INVESTIGATING COLLISION AVOIDANCE FOR SMALL UAS USING COOPERATIVE SURVEILLANCE AND ACAS X

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This report is based on the Master's Thesis of John Logan Deaton submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science at the Massachusetts Institute of Technology.

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by

John Logan Deaton and Prof. R. John Hansman

Abstract

Small Unmanned Aircraft Systems (sUAS) have proliferated over the last decade. While these platforms offer many benefits to society, they pose a dangerous mid-air collision hazard. In order to safely integrate into airspace shared by other users, sUAS must be able to avoid collisions with manned aircraft.

To better understand sUAS flight behavior and inform Collision Avoidance (CA) systems for sUAS, over 600 active UAS platforms were reviewed. The mean climb rate capability was 720 feet per minute (fpm) for all reviewed sUAS, which suggests that CA systems currently used by manned aircraft (which require 2,500 fpm climb capability) would be inappropriate for implementation on sUAS. Novel CA systems are therefore required.

Next, to assess the feasibility of CA system equipage on sUAS, the Size, Weight, Power, and Cost (SWaP-C) of equipment necessary for CA systems were studied. It was determined that a complete CA system utilizing cooperative surveillance could weigh less than 70 grams and require less than 2 W of average input power. Because cooperative surveillance broadcasts from sUAS could overload the spectrum currently used to share aviation information, signal transmissions were simulated for a population of sUAS broadcasting alongside current users. While transmitting sUAS would quickly degrade performance on the busy 1090 MHz channel, the 978 MHz channel could potentially support about 1 transmitting sUAS per square kilometer if sUAS broadcast ADS-B signals at only 80 mW.

Finally, close encounters between sUAS and manned aircraft were simulated in the Mode C Veil environment to evaluate threat resolution options used by different CA systems. Manned aircraft using existing CA systems to avoid sUAS would achieve extremely high levels of safety (risk ratios below 0.05) but would experience high rates of alerts. Furthermore, sUAS are so small that manned aircraft without CA systems would be unlikely to visually see and avoid them. Novel CA systems were modeled on sUAS and were able to avoid manned aircraft with currently-accepted levels of safety (risk ratios below 0.18) even with limited or no vertical maneuvering by using horizontal escape maneuvers (i.e. turns). Alerting rates for horizontal maneuvers were high but may be acceptable for use on sUAS. The new sUAS CA systems cooperated well with existing systems for manned aircraft and resulted in extremely low collision risk (risk ratios below 0.02) in encounters where manned aircraft and sUAS both took action to avoid collisions.

Results therefore indicate that sUAS could utilize existing cooperative surveillance systems and prototype CA policies to mitigate close encounters with manned aircraft in Mode C Veils at safety levels that are currently accepted among manned aircraft.

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Chapter 1

Introduction and Motivation

Small Unmanned Aircraft Systems (sUAS) need a way to avoid collisions with manned aircraft. Also called Unmanned Aerial Vehicles (UAVs), Remotely Piloted Aircraft (RPAs), and "drones", UAS are aircraft systems that operate without human pilots on board. The Federal Aviation Administration (FAA) has defined sUAS as UAS that weigh less than 55 pounds. Despite a dearth of sUAS before 2010, the United States and Europe now have more than one million sUAS each [1, 2]. The FAA predicts that the number of both personal-use and commercial sUAS will continue to rise rapidly, with the year-by-year fleet size displayed in Figure 1-1 [3]. The sUAS fleet already dwarfs the entire U.S. manned fleet, which is projected to remain stable at about 7K commercial aircraft and 210K General Aviation (GA) aircraft [4].

Unfortunately, sUAS pose a dangerous collision hazard to other vehicles in the sky. Unlike manned aircraft, sUAS have no pilot aboard to see other aircraft and take appropriate action to avoid them. If sUAS are allowed to roam the skies with no protections against collision, they could cause fatal accidents by impacting manned aircraft. There have already been numerous accidents and near-accidents involving sUAS, including a 2017 accident where a DJI Phantom struck an Army helicopter [5]. The FAA responded to this collision threat by prohibiting sUAS flight in almost all areas where manned aircraft can fly.[1] For example, sUAS can only operate during the day, within 400 feet of the ground, and within visual line of sight of a human

[1] See Part 107 of Title 14 of the Code of Federal Regulations (CFR).

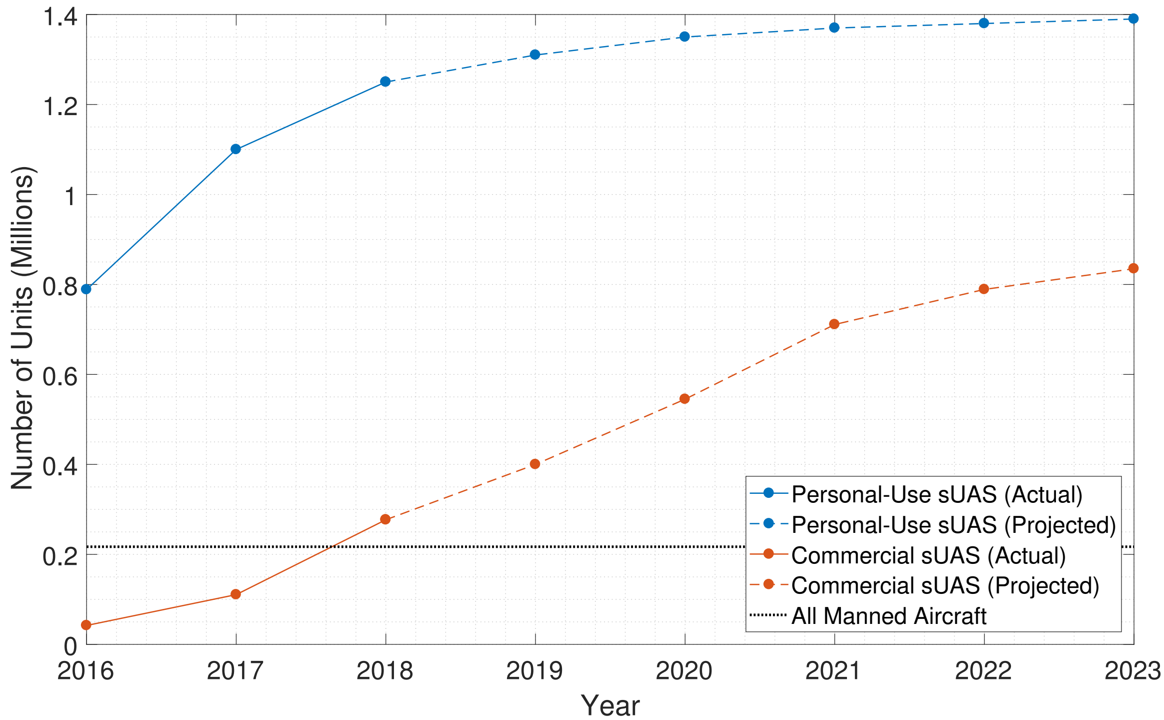


Figure 1-1: U.S. Fleet Sizes with FAA Projections through 2023

controller or observer. The FAA regulations lower the risk of collision but place strict limits on sUAS operations, and waivers often require an arduous review process.[2]

Despite these restrictions, the rising numbers and falling costs of sUAS have encouraged use in a variety of disciplines. Small UAS are now used for utility and infrastructure inspection [7, 8, 9]; aerial surveys and photography [10]; airborne video for news, sports, and film [11, 12]; disaster response, such as search and rescue [11]; and more. The most common uses of non-personal sUAS in 2017 were real estate and aerial photography (48% of uses), industrial inspection (28%), and agriculture (17%) [1]. Many new uses are also likely to come. Google,[3] Amazon,[4] and Boeing[5] are among the companies investing in autonomous delivery systems that could leverage sUAS to transport small packages. British accounting firm PwC estimates that the worldwide addressable value for sUAS applications is $127 billion [13]. The potential

[2]The National Academies shares a story of a science mission that requested a waiver for a 1.5 pound sUAS to autonomously collect data 50 feet above the ground in remote airspace north of Alaska. The waiver was denied after a full year of review, despite the negligible risk of collision [6].

[3]See Wing, owned by Google's parent company Alphabet: `https://wing.com/`

[4]See Amazon Prime Air: `https://www.aboutamazon.com/innovation/prime-air`

[5]Boeing invested $16M in sUAS delivery company Matternet: `https://mttr.net/`

for sUAS to revolutionize many different sectors is immense.

In order to allow integration into manned airspace and unlock the full economic benefits that sUAS can provide to society while maintaining an acceptable level of safety, there must be a way for sUAS to mitigate the risk of mid-air collisions with manned aircraft. This thesis explores how sUAS could equip Collision Avoidance (CA) systems to safely resolve close encounters with manned aircraft. Small UAS characteristics are first studied to better understand flight behavior and the maneuvering capabilities that may be available to avoid potential collisions. Then, surveillance systems are analyzed to determine if sUAS can detect and be detected by manned aircraft at appropriate levels of size, weight, power, cost, and bandwidth usage. Finally, encounters between manned aircraft and sUAS are modeled to assess the relative safety and alerting rates of potential CA systems. A more detailed outline of the remainder of this thesis is provided below.

Chapter 2 provides an overview of airborne CA. A brief history of CA protections is given to provide the context that motivated airborne CA systems as a final defense against mid-air collisions after the failure of other protections. It is explained that a CA system fundamentally consists of two functions: surveillance and threat resolution. The chapter discusses how both of these functions are currently accomplished among manned aircraft.

Chapter 3 performs a quantitative study of sUAS characteristics. While some qualitative aspects of sUAS are generally understood (e.g. they tend to be smaller than manned aircraft), this chapter quantifies sUAS size and performance characteristics and explores how UAS performance varies with size. The weight, span, payload, speed, climb capability, and turn capability of various UAS are analyzed.

Chapter 4 explores cooperative surveillance systems for sUAS. The Size, Weight, Power, and Cost (SWaP-C) of CA system components are compared to sUAS capabilities. The cooperative surveillance environment is then modeled to determine how the presence of additional sUAS broadcasters would affect signal reception performance for all users, including manned aircraft.

Chapter 5 evaluates different threat resolution options for sUAS. Monte Carlo simulations are used to model close encounters between manned aircraft and sUAS in the Mode C Veil environment. Three primary CA options are assessed: manned aircraft avoiding sUAS, sUAS avoiding manned aircraft, and both types of aircraft avoiding each other. CA systems for each option are evaluated on their alerting rates and their ability to safely resolve the modeled encounters.

Finally, Chapter 6 ends this thesis by summarizing major findings and considering areas for future work.

Chapter 2

Overview of Airborne Collision Avoidance

Before exploring how sUAS can perform airborne Collision Avoidance (CA), it is informative to review how CA is achieved for the manned aircraft currently using the airspace. Section 2.1 provides a brief history of the development of CA protections for manned aircraft. Then, Sections 2.2 and 2.3 review the system architecture currently enabling airborne CA. Surveillance is discussed first, followed by threat resolution.

2.1 History of Collision Avoidance Protections

Pilots have always assumed a responsibility to recognize the presence of nearby aircraft and take appropriate action to prevent fatal mid-air collisions. This responsibility is now officially codified in regulations like 14 CFR 91.113,[1] which requires that pilots in the United States maintain vigilance to "see and avoid other aircraft". In the early days of flight, this was the only protection against mid-air collisions. However, as the number of planes in the air increased and as instruments were developed to allow aircraft to fly in low-visibility conditions, this "see and avoid" responsibility became insufficient. In 1956, two aircraft collided over the Grand Canyon, resulting in 128 fatalities. While not the first mid-air collision, the accident garnered interna-

[1] This shorthand refers to Title 14 of the Code of Federal Regulations, Part 91, Section 113.

tional press and led to a public call for reform in air traffic control (ATC). In 1958, Congress created the Federal Aviation Agency, later renamed the Federal Aviation Administration (FAA).

The FAA began to better organize the airspace over the U.S. Most of the airspace higher than 1,200 feet above the ground is now controlled airspace, which falls into five classes. The airspace above flight level 180 (FL180),[2] where most commercial air carriers cruise, is referred to as Class A. Class B, C, and D refer to the airspace surrounding towered airports (generally Class B airports handle the most flights and passengers, followed by Class C, then Class D). Class E refers to all other controlled airspace, which includes non-towered airports. Uncontrolled airspace, which is generally below 1,200 feet above the ground and away from airports, is referred to as Class G. Figure 2-1 provides a visual overview of the different types of U.S. airspace. A more thorough discussion of airspace organization can be found in Chapter 15 of the FAA's *Pilot's Handbook of Aeronautical Knowledge* [14].

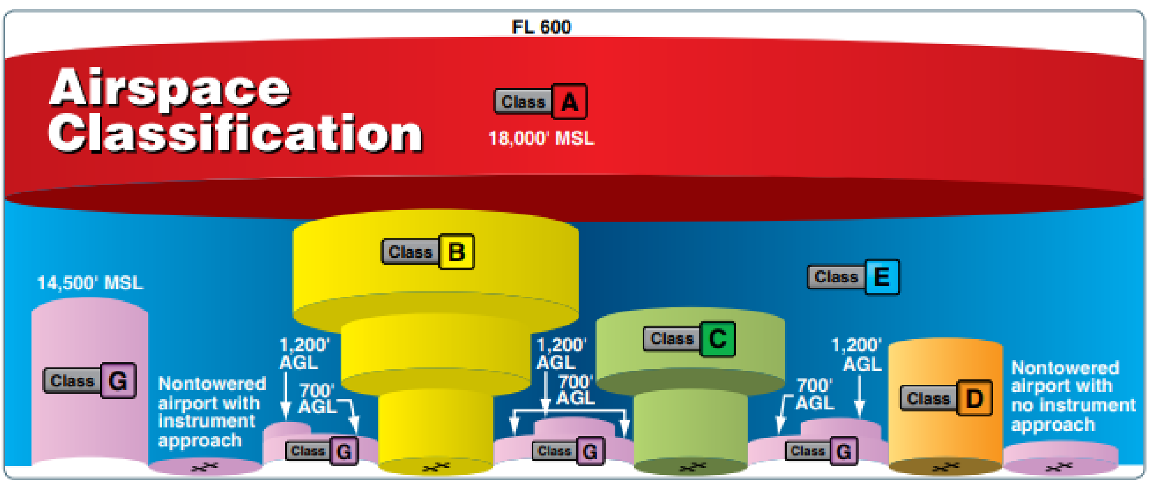


Figure 2-1: Overview of U.S. Airspace Organization

The organization of U.S. airspace allows ATC to better regulate aircraft and reduce the chance of mid-air collisions. For example, an aircraft cannot enter Class A airspace unless it is flying under Instrument Flight Rules (IFR), which requires filing a flight

[2]FL180 refers to 18,000 feet pressure altitude. At high altitudes (beginning at FL180), aircraft standardize their barometers and use pressure altitude rather than continually making local corrections for the true altitude.

plan and following ATC guidance. This helps ATC to track all the aircraft at high altitudes and route them to avoid one another. Cruising aircraft must also adhere to the hemispheric rule, which states that IFR traffic traveling west (a compass heading of 0 through 179 degrees) must fly at even thousands (4,000 ft, 6,000 ft, FL220, etc.), while IFR traffic traveling east (a compass heading of 180 through 359 degrees) must fly at odd thousands (5,000 ft, 7,000 ft, FL230, etc.). Aircraft flying under Visual Flight Rules (VFR) add 500 feet to these altitudes to provide separation between IFR and VFR traffic. The establishment of the hemispheric rule lowered the chance that aircraft would be involved in head-on collisions at high speeds, and also reduced the risk that IFR traffic following ATC guidance would encounter VFR traffic not following filed flight plans.

In the 1956 grand canyon mid-air collision, both aircraft were flying in uncontrolled airspace and the entire burden of collision avoidance fell on the pilots of those aircraft. Following the FAA's reforms to airspace structure, however, many aircraft (including nearly all commercial air carriers) remained in controlled airspace for the entirety of their flights. This allowed ground-based controllers to aid with collision avoidance by using a radar network to track and direct airborne traffic. While pilots still had the responsibility to see and avoid other aircraft in flight, ATC helped to lower the rate of mid-air collisions by providing helpful guidance to aircraft in the air.

Unfortunately, the combination of airspace structure and ATC guidance did not prevent all mid-air collisions. In a famous 1986 accident, a small privately-owned aircraft trespassed into the controlled airspace for Los Angeles International Airport without clearance and struck the tail section of a commercial airliner. All 67 people on board the two aircraft were killed, as were another 15 people on the ground in the suburb of Cerritos. This accident highlighted the need for an additional layer of safety in case one of the safeguards against collisions failed. In response, an airborne CA system was desired. Such a system would allow an aircraft (called the "ownship") to track and avoid another aircraft (called the "intruder") that posed a collision threat, without the need for ATC to intervene. Because the purpose of an airborne CA system is to provide a final layer of safety after other protections have failed, the system does not depend on airspace regulations being followed properly.

An airborne CA system requires two primary functions. First, the ownship must be able to detect the presence and relative location of the intruder. In other words, the ownship must be able to *surveil* the intruder. Section 2.2 explains how airborne surveillance is currently accomplished, and Chapter 4 explores how this could be extended to sUAS. The other function that must be accomplished by an airborne CA system is *threat resolution*. Threat resolution is the process of selecting an appropriate response to alleviate the possibility of collision once the intruder has been detected. Section 2.3 details how threat resolution is performed with current CA systems, and Chapter 5 investigates how threat resolution could be achieved in encounters involving sUAS.

2.2 Airborne Surveillance Systems

To implement a CA system, an aircraft must first know about the presence and location of other aircraft in the sky. Among manned aircraft, widespread airborne surveillance systems are *cooperative*. This means that the surveillance systems only work when both aircraft carry equipment that can cooperate with each other. Most commonly, aircraft carry transponders to share information with each other and with ground controllers. Transponders are described in greater detail below. There is also a new broadcasting system called Automatic Dependent Surveillance - Broadcast (ADS-B) for aircraft to broadcast their flight information to each other.

Because manned aircraft typically rely on cooperative surveillance systems, a CA system that depended on this surveillance information would not provide protection against an intruder who carried no position-sharing equipment. However, adding a non-cooperative sensor (like an air-to-air radar) that could detect unequipped intruders would be heavy and costly for most aircraft. Furthermore, the FAA requires aircraft flying in nearly all high-density airspace to equip a transponder (and, beginning in 2020, ADS-B), so a manned aircraft can surveil nearly all other aircraft in the busy areas where mid-air collisions are most likely. This allows a high level of safety to be achieved even without needing a non-cooperative sensor.

2.2.1 Transponders

Many manned aircraft (and ground controllers) rely on transponders to track the location of other aircraft. Transponders are a type of Secondary Surveillance Radar (SSR), which originated as an improvement and complement to Primary Surveillance Radar (PSR). PSR can be used to approximate the location and speed of distant objects by sending out electromagnetic energy (radio waves) and measuring the energy that is reflected back to the transmitter. Since radio waves travel at the speed of light, the distance to the detected object can be calculated using the energy's round-trip travel time. The speed of the object can also be calculated by measuring the Doppler shift of the reflected energy. However, it can be challenging to maintain high accuracy with PSR over long distances, particularly for altitude information. It would also be expensive for aircraft to carry air-to-air radars to accomplish airborne surveillance through PSR.

Instead, SSR became the foundation of the Air Traffic Control Radar Beacon System (ATCRBS). Unlike PSR, SSR consists of two-way communication. One transponder sends out an interrogation, a beam of energy on 1030 megahertz (MHz). If the interrogation reaches another transponder, a response signal is provided on 1090 MHz. This is also known as *active* surveillance since an action is taken (an interrogation is made) to obtain the surveillance information. Because the radio waves only travel in one direction rather than complete a round trip, SSR can provide accurate surveillance information at extremely long ranges (200-250 nautical miles) [15]. Furthermore, additional information can be encoded into the message itself. The two modes of interrogation and reply that form the basis of the ATCRBS are Mode A and Mode C. In Mode A, the response signal provides a four-digit aircraft identification code that the pilot can manually set and change during flight. Pilots flying under ATC guidance are usually assigned a four-digit code to enter, which is then used to track the aircraft during its flight. Aircraft flying under VFR keep their code set at 1200. Mode C responses provide the aircraft's pressure altitude in 100 foot increments, which is helpful to better understand the exact location of the aircraft. Transponders with both Mode A and Mode C capabilities are required to fly in most high-density airspace, to include Class A, B, and C airspace, airspace above 10,000 feet Mean Sea Level (MSL),[3] and airspace within 30 nautical miles (NM) of a Class B airport (this area is known as the "Mode C Veil"). The official requirements for transponder equipage can be found in 14 CFR 91.215.

Another mode of transponder interrogation and reply, known as Mode Select (Mode S), was created to improve upon the ATCRBS [16]. Mode S replies contain more encoded information than Mode A and Mode C replies. One of these is a unique 24-bit aircraft identification code. Unlike the Mode A code that can be changed by the pilot in flight, the 24-bit Mode S code is unique for every aircraft that has a Mode S transponder. The Mode S replies also provide greater accuracy for the aircraft's pressure altitude, which is reported in 25 foot increments rather than 100 foot increments. Other data that can be encoded in Mode S replies include flight status (airborne or on the ground), airspeed, vertical rate, magnetic heading, and more [15]. A Mode S transponder can be used in place of a Mode A/C transponder to fly in the airspace described in 14 CFR 91.215, and a mode of interrogation and reply known as intermode allows Mode A/C transponders and Mode S transponders to reply to each other. The Minimum Operational Performance Standards (MOPS) that govern the operation of ATCRBS and Mode S transponders on aircraft are given by the Radio Technical Commission for Aeronautics (RTCA) in DO-181E [17].

Transponders have been the primary equipment enabling airborne surveillance for many years. However, as mentioned earlier, a new system called ADS-B is emerging and will soon be required in most of the same airspace where a transponder is required. An overview of ADS-B is provided next.

[3] MSL is the mean altitude of the Earth's oceans. Altitude is commonly measured as the distance above this reference point. 10,000 feet MSL means 10,000 feet above mean sea level.

2.2.2 ADS-B

ADS-B, which stands for Automatic Dependent Surveillance - Broadcast, is envisioned as an improvement to the current surveillance environment that primarily involves transponders. The name for ADS-B derives from qualities that describe its operation. It is an *automatic* system that is *dependent* on Global Positioning System (GPS) data obtained from satellites to provide *surveillance* information via *broadcast*.

An aircraft transmitting ADS-B messages (referred to as "ADS-B out") reports its estimated lateral position (derived from GPS), altitude, velocity, and other information every second by broadcasting an omni-directional signal that can be received by nearby aircraft and ground stations. An aircraft with the capability to receive these messages (known as "ADS-B in") can then know the location of other aircraft with a high degree of accuracy. Unlike SSR, ADS-B is a *passive* source of surveillance since the information can be received without taking any particular action to request it. ADS-B out will be required in most of the airspace where transponders are required beginning on January 1st, 2020. For a full list of the locations where ADS-B will be required, see 14 CFR 91.225.

In the U.S., ADS-B can operate on one of two channels. The ADS-B messages can be broadcast on 1090 MHz, the same frequency as transponder replies. This allows ADS-B signals to be transmitted by a Mode S transponder that has been modified to perform a function known as Extended Squitter (ES). Accordingly, ADS-B transmissions on 1090 MHz are often referred to as 1090ES.[4] The standards regulating ADS-B on the 1090 MHz channel are given by the RTCA in DO-260B [18]. The other channel for ADS-B, which is unique to the U.S., is 978 MHz. ADS-B on 978 MHz is known as Universal Access Transceiver (UAT). It is envisioned as an alternate channel that can be used by many General Aviation (GA) aircraft and can also be used to share additional information since there are fewer concerns about interfering with transponder replies and other broadcasts on 1090 MHz. The RTCA standards

[4]It is legal to implement an ADS-B system that broadcasts on 1090 MHz even if the aircraft does not have a Mode S transponder. However, in practice, this is rare. Most aircraft that equip ADS-B but do not have Mode S transponders will likely use the 978 MHz channel.

for UAT can be found in DO-282B [19].

One of the primary advantages of ADS-B is that it provides greater accuracy for an aircraft's lateral position and direction than SSR, and it provides this information to any receiver that can process ADS-B messages. While a full discussion of the accuracy requirements for ADS-B is beyond the scope of this chapter, a few of the important metrics will be provided. ADS-B signals must provide an aircraft's position with an Estimated Position Uncertainty (EPU) of less than 0.05 NM (93 meters) 95% of the time. The probability that an aircraft's position is reported with an error greater than 0.2 NM (370 meters) must be less than 1×10^{-7} (i.e. the probability must be less than one in ten million). Furthermore, the aircraft's velocity must be reported with an error less than ten meters per second. A more thorough review of the ADS-B requirements can be found in Advisory Circular (AC) 20-165 from the FAA [20].

Another advantage of ADS-B is that it allows the transmission of additional information through ground stations. Some of the other services provided through ADS-B include Automatic Dependent Surveillance - Rebroadcast (ADS-R), Traffic Information Service - Broadcast (TIS-B), and Flight Information Service - Broadcast (FIS-B). ADS-R takes ADS-B messages that were received on one channel (1090 or 978 MHz) at a ground station and broadcasts those messages on the other channel. This allows aircraft to receive the ADS-B messages of all broadcasting aircraft, even if they can only receive broadcasts on one of the two channels. TIS-B provides airborne aircraft with information about the location of other nearby traffic. This allows an aircraft equipped with ADS-B to surveil another aircraft equipped with a transponder but not with ADS-B. TIS-B may also be used to share information about aircraft detected using ground-based PSR. FIS-B, which is only available on UAT, broadcasts real-time flight information from the FAA and National Weather Service to include weather forecasts, pilot reports, and more.

The combination of transponders and ADS-B allows airborne aircraft to obtain data about the presence and location of nearby traffic without the intervention of ATC. However, the mere knowledge of nearby aircraft is not sufficient. Appropriate evasive action must be taken when the presence of nearby traffic poses a collision hazard. Section 2.3 explains how threat resolution is currently achieved by airborne CA systems.

2.3 Airborne Threat Resolution Systems

The 1986 accident over Cerritos highlighted the need for an airborne system that could not only track the presence of nearby aircraft, but also take action to resolve the threat of collision when necessary. There are two fundamental ways that current airborne CA systems provide threat resolution. The first is by providing a *Traffic Alert* (TA). A TA is a notification to the pilot that nearby traffic poses a collision hazard. A TA generally provides an aural alert such as "Traffic, traffic!" to capture the pilot's attention, and might also provide information about the relative position of the traffic. However, TAs do not provide any recommended maneuvers to mitigate the potential conflict. The other way airborne CA systems provide threat resolution is by issuing a *Resolution Advisory* (RA). The RA is the action that the CA system recommends taking in order to avoid a collision. An example action would be to climb with a rate of at least 1,500 feet per minute (fpm) to avoid the nearby traffic. Pilots are generally expected to comply with the RA quickly (within five seconds), even if the intruder has not been visually acquired.

The threat resolution system implemented in response to the Cerritos accident is known as the Traffic Alert and Collision Avoidance System (TCAS). TCAS is currently the only fully certified CA system. An overview of TCAS is given in Section 2.3.1. The FAA is also working with the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, one of the developers of TCAS, on a future collision avoidance system known as the Airborne Collision Avoidance System X (ACAS X). ACAS X is envisioned as an improvement to TCAS and includes alternative versions for other applications such as use on unmanned aircraft. Section 2.3.2 provides an overview of ACAS X, and Chapter 5 uses the ACAS X framework to create threat resolution policies for sUAS.

There are several other airborne threat resolution systems that are either less common or are in development for future use. Examples include the Traffic Situation Awareness with Alerting (TSAA) system for GA aircraft [21], and the FLight alARM (FLARM) system used by many gliders. However, TCAS and ACAS X are the only systems that will be further discussed in this chapter.

2.3.1 TCAS

TCAS is the system used by all large air carriers and many other aircraft worldwide to provide threat resolution. The two main versions of TCAS are known as TCAS I, which provides TAs only, and TCAS II, which provides RAs in addition to TAs. In the U.S., TCAS I is required for turbine-powered, passenger-carrying aircraft with 10 to 30 seats, and TCAS II is required for commercial aircraft with more than 30 seats or a maximum takeoff weight greater than 33,000 pounds. The TCAS logic was also used to create a CA system for GA aircraft known as the Traffic Advisory System (TAS), which is functionally similar to TCAS I. A more thorough review of TCAS can be found in the FAA's introduction booklet [22], and the full MOPS are given in DO-185B [23].

To avoid the need to design and implement an entirely new airborne surveillance system, TCAS makes use of the surveillance information already available with transponders. TCAS units make active transponder interrogations to determine the relative position of other aircraft. A directional antenna is also used to estimate the bearing of intruders. This provides position information on all other aircraft with transponders, to include both Mode A/C and Mode S transponders. Two values that can be calculated from this surveillance information are the slant range r to the intruder and the closing rate $\dot{r}$ between the ownship and intruder. These two values are used to calculate τ (tau), the approximate time to the Closest Point of Approach (CPA) between the two aircraft. Equation 2.1 displays the calculation of τ by dividing the slant range by the range closure rate. This is also called the range τ to differentiate from the vertical τ. Note that τ is defined as infinite when the ownship and intruder are diverging or maintaining a constant distance. Also, τ does not represent the exact time to CPA if either aircraft is accelerating (to include turning). Based on the altitude information encoded in Mode S and Mode C transponder replies, the intruder's pressure altitude is also used to calculate a vertical τ denoting the time until the aircraft will be co-altitude. To calculate the vertical τ, the current difference in altitude is divided by the vertical closure rate.

$$\tau = \frac{r}{\dot{r}} \tag{2.1}$$

TCAS uses τ to determine when to issue TAs and RAs. Table 2.1 displays the threshold τ values for various altitudes. When both the range and vertical τ values fall below the values indicated, TCAS will issue a TA or RA.[5] Note that no RAs are given below 1,000 feet Above Ground Level (AGL). An advantage to the τ approach is that TAs and RAs are always issued the provided amount of time before CPA, even if the traffic is closing at higher speeds. A disadvantage is that traffic with a very slow rate of closure could become dangerously close to the ownship before a TA or RA is issued. To account for this, TCAS uses a minimum range known as DMOD (Distance Modification) and a minimum altitude difference known as ZTHR. If a slowly-closing intruder comes within DMOD of the ownship, it has the same effect as the range τ falling below the corresponding TA/RA threshold. Similarly, if an intruder comes within ZTHR altitude of the ownship, it has the same effect as the vertical τ dropping below the corresponding TA/RA value.

Table 2.1: TCAS Alerting Thresholds

Own Altitude (ft)	τ (sec)		DMOD (NM)		ZTHR (ft)	
	TA	RA	TA	RA	TA	RA
$<$ 1000 (AGL)	20	N/A	0.30	N/A	850	N/A
1000-2350 (AGL)	25	15	0.33	0.20	850	600
2350-5000	30	20	0.48	0.35	850	600
5000-10000	40	25	0.75	0.55	850	600
10000-20000	45	30	1.00	0.80	850	600
20000-42000	48	35	1.30	1.10	850	700
$>$ 42000	48	35	1.30	1.10	1200	800

If the TCAS RA threshold values are violated, TCAS will issue an avoidance

[5] Both TCAS I and TCAS II use these same thresholds. For TCAS I, no RAs are given.

maneuver for the pilot to follow. TCAS only issues vertical maneuvers. The first RA issued is generally a climb or descend maneuver with a rate of at least 1,500 fpm. It could also be a preventative command such as "do not climb" or "do not descend". It is assumed that the pilot will respond to the RA within five seconds with at least a quarter g acceleration, and TCAS RAs actually take precedence over ATC instructions. After the first TCAS RA has been issued, TCAS will give subsequent RAs if the conflict is not being resolved satisfactorily. Subsequent RAs can strengthen the climb or descend maneuver to 2,500 fpm, and can also reverse the recommended maneuver (i.e. a climb command can be switched to a descend command or vice versa). It is assumed that pilots will respond to subsequent RAs within 2.5 seconds with at least $0.35g$ acceleration. If both aircraft are equipped with TCAS II, then the TCAS units will communicate and coordinate RAs with each other to ensure that both aircraft select complementary maneuvers. For example, if two aircraft are on a head-on collision course, one aircraft will receive a climb RA while the other will receive an RA to descend. In any encounter, if the threat of collision is removed after an RA is issued, TCAS will issue a "clear of conflict" command to inform the pilot that the nearby traffic is no longer a factor and avoidance action is no longer needed. A program named TCAS III also explored the possibility of using horizontal escape maneuvers in addition to vertical maneuvers, but the program was discontinued due to the relatively large errors in bearing and bearing rate provided by TCAS units [24].

Based on Table 2.1, it is easy to predict the moment that TCAS will first issue a TA and RA in a given encounter between two aircraft. However, the logic that determines what RAs should be issued both initially and throughout the course of an evolving encounter is complex. DO-185B contains hundreds of pages of pseudocode that explain what action TCAS will take in a plethora of possible conditions. While this lengthy pseudocode allows a TCAS processor to quickly look up and issue the specified RA in flight, it makes it almost impossible for a human to quickly predict the exact behavior that TCAS will exhibit in a complicated encounter.

Due to the complexity of the TCAS logic, its performance has historically been assessed using Monte Carlo simulations. Numerous encounters between two aircraft are generated by varying parameters like airspeed, closing angle, and maneuvers taken throughout the encounter. TCAS is then evaluated on its ability to reduce the risk of collision in these encounters. A success metric that has been historically used to evaluate TCAS is the probability of Near Mid-Air Collision (NMAC) in these randomly-generated encounters. While not all NMACs would result in an actual collision between two aircraft, it is a highly dangerous loss of separation. In early evaluations of TCAS soon after initial implementation, NMAC was defined as two aircraft coming within 100 vertical feet of each other at CPA [25, 26]. To allow for encounters where the two aircraft might still have a large horizontal separation at CPA, NMAC has been defined in more recent studies as a simultaneous loss of 100 feet vertical separation and 500 feet horizontal separation at any point in the encounter [27]. TCAS was designed to minimize the probability of NMAC.

While the probability of NMAC is a helpful metric, it can be hard to compare between different studies. One study might create encounters where the two aircraft are always on a direct collision course and report a higher probability of NMAC, while another study might create a lot of encounters that would not result in NMAC even if no evasive action was taken by either aircraft. To account for this, the probability of NMAC is often used in another safety metric known as the *risk ratio*. Given that an encounter has occurred, the risk ratio is the probability of NMAC when a CA system is equipped (the mitigated probability) normalized for the probability of NMAC without any evasive action taken (the unmitigated probability). Equation 2.2 shows how the risk ratio is defined. A risk ratio greater than one would denote that a CA system actually causes more NMACs than it prevents, while a risk ratio less than one would show that the CA system causes fewer NMACs to occur. A minimal risk ratio is desirable for all CA systems.

$$\text{Risk Ratio} = \frac{\text{P(NMAC)}_{\text{mitigated}}}{\text{P(NMAC)}_{\text{unmitigated}}} \tag{2.2}$$

The risk ratio has become the primary success metric used to evaluate the safety of TCAS in particular and airborne CA systems in general. It is used to define the minimum performance TCAS II must achieve in the International Standards and Recommended Practices (SARPS), which are the standards set by the International Civil Aviation Organization (ICAO) to govern aviation worldwide. Volume IV of Annex 10 of these standards covers CA systems. TCAS II (known internationally as ACAS) must achieve a risk ratio no greater than 0.18 against intruders without TCAS II and no greater than 0.04 against intruders with TCAS II [28]. The MIT Lincoln Laboratory evaluation of the most recent TCAS II version reports that TCAS II achieves a risk ratio of 0.12 against unequipped intruders and 0.016 when both aircraft are equipped [27].

