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# Seeing the Threat: Pilot Visual Detection of Small Unmanned Aircraft Systems in Visual Meteorological Conditions

Jon M. Loffi
*Oklahoma State University - Main Campus*, jon.loffi@okstate.edu
Ryan J. Wallace
*Polk State College*, ryan.wallace@erau.edu
Jamey D. Jacob
*Oklahoma State University*, jdjacob@okstate.edu
Jared C. Dunlap
*Oklahoma State University*, jared.dunlap@okstate.edu

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The newswire is rife with anecdotes of near misses between UAS platforms and manned aircraft, even in the tentative state of UAS integration efforts. In March 2013, a B-777 operated by Alitalia Flight AZ608 came within 200 feet of colliding with a small multi-bladed unmanned aircraft on approach to John F. Kennedy International Airport. Just over a year later, U.S. Airways CRJ-200 passenger jet bound from Charlotte, North Carolina had a similar encounter with a small remotely piloted, fixed-wing UAS platform on approach to its Tallahassee, Florida destination (Botelho, 2014). On September 17, 2014, an NYPD helicopter came within 50 feet of colliding with a small drone, requiring the pilot to perform an evasive maneuver ("NYPD," 2014). Even small, general aviation aircraft have encountered near misses with unmanned platforms. In September 2014, a Cessna 172 sighted an unmanned aircraft passing within 100 feet below his flight altitude near Orlando-Sanford Airport (Whitlock, 2014). In the same month, a Piper Archer pilot reportedly passed within 50-100 feet from a UAS, claiming "the thing [UAS] flashed right off my wingtip" (Whitlock, 2014). Just days prior, a Cessna 172 piloted by a flight instructor reported an illuminated drone overflying his aircraft by 200 feet, remarking "it came out of seemingly nowhere" (Whitlock, 2014, p. 1). As unmanned systems proliferated the commercial and hobby markets, pilot reports of encounters and *near misses* have substantially increased in both frequency and risk. Between November 2014 and January 2016, the FAA recorded 1,346 pilot sightings and near-misses of UAS platforms—nearly 100 per month (Federal Aviation Administration [FAA], 2016c). The sheer quantity of UAS encounter sightings highlights a clear, ongoing problem.

## Problem

The threat of midair collision between unmanned and manned aircraft represents an unknown risk of integrating operations between these two disparate NAS users. Until such benchmarks are established for electronic Detect, Sense & Avoid Systems, pilots must rely on visual means to ensure positive separation from UAS platforms. Previous research is inconclusive about the effectiveness of this method of UAS-aircraft separation.

### UAS Encounter Studies

A recent study by Gettinger and Michel (2015) analyzed 921 UAS incidents involving UAS platforms and manned aircraft. The study revealed several findings, including:

- 58.8% ($n$ = 391) of UAS encounters occurred near airports where UAS operations are prohibited

- 90.2% (*n* = 708) of UAS encounters occurred above 400 feet AGL, the maximum allowable altitude for most UAS platforms
- In 21.2% (*n* = 51) of the reported cases, the UAS platform passed within 50 feet or less of the manned aircraft
- In 8.6% (*n* = 28) of reported UAS close encounters, pilots took evasive action or maneuvered to avoid a perceived potential collision

Additionally, Gettinger and Michel (2015) noted that close encounters with UAS platforms occurred at disproportionately higher rates around areas of high-density air traffic, such as major airports. Close encounters were defined as occurring when a controller or pilot spotted a drone flying near the flight path of a manned aircraft, but did not pose a collision threat (Gettinger & Michel, 2015). Between December 2014 and August 2015, pilots on final approach to Los Angeles International Airport reported 17 separate close encounters with UAS platforms (Gettinger & Michel, 2015).

The Academy of Model Aeronautics (AMA) conducted a similar analysis of UAS sightings, based on 1,346 FAA reports of UAS encounters that occurred between August 2015 and January 2016 (Academy of Model Aeronautics [AMA], 2016). The AMA's (2016) report concluded that 3.3% (*n* = 19) of UAS encounters represented "close calls" or "near misses"; that vast majority of UAS reports should be more accurately presented as "UAS sightings" (AMA, 2016, p. 1) Moreover, the AMA highlighted a disjointed relationship between the recent sales of UAS platforms and UAS encounter reports submitted to the FAA. While UAS sales have dramatically increased--estimated at more than a million UAS platforms around the 2015 Christmas season alone—reported UAS sightings have been in a steady decline since August 2015 (AMA, 2016). The AMA further identified that several reports contained references to non-UAS objects such as balloons, birds, rockets, or other non-relevant flying objects (AMA, 2016). In assessing the release of UAS encounter data, the AMA concluded that 3.4% (*n* = 46) reports could accurately be characterized as near collisions. In the report, the AMA argues that these lower, revised statistics are more accurate since these 46 reports contained textual notations of a "near mid-air collision, near miss, or near collision" (AMA, 2016, p. 2). The AMA analysis identified that 1.8% of reported cases (*n* = 24) required the pilot of the manned aircraft to take evasive action (AMA, 2016).

