ADS-B Surveillance System Performance with Small UAS at Low Altitudes

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The projected expansion of SUAS operations in the U.S. has motivated the examination into how these aircraft will "see and be seen" by other aircraft operating in the U.S. National Airspace System (NAS). One proposal is that the SUAS use a system compatible with aviation, such as the Automatic Dependent Surveillance – Broadcast (ADS-B) surveillance service. This analysis intends to highlight the impact on the Universal Access Transceiver (UAT) ADS-B system performance from a shared-use operation by SUAS. The purpose is to examine various operational scenarios and estimate UAT's ability to continue to support existing air traffic management air-to-air and air-to-ground applications. The study extended prior research and examined a multitude of scenarios from low to high stress cases. The analysis indicates the key parameters are SUAS ADS-B transmission power and SUAS traffic density. These two parameters can be balanced to attain an acceptable demand on the UAT in areas of potentially high SUAS concentration while still providing safety and utility to all aircraft.

I. Introduction

INTEREST in using small unmanned aircraft systems (SUAS) for commercial operations has greatly increased in recent years. A combination of maturing and sophisticated flight technologies, small-size, high-performance sensors, and the widespread availability of low cost platforms has precipitated an explosive growth in the applications of SUAS for commercial and humanitarian purposes[12].

Interest is seen in a business community that spans very small or startup businesses to very large businesses, with a multitude of novel applications often by operators that have not previously been involved in aviation. Traditional aviation operators have also identified SUAS as an effective and lower cost alternative to several missions currently performed by General Aviation (GA) aircraft. Examples of missions by SUAS include infrastructure inspections, real estate imagery, aerial photography and video, inventory control, small parcel delivery, news gathering, aerial sensing for agriculture, movie and television production, perimeter surveillance, facility security, raw materials inventory and many others. Most of the systems being considered operate at low altitudes, typically under 500 feet (ft) above ground level (AGL).

A. Small UAS Commercial Use in the United States

Significant developments have taken place in the recent past in legislative and regulatory frameworks associated with the use of SUAS for commercial purposes in the United States. These include:

- *Public Law:* Section 333 of the Federal Aviation Administration (FAA) Modernization and Reform Act of 2012 allowed for approval of commercial UAS operations under certain conditions (e.g., visual line of sight, under 500 ft AGL, without flight over bystanders, day time only, and other restrictions). Figure 1 below portrays the growth in the number of businesses that applied for commercial use of SUAS under section 333 between April 2014 and May 2016, illustrating the rapid increase in interest in the use of this new business tool.

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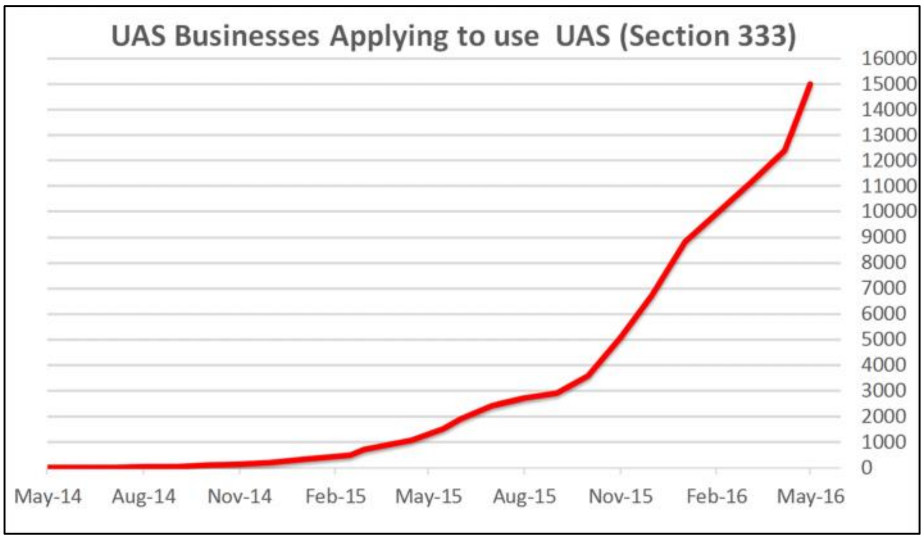
- *Aviation Rule Making:* A new "small UAS" rule (Part 107 to Title 14 Code of Federal Regulations)[1]. This rule became effective August 2016 and it allows for commercial use of SUAS while under VLOS of the operator(s), with several restrictions including but not limited to altitude, aircraft weight and speed as well as no overflight of people. The rule further enabled commercial operations of SUAS at low altitude in the U.S. national airspace system (NAS). A large majority of operators that petitioned for approval to operate SUAS under section 333 are now allowed to operate under the new aviation rule. It is expected that the new rule coupled with a streamlined process of approval for commercial SUAS pilots will lead to further exponential growth in the use of this type of system.

- *Pathfinders*: The FAA Pathfinder program is a special program partnering the FAA with industry to investigate safe methods of operating SUAS beyond what is allowed by the June 2016 SUAS rule[1]. The objectives of the current Pathfinder program include the development of a regulatory path that incrementally enables routine operations for flight over non-participating people (e.g., for news gathering) and flight beyond VLOS of the operator (e.g., supporting agricultural imaging or long-range infrastructure inspections) as well as the evaluation of SUAS detection systems near airports and other critical infrastructure



Source: FAA

Figure 1. Number of Applications for SUAS Business Use Under Section 333

In the next decade, the growing number of SUAS operations is expected to drive a large increase in air traffic volume at low altitudes. New technologies and procedures will be required to ensure safe operations. Surveillance and communication between these SUAS and other aircraft is therefore critically important to allow operations.

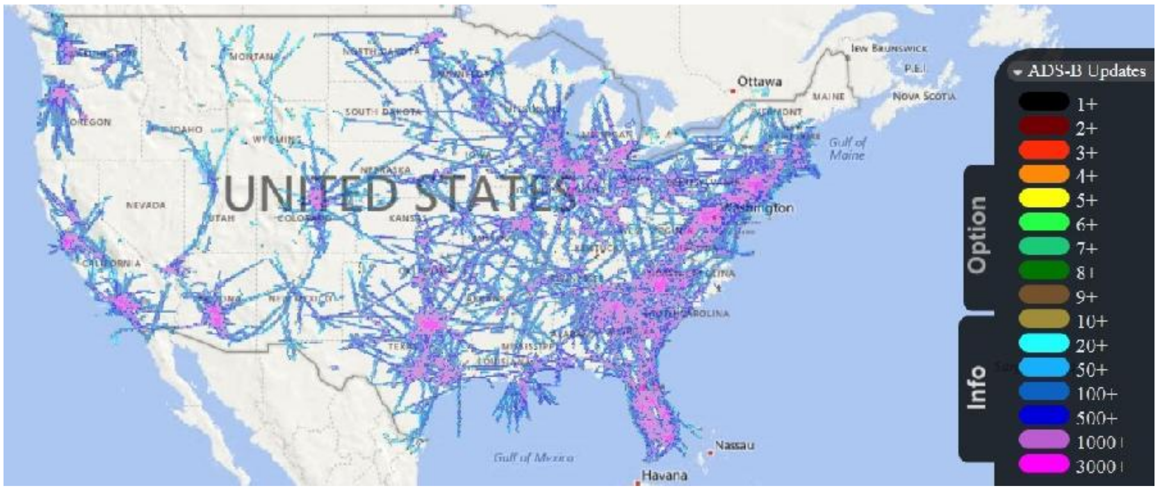
Some in the aviation community have proposed using the Automatic Dependent Surveillance – Broadcast (ADS-B) service, already FAA approved and used for air traffic management (ATM) surveillance applications in, as an enabler to a safe integration of SUAS into the NAS. Conceptually, if all aircraft in the airspace used ADS-B, aircraft identification, surveillance, and possibly conflict avoidance could be facilitated. In addition, several companies are developing low-cost, low-power ADS-B variants for SUAS surveillance. NASA's UTM (Unmanned Traffic Management) project has explored the use of ADS-B for a multitude of SUAS in cooperative flight[7]. In addition, several initiatives at FAA-designated test sites are exploring the use of ADS-B as a means of increasing situational awareness for SUAS. Finally, there are several industry initiatives to develop and mature products in this space[5][13].

