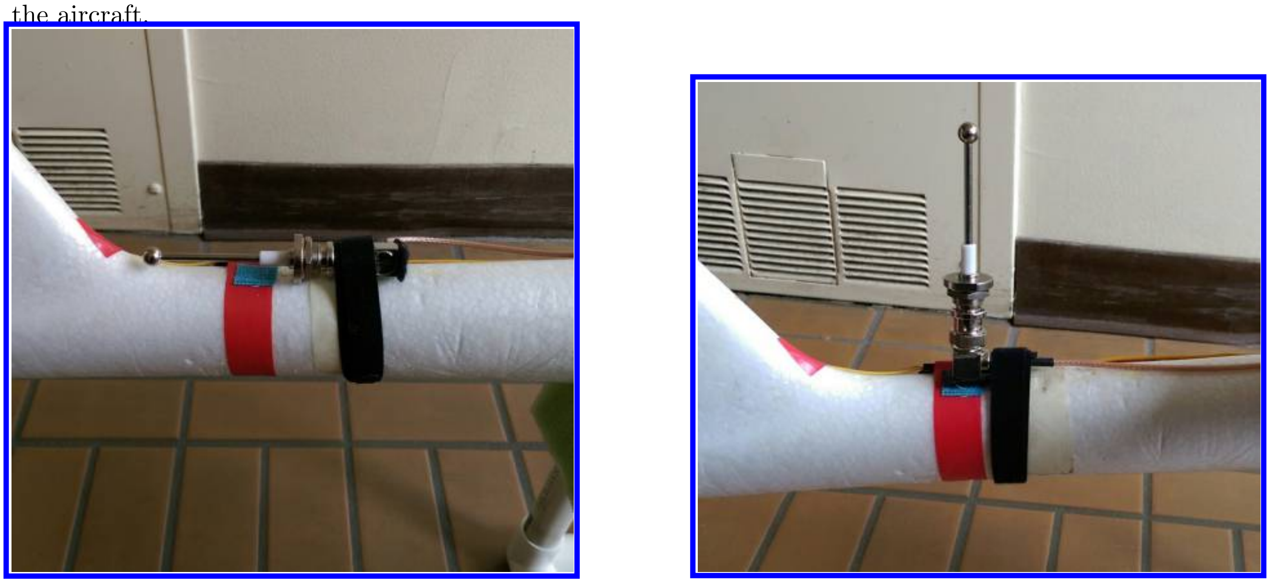
During the final flight demonstration, it was found that the LAMS was not able to receive a signal from the XPS-TR transponder mounted on the sUAS, but the Clarity ADS-B receiver was able to receive ADS-B information. After further investigation by ANPC personnel through the use of ANPC diagnostic equipment (Figure 4(b)), it was determined that the XPS-TR used on the sUAS was not sending the proper pulse widths as required by ICAO and FAA requirements. Per these requirements, pulse widths associated with aviation transponders are to be 450 ± 100 nanoseconds. The original XPS-TR transponder was sending out information with measured pulse widths of 345 nanoseconds, and therefore was rejected by the LAMS filtering software but the Clarity receiver was more forgiving with these out of tolerance signals. After this unit was exchanged for a second unit, the LAMS was able to identify and track the transponder, and the measured pulse widths were found to be 375 nanoseconds (within spec).

3. EMI and Orientation

Initial testing of the XPS-TR transponder unit in the presence of AFSL sUAS avionics indicated that electromagnetic interference could be an issue. Signals from the transmitter used to control the sUAS are seen at the in-aircraft receiver with a power of 0.1 W, while pulses sent from the transponder are sent at a power of 5 W. This large disparity in power ratings between the transponder and signals used to control the sUAS flight surfaces and associated equipment caused concern for potential loss of aircraft control and potential un-commanded changes in payload operation.

Ground testing of the transponder payload at Meadowbrook Farms and during the KDLS ground test indicated that the transponder often would not respond to changes in mode selection from altitude reporting mode back to standby mode, and this behavior was attributed to electromagnetic interference from the transponder. Additional ground testing showed that despite this supposed interference, all flight control surfaces and the motor on the sUAS remained functional without delays in movement during transponder operation. Furthermore, GPS-related mode changes were accepted by the system regardless of transponder operating state, and seamless change between normal GPS operation, GPS-denied operation, and GPS-degraded operation was observed during all ground testing. In order to further reduce the potential for electromagnetic interference affecting the operation of the payload, aluminum foil was used to wrap all payload connecting wires and line the inside of the Arduino board enclosure.

During initial flight testing of the TRAPIS payload at Meadowbrook Farms, the payload exhibited the same issues, most notably the inconsistent ability of the transponder to switch from altitude reporting mode back to standby mode. Since this issue did not affect the safety of flight and the control of the sUAS, it was not treated as a critical action item or researched further. Initial flight testing showed that all ADS-B Out capabilities of the transponder were working as expected, and during this testing the transponder antenna was oriented on the aircraft fuselage in line with the longitudinal axis as shown in Figure 20(a). Due to the orientation of the antenna and the limited payload space afforded with the TRAPIS equipment installed, the antenna ground plane was removed for initial flight testing. The removal of the antenna ground plane did not affect the reception or integrity of ADS-B information, so the ground plane was not re-installed on the aircraft.