It is important to note that data in both the AMA (2016) and Gettinger & Michel (2015) studies were based solely on the manned aircraft pilot's perceived distance from the encountered UAS platform. This represented a significant limitation, substantiated by an FAA representative who stated: "Since the majority of the pilot reports can't be verified – the drones typically don't show up on radar nor is the operator identified – we can't say for certain what the actual separation distance was…" (AMA, 2016, p. 3).

The number of cases of near mid-air collisions with UAS platforms should be cause for concern, as it is highly likely the number of mid-air collisions with UAS platforms will rise in relationship to the population of UAS platforms operating in the National Airspace System. To provide some context to these statistics, the FAA reported 461 near mid-air collisions between manned aircraft for the five-year period encompassing 2009-2013—about 92 incidences per year (FAA, 2016b). Using the AMA's most conservative assessment of near mid-air collisions between unmanned and manned aircraft, 46 incidences occurred in the 15 months of FAA-reported data. This represents a UAS near mid-air collision rate of almost 37 incidents per year. While currently below the manned aircraft average, this statistic fails to account for the expected dramatic growth of UAS platforms in the upcoming years. In its 20-year Aerospace Forecast, the FAA estimates that unmanned aircraft will top 7 million platforms by 2020 (FAA, 2016a). This expected growth in the number of UAS platforms and operators will likely cause near mid-air collisions between unmanned platforms and manned aircraft to rise.

## Visibility Studies

In 2008, researchers from Ohio University conducted an experimental visibility study designed to determine air traffic detection ranges for inexperienced pilots and simultaneously test if UAV camera systems could provide similar detection performance. The experiment used a Piper Saratoga as the manned testing aircraft and a Piper Warrior as a simulated UAS. An observer pilot [test subject] was instructed to locate and mark terrain features on a map to simulate normal pilotage workload, while simultaneously recording sighted air traffic. Seven test subjects were presented two aircraft encounters with the simulated UAS craft—one head-on encounter and one 90 degree crossing encounter. The UAS craft was flown at a vertically de-conflicted altitude 500 feet below the manned aircraft. The average detection range for the test subjects was 1.275 statute miles; the mean detection range for the 90-degree intercept was slightly further at a mean of 1.511 statute miles compared to 1.038 statute miles for the head-on intercept condition. The camera system experienced a significantly longer mean detection time of 0.417 statute miles. The authors note the small sample size of this study may affect the reliability of the presented conclusions.

In September 2015, the Colorado Aviation Association conducted a drone visibility study for agricultural aircraft. The goal of the test was to determine if lowflying agricultural application aircraft pilots could see a UAS craft and have adequate time to perform an avoidance maneuver (CAAA, 2015). The test utilized five volunteer pilots flying over five fields with Agribotix Enduro [Rotorcraft] sUAS platforms. Two of the five fields contained the UAS craft, two contained large marked orange tarps, and the fifth field remained empty (CAAA, 2015). Presumably, the orange tarps were placed to test the viability of using a visible marker to highlight the presence of UAS operations. In test fields containing the UAS, the UAS platform was flown at a lower altitude than the manned aircraft. Four manned agricultural aircraft and one helicopter was used for the test (CAAA, 2015). Pilots of the manned aircraft only located one of the UAS craft from the available eight passes (CAAA, 2015). The manned helicopter was not able to initially locate the UAS craft during moving flight, but was able to locate both craft while in stationary hover (CAAA, 2015). Colorado Agricultural Aviation Association Board President Sam Rogge highlighted the test's findings stating (CAAA, 2015):

> What I heard from a majority of the pilots was what we knew: UAVs would be difficult to see, but it turns out they're more difficult to see than we thought. It's clear that it will take a cultural change on both our parts [ag aviators and UAS operators] if we're going to work cooperatively in the airspace…operating line of sight isn't enough to mitigate safety issues. (p. 1)

Agribotix (n.d.), the company furnishing the UAS platforms for the test provided several conclusions, based on the test's results:

- "See and avoid is a terrible strategy for keeping low-altitude airspace safe" (p. 1). Experiment participants reiterated the importance of coming up with a solution to avoid simultaneous use of airspace by both manned and unmanned aircraft.
- "Audible warning of a crop duster's approach is also a terrible strategy" (p. 1). Ground test participants indicated they could visually see the manned agricultural aircraft long before they could hear them.
- "Communication is key" (p. 1). Agribotix recommends use of digital software products, such as those produced by AirMap, which allows airspace users to "declare in advance their zones of operation." (p. 1)
- "Technology might help" (p. 1). Technology such as ADS-B may help, but could prove costly.
- "Ground markers are an OK backstop" (p. 1). Ground markers, such as the marked tarps used during the test can be effective, but should not be

> the primary method for altering manned aircraft to the presence of UAS operations.

