Tower Controllers' Visual Detection of a Small Unmanned Aircraft System

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This study examined the feasibility of a tower controller visually detecting a small Unmanned Aircraft System on an airfield. In each trial, the participant—a tower controller—provided instructions to a manned aircraft in the pattern on an uncontrolled airfield. If the controller visually detected a sUAS, he/she provided a traffic advisory to the manned aircraft pilot. We varied the position and altitude of the sUAS in six trials; in one trial, no sUAS were present and in the final trial two sUAS were present. Controllers detected the sUAS 19 out of the total 72 times that a sUAS was in the vicinity of the airfield—a detection rate of 26%. If the sUAS was detected, controllers generally overestimated the altitude of the sUAS and provided inaccurate position and distance information. These results suggest it would be unlikely that a tower controller would be able to visually detect a small UAS on or near the airfield—even when UAS operations are expected and workload is relatively low. In the rare chance that the sUAS is detected, our data further indicate that the information provided by the controller to manned aircraft pilot regarding the sUAS may be incorrect.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Acronyms

AGL	Above Ground Level
ASOS	Automated Surface Observing System
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
FAA	Federal Aviation Administration
FT or ft	Feet
KGDM	Gardner Airport
MORs	Mandatory Occurrence Reports
NAS	National Air Space
UAS	Unmanned Aircraft System
sUAS	Small Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UOA	UAS Operating Area
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

Preface

This report was prepared by the Transportation Human Factors Division of the Safety Management and Human Factors Technical Center at the U.S. Department of Transportation, John A. Volpe National Transportation Systems Center. It was completed with funding from the Federal Aviation Administration. Thank you to Jason Lu, Seamus McGovern, Dylan Hasson, Karin Weber, Katie Bernazzani, Jared Young, and Aidan Schertz for assistance with data collection.

For questions or comments, please contact Tracy Lennertz, tracy.lennertz@dot.gov.

Executive Summary

As the number of small Unmanned Aircraft Systems (sUAS) operations in the National Airspace System continues to grow – so does the potential for these operations to occur in the vicinity of an airfield. Here, we examined the feasibility of a tower controller visually detecting a sUAS on an airfield. If the sUAS was visually detected, we also examined the information communicated by the controller to the manned aircraft pilot regarding the sUAS. The distance at which sUAS are detected by the controller may determine the time available to inform the pilot of the manned aircraft and consequently the time available to the pilot to initiate an avoidance maneuver.

In this field experiment, the participant—a tower controller—provided traffic pattern entry, downwind and base turn instructions to a manned aircraft flying on an uncontrolled airfield (to simulate actual operations). If the controller visually detected a sUAS, he/she provided a traffic advisory to the manned aircraft pilot. Each participant instructed the manned aircraft around the pattern eight times—six of which included one sUAS near the airfield, one included no sUAS, and finally one included two sUAS. We varied, 1) the position of the sUAS relative to the manned aircraft while in the pattern (crosswind, downwind, or final), 2) the hovering altitude of the sUAS (175 or 300 feet), and 3) the number of sUAS per trial (none, one, or two). Participants experienced each combination of position and altitude twice. When two sUAS were present—the location of the two sUAS (position and altitude) was held constant for all participants. We measured whether the controller detected the sUAS, and if so, we also measured the accuracy of controllers' estimates of sUAS altitude, position, and distance from the manned aircraft and/or airfield. Qualitative data about workload, confidence, and contributing factors was also collected.

Across all participants and trials, controllers detected the sUAS 19 out of the total 72 times that a sUAS was in the vicinity of the airfield—a detection rate of 26%. On average, each participant detected two of the eight sUAS. When two sUAS were present during the same trial, no controllers detected both sUAS. If the sUAS was detected, the controller's estimated altitude of the sUAS was compared against the actual altitude of the sUAS. On average, controllers overestimated the altitude of the sUAS. Across participants and trials, the average altitude estimate was 632 feet higher than the actual altitude of the sUAS. Of the 19 trials where a controller detected a sUAS, the controllers' position estimates were roughly accurate only four times and inaccurate 15 times. Eleven of the 15 times, the controller thought the sUAS on the wrong side of the aircraft, or in front of the aircraft when it was really hundreds of feet behind or to the side of the manned aircraft. When the sUAS was detected, controllers' estimates of sUAS distance were overall not accurate. Controllers tended to overestimate how far away the sUAS was. Controllers rated their confidence in seeing all sUAS in the vicinity of the manned aircraft. Of the 19 instances when the UAS was detected, participants were generally confident that they saw all traffic and provided an accurate traffic advisory.

Our results suggest it would be unlikely that a tower controller would be able to visually detect a small UAS on or near the airfield—even when UAS operations are expected and workload is relatively low. In the rare chance that the sUAS is detected, our data further indicate that the information provided by the controller to manned aircraft pilot regarding the sUAS may be incorrect.

Introduction

Background

The number of small Unmanned Aircraft Systems (sUAS) in the National Airspace System (NAS) continues to grow—with pilots taking to the sky for a variety of commercial (e.g., under Part 107) or recreational reasons (see Gettinger and Michel, 2017). With increased operations, the potential for these operations to occur on or near an airport also increases. A recent analysis of the Federal Aviation Administration's (FAA) Mandatory Occurrence Reports (MORs) involving UAS operations in 2016 observed that 15% of reported encounters between manned aircraft and UAS occur within one mile of the airport with an additional 33% of encounters occurring within one to five miles of the airport (Cardosi, Lu, France, Lennertz, Hoffman, & Sheridan, 2018). Of those within one mile of an airport, about 45% of the encounters report a closest proximity of 500 feet or less (Cardosi et al., 2018).

Manned aircraft pilots report many of these encounters. Approach and departure from an airport are busy phases of flight for manned aircraft pilots and distraction from critical tasks can have serious consequences. Thus, looking for a sUAS during this time is challenging, and if detected, monitoring the sUAS can distract from other time-critical tasks. For example, in a report submitted to the Aviation Safety Reporting System (ASRS), a pilot described spotting a sUAS while on approach (from Cardosi & Lennertz, 2017):

> *At 800 feet over XXX while on a visual approach to Runway XX, what at first glance seemed to be a large white bird caught my attention at our 3-3:30 position, some 200 feet-400 feet below our altitude, and an estimated 100-200 yards to our right. I'm sure I wouldn't have noticed the 'bird' over land, but it stood out against the deep blue-green of the [background]. And its wings weren't flapping. Oops. I then quickly recognized the familiar shape of a toy, it was a DJI Phantom drone. Because it was well beneath us, no avoidance maneuvering was necessary, but I called out its position to the Captain Pilot Flying (PF) and then to XX Tower, who quickly relayed the alert to traffic following us on the approach, and who, after we landed, asked me to phone the Tower Supervisor with details, which I did. Although no maneuvering was necessary, the sighting and relaying of the drone's location clearly distracted from my other duties during one of the most critical phases of flight… It may to be one of the most harmless drone/aircraft encounters on record, yet it was still, if for no other reason than the distraction, a hazard to air navigation.* (ACN 1288638, 2015)

Currently, sUAS are not permitted to operate within the controlled airspace of an airport without prior authorization from ATC,[1] and cannot exceed 400 feet Above Ground unless other conditions are met.[2] Many sUAS operators are new airspace users and may not be familiar with FAA regulations, airspace

[1] In accordance with 14 CFR §107.41.

[2] Conditions can include obtaining a waiver of 14 CFR §107.51 or Certificate of Authorization, operating within 400 ft of a structure not exceeding 400 ft above the structure's upper limit, etc.

definitions, and pilot/controller roles and responsibilities, and may therefore unknowingly fly in close proximity of an airport. The currently unpredictable nature of sUAS operations adds to the challenge of visually detecting sUAS for a controller in a tower environment. While the pilot in the example above alerted Air Traffic Control (ATC) to the presence of the UAS, so that they could alert other pilots and notify law enforcement, this will not always be feasible. In rare instances, the controller in the tower has first detected the UAS, and consequently provide traffic advisories for manned aircraft operating in the vicinity.

The purpose of this study was to explore the feasibility of a tower controller visually detecting a sUAS on the airfield, and the information that the controller could communicate to a manned aircraft pilot regarding the sUAS.

Much is already known about the human visual system and the characteristics of an object that make it easier or more difficult to see. These most important of factors include the size of the object, the distance to the observer, the contrast of the object to its background and whether it is moving (and at what speed) or stationary. It is also more difficult to describe it in detail (i.e., to identify it) than to notice that something is there (i.e., to detect it). These factors, and how they interact, are discussed in detail in Appendix C.

Past Research

Much of the past research on visual detection of UAS has focused on the ability of pilots of manned aircraft to "see and avoid" small UAS or on the ability of ground observers to visually detect a UAS.

Visual Detection of UAS by Manned Aircraft Pilots

Loffi, Wallace, Jacob, and Dunlap (2016) examined the ability of manned aircraft pilots to visually detect small UAS operating along their route of flight—the UAS varied in size (quadcopter [wingspan of 1.8 feet] vs. fixed wing [wingspan of 6.75 feet]) and whether it was hovering or moving. If the manned aircraft pilots detected the UAS, they estimated the distance between the manned aircraft and the UAS, as well as determined whether it was necessary to make an avoidance maneuver. Results indicated that manned aircraft pilots had a difficult time visually detecting the small UAS. Pilots detected the quadcopter about 37% of the time, and only at close ranges (i.e., 0.1 statute mile, or about 500 feet). Interestingly, performance did not improve when the sUAS was transiting between two locations (although the speed was unknown). When the quadcopter was detected, participants also tended to overestimate their distance from it (by about .20 statute mile), meaning that pilots would estimate the sUAS was farther away than it actually was and that there was more time available to maneuver. Based on the data, the authors conclude that only about 3 seconds would be available to a pilot to detect and avoid a small UAS; this is substantially less than the 12.5 seconds identified by the FAA as the time needed to identify and react to an aircraft (Advisory Circular 90-48D; FAA, 2016). Finally, compared to the quadcopter, pilots were better able to detect the fixed-wing UAS—which was larger than the quadcopter—and based on the data, ample time (about 15 seconds) would be available for the pilot to detect and avoid the larger fixed-wing UAS, under the ideal visual conditions tested.

A follow-on study by Wallace, Loffi, Vance, Jacob, Dunlap, & Mitchell (2018) examined the ability of manned aircraft pilots to visually detect a sUAS (wingspan of 2.1 feet) equipped with a strobe light in Visual Meteorological Conditions (VMC). Pilots flew a series of routes and were aware that a sUAS would be flying in the area. Despite the fact that it is easier to detect something that is expected, pilots only detected the sUAS about 8% of the time (3 out of 39 occurrences), at a distance ranging from 0.15 to 2.42 statute miles. When compared to the findings of Loffi et al. (2016), the application of the strobe light did not improve detection; however, as the authors note, the viewing conditions were bright afternoon sunlight.