Overall, TCAS has been an international success. It is now equipped on most air carriers worldwide. No collision has occurred in U.S. airspace between aircraft equipped with TCAS II. However, there are still numerous challenges involved with TCAS. The RTCA shares many TCAS pitfalls and recommendations for future CA systems in DO-337 [29]. One of the main concerns is that TCAS often produces excessive RAs in crowded airspace, such as the areas around busy airports. This creates the danger that pilots will become desensitized to TCAS RAs in high-density areas. In fact, the RTCA reports that high noncompliance rates among pilots is another current problem. TCAS is also inflexible in that it depends on surveillance information from transponders, and any change in avoidance maneuvers would require a complete re-investigation of the numerous cases covered by the current pseudocode. Therefore, it would be hard to adjust TCAS to future systems that could make use of alternative surveillance sources like ADS-B and other possible avoidance maneuvers.

To address these concerns, the FAA is sponsoring MIT Lincoln Laboratory to create a new CA system known as ACAS X. Section 2.3.2 provides an overview of this future CA system.

2.3.2 ACAS X

The Airborne Collision Avoidance System X (ACAS X) is a future CA system envisioned by the FAA and currently in development at MIT Lincoln Laboratory. Within the ACAS X program is a family of CA systems for various implementations in future airspace. These systems and the methodology behind them are explained below.

All versions of ACAS X determine collision avoidance maneuvers based on a Markov Decision Process (MDP), which is a framework for sequential decision-making problems that is commonly used in artificial intelligence. A simple example that visualizes an MDP is given in Figure 2-2 [30]. An MDP consists of a discrete set of states, and at each state a number of actions can be taken. In Figure 2-2, there are three states (1, 2, and 3), and two actions (A and B) can be taken from each state. An MDP also includes a dynamic model that provides the probability of transitioning from one state to another based on the action that is taken, and a cost model[6] that rewards or penalizes certain states and actions. For the system shown in Figure 2-2, the transition probabilities and rewards are shown. A *policy* is a function that provides the action that will be taken at a given state. It is possible to solve an MDP and calculate the optimal policy, which provides the action leading to the greatest expected reward (or least expected cost) at every state. The policy function is often referred to as $\pi(s)$, with s denoting the state. Similarly, the optimal policy function is often referred to as $\pi^*(s)$. For a more complete discussion of MDPs, see Chapter 17 of *Artificial Intelligence: A Modern Approach* [31].

Engineers at MIT Lincoln Laboratory demonstrated that by modeling the airborne CA problem as an MDP, TCAS-level safety could be achieved with fewer alerts [32, 33]. In the airborne CA problem, the states describe the (discretized) relative position and speed of the two aircraft, and the actions consist of doing nothing or issuing one of several RAs. The cost model heavily penalizes NMACs, but also assesses a slight penalty to issuing any kind of RA. Because the relative position of the intruder aircraft is not known perfectly, a version of an MDP known as a Partially Observable MDP (POMDP) is used. In a POMDP, observations are made and used to construct a belief state, which is then used to inform the action taken. For the airborne CA problem, sensor measurements are taken and sensor error models are used to estimate the relative position of the intruder aircraft, which becomes the belief state. Once

[6]Also called a reward model. A cost is simply a negative reward.

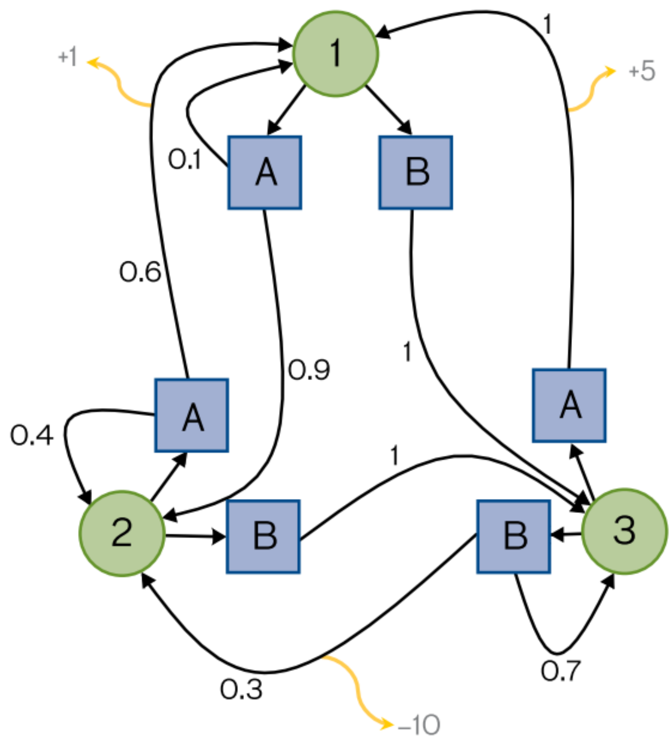


Figure 2-2: A Simple System Demonstrating a Markov Decision Process [30]

the POMDP has been fully set up, a technique called dynamic programming[7] is used to calculate the optimal collision avoidance policy. This policy is then stored as a table that can be uploaded to an aircraft, and the optimal action at any state can be looked up in real time by an on-board processor.

The POMDP framework used by ACAS X offers much more flexibility than TCAS. If an aircraft wants to use different avoidance maneuvers or a different surveillance source, a new optimal policy can be calculated and implemented. Furthermore, desired changes to the policy's behavior can be made by tweaking the cost model. For example, if the system is found to be too noisy (i.e. it is issuing too many RAs), the cost of issuing RAs can be increased such that RAs are not issued as often. Like TCAS, simulations can be used to evaluate the effects of making any changes to the policy. If any changes to the optimal policy are finalized while another version is already in use, they can easily be implemented on an aircraft by simply deleting the

[7] A further discussion of dynamic programming will not be given here but can be found in a variety of literature. One classic example is Chapter 3 of Donald Kirk's *Optimal Control Theory: An Introduction* [34].

old lookup table and downloading the new one.

The POMDP framework is enabling multiple implementations of ACAS X that are currently in development. One is known as ACAS Xa because it makes partial use of active surveillance. ACAS Xa is the ACAS X implementation that is analogous to TCAS II and is being designed for use on large manned aircraft. ACAS Xa makes use of both transponder interrogations and received ADS-B signals to provide hybrid surveillance on nearby aircraft.[8] Like TCAS II, potential avoidance maneuvers given in RAs include climbs and descents at 1,500 and 2,500 fpm. A related system known as ACAS Xo, intended to be used in tandem with ACAS Xa, allows modified policies to be used in particular operational scenarios. For example, an aircraft flying a closely-spaced parallel approach might switch from ACAS Xa to an ACAS Xo implementation that allows aircraft to fly closer parallel tracks before issuing an RA. The MOPS for ACAS Xa/Xo were approved by both the RTCA and the European Organization for Civil Aviation Equipment (EUROCAE) council in October 2018, and ICAO has adjusted standards to allow ACAS Xa to be used in place of TCAS II beginning in 2020 [35]. The RTCA refers to these MOPS as DO-385.

Another implementation of ACAS X known as ACAS Xu is in development for use on larger unmanned aircraft, such as the Global Hawk. Like Xa, Xu makes use of ADS-B and active surveillance information. However, Xu can also use an on-board air-to-air radar (like that used by NASA's Ikhana aircraft) to surveil aircraft without a transponder or ADS-B equipped. Because larger UAS often do not have the vertical maneuvering capability of larger manned aircraft, vertical RAs use a single avoidance rate of 1,000 fpm instead of the 1,500 and 2,500 fpm rates used by TCAS II and ACAS Xa. ACAS Xu also issues horizontal RAs that command a right or left turn at three degrees per second, which is a standard rate turn in aviation. The greater lateral accuracy offered by ADS-B surveillance makes these horizontal RAs tenable. ACAS Xu is still in development, but there are working prototypes of the optimal logic table that have been flight tested by MIT Lincoln Laboratory. While ACAS Xu

[8] While ADS-B provides most of the surveillance information, the current version of ACAS Xa will not initiate a surveillance track on an aircraft without a transponder.

was primarily developed for larger UAS, Chapter 5 of this thesis explores the creation of similar CA policies that could be implemented on sUAS. The version of ACAS Xu specifically being designed for sUAS is referred to as ACAS sXu.

Before designing novel CA systems, however, the size and maneuvering characteristics of sUAS should be well understood. Chapter 3 reviews hundreds of UAS platforms to better understand these sUAS parameters.

Chapter 3

Study of sUAS Characteristics

To implement Collision Avoidance (CA) systems on sUAS, the size and performance characteristics of sUAS must be well understood. A CA system would be useless to sUAS if it was too large or heavy or required too much power. Furthermore, the avoidance maneuvers utilized by a CA system must account for the performance of sUAS; otherwise, the CA system could rely on escape maneuvers that are not actually achievable. It is generally understood that sUAS differ from manned aircraft in qualitative aspects, but few attempts have been made to quantify sUAS performance and to explore the relationship between performance and weight. This chapter seeks to better quantify the flight characteristics of UAS in general and sUAS in particular by investigating UAS performance over a wide range of platforms.

The data collection for this chapter utilized the *Jane's All the World's Aircraft: Unmanned* database. A total of 627 active UAS platforms were reviewed on the Jane's database in summer 2018. After some filtering to remove UAS designed exclusively for warfare (e.g. aerial targets), long-endurance UAS with operating altitudes above 18,000 feet, and UAS weighing more than 4,000 pounds, 481 UAS platforms remained. These consisted of 123 rotor-wing platforms and 359 fixed-wing platforms, with one UAS included in both numbers because it was classified as both rotor-wing and fixed-wing.[1] The information presented in the rest of this chapter utilizes the data collected

[1] This UAS is the Helicopter Adaptive Aircraft (HADA), a UAS with both helicopter and airplane modes of flight.

on these 481 UAS platforms.

One of the easiest ways to gauge the size of an aircraft is by its weight, which was one of the parameters most readily available for UAS. Of the 481 total UAS, 426 listed either a maximum gross takeoff weight or a maximum launch weight. These two parameters were aggregated to create one metric for maximum weight. Figure 3-1 displays the distribution of maximum weights observed. Note that the bin widths in Figure 3-1 are unequal due to the much larger number of UAS observed at lower weights.

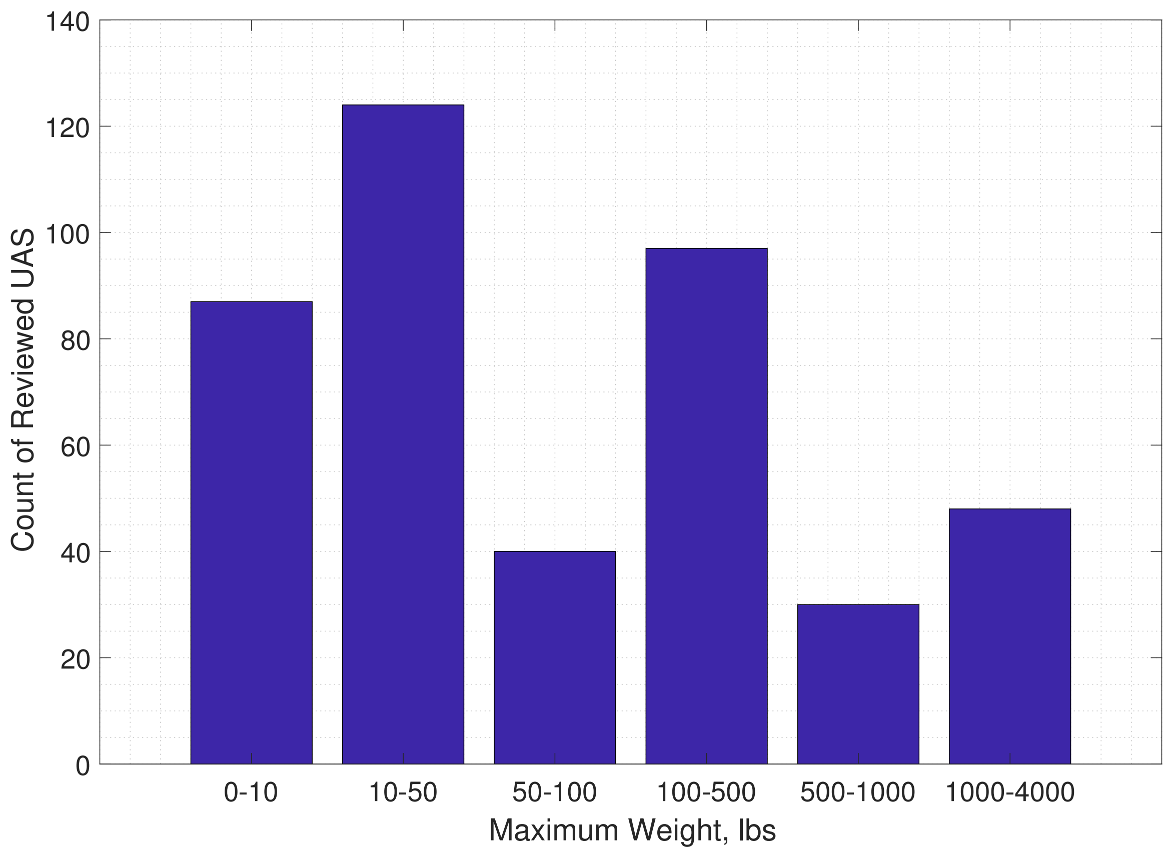


Figure 3-1: Maximum Weight Distribution of Reviewed UAS

The maximum weight provides a helpful benchmark to observe the relationship between UAS size and various other parameters. The FAA officially defines small UAS as UAS that weigh less than 55 pounds. However, 100 pounds is loosely used here as the approximate transition point between smaller and larger UAS. This is because large increases in the maximum observed span, cruise speed, maximum speed, and rate of climb were all observed as the weight increased above 100 pounds, but comparable increases were not observed between 55 and 100 pounds.

The span[2] of an aircraft can help to predict the risk of mid-air collision in close encounters with other aircraft [36]. Figure 3-2 displays the span of reviewed UAS over all weights. While much longer wingspans were observed for fixed-wing UAS above 1,000 pounds, the maximum observed wingspan was about 30 feet for UAS below 1,000 pounds and 20 feet for UAS below 100 pounds. The mean wingspan for UAS below 100 pounds was 8.5 feet. By comparison, the Cessna 172 (one of the most common GA aircraft) has a wingspan of 36 feet, while the Boeing 737 and Airbus 320 families (the most common commercial air carriers) have wingspans of about 120 feet. Among rotor UAS, the mean rotor diameter observed for UAS below 100 pounds was 4.8 feet, with a maximum value of 8 feet. The main rotor diameter of the popular Bell 206 manned helicopter, by contrast, is about 33 feet. Because of these smaller spans, sUAS may be able to fly closer to each other and to manned aircraft while maintaining the same risk of collision as two manned aircraft that are spaced farther apart. This is further discussed in Section 5.2.4.

An important performance metric for aircraft is the payload, which is the weight of cargo and passengers that can be carried. Equipping CA systems on sUAS will require on-board equipment and sensors to replace a fraction of the available payload. Figure 3-3 plots the maximum payload for reviewed UAS. To easily compare between UAS of different sizes, the payload *mass fraction* is plotted rather than the true payload. The payload mass fraction is simply the payload divided by the aircraft's maximum weight. Furthermore, the metrics "max payload" and "payload with max fuel", listed by different UAS, were aggregated into one metric. Other than a few high-performing rotor UAS weighing less than 20 pounds and a few high-performing fixed-wing UAS weighing more than 2,000 pounds, the payload mass fraction does not seem to significantly change with weight. The mean values for UAS weighing less than 100 pounds were 0.23 for fixed-wing UAS and 0.29 for rotor UAS. These values

[2]Span is used as a general term to denote both the wingspan for fixed-wing UAS and the main rotor diameter for rotor UAS.

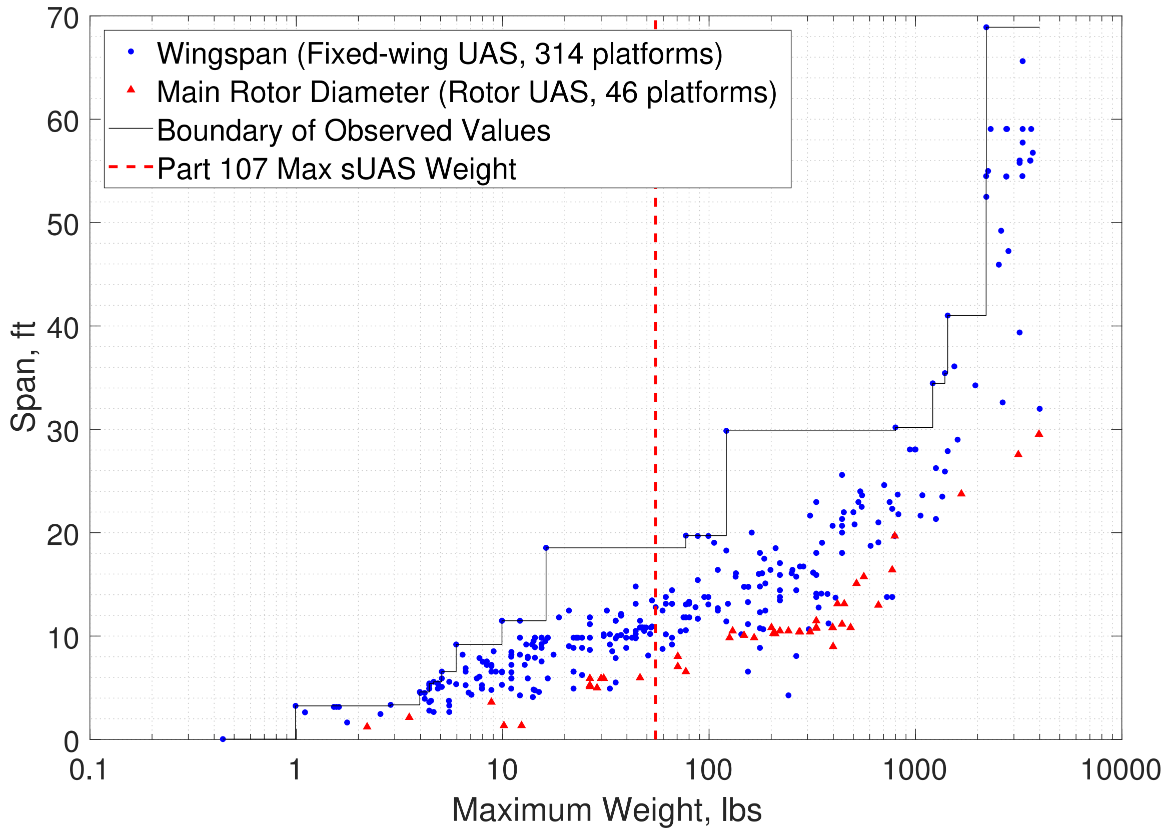


Figure 3-2: Span of Reviewed UAS

can help to estimate the feasibility of loading CA sensors and equipment onto UAS of varying sizes. Section 4.1 discusses this further.

Understanding the speeds that sUAS fly is important to model flight behavior and assess potential CA systems. Figures 3-4 and 3-5 show the reviewed flight speeds of UAS. Figure 3-4 displays the cruise speed, while Figure 3-5 displays the maximum speed. The maximum speed is the aggregate of three different speeds listed for different platforms: never-exceed speed, maximum operating speed, and maximum level speed. All the reviewed UAS had cruise speeds below 200 knots and maximum speeds below 230 knots, with the vast majority flying much slower. The highest speeds for fixed-wing UAS weighing less than 100 pounds were 80 knots for cruise speed and 120 knots for maximum speed. The mean values, however, were much lower: 36 knots for cruise speed and 63 knots for maximum speed. Rotor UAS tended to fly at slower speeds, with rotor UAS lighter than 100 pounds topping out around 45 knots cruise speed and 70 knots max speed (with many having max speeds below 40 knots). The

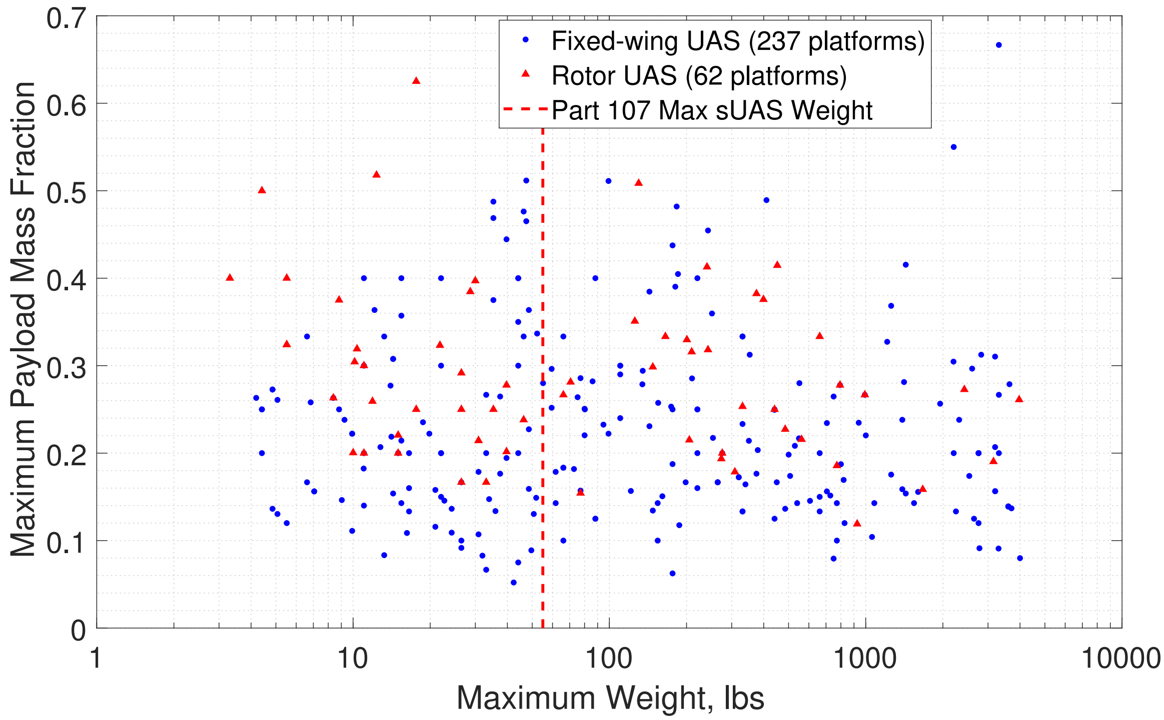


Figure 3-3: Payload Mass Fraction of Reviewed UAS

mean values for these rotor UAS were just 24 knots and 30 knots for the cruise and maximum speeds, respectively. The observed speeds for UAS under 100 pounds are used in Chapter 5 to model the speeds that sUAS fly in encounters with manned aircraft. Section 5.1 explains how simulated encounters between sUAS and manned aircraft were generated.

The speed values for smaller UAS line up well with one of the only other studies that have thus far sought to quantify sUAS characteristics. Weinert et al. collected data on advertised performance metrics for UAS with maximum weights below 55 pounds [37]. These were collected from the Association for Unmanned Vehicle Systems International (AUVSI) database. Similar to the study detailed in this chapter, Weinert et al. found that most fixed-wing sUAS listed cruise speeds below 60 knots and maximum speeds below 90 knots, while rotor sUAS tended to have cruise speeds below 40 knots and maximum speeds below 60-70 knots.

The rate of climb available to an aircraft is crucial to CA systems that rely on vertical maneuvers to escape potential collisions. Figure 3-6 shows the maximum

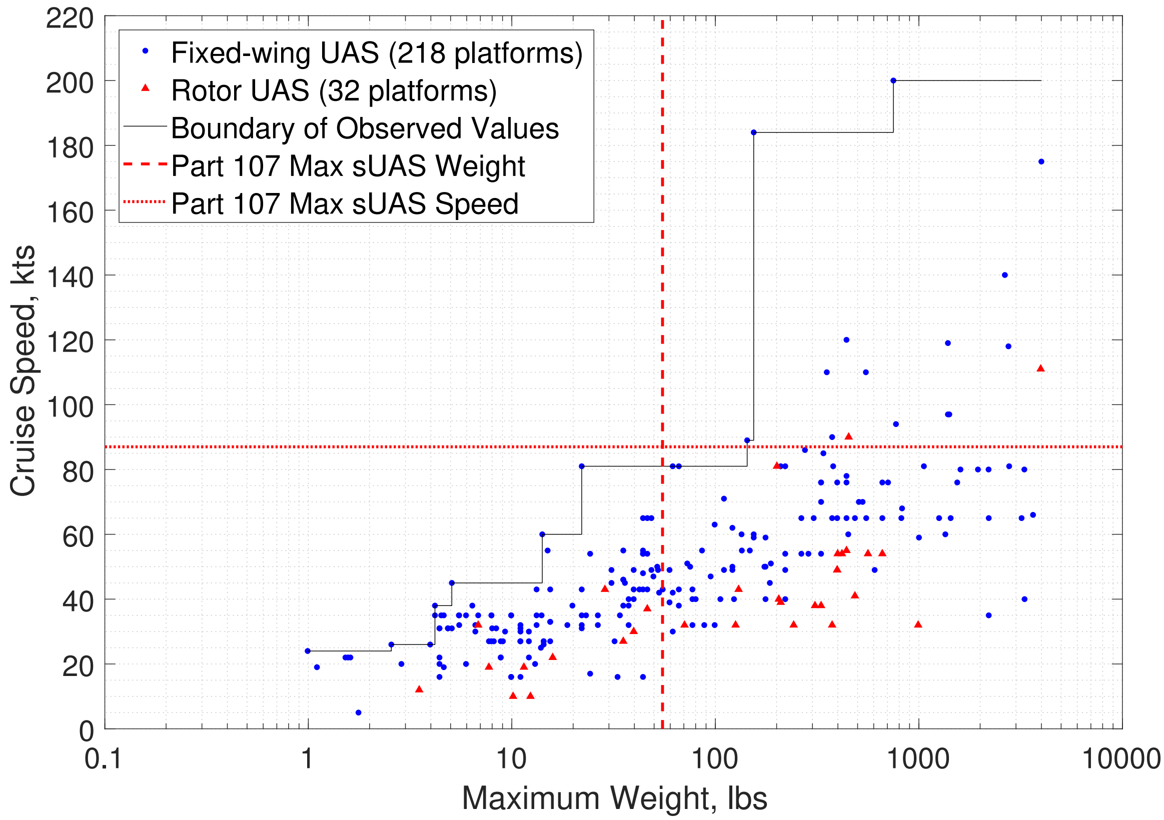


Figure 3-4: Cruise Speed of Reviewed UAS

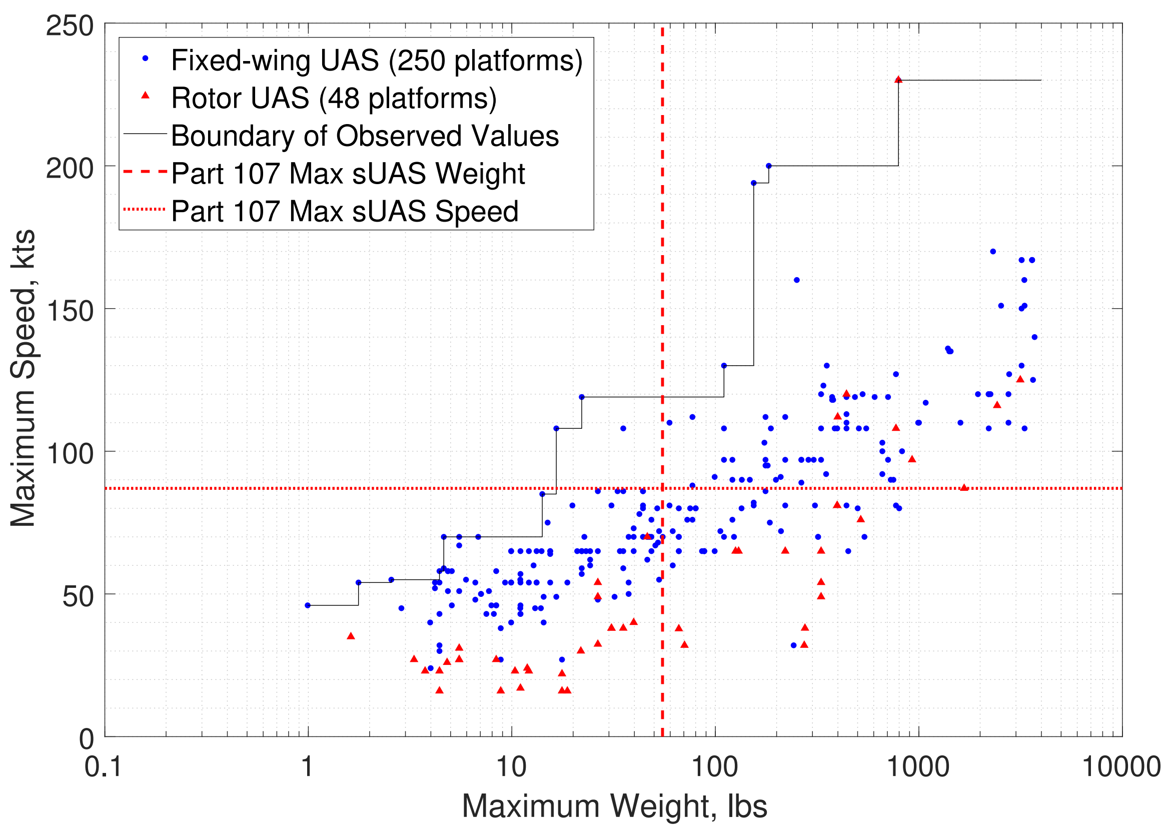


Figure 3-5: Maximum Speed of Reviewed UAS

rates of climb for various UAS. The maximum rate of climb is usually achieved at maximum power and minimal weight in sea level density conditions. Therefore, the typical rate of climb available in flight will generally be less than the maximum rate.

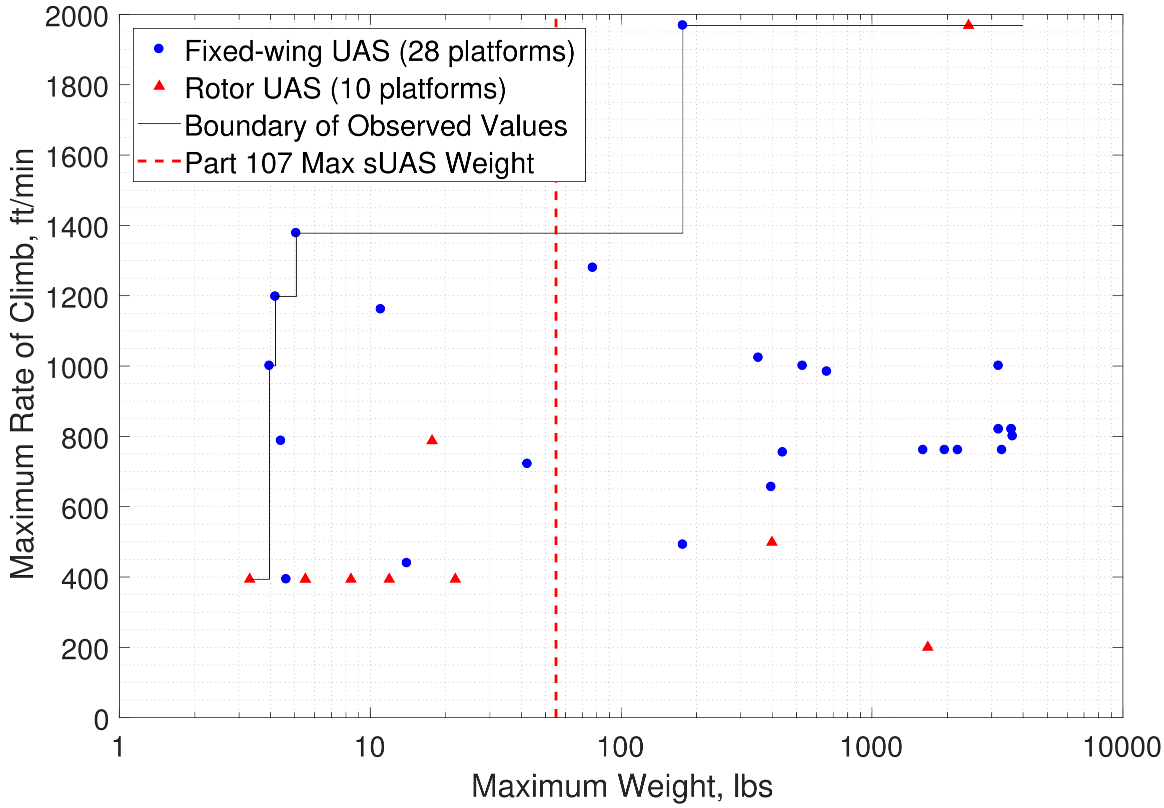


Figure 3-6: Climb Rate of Reviewed UAS

It is apparent from Figure 3-6 that fixed-wing UAS tend to have higher climb rates than rotor UAS. Among the seven rotor UAS weighing less than 100 pounds, one had a maximum climb rate of 800 fpm and none of the other eight exceeded 500 fpm. The fixed-wing UAS varied more widely. Four UAS weighing less than 12 pounds had rates exceeding 1,000 fpm, showing that even extremely light UAS can have modest climb rates. However, some fixed-wing UAS across the range of reviewed weights also had maximum climb rates below 800 fpm, so the climb rate appears to greatly depend on the individual platform. For UAS weighing less than 100 pounds, the mean rates were 930 fpm for fixed-wing UAS and 450 fpm for rotor UAS, with an overall mean of 720 fpm. It is clear that TCAS II and ACAS Xa, which command vertical rates of 1,500 to 2,500 fpm, would be inappropriate for use on sUAS. Section

5.2.2 explores how sUAS could perform threat resolution despite these lower vertical capabilities.