### Human Factors Considerations

**Visual Detection Challenges.** The FAA's (2016b) AC 90-48D cites several human factors challenges associated with visual aircraft detection:

***Refocus.*** A featureless sky can result in the eyes focusing on a natural, relaxed focal distance of 10-30 feet, which potentially reduces aircraft detection. Regularly refocusing or glancing can help to reduce this natural human tendency.

***Refocus after switching views.*** The eyes require several seconds to refocus when changing views from inside and outside the aircraft.

***Eye movements.*** Scanning visual areas in short, 10-degree arcs is the most effective method for visual aircraft detection.

***Spotting threats.*** Relative motion through peripheral vision is usually the first indication of a potential collision. Peripheral vision is most prominent when the eyes are refocusing. Aircraft on a direct collision course, however, often display no relative motion. The only visible indication of a collision is the increasing size of the object over time.

***Physical obstructions.*** Visual obstructions in the cockpit such as the instrument console and aircraft structure may require a pilot to physically maneuver the head to see the obstructed area.

***Assistance & additional equipment.*** The FAA recommends pilots enlist the aid of other crew or passengers in visually detecting hazards, particularly in traffic-dense airspace or during operations that involve elevated risk.

***Nighttime searches.*** Nighttime detection of collision threats can be particularly challenging due to the lack of object brightness, poor color contrast, and need to discern between airborne and ground lighting. Nighttime searches rely almost exclusively on peripheral vision due to positioning of the natural night blind spot. Off-center viewing can enhance night visual detection.

**Detection and Reaction Time.** According to AC 90-48D (FAA, 2016b), "Research has shown that the average person has a reaction time of 12.5 seconds.

This means that a small or high-speed object could pose a serious threat…This is particularly important with small Unmanned Aircraft Systems" (p. 2).

As presented by Table 1, pilots require a minimum of 6.1 seconds to effectively visually detect, recognize, and predict a craft's convergence collision potential (FAA, 2016b). An additional 6.4 seconds is required to adequately assess, select, and execute an appropriate evasive maneuver to avoid a converging craft (FAA, 2016b). The reduced size of UAS platforms compared to manned aircraft--particularly small UAS (sUAS) platforms with limited visual cross-sections--may make visual detection exceedingly difficult, reducing a pilot's ability to react to a converging threat in time.

Table 1

*Aircraft Identification and Reaction Time Chart*

| Event | Seconds |
|---|---|
| See Object | 0.1 |
| Recognize Aircraft | 1.0 |
| Become Aware of Collision Course | 5.0 |
| Decision to Turn Left or Right | 4.0 |
| Muscular Reaction | 0.4 |
| Aircraft Lag Time | 2.0 |
| TOTAL | 12.5 |

(FAA, 2016b, p. 2)

## Purpose

The purpose of this study was to establish a predictive UAS platform visibility model for general aviation pilots operating under visual meteorological conditions. Such benchmarks could be subsequently applied to determine the adequacy of visual means for UAS detection, identification, potential collision recognition, and evasive response decision-making.

Existing research is lacks adequate data to model UAS encounters with general aviation aircraft. The Kephart and Braasch (2008) study contained only limited data points and utilized a simulated UAV that does not adequately represent the size and configuration of UAS craft currently operating in the NAS. Similarly the CAAA (2015) study applies primarily to agricultural operations and the experimental design does not adequately emulate the type of flying conditions experienced by general aviation pilots. The study sought to discover answers to the following research questions:

1. What is the mean distance in which an aware pilot can reliably visually detect a converging sUAS platform under visual meteorological conditions?
2. Is there a substantial difference in detectability of fixed-wing vs. quadcopter UAS platforms?
3. Is there variability between a pilot's perceived visual distance from a UAS and their actual distance?
4. Based on the FAA's model for Aircraft Identification & Reaction Time, would pilots have adequate time to evade a UAS collision?

## Method

This study utilized a mixed-method research design. Twenty experimental participants were recruited from among a population of flight students at a part 141 collegiate flight program in the Midwestern United States using purposeful sampling. Patton (2015) describes purposeful sampling as "strategically selecting information-rich cases to study, cases that by their nature and substance will illuminate the inquiry question being investigated" (p. 265). Participants were assigned flight times from 1000 through 1400 [local] during peak daylight time. Four experimental sorties were flown each testing day. The same manned aircraft, a Cessna 172S G1000 general aviation aircraft, was used for these flights to ensure consistency. Sorties were each flown with two pilots: one served as the experimental subject and the other was a non-participating safety pilot. An additional safety observer accompanied each experimental sortie and assisted in recording pertinent data relative to the mission, such as time stamps and coordinated each intercept pass. The safety observer also recorded participant comments and made qualitative observations which were analyzed for trends following the experiment execution.

