Pilots' Estimation of Altitude of a Small Unmanned Aircraft System

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June 2018

DOT/FAA/TC-18/23
DOT-VNTSC-FAA-18-03

Prepared for:
US Department of Transportation
Federal Aviation Administration
800 Independence Avenue, SW
Washington, D.C. 20591

U.S. Department of Transportation
John A. Volpe National Transportation Systems Center

Volpe

Notice

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE June 2018	3. REPORT TYPE AND DATES COVERED Final report

4. TITLE AND SUBTITLE Pilots' Estimation of Altitude of a Small Unmanned Aircraft System	5a. FUNDING NUMBERS 51FA0IB700
6. AUTHOR(S) Tracy Lennertz, Andrea L. Sparko, Kim Cardosi, Alan Yost, Andrew Kendra, Jason Lu, and Tom Sheridan	5b. CONTRACT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Department of Transportation John A Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142-1093	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FAA-18-03
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Department of Transportation Federal Aviation Administration Emerging Technologies (AJV-0) 800 Independence Avenue, SW Washington, D.C. 20591	10. SPONSORING/MONITORING AGENCY REPORT DOT/FAA/TC-18/23
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Small unmanned aircraft system (sUAS) operations are growing at a rapid rate. Currently, the FAA permits both hobbyist and commercial operations; for commercial operations, the sUAS must generally be flown under 400 feet. We examined the ability of commercial and hobbyist sUAS pilots to estimate the altitude of their ownship during a realistic flying task. Participants were instructed to fly a DJI Phantom 4 Pro sUAS to three prescribed altitudes: 50 feet, 200 feet, and 350 feet from its starting point and take a photo of a target. Results indicated that participants' altitude estimates were below the prescribed altitude of 50 feet 52% of the time, and they were below prescribed altitudes of 200 feet and 350 feet 89% of the time. Performance did not differ between hobbyist and commercial pilots. Variability in absolute and barometric measurements of altitude was also observed. The results suggest that sUAS pilots are poor at judging the altitude of their ownship, especially at higher altitudes. The variability in performance and altitude measurements indicates that pilots need a reliable and standard way to measure the altitude of their ownship.

14. SUBJECT TERMS Unmanned aircraft system, unmanned aerial vehicles, UAS, sUAS, altitude estimation, ground observer	15. NUMBER OF PAGES 34
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

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 and Abbreviations

AGL	Above Ground Level
ANOVA	Analysis of Variance
ASRS	Aviation Safety Reporting System
ATIS	Automatic Terminal Information Service
BED	Lawrence G. Hanscom Field Airport
C.I.	Confidence Interval
COA	Certification of Authorization
FAA	Federal Aviation Administration
FT or ft	Feet
lbs	Pounds
LSD	Least Significant Difference
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
VLOS	Visual Line of Sight
VMC	Visual Meteorological Conditions

Preface

This report was prepared by the Aviation 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 Maura Lohrenz and David Moore for comments on an earlier draft.

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Executive Summary

Small unmanned aircraft system (sUAS) operations are growing at a rapid rate, with an increasing number of civilian operations. Currently, the FAA permits both hobbyist and commercial operations. The requirements for the operations differ; for commercial operations, the sUAS must generally be flown under an altitude of 400 feet or within 400 feet of a structure. Past data indicate that operators are poor at judging the altitude of sUAS, and there is variability in the altitude information that is presented to the operator. Here, we examined the ability of commercial and hobbyist sUAS pilots to estimate the altitude of their ownship during a realistic flying task. Participants flew a DJI Phantom 4 Pro to three prescribed altitudes: 50 feet, 200 feet, and 350 feet. In each trial, the participant flew the sUAS from its starting point, hovered at what he or she estimated to be the prescribed altitude, and took a photo of a target. Results indicated that participants' altitude estimates were below the prescribed altitude of 50 feet (i.e., they flew the sUAS at a lower altitude than instructed) 52% of the time and below prescribed altitudes of 200 feet and 350 feet 89% of the time. Despite differences in pilots' backgrounds, performance did not differ between hobbyist and commercial pilots. Variability in absolute and barometric measurements of altitude was also observed. Taken together, the results suggest that sUAS pilots, regardless of their experience, are poor at judging the altitude of their ownship—especially at higher altitudes. The variability in performance and altitude measurements indicates that pilots need a reliable and standard way to measure the altitude of their ownship, especially given the increasingly complex environments in which sUAS intend to fly.