A concern is that if ADS-B is also used by low-altitude SUAS, ADS-B frequency congestion may impact ATM applications and limit SUAS fleet growth.

B. Motivation

The projected expansion of SUAS operations in the U.S. has motivated the examination into how these aircraft will "see and be seen" by one another, as well as other aircraft operating in the NAS. One proposal is the SUAS use an ATM surveillance service, such as ADS-B. In the U.S., Universal Access Transceiver (UAT) would likely be a preferred candidate for SUAS use given UAT's system architecture, its FAA-designated operating environment, and its independence from some safety-critical ATM surveillance systems (e.g., Traffic Alert and Collision Avoidance System).

There are many emerging operating concepts for SUAS in the U.S. and it is becoming clear that SUAS operating below 400 ft AGL will accomplish many of the mission objectives and there is little air traffic in this airspace (away from airports). Envisioned uses of SUAS are increasing and will inevitably occur near large metropolitan areas. Figure 2 shows a density plot for a twelve-hour period of ADS-B real-world traffic updates, for traffic below the software-preset altitude of 17,000 feet. This image presents a clear picture of the relative density of current ADS-B use throughout the continental U.S.

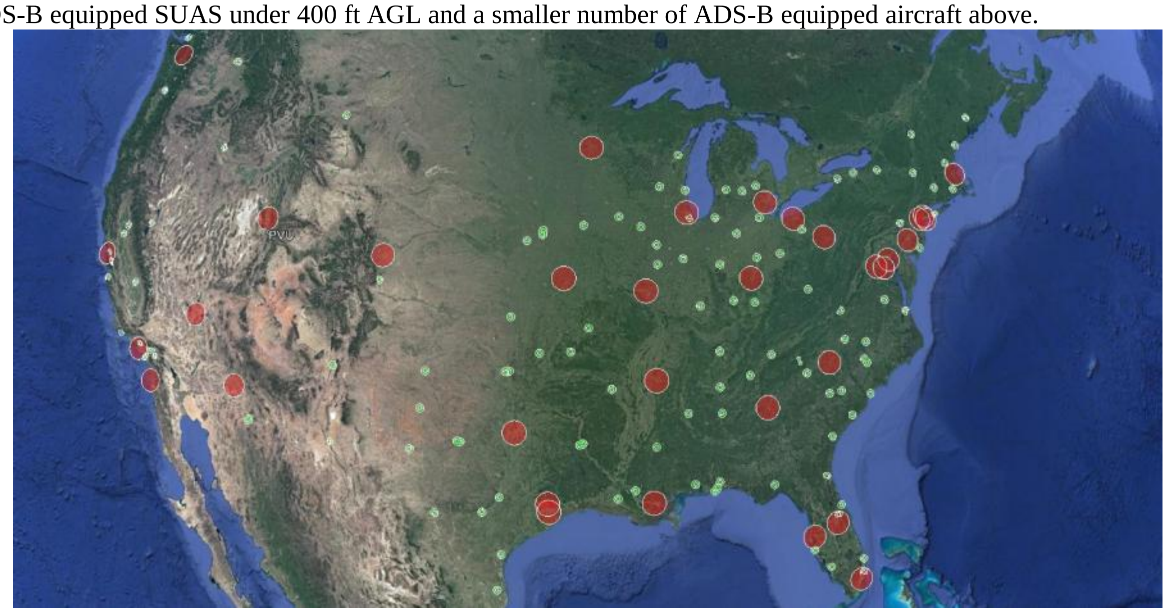


Source: FAA

Figure 2: ADS-B Updates Below 17,000 feet MSL for a Twelve Hour Period – October 2016

Aircraft operating above 10,000 ft and around the nation's busiest airports (i.e., Class B and C Airspace including the Mode-C Veil) will have to operate with ADS-B by 2020[6]. As is the case with radar transponders, there is substantial airspace where ADS-B is not required, though advisable to increase air safety. Figure 3 below shows the areas of the country below 10,000 ft where aircraft will have to operate with ADS-B[2].

In some areas of the country, growth in SUAS may result in an airspace traffic density that significantly exceeds densities currently seen in aviation. This could result in an operationally complex airspace with large numbers of ADS-B equipped SUAS under 400 ft AGL and a smaller number of ADS-B equipped aircraft above.



Source: FAA

Figure 3: ADS-B/Transponder Rule Airspace under 10,000ft

SUAS growth will likely occur in higher population areas which will also have the largest concentration of ADS-B aircraft. Figure 4 below portrays what such a future may look like. In a virtual environment, a cityscape was created and a large number of SUAS were deployed in or near the urban area performing multiple missions. All buildings, aircraft and distances are to scale. Small UAS are displayed here at up to 400 ft AGL. In order to facilitate the visualization, all SUAS are highlighted by spheres eight feet in diameter, which greatly exaggerate their size.

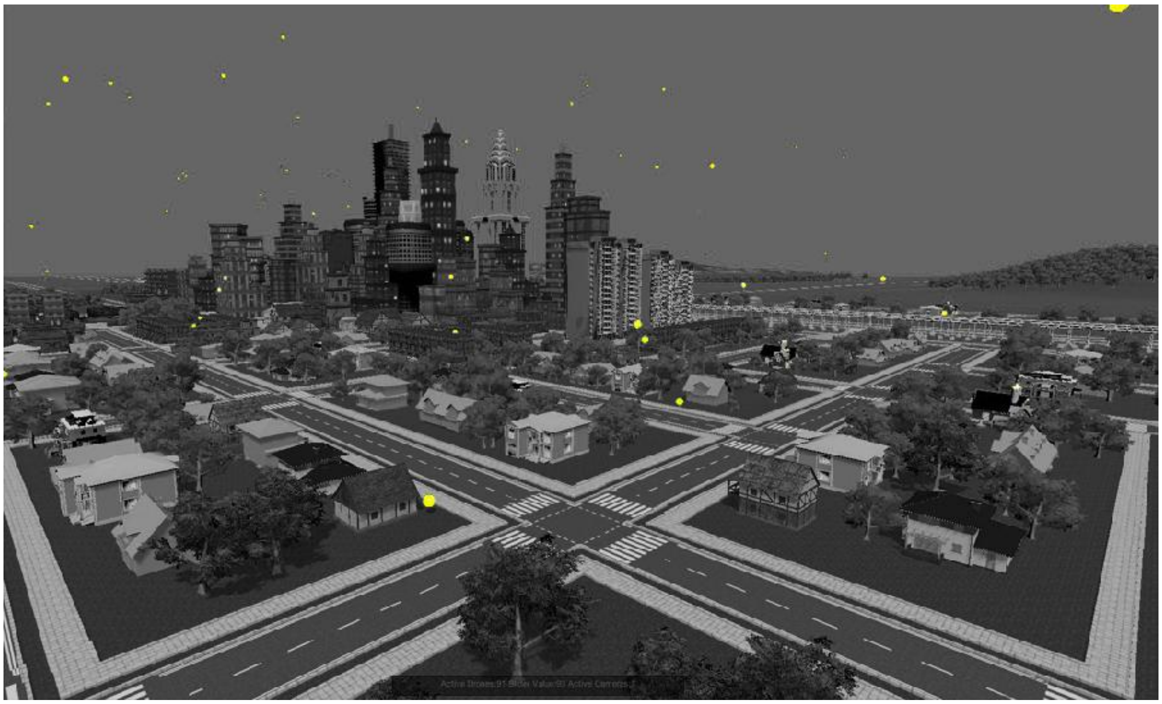


Figure 4: Simulation of Future High Density SUAS Operations (90 drones per square mile) (SUASs Enveloped in 8ft Diameter Yellow Spheres for Better Visibility)