Experimental participants were instructed to visually detect a small UAS craft flying on an altitude de-conflicted intercept course with the aircraft in a protected airspace area. The UAS craft were launched and controlled from ground operators located at a local RC flying field, and operated under an existing 333 exemption and Certificate of Authorization (COA) for the airspace. The sUAS craft were positioned in proximity to the manned aircraft's assigned course. Subject pilots flew along an assigned intercept axis, bisecting the UAS operations area, during which each scenario was presented. Each pair of participants encountered the same group of six scripted scenarios, which included:

- Intercept 1: Control Scenario in which no UAS was launched

- Intercept 2: Hovering quadcopter UAS on port side of aircraft course
- Intercept 3: Hovering quadcopter UAS on starboard side of aircraft course
- Intercept 4: Quadcopter UAS transitioning from port to starboard side
- Intercept 5: Quadcopter UAS transitioning from starboard to port side
- Intercept 6: Fixed-wing UAS orbiting on head-on aspect relative to aircraft course

Table 2

*Participant Aeronautical Demographics*

| Flight | Age Bracket | FAA Pilot Certificate(s) | Medical Certificate | Reported Vision | Vision Correction |
|---|---|---|---|---|---|
| 1 | 60-65 | ATP | 2nd Class | 20/20 | Corrected |
| 2 | 20-25 | CFI/MEI | 1st Class | Unknown | Unknown |
| 3 | 20-25 | CFI/MEI | 1st Class | 20/20 | Corrected |
| 4 | <20 | PPL w/ IR | 1st Class | 20/20 | Corrected |
| 5 | 20-25 | CPL | 1st Class | 20/20 | Uncorrected |
| 6 | <20 | PPL | 3rd Class | 20/20 | Corrected |
| 7 | 20-25 | CFI/CFII | 1st Class | 20/20 | Uncorrected |
| 8 | 20-25 | ATP | 1st Class | 20/20 | Corrected |
| 9 | 20-25 | CPL | 2nd Class | 20/20 | Uncorrected |
| 10 | 20-25 | PPL w/ IR | 3rd Class | 22/20 | Corrected |
| 11 | 20-25 | CPL | 2nd Class | Unknown | Unknown |
| 12 | 20-25 | CFI/CFII | 1st Class | 20/20 | Uncorrected |
| 13 | 20-25 | ATP | 1st Class | 20/20 | Uncorrected |
| 14 | 20-25 | CFI | 3rd Class | 20/20 | Uncorrected |
| 15 | 20-25 | CFI/CFII | 3rd Class | 20/20 | Uncorrected |
| 16 | 20-25 | CPL | 1st Class | Unknown | Unknown |
| 17 | 20-25 | PPL w/ IR | 3rd Class | 20/20 | Corrected |
| 18 | 20-25 | CPL | 3rd Class | 20/20 | Uncorrected |
| 19 | 25-30 | CFI/CFII/MEI | 1st Class | 20/20 | Corrected |
| 20 | 20-25 | CFI/CFII | 1st Class | 20/20 | Uncorrected |

Note: (PPL = Private Pilot License; IR = Instrument Rating; CPL = Commercial Pilot license; CFI = Certified Flight Instructor; CFII = Certified Flight Instructor-Instrument; MEI = Multi-Engine Instructor; ATP = Airline Transport Pilot). All commercial pilots and above were instrument rated. Vision correction indicates if participant medical certificate required wear of corrective lenses.

If participants visually identified a UAS during the intercept, they were asked to estimate the distance between the aircraft and UAS platform, as well as verbally select an escape or avoidance maneuver.

For the scenarios, the researchers used a 3D Robotics *Iris* for the quadcopter UAS. The Iris' dimensions measure 1.8 feet by 1.8 feet, from motor to motor [excluding propeller width](Kike, 2015). The craft was colored white for maximum ground contrast and visibility, and to simulate the color of the majority of quadcopters currently operating in the NAS.

An RMRC *Anaconda* was used for the fixed-wing UAS craft. The Anaconda has a length of 4.62 feet, has a wingspan of 6.75 feet, and is primarily composed of hardened Styrofoam (Ready Made Remote Control, 2016). The craft was colored white for maximum ground contrast and visibility.