Introduction

Small unmanned aircraft systems (sUAS) are taking to the sky at a rapid rate. A recent study (U.S. Department of Transportation (DOT) Volpe National Transportation System Center, 2013) predicts that over 250,000 UAS will be in operation around 2035 and about 70% of these will be civilian operations. Currently, the Federal Aviation Administration (FAA) permits both hobbyist (i.e., "flying for fun") and commercial (e.g., aerial photography, real estate, infrastructure repair, or emergency services) operations. The FAA requirements differ for the operator and aircraft, depending on the purpose of flight. For hobbyists, the sUAS must be flown within visual line of sight (VLOS) of the operator or an observer, must be under 55 pounds (lbs.), and must be flown at least five miles away from an airport unless prior authorization is received from Air Traffic Control. Hobbyists are also required to follow a community-based set of guidelines (i.e., the Academy of Model Aeronautics Safety Handbook, 2018). There are no specific pilot requirements for hobbyist operators. For commercial operations, under Title 14 of the Code of Federal Regulation (14 CFR) Part 107 (cf. FAA Advisory Circular 107-2, 2016), the aircraft must also be under 55 lbs., the operator must be at least 16 years old and have a Remote Pilot Airman Certificate, and must follow several operating rules—the aircraft must be flown in uncontrolled (Class G) airspace and must be kept in VLOS. The sUAS must also be flown under 400 feet above ground level (AGL) or within 400 feet of a structure (e.g., up to 400 feet above a structure; see faa.gov/uas). Note that many of these restrictions can be waived with approval from the FAA. While these requirements are necessary to integrate sUAS into the National Airspace System, it is unclear whether operators can accurately perform such tasks. In particular, it is not clear that operators can accurately judge the altitude of their aircraft without technical assistance (such as an altimeter).

Data indicate that people are poor at judging the altitude of their ownship. Crognale (2009) studied ground observers' ability to judge distance and altitude and to determine whether or not the UAS was on a potential collision course with another aircraft. He found that the ability to judge distance and altitude varied by observer with "relatively low accuracy for altitude judgments and worse than that for distance judgments" (p. 44). Judgments of potential collision were also inconsistent between observers. While these results are useful, additional data are needed to address current sUAS operations, occurring under 400 feet, for three reasons. First, the UAS used in Crognale (2009) had six to nine foot wingspans, which are much larger than typical quadcopters. Second, the lowest altitude tested was 200 meters (656 feet), which exceeds the altitudes that sUAS are currently permitted to fly. Finally, participants estimated altitude only and were not engaged in a realistic flying task. For these reasons, data are needed to assess sUAS pilots' ability to estimate their own vehicle's altitude.

Moreover, research indicates that the human visual system may not be sufficient to comply with some of the requirements of Part 107 operations (Williams & Gildea, 2014; Woo, 2017). In particular, it is difficult for a pilot or visual observer to maintain visual contact with a sUAS, especially when carrying out other duties, such as scanning for traffic. Estimating the altitude of ownship may be even more difficult if one is required to momentarily take one's eyes off the sUAS to complete concurrent tasks.

sUAS vary widely, in both price and complexity. Some sUAS cannot track the altitude of the unmanned vehicle. Of sUAS that have an altitude tracking capability, the controls on sUAS may not allow the operator to monitor the altitude in real time. Currently, there is not a requirement for sUAS to have an altitude reporting capability under Part 107. When altitude is reported, there is no standard reference point from which to measure it (i.e., ground-based, pressure-based, or referenced from the altitude of the "launch point").

A 2016 report from the Aviation Safety Reporting System (ASRS) from a pilot highlights the inconsistency in altitude reporting during a small UAS operation:

> "I hold two FAA ratings: Part 61 Private Pilot … and Part 107 Remote Pilot, small Unmanned Aircraft System… it is believed the altitudes indicated during flight were not accurate even after the UAS was properly calibrated over a grass surface. Some of the recorded altitudes indicate higher than 400 Above Ground Level [AGL] and … this may be a composite measurement of the launch point altitude [and the terrain the sUAS was flown over]."

Another ASRS report indicates that the controls put in place to prevent the sUAS from flying higher than intended do not always work:

> "The application has an altitude limitation option which was on by default to … on or about 9 meters …The aircraft was outside and went into an uncontrolled straight vertical climb. The…range is about 20 meters, which it rapidly exceeded and lost connectivity with the controller. The UAS, being so small (approximately 5 inches in length, 5 inches in width, and 2 inches height) continued to climb until we lost visual contact. The device had approximately 80% battery life remaining, and can fly up to 5-10 minutes at full charge. I do not know how high the UAS climbed out of control before it began a descent. The UAS has not been found. There were no other aircraft in the immediate vicinity" (2014, as reported in Cardosi & Lennertz, 2017).

Given the requirements for sUAS flight, the lack of operational data, and the current limitations on sUAS flight control, data are needed to understand pilots' ability to estimate the altitude of their unmanned vehicle.

Purpose

The current study examined the ability of commercial and hobbyist sUAS pilots to estimate the altitude of a sUAS. Pilots were instructed to fly a small quadcopter UAS (a DJI Phantom 4 Pro) to three prescribed altitudes: 50 feet, 200 feet, and 350 feet. In each trial, the pilot flew the UAS to a specified location, hovered at one of three prescribed altitudes, and took a photo of a target on the ground (a configuration of cones). Pilots used their own judgement in determining their altitude. Each pilot flew to all three altitudes, three times (9 trials); trial order was randomized.

Pilots varied in their level of experience: one-half of the participants were Part 107 (commercial sUAS) pilots; the other half were hobbyist pilots. All flights occurred on a model aeronautics airfield, in Class G airspace, and in Visual Meteorological Conditions (VMC). The "absolute" altitude of the sUAS was measured using a range finder, an inclinometer (measuring the angle of the UAS by an observer at a known distance), and an image analysis of the photos taken from the sUAS (calculating altitude from the image based on the known geometry of the target). Pilots' judgments of ownship altitude were compared with the absolute altitude measurements.