C. Past and Current Research

A previous study by MITRE CAASD explored a challenging juxtaposition of large fleets of SUAS at low altitudes (under 500ft AGL) with high density GA aircraft over 500ft AGL[6]. Results suggested a measurable increase in ADS-B co-channel interference may negatively impact GA aircraft ADS-B air-to-air performance. Results also indicated that the performance of ADS-B between SUAS and other SUAS was not affected by the presence of GA aircraft at traffic levels projected to be UAT equipped by 2020. A recommendation from this study was to look at lower SUAS transmit power to reduce co-channel interference while maintaining sufficient air-to-air performance between SUAS at close range. Additionally, air-to-ground ADS-B performance for ATM separation services was not examined.

MITRE CAASD has continued researching the sensitivity of the UAT ADS-B system to the introduction of ADS-B equipped SUAS, looking more extensively into air-to-air and air-to-ground operational scenarios.

II. Technical Approach

A. Illustrative Use Cases

To assess the operational impact of the widespread use of ADS-B in fleets of SUAS two example use cases are used. The first case is an air-to-air ATM application and the second is an air-to-ground ATM application. These use cases reflect current FAA approved uses of the ADS-B service.

1. Use Case One: Air-to-Air GA Traffic Situation Awareness with Alerting (TSAA)

The ADS-B Traffic Surveillance Systems and Applications (ATSSA) Minimum Aviation System Performance Standards[8] requires a 95% confidence level update interval as a function of air-to-air separation range as shown in Table 1. These requirements apply for foundational ADS-B application Enhanced Visual Acquisition (EVAcq) and TSAA.

Table 1. Air-to-Air 95% Probability of Decode Update Intervals

	Air-to-Air Range		
	3 NM	10 NM	20 NM
Update Interval	3 seconds	5 seconds	7 seconds

Illustrative scenario. Aircraft 1, an ADS-B In equipped GA aircraft is level at 18,000 feet. This aircraft is equipped with the TSAA application[9][10]. A second ADS-B Out aircraft, Aircraft 2 is climbing through FL180 and is on a head-on track toward the first aircraft. The two aircraft are flying at 200 knots. The TSAA application onboard Aircraft 1 has been monitoring and continuously updating 25 seconds of track information about Aircraft 2 and applying a look ahead prediction of 60 seconds to Aircraft 2's track. At the given aircraft speeds, the algorithm is looking at a 6.7 NM per minute closure rate. RTCA DO-338[8], describes the EVAcq range as being less than 10 NM for GA aircraft. The Airborne Surveillance and Separation Assurance Processing algorithm starts checking the required position reports for accuracy inside of 30 NM, unless the report has a valid Traffic Alert and Collision Avoidance System report[9].

2. Use Case Two: Air-to-Ground ATM separation services

The FAA ADS-B/ADS-R Critical Services Specification[3] requires a 95% confidence level update interval for current ATM separation standards as shown in Table 2. These requirements apply to three and five mile separation standards generally used in controlled terminal and en route airspace, respectively.

Table 2. Air-to-Ground 95% Probability of Decode Update Intervals

	ADS-B Service Volume	
	Terminal (3-mile)	En Route (5-mile)
Update Interval	3 seconds	6 seconds

Illustrative scenario. Aircraft 3, an ADS-B Out equipped UAS operating under a Civil COA with a waiver for beyond visual line of sight operations, is flying at 400 ft inspecting powerlines. The flight path of the UAS will transit the edge of a Class C airspace. The operator of the UAS has filed a flight plan and is in contact with the Tower controller of the Class C airspace per requirements of the COA. Since the UAS is equipped with ADS-B Out it is able to be seen by the ATM surveillance system. The ADS-B/ADS-R Critical Services Specification[3] states that the ADS-B service "shall provide for each aircraft/vehicle in the terminal domain and ADS-B Report containing position information with an update interval no greater than 3.0 seconds (95%) at each Service Delivery Point (SDP)" to support terminal surveillance.

B. UAT System Performance Model

MITRE CAASD used a UAT parametric performance model created during the FAA's ADS-B system development between 1995 and 2005 to support analyses for the avionics performance requirements. The model computes the probability of being able to decode received ADS-B messages as a function of range in an interference environment. It conforms to the UAT Minimum Operational Performance Standards (MOPS)[11][4] with industry standard link budgets assuming free-space propagation. It includes representative aircraft and ground-radio antennas and receivers, and accounts for typical channel losses and fade margin. The model can use a range of transmit power levels and receiver sensitivities (minimum trigger levels [MTL]). This study assumed all GA aircraft are transmitting 25 Watts (W) (44 decibels relative to a milli-Watt [dBm]) of effective radiated power (ERP) and have a receiver MTL of -93 dBm for a 90% message decode probability. A smooth Earth model is assumed and does not take into account the effects of terrain or buildings on the channel.

Traffic densities are accounted for in the UAT system model and drive channel loading and co-channel interference. UAT is dedicated to only ADS-B services, so it is a self-interfering system without influence from non-ADS-B systems. Therefore, only transmissions to and from UAT equipped aircraft need to be considered. The traffic density for GA aircraft used is based on 2020 FAA traffic growth projections for the high-density Northeast U.S. This baseline traffic count assumes 760 aircraft within a 200 NM radius and 20% of these aircraft are UAT equipped. Therefore, ADS-B message transmissions are modeled for 152 aircraft. The baseline traffic count further assumes 87% of the non-UAT traffic is operating below the ADS-B rebroadcast (ADS-R) service ceiling of FL230 (i.e., the upper limit of traffic provided by ADS-R), so ADS-R message transmissions are modeled for 529 aircraft. The model distributes the traffic both horizontally and vertically and is capable of applying growth factors. Additionally, the model can locate the traffic density relative to a subject UAT receiver using a parameter offset distance.