*Figure 1.* Anaconda Fixed-Wing UAS (left). Iris Quadcopter UAS (right). During the experiment, the Iris was colored white to increase visibility.

Geolocation information from both sets of UAS craft was recorded using the Mission Planner Software suite. Manned aircraft geolocation information was collected by extracting recorded GPS coordinates from the G-1000 avionics suite. Experiment participants were instructed to verbally indicate when they visually located each UAS craft. A safety observer flew on each sortie and was responsible for recording and timestamping each successful sighting. Visual distance information was derived by extracting geolocation coordinates, from both the manned aircraft and UAS platforms and subsequently correlating the sighting time. Both sets of coordinates were then input into Google Maps to derive visual distance information. It is important to note that the reported distance information represents only lateral distance, irrespective of altitude differences: it does not account for the increased slant range between the aircraft and UAS platforms.

The manned aircraft was equipped with a small, externally-mounted GoPro Electro-Optical video camera during select sorties. The camera was not included on all sorties due to technical and operational limitations. Select images were extracted and presented in the findings to provide readers a visual representation of the visual conditions of the experiment.

To ensure safety during the experiment, the researchers equipped both UAS platforms with a proprietary, miniaturized ADS-B device developed by uAvionix. The portable equipment allowed the safety observer in the aircraft to monitor the true position of the UAS platforms in near real-time on a tablet device and alert the crew to a real-world collision threat.

*Figure 2*. uAvionix proprietary ADS-B device installed on UAS (left) and aircraft (right). (Used with permission)

## Limitations

The experiment was conducted in accordance with the established plan with minor caveats:

- Experiment measured only the lateral distances between manned and unmanned aircraft encounters.
- Due to an experiment execution error, intercept 3 was consistently but incorrectly conducted on the port side of the aircraft course
- Flight 8, Intercepts 1-5 were intended to be flown using the Iris Quadcopter, however, the UAS platform malfunctioned. As a result, the fixed-wing Anaconda UAS platform was used for these intercepts. Data collected during these intercepts was removed from statistical calculations when appropriate to avoid compromising study validity.
- The Anaconda UAS encountered a malfunction during Flight 9, Intercept 6. As a result, an alternate fixed-wing *Sky Surfer* platform was used for this intercept. No telemetry data was collected during this intercept.

## Findings & Discussion

The experiment was conducted during periods of visual meteorological conditions between July 7 and July 18, 2016. Researchers collected data for 119 intercepts among the 20 experimental flights. Flight time for all experimental flights totaled 13.0 hours.

### Detectability

Overall, the UAS craft were detected on 40.3% (*n* = 48) of the intercepts. No participants reported a false-positive sighting of a UAS platform during the first control intercept. The Iris quadcopter was detected during 36.8% of the possible intercepts (*n* = 28) and the Anaconda fixed-wing platform was detected during 87.0% (*n* = 20) of the possible intercepts. A summary of UAS detection findings by intercept are presented in table 3: detailed findings are presented in table 4.

Table 3

*Summary Statistics: Detection Ranges by UAS Platform & Intercept*

| UAS Type / Intercept # | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Iris (Quadcopter) | | | | | |
| Mean | 0.053 | 0.092 | 0.026 | 0.028 | |
| Median | 0 | 0.07 | 0 | 0 | |
| Mode | 0 | 0 | 0 | 0 | |
| Detection Rate | 36.8% | 57.9% | 26.3% | 26.3% | |
| Anaconda (Fixed-Wing) | | | | | |
| Mean | | | | | 0.493 |
| Median | | | | | 0.45 |
| Mode | | | | | 0 |
| Detection Rate | | | | | 84.2% |

Note: All ranges in statute miles (SM). Zero figures indicate the UAS was not detected.

### Detection Range

The detection range for the Iris and Anaconda UAS platforms varied considerably. As shown in Table 3, the mean detection range for the Iris quadcopter was consistently less than 0.10 statute miles (SM), with the furthest detection occurring at 0.31 SM. Conversely, the mean Anaconda UAS detection range was 0.49 SM, with the furthest detection occurring at 1.36 SM. To provide perspective on this finding, W.D. Howell (as cited in Watson, Ramirez, and Salud, 2009), conducted a 1957 field study that analyzed pilot detection range to a converging manned DC-3 aircraft. Howell determined the detection range varied from 5.5 km [3.4 SM] to 8.7 km [5.4 SM]. Similarly, the Kephart and Braasch (2008) study revealed mean detection range to the much smaller manned Piper Warrior aircraft was 1.275 SM.

This initial finding was not necessarily unexpected, as the Anaconda's visible wing surface area was a relatively large visible target of 5.27 ft$^2$, vs. the Iris' small 3.24 ft$^2$ visible surface dimension. It is possible, however, that this visibility finding could be confounded by the intercept type and aspect angle relative to the manned aircraft.