(a) ADS-B antenna in original orientation. (b) ADS-B antenna in modified orientation.

Figure 20. Mounting ADS-B near empennage.

Once the secondary transponder had been installed on the aircraft and the LAMS was able to identify and track the sUAS, the orientation of the antenna proved to be an issue. In normal aircraft applications, transponder antennas are oriented vertically either under or on top of the fuselage of the aircraft. This orientation is required due to the vertical polarity of the transponder antennas, and the large size of the aircraft fuselage relative to the antenna wavelength provides a proper ground plane for the antenna. The original transponder antenna position and orientation on the sUAS prevented the antenna from being vertically oriented with respect to the LAMS system. Furthermore, when the nose of the aircraft pointed directly towards or away from the LAMS system, the antenna was oriented in such a way that the signal was lost. This resulted in the LAMS track being continually dropped and regained as the sUAS made turns in the test airspace. In order to remedy this issue, the transponder antenna was placed in a vertical orientation, but still did not have a dedicated grounding plane as shown in Figure 20(b). Once the antenna was vertically oriented, the LAMS equipment was able to continuously track the aircraft, and signal was not lost between the aircraft and the LAMS station.

Figure 21. Flight team outside the MFOC with the sUAS used for flight testing.

IV. Conclusions and Further Research

Based on the results of the ground tests and flight tests, several main conclusions can be drawn. The conclusions should pave the way forward for additional research to be completed as desired by the AFSL and associated industry partners.

Through initial ground testing in the spring of 2016 and flight testing at Meadowbrook Farms and KDLS, it was shown that an ADS-B In transponder could be worked into a commercial off-the-shelf sUAS with consumer-grade avionics and function properly. The full transponder payload weighed several pounds, and although the volume pushed the payload capacity limits of a Skywalker 1900, the transponder payload package would fit easily in larger sUAS models. Although transponder antenna mounting proved difficult with an adequate ground plane on the aircraft fuselage, ADS-B information was received from the aircraft and the antenna setup was able to be tracked using the LAMS equipment at the KDLS airfield. Additionally, GPS position information provided by the sUAS GPS unit in the ADS-B packets was accurate enough for all required operations, although GPS accuracy could have been increased by using more advanced GPS equipment.

Based on the information gathered from flight test results, it was shown that the LAMS system could serve as a suitable tracking method for sUAS aircraft operating in GPS-degraded or GPS-denied environments. Position information gathered from the LAMS station at KDLS indicated that the LAMS was able to track the sUAS accurately. Comparison of the position information gathered from the ADS-B and LAMS data streams showed that the LAMS position estimates remained close to the ADS-B position estimates within sufficient error bounds. Furthermore, the ability of the LAMS to track the sUAS aircraft operating on a small flight path with high fidelity in difficult conditions proved the utility of the system for primary and secondary tracking purposes. During simulated GPS-degraded and GPS-denied operations, the LAMS continued to track the sUAS appropriately, and the integrity of the LAMS position estimates was not altered by erroneous GPS information. The LAMS demonstrated the ability to track multiple vicinity aircraft at the same time regardless of the GPS integrity associated with each of the aircraft being tracked.

Comparison of the altitudes gathered from the ADS-B and LAMS data streams for the sUAS showed variation that was initially troubling. After analysis, it seems that the differences between the reported GPS and corrected pressure altitudes could be attributed to uncalibrated placement of the pressure altimeter without proper access to an outboard static source and the use of a consumer-level sUAS GPS unit. Additional analysis of the differences between the reported altitudes could provide further insight into possible reasons for the differences. Nonetheless, the differences between GPS altitudes and corrected pressure altitudes seen during flight testing fall within reasonable error bounds.

Although the transponder payload proved reliable and capable of being carried on a commercially-available sUAS, the transponder mode switching functionality should be investigated further. During testing, switching between the standby mode and altitude reporting mode proved inconsistent and difficult. While this difficulty could be attributed to possible electromagnetic interference, mode switches between GPS-denied and GPS-degraded operation of the transponder happened quickly and reliably without delay. In addition to an investigation of the mode switching capability, additional research should be performed to further lower the volume necessary to carry all transponder-related payload components for flight on smaller sUAS.

Based on the position and altitude information provided by the ADS-B transponder through the ADS-B and LAMS data streams, further research should be conducted to investigate ground plane requirements for the transponder antenna. Since aircraft space came at a premium for the Skywalker 1900, the antenna was placed on the aircraft without in-depth consideration of orientation or ground plane requirements. Depending on the sUAS model flown for further testing, preliminary research should be conducted to determine the proper placement of the transponder antenna and associated ground plane. Furthermore, research should be done to determine the proper placement of external static pressure ports on any sUAS associated with further testing. Since the pressure altimeter was not plumbed to any aircraft external static pressure port during flight testing, discrepancies between the GPS altitude and corrected pressure altitude arose. In order to correct these discrepancies and narrow down the source of potential altimetry issues, external static pressure port locations should be researched for sUAS airframes involved in further testing.

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