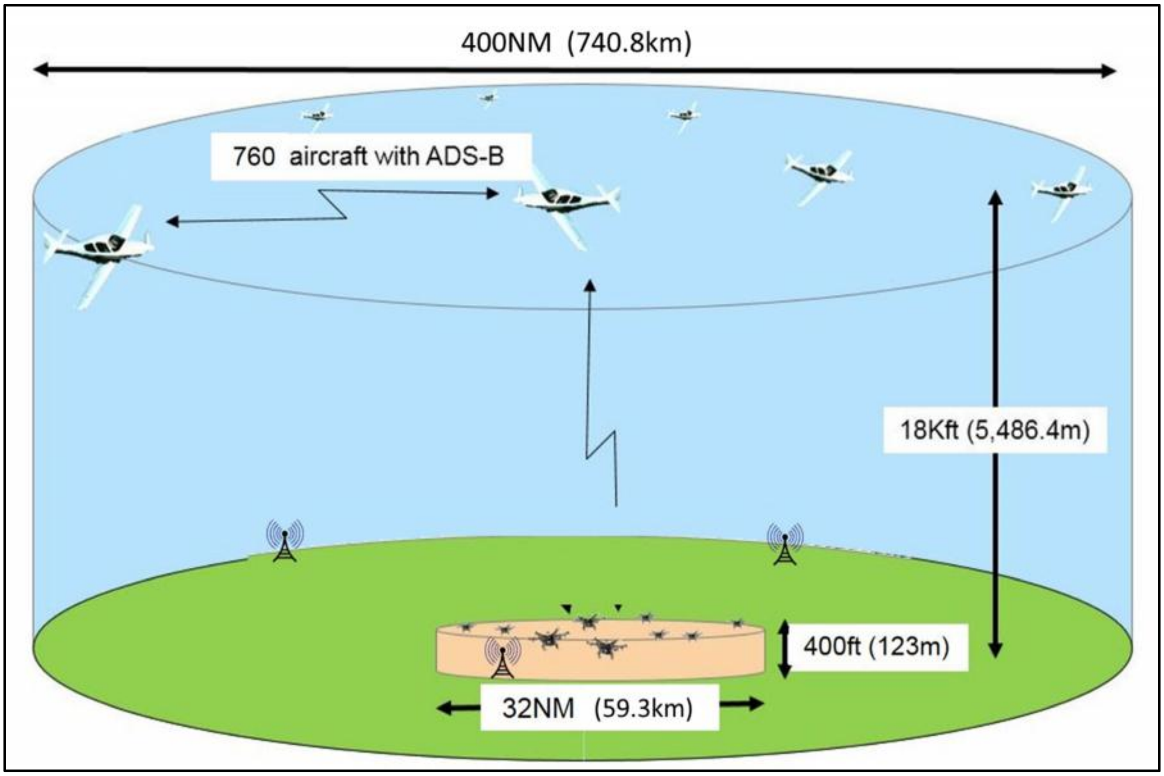


Figure 5: Modeled Airspace Environment

Figure 5 illustrates the UAT performance modeling environment. The subject aircraft receiver used in air-to -air applications (use case 1) is on a GA aircraft at 18,000 ft (FL180 is the top of the UAT service volume) getting maximum exposure to ADS-B transmissions from other aircraft and ADS-R of non-UAT equipped aircraft[5]. The aircraft has a UAT MOPS compliance receiver and a zero-gain, omnidirectional aircraft antenna. The subject ground station receiver used in air-to-ground ATM surveillance applications (use case 2) has an omni-directional antenna with 9 dBi of gain located 60 ft above the ground, and signal transfer losses of 3 dB.

The SUAS are uniformly distributed within a volume close to the ground below 400 ft. Variations of the SUAS transmit power and traffic density are independent variables in this study.

III. Analytical Approach

This study examined the impact on the UAT ADS-B service to support air-to-air and air-to-ground ATM applications in the national airspace system when SUAS are introduced into the airspace in various quantities and transmitting on UAT once per second at selected power levels. A model-based approach was used to determine the impact while considering the current ADS-B surveillance requirements for the ATM applications. The ATM applications considered were the GA aircraft-based TSAA and air traffic separation services at three miles and five miles as described in the two use cases above. The first step was to baseline the UAT system performance prior to introducing SUAS. This work is presented in reference 1 and revalidated in this study relative to the ATM applications. The second step was to model the shared-use UAT performance and determine what combination of SUAS densities and transmit power levels would not impact the ATM applications.

Transmission power determines the distance at which an ADS-B surveillance message can be decoded by a receiver. Four transmission power levels for SUAS were tested in this study: 1 W, 0.1 W, 0.05 W, and 0.01 W. The previous MITRE CAASD study used 1 W and is included here as a baseline power level case. Transmit powers of

[5] Though the GA aircraft is placed at 18,000 ft, analysis has shown no sensitivity to this height above a cluster of SUAS, being within line of sight is the only critical condition.

0.1W, 0.01 W and 0.05 W were considered as they may provide sufficient range for SUAS-to-SUAS communications and may lessen the impact on other traffic operations.

Traffic density combined with the transmission power determines the level of co-channel interference observed by a subject receiver within line of sight. Four levels of SUAS traffic density were tested: 5 SUAS per square kilometer (km^2) (14,000 SUAS total), 3 SUAS/ km^2 (8,500 SUAS total), 1 SUAS/ km^2 (2,000 SUAS total), and 0.5 SUAS/ km^2 (1,400 SUAS total). Each population of SUAS is assumed to be operating directly below the subject GA aircraft performing the TSAA application.

Table 3. Schematic of Airspace Conditions and Aircraft Density

Scenarios	**Transmit Power 1W**	**Transmit Power 0.1W**	**Transmit Power 0.05W**	**Transmit Power 0.01W**	**High sUAS Traffic *(5UAS/km²)***	**Medium sUAS Traffic *(3UAS/km²)***	**Low SUAS Traffic (1UAS/km²)**	**Very Low SUAS Traffic (0.5UAS/km²)**
Scen 1	X				X			
Scen 2		X			X			
Scen 3			X		X			
Scen 4				X	X			
Scen 5	X					X		
Scen 6		X				X		
Scen 7			X			X		
Scen 8				X		X		
Scen 9	X						X	
Scen 10		X					X	
Scen 11			X				X	
Scen 12				X			X	
Scen 13	X							X
Scen 14		X						X
Scen 15			X					X
Scen 16				X				X

A full factorial test run model was used to examine the four levels of SUAS traffic density with the four transmit power levels. The UAT system performance model was run for both the air-to-air TSAA and air-to-ground ATM separation use cases. In practice, a fractional test was performed because not all test cases were run once the UAT system modeling results of some subsets revealed either higher power or density was not supportable. Table 3 shows the scenario combinations used. As noted above, the previous MITRE CAASD study looked at Scenario 1. It is included here for completeness, to serve as a baseline, and to ensure improvements to the UAT performance model didn't inadvertently change previous findings.

IV. Results and Analysis

This study analyzed UAT air-to-air and air-to-ground system performance against currently published ADS-B application requirements with SUAS shared-use. The following sections will summarize the findings of this analysis. The work builds on previous research and many unknowns and considerations remain that are beyond the scope of this analysis. Full consideration of operational constraints and limitations is needed, before any consensus conclusions are made about SUAS impact on the current UAT system.

The UAT system is fundamentally modeled as a statistical communication system and before any channel loading or ATM applications are considered, the reception statistics are presented. Figure 6 shows a one-second quantized update interval at 95% and 50% confidence levels versus the probability of UAT message decode. The lower the probability of decoding a message translates to a longer period between updating the ADS-B data transmitted. These statistic apply to both air-to-air and air-to-ground communications. The ADS-B service standards generally use the 95% confidence curve as a performance metric.