Given that current FAA Part 107 regulations permit flight under 400 feet, the chosen altitudes examined pilot behavior at allowable altitudes. The DJI Phantom 4, a popular sUAS typically flown by both commercial and hobbyist pilots (Gettinger & Michel, 2017), was used. Pilots took a photo to replicate a typical task that a sUAS is used for during flight.

Method

Participants

Eighteen sUAS pilots (9 commercial, 9 hobbyist) participated. Nine of the participants were commercial pilots who held a Remote Pilot Airman Certificate under Part 107 (n=8) or had a Certificate of Waiver or Authorization (COA) from the FAA to operate UAS (n=1). The other nine participants were hobbyist pilots who were employed by the U.S. DOT Volpe Center. Commercial pilots were compensated for their participation with $200 in Amazon.com purchase cards. Volpe Center employees were paid for their time as part of their normal work day and their travel expenses were reimbursed.

All participants owned a small quadcopter UAS or operated one on a regular basis. Table 1 provides a list of the make/model of sUAS owned, along with how many participants owned it (several participants owned more than one). A background questionnaire gathered additional information about participants' sUAS use. When asked how many times they had flown their sUAS in total and in the past year, most participants only listed one number; commercial pilots had flown between 15 to 700 times and hobbyist pilots had flown between five and 20 times. Three commercial pilots specified their total flights in the past year, which ranged from 15 to 60 times, and one hobbyist pilot reported flying 12 times in the past year.

Table 1. Make and model of sUAS owned by participants.

Make/Model	Commercial	Hobbyist	Total
DJI Phantom 1/2/3/4 [Pro/Advanced]	5	3	8
DJI Mavic [Pro]	6	1	7
DJI Inspire [1 Pro]	2	0	2
Toy, make/model unknown	0	2	2
PS3	1	0	1
DJI Spark	1	0	1
Parrot AR drone	0	1	1
Typhoon	0	1	1
Protocol Neo-Drone Mini	0	1	1
DX-4 by Sharper Image	0	1	1
None	0	1	1

Participants were also asked to describe their typical sUAS flight. Their responses were placed into categorizes by flight purpose, and are listed in Table 2.

Table 2. Participants' typical sUAS flight purpose.

Purpose	**Commercial**	**Hobbyist**	**Total**
Aerial photography/videography	8	2	10
Fun, leisure	0	7	7
Aerial surveying	1	1	2
Research, measurements	0	2	2
Skill building, practice	1	1	2

Facility, Equipment, and Materials

Flying Field

The study was conducted in a field located in Acton, Massachusetts, with permission from the town. The field was chosen because it was flat and there were minimal visual references to altitude within close proximity of the field (trees, telephone poles, and a highway were visible several hundred yards away, but participants were not given their distances or height). The field was located about five and a half miles from Lawrence G. Hanscom Field Airport (BED), which was used as a reference point for obtaining weather information via the Automatic Terminal Information Service (ATIS).

Eleven orange traffic cones were placed in the field in a "+" shape, approximately 200 feet from the participant. The cones served as a target for participants to fly out to and hover when establishing altitude. The cones were placed at specified distances from each other so that they could be used by the experimenters to calculate altitudes from the sUAS photographs. A picture of the flying field is provided in Figure 1. An aerial image of the target configuration is shown in Figure 2.

Figure 1. Flying field.

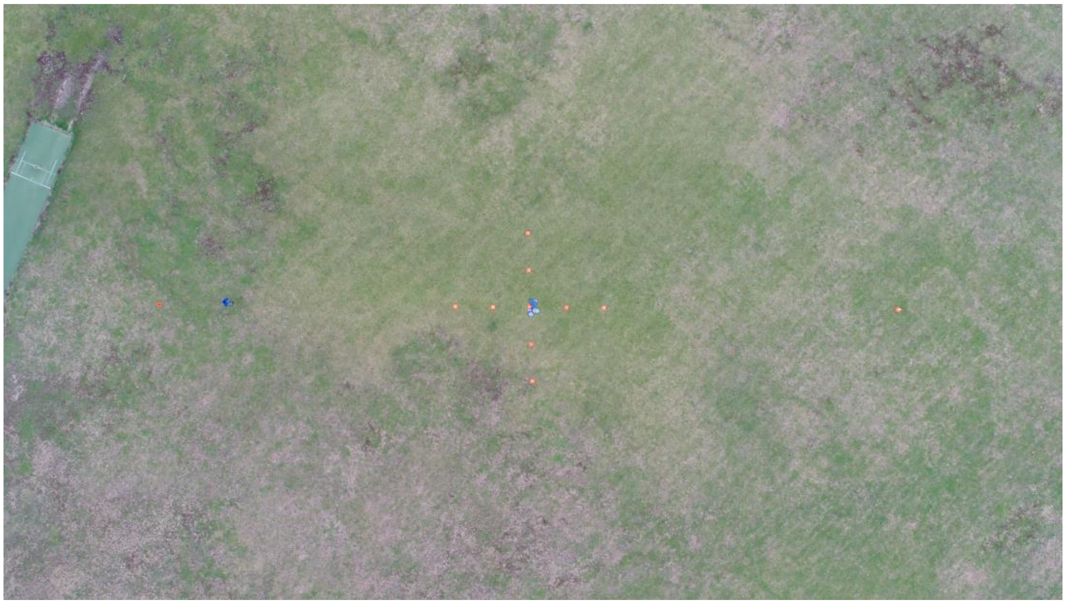

Figure 2. Aerial image of target configuration (from 200 feet).