The turn rate capability of an aircraft is also critical to CA systems if horizontal escape maneuvers are used. While none of the reviewed UAS in the Jane's database listed a maximum turn rate or a maximum bank angle, the fundamental dynamics of flight can be used to show that sUAS would be capable of high turn rates due to the low flight speeds that were observed. Equation 3.1 displays the calculation for turn rate ω in a constant-speed, level turn [38]. This equation depends only on the physics of flight and is valid for any aircraft that can maintain altitude and airspeed in a turn.

$$\omega = \frac{g}{V}\sqrt{n^2 - 1} \tag{3.1}$$

Because g refers to the gravitational constant, the turn rate depends on two variables: the aircraft's velocity or airspeed V, and the load factor n. The load factor is defined as the ratio between an aircraft's lift and weight, and is commonly referred to as the number of g's the aircraft is pulling. The load factor in a constant-speed, level turn can also be used to calculate the bank angle ϕ, as shown in Equation 3.2.

$$n = \frac{1}{\cos\phi} \tag{3.2}$$

Equation 3.1 was used to plot an aircraft's turn rate at various speeds and load factors, as shown in Figure 3-7. Recall from Figure 3-4 and Figure 3-5 that most UAS weighing less than 100 pounds have cruise speeds below 60 knots and maximum speeds below 90 knots. Figure 3-7 shows that, at these low speeds, even a modest load factor leads to a fast turn rate. For example, a load factor of just 1.15 (corresponding to a constant 30-degree banked turn) would lead to a turn rate of over 10 degrees per second at 60 knots and over 20 degrees per second at 30 knots. A standard rate turn in aviation, commonly used by manned aircraft, is just 3 degrees per second. Therefore, even at modest load factors, sUAS would be capable of extremely high turn rates at the low speeds typical of their flight regimes. This suggests that sUAS could potentially use horizontal maneuvers to avoid collisions, which may be more effective due to the limited climb capabilities available. Section 5.2.2 evaluates novel CA systems for sUAS that recommend turns instead of vertical maneuvers to avoid collisions.

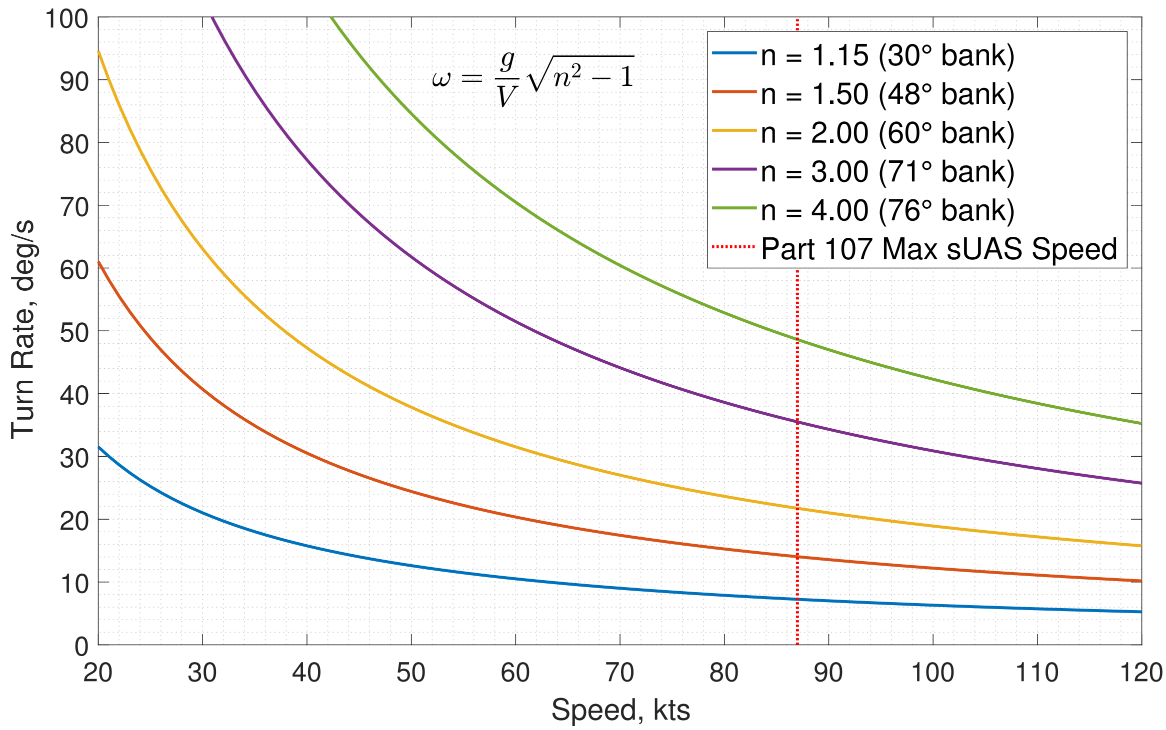


Figure 3-7: Turn Rate of a Constant-Speed, Level Turn

Table 3.1 provides a quick reference for many of the sUAS metrics discussed in this chapter. Again, sUAS here include all reviewed UAS with a maximum weight below 100 pounds. As can be seen from the boundary of observed values in Figure 3-2 and Figures 3-4 through 3-6, several parameters experienced sharp increases as

Table 3.1: Mean Metrics for Reviewed sUAS

Metric	Fixed-Wing sUAS	Rotor-Wing sUAS
Span	8.5 ft	4.8 ft
Payload Mass Fraction	0.23	0.29
Cruise Speed	36 kts	24 kts
Maximum Speed	63 kts	30 kts
Rate of Climb	930 fpm	450 fpm

UAS weight increased above 100 pounds.

As has been discussed throughout this chapter, the quantification of these UAS metrics is important to inform CA systems for sUAS. The lower vertical rate capabilities of sUAS make TCAS II, ACAS Xa, and even ACAS Xu inappropriate for implementation on sUAS. However, low flight speeds make high turn rates easily achievable, so CA systems for sUAS could potentially use horizontal maneuvers to augment or replace vertical maneuvers. Chapter 5 uses the information presented in this chapter to model sUAS flight behavior and create novel CA systems that utilize lower-rate vertical maneuvers in addition to turns. However, to actually implement CA logic, sUAS must equip sensors to determine the location of other aircraft. The payload and climb rate data from this chapter can help to determine the feasibility of sUAS carrying surveillance systems that require varying levels of weight and power. This is explored in Chapter 4, which investigates cooperative surveillance systems for sUAS.

Chapter 4

Investigating Cooperative Surveillance for sUAS

In order to perform Collision Avoidance (CA), sUAS must first be able to detect the presence and location of other aircraft. This is known as surveillance. As detailed in Section 2.2, manned aircraft primarily rely on cooperative surveillance systems to share position information through radio frequency signals. This chapter explores how sUAS can equip similar cooperative surveillance systems to detect nearby traffic and also share their own position information with other aircraft in the sky.

One primary concern for sUAS to equip CA systems is that the surveillance sensors and other equipment needed are heavy and expensive. For example, the RTCA in 2017 released standards for CA systems on large UAS but admitted that the surveillance equipment required could weigh hundreds of pounds and would be infeasible for sUAS [39]. To address this concern, Section 4.1 investigates the Size, Weight, Power, and Cost (SWaP-C[1]) of representative equipment that would allow sUAS to perform CA functions. As Section 4.1 will show, equipping a non-cooperative sensor like an air-to-air radar would indeed be challenging for sUAS, but cooperative surveillance equipment is far more plausible for even the smallest of UAS.

A serious concern about sUAS using cooperative surveillance is that an influx

[1] This unusual acronym was created because an abbreviation was first developed for Size, Weight, and Power (SWaP), and cost was later added.

of many additional aircraft broadcasting on the spectrum used to share aviation information could cause a high level of noise and degrade signal reception for all users. Section 4.2 models a dual population of sUAS and manned aircraft users on both the 1090 and 978 MHz channels to simulate signal reception performance in a crowded environment. It appears that a high density of sUAS could indeed cause a serious degradation of surveillance performance, so Section 4.2 considers the combinations of channel, sUAS density, and sUAS transmission power that could allow for satisfactory performance.

4.1 Size, Weight, Power, and Cost Analysis

Small UAS have limited budgets in term of Size, Weight, Power, and Cost (SWaP-C). This section will begin by reviewing representative equipment with low SWaP-C values that sUAS could potentially equip to perform CA. While all the equipment reviewed in this section can achieve the technical specifications needed for their intended uses, not all have officially been approved for use in flight on sUAS. The purpose of this section is not to recommend specific equipment that should be used on sUAS, but rather to estimate the SWaP-C values needed to implement a CA system with current technology.

To perform CA, sUAS must first be able to determine their own position. The most fundamental sensor needed is a barometer, which provides pressure altitude. Determination of lateral position is also required for ADS-B signals and for autonomous navigation in general. This can be done with a GPS receiver. Any GPS used for ADS-B must meet stringent accuracy and integrity requirements, some of which are given in Section 2.2.2. Therefore, a GPS used for CA would probably need to be WAAS-enabled or use some other source of augmentation. One representative position source for sUAS is the FYXnav-B from uAvionix,[2] a company that designs lightweight sensors for UAS. The FYXnav-B features a WAAS GPS integrated with a barometer that both meet the accuracy and integrity requirements for ADS-B.

[2]Specifications for all uAvionix products were obtained at: `https://uavionix.com/uas/`

If sUAS can determine their own location, they can share that information with other aircraft. A transmitter capable of transmitting radio signals on 1090 or 978 MHz would be needed to create ADS-B signals that provide sUAS position information to nearby traffic. An antenna capable of receiving signals on at least one of these channels would allow sUAS to receive broadcasts, as well. The transmission and receiving functions could also be combined in a single transceiver. Alternatively, a transponder could be used in place of (or in addition to) ADS-B. A few more uAvionix products were used as representative equipment for sUAS to broadcast and receive position information. The pingRx weighs just five grams and would allow sUAS to receive ADS-B signals, but does not perform any additional functions. An all-in-one sensor is the ping2020i, which contains an integrated barometer, GPS, and ADS-B transceiver that could single-handedly allow sUAS to broadcast their position information on 978 MHz and receive ADS-B signals on both channels. The ping2020i broadcasts ADS-B signals at 20 W, which is within the power range for the standard class of ADS-B transmitters on UAT [19]. If a transponder is desired, a similar product is the ping20Si, which includes an integrated barometer, GPS, and Mode S transponder that can transmit ADS-B on 1090ES. The ping20Si also transmits at a power of 20 W, which is below the minimum value currently allowed [17]. However, as Section 4.2 will demonstrate, lower-power transmissions could allow sUAS to be detectable at sufficient range while also generating less electromagnetic interference.

To use any received signals for a CA system, there must also be an on-board processor that can provide threat resolution based on the available surveillance information. A representative processor for sUAS is the Raspberry Pi 3 Model B+, which engineers at MIT Lincoln Laboratory have used to implement modified versions of ACAS X on sUAS. The Pi B+ is light and inexpensive but still has 1 GB of RAM that can be used to process threat resolution logic in flight.[3]

While the focus of this chapter is on cooperative surveillance, sUAS could also perform non-cooperative surveillance by equipping sensors to detect aircraft that are

[3]Detailed Pi B+ specifications were found from hobbyists at the following websites:
`http://socialcompare.com/en/comparison/raspberrypi-models-comparison`
`https://www.jeffgeerling.com/blogs/jeff-geerling/raspberry-pi-zero-power`

not sharing position information through a transponder or through ADS-B signals. Detecting other aircraft at sufficient range to avoid collisions would probably require the use of an air-to-air radar. NASA's Ikhana UAS was able to use an on-board radar to detect other aircraft in flight, but the radar would be too large to equip on sUAS. A smaller radar that could be representative for use on sUAS is the Fortem TrueView R20.[4] The R20 is much smaller than the radars currently used by larger UAS, but it is still much larger than any of the other pieces of equipment that have been listed in this section. It is capable of detecting one square meter of radar cross section from 1,500 meters away.

Table 4.1 provides an overview of the size, weight, power, and cost of the representative CA equipment listed for sUAS. The pieces of equipment in Table 4.1 can be combined to create multiple different versions of CA systems. For example, the pingRx, FYXnav-B, and Pi B+ could be combined to implement a CA system that performs threat resolution based on received ADS-B signals, but does not actually broadcast. Table 4.2 provides the total size (volume), weight, average power required, and cost of three representative CA systems based on the equipment from Table 4.1. The first is a broadcast-only system using ADS-B that would alert other aircraft of the ownship's presence and could track the location of intruders, but would not provide threat resolution. This system could also receive transmitted signals without broadcasting if desired. The second representative system adds a CA processor, which could provide threat resolution based on the received signals from other aircraft. Finally, the third representative system adds the air-to-air radar that could detect non-cooperative intruders.

To determine the feasibility of a CA system weight, it is helpful to look at its mass fraction. The mass fraction is simply the weight of the CA system divided by the total takeoff weight of the aircraft. Figure 4-1 plots the mass fractions of the representative systems from Table 4.2 at a variety of weights. The curves would be approximately the same if using a Mode S transponder in addition to ADS-B, since the ping20Si and ping2020i differ in weight by only three grams. For reference, the

[4] TrueView specifications were found at: `https://fortemtech.com/products/trueview-radar/`

Table 4.1: Size, Weight, Power, and Cost of Representative sUAS CA Equipment

Product	Function	Size	Weight	Power	Cost
uAvionix FYXnav-B	Position source	42x18 mm	27g	500 mW	$500
uAvionix pingRx	ADS-B receiver	34x19x8 mm	5g	150 mW	$250
uAvionix ping2020i	ADS-B transceiver & position source	25x40x16 mm	23g	500 mW	$2,000
uAvionix ping20Si	Transponder & position source	50x25x17 mm	20g	1 W	$3,000
Raspberry Pi B+	CA Processor	57x86x17 mm	45g	900 mW	$35
Fortem TrueView R20	Air-to-Air Radar	206x81x47 mm	780g	38 W	$10,000

mean payload mass fractions observed among reviewed sUAS in Chapter 3 were 0.23 for fixed-wing UAS and 0.29 for rotor UAS. However, observed values varied widely, with a minimum of 0.05 and a maximum of 0.62. The acceptable mass fraction for a CA system may therefore vary widely depending on the individual platform.

From Figure 4-1, it is easy to determine how large UAS must be to achieve a desired mass fraction for one of the representative systems from Table 4.2. For example, consider a UAS platform that wants a CA system with a mass fraction less than 5%. The total takeoff weight of the UAS would need to be at least about 1 pound to equip

Table 4.2: Size, Weight, Power, and Cost of Representative sUAS CA Systems

CA System	Product(s)	Size	Weight	Power	Cost
Broadcast Only	ping2020i	16 cm^3	23g	0.5 W	$2,000
Add CA Processor	ping2020i, Pi B+	99 cm^3	68g	1.4 W	$2,035
Add Air-to-Air Radar	ping2020i, Pi B+, R20	884 cm^3	848g	39.4 W	$12,035

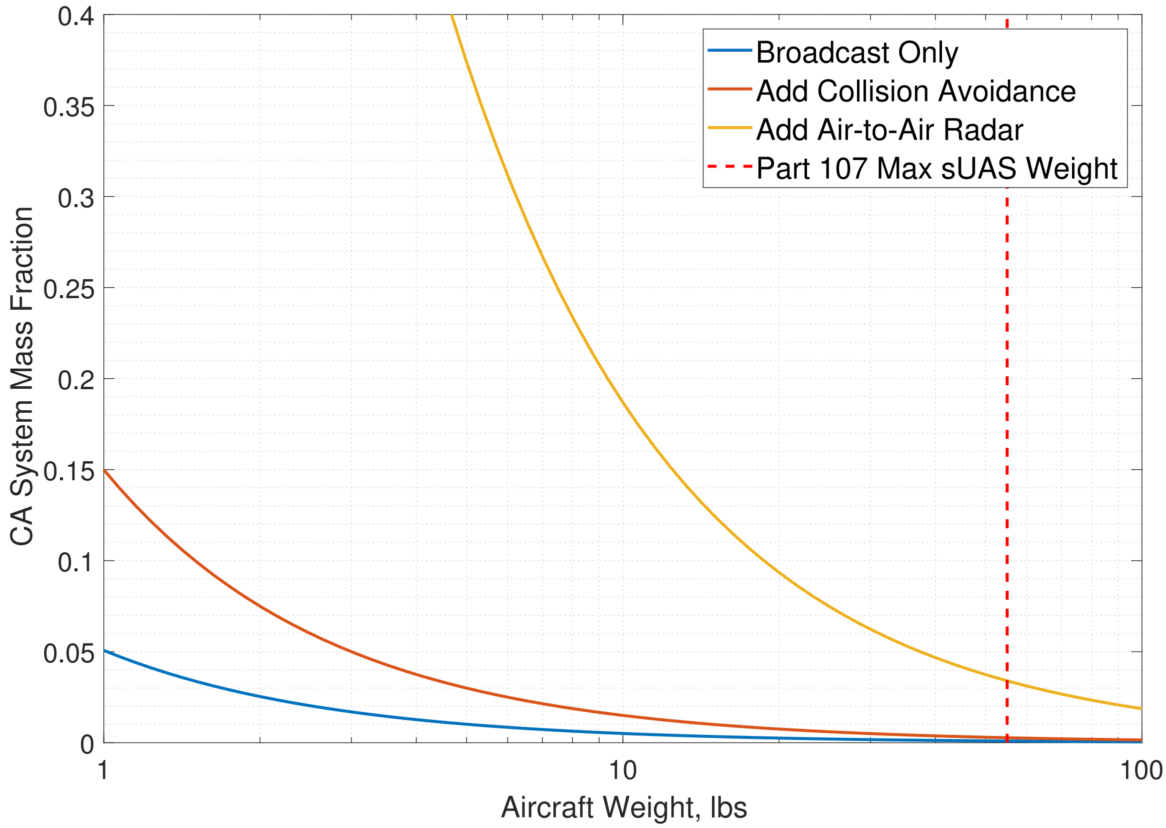


Figure 4-1: Mass Fraction of Representative sUAS CA Systems

a broadcast-only system, 3 pounds to add a CA processor, and 40 pounds to add an air-to-air radar. It is apparent that even very small UAS could handle the weight required for a broadcast-only system, and also for the addition of a CA processor. Adding an on-board radar would require the UAS to be an order of magnitude heavier, which is why this chapter focuses on cooperative surveillance for sUAS. However, the air-to-air radar could still be a feasible option for sUAS large enough to equip it.

Another critical aspect of a CA system for sUAS is the input power required. It is more difficult to generalize the power requirements because many UAS generate power for both thrust and on-board equipment in different ways. Furthermore, the study in Chapter 3 did not reveal any data about on-board electric power available to the UAS platforms studied. However, one parameter that is more familiar to UAS (and manned aircraft as well) is the rate of climb available, and it is possible to relate the rate of climb to the power available by using specific excess power. An aircraft's excess power is the power available beyond what is required to sustain flight.

Specific excess power, often abbreviated P_s, is excess power normalized by weight. The calculation for P_s is given in Equation 4.1. An aircraft's P_s denotes its ability to change its energy by either changing its airspeed ($\frac{dV}{dt}$) or altitude ($\frac{dh}{dt}$).

$$P_s = \frac{P_{\text{excess}}}{W} = \frac{V}{g}\frac{dV}{dt} + \frac{dh}{dt} \tag{4.1}$$

The important observation is that when airspeed is constant (i.e. $\frac{dV}{dt} = 0$), the specific excess power is equal to the aircraft's rate of climb ($\frac{dh}{dt}$). Therefore, by dividing a CA system's required power by the aircraft weight, it is possible to calculate a rate of climb penalty that UAS will experience when diverting on-board power to a CA system. This assumes an ideal 100% conversion efficiency between the electric power used to run the CA system and the power used to generate thrust.

Figure 4-2 plots the rate of climb penalty for the representative CA systems from Table 4.2 based on Equation 4.1. For reference, in the study of UAS climb capabilities detailed in Chapter 3, the mean value among all sUAS was 720 fpm. A penalty of 36 fpm would therefore mark a 5% reduction in maximum climb performance. Actual flight conditions where the available climb rate is less than maximum would cause an even larger percent reduction.

Like Figure 4-1, Figure 4-2 can be used to determine the size that UAS must be to keep a given CA system below a desired climb rate penalty. Suppose a UAS platform wants to keep the climb rate penalty from a CA system less than 25 fpm. The minimum UAS weight to achieve this would be less than 1 pound for the broadcast-only system, about 2.5 pounds to add a CA processor, and about 70 pounds to add the air-to-air radar. In this case, the increase in size necessary to add the radar is even more dramatic, requiring the UAS to be nearly thirty times larger.

As evidenced by Figures 4-1 and 4-2, UAS do not need to be large at all for cooperative surveillance and CA processors to become feasible. It is the non-cooperative radar sensor that requires more than an order of magnitude increase in size. However, even if sUAS can equip cooperative surveillance systems, there are concerns that a large number of additional broadcasters on existing aviation channels will cause so

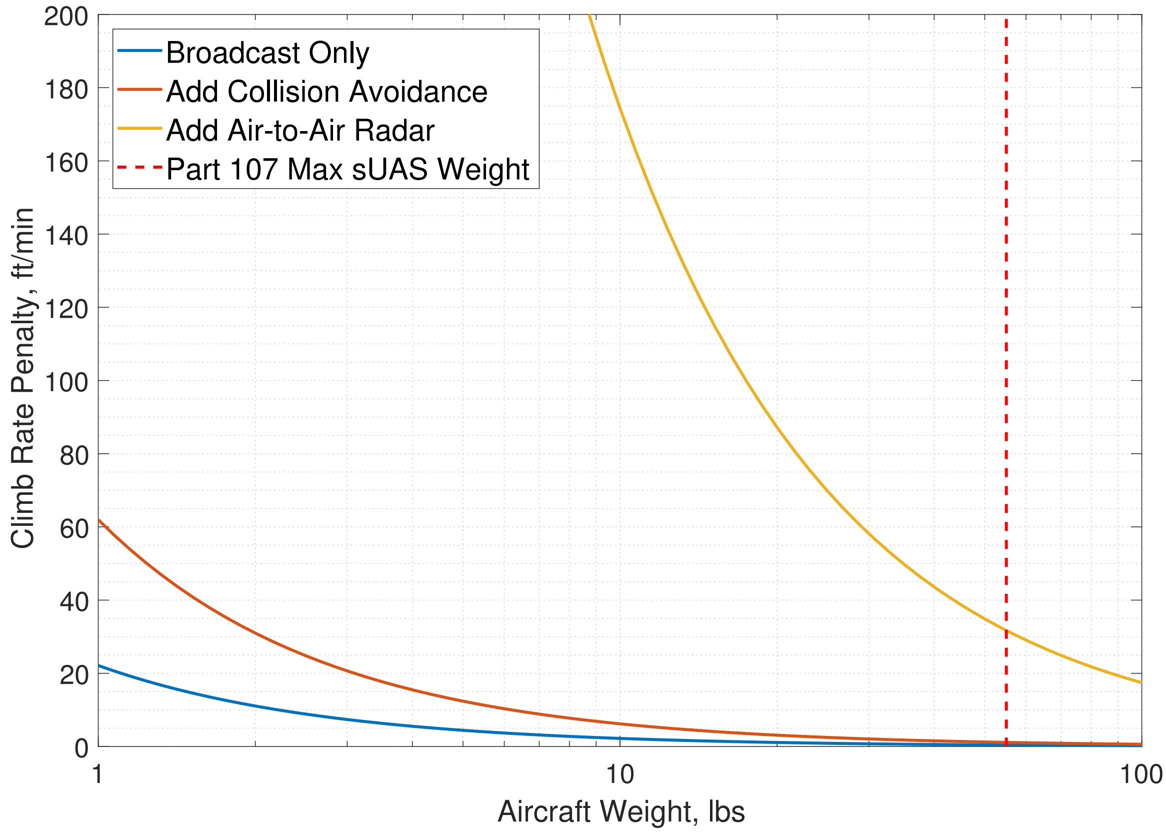


Figure 4-2: Rate of Climb Penalty for Representative sUAS CA Systems

much noise that the spectrum will become unusable. Section 4.2 models the aviation broadcasting environment to investigate how sUAS broadcasters could affect signal reception performance.

4.2 Broadcasting Analysis

As noted in Chapter 1, sUAS are quickly becoming far more numerous than manned aircraft. While cooperative surveillance could allow sUAS to detect and be detected by other aircraft, it is important to investigate whether the spectrum used by cooperative surveillance could support a large number of new users. If the number of broadcasters on a particular channel becomes too large, signals can interfere with one another and it can become difficult to decode the messages sent by other transmitters.

In order to better understand the effect that additional sUAS broadcasters would have on signal reception for all users, transmissions were modeled for a dual population of manned aircraft and sUAS. Based on current operations in high-density areas, the population of manned aircraft was modeled as uniformly distributed by distance from a central point. The value of the manned aircraft density was set at 4.7 aircraft per Nautical Mile (NM), or 2.5 aircraft per kilometer (km). In other words, about 5 aircraft would be contained within a 1 NM radius of the center, then an additional 5 aircraft would be contained between 1 NM and 2 NM of the center, and so on. This distribution is a good model for manned aircraft because it concentrates traffic around the center of the distribution in the same way that real manned aircraft traffic clusters around an airport or urban area, and becomes more sparse away from that central location. This type of distribution has been used to model manned traffic in the Los Angeles basin at a value of 5.25 aircraft per NM [18, 19, 40], and is used to define the maximum density at which TCAS [23] and ACAS Xa [35] can meet transponder surveillance requirements. The ICAO SARPS also use this type of distribution [28]. The density of 4.7 aircraft per NM is used here because it mimics the population of aircraft assumed by the TCAS and ACAS Xa MOPS as well as by the ICAO SARPS.

Because it is not yet known how sUAS will be distributed when conducting real operations, two different distributions were used to model a population of sUAS. The first was the uniform distance distribution used by the manned aircraft. The other distribution was uniform by area instead of distance. This means that one square NM would contain the same number of sUAS no matter where that square NM was located. This distribution may be a better model for sUAS behavior since sUAS can operate without an airport. On the other hand, sUAS may still end up clustered around urban areas due to the larger number of people living there. Because of this uncertainty, both types of distributions were assessed.

To better visualize the two distributions used, Figure 4-3 compares the number of aircraft contained within a given range for various densities of both the uniform distance and uniform area distributions. The plot uses range units of km to mirror previous studies on broadcasting sUAS densities [41, 42], but the plotted lines would remain the same if using a different range unit such as NM.

As seen in Figure 4-3, the distance distributions (plotted as solid lines) tend to have more aircraft at closer ranges while the area distributions (plotted as dashed lines) tend to have more aircraft at longer ranges. As one example, a uniform distance distribution of 40 aircraft per km and a uniform area distribution of 1 aircraft per square km would both contain 500 aircraft within a 12.5 km radius of the center. The distance distribution would contain more aircraft within radii less than 12.5 km, while the area distribution would contain more aircraft within radii greater than 12.5 km. This demonstrates how the uniform distance distribution leads to a greater clustering of aircraft around the center of the distribution.

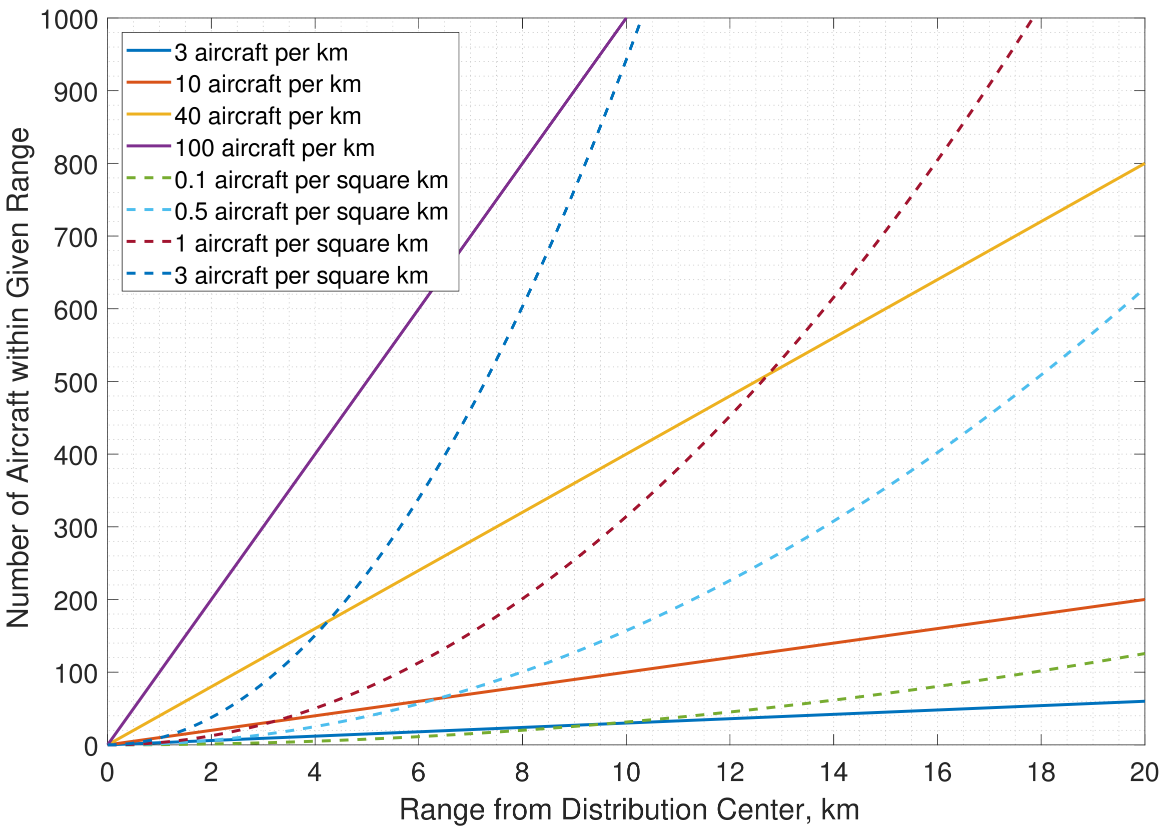


Figure 4-3: Comparison of Distributions used to Model Populations of Manned Aircraft and sUAS in High-Density Areas

It is hard to predict the exact density of future sUAS operations with either of the types of distributions. One study predicted that potential future sUAS uses over Chicago would lead to a density of 4.5 sUAS per square NM (1.3 per square km) [43]. In a uniform area distribution of 4.5 sUAS per square NM, there would be 350 sUAS within a 5 NM radius. By contrast, the assumed distribution of manned aircraft has only 24 aircraft within the busiest 5 NM radius. Small UAS may therefore operate at densities that are an order of magnitude larger than what is currently seen with manned aircraft. Other studies have also assumed a uniform area distribution of sUAS with densities ranging from 0.5 to 5 sUAS per square km [41, 42].

In order to account for uncertainty in future sUAS operations, multiple simulations were run to assess each type of sUAS distribution at a variety of density values. In each case, the population of sUAS was overlaid with the population of manned aircraft, and signal reception performance was assessed. Various transmission power levels were also modeled for sUAS since lower transmission powers create less interference for manned aircraft signals.

Section 4.2.1 explains how ADS-B signals on the 978 (UAT) and 1090 MHz channels were modeled to predict reception performance in the presence of this dual population of broadcasters. Section 4.2.2 shares the simulation results for various sUAS populations and transmission powers. The use of transponders by sUAS is also discussed in Section 4.2.3.

4.2.1 Modeling the ADS-B Signal Environment

ADS-B signals are actually broadcast quite differently on UAT and 1090. However, both channels use Time-Division Multiple Access (TDMA) to allow a large number of signals to be shared at once. TDMA is a method that has broadcasters transmit their messages at different times so that the messages do not interfere with one another. For example, if there were 2,000 users that each needed to transmit a 500 microsecond (μs) message every second, then each user could be assigned a 500 μs time slot.

Figure 4-4 displays the TDMA scheme used by UAT [19]. Since ADS-B messages

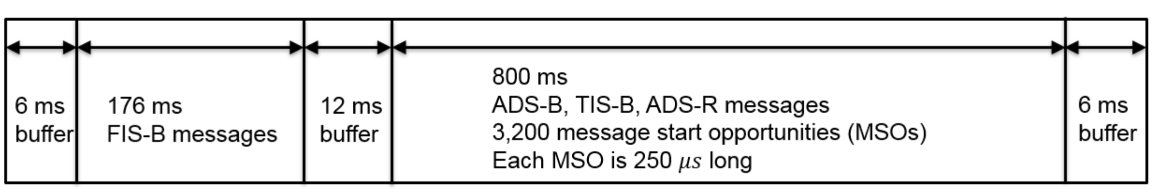


Figure 4-4: UAT TDMA Scheme per Second (Not to Scale)

are broadcast once every second, this scheme divides each second into a number of time slots. There is a 176 ms block reserved for FIS-B messages; an 800 ms block for ADS-B, TIS-B, and ADS-R messages; and 12 ms buffers in between on both ends. The main 800 ms block is broken up into 3,200 Message Start Opportunities (MSOs) that are each 250 μs long, the amount of time required for one ADS-B message on UAT.

Every second, each aircraft broadcasting on UAT randomly chooses, with equal probability, one of the 3,200 MSOs to broadcast its ADS-B message. To keep aircraft from systematically interfering with one another, the pseudo-random process used to choose an MSO each second is independent of any previous MSO chosen and any other broadcaster. As long as all aircraft within transmitting range choose different MSOs, many ADS-B messages can be successfully received each second. However, if two aircraft in close proximity choose the same MSO, then their messages will overlap and interfere with each other.

Duffield and McLain developed an expression to calculate the probability of transmitters interfering with one another in the TDMA scheme used by UAT [44]. If there are n total transmitters and x time slots to choose from, then the probability of interference $P(I)$ for a given message (i.e. the probability that at least one other transmitter will choose the same time slot in a given second) can be calculated using Equation 4.2. For UAT, x would be equal to 3,200 time slots (MSOs). The notation $\binom{n}{k}$ denotes a combination, which is also referred to as the binomial coefficient.

$$P(I) = \binom{n-1}{1}\frac{1}{x} + \cdots + (-1)^{n-1}\binom{n-1}{n-2}\frac{1}{x^{n-2}} + (-1)^{n}\binom{n-1}{n-1}\frac{1}{x^{n-1}} \tag{4.2}$$

Equation 4.2 can be simplified to provide an alternative calculation for the probability of interference that does not require an approximation method for large combinations. Consider n total transmitters each choosing one of x time slots. The first transmitter begins by choosing a time slot. Each of the subsequent $n-1$ transmitters can then choose one time slot of x possibilities, which means there are x^{n-1} ways the remaining $n-1$ transmitters can choose time slots. Of these possibilities, each of the subsequent $n-1$ transmitters has $x-1$ possible choices that will not interfere with the first transmitter, meaning there are $(x-1)^{n-1}$ ways the subsequent $n-1$ transmitters can all choose time slots that do not interfere with the first transmitter. Since all choices are made randomly with equal probability, it is possible to use the discrete uniform probability law to find the probability of no interference by dividing the number of outcomes leading to no interference by the total number of outcomes possible. Equation 4.3 displays this calculation for the probability of no interference, $P(I^C)$. The probability of interference $P(I)$ found in Equation 4.2 can be calculated by subtracting $P(I^C)$ from 1. This is a far simpler method that allows an easy and exact calculation for even a large number of transmitters.

$$P(I^C) = \left(\frac{x-1}{x}\right)^{n-1} = 1 - P(I) \tag{4.3}$$

This method can also be extended to calculate the probability of an exact number of other transmitters interfering with a given transmitter. As mentioned above, once the first transmitter chooses a time slot, there are x^{n-1} ways for the remaining $n-1$ transmitters to choose time slots. Of these, there are $\binom{n-1}{i}(x-1)^{n-1-i}$ ways that exactly i other transmitters can choose the same time slot as the first transmitter. Equation 4.4 again uses the discrete uniform probability law to calculate the probability of exactly i other messages overlapping with a given message. Equation 4.4 is equivalent to Equation 4.3 when i is set to zero.

$$P(\text{exactly } i \text{ overlaps}) = \frac{\binom{n-1}{i}(x-1)^{n-1-i}}{x^{n-1}} = \binom{n-1}{i}(x-1)^{-i}\left(\frac{x-1}{x}\right)^{n-1} \tag{4.4}$$

Equations 4.3 and 4.4 were used to calculate the probability of encountering interfering messages on UAT. However, the 1090 MHz environment is more complex. Rather than choosing one predefined time slot to broadcast an entire ADS-B message, aircraft broadcasting on 1090 transmit position and velocity reports each every 0.4 to 0.6 seconds, one identification report every 4.8 to 5.2 seconds, and other event-driven reports including changes in TCAS RA status or position accuracy. Overall, the average number of messages broadcast per second is at least 4.8 and can be as high as 6.2. All reports are 120 μs long, with at least 5 μs of buffer needed in between. Therefore, a maximum of 8,000 reports could be received per second without interference if they were intentionally spaced one after another.