A recent related study by the same group (Wallace, Vance, Loffi, Jacob, Dunlap, Mitchell, Thomas, & Whyte, 2019) examined the ability of a manned aircraft pilot to visually detect a sUAS (a DJI Phantom 4) on final approach. The authors note this would be a difficult phase of flight to make an evasive maneuver, if needed, given the speed and altitude of the aircraft. Ten participants flew a series of final approaches in VMC, in which a sUAS was either moving or static at a pre-determined location on final approach. In all trials, the UAS was at 50 feet Above Ground Level (AGL). Pilots detected the sUAS about 30% of the time—at an average distance of 1,382 feet. The detection rates improved to 50% when the sUAS was moving (speed not specified); when static, the detection rate was 13.6%. These results suggest that it would be challenging for a manned aircraft pilot to visually detect a sUAS on final approach, even when the pilot is aware that sUAS are operating in the vicinity.

Related work by Woo (2017) modeled the probability of a manned aircraft pilot to see and avoid a small UAS. Taking into account factors such as the size of the UAS, the airspeed of the unmanned and manned aircraft, and the time needed to identify and react to an aircraft, Woo determined that the likelihood that a manned aircraft pilot could see and maneuver to avoid a sUAS was less than ten percent. Specifically, if a manned aircraft is traveling at 60 knots, on average a one-square-foot sUAS is predicted to be detected by the manned aircraft pilot about 9.5% of the time, sUAS detection decreases with increasing speed of the manned aircraft; with a manned aircraft speed above 140 knots, the sUAS is predicted to be detected by the pilot less than one percent of the time—in a high-contrast scenario (Woo, 2017, see Table 21).

Taken together, these results echo the event described by the pilot in the narrative above: small UAS are hard to detect in the air, and tend to be seen only at close distances.

Visual Detection of UAS by Ground Observers and UAS Pilots

A related area of research applies to the ability of ground observers and sUAS pilots to provide a "see and avoid" capability to UAS operations. Crognale (2009) examined the ability of ground observers to visually detect a fixed-wing UAS—when the location of the UAS was either known or unknown. When the location of the UAS was unknown (i.e., the UAS flew towards the observer from an unknown direction between 100-200 feet AGL), participants detected it when it was an average distance of 327 meters or about 1,073 feet away. There was a lot of variability among participants, and in some cases, participants failed to detect the UAS entirely. Participants' visual detection improved when the location of the UAS was known (i.e., the UAS flew above the participant into the distance and returned back, the participant indicated when they lost and re-gained sight of the UAS). On average, participants reported seeing the UAS at a distance of about 1276 meters (or 4,186 feet) when moving away, and a distance of 898 meters (or 2,950 feet) when the UAS was coming back. Note, however, the UAS used by Crognale (2009) had about a 10-foot wingspan, which is considerably larger than the small quadcopters that are widely in use today. Consequently, the UAS by Crognale (2009) may be easier to detect, in general, than the one used by Loffi and colleagues.

Crognale (2009) also examined the ability of ground observers to judge the relative distance and altitude of the UAS. He found that performance varied by observer with "relatively low accuracy for altitude judgments and worse than that for distance judgments" (p. 44). Judgments of potential collision (albeit between two manned aircraft) were also inconsistent between observers.

A field study by Lennertz et al. (2018) examined the ability of hobbyist and commercial sUAS pilots to estimate the altitude of their ownship (a DJI Phantom 4 Pro quadcopter). Participants, on the ground, flew the sUAS to a pre-determined altitude (50, 200, or 350 feet) and took a photo over a target. No differences in altitude estimation were observed between commercial and hobbyist pilots—but similar to the findings of Loffi et al. (2016)—participants tended to overestimate the altitude of their ownship, estimating that it was flying at a higher altitude than it actually was. This was most pronounced at 350 feet, where the mean altitude flown by participants was about 250 feet. Note some participants did actually fly above the intended altitude. While participants were generally cautious in estimating altitude, regardless of experience, operators may be less conservative in actual operations. The results suggest that pilots need a reliable and standard way to determine the altitude of their ownship, especially given the increasingly complex environments in which sUAS intend to fly (i.e., near an airport)—where it may be challenging for the pilot or ground observer to maintain visual contact.

Visual Detection of UAS by Tower Air Traffic Controllers

The findings above are not directly applicable to Air Traffic Controllers in the tower. The main tasks of tower Air Traffic Controllers (i.e., local control) are to separate aircraft and issue safety alerts to "prevent a collision involving aircraft operating in the system" (2-1-1; 2-1-2, JO 7110.65Y, 8-15-2019). Tower Controllers are routinely responsible for the visual detection and identification of many objects and features in the airport traffic pattern. Compared to ground observers, tower controllers may be better able to visually detect a sUAS and estimate distance between aircraft given their vantage viewing location, communication with multiple nearby aircraft, familiarity with the airfield (including height and distance of nearby landmarks), available tools, and expertise in visually scanning for traffic. However, the time parameters and accuracy of such estimates are unknown.

A study by van Schaik, Roessingh, Lindqvist, and Fält (2010) identified 31 visual tasks for tower controllers—ranging from detecting a large-size bird (such as a goose) to determining if an aircraft has its landing lights on. A sample of tower controllers estimated the range at which he/she could view each of these objects and to rate the relative importance of detecting each of the objects. Note, visual detection of UAS (small or large) was not included in the list of tasks for tower controllers. The size of the small UAS in the current study, however, is similar to a large bird, which was included (note, Loffi and colleagues also compared the sUAS to a large bird in their 2016 study). Controllers estimated a viewing range of about 1800m, roughly 5,900 ft or a little over a mile for a large bird. This was under ideal conditions (i.e., good visibility and daylight) but without binoculars. Compared to other objects, such as an aircraft on final or aircraft landing lights, a large bird (and a small UAS) would be difficult to see.[3] Based on the past work on visual detection, this may be an optimistic estimate for visually detecting a sUAS.

Even when an observer—on the ground, in the air, or in the control tower—is aware of the presence of a UAS in the vicinity, the ability to visually detect and recognize a small UAS will be severely limited by the capabilities of the human visual system. A review by Williams and Gildea (2014; see also Woo, 2017) points out the limitations of the human visual system, and in particular, how challenging it may be for a pilot or visual observer to maintain visual contact with the sUAS, especially when it is moving (although it is easier to *detect the presence of* a moving target than a stationary one).

The current study explores the likelihood that a tower controllers would be able to detect a sUAS operating in an airport traffic pattern and judge its distance from a manned aircraft.

Purpose

Here, we examined the feasibility of a tower controller visually detecting a sUAS on or near the airfield, and the information that the controller could communicate to a manned aircraft pilot regarding the sUAS. The distance at which sUAS are detected by the controller may determine the time available to inform the pilot of the manned aircraft and consequently the time available to the pilot to initiate an avoidance maneuver.

In this field experiment, the participant—a tower controller—provided instructions to a manned aircraft (flown by a member of the research team) in the pattern on an uncontrolled airfield. The participant was located on the ground. In the majority of trials, a sUAS (also flown by a member of the research team) hovered at a pre-determined location on the airfield. The location of the small UAS varied relative to the manned aircraft's positon in the pattern (e.g., crosswind, downwind, final approach path—all between 800 to 1,500 feet away from the controller) at an altitude (AGL) of either 175 or 300 feet. In one of the trials, a sUAS was not present on the airfield. On the final trial, there were two sUAS on the airfield. If the controller detected the small UAS, he/she estimated the altitude of the sUAS, the distance

[3] In many ways, however, birds would easier to detect than a small UAS in the tower environment: birds tend to move—making them easier to detect—whereas UAS can appear stationary. Tower controllers may also have expectations of when and where birds might appear on the airfield, which could improve detection of birds compared to sUAS. Usually, controllers will see groups of birds as opposed to individual birds. It is rare to give a bird advisory for a single bird.

of the sUAS from the manned aircraft, and provided a traffic advisory to the manned aircraft regarding the sUAS.

We predicted that the sUAS would be difficult for the participant to detect, especially at higher altitudes compared to lower altitudes (e.g., 175 vs. 300 feet); however, may vary by the location and sky conditions of the sUAS in the traffic pattern.

Method

Participants

Nine tower controllers participated; four were retired and five currently control traffic at a contract tower. Eight participants were compensated with a $300 purchase card. One participant, an employee of the Volpe Center, was compensated as part of the normal workday and travel expenses were reimbursed.

All participants had experience controlling local (tower) traffic. A background questionnaire gathered additional information about participants' experience. Participants had an average of 27 years tower experience (range 7-40 years). All participants had experience with an airport in Class D airspace, four participants also had experience with an airport in Class B airspace, and three had experience with an airport in Class C airspace. In addition to working the local (tower) position, participants also had experience working ground (n = 9), flight data (n = 9), approach (n = 7), en route (n = 1), and other positions (such as a manager or in Air Traffic Management, n = 5). Participants were also asked to describe how often they encountered sUAS in their airspace; responses were variable and ranged from never to two-three times per week to two times per day. Three participants were familiar with FAA regulations related to sUAS, such as Part 107.[4]

Facility, Equipment, and Materials

Airport

The study was conducted at Gardner Municipal Airport (GDM) in Gardner, Massachusetts. GDM is a public, non-towered airport, with a single runway, in Class G airspace. This airport was chosen primarily because it had very little traffic during the weekday hours that the study was planned to take place. Permission was obtained from the airport manager prior to conducting the field study. A UAS Operating Area (UOA) Notification was published on each day that the study occurred. An aerial image of GDM,

[4] Note, this question was not asked of the first two participants.

with the location of each sUAS and the participant controller (i.e., ATC) is shown in Figure 1.

Figure 1. An aerial image of GDM.

Small UAS

The sUAS used in this study was a DJI Phantom 4 Pro as shown in Figure 2. sUAS pilots controlled it with a small tablet display. The DJI Phantom 4 Pro has a diagonal rotor span of approximately 14 inches and weighs about 3 pounds. The study required three sUAS pilots. Each pilot, located at a different location on the airfield as shown in Figure 1, had a designated and identical sUAS, and five batteries (each battery could last up to 20 minutes of sUAS flight time).

Figure 2. The sUAS used in the current study: a DJI Phantom 4 Pro.

Manned Aircraft

The manned aircraft used in this study was a Cessna 172 or a Piper Warrior—dependent on aircraft availability.

Forms and Questionnaires

Each participant was required to read and sign an Informed Consent Form when they arrived at the field; this form provided an overview of the study and explained the participant's assurances and rights.

Participants also completed three types of questionnaires.

- The background questionnaire was completed before the experimental trials; it asked about the participants' experience as a controller.
- The post-trial questionnaire was completed after each of the 12 trials; it asked participants to rate their confidence in 1) seeing all of the sUAS flying in vicinity of the manned aircraft, and 2) if applicable—providing an accurate traffic advisory to the manned aircraft. Participants were also asked to share any additional comments.
- The post-experiment questionnaire was completed after all trials were completed; it asked pilots about their experience in the study (strategies to estimate the location, distance and altitude of the sUAS, factors that influenced performance, overall task difficulty, and workload).