Small UAS

The sUAS used in this study was a DJI Phantom 4 Pro with a small tablet display. This sUAS, shown in Figure 3, has a diagonal rotor span of about 14 inches and weighs about 3 pounds. The display's altitude readout was concealed by a piece of tape so that participants could not use it for their altitude estimates. Six extra batteries were kept charged in the case of a battery change.

Figure 3. The DJI Phantom 4 Pro.

Altitude Measurement Tools

Altitude was measured when the sUAS was hovered over the center cone to take the aerial photograph. Four methods of altitude measurement were used:

1. sUAS—The barometric AGL altitude of the sUAS, above the takeoff point, was captured and included in the Exchangeable Image File Format in the aerial photos taken by the participant.
2. Range Finder—An experimenter positioned at the center cone used a range finder to measure the vertical distance from the ground to the sUAS. The range finder has an accuracy of +/- 1.5 feet. The range finder typically measured the altitude from the body of the sUAS, which falls about one foot below the rotors, however this may have been less accurate at higher altitudes. Given these parameters, the accuracy of the range finder was about +/- 3 feet.
3. Inclinometer—Experimenters used an inclinometer to measure the angle between the ground and the sUAS. The inclinometer has an accuracy of +/- 0.25 degrees. Note, the accuracy of the inclinometer declines as its angle increases.
4. Image analysis—Using the camera resolution and distance between cones, altitude was calculated by counting the number of pixels between the cones in the aerial photograph taken from the sUAS.

Forms and Questionnaires

Each participant was required to read and sign an Informed Consent Form when they first 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 flying the sUAS; it asked about the participants' past experience with sUAS. The post-trial questionnaire was completed after each of the nine trials; it asked participants to rate how confident they were that the sUAS flew to the correctly prescribed altitude, and for additional comments if they had them. The post-experiment questionnaire was completed after all trials were completed; it asked pilots about their experience participating in the study (strategies, task difficulty, and workload). All forms and questionnaires were filled out 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 Appendices A and B.

Logs and Checklists

Experimenters used a paper log sheet to record the pre- and post-experiment weather, altitude measurements, and the times that each aerial photograph was taken. The log sheets also had a checklist for giving the sUAS operation instructions and directing the practice flight. A separate log sheet was used to keep track of the Amazon purchase cards distributed. The experiment log sheet is provided in Appendix C.

Design

The experimental design included two independent variables: 1) prescribed altitude (three levels: 50 feet, 200 feet, 350 feet) and 2) experience (two levels: commercial, hobbyist). Each participant flew the sUAS to all three prescribed altitudes three times, for a total of nine trials. The trials were separated into three blocks, each containing the three prescribed altitudes in a random order. The order was randomized for each block for each participant to counteract potential order effects.

Procedure

Participants completed the study individually. Three experimenters were present to take altitude measurements and administer the questionnaires and instructions. The study was conducted in VMC during the day.

After obtaining Informed Consent, the participant completed a background questionnaire. Next, an experimenter demonstrated the sUAS controls to the participant. The participant then flew a practice trial to familiarize him or herself with the field and the sUAS controls, including how to take a photo. After the practice trial, the participant flew the nine trials in three blocks. For each trial, the participant flew the sUAS from its starting point near the participant to the cones, hovered over the center cone at what he or she estimated to be the prescribed altitude, and took a photo. The participant was not instructed on how to reach altitude. The sUAS remained in hover while the experimenters took range-finder and inclinometer measurements. When the experimenters were done taking measurements, the participant was instructed to return the sUAS to its starting point and turn the engines off to recalibrate the barometer. No feedback was given to the participants as to the actual altitude of the sUAS during the experiment. Following each trial, an experimenter administered a short questionnaire that asked the participant to rate his or her confidence that the sUAS flew to the correctly prescribed altitude. After all nine trials were completed, the participant completed a post-experiment questionnaire. The participant was then given the debriefing sheet. The entire study took approximately one hour to complete per participant.

Results

Altitude Measures

Two types of altitudes were measured in this study: barometric and absolute. Barometric altitude is the height AGL of the sUAS as measured by differences in barometric pressure between the takeoff point and the barometric pressure at the current altitude; this is the altitude that pilots would typically use on a sUAS display. Absolute altitude, as measured by the range finder, inclinometer, and image analysis, was the actual distance between the sUAS and the ground. For assessing participants' accuracy in estimating altitude, absolute altitude was used as the dependent variable because pilots would be expected to use height-off-the-ground as a basis for their estimates when using a sUAS without telemetry. The three measures of absolute altitude were highly correlated (all $r > .99$, $p < .001$), so the average of all three measures was used in the statistical analyses.