The methods used to calculate the probability of interference on UAT cannot be directly applied to the 1090 environment because the messages are transmitted randomly in continuous time rather than during one of a discrete number of time slots. Instead, a Poisson process was used to model the probability that interference would be received in the time needed to decode one ADS-B message. Equation 4.5 gives the probability of receiving k overlapping ADS-B messages during a time frame in which λ total messages are expected. Because 125 μs are needed to successfully receive and decode one ADS-B position report, λ was calculated as the number of ADS-B messages from other aircraft expected to be received in any 125 μs window. If n total aircraft each transmit m messages per second, then Equation 4.6 gives the number of ADS-B messages expected to be received from other aircraft over any 125 μs period. Since the average number of messages transmitted on 1090 can range from 4.8 to 6.2 each second, m was set to 5 to simulate a minimal but nonzero amount of extra event-driven messages.

$$P(k \text{ overlaps}) = e^{-\lambda}\frac{\lambda^k}{k!} \tag{4.5}$$

$$\lambda = m(n-1)\left(\frac{125\,\text{x}\,10^{-6}\,\text{s}}{1\,\text{s}}\right) \tag{4.6}$$

Using Equations 4.3 through 4.6, it is possible to calculate the probability that a message on either ADS-B channel will encounter interference from other ADS-B messages for a given number of transmitters. However, this is not sufficient to calculate the probability of signal reception. The probability of successfully decoding a message also depends heavily on the signal's power upon reception. If a signal is extremely weak, it will not be decoded even in the absence of interference. On the other hand, a strong signal can sometimes still be decoded even in the presence of weaker interference.

The RTCA provides ADS-B receiver standards in DO-260B for 1090 MHz and DO-282B for UAT [18, 19]. The Minimum Trigger Level (MTL) for UAT receivers is required to be at least -93 dBm, or decibels in relation to a milliwatt. MTL is defined as the power at which messages must be successfully decoded at least 90% of the time in the absence of interference. Even if a different signal is broadcast on the same MSO, the stronger signal must still be successfully decoded with 90% probability if it is at least 4 dB stronger than the weaker signal. Similarly, DO-260B sets the MTL at -71 dBm for the standard ADS-B transmitting class on 1090. Required performance in the presence of an interfering signal is provided in more detail and a 90% success rate is achieved when one signal is about 5.8 dB stronger than the other.

Based on these standards and ADS-B receiver performance data in DO-260B, a logistic function was used to model the probability of successful message reception based on received signal power. Equation 4.7 shows the logistic function used, which provides the probability of successful reception $P(S)$ of a signal received at power P_r. The constant k was set to 1.9 for UAT and 1.3 for 1090 based on the receiver requirements laid out in DO-282B and DO-260B, respectively. P_{ref} is a reference power at which the signal will be decoded with 90% success. Equation 4.7 was used to model the probability of successful reception in the absence of interference with P_{ref} set at MTL, and to calculate the probability of success in the presence of an interfering signal with P_{ref} set at 4 dB (UAT) or 5.8 dB (1090) above the power of the interfering signal.

$$P(S) = \left(1 + \frac{1}{9}\exp\left[-k(P_r - P_{\text{ref}})\right]\right)^{-1} \tag{4.7}$$

To calculate the probability of successful reception in terms of distance from a transmitter, it is necessary to calculate how the received power of a signal changes as it travels through free space (i.e. air). This was done using the isotropic Friis transmission equation, displayed in Equation 4.8 [45]. Equation 4.8 relates the received power P_r of a signal with its transmission power P_t and range r. The frequency of the signal is given by f, and c is the constant speed of light, approximately 300 million meters per second. As Equation 4.8 shows, the received power of a signal traveling through free space decays with the square of the distance traveled. The isotropic version of the equation was used because all ADS-B transmissions are isotropic (i.e. omni-directional) and any receiver gains would equally amplify both a desired signal and any co-channel interference, which was the only type of interference modeled.

$$P_r = P_t \frac{c^2}{(4\pi f r)^2} \tag{4.8}$$

Next, to calculate the number of transmitters that could cause interference, it is necessary to model the distribution of transmitters in space. As discussed above, two different distributions of aircraft were used to accomplish this. One was a population of aircraft uniformly distributed by distance from a central point. The aircraft of interest was assumed to be at the center of this distribution to calculate the worst-case receiver performance, which means that other aircraft were uniformly distributed by range from this aircraft. The number of transmitters in range, n, was then simply the distribution density times the range r_{max} at which the signal degrades to the minimum power being considered for interference. For UAT, the minimum power considered was 4 dB below MTL, and for 1090 it was 5.8 dB below MTL.

Equations 4.3 through 4.6 were used to first find the probability that a given number of signals cause interference. For two or more overlapping signals, the probability of successful reception was assumed to be zero because DO-260B and DO-282B only require success in the presence of one interfering ADS-B signal. The probability of success given no interfering signals was found using Equation 4.7 and setting P_{ref} to MTL. Calculating the probability of success given one overlapping signal required integrating over all transmitters.

For the uniform distribution by range, the integration is shown in Equation 4.9. The probability of success against a signal from a given distance is multiplied by the differential probability $\frac{dr}{r_{\text{max}}}$ of the overlapping signal originating from that distance.

This probability was calculated by using Equation 4.8 to convert range to interfering signal power and then using Equation 4.7 to calculate the probability of success against an interfering signal of that strength.

$$P(S) = \frac{1}{r_{\max}} \int_0^{r_{\max}} P(\text{success against signal at range } r) \quad dr \tag{4.9}$$

The other distribution of aircraft considered was a uniform distribution by area. The number of transmitters n was found in the area distribution by multiplying the density of the distribution by the total area considered, which was $\pi r_{\max}^2$. The probability of success given that there was one overlapping signal was found by integrating over area rather than distance. This was done using polar coordinates, as shown in Equation 4.10. For brevity in Equation 4.10, r_m refers to $r_{\max}$ and $P(\cdot)$ refers to the probability of success against an interfering signal from range r.

$$\begin{aligned} P(S) &= \int_A P(\text{success against signal at range } r) \quad \frac{dA}{\pi r_m^2} \\ &= \frac{1}{\pi r_m^2} \int_0^{r_m} \int_0^{2\pi} P(\cdot) \quad r d\theta dr \\ &= \frac{1}{\pi r_m^2} \int_0^{r_m} 2\pi r P(\cdot) \quad dr \\ &= \frac{2}{r_m^2} \int_0^{r_m} r P(\cdot) \quad dr \end{aligned} \tag{4.10}$$

Finally, Equation 4.11 provides the calculation for $P(S)$, the overall probability of successful message reception despite possible ADS-B interference. $P(I^C)$ and $P(1 \text{ overlap})$ were calculated using Equations 4.3 through 4.6. $P(S|I^C)$ was calculated using Equations 4.7 and 4.8. $P(S|1 \text{ overlap})$ was calculated using one of the integration equations, which also required many of the preceding equations. The integrals were solved numerically using the trapezoidal method. Equation 4.11 therefore gives the probability of successfully receiving an ADS-B message from an aircraft at a given distance away in a high-density environment.

$$P(S) = P(I^C)P(S|I^C) + P(1 \text{ overlap})P(S|1 \text{ overlap}) \tag{4.11}$$

Other ADS-B signals should be the only source of co-channel interference on the 978 MHz channel. However, the 1090 MHz channel includes other signals, most notably ATCRBS and Mode S replies. Both TCAS and ACAS Xa are required to meet performance requirements in an environment containing 30,000 ATCRBS messages per second at power levels above −71 dBm, with 15,000 messages at least −68 dBm, 7,500 messages at least −65 dBm, and so on. Similarly, ACAS Xa is required to maintain performance in an environment with many Mode S replies, including 5,900 messages at power levels of at least −74 dBm. The distribution of ATCRBS and Mode S signals given in the TCAS and ACAS Xa MOPS were used to model additional interference on the 1090 channel.

Success against ATCRBS and Mode S interference were modeled independently of ADS-B interference and independently of each other. A Poisson process was used to calculate the probability of a given number of messages arriving during the time needed for a position report (125 μs). The equation for a Poisson process is given above in Equation 4.5. This allowed the probability of encountering overlapping ATCRBS and Mode S replies to be calculated. The probability of success given interfering ATCRBS or Mode S messages was calculated based on the required performance against these sources of interference laid out in DO-260B.

The probability of success against ATCRBS and Mode S messages was multiplied by the probability of success in Equation 4.11 to give a final probability of successfully receiving each ADS-B position report on 1090 MHz.[5] Note that each aircraft on UAT broadcasts one ADS-B message per second, while each aircraft on 1090 MHz broadcasts a position report every half second. To directly compare the results between UAT and 1090, Equation 4.12 was used to convert the probability $P(S_h)$ of receiving a position report each half second to the probability $P(S_f)$ of receiving at least one of the two position reports each full second on 1090 MHz.

$$P(S_f) = 1 - (1 - P(S_h))^2 \tag{4.12}$$

[5]Because ADS-B, ATCRBS, and Mode S interference were modeled independently, the overall probability of success is simply the product of the individual probabilities of success.

4.2.2 ADS-B Signal Performance Results

The methods discussed in Section 4.2.1 were used to calculate the probability of successfully receiving ADS-B signals each second in a high-density environment containing both manned aircraft and sUAS. As detailed above, the manned aircraft were modeled as uniformly distributed by distance at a density of 4.7 per NM. Various density values were assessed for the sUAS using both the uniform distance and uniform area distributions.

In all of these cases, the densities used represented the densities of transmitting aircraft, so it is possible that higher densities could result in the same reception performance if many aircraft do not transmit. However, due to ADS-R, every aircraft that transmits ADS-B signals will cause a signal to be generated on both channels (1090 and 978 MHz). Furthermore, TIS-B will cause many UAT signals to be generated for aircraft that are not even equipped with ADS-B. In this simulation, performance was evaluated with the given densities of aircraft broadcasting ADS-B on the same channel. The real signal environment would include ADS-R and TIS-B signals, but the overall number of ADS-B messages would be similar.

For the UAT simulation, all manned aircraft transmitted ADS-B messages at 25 W, which is within the range for the standard transmitter class.[6] On 1090 MHz, all the manned aircraft were simulated as transmitting at 125 W, the standard value. The minimum transmission levels currently allowed are 7 W on UAT and 70 W on 1090. However, it is possible that sUAS could be allowed to transmit at lower levels, so different levels of sUAS transmission power were assessed.

Figures 4-5 and 4-6 display the simulation results for the population of manned aircraft alone, without the presence of any sUAS. The probabilities shown on the y-axes are the probabilities that a manned aircraft's signal (transmitted at 25 W for UAT and 125 W for 1090) will be successfully received and decoded each second when the transmitting aircraft is at the range denoted on the x-axis. It is apparent that ADS-B signals can be received with a high probability of success even among a high

[6]This is class A1 as described in DO-242A, which is the transmission class designed for collision and conflict avoidance [40].

density of manned aircraft.

TCAS requirements can provide a reference for the surveillance range needed for a CA system. The use of TCAS II requires that surveillance on intruding aircraft be established before the aircraft comes within 4 NM at lower altitudes (below 10,000 feet MSL) and 14 NM at higher altitudes [23]. These requirements exist so TCAS can establish surveillance before the RA τ thresholds shown in Table 2.1 are violated. Below 10,000 feet, all aircraft are required to fly no faster than 250 knots and the maximum RA τ threshold is 25 seconds. At a maximum head-on closing speed of 500 knots, two aircraft would be 25 seconds from the Closest Point of Approach (CPA) when they are 3.5 NM away. This is rounded up to a 4 NM requirement (29 seconds before CPA) to allow a surveillance track to be established and a TA to be issued before the RA must be issued. Above 10,000 feet, the maximum RA τ threshold is 35 seconds, but there is no limit on maximum speed. A maximum closing rate of 1200 knots was assumed by the TCAS MOPS based on the maximum speed that most commercial air carriers fly, which would mean that 11.7 NM would be traversed in the 35 seconds leading up to CPA. To again allow for some additional time as well as potentially higher speeds, this is rounded up to a 14 NM surveillance requirement. The ACAS Xa MOPS adopted these same requirements [35]. Furthermore, TCAS II assumes that surveillance information will be obtained on each intruder with at least 93% success each second, while ACAS Xa assumes a success rate of at least 91%. The ICAO SARPS provide a similar requirement that a surveillance track must be established on an intruder with 90% success 30 seconds before CPA [28].

While TCAS and ACAS Xa require transponder interrogations in addition to any ADS-B surveillance information used, the value of 14 NM can still provide a reference for the range at which a manned aircraft should be detectable with high probability of success. Based on the simulation of manned aircraft without sUAS, Figures 4-5 and 4-6 show that ADS-B signals can be received with more than 0.92 probability of success at ranges beyond 14 NM on both 978 and 1090 MHz, even with a high density of manned aircraft.

As mentioned, the minimum ADS-B transmission powers currently allowed are

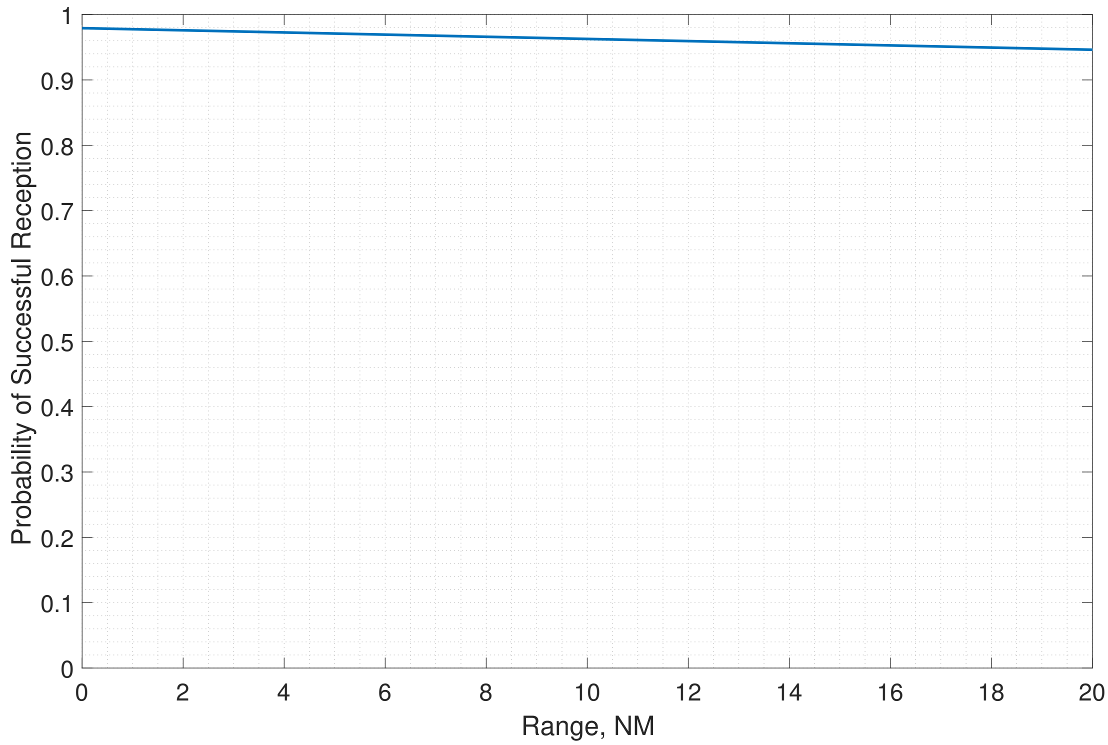


Figure 4-5: ADS-B Signal Reception from an Individual Transmitter on UAT (Manned Aircraft Only with 25W Transmit Power)

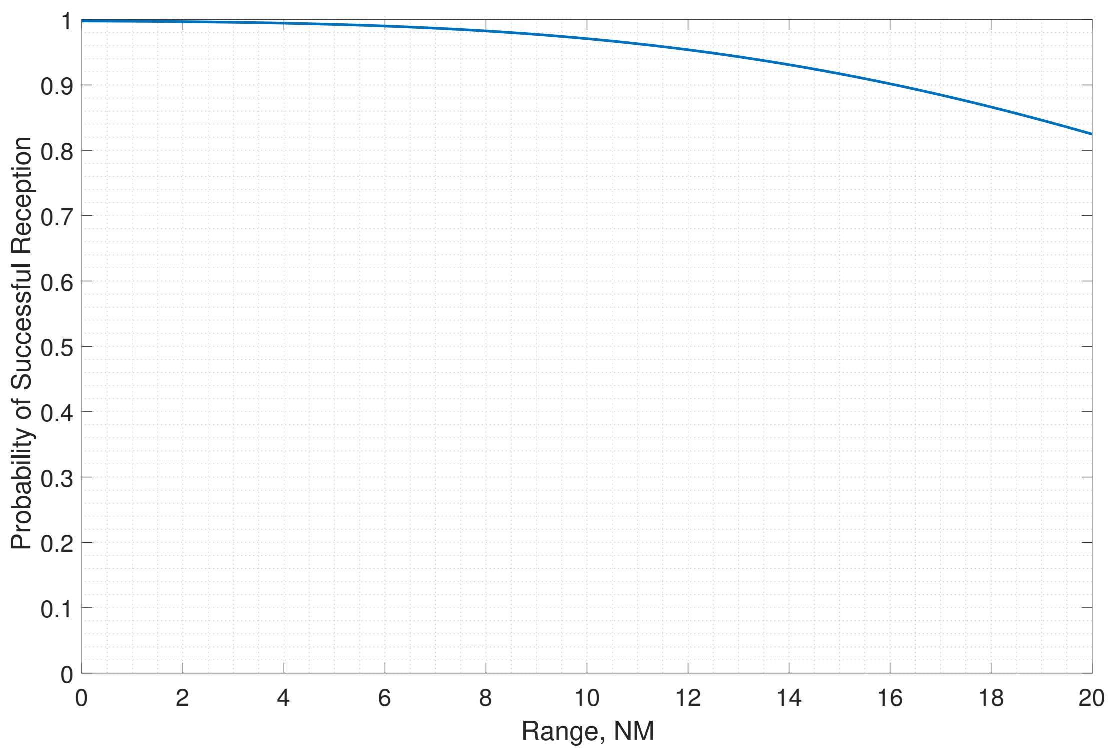


Figure 4-6: ADS-B Signal Reception from an Individual Transmitter on 1090 (Manned Aircraft Only with 125W Transmit Power)

7 W on UAT and 70 W on 1090. The sUAS populations described above were added to the population of manned aircraft, and all sUAS transmitted at these lower powers in the simulation. At a density of 1 sUAS per square km for the uniform area distribution, the probability of signal reception was approximately zero at all distances considered on both 1090 and UAT. At a uniform distance distribution of 50 sUAS per km, which contains a similar number of sUAS near the center of the distribution but fewer sUAS overall, success probabilities remained below 0.3 for UAT and 0.2 for 1090 at all distances. This demonstrates that, if sUAS and manned aircraft operate at predicted densities and all sUAS equip standard versions of ADS-B, then the ADS-B environment would become so noisy that it would be effectively unusable in high-density areas.

The current ADS-B architecture could therefore not support the predicted population of sUAS if all (or most) of them broadcast at power levels that are currently allowable. However, it is possible that sUAS could transmit at lower powers. Figure 4-7 plots the distance at which signals of various powers would be received at the MTL for UAT, which is −93 dBm. On 978 MHz, a signal broadcast at just 50 mW would still be above MTL when received by an aircraft 4 NM away. Because sUAS should always be flying at lower altitudes below 10,000 feet, it should not be necessary to surveil them from more than 4 NM away. Furthermore, most sUAS fly much slower than the 250 knot maximum speed assumed for manned aircraft. In Chapter 3, the highest maximum speed observed among sUAS was about 120 knots. If the maximum closing rate between a manned aircraft and sUAS is assumed to be 370 knots instead of the standard 500 knots, and surveillance is again desired to be established 29 seconds before collision, then the surveillance requirement would drop to 3 NM instead of 4 NM. Small UAS could therefore transmit signals as weak as about 26 mW on UAT and still be detected by manned aircraft in time to avoid a collision. The same argument can be applied for the 1090 channel. Figure 4-8 shows the distance at which signals would be received at −79 dBm, the MTL on 1090 MHz. Signals could be transmitted at just 800 mW and still be received above MTL at a range of about 3 NM. Using these low-power signals would have the additional benefit of reducing the input power needed from the sUAS, which would lower the power requirements shown in Tables 4.1 and 4.2.

Small UAS could therefore decrease the interference caused by their ADS-B signals by transmitting at far lower powers. The probability of successful signal reception was reevaluated with lower powers for the sUAS. Figures 4-9 and 4-10 demonstrate how a lower sUAS transmission power can lead to a higher probability of reception for all users at closer ranges. In both cases, the uniform area distribution was used with densities of 0.5, 1, and 2 sUAS per square km. In Figure 4-9, the sUAS all transmitted signals with 1 W power (about the power of a cell phone signal). This caused many interfering signals to be present, which led to a low probability of success for both types of signals at all ranges.

However, when the sUAS transmission power was lowered to 0.1 W (100 mW), as shown in Figure 4-10, performance increased since fewer sUAS signals caused interference. The probability of successfully receiving a manned aircraft's signal increased dramatically for all three densities as the sUAS transmission power dropped from 1 W to 100 mW. And, despite the decrease in transmission power, the probability of receiving sUAS signals at close ranges also increased for each of the evaluated densities. These figures demonstrate how the interfering effects of sUAS signals can be greatly reduced if the transmission power is kept low. The same relationship was observed on the 1090 MHz channel and for the uniform distance distribution of sUAS, although figures are here omitted for brevity. Additional plots for 1090 MHz and for the uniform distance distributions of sUAS are provided in Figures A-1 through A-6 in Appendix A.

It was desired that manned aircraft signals be received at 14 NM with a probability of at least 0.9. Similarly, it was desired that sUAS signals be received at 3 NM with a probability of at least 0.8. This would allow existing manned aircraft to maintain the surveillance performance expected for CA systems while also providing surveillance information on sUAS at ranges necessary for CA. To determine the maximum sUAS density and corresponding transmission power that could achieve these criteria of success, the probability of successful signal reception was plotted for manned aircraft

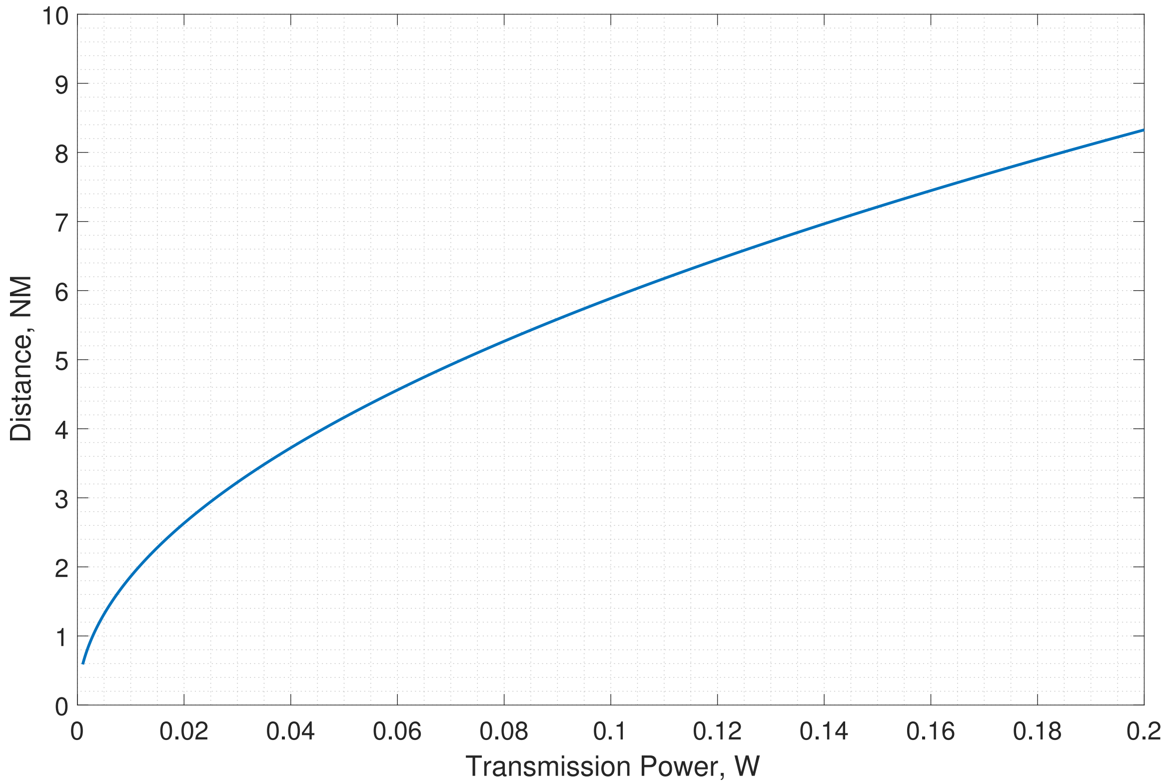


Figure 4-7: Distance Signal would be Received at MTL (−93 dBm) on 978 MHz

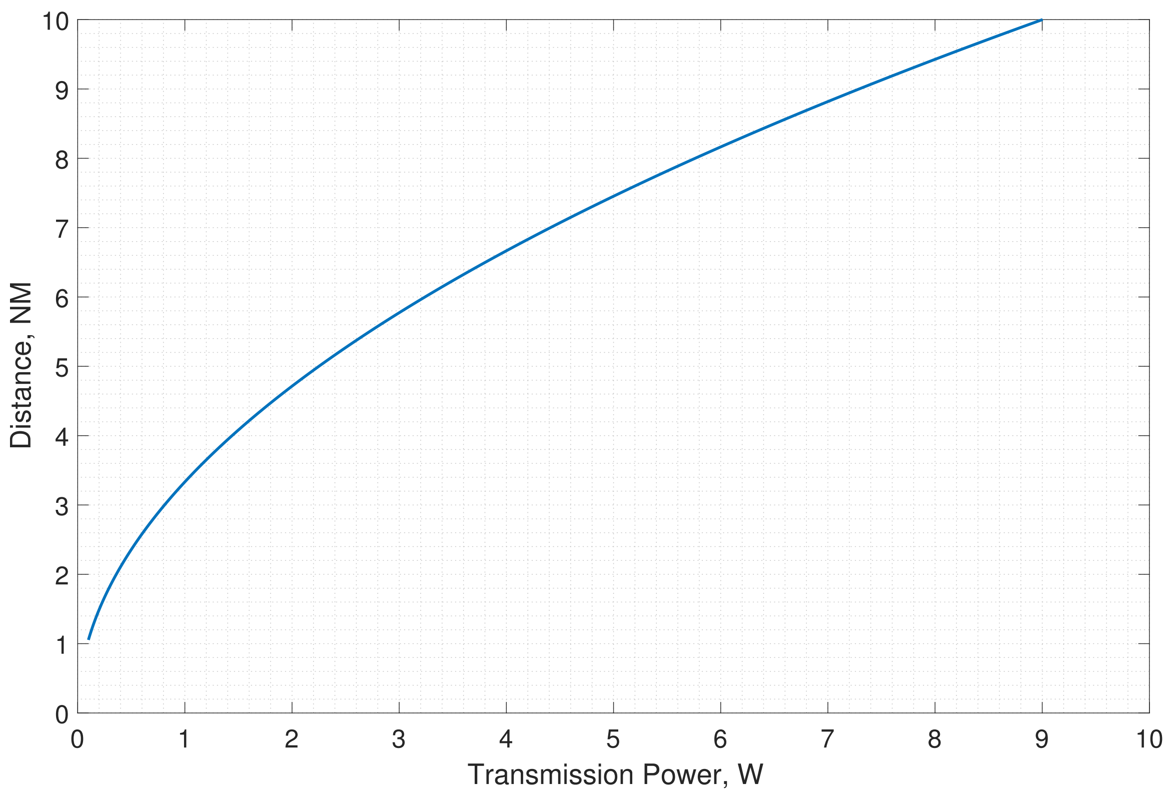


Figure 4-8: Distance Signal would be Received at MTL (−79 dBm) on 1090 MHz

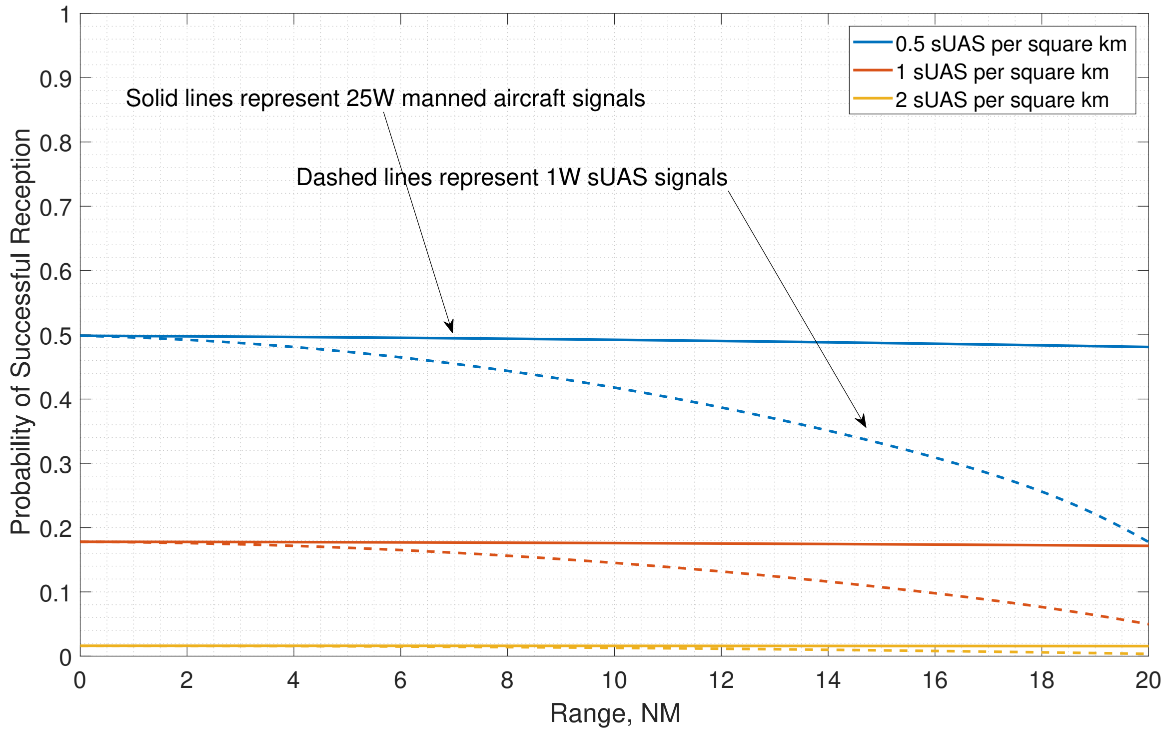


Figure 4-9: Shared-use ADS-B Signal Reception from an Individual Transmitter on UAT (sUAS transmit at 1W with Uniform Area Distribution)

signals at 14 NM and sUAS signals at 3 NM across a wide variety of sUAS transmission powers and densities.

Figure 4-11 displays the probability of receiving a manned aircraft's 25 W signal on UAT at a distance of 14 NM. Transmission powers for sUAS vary across the x-axis, and curves are plotted for multiple sUAS densities. A similar plot is provided in Figure 4-12 for sUAS signals at a range of 3 NM. Figures 4-11 and 4-12 assume a uniform area distribution of sUAS. Plots for 1090 MHz and for the uniform distance distribution of sUAS are presented in Figures A-7 through A-12 in Appendix A.

Based on the simulation results and desired success criteria, it appears that the UAT channel could support 1 sUAS per square km with the uniform area distribution if the transmission power is set at 80 mW. The corresponding value for the uniform distance distribution is 40 sUAS per km, with the same transmission power. The 1090 channel, however, could only support 0.1 sUAS per square km with the uniform area distribution or 10 sUAS per km with the uniform distance distribution. The sUAS transmission power in both of these cases would be 3 to 5 W. The lower capacity

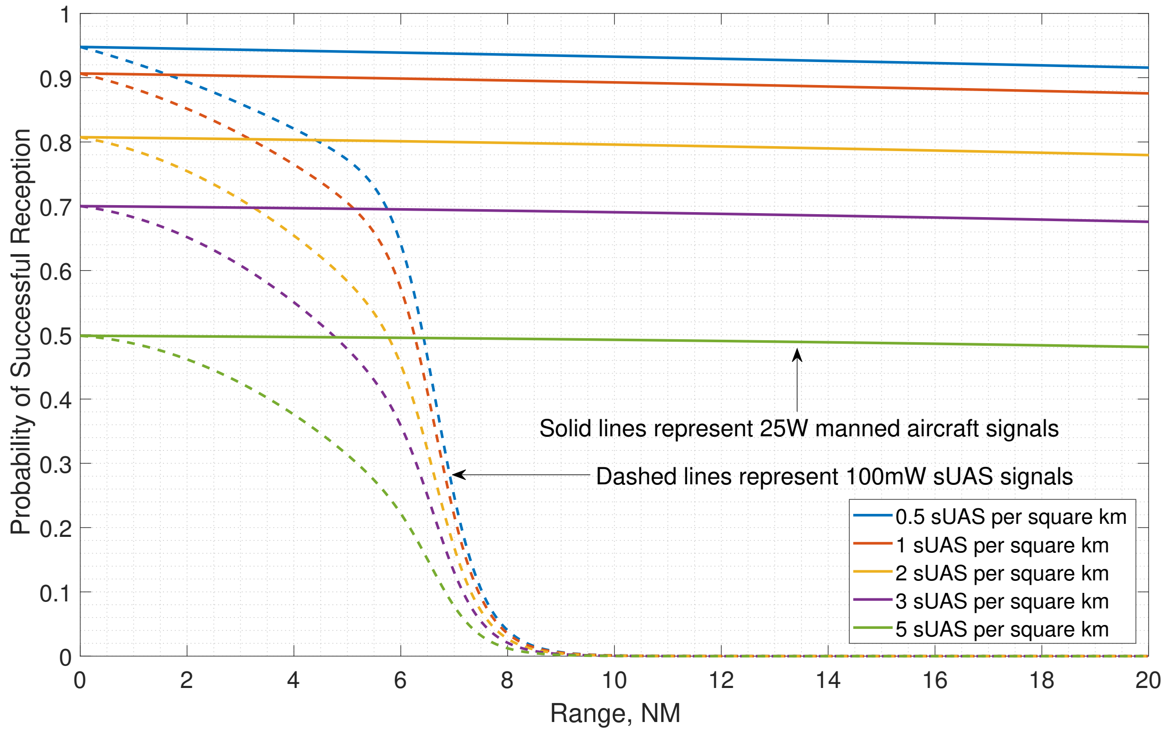


Figure 4-10: Shared-use ADS-B Signal Reception from an Individual Transmitter on UAT (sUAS transmit at 100mW with Uniform Area Distribution)

of the 1090 channel partially results from the shared-use of ATCRBS and Mode S: stronger sUAS signals cause more interference to manned aircraft while weaker sUAS signals are more susceptible to ATCRBS and Mode S interference, so it is challenging to reach high probabilities of success for both manned aircraft and sUAS signals at high densities of aircraft.