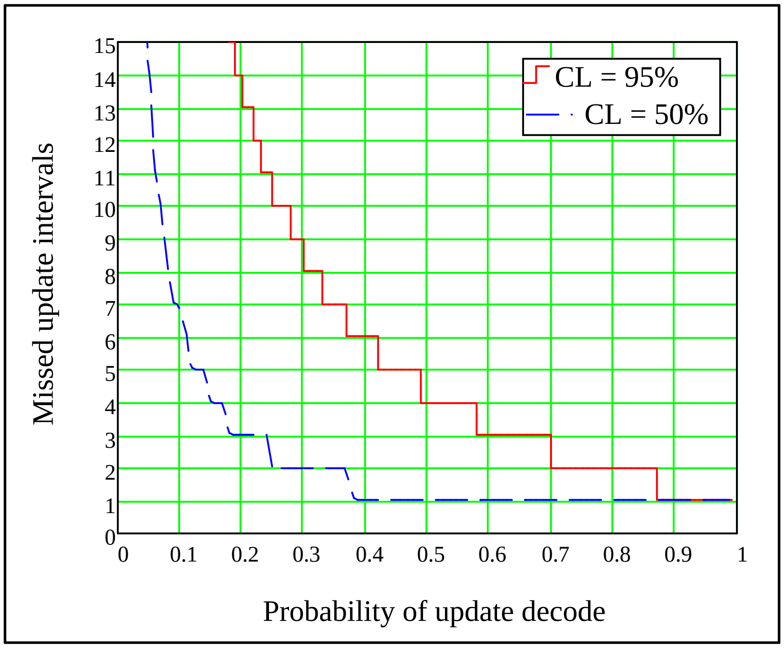


Figure 6: Missed Update Interval vs Probability of UAT Message Update Decode

A. GA UAT Performance (without SUAS): GA Air-to-Air Example

The theoretical UAT system performance as observed by single GA aircraft in the modeled environment defined above (Figure 5) without SUAS shared-use is shown in Figure 7. The GA aircraft is subjected to co-channel interference from other UAT transmitting GA aircraft and from the ADS-R transmissions on UAT from ground radio stations. The aggregate of these transmissions as viewed from the perspective of the subject receiving aircraft is also referred to as false replies unsynchronized in time ("fruit"). The ADS-R contributes the majority of the interference from the non-UAT aircraft below FL230 within the 200 NM traffic volume modeled. The UAT transmissions are once per second. A 60% probability of decoding a received message in this co-channel interference environment results the air-to-air performance of about 100 NM. This range provides sufficient margin for GA air-to-air ATM applications. The closer the two GA aircraft are the greater the probability of message decoding which approaches 1.0 as the aircraft are within 10 NM of each other.

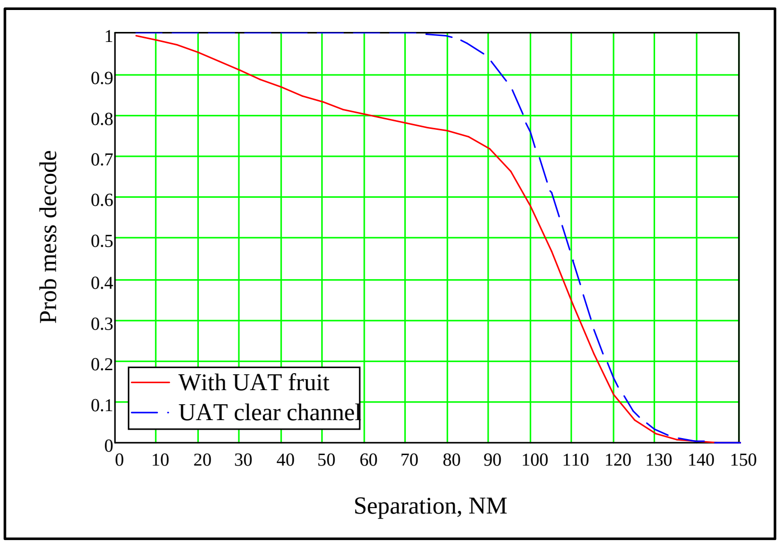


Figure 7: Probability of UAT Message Decode of UAT vs Air-to-Air Separation Range

B. SUAS UAT Performance: SUAS Air-to-Air Example

The use of UAT by SUAS may be for air-to-air applications between SUAS, between SUAS and GA aircraft, and among SUAS operators for fleet management. The necessary air-to-air range is undetermined. The ADS-B range is directly proportional to the transmit power level, the higher the power level, the greater the level of co-channel interference. The 2016 MITRE CAASD study assumed a SUAS UAT transmit power of 1 W, which would provide an air-to-air range in excess of 10 NM. Several additional lower power levels were assessed in the current study. These levels and their corresponding estimated air-to-air ranges are shown in Figure 8. The UAT MTL of -93 dBm is overlaid as a reference. It can be seen that orders of magnitude lower transmit power by SUAS should provide up to a few miles range and may be sufficient for their operational needs. However, 1 dB of standard deviation can have an effect of about 1 NM range at 0.01 W.

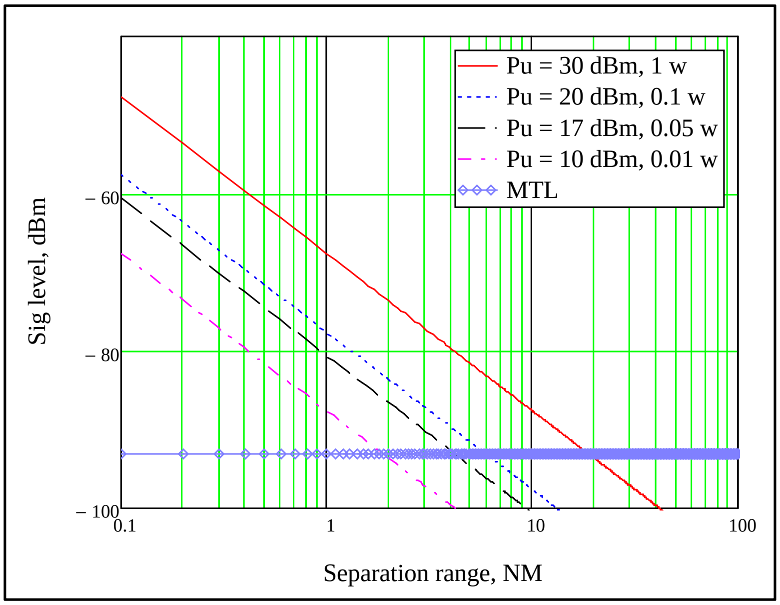


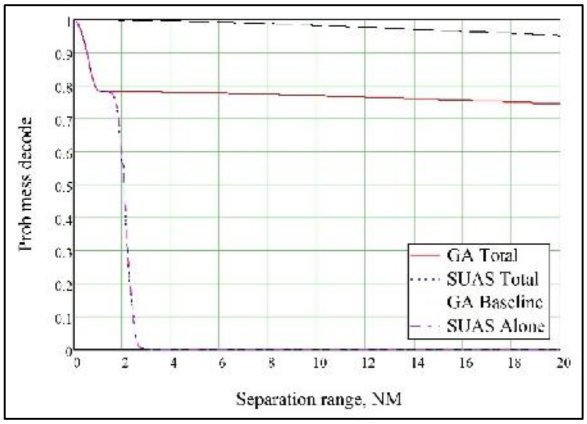
Figure 8: UAS Signal Level vs Separation Range for Varying Power