All questionnaires were completed on paper with clipboards. When the study was complete, participants were given a debriefing sheet that provided a brief study summary and contact information. The forms and questionnaires are provided in Appendix D.

Logs and Checklists

All members of the research team used a one-page paper checklist to monitor the trial number and experimental condition. The checklist provided the trial order, sUAS location (and sUAS pilot responsible), and sUAS altitude. The team members on the ground (i.e., everyone but the manned aircraft pilots) also had a detailed experimental protocol/checklist with instructions for sUAS operations—for when to launch the sUAS, when to land the sUAS, and the communication protocol among the ground researchers. The checklist also included prompts to record pre- and post-experiment weather, whether the controller detected each sUAS, and if detected, the time and content of the controller's traffic advisory to the manned aircraft. A separate log sheet was used to keep track of the purchase cards distributed.

Design

Since each participant was exposed to all of the conditions, the experimental design had three within-participant independent variables:

1) Position of the sUAS relative to the manned aircraft (crosswind, downwind, or final),
2) Altitude of sUAS (175 or 300 feet), and
3) Number of sUAS (none, one, or two).

Each participant experienced eight total trials. In six trials, participants experienced each combination of position and altitude twice. In each of these trials, only a single sUAS was present. In one trial, a sUAS was not present on the airfield. This was included to ensure that the participants did not expect to see a sUAS each time. In one trial, always the final trial, two sUAS were present—the location of the two sUAS (position and altitude) was held constant on this final trial for all participants.

We measured whether the controller detected the sUAS, and if so, we measured the accuracy of controllers' estimates of sUAS position, altitude, and distance from the manned aircraft and/or airfield.

Qualitative data about workload, confidence, and contributing factors was also collected via questionnaire.

Procedures

The research team comprised:

- One participant controller, with two researchers (a lead and an assistant) on the ground,
- Three sUAS pilots on the ground (one stationed at each location in the pattern),
- Two manned aircraft pilots.

All pilots (sUAS and manned aircraft) were members of the research team. The controller and two researchers were located at constant location in the center of an apron used for aircraft parking. The apron was located to the east of the runway, roughly in the center of the traffic pattern.

After obtaining informed consent, the controller filled out a background questionnaire and was familiarized with the airfield, briefed on the planned flight path of the manned aircraft and how to communicate with the manned aircraft pilot. The controller was informed that a sUAS may be operating in close proximity to the airfield and provided an example of FAA phraseology to communicate a UAS advisory to the manned aircraft pilot (see Appendix A, from FAA Order 7200.23A). Once the participant was comfortable with these tasks, the field study began.

For each trial, the manned aircraft entered a left traffic pattern for Runway 18 on the crosswind leg, from a holding location to the west of the airfield, flew the pattern one time, and executed a low approach at 500 AGL to provide an altitude buffer between the sUAS and the manned aircraft. The trial ended when the manned aircraft passed the researchers and controller as it flew over the runway, before returning to the holding location. The manned pilot was responsible for ordering the trial be discontinued and the sUAS to land in the event of another aircraft entering the traffic pattern at the airport.

Prior to each trial, the assistant researcher instructed one of the sUAS pilots (or two pilots, if it was the final trial) to fly their designated sUAS to a predetermined altitude, either 175 feet or 300 feet. During this time the manned aircraft flew in the holding location. While the assistant researcher was coordinating the trial, the lead researcher attempted to keep the controller occupied (i.e., not looking for sUAS as they were launching) with equipment set-up or the post-trial questionnaire. After the sUAS was in position, the lead researcher instructed the controller to begin the trial by instructing the manned aircraft to enter the traffic pattern. The controller instructed the aircraft to turn crosswind, downwind, and base for a reasonable, standard, traffic pattern. The study had eight trials total: six trials with one sUAS, one trial without a sUAS but still following the procedures, and one trial (the final trial) with two sUAS—one on the crosswind leg at 175 feet and the other on final at 300 feet. The locations and altitudes were held constant for all participants. Similar to normal operations, binoculars were available for the controller to use as he/she saw fit.

If the controller detected the sUAS, he/she estimated the distance of the sUAS from the manned aircraft, estimated the altitude of the sUAS, and provided a traffic advisory to the manned aircraft regarding the sUAS (e.g., UAS at 2 o'clock, quarter mile, 300 feet). The researchers recorded the approximate time, to the second, that the controller gave the sUAS traffic advisory to the manned aircraft (these times were used later in the data analysis).

Following each trial, participants completed a short questionnaire. The participant was verbally asked to answer the questions; the assistant researcher recorded the responses. During this time, the sUAS landed (i.e., returned to base) and the manned aircraft flew to the holding location, and the trial reset. A new trial began after the sUAS was launched into location and when the controller instructed the manned aircraft to enter the pattern.

At the conclusion of the experiment, participants completed a post-experiment questionnaire. The participant was not provided feedback on his/her performance throughout the study. See Appendix D for a step-by-step protocol.

Each trial took about 10 minutes. The entire field experiment took about two hours.

Weather Conditions

The study was conducted under Visual Flight Rules (VFR) weather conditions during daylight hours, with winds less than or equal to 20 knots. Local weather conditions were obtained by calling the Automated Surface Observing System (ASOS) at Fitchburg Municipal Airport (KFIT). This airport is about approximately 11 nautical miles from GDM. To document lighting and cloud conditions, a photo of the airfield was taken before and after each experiment. Note, this is an approximation, as the weather and cloud conditions may have changed during the course of the study. We did not control for this variable but documented it for our analyses.

Additional Procedures

Procedures for 1) communication between the controller, manned aircraft pilot, and sUAS pilots, and 2) a lost link are shown in Appendix B.

Results

Recall that we measured whether the controller detected the sUAS and, if so, we measured, 1) the accuracy of the estimated altitude of the sUAS, 2) the accuracy of the estimated position of the sUAS and 3) the accuracy of estimated distance of the sUAS relative to the manned aircraft or a position on the airfield. The accuracy of controllers' estimates was calculated at the time of detection, which was recorded by the researchers. Recorded times are only approximations, due to variations in how long it took for controllers to provide the traffic advisory and for the researchers to write it down. Qualitative data, collected via questionnaire, about workload, confidence, contributing factors and strategies were also collected. We describe each of these results, in turn.

Detection of the sUAS

Controllers were counted as detecting a sUAS only if they detected it before the manned aircraft passed the sUAS in the pattern. (On a few occasions, the controller detected the sUAS after the manned aircraft had passed the sUAS, too late to avoid detecting a potential traffic conflict). Across all participants and trials, controllers detected the sUAS 19 out of the total 72 times that a sUAS was in the vicinity of the airfield—a detection rate of 26%. On average, each participant detected two of the eight sUAS. The lowest number detected was zero and the highest number detected was four. There was no effect of trial order. The distance of the sUAS did not appear to affect detection rate, but there were too few data points conduct a statistical analysis. Figure 3 shows the percent of sUAS detected by location and altitude on the primary axis. The average distance between the controller and the sUAS is on the secondary axis (shown as a black "X").

When two sUAS were present during the same trial, no controllers detected both sUAS. There were also no false detections (e.g., misidentifying a bird as a sUAS) on the trial with no sUAS, or otherwise, that were not immediately corrected by the controller.

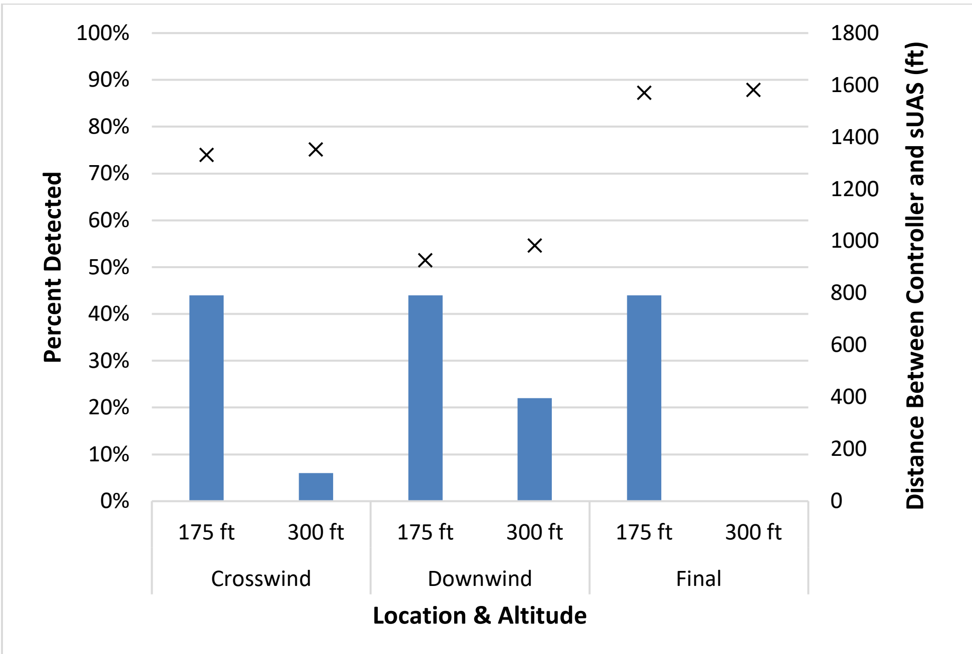

Figure 3. The percent of sUAS detected by location and altitude.

The detection data were analyzed with the Cochran's Q test. Cochran's Q is a non-parametric repeated-measures test that compares the probability of success (in this case, of detecting the sUAS) across different conditions, where each participant experienced all of the conditions. We ran two Cochran Q tests, one to examine differences in the proportion of detected sUAS by sUAS location, and one to examine differences by sUAS altitude. Neither test was statistically significant. Figure 4 and Figure 5 show the average percent of sUAS detected per controller, by location and altitude, respectively.

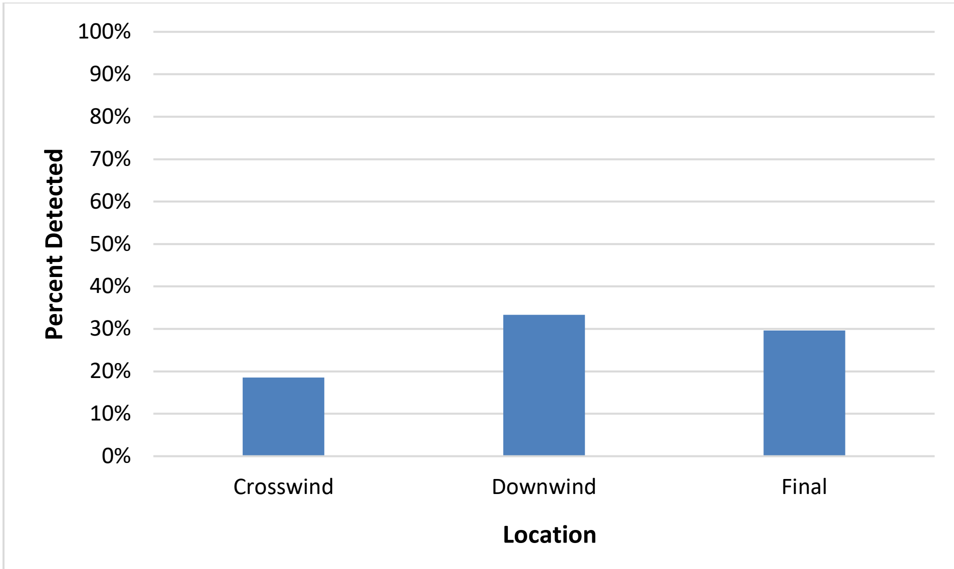

Figure 4. The average percent of sUAS detected per controller, by location.