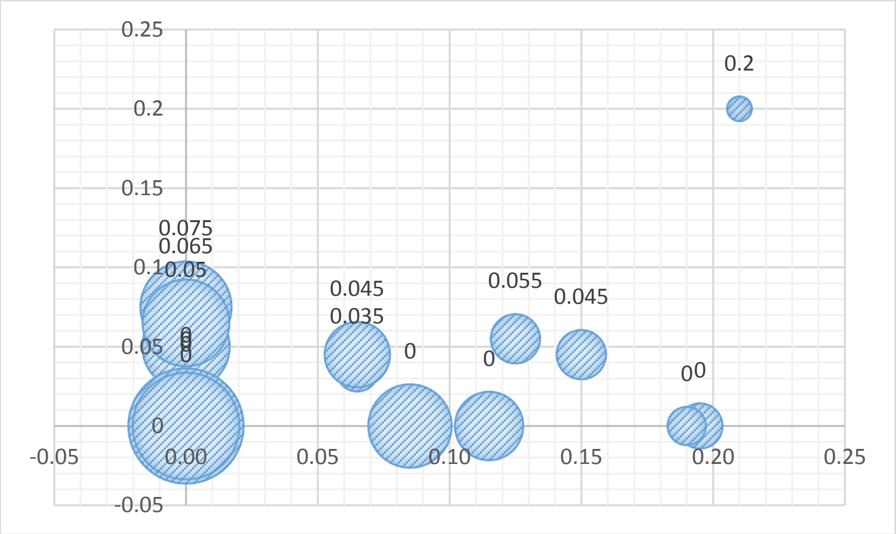

*Figure 3.* Bubble Chart of Detection Distances by Intercept Type for Side Hover Iris, Transitioning Iris, and Head-on Anaconda UAS profiles. Pilot detection distance for the side hovering Iris is depicted on the x-axis; distance for transitioning Iris on the y-axis; and detection distance for head-on Anaconda depicted by the relative size of plotted bubble point. All distances presented in statute miles (SM).

A comparison was made in Figure 3 of the three types of intercepts by aspect: side hovering Iris, transitioning Iris, and head-on orbiting Anaconda. Participants showed generally poor success in detecting all three platforms. Participants seemed to experience the most difficulty detecting the transitioning Iris UAS. Participants who best detected the Anaconda UAS generally did not detect the transitioning Iris until the UAS was in proximity to the aircraft.

This was a rather unexpected finding. Since peripheral vision is highly sensitive to motion, a pilot who used the same scanning approach to detect the head-on Anaconda UAS should have noticed the transitioning Iris in their peripheral vision. Moreover, it also seems unlikely that a pilot would have better success detecting the stationary, hovering Iris vs. the transitioning Iris; however, the data suggest this counterintuitive result.