Two other recent studies on sUAS UAT usage have been conducted by MITRE [41] and NASA Glenn Research Center [42]. Both of these studies created simulated populations of manned aircraft and sUAS transmitting on 978 MHz and evaluated receiver performance for air-to-air transmissions. While the simulation setups were different from this study and from each other, it is still beneficial to compare the general trends of the results observed.

Both the MITRE and NASA Glenn studies simulated sUAS transmission powers of 10 mW, 50 mW, 100 mW, and 1 W at uniform area densities of 1, 3, and 5 per

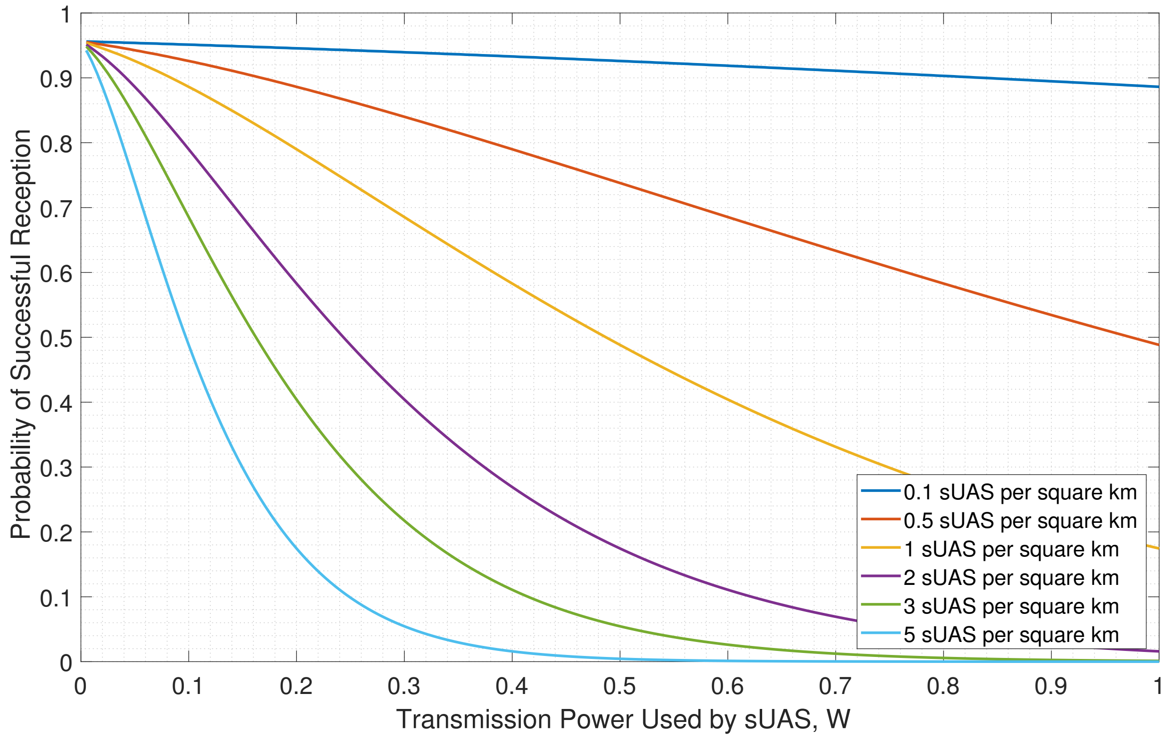


Figure 4-11: Probability of Receiving Manned Aircraft ADS-B Signals each Second at 14 NM Range on UAT (sUAS Distributed with Uniform Area Distribution)

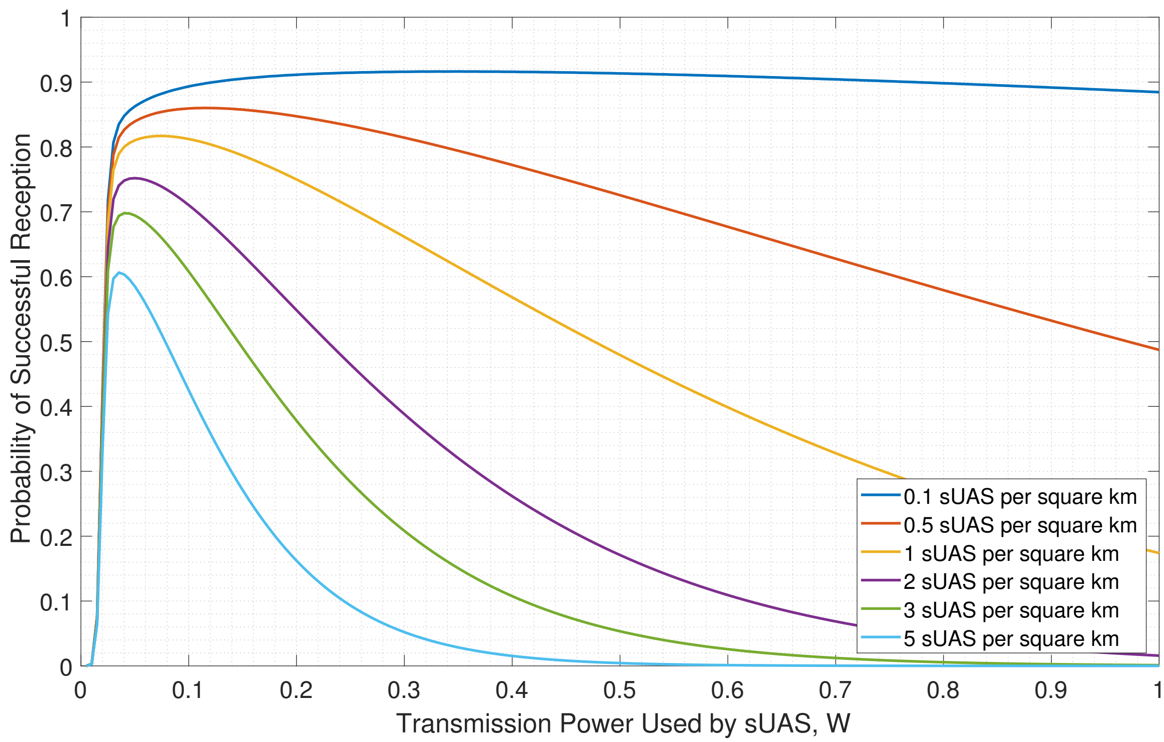


Figure 4-12: Probability of Receiving sUAS ADS-B Signals each Second at 3 NM Range on UAT (sUAS Distributed with Uniform Area Distribution)

square km (as well as 0.5 per square km for MITRE).[7] Both organizations concur that a transmission power of 1 W for sUAS would be infeasible for all aircraft densities considered. MITRE argues that 10 mW power would be tenable at all densities considered, while the 50 and 100 mW powers would be usable for densities of 0.5 and 1 sUAS per square km but not at the higher densities. From the NASA Glenn report it appears that transmission powers of 50 and potentially 100 mW may be acceptable at a density of 1 aircraft per square km, while the greater densities created too much interference. The 10 mW power was acceptable at up to 3 aircraft per square km.

The results of the simulation detailed in this section largely agree with the results from MITRE and NASA Glenn. As Figure 4-11 shows, using a transmission power of 1 W at densities greater than or equal to 0.5 sUAS per square km would cause an extremely low probability of successful reception for manned aircraft signals at 14 NM on UAT. A transmission power of just 10 mW could support manned aircraft signals at all the densities of sUAS considered, which supports the findings from MITRE. However, Figure 4-12 shows that this extremely low power would not allow sUAS signals to be detected with sufficient range to avoid collisions. As discussed above, sUAS transmissions on UAT should use a power no lower than about 26 mW. The results detailed in this section agree with MITRE and NASA Glenn that up to about 1 sUAS per square km could be supported on UAT if signals for both manned aircraft and sUAS are to be received with high probability of success at appropriate ranges.

One final factor that is worth briefly considering for ADS-B is the "target limit" for UAT. The document (DO-282B) regulating ADS-B communication on UAT states that ADS-B systems can discard information on individual targets if a certain target limit has been reached [19]. For the standard equipment class for aircraft that fly below 18,000 feet, the target limit is 300 aircraft. This means that, if a manned aircraft with ADS-B detects more than 300 aircraft, many of the targets could be discarded and the pilot would not know about the detected traffic. In an attempt to keep the targets visible that most pose a collision threat, DO-282B specifies that

[7] In the MITRE study, these were the densities of sUAS. In the NASA Glenn study, these were the densities of all aircraft combined.

the 300 targets at the closest range (and not the strongest signal power upon reception) should be retained, while all others can be thrown out. Unfortunately, this requirement could cause a population of sUAS to blank out manned aircraft at farther distances, even if the manned aircraft are transmitting at much higher power levels. This is problematic because the manned aircraft could pose a much higher collision threat, even if they are at much farther distances (since they may be flying far faster than the sUAS). While this problem could be resolved by simply changing the standards regarding this target limit, there are thousands of ADS-B units that have already been manufactured according to DO-282B, and it would be costly to recall and modify all of them. Therefore, sUAS transmission powers and densities should be maintained such that there are fewer than 300 sUAS visible to manned aircraft at any particular time. A density of 1 sUAS per square km transmitting at 80 mW would cause almost exactly 300 sUAS signals to be received above MTL, so overloading the target limit is a relevant concern that should be considered.

A possible alternative to ADS-B is to have sUAS use transponders to detect and be detected by other aircraft. Section 4.1 showed that sUAS could potentially carry a low-weight, low-power Mode S transponder. Considerations for transponder use on sUAS are reviewed in Section 4.2.3.

4.2.3 Consideration of Mode S Transponder Usage

As discussed in Section 2.2, there are two primary ways that manned aircraft currently accomplish airborne surveillance. One is through the use of ADS-B, which was reviewed for sUAS in Sections 4.2.1 and 4.2.2. The other is through the use of transponders, which is another way that sUAS could potentially detect and be detected by manned aircraft. In fact, the current versions of TCAS II and ACAS Xa would not issue RAs against sUAS unless they were equipped with Mode C or Mode S transponders. Section 4.1 noted that even lightweight sUAS could potentially carry Mode S transponders (see the Ping20Si in Table 4.1). This section considers the effects of having sUAS equip Mode S transponders to perform surveillance.

An important characteristic of Mode S transponders is the unique 24-bit address assigned to every aircraft that uses one. The 24-bit scheme allows for nearly 17 million unique addresses to be generated ($2^{24} = 16,777,216$). The U.S. has been allotted about one million of these addresses, of which about 900,000 are available for use by civil aircraft. It would clearly be infeasible to assign addresses to every sUAS in America, of which there are already over one million [1]. Widespread use of Mode S transponders on sUAS would therefore require addresses to be duplicated. Transponders would not be able to track aircraft with identical addresses if they are encountered at the same time. This could perhaps be somewhat mitigated by only allowing duplicates among sUAS and ensuring that sUAS with duplicate addresses are operating in different parts of the country. However, this still betrays the intent of Mode S addresses, which is for each aircraft to be assigned a uniquely-identifying value.

Another problem is the massive amount of interrogations and replies that would be required if a large number of sUAS equip Mode S transponders. TCAS interrogators were designed such that no aircraft would receive more than 280 interrogations per second in high-density environments [23]. This saturation limit is reached when there are more than 280 aircraft in a 30 NM radius, which would occur in all the dual populations of manned aircraft and sUAS considered in this chapter. Even if sUAS use transponders that generate only reply signals and not interrogation signals, these 280 broadcasts per second would require a lot of electrical power for the sUAS and would also create a lot of interference.

The probability of receiving Mode S replies in the presence of interference was modeled using methods similar to those detailed in Section 4.2.1. The population of manned aircraft described above was again overlaid with sUAS populations of various densities and transmission powers, with the sUAS now generating Mode S reply signals rather than ADS-B signals. ATCRBS, Mode S, and ADS-B signals were modeled for the manned aircraft. A Poisson process (Equation 4.5) was used to estimate the probability of not encountering any signals strong enough to create interference in the 64 μs needed to receive a Mode S reply. Equation 4.8 was again used to relate reception power and range, which allowed a success probability to be calculated for a given range and transmission power. The power of Mode S replies are similar to ADS-B signals on 1090 MHz: the typical response power is 125 W, with a minimum power of 70 W.

As was the case for ADS-B, sUAS generated so much interference when using the minimum power of 70 W that the probability of receiving signals at appropriate ranges for collision avoidance was extremely low. However, even when using lower-power signals, performance remained poor. Small UAS would need to use a transmission power of at least 800 mW for the Mode S replies to remain above MTL at a range of 3 NM. Figure 4-13 displays the predicted performance for manned aircraft and sUAS reply signals with the uniform area distribution and a reply power of 800mW for sUAS. Figure A-13 in Appendix A displays a similar plot using a uniform distance distribution of sUAS. Even at this extremely low transmission power, performance was poor for both manned aircraft and sUAS reply signals. The performance of sUAS replies could be improved by increasing the transmission power, but this would only decrease the performance of the manned aircraft reply signals. The lowest densities evaluated (0.1 per square km in the uniform area distribution and 3 per km in the uniform distance distribution) could still not support the desired probabilities of success. It is apparent that Mode S transponders would be unsuitable for widespread use on sUAS. Mode S transponders were designed to produce less interference than Mode A/C transponders, so it would therefore be unwise to equip Mode A/C transponders on a large number of sUAS, as well.

These results, together with the 1090 ADS-B results, suggest that sUAS should not broadcast en masse in any capacity on 1090 MHz. It is already a busy environment with a combination of ATCRBS, Mode S, and ADS-B signals, and an influx of new sUAS signals would quickly overload the channel. In rural and less populous areas, the use of 1090 MHz by sUAS (e.g. crop-inspection UAS) could remain a valid option. But this should be seen as an exceptional case, and the majority of sUAS should not broadcast on 1090 MHz.

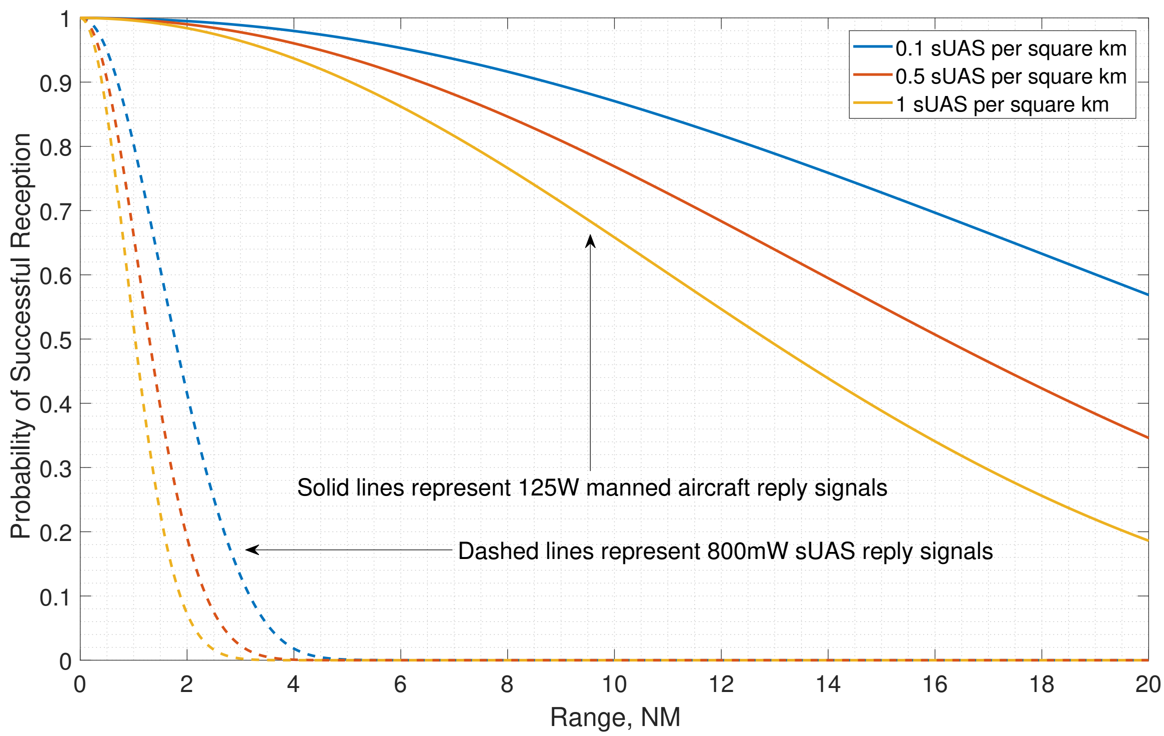


Figure 4-13: Shared-use Mode S Performance (sUAS reply at 800mW with Uniform Area Distribution)

4.3 Summary of Surveillance Analysis

In conclusion, this chapter explored the use of cooperative surveillance by sUAS to detect and be detected by manned aircraft. The sensors needed for airborne surveillance were reviewed and compared to sUAS capabilities. Both transponders and ADS-B, the two methods of cooperative surveillance currently used by manned aircraft, were considered for use on sUAS. The broadcasting environment was modeled on both 978 and 1090 MHz to predict signal reception performance if a new population of broadcasting sUAS joins the existing population of broadcasting manned aircraft.

It was determined that sUAS could potentially equip a position source, radio transceiver, and collision avoidance processor at low size, weight, power, and cost. This includes both ADS-B and Mode S transponders as valid broadcasting options. Small UAS could similarly equip a system that receives manned aircraft signals without broadcasting. However, adding even the smallest air-to-air radar as a non-cooperative surveillance sensor would require an order of magnitude increase in sUAS size. This demonstrates the advantage of cooperative surveillance for sUAS.

Even if it is feasible for sUAS to broadcast, however, it may not be wise. Table 4.3 summarizes the maximum sUAS densities that supported the desired probability of successful ADS-B signal reception. It was observed that sUAS broadcasts on 1090 MHz would overwhelm the channel in high-density situations. Assuming a uniform distribution of sUAS by area, the use of ADS-B could support up to about 0.1 sUAS per square km if sUAS transmit at powers of 3 to 5 W. If sUAS are instead distributed by distance like manned aircraft, then about 10 sUAS per km could be supported. However, the higher densities predicted for future urban sUAS operations (which could be on the order of 1 sUAS per square km) would generate too much interference. The capacity for transponder usage on sUAS is even lower, with even 0.1 sUAS per square km (in the area distribution) or 3 sUAS per km (in the distance distribution) seriously degrading signal reception performance for manned aircraft.

Table 4.3: Maximum Allowable Transmitting sUAS Densities for ADS-B

Based on desired success probabilities of 0.9 for manned aircraft signals at 14 NM range and 0.8 for sUAS signals at 3 NM range

Channel	Distribution Type	Max sUAS Density	sUAS Transmission Power
UAT	Area	1/sq km	80 mW
UAT	Distance	40/km	80 mW
1090	Area	0.1/sq km	5 W
1090	Distance	10/km	5 W

The UAT channel (978 MHz) offers more capacity for sUAS since there is no interference from ATCRBS or Mode S replies. While the minimum transmission power currently allowable (7 W) would not allow for a large number of sUAS, lower transmission powers may be feasible. At a density of 1 sUAS per square km, the probability of successfully receiving a manned aircraft's 25 W ADS-B signal at 14 NM range (the surveillance range needed for collision avoidance between two higher-altitude manned aircraft) would be kept above 0.9 if sUAS transmit at 80 mW. This would provide greater than 0.8 probability of successfully receiving the sUAS signals at a range of 3 NM, which should be sufficient for collision avoidance due to the lower speeds and altitudes at which sUAS fly. These probabilities of success could also be achieved if sUAS are uniformly distributed by distance at a density of 40 per km. The minimum recommended transmission power for sUAS on UAT is 26 mW, which is the minimum power that keeps the signal above MTL (-93 dBm) at a range of 3 NM.

While care must be taken not to produce too much interference through broadcasting, a high number of sUAS could still *receive* signals on both the 978 and 1090 MHz channels if they did not broadcast anything in return. This would not provide manned aircraft with position information from these sUAS, but it would allow sUAS to learn the location of nearby manned aircraft traffic.

Multiple options therefore exist for surveillance links between manned aircraft and sUAS. To actually avoid collisions, however, this shared information must be used to perform threat resolution. Chapter 5 evaluates threat resolution between manned aircraft and sUAS.

Chapter 5

Evaluating Threat Resolution with sUAS

Safely resolving close encounters between sUAS and manned aircraft requires threat resolution. As detailed in Section 2.3, threat resolution is the process of taking appropriate action to avoid a potential collision given the location of nearby traffic. Because sUAS have different flight characteristics than manned aircraft (as explored in Chapter 3), sUAS would not be able to utilize current threat resolution systems. This chapter evaluates how threat resolution could be achieved in aircraft encounters involving sUAS.

There are three system architectures that would implement threat resolution between manned aircraft and sUAS. The first option, which will be called Case I, is to have manned aircraft bear the primary responsibility of avoiding sUAS. This means that sUAS would not be required to perform threat resolution, because manned aircraft would adjust their flight paths as necessary. This could be an option since Chapter 4 showed that it may be feasible for a limited population of sUAS to broadcast position information to manned aircraft. Having manned aircraft perform the necessary escape maneuvers would also alleviate any concerns about the limited climb capabilities of sUAS observed in Chapter 3. Case II refers to the opposite option, where sUAS shoulder the primary responsibility of giving way to manned aircraft in order to prevent collisions. This option would not require sUAS to broadcast position information, which would allow a greater density of sUAS to fly without encountering many of the signal interference problems discussed in Section 4.2. Finally, manned aircraft and sUAS could both equip CA systems and avoid each other. This is labeled as Case III. Table 5.1 summarizes the three threat resolution options.

Table 5.1: Threat Resolution Architectures for Manned Aircraft and sUAS

Name	System Architecture
Case I	Manned aircraft avoid sUAS
Case II	sUAS avoid manned aircraft
Case III	Manned aircraft and sUAS avoid each other

It is not necessary to choose one of these three options and apply it everywhere. In fact, there are significant trade-offs that must be considered when implementing any of these options in a particular section of airspace. For example, Case III would clearly offer the highest level of safety, because both manned aircraft and sUAS would be taking action to avoid each other. However, as explained in Section 4.2, it would be unwise to have a large population of sUAS all broadcasting their position information. Small UAS that do not broadcast their position information would not be visible to manned aircraft (except by visual acquisition), meaning Case II would likely be the only option available. On the other hand, as detailed in Chapter 3, some sUAS fly at extremely slow speeds and are not capable of high rates of climb. This would make it difficult for these sUAS to avoid more capable manned aircraft, meaning Case II would not be a wise option. Therefore, it might be necessary to implement different CA protections in different sections of airspace, or to prohibit sUAS that do not meet certain requirements from flying in some areas. This is already done among manned aircraft, with specific equipment such as transponders being required in certain sections of airspace.

Furthermore, each architecture listed in Table 5.1 is an abstraction representing a multitude of different CA options. Case I, for example, could entail the manned aircraft using a CA system like TCAS, or it could have the pilots of manned aircraft simply use their eyes to visually see and avoid sUAS. Section 5.2 reviews the three cases from Table 5.1 in more depth to predict the relative safety and feasibility of each architecture.

To evaluate CA systems, it is first necessary to model the interactions of the aircraft that will be required to avoid each other. As explained in Section 2.3, simulated encounters between aircraft were used throughout the entire development and evaluation of TCAS and are currently being used to design and test ACAS X. In order to model potential encounters between manned aircraft and sUAS, data on real manned aircraft trajectories were obtained. Simulated sUAS trajectories were also created based on desired uses. The manned aircraft and sUAS trajectories were then broken up into 120-second snippets and paired with each other in a Monte Carlo simulation to create realistic encounters between the two types of aircraft. The trajectories were paired such that the two aircraft would be in close proximity 80 seconds after the beginning of the encounter. This would allow potential CA systems to be evaluated on a wide variety of modeled encounters between manned aircraft and sUAS.

Section 5.1 provides a more thorough explanation of the process used to generate simulated encounters between manned aircraft and sUAS. In total, one million encounters were created in the Monte Carlo simulation. Section 5.2 then shares the results that were obtained when evaluating the different CA options listed in Table 5.1 on this set of one million encounters.

5.1 Encounter Generation

CA systems have historically been evaluated on their ability to prevent a Near Mid-Air Collision (NMAC), which is generally defined as two aircraft simultaneously coming within 100 feet vertically and 500 feet laterally. The most common safety metric for CA systems is the risk ratio, given in Equation 2.2 and repeated below as Equation 5.1. The risk ratio is useful in determining the proportion of encounters between aircraft that CA systems are able to resolve satisfactorily. A lower risk ratio denotes a safer CA system.

$$\text{Risk Ratio} = \frac{\text{P(NMAC)}_{\text{mitigated}}}{\text{P(NMAC)}_{\text{unmitigated}}} \tag{5.1}$$

Because TCAS was not designed until the 1980s, airborne collision avoidance systems for manned aircraft have always had decades of flight data to work with. These data have been used to create numerous realistic encounters between manned aircraft, and CA systems have then been assessed based on their ability to resolve these encounters. Unfortunately, because sUAS are not currently operating in most of the desired capacities, there are limited flight data available to similarly model sUAS flight behavior. Due to this limitation, sUAS flight behavior was instead simulated based on predicted uses. These simulated tracks were paired with real manned aircraft trajectories to model notional encounters between manned aircraft and sUAS. A Monte Carlo simulation was used to ensure that encounter parameters (such as convergence angle and rate) were modeled across a wide range of realistic values. The encounter generation process is described in more detail below.

First, actual recorded manned aircraft trajectories were obtained. All data were collected from the MODSEF radar at MIT Lincoln Laboratory, which is about 13 Nautical Miles (NM) northwest of Boston Logan International Airport (BOS). These data were filtered to create aircraft trajectories for manned aircraft that were observed flying within the Mode C Veil for BOS. The altitude distribution of observed trajectories is provided in Figure 5-1. As explained in Section 2.2, the Mode C Veil is a 30 NM radius around Class B airports where a Mode C transponder is required for flight below 10,000 feet. ADS-B out will also be required in this airspace beginning in 2020. The Mode C Veil was used to characterize manned aircraft behavior because it is one of the most likely places where sUAS will fly Beyond Visual Line of Sight (BVLOS) and in close proximity to manned aircraft. The RTCA designated Mode C Veils as a focus area for sUAS and recommended the FAA allow BVLOS operations for sUAS within Mode C Veils due to the requirement that all manned aircraft share their position, and also the large proportion of the U.S. population that could be served by sUAS operations (56% of Americans live within a Mode C Veil) [46]. Mode

C Veils are also busy areas for manned aircraft due to the nearby Class B airport and metropolitan area. The high levels of traffic predicted for all types of aircraft in Mode C Veils means that the risk of close encounters between manned aircraft and sUAS will be higher than in less busy sections of airspace.

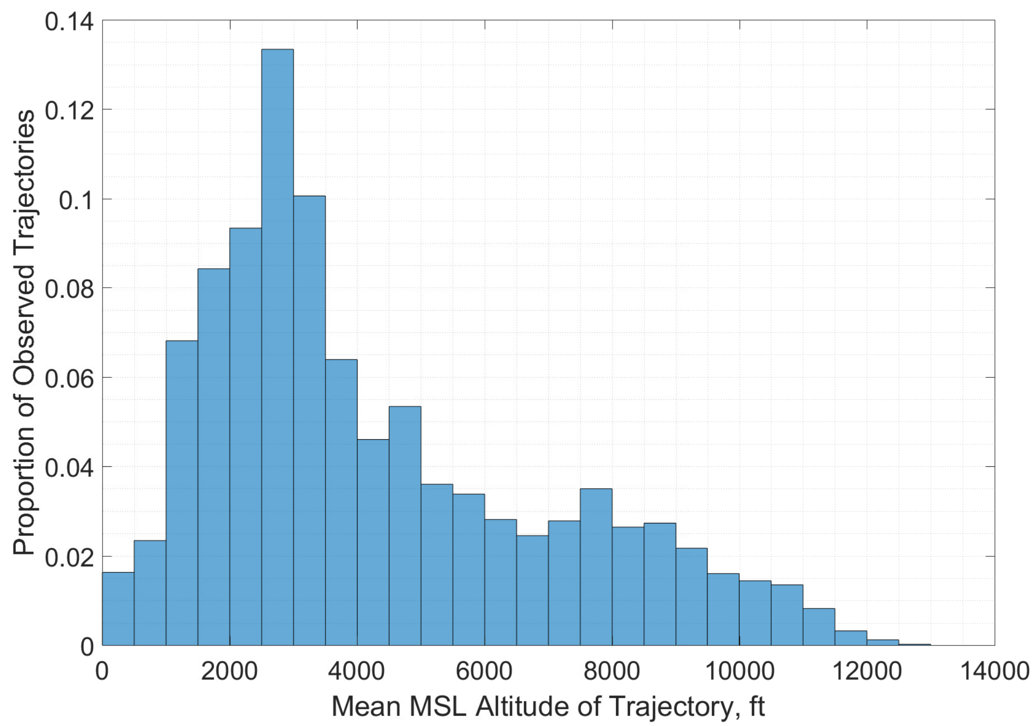


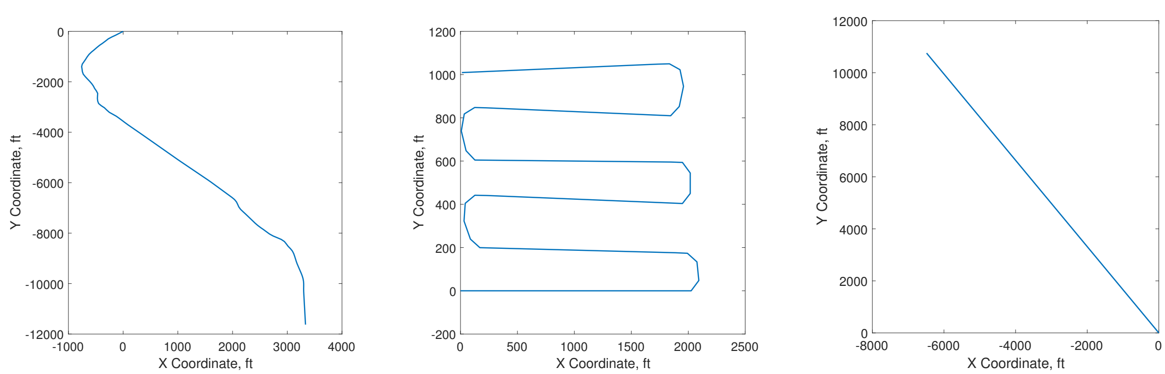
Figure 5-1: Altitude Distribution of Manned Aircraft Trajectories

It was desired that simulated encounters between sUAS and manned aircraft be 120 seconds long, with the Closest Point of Approach (CPA) occurring around 80 seconds into the encounter. This would allow any simulated CA system to establish a surveillance track before evasive action is needed, and would also provide sufficient time following the unmitigated CPA to ensure that a simulated CA system does not cause an unsafe situation to occur later in the encounter. The manned aircraft data were therefore used to create 120-second snippets of manned aircraft flights within the BOS Mode C Veil. In total, 88,468 of these 120-second trajectories were created. Because the relative geometries of the encounters and not their absolute location were of interest, the lateral geospatial coordinates of the trajectories were converted to relative Cartesian distances to allow for easy pairing with the sUAS trajectories.

Because sUAS are not yet in regular operation over U.S. cities and real recorded trajectories do not yet exist, simulated trajectories were desired. Simulated ground tracks were implemented by collaborating with Weinert and Underhill, who modeled sUAS behavior based on desired uses and geospatial data [47]. In particular, three types of missions were modeled in the greater Boston area. Infrastructure inspection was modeled by simulating flight over railroads; land surveying and photography were modeled by simulating lawnmower patterns flown over recreational areas; and point-to-point package delivery was modeled by flights between hospitals, which are likely to be among the first users of package delivery using sUAS. Examples of these three types of trajectories are shown in Figure 5-2. In total, there were 386 infrastructure ground tracks, 6,229 surveying tracks, and 257,699 point-to-point delivery tracks. Like the manned aircraft trajectories, these tracks used relative Cartesian coordinates to describe the aircraft's lateral position.

These ground tracks simulate desired sUAS missions, but they do not specify the speed that sUAS will fly along them. To statistically model the speeds that sUAS would fly along these tracks, the UAS study detailed in Chapter 3 was used to construct a Cumulative Density Function (CDF) of the cruise speeds among reviewed sUAS. This CDF is displayed in Figure 5-3, and was used to set the speed of sUAS in simulated encounters with manned aircraft.