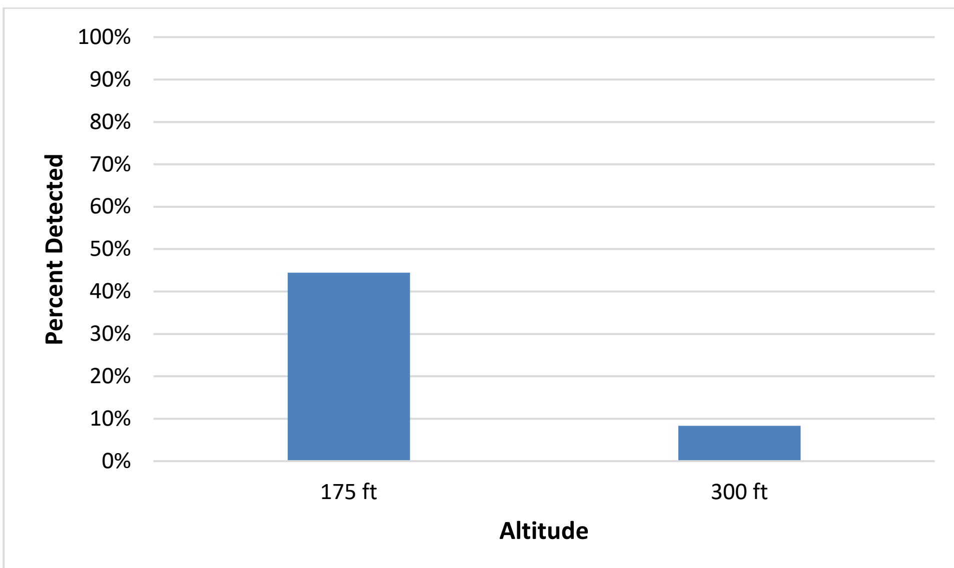

Figure 5. The average percent of sUAS detected per controller, by altitude.

Use of binoculars

An experimenter recorded whether the controllers used binoculars when they detected a sUAS. Of the 19 times that controllers detected a sUAS, he or she saw it with binoculars 8 times and with natural vision 10 times. Three of the 10 times that the controller saw the sUAS with natural vision, he or she confirmed the presence of the sUAS with the binoculars before providing a traffic advisory to the manned aircraft (this information was verified with the controller verbally following the trial).[5] There was no statistically significant difference between the number of detections with vs. without binoculars

[5] On one of the 19 trials, the experimenter forgot to record whether the controller used binoculars.

(chi-square $p > .60$).

Appearance of sUAS

Recall that the sUAS, a DJI Phantom 4 Pro, was white (as shown in Figure 2). Following the trials in which a sUAS was detected, an experimenter asked the controller what color the sUAS *appeared* to be. Of the 19 instances in which the sUAS was detected, it was identified as appearing to be a light color (e.g., white, silver, or light gray) nine times, and to be a dark color (e.g., black or dark gray)[6] three times. While, in general, the perceived shade of the sUAS will depend on the color of the background and the contrast between the sUAS and the background, in this case, recorded weather data showed no relation between the perceived shade of the sUAS and the sky conditions. During the conduct of the study, the sky ranged from clear to broken clouds.

Controller age and experience

Controllers provided information about their demographics and previous experience on the background questionnaire. We used Pearson (r) correlations to determine if there was a relationship between the total number of detected sUAS and the controllers' age, years as a controller, and years in the Tower, but found no significant effects (all $r < .3$, $p > .10$). We also found no significant differences in the number of sUAS detected by employment status (active or retired) or 20/20 vision (corrected or uncorrected) (t-tests, all $p > .10$).

Altitude Estimation of the sUAS

If the sUAS was detected, the controller's estimated altitude of the sUAS was compared against the actual altitude of the sUAS. Controllers estimated sUAS altitudes in various formats. Sometimes controllers estimated altitude in reference to the ground and sometimes they estimated it in reference to the manned aircraft. For the data analysis, the estimates in reference to the manned aircraft were converted to AGL based on the altitude that the manned aircraft flew at on all trials (about 1,000 ft AGL).[7] The controllers were told that the aircraft would be flying at 1,000 ft AGL in the pre-experiment briefing. Some controllers also gave a range of altitudes in their estimates, for example, between 300 and 500 ft. We used the average of these ranges for the data analysis.

On average, controllers overestimated the altitude of the sUAS. Across participants and trials, the average altitude estimate was 632 ft higher than the actual altitude of the sUAS. The smallest altitude error was 125 ft, with an estimate of 300 ft when the sUAS was actually at 175 ft, on the crosswind leg. The largest altitude error was 2,700 ft, with an estimate of 3,000 ft when the sUAS was actually at 300 ft

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[6] Seven were an undetermined color because the experimenter only started asking about the sUAS color after the first few participants.

[7] The aircraft flew at about 1,000 ft AGL on the crosswind and downwind leg, then descended to about 500 ft AGL on extended downwind to base and final. In all trials where the controller estimated sUAS altitude in reference to the manned aircraft, the manned aircraft was on the crosswind or downwind leg at about 1,000 ft AGL.

on the downwind leg.

Only three controllers indicated they had knowledge of Part 107 regulations.[8] Familiarity with Part 107 should include the knowledge that sUAS are not allowed to fly above 400 ft AGL without authorization. Interestingly, two of the three pilots with Part 107 knowledge gave altitude estimates above 400 ft AGL.

Figure 6 provides the average estimated altitude by sUAS location and actual altitude of the sUAS. The black line in each bar represents the actual altitude of the sUAS. With missing data points in some conditions, and few data points overall, we could not conduct statistical analyses to determine whether there were significant differences in controllers' altitude estimates by sUAS location or actual altitude. There were no correlations between controllers' altitude estimates and their age, years as a controller, or years working in the Tower (all $r < .1$).

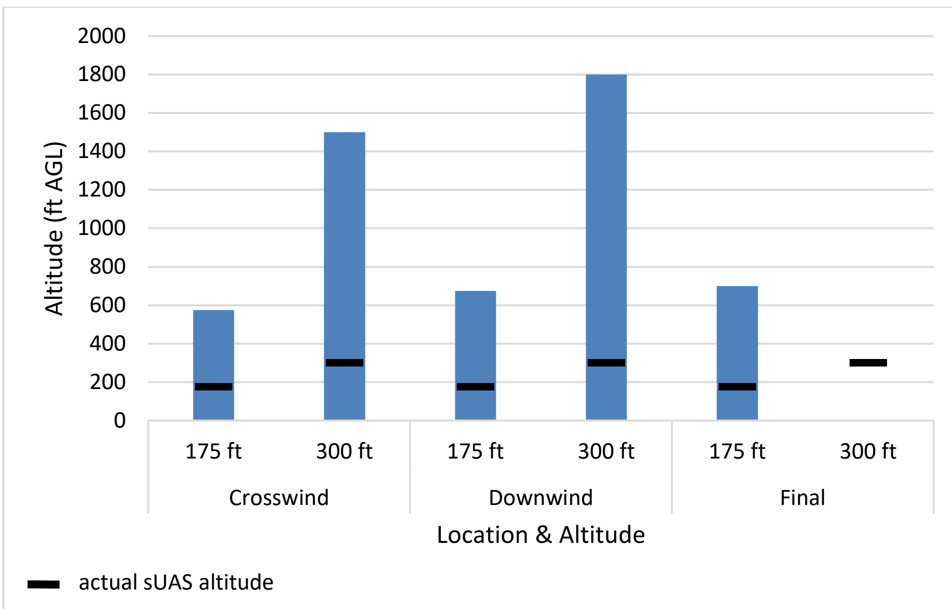

Figure 6. Average altitude AGL estimates by location and altitude.

Position Estimation of the sUAS

As with their altitude estimations, controllers used a variety of references and formats for estimating the position of detected sUAS. For example, some controllers gave a clock position (e.g., "UAS activity, 12 o'clock") and others just indicated whether the sUAS was left or right of the manned aircraft. Most controllers provided the sUAS position in reference to the aircraft, but a few provided position in reference to the airfield or planned traffic pattern (e.g., "UAS activity, north of final approach course, abeam the numbers"). To assess the accuracy of controllers' position estimates, we used Google Earth to plot the latitude/longitude coordinates of both the manned aircraft and sUAS at the time of each

[8] Note, however, that we did not collect this information from two controllers.

traffic advisory. Then, we compared the controller's estimated position of the sUAS to the actual position as indicated in Google Earth. Note that we did not record the manned aircraft heading, so we used the aircraft track to determine its direction relative to controllers' clock position estimates. Aircraft heading would be necessary to assess the precision of clock position estimates, particularly when the manned aircraft pilot had to adjust heading to correct for winds. Moreover, controllers may have had difficulty determining the heading of the manned aircraft, especially at far distances, such as when the aircraft was on its way from the holding area to the airfield. Controllers may have made assumptions about the aircraft heading based on the planned track and/or wind. However, when controllers made an error estimating sUAS position, the error was usually large enough that it could not be explained by an error in heading estimation.

There was a statistically significant difference between the number of accurate and inaccurate position estimates, $\chi^2 = 7.35$, $p < .01$. Of the 19 trials where a controller detected a sUAS, the controllers' position estimates were roughly accurate only four times and inaccurate 15 times. Eleven of the 15 times, the controller thought the sUAS on the wrong side of the aircraft, or in front of the aircraft when it was really hundreds of feet behind or to the side of the manned aircraft. In all of these cases, it appeared that the error was due to the controller thinking the aircraft was farther away from the airport than it actually was—most of the time, the controller thought the sUAS was even farther away from the airport than the manned aircraft was, when in reality the sUAS was at a minimum about 1,900 feet (.31 NM) closer to the airport than the manned aircraft was. Figure 7 shows an example—in this trial, the controller reported the sUAS as being on the manned aircraft's "right side [at] 2 o'clock" when the sUAS was really on the left at approximately 10-11 o'clock.

Figure 7. Example trial illustrating the position of the sUAS in relation to the manned aircraft.