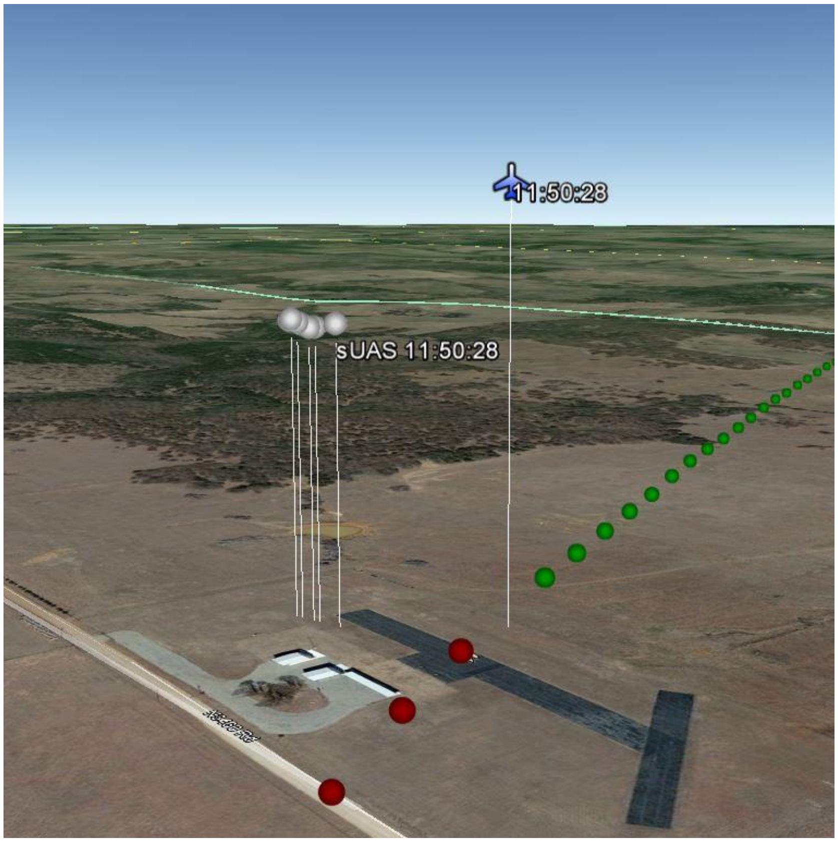

*Figure 4.* Google Earth depiction of Flight 6, Intercept 5. Aircraft silhouette shows relative lateral and vertical position of manned aircraft at time of visual encounter. Gray plots indicate relative lateral and vertical telemetry of UAS. Red plots indicate path of aircraft pre-sighting: Green plots show path of aircraft post-sighting. Plot length varies between 1-3 second intervals.

A Google Earth map showing the telemetry of the aircraft relative to the UAS is presented to show the relative visual aspect for the two most extreme elements of the data. Figure 4 shows the closest encounter in which participants were able to spot the Iris UAS, which occurred during Flight 6, Intercept 5. Collected telemetry indicated the distance between the UAS and aircraft to be 0.06 SM.

Similarly, Figure 5 shows the furthest sighting of the Anaconda UAS, which occurred during Flight 19, Intercept 6. Telemetry indicated the distance between the UAS and aircraft to be 1.36 SM.

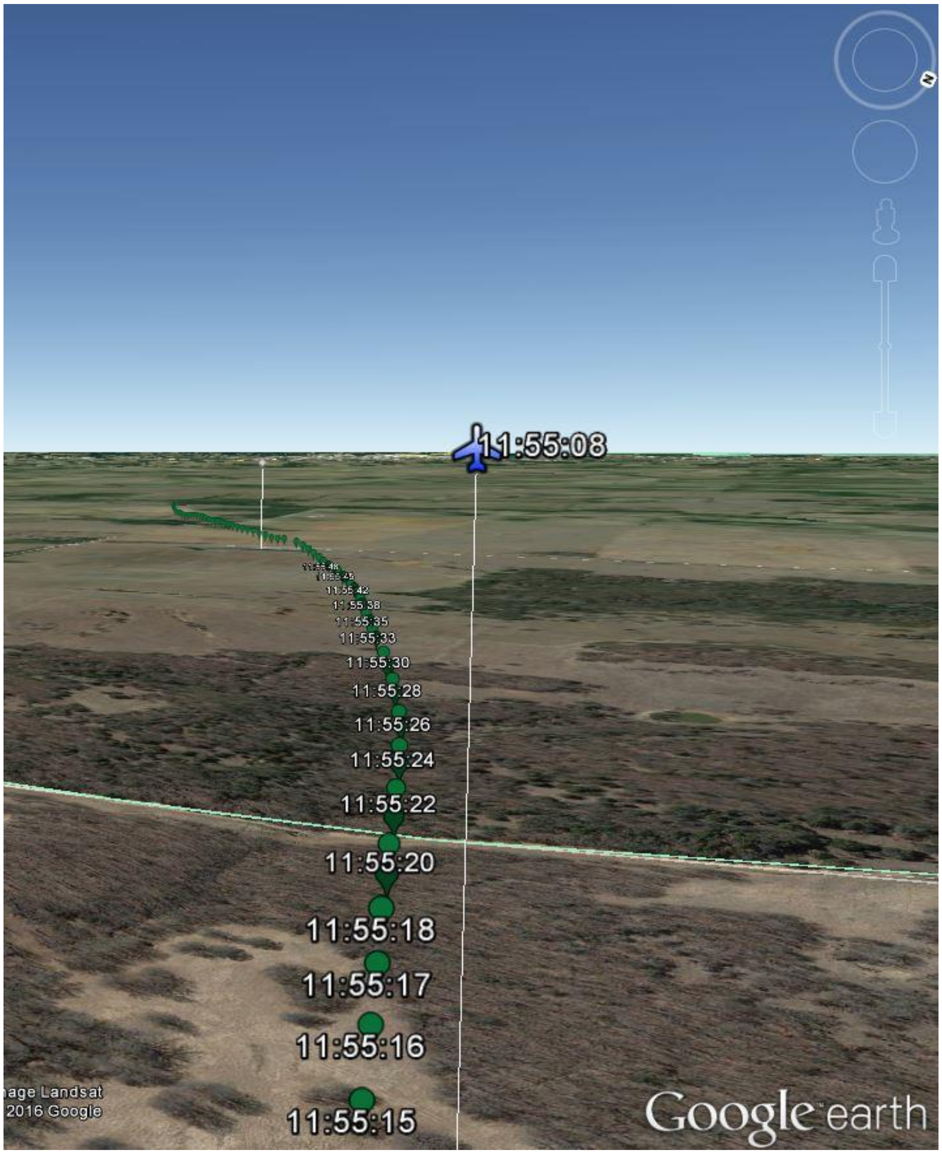

*Figure 5.* Google Earth depiction of Flight 19, Intercept 6. Aircraft silhouette and gray UAS plot shows relative lateral and vertical position of manned aircraft at time of visual encounter. Green plots indicate path of aircraft post-sighting.