The real manned aircraft trajectories and simulated sUAS trajectories detailed above were used to create a Monte Carlo simulation of encounters between manned



(a) Aerial Inspection (b) Land Surveying (c) Package Delivery

Figure 5-2: Examples of Simulated sUAS Trajectories

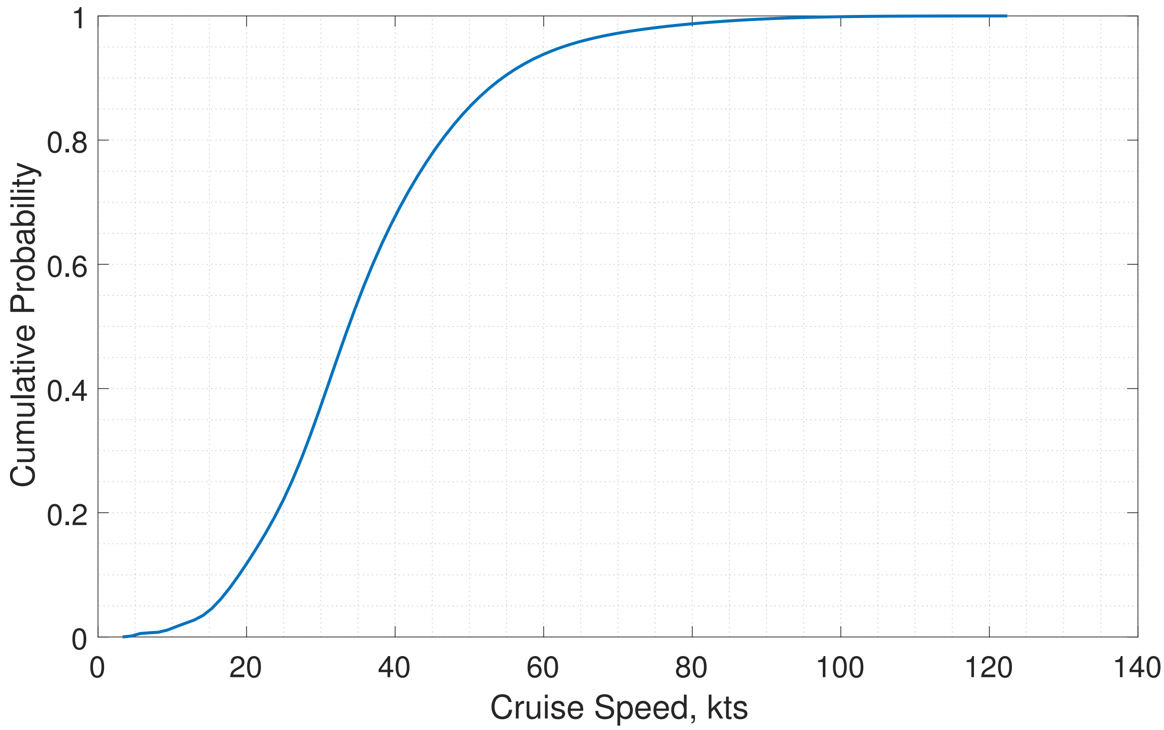


Figure 5-3: CDF of Cruise Speeds for Reviewed sUAS

aircraft and sUAS. For each encounter, one manned trajectory and one sUAS trajectory were first selected for pairing. Each of the manned aircraft trajectories had equal probability of being selected. Due to the large imbalance in numbers of each type of sUAS trajectory, the type of sUAS track was first selected with equal probability among the three modeled types (inspection, surveying, delivery), and the ground track was then selected among the available options with equal probability. This was done to ensure that all three types of sUAS tracks would be represented regularly in the Monte Carlo simulation. After the ground track was selected, the sUAS speed was set by sampling from the CDF shown in Figure 5-3. The sampled speed and ground track were used to create a simulated 120-second trajectory in Cartesian coordinates.

The two separate trajectories were then paired to create an encounter between a manned aircraft and sUAS. The sUAS trajectory was set up to begin at the origin of the Cartesian coordinate system, and the manned aircraft trajectory was translated so that the two trajectories simultaneously passed through the same spatial point 80 seconds into the encounter. To add variation to the convergence angle between the two aircraft, the manned trajectory was rotated about the point of collision by an angle uniformly sampled from 0 to 2π.

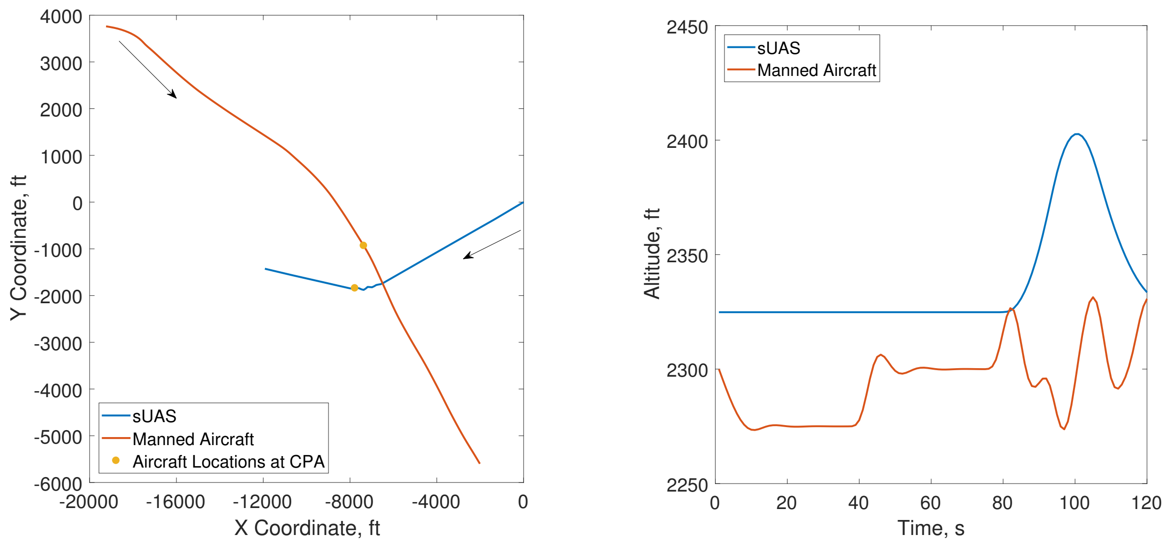
Next, randomly-sampled miss distances were applied so that the two aircraft would pass close to each other but would not pass through the exact same point. It was desired that most encounters have a relatively small Vertical Miss Distance (VMD) at CPA. A more spread-out distribution of Horizontal Miss Distance (HMD) was desired, because horizontal CA maneuvers can cause an NMAC to occur even if the original miss distance would have been as high as 5,000 feet.[1] Also, it was desired that the unmitigated probability of NMAC among the generated encounters would be on the order of 10%. To achieve these goals, the VMD applied for each encounter was sampled from a zero-mean Gaussian distribution with a standard deviation of 100 feet, and the HMD was sampled from a uniform distribution from -5000 to 5000 feet. The VMD was applied such that a positive distance placed the sUAS above the manned aircraft. The HMD was applied tangential to the manned aircraft's flight path at the 80-second point, with positive distances moving the aircraft to its right and negative distances moving it to its left. Based on these two distributions, 6.8% of encounters should result in an NMAC at the 80-second mark. Due to variations in trajectories that cause the time of CPA to not always occur at the exact 80-second point, an NMAC occurred in about 8% of generated trajectories.

Encounters in the Monte Carlo simulation were generated as described above, but some generated samples were rejected to ensure that trajectories did not initiate with the aircraft too close to each other. If a generated encounter had the two aircraft begin their trajectories within 1.5 NM slant range of each other, or if the time of CPA was more than 5 seconds away from the 80-second point, then the encounter was rejected.

In short, each encounter was generated by first randomly selecting one actual manned aircraft trajectory and one simulated sUAS trajectory. The manned trajectory was translated to set up a collision at 80 seconds and rotated by a random angle. Miss distances were then randomly sampled to provide some separation between the

[1] This had been observed based on tests of the horizontal logic for ACAS Xu.

aircraft at the 80-second point. If the two aircraft started the encounter within 1.5 NM of each other, or the CPA did not occur 75 to 85 seconds after the encounter began, the encounter was rejected and a new one was generated. Figure 5-4 displays an example generated encounter.



(a) Ground Track

(b) Altitude

Figure 5-4: Example Generated Encounter between a Manned Aircraft and sUAS

This process was used to create a Monte Carlo simulation by generating one million unique encounters. Table 5.2 reviews the values that were sampled in each Monte Carlo trial, as well as the parameters that were set beforehand and remained unchanged. The large number of generated encounters ensures that a wide range of convergence rates, convergence angles, maneuvers during the encounter, and other factors that could affect CA systems was represented. This set of one million encounters was used to evaluate the threat resolution architecture options listed in Table 5.1. Section 5.2 provides the results of this evaluation.

5.2 Collision Avoidance Architecture Analysis

As discussed above and summarized in Table 5.1, there are fundamentally three options for collision avoidance between manned aircraft and sUAS: the manned aircraft could avoid the sUAS, the sUAS could avoid the manned aircraft, or they could both

Table 5.2: Summary of Monte Carlo Parameters

Set (Unchanging) Parameters	Sampled Parameters
Encounter length: 120s	Manned aircraft trajectory
Time of CPA: $t = 80s$	sUAS trajectory
sUAS Speed distribution: CDF (Fig. 5-3)	sUAS speed
VMD distribution: Gaussian(0, 100)ft	VMD at $t = 80s$
HMD distribution: Uniform(-5000, 5000)ft	HMD at $t = 80s$
Unmitigated P(NMAC): $\approx 10\%$	Trajectory rotation angle

avoid each other. Sections 5.2.1 through 5.2.3 detail how each of these three cases were evaluated, with a particular focus on the safety and alerting rates of each option. While the cases were assessed based on their ability to minimize the probability of NMAC, Section 5.2.4 provides a brief discussion of how this probability relates to the probability of an actual Mid-Air Collision (MAC). All evaluations of threat resolution logic were performed on the encounter set generated as explained in Section 5.1.

5.2.1 Case I: Manned Aircraft Avoid sUAS

Section 2.3 summarizes how manned aircraft currently perform threat resolution. At a minimum, the pilots aboard all manned aircraft are required to see and avoid other aircraft using visual acquisition. This is the only protection against collision for many GA aircraft. Some larger aircraft are equipped with systems that provide Traffic Alerts (TAs) to notify pilots of nearby traffic, but the pilots must still take appropriate action to avoid collision. Finally, all large commercial air carriers and some other aircraft are equipped with TCAS II, which provides Resolution Advisories (RAs) that actually command the maneuvers to be taken to avoid collision.

Systems that issue RAs are the easiest to simulate, because the recommended maneuvers provided at a given flight condition can be determined from the CA system's threat resolution logic and then implemented to alter the manned aircraft's flight trajectory (this assumes that the pilot properly complies to the RAs issued). Three different CA systems were evaluated using the encounter set from Section 5.1. The first was TCAS II. The ICAO SARPS require that TCAS II achieve a risk ratio no greater than 0.18 in encounters with aircraft that are sharing their position but are not equipped with TCAS II [28]. The second CA system assessed was ACAS Xa. Since both TCAS II and ACAS Xa provide RAs that require a 1,500 to 2,500 fpm climb or descent rate, a modified policy was desired that used lower vertical rates. This policy could evaluate the safety of less capable GA aircraft avoiding sUAS using a potential future CA system. Based on the vertical logic for ACAS Xu Run 4, a notional GA policy was implemented that provided RAs commanding climb or descents at 1,000 fpm.

These three threat resolution policies were evaluated on the encounter set, with the manned aircraft simulated as following any RAs issued. The manned aircraft responded to any initial RA after a five second delay and with $0.25g$ acceleration, and any subsequent RAs after a three second delay and with $0.35g$ acceleration. Since Chapter 4 concluded that sUAS could potentially broadcast their position information using ADS-B, it was assumed that the manned aircraft received surveillance information for the sUAS with the minimum accuracy required for ADS-B (see Section 2.2.2 for a brief review of some of these requirements).

Figure 5-5 displays the risk ratio results for the three threat resolution systems evaluated. For reference, the TCAS II requirement of 0.18 is shown as a dashed black line. Clearly, all three policies are able to achieve far higher levels of safety than is required for TCAS II. This makes sense based on the analysis from Chapter 3 because sUAS are much slower than manned aircraft, leading to less dynamic uncertainty in their trajectories. In other words, even if the sUAS performed unexpected maneuvers after an RA was issued, the RA would likely still provide sufficient separation to avoid an NMAC. As shown by the GA policy, even a vertical rate of 1,000 fpm allows a low risk ratio.

A serious downside to issuing RAs against sUAS is that it could cause an excessive number of alerts. The RTCA notes that excessive alerting is already an issue among manned aircraft alone, which leads to pilot noncompliance with RAs [29]. The use of CA systems that issue RAs against sUAS could cause alerting to become even more excessive. Figure 5-6 displays the proportion of encounters that caused each

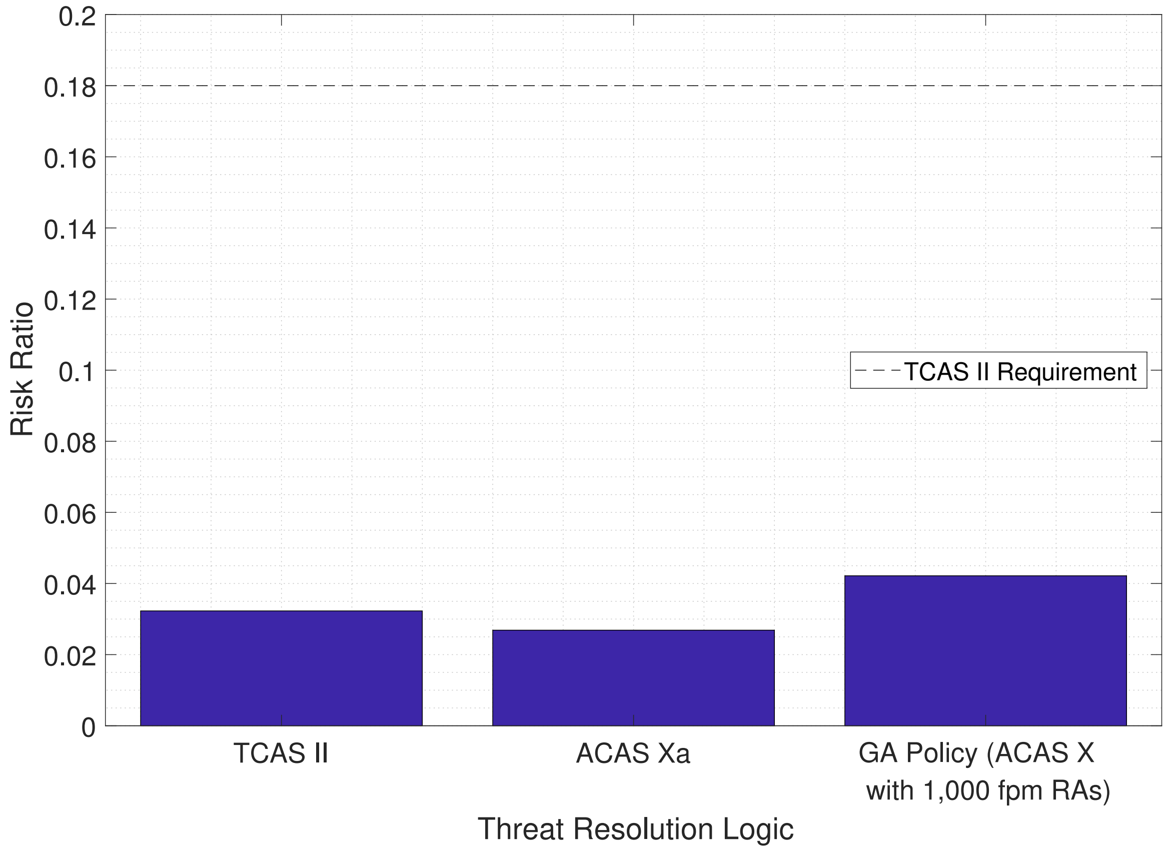


Figure 5-5: Risk Ratios for Manned Aircraft Avoiding sUAS with RA-issuing Systems

threat resolution system to generate at least one RA. While TCAS II issued the most RAs, all three systems generated an RA in over 64% of the simulated encounters. When determining whether to equip manned aircraft with CA systems that generate RAs against sUAS, it will be important to consider that many additional RAs can be expected for aircraft that fly in close proximity to sUAS. This is particularly a problem for manned aircraft because human pilots might deem a noisy system to be a nuisance and begin to ignore the guidance issued.

Most manned aircraft, however, are not equipped with CA systems that provide RAs. Some aircraft have systems that provide TAs only, and many aircraft rely purely on visual see-and-avoid. These include many of the GA aircraft that fly at lower altitudes where most sUAS will be flying. Since these types of systems will be common among manned aircraft encountering sUAS, a visual acquisition model was implemented and evaluated on the encounter set.

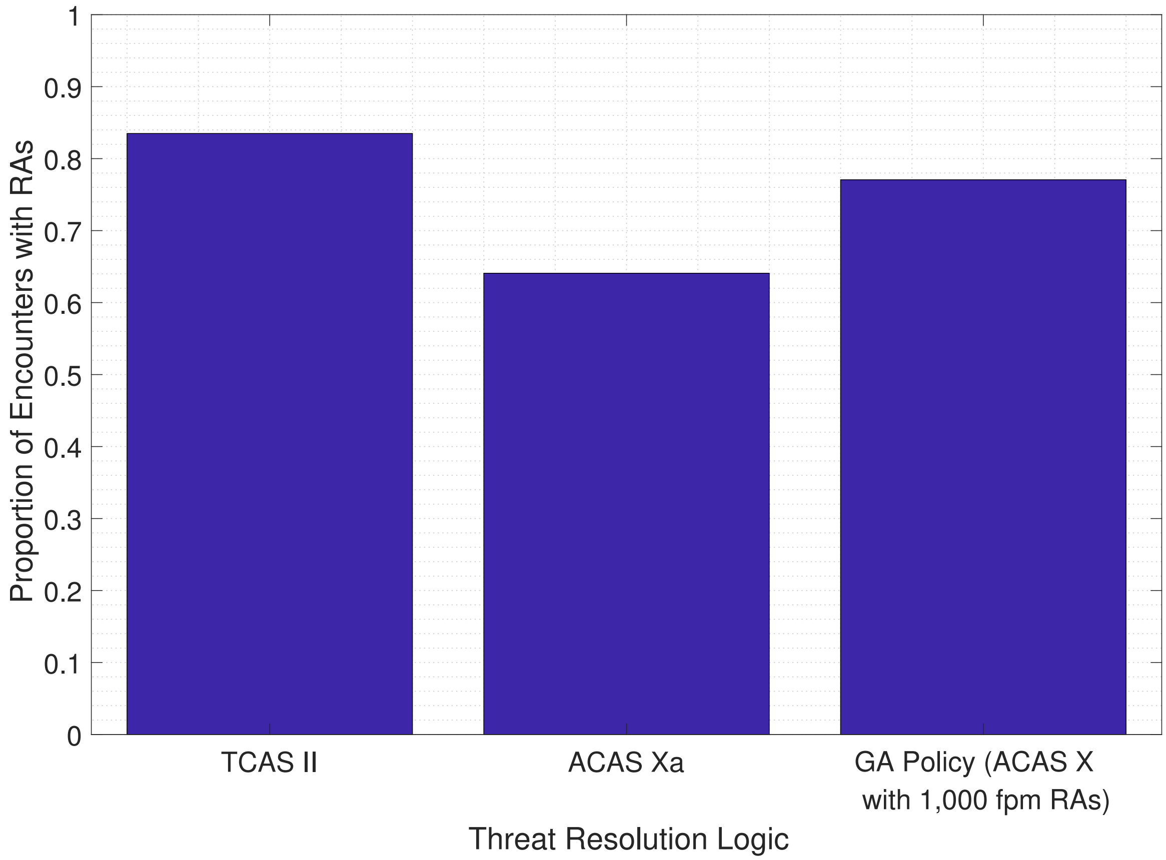


Figure 5-6: RA Rates for Manned Aircraft Avoiding sUAS with RA-issuing Systems

Based on experimental flight tests, Andrews at MIT Lincoln Laboratory developed a mathematical model to predict when manned aircraft pilots are able to visually acquire nearby aircraft [48, 49]. Andrews reported that a pilot's instantaneous probability of visually acquiring a nearby aircraft during a visual scan was directly proportional to the angular size of the target. This can be given by $\frac{A}{r^2}$, where A is the surface area of the target presented to the pilot, and r is the range to the target. For some reference A values, Andrews analyzed the mid-air collision over Cerritos and found that the commercial aircraft (a DC-9) presented 588 square feet of surface area to the GA pilot, while the GA aircraft (a Piper Archer) presented 72 square feet of surface area to the pilots of the DC-9.

Equation 5.2 provides the calculation for $\lambda(t)$, the instantaneous probability of a pilot visually detecting another aircraft. The exponential term corrects $\lambda(t)$ when the visibility R is less than infinity (note that as R goes to infinity, the entire exponential term goes to one and ceases to affect the equation). The minimum visibility required for VFR flight is 3 statute miles in much of U.S. airspace below 10,000 feet MSL.[2] The constant β is a constant of proportionality that was determined during flight test. Andrews found that β was equal to 17,000 normally, but increased to 140,000 when a traffic alert was issued to the pilot about the nearby traffic.

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{P(\text{acq in } \Delta t)}{\Delta t} = \beta \frac{A}{r^2} \exp\left(-2.996 \frac{r}{R}\right) \tag{5.2}$$

To find the overall probability of a pilot visually acquiring a nearby target during an encounter, $\lambda(t)$ can be integrated over the time that the pilot is looking outside the aircraft (t_1 to t_2). Equation 5.3 shows this calculation. Andrews assumed that a pilot who had not visually acquired another aircraft prior to 12 seconds before a collision would not be able to take appropriate evasive action. This concurs with more recent research from the FAA, which reports that a pilot must visually acquire an aircraft 12.5 seconds before collision in order to perform an appropriate escape maneuver [50].

$$P(\text{acq by } t_2) = 1 - \exp\left(-\int_{t_1}^{t_2} \lambda(t) dt\right) \tag{5.3}$$

Equations 5.2 and 5.3 were used to calculate the probability that a manned aircraft would be able to visually acquire the sUAS in the simulated encounters. The visual surface area of the sUAS was assumed to be 10 square feet. Risk ratios were calculated based on the mean probability of the manned aircraft visually acquiring the sUAS 12 seconds before CPA in encounters that would have otherwise resulted in an NMAC. This assumes that pilots relying on visual acquisition would not cause any encounters to become NMACs that were originally not NMACs.

Figure 5-7 plots the results for visual see-and-avoid in the simulated encounters. Curves are provided for both unaided pilots and pilots receiving TAs (based on TCAS logic). While TAs clearly provide a safety benefit, it is apparent that all manned aircraft would struggle to visually acquire sUAS, especially when flying in minimum

[2] Specifically, the minimum visibility required for VFR flight is 3 statute miles in Class B, C, and D airspace, Class E airspace below 10,000 feet, and Class G airspace at night below 10,000 feet.

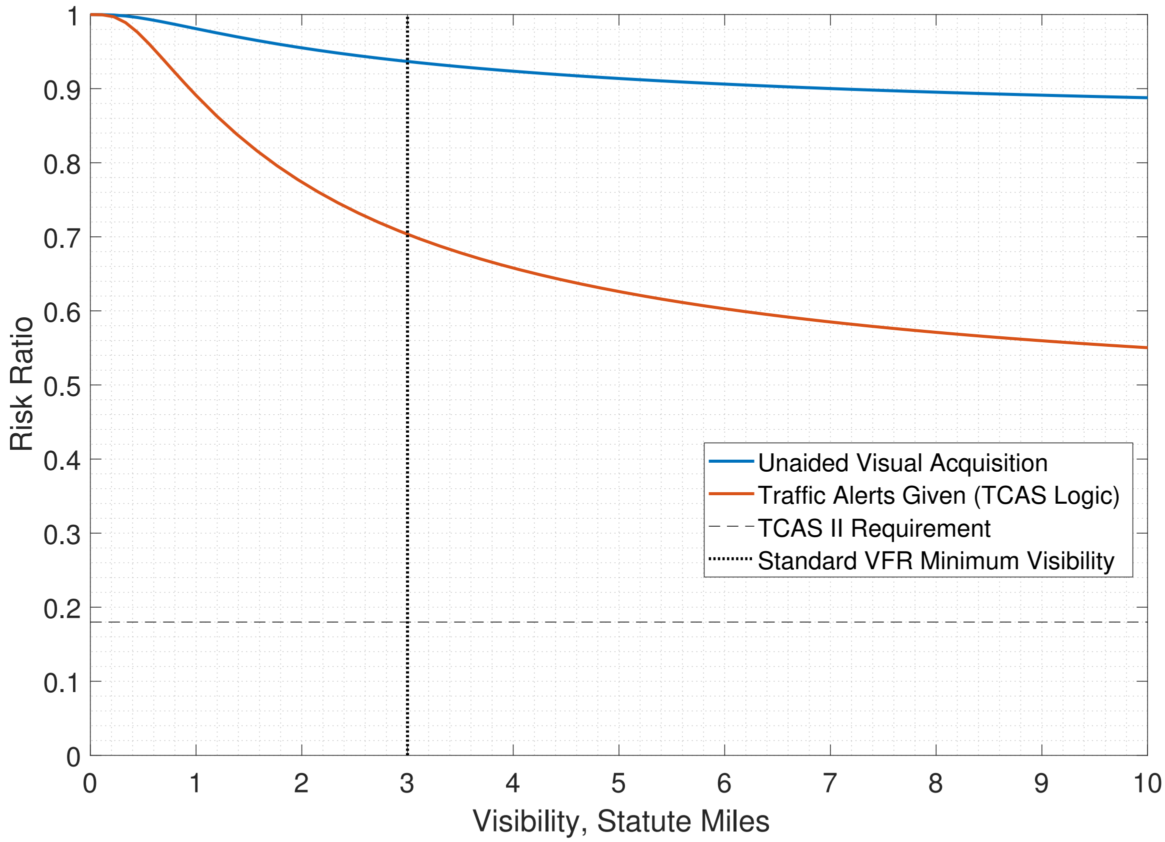


Figure 5-7: Risk Ratios for Manned Aircraft using Visual See-and-Avoid

VFR conditions. At a visility of three statute miles, visual see-and-avoid is able to resolve just 6% of NMACs without TAs and 30% of NMACs even with TAs. In Class G airspace during the day, which is where many sUAS may fly because it is close to the ground, the minimum visibility for VFR is actually just one statute mile; at this visibility, very few encounters would be resolved by visual see-and-avoid. The risk ratios for infinite visibility are still fairly high: 0.85 for unaided visual acquisition and 0.45 with TAs. Furthermore, the visual area for many sUAS may be even smaller than the 10 square feet assumed; as one example, the ScanEagle, which has a wingspan of 10.2 feet, would present 2 to 3 square feet of visual area in a head-on encounter. Considering that most aircraft other than large commercial air carriers do not currently carry CA systems that issue RAs, and that many aircraft do not even have CA systems that issue TAs, it would be unwise to rely on manned aircraft to visually see and avoid sUAS.

Therefore, while the evaluation of Case I showed that CA systems with RAs could achieve low risk ratios in encounters with sUAS, there were some concerns observed with the concept of manned aircraft avoiding sUAS. CA systems with RAs, while safe, could generate a high number of alerts. This, in turn, could lead to pilot noncompliance with RAs, which would decrease safety. Furthermore, manned aircraft relying on visual see-and-avoid would not be able to resolve many encounters with sUAS. With both the strengths and limitations of Case I in mind, Case II was next evaluated.

5.2.2 Case II: sUAS Avoid Manned Aircraft

Instead of placing the burden of collision avoidance on manned aircraft, sUAS could be expected to perform all necessary evasive maneuvers. This would best reflect current Part 107 rules that require sUAS to always yield right-of-way to manned aircraft. The advantage of this approach is that it would allow sUAS operations without disrupting current operations among manned aircraft. However, there are concerns that sUAS would not be able to avoid manned aircraft. As detailed in Chapter 3, sUAS are slower and cannot climb or descend as fast as most manned aircraft, which makes it harder to perform CA. This section explores the equipage of modified CA systems on sUAS.

Because few sUAS can achieve climb rates of 1,500 fpm, there are no operational CA systems that they could equip. Prototypes exist of ACAS Xu, but it is being designed for larger unmanned aircraft and the vertical rates used are 1,000 fpm, which is still greater than many sUAS can achieve. It was apparent that custom threat resolution logic would need to be designed to evaluate how sUAS might avoid manned aircraft.

Section 2.3.2 reviews the methodology underlying ACAS X. This methodology was used to create optimal policies for sUAS with lower vertical rates. The cost and dynamic models for ACAS Xu Run 4 were used to generate 13 optimal policies. The first policy used vertical maneuvers of 300 fpm, the next policy used vertical maneuvers of 400 fpm, and so on through 1,500 fpm. Each optimal policy was generated by using dynamic programming to perform value iteration and generate a final lookup table that provided the optimal action at every flight condition. Each lookup table requires about 57 MB of disk space and could be used by sUAS in-flight to determine when evasive action is necessary to avoid a collision.

Because sUAS are capable of fast turn rates (as was discussed in Chapter 3), horizontal CA maneuvers were also desired. The ACAS Xu program has explored horizontal logic that uses turns of 3 degrees per second to perform CA. However, sUAS can turn much faster than 3 degrees per second (see Figure 3-7), so policies with higher turn rates were desired. Based on the ACAS Xu Run 4 horizontal logic, dynamic programming was again used to create optimal policies, this time for horizontal policies that used turn rates of 3, 6, 9, 12, and 15 degrees per second. The state space discretization was adjusted to eliminate higher speeds and provide finer resolution at the lower speeds that sUAS will fly. Unfortunately, the higher turn rates caused the angular resolution used in the state space discretization to be too poor to properly represent evolving encounter geometries. As a result, non-optimal behavior was observed and the policies were not fit for flight. While the use of higher turn rates is an ongoing area of research for ACAS sXu, the policies using rates of 3 and 6 degrees per second still exhibited optimal behavior. These policies were used to evaluate the effect of sUAS using turns to perform CA. Due to the greater number of state variables needed for the horizontal logic, the lookup tables require about 8 GB of disk space. It is desired that future lookup tables can be reduced in size for easier implementation on sUAS, but for the purposes of this study, these tables allowed horizontal policies for sUAS to be evaluated.

The policies discussed above were implemented on sUAS and simulated on the encounter set detailed in Section 5.1. In addition to the separate vertical and horizontal logic, a "blended" logic was tested by implementing the vertical and horizontal policies simultaneously. Since a high degree of autonomy is desired for future operations, it was assumed that no pilot was in direct control of the sUAS, and the sUAS responded to all RAs automatically in simulation.

Figure 5-8 displays the simulation results. To surpass TCAS II requirements

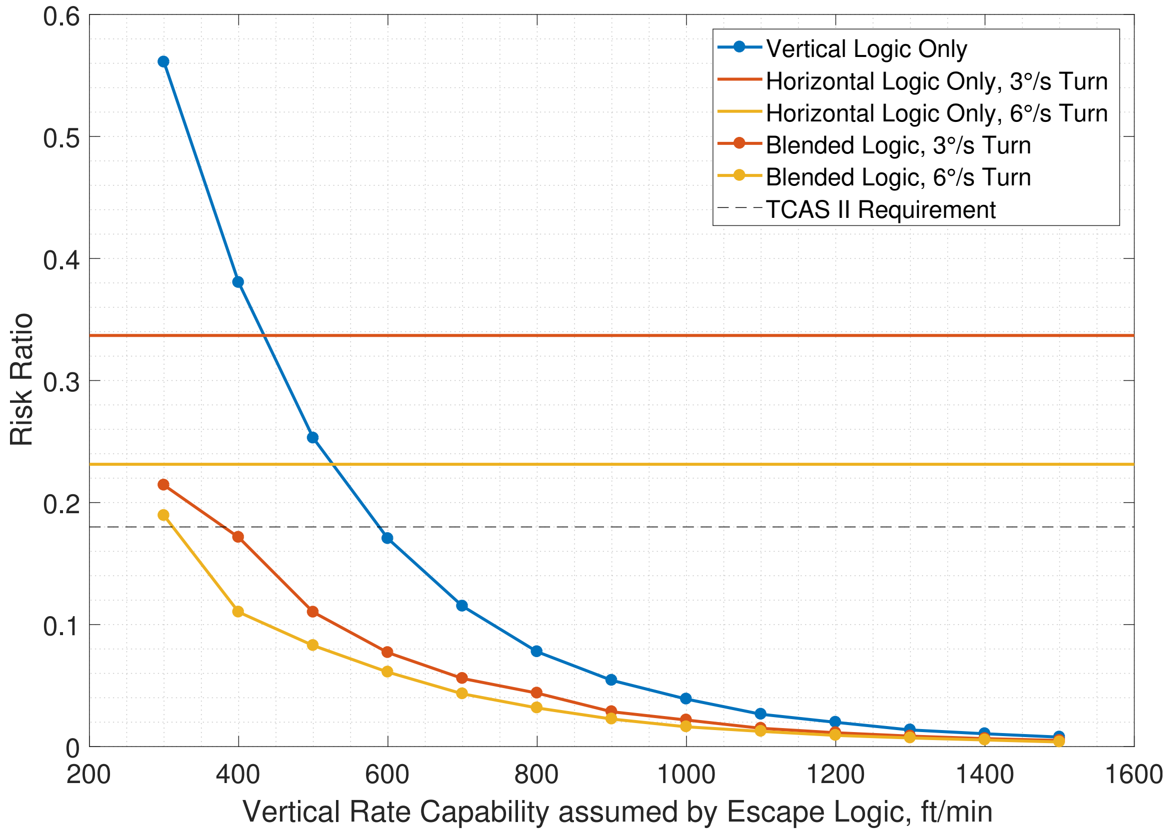


Figure 5-8: Risk Ratios for sUAS Avoiding Manned Aircraft

using vertical maneuvers alone, a vertical rate capability of 600 fpm is needed. If it is assumed that the vertical rate used by a CA system should not be higher than 50% of the maximum rate possible for the platform, then 13% of the reviewed sUAS could reach this capability (see Figure 3-6). This includes 22% of the fixed-wing sUAS and none of the rotor-wing sUAS. With the blended logic, however, the vertical rate needed to surpass TCAS falls to 400 fpm. This allows 56% of the reviewed fixed-wing sUAS and 31% of the total sUAS (but still no rotor sUAS) to beat the 0.18 benchmark, if it is again assumed that the vertical policy rate should be no greater than half of the maximum possible rate for the individual UAS.

Figure 5-9 shows the RA rates experienced by the sUAS. Only one line is plotted for horizontal logic because both turn rates assessed (3 and 6 degrees per second) resulted in near-identical alerting rates. The vertical logic alone tended to issue fewer RAs as the vertical capability increased, while the RA rate for the blended logic remained fairly constant as the vertical capability changed. The alerting rate for the vertical logic was always lower than the rate for TCAS II on manned aircraft (0.83), but was always higher than the ACAS Xa rate for manned aircraft (0.64). The values were comparable to the GA policy for manned aircraft, which had an alerting rate of 0.77. All policies that incorporated horizontal logic, however, issued RAs in almost every encounter. It appears that the higher safety of utilizing horizontal logic comes with a higher alerting rate. This is a less critical problem for sUAS because there are no on-board pilots who could quickly become annoyed and begin ignoring RAs. Still, excessive alerting rates could make it difficult for sUAS to complete their missions since they would often be diverting to avoid collisions.