Estimation Accuracy

Participants' accuracy in estimating altitude was examined two ways. First, the overall accuracy was assessed by looking at the distribution of participants' achieved altitudes (i.e., their estimates) at each prescribed altitude (50, 200, and 350 feet). One-sample t-tests compared the average achieved altitude to the prescribed altitude to see if participants' estimates were significantly different from prescribed. Second, achieved altitudes were converted into absolute deviations from prescribed altitude, i.e., the difference between participants' achieved altitude and prescribed altitude, regardless of whether the estimate was higher or lower than prescribed. Absolute deviation was used as the dependent variable in a factorial analysis of variance (ANOVA) that tested for potential effects of three variables: prescribed altitude (50, 200, 350 feet), practice (trials 1, 2, and 3), and pilot experience (commercial, hobbyist). Altitude and trial were compared within participants and experience was compared between participants.

Figure 4 shows the distribution of achieved altitudes. The lower, middle, and upper lines that form the box represent the 25th, 50th, and 75th percentiles, respectively. The average achieved altitude, calculated across all participants and trials, is represented by the red "X". The error bars are the minimum and maximum. The majority of participants' estimates were below the prescribed altitude (i.e., they flew the sUAS at a lower altitude than instructed): 52% of trials were below the prescribed altitude of 50 feet, and 89% of trials were below prescribed altitudes of 200 feet and 350 feet. Eleven percent of trials were above prescribed altitudes of 200 feet and 350 feet. At the prescribed altitude of 200 feet, the 11% consisted of trials from three participants: one participant was above 200 feet for all three trials, one participant was above for two trials, and one participant was above for one trial. The 11% of trials that were above the prescribed altitude of 350 feet were flown by two participants; both were above 350 feet for all three trials (one participant was the same pilot who flew above 200 feet for all three trials, and the other was the participant who flew above 200 feet once). All of the trials that were flown above the prescribed altitude of 350 feet exceeded 400 feet. One participant flew as high as 520.5 feet and the other flew as high as 611.5 feet.

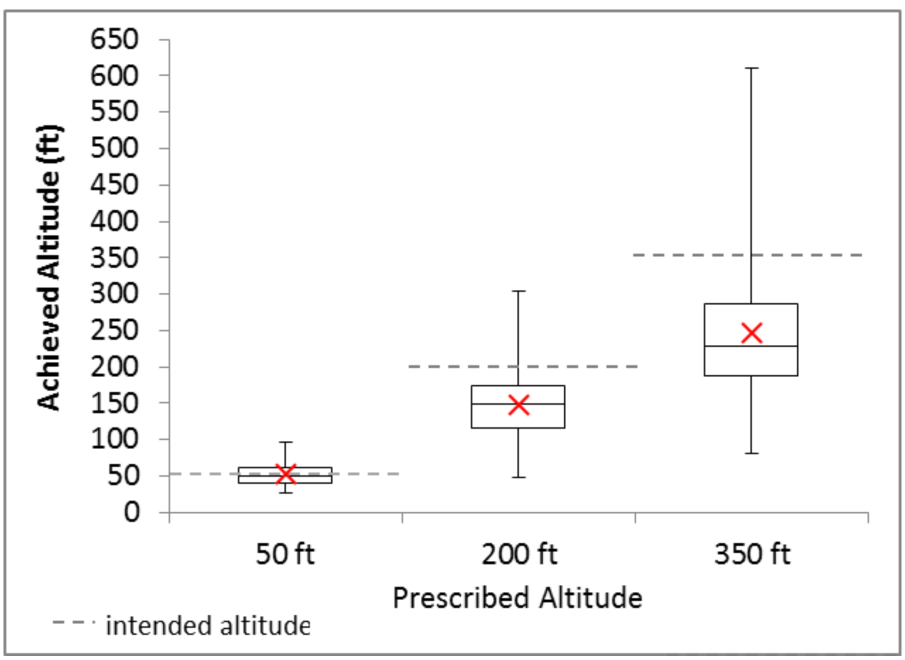

Figure 4. Distribution of achieved altitudes.

Results of the t-tests revealed that participants' estimates of 50 feet were relatively close to 50 feet (no statistically significant difference between prescribed and achieved altitude; *M*(achieved)=52.5, *SD*=17.1). However, when estimating 200 feet, participants' achieved altitudes were significantly low at an average of 148.4 feet (*SD*=53.8), $t(53) = -7.05$, $p < .001$. They were also significantly low when estimating 350 feet, with an average achieved altitude of 247.4 feet (*SD*=111.7), $t(53) = -6.57$, $p < .001$. In the ANOVA results, there was a significant main effect of altitude, indicating that participants' estimation error was significantly different depending on prescribed altitude, $F(1.19, 18.99) = 72.96$, $p < .001$ (due to a violation of sphericity, the degrees of freedom were adjusted using the Greenhouse-Geisser correction). Pairwise comparisons using Fisher's Least Significant Difference (LSD) test revealed that the average deviation from prescribed altitude got larger as prescribed altitude increased (all $p < .001$). Table 3 shows the mean, SD, 95% confidence interval (C.I.), and range of the absolute deviation from each prescribed altitude.