C. SUAS/GA Shared-Use of UAT: Air-to-Air Example

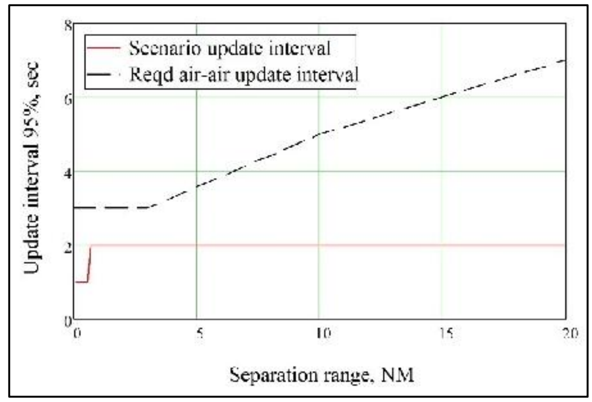
The 2016 MITRE CAASD study[6] considered an air-to-air operating scenario with a GA aircraft receiving ADS-B data over a high-density SUAS environment and each SUAS transmitting once per ten seconds at 1 W[6] (a modification of scenario 1 in Table 3). That analysis showed that a GA aircraft would not likely be able to support the range and update interval for the ATM applications in Table 1.

Maintaining the aviation-standard once per second broadcast rate in the high-density SUAS environment, a reduction in SUAS transmit power was analyzed to see if a lower power ADS-B was supportable while achieving the needed GA air-to-air performance. A SUAS transmit power of 0.01 W (scenario 4 in Table 3) appears to be acceptable with some margin while still enabling an acceptable SUAS air-to-air range. Figure 9 presents the GA and SUAS shared-use UAT performance. The left side is the probability of message decode for a GA aircraft operating over a high-density SUAS environment and showing its able to achieve 75-80% message decode success. The GA air-to-air range performance without SUAS-use of UAT is indicated by the dashed, black line at the top with >95% success out to 20 NM. Also shown is the SUAS air-to-air range with and without the ATM air traffic, which overlap suggesting the ATM traffic has no effect on the SUAS range performance. The right side shows this scenario enables the update requirements for GA air-to-air ADS-B applications to be achieved. A doubling of the number of manned aircraft in the 200 NM volume (not shown here) has no impact on the GA air-to-air capability at this SUAS transmit power level.

[6] Based on SUAS industry feedback, a once per second broadcast rate is used as the basis for this study.



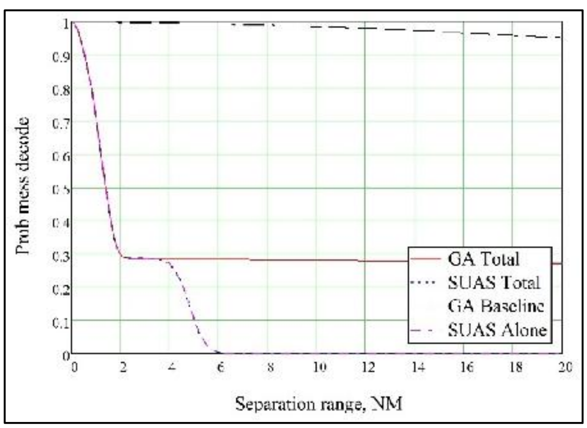
Shared-use UAT performance



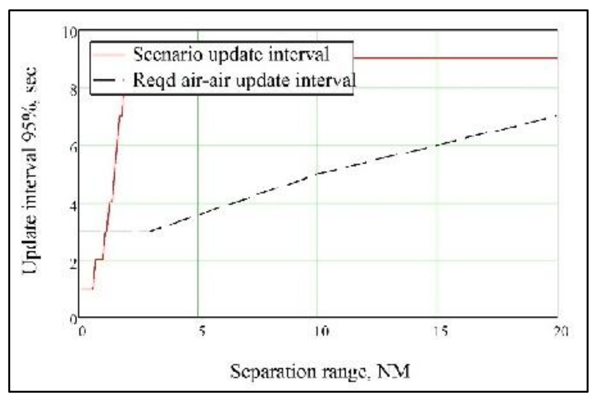
Comparison of scenario supported update interval with required 95% air-to-air update interval

Figure 9: Shared-Use UAT Performance for Air-to-Air Applications: Scenario 4 (5 SUAS/km2, 0.01 W)

Shared-use of UAT at high SUAS density (scenario 3 in Table 3) is no longer acceptable when the SUAS power level is increased to 0.05 W as shown in Figure 10. This shows the sensitivity of the transmit power level and its impact in a high-density SUAS environment. Note that reducing the manned traffic level to 100 aircraft within the 400 NM volume has no impact. However, there is sensitivity to the placement of the GA aircraft relative to the SUAS traffic density and offsetting the GA aircraft by as much as 20 NM has noticeable performance improvement due to free space power loss.



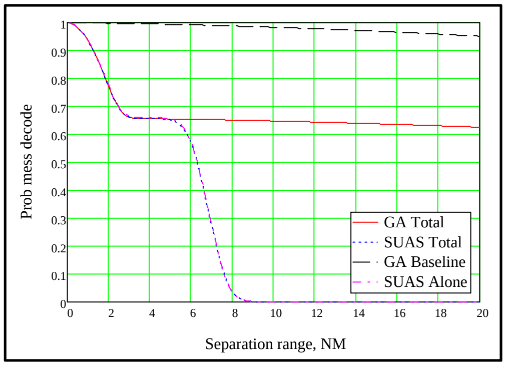
Shared-use UAT performance



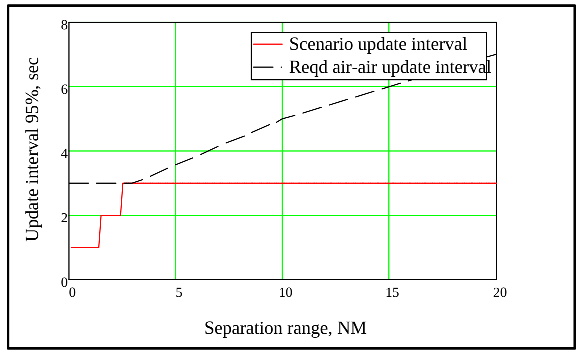
Comparison of scenario supported update interval with required 95% air-to-air update interval

Figure 10: Shared-Use UAT Performance for Air-to-Air Applications: Scenario 3 (5 SUAS/km^2, 0.05 W)

Reducing the density of SUAS, and thus the co-channel interference, has a positive effect on air-to-air performance for both GA aircraft and SUAS. The study looked at the trade-off in SUAS density and transmit power. As an example, reducing the SUAS density to 1 SUAS/km^2 from 5 may enable the SUAS transmit power to increase by an order of magnitude to 0.1 W (scenario 10 in Table 3). As shown in Figure 11, both the GA aircraft and the SUAS achieve a 60% probability of message decode. The SUAS air-to-air range more than doubles and the GA aircraft appears to achieve the required 95% air-to-air update interval for the ATM applications.