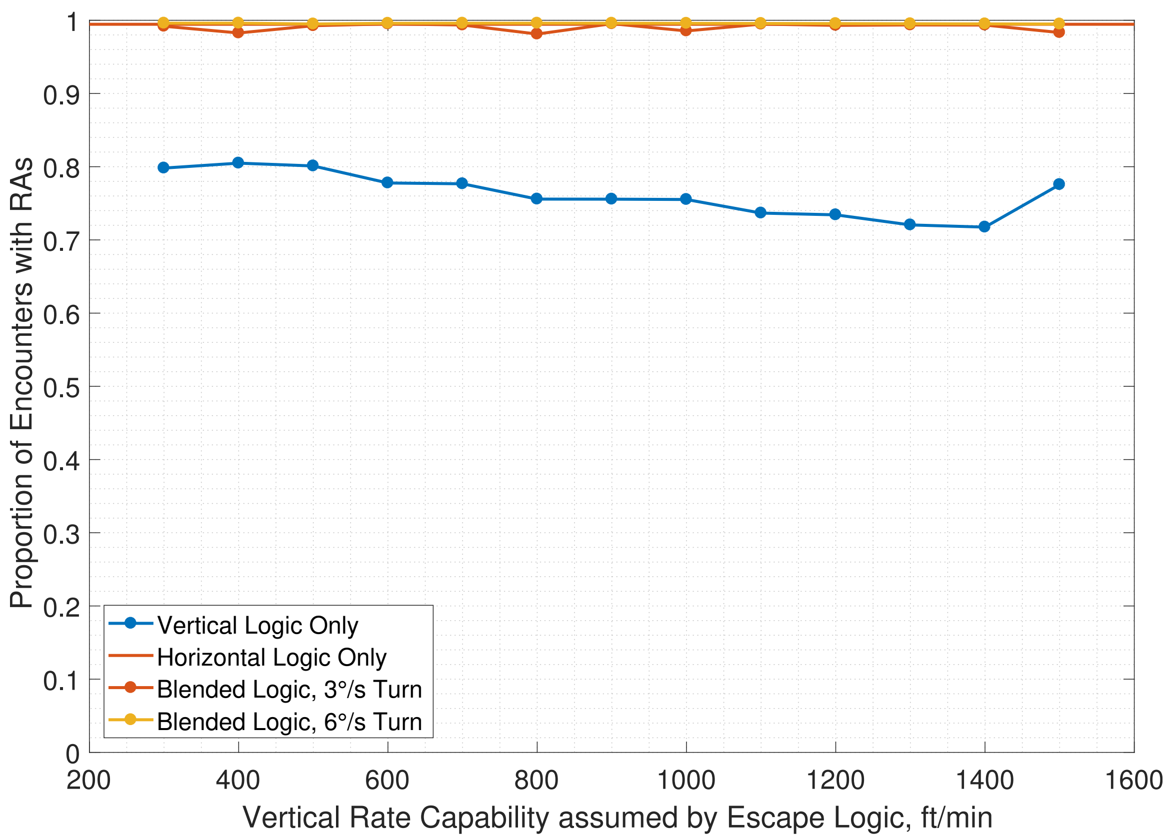


Figure 5-9: RA Rates for sUAS Avoiding Manned Aircraft

Because the CDF shown in Figure 5-3 was used to sample sUAS speeds in the encounter set, many encounters featured sUAS flying at extremely low speeds. This limited the effectiveness of horizontal maneuvers, which do not provide as much separation following a turn when airspeed is low. To assess horizontal maneuvers for sUAS flying at slightly higher speeds, a modified encounter set was generated. All of the same steps detailed in Section 5.1 were followed, except that any sUAS speed sample below 30 knots was rejected. This process provided another one million encounters, now with sUAS traveling faster than 30 knots in all of them. The modified encounter set was used to again simulate the vertical, horizontal, and blended policies. Figure 5-10 plots the risk ratio results for the modified encounter set. The RA rates for these higher speeds were nearly identical to those shown in Figure 5-9, so an additional plot is not included.

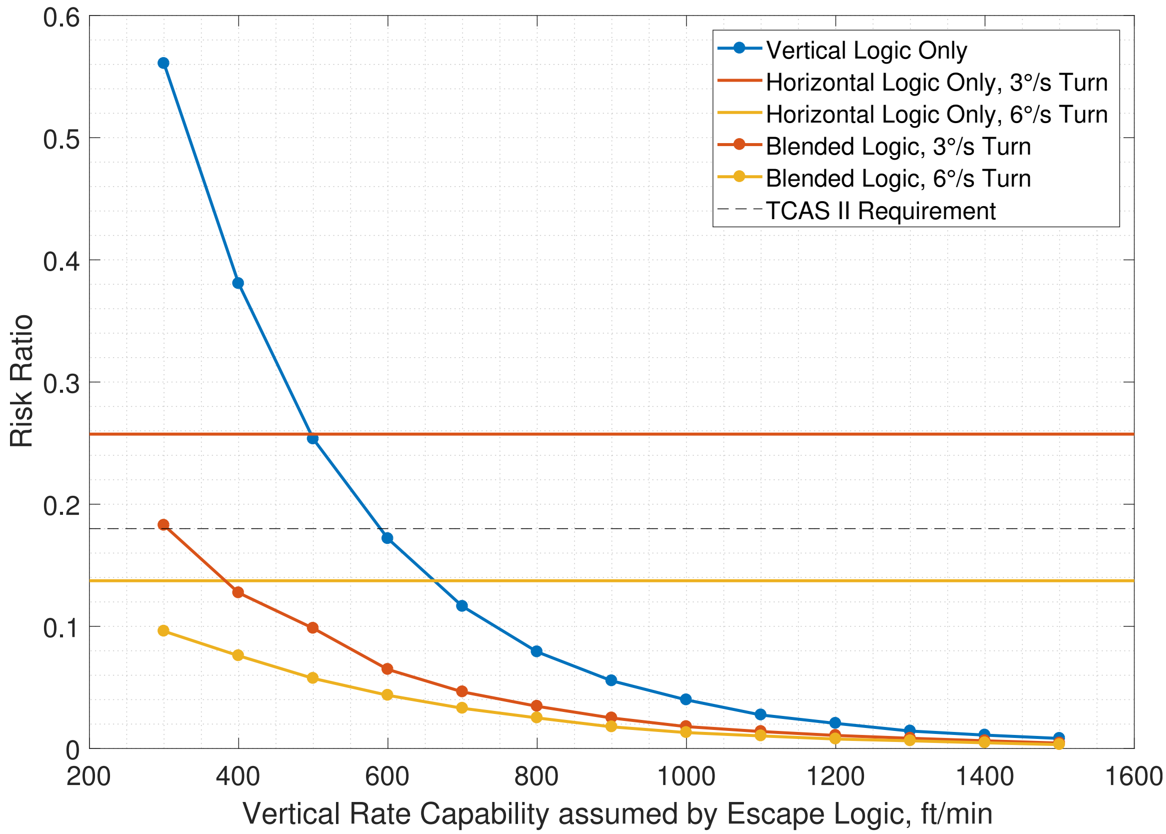


Figure 5-10: Risk Ratios for sUAS with Airspeed Above 30 knots

As shown in Figure 5-10, the greater sUAS speeds led to lower risk ratios for all policies incorporating horizontal maneuvers. All policies using turns of 6 degrees per second, even without vertical maneuvers, avoided manned aircraft more successfully than TCAS II is required to. This is an important result because, as Figure 3-7 demonstrates, a turn rate of 6 degrees per second should be easily achievable for nearly all sUAS. By incorporating horizontal logic and using turns to perform collision avoidance, sUAS flying faster than 30 knots could achieve a high level of safety against manned aircraft regardless of vertical capability. In the study detailed in Chapter 3, 66% of sUAS had cruise speeds above 30 knots, which included 69% of fixed-wing and 33% of rotor-wing sUAS. The prototype package delivery sUAS used by Google affiliate Wing can travel at speeds up to 65 knots.[3]

Small UAS that do not meet the capabilities listed above could be prohibited from flying BVLOS alongside manned aircraft. The many UAS that do meet these capabilities could achieve a satisfactory level of safety in encounters with manned aircraft even if the manned aircraft do not take evasive action. This means that these UAS would not necessarily need to broadcast their own position, which could alleviate many of the concerns detailed in Section 4.2 and allow higher densities of sUAS to operate.

A final threat resolution architecture option is to have the manned aircraft and sUAS both equip CA systems and avoid each other. The evaluation of this option is detailed in Section 5.2.3.

5.2.3 Case III: Manned Aircraft & sUAS Avoid Each Other

In an encounter between a manned aircraft and sUAS, it is possible that both aircraft will be equipped with CA systems. While it is unlikely that this will be required in all airspace, it could be a common occurrence if the Case I and Case II architectures are used in different areas. This section reviews a combination of many of the CA systems implemented in Sections 5.2.1 and 5.2.2 to evaluate dual-equipped encounters.

The encounter set from Section 5.1 was used to simultaneously implement one of the three manned aircraft RA systems detailed in Section 5.2.1 with the vertical and horizontal sUAS logic detailed in Section 5.2.2. The risk ratio results are plotted in Figure 5-11. When the vertical logic was used for sUAS, the manned aircraft and sUAS coordinated vertical maneuvers. All of the combinations evaluated resulted in risk ratios far below the maximum allowed in the ICAO SARPS for dual-equipped TCAS II encounters, which is a risk ratio of 0.04 [28]. Blended policies and higher-rate vertical policies were not evaluated for sUAS since they would only further reduce the

[3] See the discussion of design here: `https://x.company/projects/wing/`

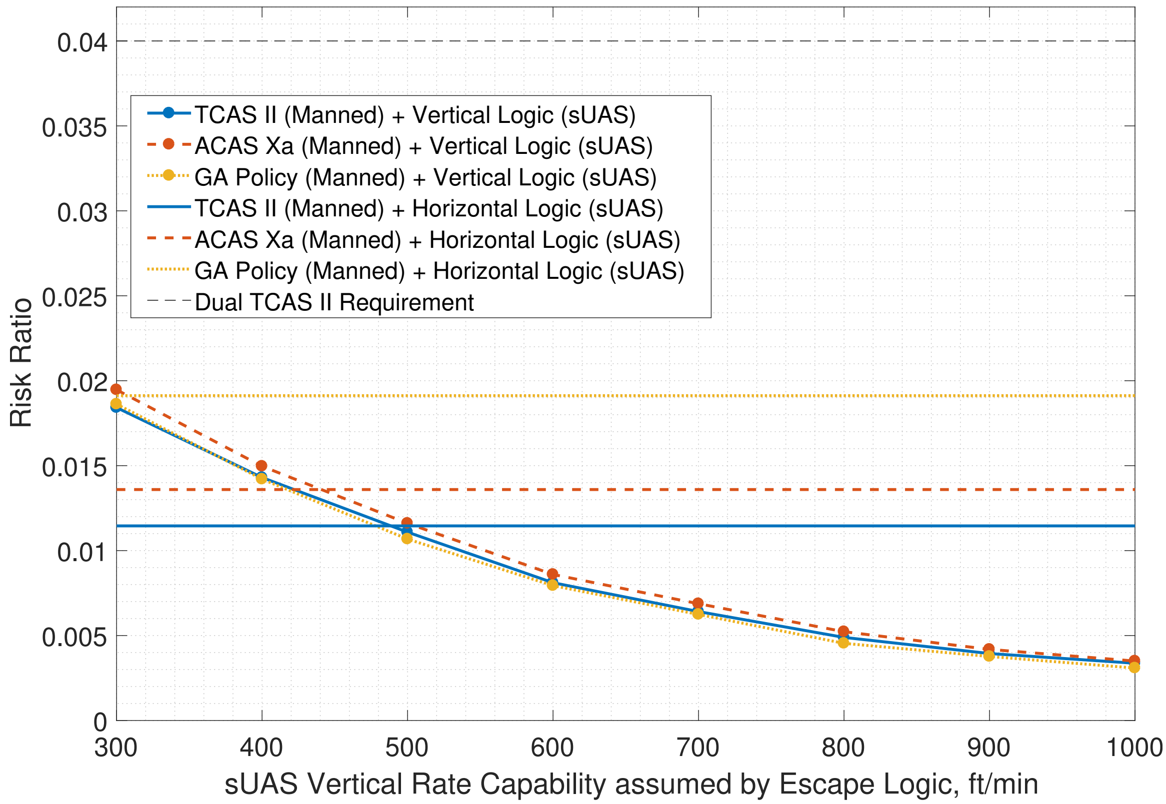


Figure 5-11: Risk Ratios for Cooperative Collision Avoidance

risk ratio. It is clear that encounters between sUAS and manned aircraft would achieve an extremely high level of safety if both aircraft are equipped with CA systems. In all cases tested, the cooperative risk ratio is lower than it would have been if either CA system was used individually. This is a promising result, demonstrating that none of the evaluated CA systems would work against each other in implementation.

The alerting rates are not plotted for the dual-equipped encounters because they were almost identical to the individual alerting rates observed in Case I for the manned aircraft (Figure 5-6) and in Case II for the sUAS (Figure 5-9). Therefore, while equipping both manned aircraft and sUAS with CA systems leads to the lowest risk ratios, it would also cause high alerting rates for both types of aircraft.

Encounters were not evaluated between sUAS using CA systems and manned aircraft using visual see-and-avoid. It is hard to predict the maneuvers that individual pilots would select to avoid sUAS after visual acquisition, which makes it difficult to simulate the coordinated results of sUAS taking evasive action using CA systems in conjunction with manned aircraft performing avoidance maneuvers based on visual detection. However, as can be seen when comparing Figure 5-7 with Figures 5-8 and 5-10, the risk ratios for sUAS avoiding manned aircraft were much lower than the risk ratios for manned aircraft performing CA based on visual acquisition. This suggests that sUAS would be performing most of the evasive maneuvers in these encounters. Most of the time, especially for manned aircraft that do not have TA-issuing systems, the manned aircraft would probably continue along unaware as the sUAS adjusted course to avoid a collision. Therefore, the risk ratios for encounters between sUAS with CA systems and human pilots relying on visual acquisition should be similar to the risk ratios displayed in Figures 5-8 and 5-10. Because it is so difficult for human pilots to visually detect targets as small as sUAS, the sUAS would be the aircraft providing most of the mitigation to prevent NMACs.

5.2.4 Discussion of MAC vs. NMAC

Sections 5.2.1 through 5.2.3 evaluated the safety of the collision avoidance architectures from Table 5.1 based on the risk ratio, which is defined using the mitigated and unmitigated probabilities of NMAC (see Equation 5.1). This follows from the TCAS and ACAS X programs, which have both used the risk ratio as the primary safety metric to define success. The worldwide acceptance of the risk ratio as the safety metric for airborne CA systems is reflected in its use to define official requirements in the ICAO SARPS [28].

While past CA systems have been designed to prevent NMACs, the ultimate goal is to prevent actual Mid-Air Collisions (MACs). Historically, it has been assumed that 10% of NMACs will result in MACs [51]. In other words, it has been estimated that $P(\text{MAC}|\text{NMAC}) = 0.10$. This assumption has been used to calculate acceptable risk ratios that are defined based on the probability of NMAC, which is much easier to assess in simulation and does not depend on the size of the two aircraft encountering each other. The probability of NMAC therefore serves as a surrogate risk estimate for the probability of MAC.

However, the assumption that $P(\text{MAC}|\text{NMAC}) = 0.10$ is not accurate in all encounters. Kochenderfer et al. demonstrated that $P(\text{MAC}|\text{NMAC})$ actually depends heavily on the size of the two aircraft encountering each other [36]. Figure 5-12 displays $P(\text{MAC}|\text{NMAC})$ based on the combined size (the sum of wingspans) of the two aircraft in an encounter [37]. Aircraft without TCAS were evaluated because the historical assumption of 10% was based on the two aircraft not being equipped with CA systems.[4]

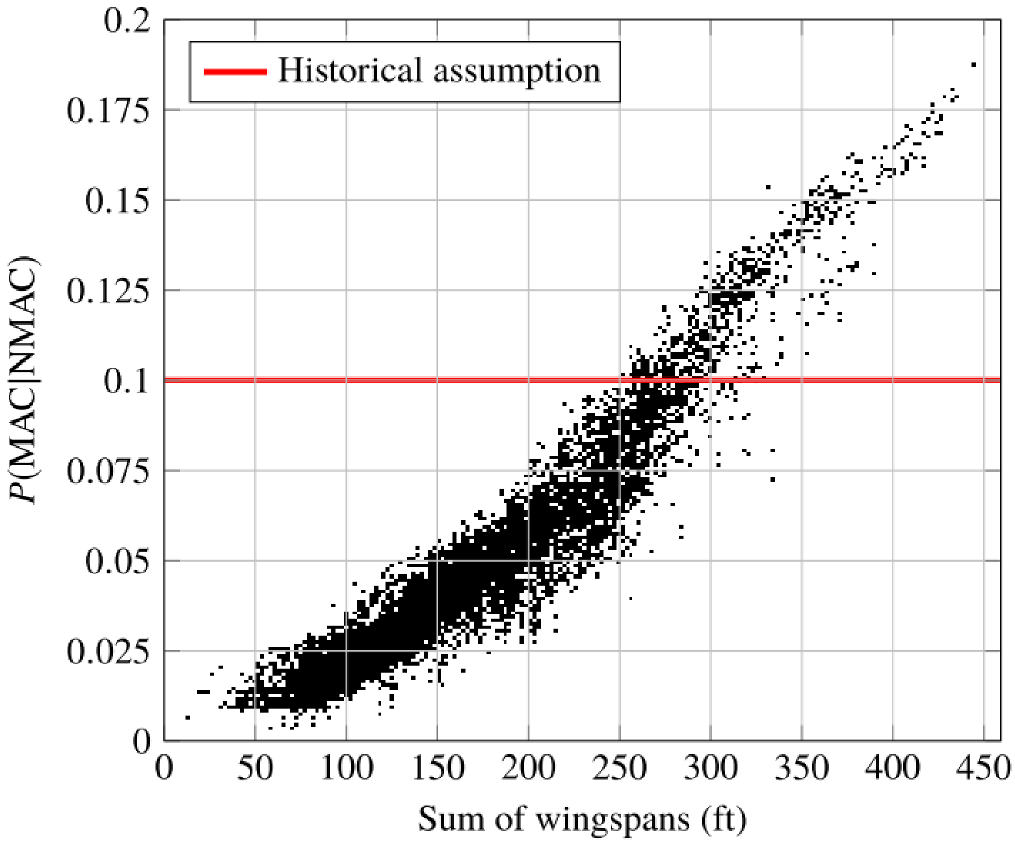


Figure 5-12: $P(\text{MAC}|\text{NMAC})$ for Aircraft without TCAS based on Modeled Encounters between Aircraft of Varying Sizes [36, 37]

The wingspans of commercial air carriers are generally around 120 feet but can be greater than 200 feet, so the historical assumption seems to be fairly accurate for an encounter featuring two air carriers. However, for an encounter between two smaller aircraft, $P(\text{MAC}|\text{NMAC})$ is actually much lower. Smaller GA aircraft tend to have

[4]The estimate that $P(\text{MAC}|\text{NMAC}) = 0.10$ was based on the two aircraft operating without CA systems, but was still used in the design of TCAS. This was done intentionally to add extra margin of safety, since it was assumed that CA systems would only reduce $P(\text{MAC}|\text{NMAC})$.

wingspans below 50 feet. The Cessna 172, one of the most common GA aircraft ever produced, has a wingspan of 36 feet. The sUAS study detailed in Chapter 3 showed that sUAS are even smaller, with a mean wingspan of 8.5 feet among fixed-wing sUAS.

In encounters between sUAS and manned aircraft, $P(\text{MAC}|\text{NMAC})$ would therefore be much lower than historically assumed. Based on Figure 5-12, the value of $P(\text{MAC}|\text{NMAC})$ for sUAS would be approximately 0.06 in encounters with the largest manned aircraft (e.g. B747, A380), 0.03 in encounters with more typical commercial air carriers (e.g. B737, A320), and only about 0.01 in encounters with smaller GA aircraft (e.g. Cessna 172). Because most sUAS are expected to fly close to the ground and away from busy airports, encounters with smaller GA aircraft are the most likely.

CA systems for sUAS may therefore be able to accept risk ratios greater than 0.18, which was used as a point of reference in this section due to its inclusion in the ICAO SARPS but was based on the assumption that $P(\text{MAC}|\text{NMAC}) = 0.10$. Since the actual $P(\text{MAC}|\text{NMAC})$ will likely be two to ten times smaller in encounters between sUAS and manned aircraft, a higher risk ratio may be acceptable. This, in turn, could allow sUAS with lower performance characteristics to achieve the desired risk ratio based on Figures 5-8 and 5-10. While quantifying an exact acceptable risk ratio for encounters involving sUAS is beyond the scope of this thesis, it appears that this risk ratio could be greater than 0.18.

5.3 Summary of Threat Resolution Analysis

In summary, encounters between sUAS and manned aircraft were modeled using a Monte Carlo simulation based on actual manned aircraft trajectories and simulated sUAS trajectories. The encounter set generated in the Monte Carlo simulation was used to evaluate the three primary system architecture options for collision avoidance between manned aircraft and sUAS. These included the options for manned aircraft to avoid sUAS (Case I), sUAS to avoid manned aircraft (Case II), and both types of aircraft to avoid each other (Case III).

For Case I, when manned aircraft equipped CA systems that issued RAs, they were able to avoid sUAS with high levels of success in simulation. Even with a notional GA policy that commands vertical rates of 1,000 fpm, manned aircraft achieved risk ratios below 0.045, far below the maximum allowable value (0.18) for TCAS II. However, RAs were issued in the vast majority of simulated encounters (84% of encounters for TCAS II), which could cause pilots to perceive that the systems are too noisy. Furthermore, manned aircraft were not able to avoid sUAS well when relying on visual acquisition. Unaided visual acquisition was almost worthless, with a risk ratio of 0.85 even if conditions were assumed to offer infinite visibility. Equipping a CA system that issued TAs helped, but risk ratios were still unacceptably high: 0.45 for infinite visibility and above 0.5 for more realistic conditions. Based on the results of this simulation, manned aircraft should not rely upon visual acquisition alone to avoid sUAS, even if traffic alerts can be generated.

The success of sUAS avoiding manned aircraft (Case II) depended heavily upon the performance capabilities of the sUAS. However, sUAS using blended (both horizontal and vertical) CA logic were able to achieve a risk ratio of 0.11 if a vertical rate of 400 fpm and a turn rate of 6 degrees per second could both be achieved. Nearly all sUAS should be able to reach this turn rate consistently (see Figure 3-7), and the majority of reviewed fixed-wing sUAS had a maximum climb rate that was at least twice as high as 400 fpm (see Figure 3-6). Furthermore, when sUAS traveled at speeds of at least 30 knots in simulation, a risk ratio of 0.14 could be achieved with horizontal logic alone using a turn rate of 6 degrees per second. Of the reviewed sUAS, 69% of fixed-wing and 33% of rotor-wing platforms listed cruise speeds above 30 knots (see Figure 3-4). Therefore, a majority of fixed-wing sUAS and many rotor-wing sUAS could meet TCAS II requirements when avoiding manned aircraft, even if the manned aircraft take no evasive action. However, high alerting rates were also observed for sUAS, with the horizontal logic issuing RAs in almost every encounter. Small UAS can tolerate higher alerting rates due to the lack of on-board pilots, but excessive alerting could still make it difficult to accomplish desired missions.

Finally, a review of dual collision avoidance (Case III) revealed that equipping both manned aircraft and sUAS with CA systems reduced the risk ratio far lower than only equipping one or the other. This demonstrates that all of the evaluated CA systems worked together constructively. All evaluated combinations of manned and sUAS CA systems resulted in risk ratios below 0.02, which is far below the maximum allowable value (0.04) for dual-equipped TCAS II encounters.

While safety results are already promising when evaluated against the reference risk ratio of 0.18 for TCAS II, it is likely that higher risk ratios can be accepted for encounters involving sUAS. This is because the TCAS value was determined by assuming that 10% of near mid-air collisions will result in actual mid-air collisions; for encounters between sUAS and GA aircraft, this proportion should actually be on the order of 1% (see Figure 5-12). A higher risk ratio could therefore be tolerated while still preserving the desired level of risk for actual mid-air collisions in encounters between manned aircraft and sUAS.

Chapter 6

Summary and Conclusion

There are now over one million small Unmanned Aircraft Systems (sUAS) in each the United States and Europe, with fleet sizes expected to continue growing. These platforms could offer many benefits to society but are currently prohibited from flight in almost all areas where manned aircraft fly. Motivated by the desire to enable sUAS integration into the airspace without creating undue collision risk for manned aircraft, this thesis investigated Collision Avoidance (CA) systems that could safely mitigate close encounters between manned aircraft and sUAS.

Over 600 UAS platforms were first reviewed to better understand the size and flight characteristics of sUAS. Table 6.1 summarizes the mean metrics for the sUAS that were studied. The low rates of climb available to sUAS make all existing CA systems untenable. However, the low flight speeds of sUAS mean that high turn rates could be achieved with minimal load factors. CA systems for sUAS were therefore desired that utilized horizontal maneuvers in addition to lower-rate vertical maneuvers.

Table 6.1: Mean Metrics for Reviewed sUAS

Metric	Fixed-Wing sUAS	Rotor-Wing sUAS
Span	8.5 ft	4.8 ft
Payload Mass Fraction	0.23	0.29
Cruise Speed	36 kts	24 kts
Maximum Speed	63 kts	30 kts
Rate of Climb	930 fpm	450 fpm

Implementing CA systems on sUAS requires airborne surveillance to be accomplished with on-board sensors. The Size, Weight, Power, and Cost (SWAP-C) of equipment required for CA systems were reviewed to inform the feasibility of equipage on sUAS. Table 6.2 reviews the SWaP-C values for three representative CA systems. While a non-cooperative radar sensor could be difficult for sUAS to equip, the CA systems utilizing cooperative surveillance are much more manageable.

If sUAS broadcast cooperative surveillance signals, though, the spectrum used to share aviation information could be overloaded. Signal transmissions were modeled for populations of sUAS broadcasting in tandem with existing users. While sUAS transmissions at current powers would quickly degrade performance for all users, lower-power transmissions could be viable. Table 6.3 provides the maximum densities of transmitting sUAS that would allow the desired probabilities of successful signal reception at ranges appropriate to perform CA. The use of Mode S transponders is not listed in the table but would be unable to support the lowest densities of sUAS considered (0.1 sUAS per square km in the area distribution and 3 sUAS per km in the distance distribution), even at the lowest possible transmission powers. ADS-B therefore appears to be the more viable surveillance option for broadcasting sUAS, with the 978 MHz UAT channel offering more capacity than the busy 1090 MHz channel. Small UAS could operate at higher densities than listed in Table 6.3 and could receive cooperative surveillance signals as long as they do not all transmit.

Finally, close encounters between manned aircraft and sUAS were modeled in the Mode C Veil environment to evaluate three primary threat resolution options: manned

Table 6.2: Size, Weight, Power, and Cost of Representative sUAS CA Systems

CA System	Product(s)	Size	Weight	Power	Cost
Broadcast Only	ping2020i	16 cm^3	23g	0.5 W	$2,000
Add CA Processor	ping2020i, Pi B+	99 cm^3	68g	1.4 W	$2,035
Add Air-to-Air Radar	ping2020i, Pi B+, R20	884 cm^3	848g	39.4 W	$12,035

Table 6.3: Maximum Allowable Transmitting sUAS Densities for ADS-B

Based on desired success probabilities of 0.9 for manned aircraft signals at 14 NM range and 0.8 for sUAS signals at 3 NM range

Channel	Distribution Type	Max sUAS Density	sUAS Transmission Power
UAT	Area	1/sq km	80 mW
UAT	Distance	40/km	80 mW
1090	Area	0.1/sq km	5 W
1090	Distance	10/km	5 W

aircraft avoiding sUAS, sUAS avoiding manned aircraft, and both types of aircraft avoiding each other. Manned aircraft using existing and notional future CA systems were able to avoid sUAS with risk ratios far below the maximum currently allowed for TCAS II (0.18), even when using vertical maneuvers of 1,000 feet per minute (fpm). However, alerting rates were high, which could cause pilots to ignore the recommended guidance. Furthermore, visual see-and-avoid provided limited success for manned aircraft due to the small size of sUAS, so the vast majority of manned aircraft not equipped with RA-issuing systems would have limited ability to mitigate close encounters with sUAS.

Novel threat resolution policies were designed for sUAS to evaluate the option of sUAS avoiding manned aircraft. Policies were created for various rates of both vertical and horizontal maneuvers to account for sUAS of varying performance capabilities. Success depended greatly on sUAS maneuvering capability, but the level of safety required for manned aircraft CA systems was achieved at many combinations of maneuvering capabilities and escape maneuvers used. Table 6.4 displays the minimum sUAS performance that achieved this safety metric for each type of escape logic. Horizontal maneuvers led to extremely high alerting rates while alerting rates for vertical maneuvers were similar to manned aircraft CA systems.

The novel sUAS policies were also simulated in tandem with manned aircraft CA systems to assess safety with both aircraft avoiding each other. All evaluations resulted in risk ratios less than half of what is currently required in dual TCAS II encounters (0.04). Safety was always higher when both aircraft were equipped

Table 6.4: Minimum sUAS Performance to Avoid Manned Aircraft with a Risk Ratio below 0.18 when Manned Aircraft take no Evasive Action

Type of Escape Maneuvers Used	Minimum Performance
Vertical Maneuvers Only	Climb Rate of 600 fpm
Horizontal Maneuvers Only	Turn Rate of 6°/s at 30 kts
Vertical & Horizontal Maneuvers	Climb Rate of 400 fpm and Turn Rate of 3°/s

with CA systems than when only one was equipped, which shows that the sUAS escape maneuvers would work constructively with manned aircraft CA systems. Dual equipage did not appear to change the alerting rates observed when only one aircraft was equipped with a CA system.

There are therefore viable options for sUAS to utilize existing cooperative surveillance systems and prototypes of novel CA policies to mitigate close encounters with manned aircraft in the Mode C Veil environment. Limited populations of sUAS could equip low-power versions of ADS-B or transponders to become visible to manned aircraft, which would allow manned aircraft with RA-issuing systems to safely avoid them. Alternatively, higher densities of sUAS could receive ADS-B signals and use modified ACAS X policies to avoid manned aircraft, which would allow current levels of safety to be achieved if the sUAS meet the performance characteristics listed in Table 6.4. These options could be used to allow some sUAS to begin integrating into the airspace currently used by manned aircraft.

Future research can be accomplished to extend the work completed in this thesis. For surveillance, this thesis focused on sUAS using existing airborne cooperative surveillance systems. Future research could consider non-cooperative or ground-based surveillance systems for sUAS. Communications among sUAS could also be accomplished using a novel system on a different radio frequency. If this option is pursued, the methods presented in this thesis could be used to assess how the system may perform among a large population of sUAS users.

The encounters modeled in this thesis were restricted to manned aircraft and sUAS in the Mode C Veil environment, a likely location for sUAS operations. However, future studies could similarly model encounters in different locations and for different types of aircraft. For example, encounters between sUAS and rotorcraft or between sUAS and other sUAS could be modeled. CA policies using different escape maneuvers or a methodology different from ACAS X could also be designed and tested for sUAS.

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Appendix A

Additional Broadcasting Plots

Chapter 4 of this thesis modeled signal transmissions for a dual population of manned aircraft and sUAS to investigate how an additional presence of sUAS broadcasters would affect performance for the cooperative surveillance systems currently used by manned aircraft. Sections 4.2.2 and 4.2.3 presented the results for modeled ADS-B and Mode S transmissions by sUAS. For brevity, plots were only presented for the uniform area distribution of sUAS and the 978 MHz channel for ADS-B transmissions. This appendix provides analogous plots for the other scenarios considered.

Figures A-1 through A-6 demonstrate how lower sUAS transmission powers on ADS-B lead to greater probabilities of success for manned aircraft signals at all distances and sUAS signals at close distances. Example transmission powers of 1 W and 100 mW are plotted for UAT while powers of 10 W and 3 W are plotted for 1090. Figures A-7 through A-12 plot the probability of success for manned aircraft ADS-B signals at 14 NM range and sUAS signals at 3 NM range at a variety of sUAS transmission powers and densities. These plots can be used to find the maximum sUAS densities and corresponding transmission powers that can support the desired success probabilities of 0.9 for manned aircraft signals at 14 NM range and 0.8 for sUAS signals at 3 NM range. Tables 4.3 and 6.3 summarize these densities and powers. Finally, Figure A-13 provides results for a uniform distance distribution of sUAS using Mode S transponders that reply at 800 mW.