Table 3. Absolute deviation (in feet) from prescribed altitude.

Prescribed Altitude	Mean	SD	95% C.I.	Range
50 ft	13.4	7.5	9.5-17.2	1.0-46.6
200 ft	63.0	37.2	44.9-81.1	1.5-151.9
350 ft	137.9	61.7	108.1-167.8	11.0-269.5

There were no significant effects of pilot experience or trial and there were no interactions. That is, commercial pilots were no better at estimating altitudes than hobbyist pilots. Estimation error did not improve with practice (as expected, since participants were not given feedback on their estimates). For most participants, the direction of their estimation error was consistent across trials (i.e., always above or always below prescribed altitude), but the magnitude of the error varied across trials for most participants.

Absolute vs. Barometric Altitude

The above results suggest that pilots are poor at estimating sUAS absolute altitude at the higher altitudes used in this study. In some sUAS operations, pilots may have a barometric altitude readout available on their sUAS display. Barometric altitude is determined based on a standard day temperature of 15ºC, and any variation from that temperature will cause inaccuracies. To demonstrate the inaccuracies, a paired t-test compared participants' absolute altitude (averaged across the three measurements) to barometric altitude for each trial. On average, barometric altitudes were 7.5 feet greater than absolute altitudes, and this difference was statistically significant, $t(158) = 14.26$, $p < .001$. Thus, even with a sUAS altitude readout, pilots' achieved altitudes may only be an approximation of absolute altitude.

Confidence Ratings

Participants' post-trial confidence ratings were provided by choosing one of three options: not at all confident, somewhat confident, and very confident. Numeric scores were assigned to each answer choice, with 1 = not at all confident and 3 = very confident. The median score was 2, “somewhat confident,” for all prescribed altitudes. There were no significant differences in participants’ confidence by pilot experience and confidence did not improve with subsequent trials.

Strategies and Factors that Influenced Altitude Estimation

On the post-experiment questionnaire, participants were asked to describe any strategies they used to estimate the altitude of the sUAS and what factors influenced their altitude estimation. Participants’ responses are summarized below (with n=number of participants). There were no differences in responses based on pilot experience.

Strategies identified by participants

- Guessed the height of visual references that were either present (trees, telephone pole, own height) or imagined (house, football field) (n=14), sometimes multiplying those guesses to reach the desired altitude (n=7)
- Referenced the size of sUAS in the sky or on the screen (n=5)
- Used the rate of ascent to help estimate altitude (n=3)
- Guessed height with no references (n=2)
- Other: Noted viewing angle at an estimated altitude (e.g., 10 feet) and increased angle in increments to achieve prescribed altitude (n=1); Flew sUAS closer to self when estimating lower altitudes, before flying to target (n=1)

Factors identified by participants that influenced altitude estimation

- Pilot’s distance from the sUAS/cones (n=5)
- Lack of visual references (n=2)
- Caution/desire not to exceed prescribed altitude (n=2)
- Other: Limited experience (n=1); Small size of the DJI Phantom 4 Pro made it appear farther away than it actually was (n=1)

Task Difficulty and Workload

Participants were asked on the post-experiment questionnaire to rate the difficulty of the task of hovering at the specified altitude and taking a photo. They were also asked to describe any factors that impacted their workload. All 18 participants rated the difficulty of the task as “easy.” The factors that participants listed as impacting their workload varied, but factors that were mentioned by more than one participant included wind (n=5), cold (n=3), presence of the experimenters (n=3), and the ease and functionality of the DJI Phantom 4 Pro (e.g., auto-hover; n=2). Three participants said that the task was easy and no factors influenced their workload.

Discussion

Given the lack of operational data, the requirements for sUAS flight, and the limitations on sUAS flight control, the current research examined the ability of pilots to estimate the altitude of their small unmanned aerial vehicle (UAV). Due to pilot requirements for Part 107 operations, we were further interested in differences in performance between commercial and hobbyist pilots. We also examined the effect of practice during the experiment itself.

Despite differences in background, performance did not differ between hobbyist and commercial pilots: there was no effect of experience. Pilots in both groups performed similarly in estimating the three different altitudes. We also did not observe any effect of practice without feedback; participants did not improve their ability to estimate altitude throughout the course of the study. Our main finding is that participants are generally poor at estimating the altitude of a small unmanned vehicle and estimation performance is worse at higher altitudes. Participants were generally conservative in their flight altitudes, such that their altitude estimates were below the prescribed altitude of 50 feet 52% of the time, and they were below prescribed altitudes of 200 feet and 350 feet 89% of the time. Thus, the majority of participants overestimated the altitude of their sUAS at higher altitudes, and so flew lower than were instructed; few participants actually reached the prescribed altitudes of 200 or 350 feet. These errors were 'fail safe' in that pilots thought they were flying higher than their actual altitude. Without an observer monitoring their altitude, however, errors in which pilots thought they were flying lower than their actual altitude would be expected to occur more frequently.