Shared-use UAT performance



Comparison of scenario supported update interval with required 95% air-to-air update interval

Figure 11: Shared-Use UAT Performance for Air-to-Air Applications: Scenario 10 (1 SUAS/km^2, 0.1 W)

To summarize the air-to-air shared-use UAT performance, there is a clear trade-off in SUAS density and SUAS transmit power level to be made while preserving ATM applications needs. The results are for the combined ATM-SUAS environment depicted in Figure 5. The SUAS density is expressed in the number of SUAS/km^2 along with the number of SUAS this density represents within a 16 NM radius below 400 ft. The probability of a GA aircraft being able to decode air-to-air ADS-B messages for the combinations of SUAS densities and power levels for the assumed ATM air traffic density noted earlier are summarized in Table 4. Decode probabilities of approximately 60% or greater with 95% confidence (see Figure 6) yield acceptable ATM application performance and are bold in the table. Cells showing greater than or less than values were combinations not tested because neighboring cases made the circumstances relatively clear, obviating the need for further analysis. For instance, since a 78% decode probability is achievable at 0.01 W in high-density SUAS, lower density SUAS will also work. On the contrary, any SUAS density at 1 W is questionable at these SUAS traffic densities.

Table 4. Summary of Air-to-Air Probability of Message Decode

SUAS density / SUAS w/in 16 NM radius	**SUAS Transmit Power (ERP)**			
	1 W	**0.1 W**	**0.05 W**	**0.01 W**
5 / 14000	<0.25	0.10	0.30	**<u>0.78</u>**
3 / 8500	<0.25	0.27	0.48	**>0.78**
1 / 2800	0.25	**<u>0.68</u>**	**<u>0.80</u>**	**>0.80**
0.5 / 1400	0.50	**<u>0.80</u>**	**>0.80**	**>0.80**

D. SUAS/GA Shared-Use of UAT: Air-to-Ground Example

ATM applications include providing separation services to aircraft. Radar and ADS-B are the surveillance sources used by air traffic controllers to apply either 3-mile or 5-mile separation standards. The ADS-B service uses an infrastructure of radio stations throughout the U.S. to receive ADS-B messages transmitted from aircraft. The FAA's required update interval for ADS-B reception to support these separation standards is provided in Table 2 above. Looking at Figure 6, a 60% GA aircraft UAT message decode probability with 95% confidence is necessary to attain an update interval of 3 seconds. For a 6 second update interval, a message decode probability of 40% is necessary at 95%. The air-to ground coverage is determined by the decode probability required for the desired air-to-air separation at the air-to-ground range of the aircraft pair to be separated. It should be noted that the current ADS-B services exceeds these minimum update interval requirements.

The shared-use of UAT by SUAS will potentially impact a ground-based receiver's ability to decode messages. The ground radio infrastructure is robust and ADS-B messages are often received by multiple stations hundreds of miles away. Aircraft at lower altitude (i.e, a few thousand feet) are heard by fewer stations due to line of sight limitations. SUAS operating below 400 ft will only affect the receiver performance of a station within a few miles, but that impact may be significant depending on the density of SUAS and their transmitting power.

For an ADS-B radio station centered in a 400 NM volume with the FAA 2020 traffic density and no SUAS, the ground receiver (with -93 dBm MTL, an elevated antenna 60 ft AGL with 9 dBi gain, and 3 dBi of signal transfer losses) observes a UAT co-channel interference rate as shown in Figure 12. The majority of air-to-ground UAT receptions are directly from GA aircraft since the ADS-R interference seen from neighboring relay stations is limited because of line of sight.

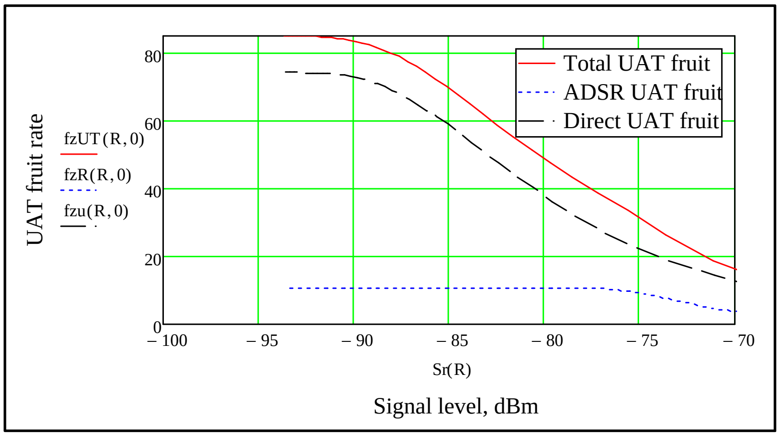


Figure 12: Ground UAT Receiver Reception of GA Aircraft Only

When the radio station is placed in a high-density SUAS traffic environment any transmissions within line of sight will be heard by the ground receiver. These transmissions represent co-channel interference because the radio station is expected to receive GA aircraft ADS-B messages, not the SUAS messages. At the lowest analyzed SUAS power level, the ground receiver decode probability is close to the 40% minimum reception rate to support 5-mile separation services. The ground receiver performance is provided in Figure 13. The reduced GA ADS-B message decode rate is due to the concentration of SUAS within line of sight of the station effectively reducing the receiver sensitivity with the large number of interfering transmissions.

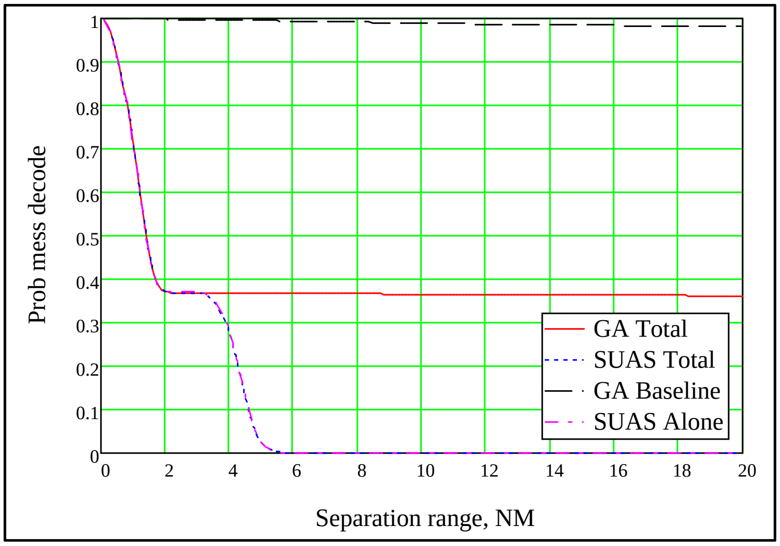


Figure 13: Shared-Use UAT Performance for Air-to-Ground Applications: Scenario 4 (5 SUAS/km2, 0.01 W)

Maintaining the low-power level and reducing the SUAS density from high (scenario 4 in Table 3) in the previous example to medium (scenario 8 in Table 3) illustrates the effect density has on the ground receiver performance. The ground receiver message decode improves to above 50% in Figure 14. Further reducing the SUAS density to low (scenario 12 in Table 3) improves the decode probability to greater than 80%.