The remaining four of the 15 times, the controller's estimate was only slightly off. For example, the controller may have reported the sUAS as being to the right of final, when it was really aligned with final. These four trials were the only ones in which the controllers gave estimates in reference to the airfield, not the aircraft. From their position on the ground, controllers may have had difficulty seeing the airport layout (e.g., where the runway ended) and using it to make accurate position judgments. It is possible that these small errors may have been eliminated if controllers were elevated in the Tower. While it might seem that controllers were more accurate when they estimated position in reference to the airfield than to the aircraft, it is important to keep in mind that controllers gave accurate estimates in reference to the aircraft just as often as they did in reference to the airfield (n=4).

Distance Estimation of the sUAS

Controllers estimated the distance of the detected sUAS, either from the airfield or from the manned aircraft, depending on the controller's preference. Some controllers did not provide a reference point (e.g., simply said "1 mile" instead of "1 mile from the airport"); for these cases, we assumed the reference point to be from the manned aircraft, since that is what controllers typically use in the Tower. Since the controller stood roughly in the center of the airfield, we used the controller's position as the airfield reference point when calculating the difference between estimated and actual distance of the sUAS, unless the controller provided a specific reference point on the airfield. We also assumed that all distance estimates were in nautical miles (NM), whether the controller said "nautical miles" or "miles," since controllers are used to reporting nautical miles on the radar scope. Some controllers gave a range of values for their distance estimate (e.g., "between 1.5 and 2 miles"). We used the average of the ranges for the analysis.

The controller failed to provide a distance estimate in two of the 19 trials. In the majority of the remaining 17 trials, the controllers overestimated how far away the sUAS was (n=13). When controllers used the airport as a reference (n=8), they overestimated the distance between the sUAS and the airport 100% of the time—confirming the findings from the position estimate data. When controllers used the manned aircraft as a reference (n=9), they overestimated the distance between the sUAS and the aircraft 56% of the time. Figure 8 and Figure 9 show the sUAS distance estimates for individual trials by sUAS position and altitude, from the airport and the manned aircraft, respectively.[9] The black line in each bar represents the actual distance of the sUAS to the airport or aircraft. With missing data points in some conditions, and few data points overall, we could not conduct statistical analyses to determine whether there were significant differences in controllers' distance estimates by sUAS location or altitude.

[9] To have a standard reference point for the figures, we only plotted the data from 15 trials—9 in reference to the aircraft and 8 in reference to the airport (controllers' position). We omitted two trials where the controller used the end of the runway as a reference—both overestimated the distance of the sUAS, one by .44 NM and one by 1.19 NM.

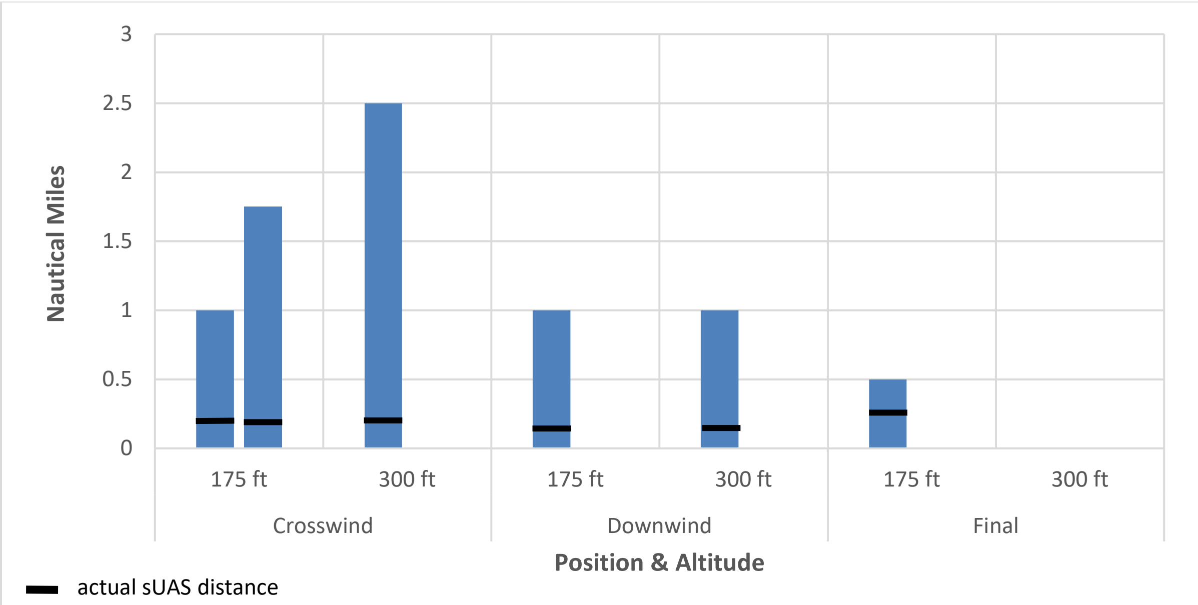

Figure 8. Individual estimates of sUAS distance from the airport by sUAS position and altitude.

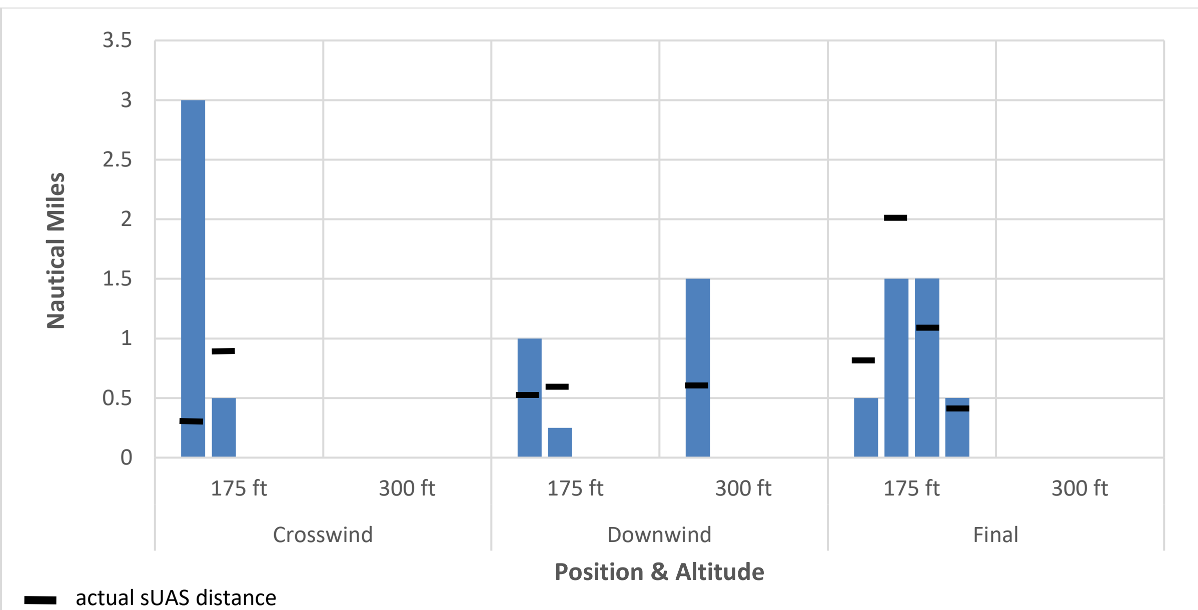

Figure 9. Individual estimates of sUAS distance from the manned aircraft by sUAS position and altitude.

Taken together, the data suggest that controllers' estimates of sUAS distance were overall not accurate. Table 1 shows the average absolute difference between controllers' estimates of sUAS distance and the actual distance of the sUAS—i.e., the controllers' error, regardless of whether they overestimated or underestimated or what reference point they used —by sUAS location and altitude.[10]

Table 1. Average absolute difference between estimated and actual distance of the sUAS.

Location	Altitude	
	175 ft	300 ft
Crosswind	1.35 (n=4, SD=1.09)	2.29 (n=1, no SD)
Downwind	0.50 (n=3, SD=0.29)	2.08 (n=2, SD=1.76)
Final	0.60 (n=7, SD=0.50)	N/A (no detected sUAS)

Confidence Ratings

After each trial, participants were asked to rate their confidence in seeing all UAS in the vicinity of the manned aircraft. Participants' provided their ratings on a scale of 1 to 10 (1 = not at all confident, 10 = very confident). Of the 19 instances when the UAS was detected, the median score was 8 -- meaning that participants were generally confident that they saw all traffic. When the UAS was not detected, the median confidence score was 5.

If a UAS was detected, participants rated their confidence in providing an accurate traffic advisory to the manned aircraft (including position, distance, and altitude). The median score for both location and altitude was 8; the median score for distance was 7. Thus, participants were slightly more confident about the location and altitude of the UAS relative to the manned aircraft, and slightly less confident about distance.

Strategies and Factors that Influenced sUAS Detection

Strategies used by participants

In the post-experiment questionnaire, participants mentioned several strategies to identify the sUAS, and if identified, to estimate its location, distance, and altitude relative to the manned aircraft. (Note, in some cases, participants listed more than one strategy, and in other cases, participants did not specify a strategy).

To identify the UAS, participants mentioned:

- Scanning the environment / horizon (n = 7)
- Using binoculars (n = 5)
- Visual references/geography (n = 2)

[10] There were small but statistically non-significant correlations between controllers' average distance estimation error and their age and years of tower experience. Both age and tower experience were positively associated with estimation error—that is, the older controllers were and the more tower experience they had, the worse their distance estimates were. The older controllers were, the greater their error was (r = .40). Controllers also showed a small increase in error associated with more years in the tower (r =.31), but years of tower experience might be confounded by age.

- Looking for movement or light [associated with the sUAS] (n = 1)
- Tracking the movement of the manned aircraft (n = 1)

To estimate the **location** of the UAS, participants used
- The altitude of the manned aircraft (n = 2)
- Compass points (North, South, East, and West; n = 2)
- The relative clock position of the aircraft / the flight path of the manned aircraft (n = 2)
- Geography (e.g., trees) or landmarks (n = 2)
- Scanning from the horizon to the manned aircraft (n = 1)

Participants estimated the **distance** of the UAS based on:
- The traffic pattern of the manned aircraft / distance relative to a point in the pattern (n = 4)
- Compared to a size of a bird (n = 1)
- Past experience (n = 1)
- A reference distance (e.g., 2 miles; n = 1)

To estimate the **altitude** of the UAS, participants used:
- The relative altitude of the manned aircraft (n = 3)
- Knowledge of FAA regulation regarding UAS operations (i.e., below 400 feet; n = 1)

Factors identified by participants that influenced sUAS Detection

In the post-experiment questionnaire, participants identified factors that influenced the ability to detect the sUAS and provide a traffic advisory. Factors that were mentioned by more than one participant included location on the ground (as opposed to a tower, n = 3), knowledge of past UAS activity in the area (n =2), weather/sky conditions (n=2), and the size of the sUAS (n=2).