Participants' confidence in performance did not vary by altitude; participants generally reported they were "somewhat confident" in their ability to fly the sUAS to the prescribed altitude. It is not surprising that this did not differ by experimental trial, as no effect of experience was observed. It is surprising, however, that this did not vary by altitude, given that altitude estimation performance actually declined at higher altitudes. Participants mentioned several strategies used to estimate the altitude of the sUAS. Most often, participants indicated that they used the height of nearby references, such as a tree or telephone pole. The site of the study, however, a relatively flat field, had few visual references. It is possible that performance at estimating higher altitudes may improve with the presence of reliable visual references, and/or accurate feedback. Participants also indicated the task was "easy", in some cases, this was attributed to ease and functionality of the DJI Phantom 4 Pro.

These results suggest that sUAS pilots are generally cautious and would likely fly their ownship below 400 feet in real-world operations. Even though participants were engaged in a real-world task (operating a sUAS and taking a photo), it is important to note that their behavior may have been tempered since it was being observed (in fact, two participants mentioned that a desire not to exceed the prescribed altitude influenced their estimation). Operators are likely to be less conservative in actual operations. In a minority of cases, as observed in the current study, pilots may exceed the 400 feet threshold. Given these cases, it is imperative that error mitigation strategies are in place (such as a means for the pilot to view the absolute altitude of the sUAS in real time or controls that prevent the sUAS from flying above a prescribed altitude).

Finally, our field data demonstrates the variability in measuring the altitude of the sUAS. There was a significant difference between the absolute altitude (as measured by the range finder, inclinometer, and the image analysis) and the barometric altitude (as measured onboard the sUAS). The FAA currently does not require a standard way to measure or indicate ownship altitude to sUAS operators. Given the responsibility of operators to fly the sUAS below 400 feet (or within 400 feet of a structure), it is imperative that operators have accurate tools to determine their altitude. It would also be prudent to offer basic training to operators on how to estimate altitude. In particular, it is possible to estimate the altitude of the UAV if one roughly knows both the ground distance from the target, and viewing angle of the UAV (e.g., the UAV is about 100 feet away and at an incline of about 45 degrees). While this method would only generate an estimate, it may be helpful for operators to be aware of this heuristic, especially in the absence of an altitude indicator. This method could be covered in training for Part 107 pilots. Training could also include the heights of common objects that could be used as reference when estimating altitude (e.g., telephone poles are about 40 feet, a one-story buildings is about 10 feet). A review of the FAA's Remote Pilot – Small Unmanned Aircraft Systems Study Guide (2016) indicates that these heuristics to estimate altitude are not included.

Limitations of the Current Research

Despite the real-world applicability of the results, the current study has some limitations. In particular, we examined operator performance against a single background: an unobstructed sky view with a horizon of trees. In general, this background was not complex and it was easy to maintain visual contact with the UAV at all times. As previously mentioned, performance may actually improve with a background that allows the operator to compare the altitude of the UAV with a nearby structure (e.g., a tall tree or a building). It may also, however, be more difficult to maintain visual contact with the UAV in a more complex environment with a partially obstructed view (e.g., nearby trees, mountains, or buildings; cf. Crognale, 2009, Loffi, Wallace, Jacob, & Dunlap, 2016).

Another limitation of the current work is that only one sUAS was a tested, albeit a readily available and popular model—the DJI Phantom 4 Pro. Many sUAS, however, are smaller in size and lack the sophisticated and easy-to-use controls of the Phantom 4 Pro. With a smaller and less sophisticated sUAS, it would likely be even more difficult to judge the altitude of the UAV. It is also easier to estimate the altitude of a stationary object compared to a moving one (cf. Williams & Gildea, 2014), in our case, the UAV as it hovered over the target to take a photo. Unmanned aircraft are often not stationary in real-life operations, for example, with emergency response, or real-estate photography.

Conclusion

Taken together, the results suggest that sUAS pilots, regardless of their experience, are poor at judging the altitude of their ownship. Though participants were "somewhat confident" in their performance regardless of altitude, participants overestimated their achieved altitude, flying lower than instructed, especially at higher altitudes. The presence of additional visual cues, such as buildings or trees, may provide a point of reference and assist pilots in judging their own altitude.

Future integration seeks to enable operations over people and in extended or beyond visual line of sight (FAA, 2012; 2013; 2016). The variability in performance and altitude measurements indicates 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.

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Appendices

Appendix A: Participant Forms

Appendix A contains the:

- Informed Consent Form
- Debriefing Form

Informed Consent Form

Individual's Consent to Voluntary Participation in a Research Project
Small UAS (sUAS) Pilot Altitude Estimation Study
US Department of Transportation (DOT) Volpe Center

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. This study is funded by the Federal Aviation Administration (FAA), Emerging Technologies Division.

Purpose of Study. Currently, the FAA requires that small Unmanned Aircraft Systems (sUAS) are flown below 400 feet and within visual line of sight. The current field measurements will examine the ability of pilots to estimate the altitude of a sUAS. This work will inform the criteria for conducting quantitative assessments of preapproved altitudes for sUAS and inform analyses of risk. This study hs been reviewed and approved by an Institutional Review Board.