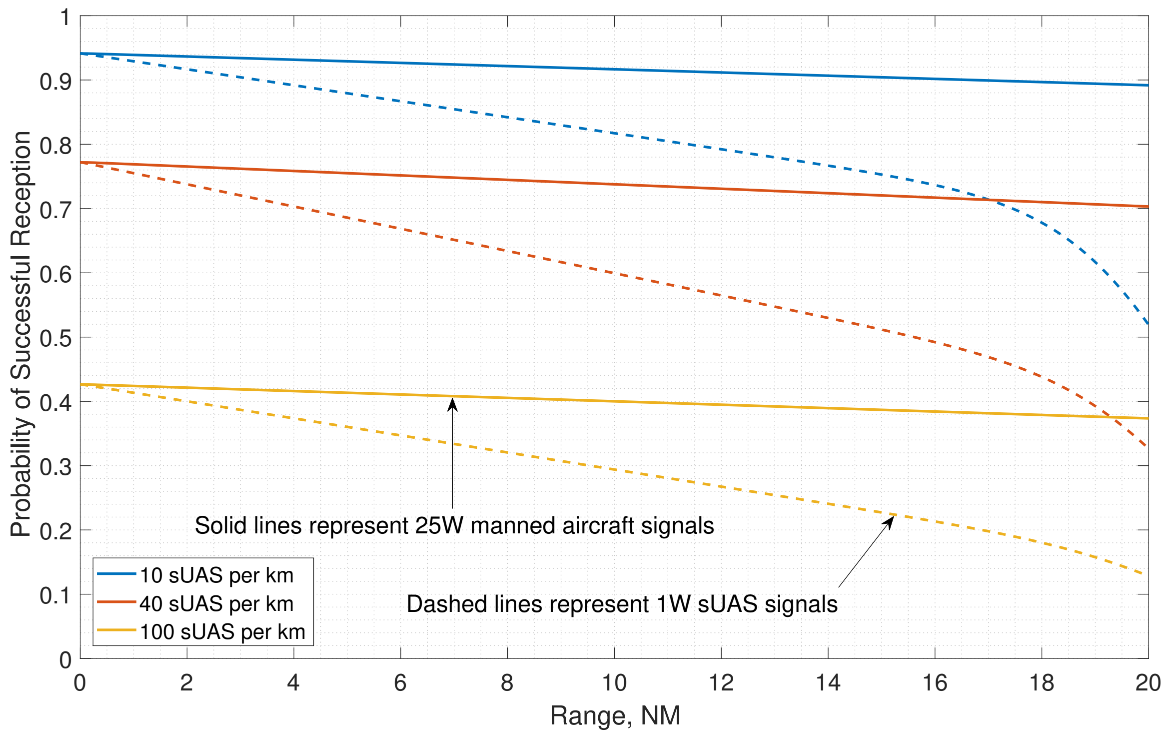

Figure A-1: Shared-use ADS-B Signal Reception from an Individual Transmitter on UAT (sUAS transmit at 1W with Uniform Distance Distribution)

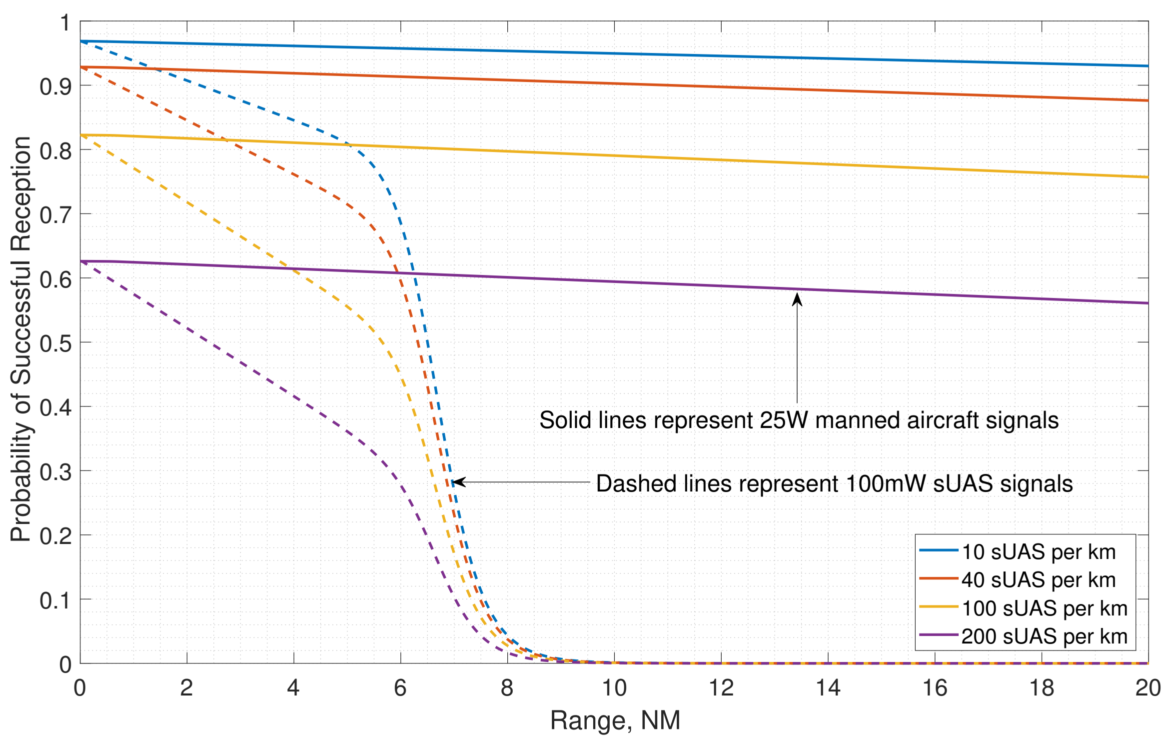

Figure A-2: Shared-use ADS-B Signal Reception from an Individual Transmitter on UAT (sUAS transmit at 100mW with Uniform Distance Distribution)

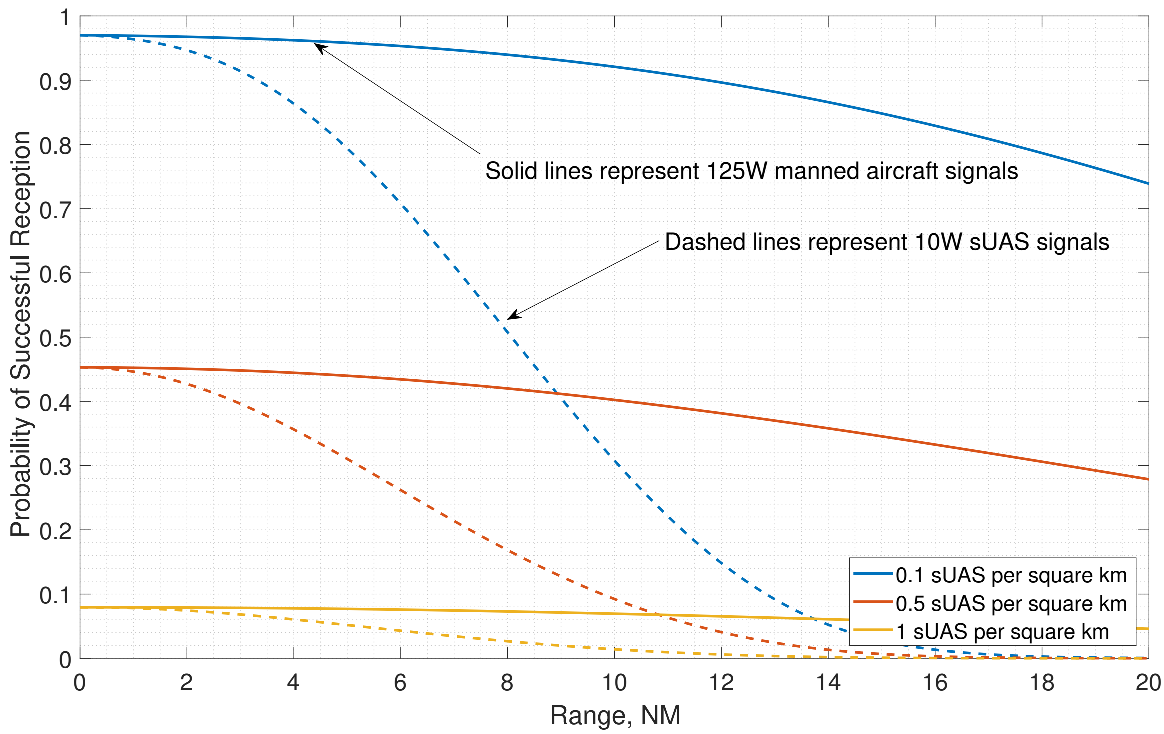

Figure A-3: Shared-use ADS-B Signal Reception from an Individual Transmitter on 1090 (sUAS transmit at 10W with Uniform Area Distribution)

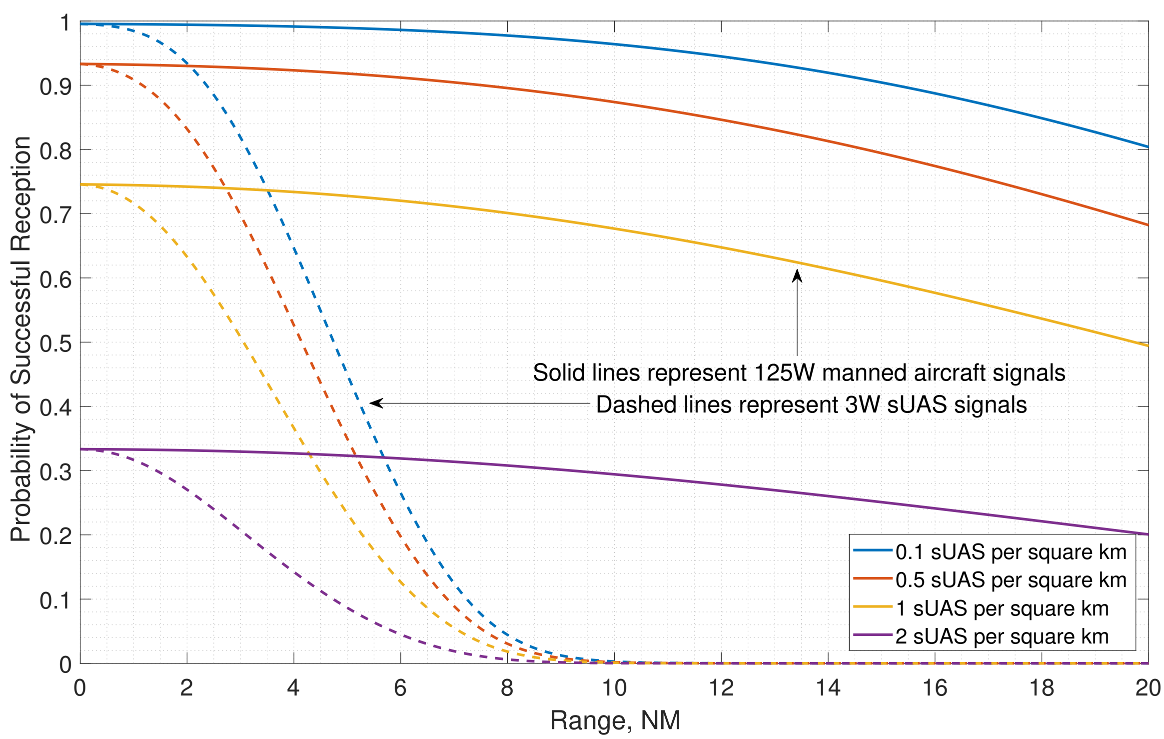

Figure A-4: Shared-use ADS-B Signal Reception from an Individual Transmitter on 1090 (sUAS transmit at 3W with Uniform Area Distribution)

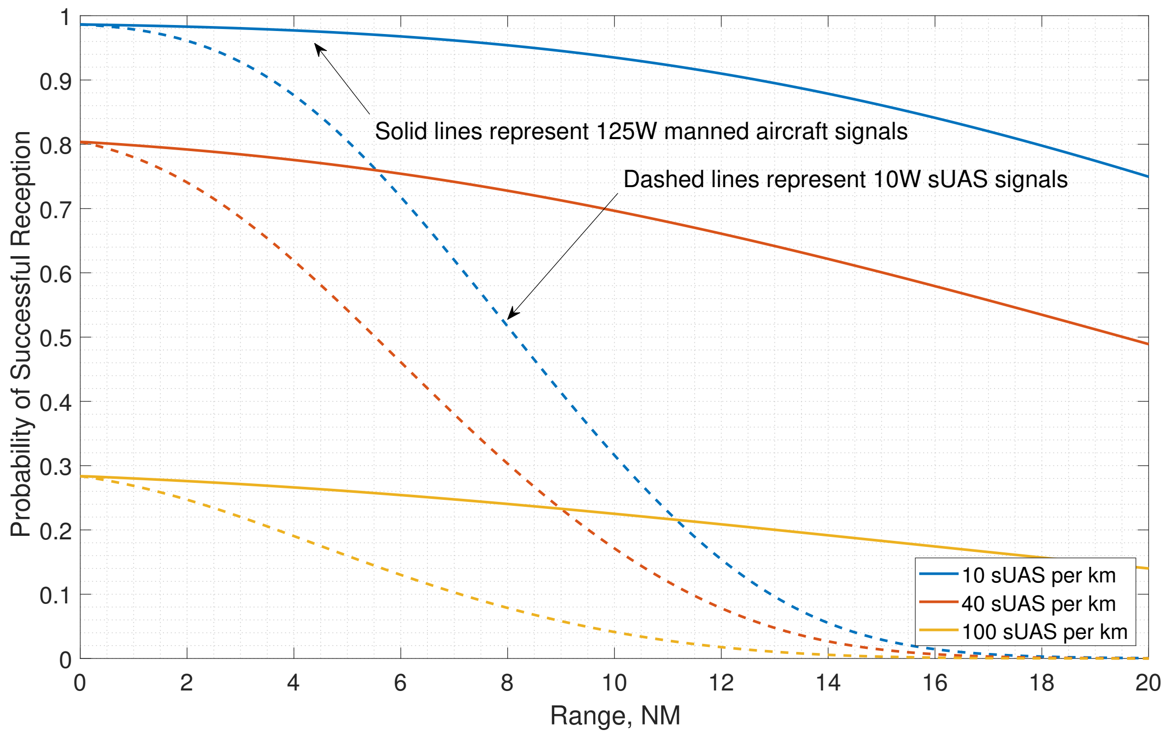

Figure A-5: Shared-use ADS-B Signal Reception from an Individual Transmitter on 1090 (sUAS transmit at 10W with Uniform Distance Distribution)

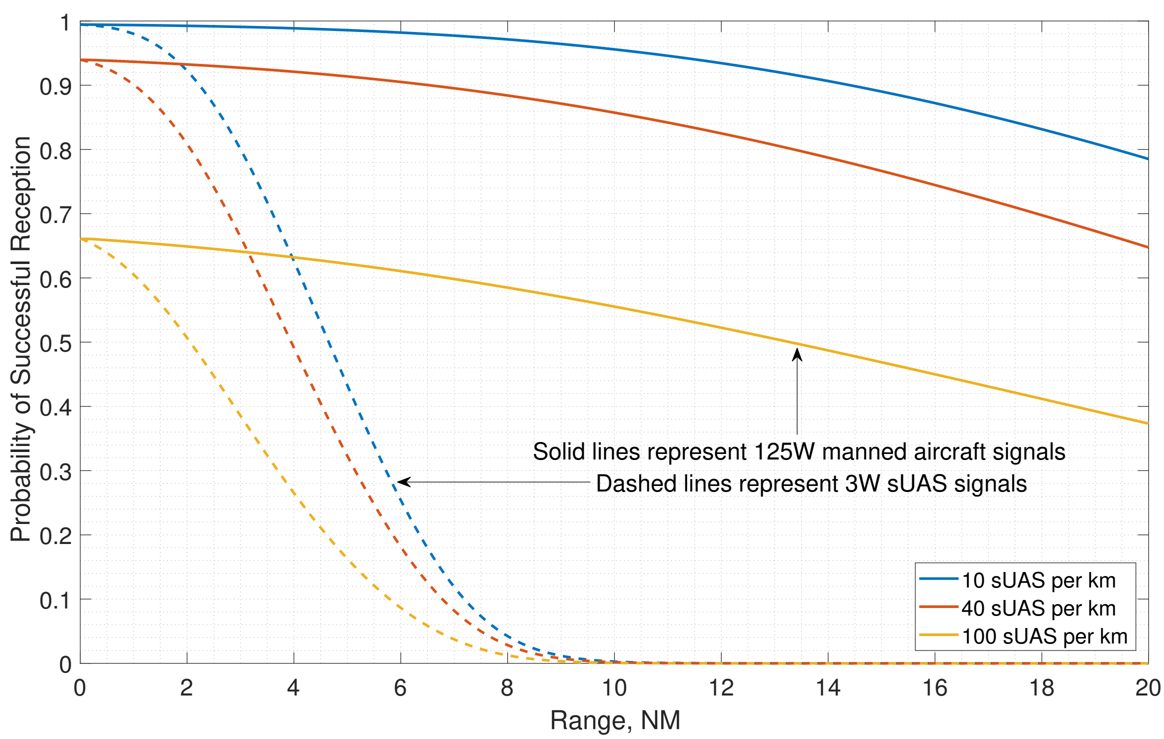

Figure A-6: Shared-use ADS-B Signal Reception from an Individual Transmitter on 1090 (sUAS transmit at 3W with Uniform Distance Distribution)

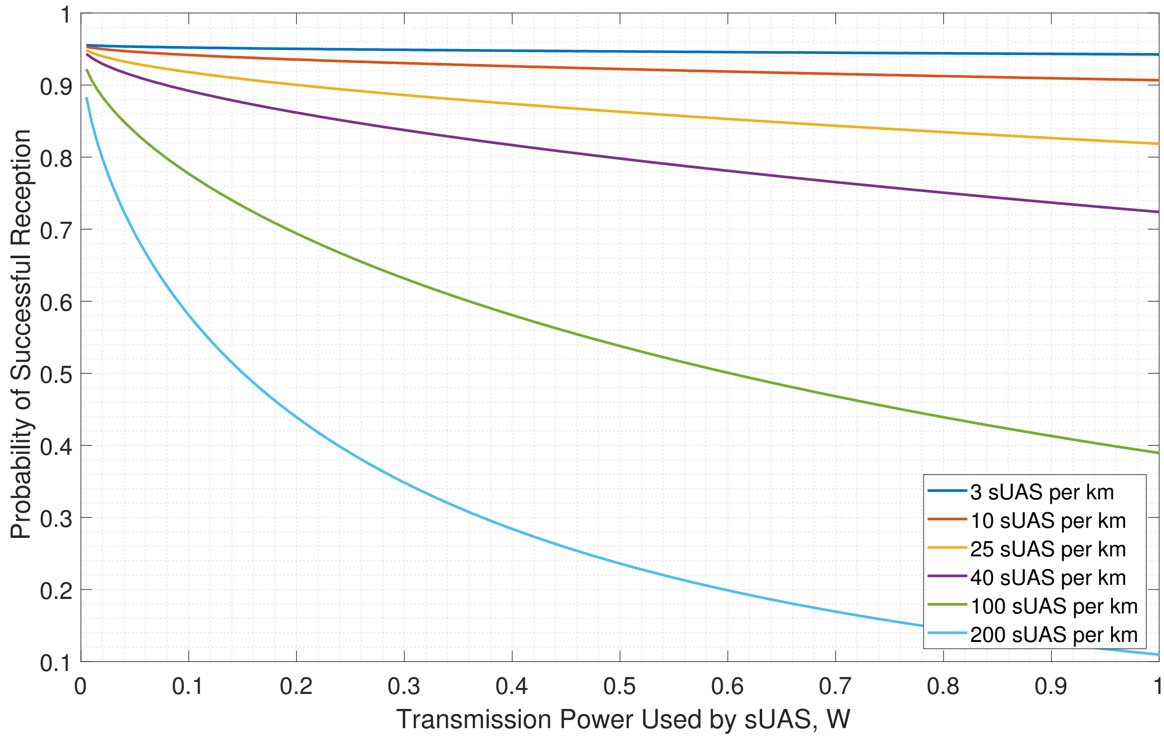

Figure A-7: Probability of Receiving Manned Aircraft ADS-B Signals each Second at 14 NM Range on UAT (sUAS Distributed with Uniform Distance Distribution)

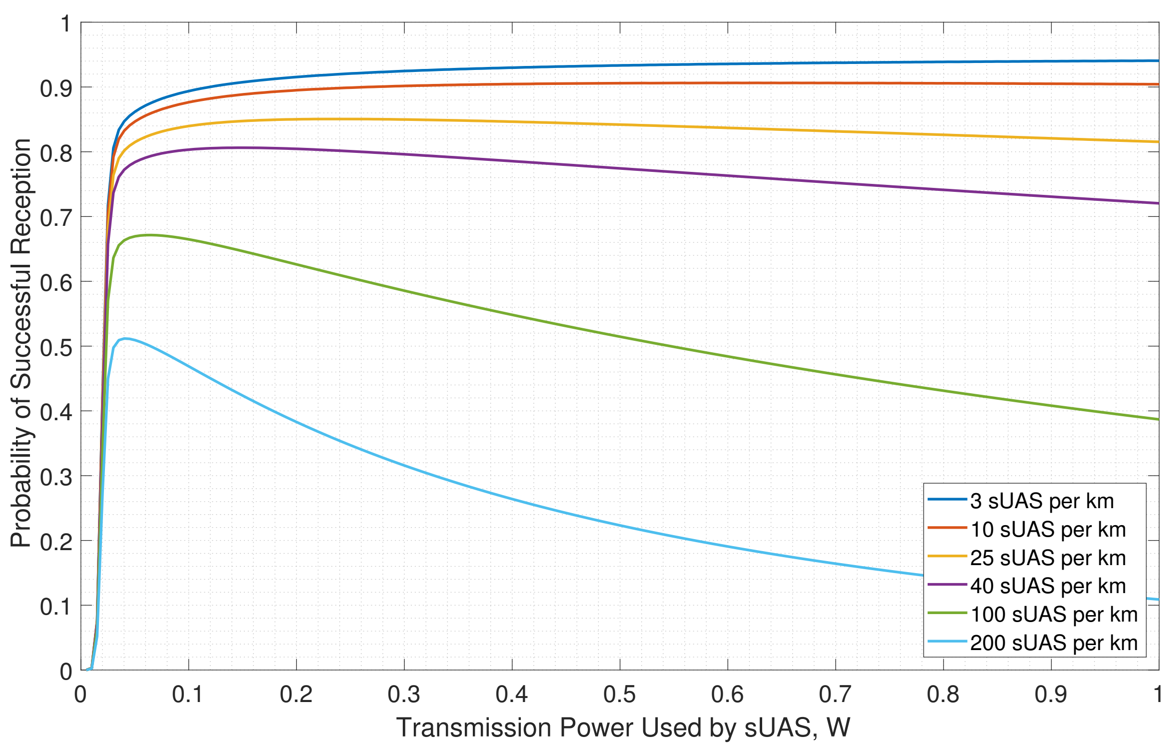

Figure A-8: Probability of Receiving sUAS ADS-B Signals each Second at 3 NM Range on UAT (sUAS Distributed with Uniform Distance Distribution)

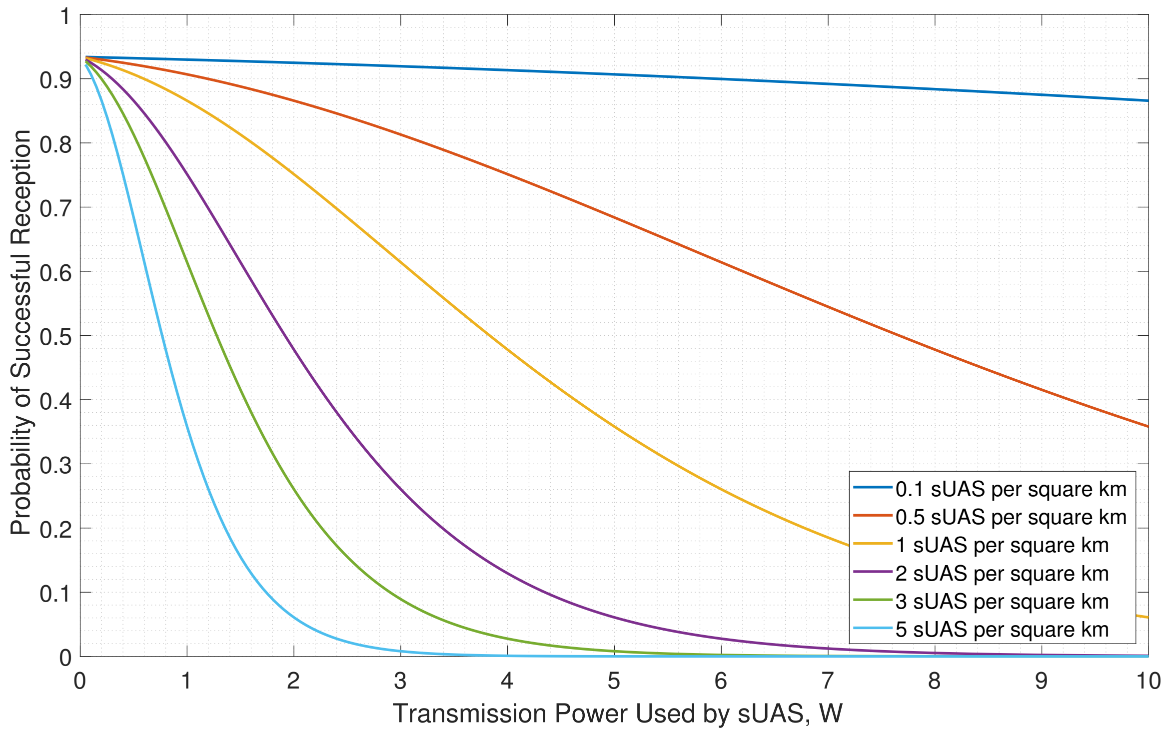

Figure A-9: Probability of Receiving Manned Aircraft ADS-B Signals each Second at 14 NM Range on 1090 (sUAS Distributed with Uniform Area Distribution)

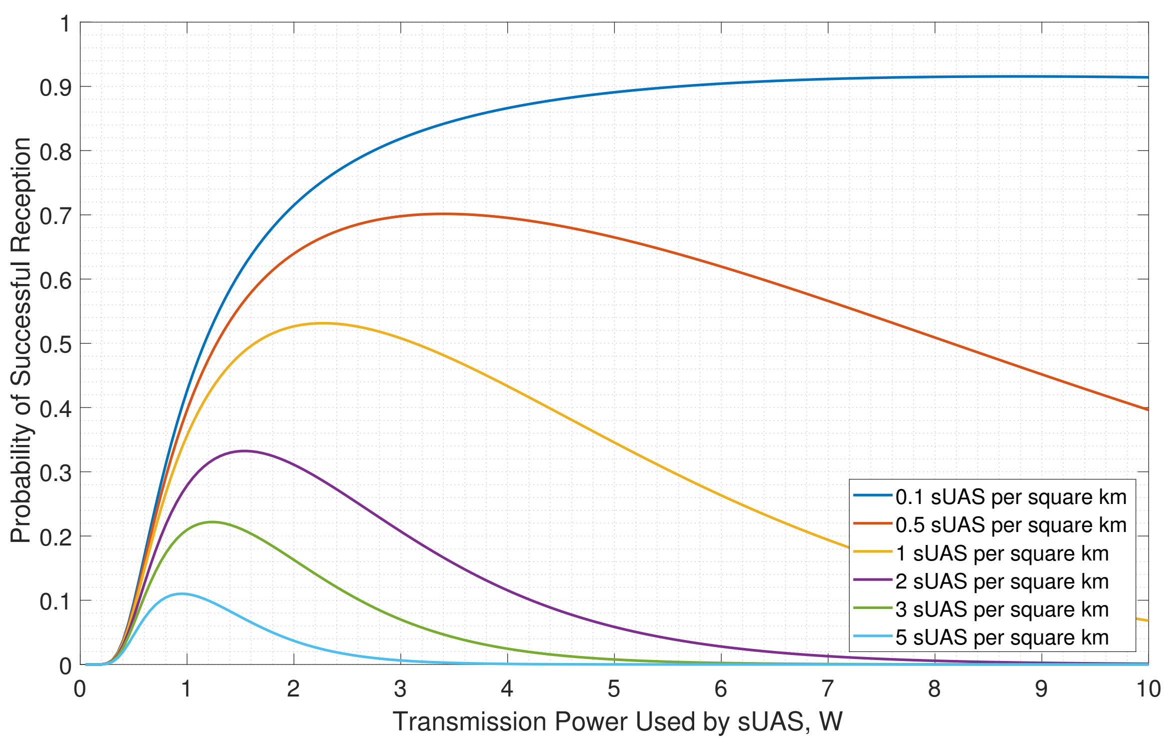

Figure A-10: Probability of Receiving sUAS ADS-B Signals each Second at 3 NM Range on 1090 (sUAS Distributed with Uniform Area Distribution)

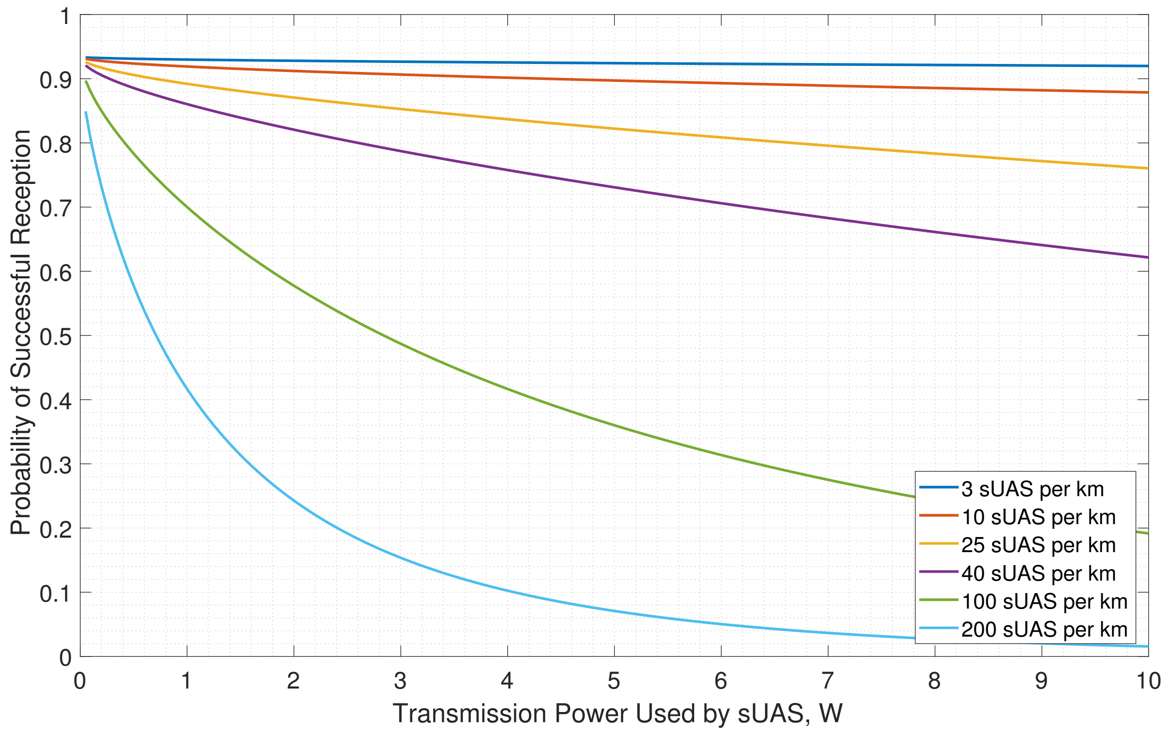

Figure A-11: Probability of Receiving Manned Aircraft ADS-B Signals each Second at 14 NM Range on 1090 (sUAS Distributed with Uniform Distance Distribution)

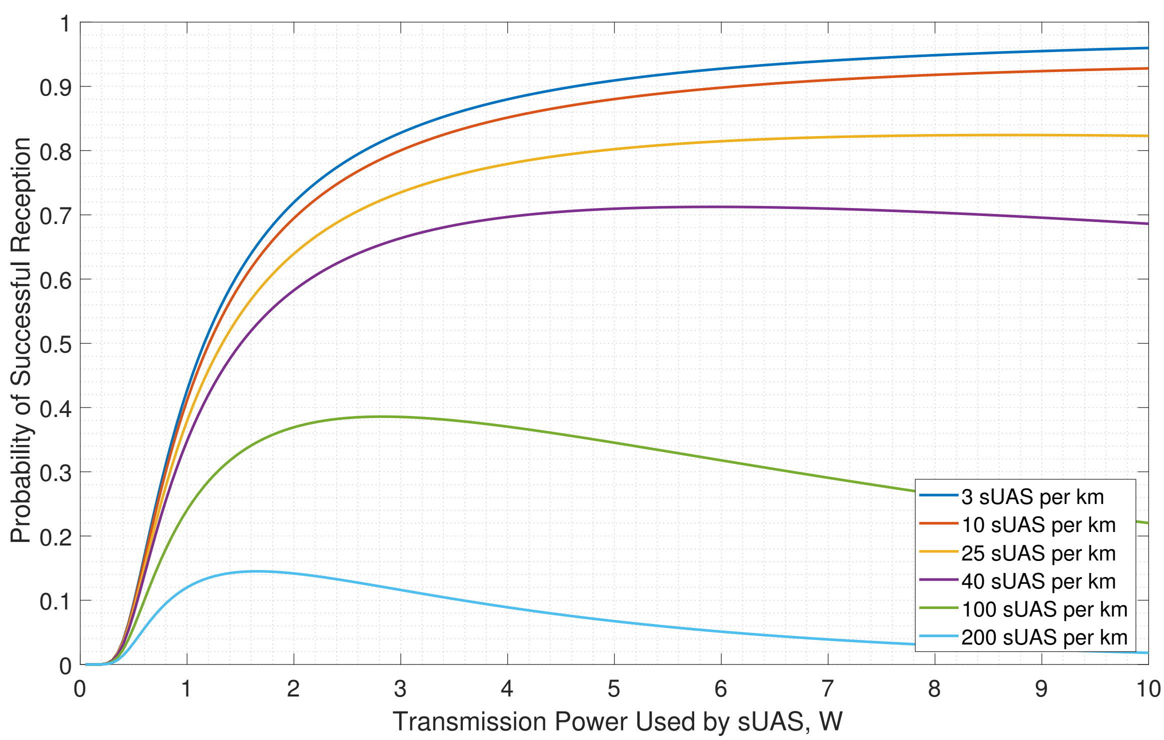

Figure A-12: Probability of Receiving sUAS ADS-B Signals each Second at 3 NM Range on 1090 (sUAS Distributed with Uniform Distance Distribution)

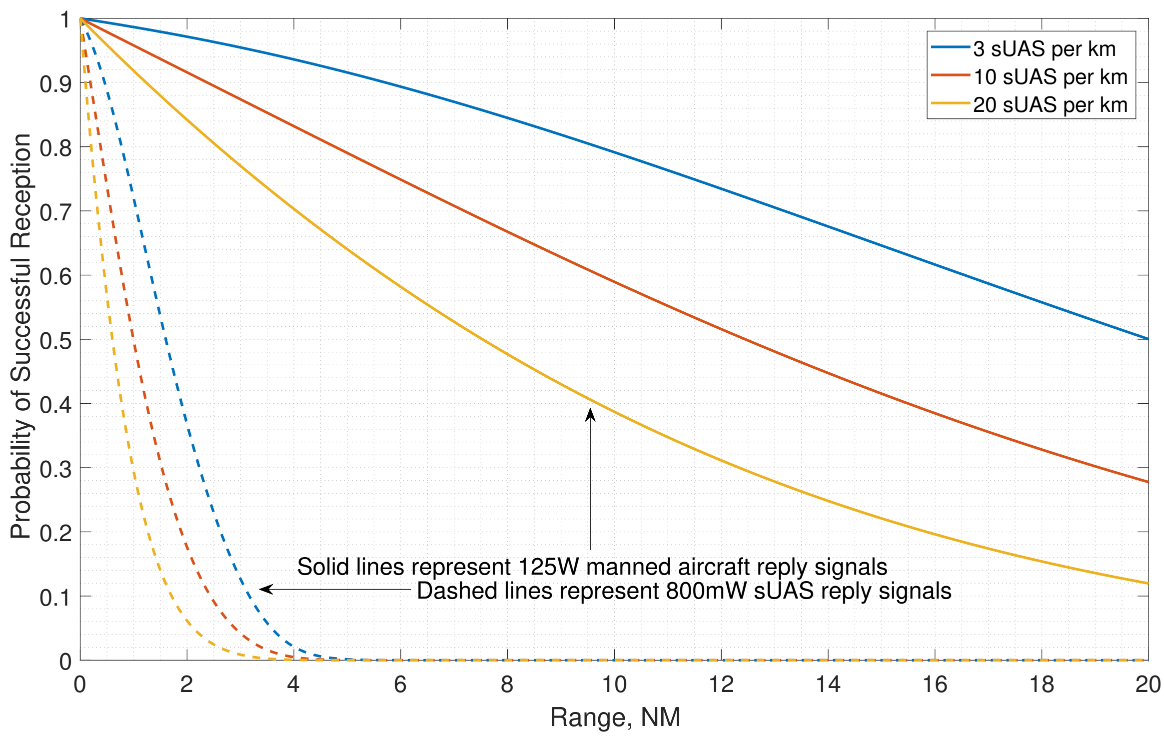

Figure A-13: Shared-use Mode S Reply Signal Reception from an Individual Transmitter (sUAS reply at 800mW with Uniform Distance Distribution)