Task Difficulty and Workload

Participants were asked on the post-experiment questionnaire to rate the difficulty of providing instructions to the manned aircraft and scanning for sUAS traffic. They were also asked to describe any factors that impacted their workload. Four participants rated the task as “difficult,” four rated the task as “moderate,” and one participant noted that it was “difficult” to provide instructions to the manned aircraft but “easy” to scan for traffic. Factors impacting workload that were mentioned by more than one participant included clouds (n=2), the size of the UAS (n=2), birds (n = 2), and the location on the ground (n=2).

Discussion

The current field study sought to examine the ability of tower controllers to detect a small UAS on the airfield, and provide a traffic advisory to a manned aircraft flying in the vicinity. In our study, a controller—at a constant location on the ground—provided traffic pattern entry, downwind and base turn instructions to a manned aircraft flying on an uncontrolled airfield (to simulate actual operations). In six out of eight trials, a stationary small UAS hovered at a pre-determined location on the airfield (either at crosswind, downwind or final) at either 175 or 300 feet. If the controller visually detected the small UAS, he or she provided a traffic advisory (location, distance, altitude) to the manned aircraft. In one trial, a UAS was not present, and in the final trial, two UAS were present. Given past results, we predicted that it would be challenging for a controller to visually detect a small UAS—especially when the UAS is stationary and in daytime conditions. We further predicted that the ability to visually detect the UAS would be moderated by the location and altitude of the UAS on the airfield.

Re-Cap of Results and Implications

In our field study, participants visually detected the small UAS only 26% of the time (or 19 out of 72 instances). Participants detected the UAS more often when it was at 175 opposed to 300 feet (however, this difference was not statistically significant—likely due to the small number of observations). Participants detected the UAS slightly more often on downwind and final compared to crosswind—this may be due to the location of the controller relative to the flight path of the aircraft, the direction of the sun (which was generally in the southerly direction like that of the crosswind sUAS relative to the controller), or the length of time the aircraft spent at each leg—again this finding was not statistically significant.

If the UAS was visually detected, we examined the information provided by the controller to the manned aircraft pilot in the traffic advisory. In line with past research (Lennertz et al., 2018; Loffi et al., 2016), we found that participants *overestimated* the altitude of UAS. In some cases, controllers in our study estimated the UAS was flying above the altitude of the manned aircraft, when in fact it was hundreds of feet below it. We also observed that participants tended to provide inaccurate information on the position of the sUAS. In many cases, the controller provided the complete wrong direction, for example telling the pilot to look for UAS traffic on the right when it was really on the left. Controllers also tended to overestimate the distance of the sUAS to the manned aircraft. Taken together, this could lead to the incorrect assumption that more time was available for the manned aircraft to react to the sUAS than there actually was.

The phraseology used to provide the traffic advisory to the manned aircraft varied (see Appendix A for some examples) – this likely reflects the difficulty in providing an accurate traffic advisory to the pilot of the manned aircraft. In general, participants tended to be overconfident about their ability to provide accurate information the manned aircraft. Specifically, when a UAS was visually detected, participants tended to be confident/very confident that they had seen all UAS traffic in the vicinity—yet, no participant reported detecting two UAS (when two UAS were present). Interestingly, participants were also confident about their ability to provide an accurate traffic advisory, including both information on the sUAS location and altitude. Thus, there was mismatch between how well participants thought they did, and how well they actually did—in terms of both detecting the UAS and providing traffic information. While participants were confident about the information they provided to the manned aircraft, the information was often incorrect. Our data, taken together with past research, indicate that controllers cannot reliably detect a small UAS operating in their airspace –even under conditions of low workload when they know that a UAS may be present.

Limitations of the Current Study

The current field study has several limitations. First, we did not control for weather conditions. While the study was conducted in VFR weather conditions during daylight hours, with winds less than or equal to 20 knots—there was variability in the cloud cover. On some days, the sky was blue with few clouds; on other days, the sky appeared gray. These conditions can change the appearance of the UAS—making it appear either white or gray to the controller participant—and likely impact visual detection. Second, controllers in our study were located on ground (for logistical reasons) rather than in a tower. Controllers mentioned this as a factor that they believe influenced their performance. While having the controller on the ground, as opposed to in a tower, would slightly change the angle of the view and could affect the accuracy of the judgement of position of the sUAS relative to the manned aircraft, it would not affect the ability to detect the presence of a sUAS, unless it changed the contrast between the sUAS and the background. That is, when the sUAS hovered at 175 feet, it is likely that the controller would have seen the ground as a background instead of the sky—this may have made it easier for controllers to see the sUAS. On the other hand, tinted windows in the tower would reduce contrast and make detection more difficult. Third, only one UAS model was examined in our study, it did not vary in color or size—two variables that can impact detection. Finally, this field study included a limited number of participants, and these participants may have had expectations that a UAS would be present on the airfield. This expectation may have improved performance (though, this does not appear to be the case, given the generally low detection rate).

Conclusion

Our results, in line with past findings, suggest that it would be very unlikely that a tower controller would be able to visually detect a small UAS on or near the airfield—even when UAS operations are expected and workload is relatively low. In the rare chance that the UAS is detected, our data further indicate that the information provided by the controller to manned aircraft pilot regarding the UAS may be incorrect. Moreover, it may give the false impression to the pilot that more time is available to visually detect the UAS and maneuver if needed. Given the performance of the human visual system (cf. Williams and Gildea, 2014) and the variability in UAS operations—it is unlikely that training would have much impact on performance. Additional solutions, such as those that limit the airspace for the UAS in proximity to an airfield (i.e., geofencing) or provide an indication of UAS operations to the controller that do not depend on human visual detection, would be needed. Using these and other data on detectability, future work could develop a model to predict whether a sUAS would be detected by a controller, given specific parameters (such as the size of the UAS, weather conditions, presence of movement, and viewing location).

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Appendix A

Excerpt from FAA Order 7200.23A - UAS Advisory Phraseology

3. Advisory Information.

a. Issue UAS advisory information for known activity, in accordance with FAA Order JO 7110.65, 2-1-21.

EXAMPLE-
U-A-S (OR UNMANNED AIRCRAFT SYSTEM) ACTIVITY, (position), (distance), (course), (type UA), (altitude).
EXAMPLES-
"U-A-S activity, 12 o'clock, 1 mile, southbound, quad copter, 400 feet and below."
"Uunmanned aircraft system activity, 2 miles east of Brandywine Airport, 300 feet and below."

b. Issue UAS advisory information for pilot-reported or tower-observed activity, in accordance with FAA Order JO 7110.65, 2-1-21. Continue to issue advisories to potentially impacted aircraft for at least 15 minutes following the last report.

EXAMPLE-
U-A-S (OR UNMANNED AIRCRAFT SYSTEM) ACTIVITY REPORTED/OBSERVED, (position), (distance),(course),(type UA),(altitude).
EXAMPLES-
"U-A-S activity reported, 12 o'clock, 1 mile, altitude reported one thousand two hundred."
"Unmanned aircraft system activity observed, 1 mile east of Trenton Airport, altitude unknown."

Example Phraseology used in the UAS Traffic Advisory

Phraseology used by controllers in this study to advise the manned aircraft of UAS traffic is shown below. Note, all communications from the controller to the aircraft were proceeded by the Aircraft call sign; it is not shown here).

- UAS activity observed on the base, at your 12 o'clock, approximately half a mile at 500'
- Looks like UAS activity on the left base approximately ½ mile, 12 o'clock, altitude unknown…
- Be advised UAS activity, in the midfield left downwind of runway 36, approximately 1000'
- You can enter the downwind and that UAS activity will be at your 12 o'clock, approximately midfield left downwind runway 36, about 1000'
- Turn base, as you enter the base UAS activity spotted on short final for runway 36
- That UAS short final, that UAS activity 500' short final
- There does appear to be aircraft low off your right side, altitude unknown, small, appears to be stationary
- There does appear to be some sort of aircraft just south of the field approximately 2 to 3 miles, 15 to 2000'
- That traffic appears to be off your right side, I'd say about your 2 o'clock high
- There appears to be some type of vehicle low off your right side, I think it might be behind you at this time, appears to be a white drone of some type
- There appears to be some type of aircraft in your 11 to 10 o'clock position, a mile, just abeam the number on the north side of runway 18
- Appears to be a white drone of some type, just off the numbers of runway 18, appears to be about 2000'
- That's a white drone and it appears to be just to the north of the final approach course
- UAS activity off to your right and straight ahead, I would say same altitude, about half a mile away, off to your right
- That UAS activity would be beneath you now off to your right
- As you depart runway 18 the UAS activity will be pretty much, just a bit, off to your left, straight ahead off to your left again, same altitude, appears to be circling one mile from the departure end
- UAS activity off to your left, 500' below your position, UAS activity is descending
- UAS activity your 12 o'clock, straight ahead, appears to be 500' below you about a quarter mile from you
- UAS activity behind you, no factor
- You can start inbound on the crosswind, enter the left downwind for runway 18, drone activity, about a mile south west of the field, at or below 600'
- UAS activity on the approach course, just slightly right of the approach course, approximately 500'
- Appears that it is stationary. The drone still right of course on the final about a half mile out

Appendix B

Communications Procedures

Given that this study took place on an airfield that was in use by other aircraft in the vicinity, the team used the multi-comm frequency (a lesser-used frequency) to communicate about the experiment. The participant controller and the manned aircraft pilots used the multi-comm frequency to communicate with each other. The sUAS pilots and the assistant researcher on the ground monitored the multi-comm frequency for their own awareness. The manned aircraft pilots also monitored the Unicom/CTAF frequency. The sUAS pilots and both researchers on the ground used small handheld radios (walkie-talkies) to communicate with each other.

- The lead researcher announced the start of each trial over the handheld radios. This let the sUAS pilot(s) know at what position and altitude to launch the sUAS.
- The participant controller provided instructions and the UAS traffic advisory via the multi-comm frequency.
- The manned aircraft pilot made normal traffic calls on the multi-comm, as turn instructions were received from the controller.
- If another aircraft appeared or was inbound to the airport, the protocol called for the pilot of the manned aircraft to call a hold on the multi-comm. This only happened on one trial across all nine participants. When this happened, the manned aircraft pilot instructed the sUAS pilot to land and the trial was repeated when traffic was clear.
- A communications check was made on the multi-comm and handheld radios before the field study began. Any loss of communications between the sUAS pilots and the research team would terminate the field study; this did not occur.

Lost Link Procedures

In case that the command and control link with the sUAS was lost, the research team developed a clear lost link procedure. If the link is lost for more than 3 seconds, the Phantom 4 Pro software would initiate a “Return to Home” Function. This involved the sUAS descending to a user prescribed altitude and returning to its takeoff point. Since the sUAS was hovering above the sUAS pilot, a lost link would mean a descent to a landing. The “Return to Home” altitude was set 50 feet. A lost link condition would be reported to the controller on the multi-comm by the sUAS pilot. Note, this event did not occur in the study.

Appendix C

Comparison of Experimental Results to Other Tests of UAS Visibility

The current experiment sought to replicate, insofar as practicable, the conditions experienced by an air traffic controller when monitoring an arriving aircraft, while at the same time seeking to detect any UAS that might interfere with that aircraft. These conditions differed from the few other experiments seeking to measure UAS detectability.