Procedure. The entire experiment is expected to take about one hour. You will fly a DJI Phantom 4 sUAS to a pre-determined altitude, briefly hover at that altitude and take a photo of a target object. You will use your judgement to estimate the altitude of the vehicle. You will not physically handle the sUAS, all set-up will be carried out the by experimenter. When you are done with each trial and the experiment as a whole, you will be asked to fill out a brief questionnaire about the experience.

Discomfort and Risks. Overall risk involved with participating in this study is low. The sUAS will be flown in accordance with all FAA rules and regulations. You acknowledge and assume all risk of injury ordinarily associated with UAS operations.

Benefits to You. Participation provides you with the opportunity to aid in the development of recommendations/requirements for the integration of sUAS into the National Airspace System. We also hope that you will enjoy having a chance to fly the sUAS.

Assurances and Rights of the Participant. Your participation in this experiment is completely voluntary. The data you provide and that is collected by Volpe will be kept confidential within the research team. Your data shall remain anonymous. You will not be identifiable by name or description in any reports or publications about this study. You understand that no Personally Identifiable Information [PII] will be disclosed or released, except as required to carry out this study or as required by law or by DOT policy. You may withdraw from this study at any time without penalty. Data provided until the point of termination 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 study.

Organization Responsible for this Study. 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, whose contact information is below. This study is funded by the Federal Aviation Administration, Emerging Technologies Division. If you have any questions, please let us know. For further information about this study, please contact:

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 study 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 study under the conditions described. I have received a copy of this consent form.

Signature of participant ___________________________________ Date __________

Signature of experimenter ___________________________________ Date __________

Signature of witness ____ Date __________

Debriefing Form

Small UAS (sUAS) Pilot Altitude Estimation 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. We also hope that you enjoyed flying the sUAS.

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, Emerging Technologies Division. 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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Appendix B: Questionnaires

Appendix B contains the:

- Demographics Questionnaire
- Post-trial Questionnaire
- Post-experiment Questionnaire

Background Questionnaire

Participant number: _______
Date: ___________________

1. Age
2. Gender
3. Do you own a small Unmanned Aircraft Systems (sUAS)? If yes, what make(s)/model(s)? How long have you owned the sUAS?
4. Approximately how many times have you flown the sUAS? (Total and in the past year?)
5. Please describe your typical sUAS flight. (Include typical purpose of flight, duration, and route).
6. Do you have experience flying any other aircraft (including both manned and unmanned)? If yes, please describe aircraft and hours of flying experience.
7. Do you hold a Remote Pilot Airman Certificate? If yes, when did you obtain it?

Post-Trial Questionnaire

Participant Number: ____________
Date: ________________________
Trial Number: _________________
Experimenter ID:_______________

How confident are you that the UAV flew to the correctly prescribed altitude?

- not at all confident
- somewhat confident
- very confident

Any additional comments on this trial:

____

____

Post-Experiment Questionnaire

Participant Number: ____________
Date: ________________________
Trial Number: _________________
Experimenter ID:_______________

1. Please describe any strategies you used to estimate the altitude of the UAV.
   ____
   ____

2. What factors do you think would influence your altitude estimation?
   ____
   ____

3. Please rate how difficult it was for you to both hover at the specified altitude and take a photo.
   - Difficult
   - Moderate
   - Easy

4. What factors do you think impacted your workload?
   ____
   ____

5. Please share any other comments you had about this experiment.
   ____
   ____

Appendix C: Experiment Log Sheet

Subject #: ________ Date: ____________ Time: ___________

Commercial ______ Hobbyist _________

BEFORE	**AFTERs**
Time:	**Time:**
Wind:	**Wind:**
Sky:	**Sky:**
Altimeter Setting:	**Altimeter Setting:**
Temperature:	**Temperature:**

CHECKLIST	**COMPLETE**
Take before photo	
Practice UAV controls	
1. Controls for take-off	
2. Controls for maneuvering right/left	
3. Controls for taking a photo	
4. Controls returning to base	
Practice Run	
1. Takeoff climb ~20 feet	
2. Fly to target	
3. Rotate drone 360 degrees	
4. Take a photo	
5. Climb ~ 20 feet	
6. Fly Right 30 feet	
7. Descend 20 feet	
8. Fly left 30 feet back to target	
9. Return to starting point	
Post-test: Take after photo	

Trial #1		Range Finder Altitude YDS	Time 4 Digits	Inclinometer (Deg)
1	Takeoff			
	350 Ft Photo			
	Return			
2	Takeoff			
	50 Ft Photo			
	Return			
3	Takeoff			
	200 Ft Photo			
	Return			

Trial #2		Range Finder Altitude YDS	Time 4 Digits	Inclinometer (Deg)
1	Takeoff			
	200 Ft Photo			
	Return			
2	Takeoff			
	50 Ft Photo			
	Return			
3	Takeoff			
	350 Ft Photo			
	Return			

Trial #3		Range Finder Altitude YDS	Time 4 Digits	Inclinometer (Deg)
1	Takeoff			
	200 Ft Photo			
	Return			
2	Takeoff			
	350 Ft Photo			

	Return			
3	**Takeoff**			
	50 Ft Photo			
	Return			

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