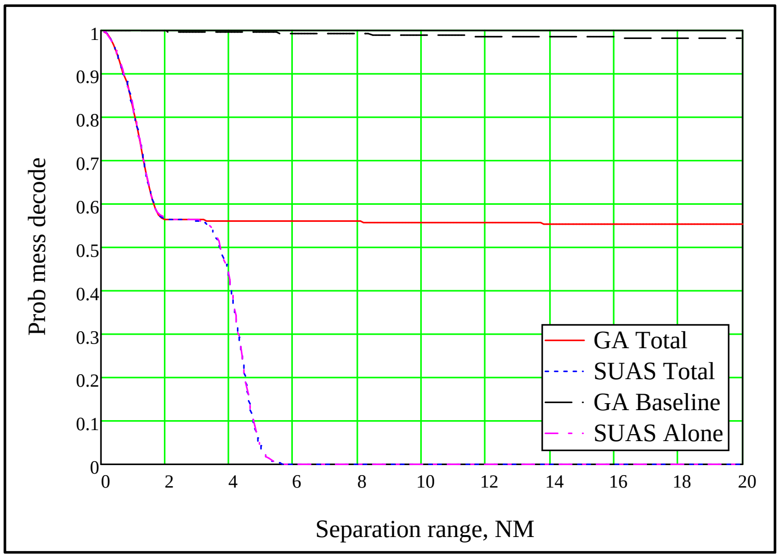


Figure 14: Shared-Use UAT Performance for Air-to-Ground Applications: Scenario 8 (3 SUAS/km^2, 0.01 W)

Extending the analysis to further reducing the SUAS density to very-low allows for an increase in transmit power and achieving a 60% message decode probability by the ground receiver. A decode probability of 60% for GA UAT messages supports a 3 second update at 95%. This relationship (scenario 14 in Table 3) is shown in Figure 15.

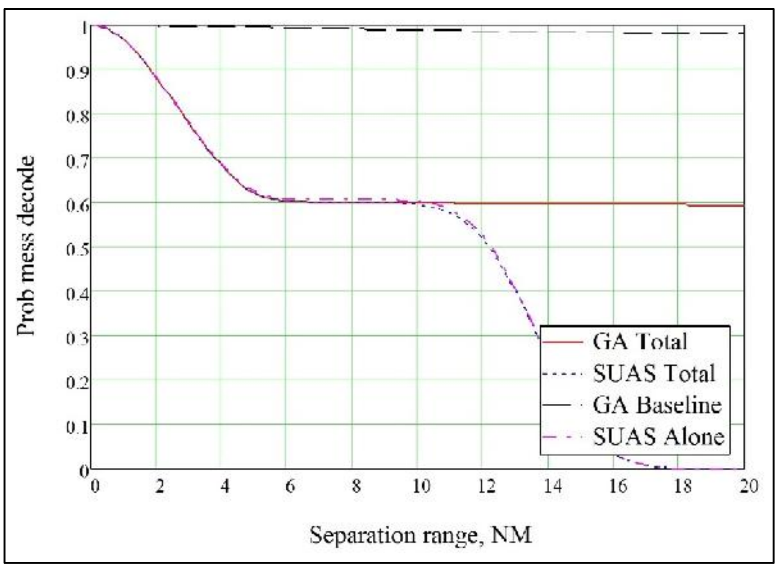


Figure 15: Shared-Use UAT Performance for Air-to-Ground Applications: Scenario 14 (0.5 SUAS/km^2, 0.1 W)

Offsetting the SUAS traffic distribution from an ADS-B radio station can also improve the performance. The improvement, above what has been shown by decreasing SUAS density around the ground station, is due to limitations in line of sight and free space loss. The further away from the radio station the SUAS are, the fewer transmissions are received. The analysis of scenario 2 (high-density SUAS and 0.1 W) suggests an offset of 20 NM is necessary to get the ground receiver decode probability to approximately 60%. This result suggests that although a hole in coverage will exist over ground stations located within the high-power or high-density SUAS clusters, the diverse reception from neighboring radio stations in the ADS-B service may still support terminal area ATM separation requirements.

Consistent with the air-to-air performance, the air-to-ground shared-use UAT performance has similar trade-offs in SUAS density and SUAS transmit power level to be made to preserve ATM applications needs. The following summary of results is for the environment depicted in Figure 5 with a ground radio station located in the middle of the SUAS traffic. The probability of being able to decode air-to-ground ADS-B messages for the combinations of SUAS densities and power levels for the assumed ATM air traffic density noted earlier are summarized in Table 5. Decode probabilities of approximately 60% or greater are bold. Cells showing greater than or less than values were combinations not tested because neighboring cases made the circumstances relatively clear, obviating the need for further analysis. The promising power-density relationship tend to favor lower SUAS densities than was permissible in the air-to-air results. Any transmit power associated with a high-density SUAS environment or any SUAS density at 1 W remains questionable given the assumption used regarding smooth-earth and no terrain or building obstructions.

Table 5: Summary of Air-to-Ground Probability of Message Decode

UAS density / UAS w/in 16 NM radius	**SUAS Transmit Power (ERP)**			
	1 W	**0.1 W**	**0.05 W**	**0.01 W**
5 / 14000	<0.25	<0.35	<0.10	0.38
3 / 8500	<0.25	<0.35	0.10	**0.58**
1 / 2800	0.25	0.35	0.50	**0.82**
0.5 / 1400	0.50	**0.60**	**0.70**	**>0.82**

V. Key Findings

The key findings from this analysis are summarized below.

General:

- Most UAT interference is from ground-based ADS-R of non-UAT ADS-B equipped aircraft (this analysis assumed all aircraft in the modeled environment were ADS-B equipped).
- UAT supports the current ATM air-to-air and air-to-ground ATM applications.
- ATM legacy GA traffic levels have little impact on shared-use UAT performance.
- SUAS density has the predominant impact on shared-use UAT performance.

UAT air-to-air ATM application support:

- UAT can likely support GA ATM air-to-air application requirements with high-density/very low-power SUAS (5 SUAS/km^2 at ERP = 0.01 W) and high-density ATM traffic (also with 2 x high-density ATM traffic).
- UAT can likely support GA ATM air-to-air application requirements with low-density/low-power SUAS (1 SUAS/km^2 at ERP = 0.05 W) at any ATM traffic density.
- UAT can likely support GA ATM air-to-air application requirements with low-density/medium-power SUAS (1 SUAS/km^2 at ERP = 0.1 W) and high-density ATM traffic.
- Horizontal offset of the GA aircraft receiver from the SUAS distribution reduces the SUAS impact on air-to-air UAT performance.

UAT air-to-ground ATM application support:

- UAT can likely support air-to-ground ATM applications requirements with medium-density/very-low power SUAS (3 SUAS/km2 at ERP = 0.01 W) with radio station diversity reception and high-density ATM traffic.

- Some of the UAT co-channel interference produced by ADS-R is below line of sight for ADS-B ground radio stations and thus, does not contribute to the air-to-ground reception performance to the extent SUAS transmissions might.
- Displacement of the SUAS traffic from the ADS-B ground radio station effectively reduces the SUAS impact on ATM air-to-ground application performance due to line of sight limits.

VI. Conclusion and Future Work

This study extended prior research and examined a multitude of scenarios from low to high stress cases. The analysis indicates the key parameters are SUAS ADS-B transmission power and SUAS traffic density. These two parameters can be balanced to attain an acceptable demand on the UAT in areas of potentially high SUAS concentration while still providing safety and utility to all aircraft.

Future work should focus on continuing to validate the assumptions and analyses as the models and findings presented here are considered preliminary estimates. Continue to investigate the many operational considerations for the extensive range of SUAS applications and the integrated use of ADS-B or ADS-B like systems in the national airpsace.

Presented results showed how key parameters affect current system performance if fleets of UAT equipped SUAS are added to the national airspace. It has been shown that there are ranges of transmit power and traffic density that are compatible with the current system. This analysis was modeled, and as with all models, assuptions and constraints affect the results. A feasibility evaluation for a particular future fleet should include specific details on the fleet size, distribution, transmit power, number of aircraft simultaneously transmiting, manned aircraft traffic, distance from SUAS to ground stations, terrain details and other parameters.

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