Nevertheless, results of the current experiment, in terms of frequency of detections and slant range when UAS were detected, are consistent with what might be expected from related experiments as well as basic research on target detection. In the current experiment, the slant ranges for detections ranged from 945 feet to 1,641 feet.

The variables at play

Several variables impact the ability of an observer (in our case, an air traffic controller) to visually detect an object (in our case, an sUAS): target size, viewing distance, contrast, weather/atmospheric conditions motion, area of visual field, observer visual acuity and fatigue. We briefly review each in turn, as they relate to the results of the current study.

Target size and viewing distance (retinal angle)

As Figure 10 indicates, retinal angle, that is target size divided by viewing distance, plays a large role in whether an object will be detected by an observer. Under ideal conditions, for example, the detection of a black circle against a white background, the threshold (50%) detection generally occurs at a retinal angle (arc tangent) of 0.5 arc minutes (30 arc seconds). Seldom, however, are such ideal conditions encountered in real-world target detection. These conditions would not be expected to occur for a tower controller at an airport.

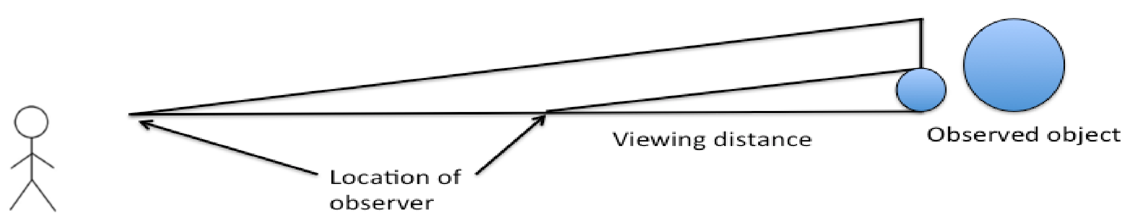

Figure 10. Graphical explanation that visual angle = (target diameter divided by viewing distance = tangent of retinal angle).

Contrast

In addition to retinal angle, contrast between the detected object and the UAS also plays a major role in what can be seen. Contrast is typically measured in terms of the brightness difference between target and background, or sometimes with that difference as a ratio relative to the background brightness (Weber fraction). In the present experiment, a white UAS was viewed against a mostly bright sky with varying cloud cover and cloud complexity (intermittent white/gray clouds against a blue sky). Occasionally the UAS may have caught the glint of the sun against a slightly darker sky. Brightness differences varied from 0.03 to 0.33 (Weber contrast), not a very high contrast situation. In general, at fixed retinal angle, target detection has been shown to be proportional to contrast. Thus, visual angle and contrast are closely coupled in determining what can be seen. Studies of what can and cannot be seen usually involve defining the detection threshold as what is visible 50% of the time.

Weather conditions

For distant targets, weather conditions may reduce the contrast. We could not control for atmospheric/weather conditions in the current study. The UAS may have been easier to detect under some conditions.

Motion

A moving target is somewhat easier to detect than a fixed one. In the current study, the UAS was stationary throughout the experimental trials—making it harder to detect that if it was moving.

Area of field of observation

Assuming the observer randomly searches within a given area of sky, the larger that area the longer the time required to find a target, which would account for the observer missing the target if the available time is insufficient. Use of binoculars enhance effective target size but increase area of the field to be observed, so that these two variables trade off.

Observer visual acuity

Poorer visual acuity would result in more targets missed. Since participants in this experiment had normal visual acuity, we assume this was not a major factor.

Observer visual fatigue

The current study was not long enough to make visual fatigue a significant factor in UAS detection for the controllers. It is unknown how much visual fatigue affects detection in actual operations

Attention and Workload

The most important factor that will determine whether or not something is noticed concerns where attention is directed at the time and what other tasks the observer is performing. In our experiment, the observer's sole task was to be on the lookout for a sUAS and inform the pilot of its presence. Because of this, these results would have to be interpreted as 'best case' and likely unachievable by a busy controller. In actual operations, a controller's attention is necessarily directed to various positions in and outside of the tower cab and to various locations on the airfield. While it would be feasible to incorporate all of these factors in a study, the cost would be considerable. Therefore, this 'best case' exploration was conducted first in order to determine if a more comprehensive study was desirable.

Comparisons with other target detection data

Duntley (1948) target threshold curves

Figure 11 provides a classical and widely accepted set of plots of the threshold (50% detection) distance for a target of given size, for a given Weber contrast, and for a given meteorological range (optical measure of transparency of the atmosphere). This set of plots is for full daylight and exclusive of the complexities in this experiment for detecting a target of complex shape while also monitoring an aircraft arrival. One uses this nomogram by drawing a straight line from the meteorological range at left to the contrast at right, and where that line intersects the curve for target area (square feet) determines the threshold distance.

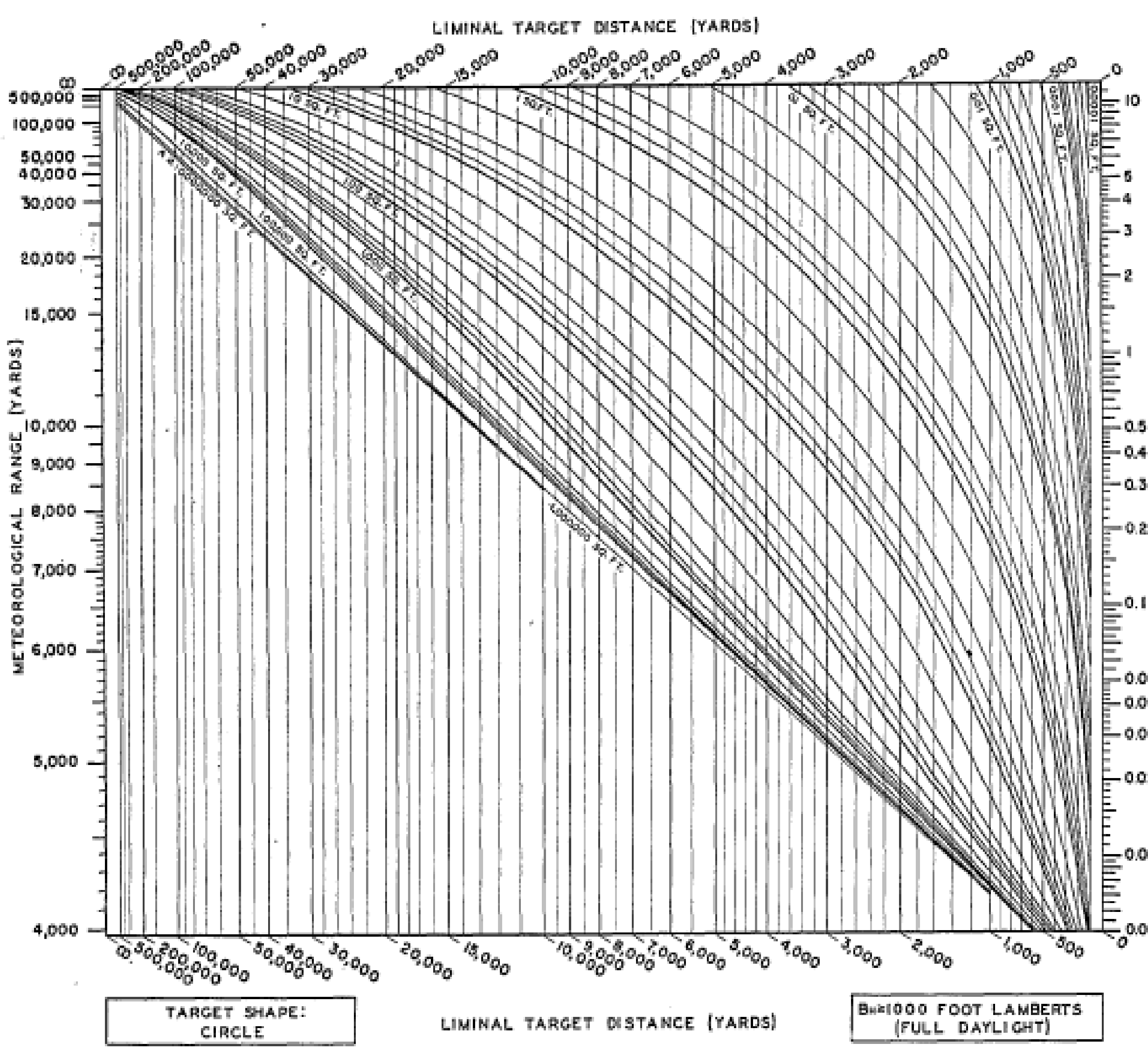

Figure 11. Nomogram showing threshold target distance as a function of target area, Weber contrast ratio, and meteorological range of the atmosphere. From Duntley (1948).

These curves were determined for much larger targets than used here, so we are working at the extreme right side of the nomogram. Nevertheless, for example, for meteorological distance of 10,000 yards and a target with contrast of 0.2 and 0.1 square foot area, the indicated liminal range is roughly 400 yards (= 1200 ft), about the same as the results in this experiment. Note that the non-circular projected area of the UAS was probably closer to 0.5 square feet, but the contrasts in this experiment were mostly smaller than 0.2, so these two factors would work in opposite directions and tend to counterbalance one another. Further, the Duntley curves are for ideal visibility conditions and 50% detection (in this experiment the detection rate was smaller). For all these reasons, including the greater complexity of this experiment, we conclude that to be detected the UAS had to be slightly closer than the equivalent combinations of contrast and target size in the Duntley curves.

Crognale (2009) experiment on detection of fixed wing UAS

In Crognale (2009), a Boeing Scan Eagle UAS pictured in Figure 12 was flown repeatedly toward ground-based experimental observers in fair weather at 25 m/s, and observers reported first sighting. Figure 13 shows that detection distances averaged 327 m = 981 feet with significant variability. The UAS wingspan was 3 m, but the projected image of the fuselage was closer to 0.5 m, closer to the projected image of the UAS in the present experiment. The visibility contribution of the wings is unclear.

Figure 12. A Boeing Scan Eagle photo from the viewpoint of the ground observer.

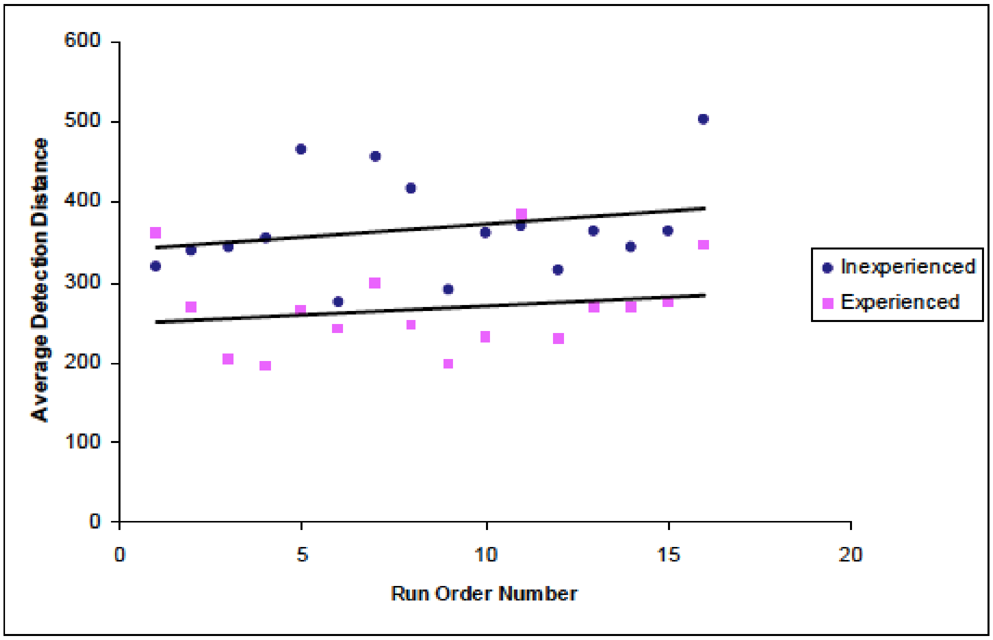

Figure 13. UAV detection distance results. Data from Crognale (2009). Y-axis is in meters.

Visual acuity from standard clinical acuity tests

Visual acuity is normally measured in a clinic by having the observer identify letters of the alphabet from a standardized Snellen eye chart, where the letters are 5 min of arc high, with 1 min of arc gaps between elements of the letters that must be resolved in order to discriminate the letters from one another. At 6 m distance 20-20 vision requires resolving gaps of 1.75 mm, a ratio of 0.0003, or about 1 arc min. This is not quite the same as detecting a black dot against a white background.

However, for comparison purposes, we note that a one foot diameter circular target at 1000 feet is 3.4 minutes of arc, and so 0.7 diameter target at 1300 feet (closer to the results in this experiment), is a ratio of .00054, roughly 1.7 min of arc. Thus, the target detection for observers in this experiment is close to the 1 min or arc gap resolution for 20-20 vision, and much better than just detecting the whole 5 minute of arc high Snellen letter itself.

Appendix D

Experimental Materials

- Informed Consent Form
- Questionnaires
    - Pre-Experiment/Background Questionnaire
    - Post-Trial Questionnaire
    - Post-Experiment Questionnaire
- Debriefing Form

Informed Consent Form

Individual's Consent to Participation in a Research Project
Small UAS (sUAS) Tower Controller Research
US Department of Transportation (DOT) Volpe Center

This research involves an experiment that is being conducted by the John A. Volpe National Transportation Systems Center, United States Department of Transportation (USDOT), and led by Dr. Kim Cardosi. This research is funded by the Federal Aviation Administration (FAA).

Purpose of Research. The number of small unmanned aircraft systems (sUAS) in the National Airspace System continues to grow. With increased operations, the potential for these operations to occur on or near an airport also increases. The purpose of this field experiment is to examine the ability of tower controllers to detect the presence of a small UAS operating in an airport traffic pattern and judge its distance from a manned aircraft. This research has been reviewed and approved by an Institutional Review Board. Up to nine participants will participate in this research.

Procedure. Each individual's participation is expected to take about two hours. The entire experiment will take place over the course of approximately one month.

From a constant location on the airfield, the participant (you) will provide instructions to a manned aircraft in the traffic pattern. On some trials, a small UAS will be present on the airfield. If you see the small UAS, you will inform the experimenter and provide a traffic advisory to the manned aircraft, if appropriate. You will use your best judgement to complete these tasks. When you are done with each trial and your participation as a whole, you will be asked to fill out a brief questionnaire about the experience. Audio recordings will be made during the study so that the researchers can review relevant communications later if needed. You must be able to stand throughout each trial (about 15 minutes). A chair will be available to sit down between trials, if you desire to do so. Your participation in each trial and your completion of the questionnaire is considered experimental. There are no alternative procedures.

Facilities. A bathroom is available on site and breaks will be provided as needed.

Discomfort and Risks. Risk involved with participating in this research is minimal, but, as with all UAS operations, does include the risk of collision between the participant and the sUAS. The manned aircraft and sUAS will be flown in accordance with all FAA rules and regulations. Neither the manned aircraft nor the sUAS will be flown directly over you. The research will only be conducted under good weather conditions, in which Visual Flight Rules apply and the wind is equal to or less than 20 knots, during daylight hours. If a medical emergency occurs, a member of the team will call 911 and cooperate fully to facilitate prompt medical attention. The participant assumes all risk of personal injury and related costs associated with participation. Notwithstanding this, for injuries resulting from wrongs committed by federal employees, the participant may seek redress under the Federal Tort Claims Act.

If you are an active tower controller, should you suffer a medical event while participating in the study, you agree to follow FAA and facility guidance on reporting this event.

Benefits to You and Compensation. Participation provides you with the opportunity to aid in the development of recommendations and/or requirements for the integration of sUAS into the National Airspace System. The only direct benefit to you is a $300 gift card for your participation. Full compensation will be provided for partial participation. Partial participation is defined to mean, at a minimum, attendance at the airfield on the participant's scheduled day and time of participation.

Costs. You are responsible for all costs incurred for participation this research, including but not limited to transportation costs to travel to and from the airfield, refreshments during participation and medical expenses resulting therefrom, if any.

Assurances and Rights of the Participant. Your participation in this experiment is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. Discontinuing participation at any time will involve no penalty or loss of benefits to which you are otherwise entitled.

The data you provide and that is collected by Volpe will be kept confidential. Audio recordings will be stored in a secured location; only the research team will have access to them. Your data shall remain anonymous and will be stored electronically in accordance with the National Archives and Records Administration (NARA) federal retention schedule. You will not be identifiable by name or description in any reports or publications about this research. You understand that no Personally Identifiable Information [PII] will be disclosed or released, except as required to carry out this research or as required by law or by DOT policy. DOT Policy concerning PII is provided in DOT Order 1351.18, "Privacy Risk Management." DOT Order 1351.18 permits the sharing of this data internally (e.g. as required in a federal government audit), so long as the purpose of sharing this data is compatible with the purpose for which it was originally collected.

If you withdraw from participation, data provided until the point of withdrawal will be stored and could potentially be used in the analysis. If you determine that you do not want your data used, you may inform the experimenter and your data will not be used for this research.

Orderly Termination. If you wish to withdraw for any reason, you must verbally inform the researcher and if entitled to compensation based on partial participation, will sign to indicate receipt thereof.

Your participation may be terminated, without regard to consent, if you do not/are unable to follow the instructions provided by the researchers. Researchers from the Volpe Center are available to any questions concerning procedures throughout the research.

Significant Findings during the Course of Research. Given the short duration of each individual's participation and the experiment overall, no significant findings are anticipated that would alter the planned procedures. It is unlikely, then, that this will impact the participant's willingness to continue participation.

Organization Responsible for this Research. This research is conducted by the John A. Volpe National Transportation Systems Center, United States Department of Transportation (USDOT), and led by Dr. Kim Cardosi, whose contact information is below. This research is funded by the Federal Aviation Administration. If you have any questions, including those pertaining to the research, a research participant's rights, and whom to contact in the event of a research-related injury, please contact:

Dr. Kim Cardosi
US DOT Volpe Center, 55 Broadway, Cambridge, MA 02142
Kim.Cardosi@dot.gov 617-494-2696

Statement of Consent. Please sign your name below so we have a record that you are voluntarily participating in this research and understand the information provided in this document. This document is stored separately from all other data you provide.

I have read this consent document. I understand its contents, and I freely consent to participate in this research under the conditions described. I have received a copy of this consent document.

Signature of participant ___________________________________ Date __________

Signature of experimenter ___________________________________ Date __________

Signature of witness ____ Date __________

Pre-experiment / Background Questionnaire

1. Age: _______
2. Gender: ______
3. Have you worked as an air traffic controller (ATC)? _______
4. Do you have Tower experience? _______
5. Confirm that you have 20/20 vision or better by selecting one of the following:
   __ 20/20 or better uncorrected
   __ Corrected to 20/20 or better
6. Please describe your ATC experience:

   a. Employment status (circle one): Current Controller Retired Controller

      If you are retired, how long has it been since you were employed as a controller (in years)? _________

   b. Length of employment (in years): ________

   c. Estimate your Tower experience (in years): _______

   d. Please list the airport Towers that you have worked at (if many, just list the five you worked at most):

   e. What controller positions have you worked? (check all that apply)

      __ Flight Data/Clearance Delivery
      __ Ground
      __ Local (Tower)
      __ Approach/TRACON
      __ En Route
      __ Other (e.g., air traffic management)

   f. In your experience as a controller, about how often do/did you encounter small Unmanned Aircraft Systems (sUAS; under 55 lb, Part 107) operating within your airspace? (e.g., one sUAS per day, three per week, etc.)

Post-trial Questionnaire

On a scale of 1-10 (1 = not at all confident, 10 = very confident), how confident are you that you:

1. Saw all of the small Unmanned Aircraft Systems (sUAS) that were flying in the vicinity of the manned aircraft? _______

2. Provided accurate traffic advisory information (sUAS location, distance, and altitude) to the manned aircraft (if applicable)?

   Location: _______

   Distance: _______

   Altitude: _______

Do you have any additional comments in this trial?

Post-experiment Questionnaire

1. Please describe your experience or knowledge of small Unmanned Aircraft System (sUAS) regulations in the US.

The following questions are about your experience during the experiment today.

2. Please describe any strategies you used to identify the presence of the sUAS:

3. Please describe any strategies you used to estimate the following:

    a. Location of the sUAS relative to the manned aircraft:

    b. Distance of the sUAS from the manned aircraft:

    c. Altitude of the sUAS:

4. What factors do you think would influence your ability to see the sUAS and provide an accurate traffic advisory (sUAS location, distance, and altitude) to the manned aircraft?

5. Please rate how difficult it was for you to both provide instructions to the manned aircraft and scan for sUAS traffic (please check one).

___ Difficult

___ Moderate

___ Easy

6. What factors do you think impacted your workload?

7. Please share any other comments you have about the experiment:

Debriefing Form

Small UAS (sUAS) Tower Controller Study
Summary

Thank you for participating in the study! Your participation provides the opportunity to aid in the development of recommendations/requirements for the integration of small Unmanned Aircraft Systems (sUAS) into the National Airspace System. The results will help to inform where sUAS are able to fly, and help to inform analyses of risk.

Please keep in mind that confidentiality is important to the validity of this field experiment. Please do not discuss the details of this experiment with any other participants or your friends.

This study is being conducted by the John A. Volpe National Transportation Systems Center, United States Department of Transportation (USDOT), and is being led by Dr. Kim Cardosi. The study is funded by the Federal Aviation Administration. If you have any questions or comments, please let us know.

For further information about this study, please feel free to contact:

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