Table 4

*UAS Detection Range by Flight & Intercept*

| Intercept | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| UAS Maneuver<br>Aspect | Hover<br>Port | Hover<br>Port | Transition<br>Port>Starboard | Transition<br>Port>Starboard | Orbit<br>Head-on |
| UAS Type | Iris | Iris | Iris | Iris | Anaconda |
| Flight | | | | | |
| #1 | | 0.39 | | | 0.22 |
| #2 | 0.17 | | | | 0.72 |
| #3 | | | | | 0.98 |
| #4 | 0.08 | 0.15 | | | 0.49 |
| #5 | 0.31 | 0.07 | | | 0.16 |
| #6 | | 0.08 | | 0.06 | |
| #7 | | | | 0.10 | 0.79 |
| #8 | 0.34* | 0.08* | 0.19* | 0.21* | 0.07 |
| #9 | | 0.07 | 0.05 | | No Data** |
| #10 | 0.09 | 0.14 | | | |
| #11 | | 0.13 | | 0.07 | 0.19 |
| #12 | 0.11 | 0.19 | 0.09 | | 0.26 |
| #13 | 0.13 | 0.12 | 0.11 | | 0.26 |
| #14 | | | | | 0.61 |
| #15 | | 0.13 | 0.09 | | 0.45 |
| #16 | 0.13 | 0.28 | | 0.18 | |
| #17 | | | 0.15 | | 0.86 |
| #18 | | | | 0.13 | 0.78 |
| #19 | | | | | 1.36 |
| #20 | | | | | 1.17 |

*Flown with Anaconda fixed-wing UAS, rather than Iris Quadcopter; data excluded from certain calculations; **Crew sighted UAS, however, no telemetry data was collected (excluded from data calculations); [Note: All ranges in statute miles (SM). Blank fields indicate UAS was not spotted during intercept]

## Pilot Distance Estimation

Immediately following each intercept, participants estimated the distance between the aircraft and UAS platform. Researchers collected 47 pilot distance estimates and compared the estimates to the tracked GPS distances to determine estimation error. Pilot estimates varied from 0 ft [imminent collision/collision] to 1.59 SM. This data is reflected in Table 5.

Table 5

*UAS Detection Range Pilot Estimate Differentials by Intercept & Flight*

| | 2 | | | 3 | | | 4 | | | 5 | | | 6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flt | Act | Est | Δ | Act | Est | Δ | Act | Est | Δ | Act | Est | Δ | Act | Est | Δ |
| 1 | | | | .39 | .50 | -.11 | | | | | | | .22 | 0 | .22 |
| 2 | .17 | .25 | -.08 | | | | | | | | | | .72 | .50 | .22 |
| 3 | | | | | | | | | | | | | .98 | 1.50 | -.52 |
| 4 | .08 | .04 | .04 | .15 | .095 | .06 | | | | | | | .49 | .095 | .40 |
| 5 | .31 | .25 | .06 | .07 | .25 | -.18 | | | | | | | .16 | .25 | -.09 |
| 6 | | | | .08 | 1.0 | -.92 | | | | .06 | 1.0 | -.94 | | | |
| 7 | | | | | | | | | | .10 | .125 | -.03 | .79 | .25 | .54 |
| 8 | .34 | .25 | .09 | .08 | .125 | -.05 | .19 | 1.4 | -1.21 | .21 | 1.8 | -1.59 | .07 | .095 | -.03 |
| 9 | | | | .07 | .057 | .01 | .05 | .047 | 0 | | | | N/A | .152 | N/A |
| 10 | .09 | .09 | 0 | .14 | .076 | .06 | | | | | | | | | |
| 11 | | | | .13 | .057 | .07 | | | | .07 | .019 | .05 | .19 | 0 | .19 |
| 12 | .11 | .25 | -.14 | .19 | .75 | -.56 | .09 | .25 | -.16 | | | | .26 | .25 | .01 |
| 13 | .13 | .08 | .05 | .12 | .19 | -.07 | .11 | .057 | .05 | | | | .26 | .114 | .15 |
| 14 | | | | | | | | | | | | | .61 | .379 | .23 |
| 15 | | | | .13 | .057 | .07 | .09 | .028 | .06 | | | | .45 | .076 | .37 |
| 16 | .13 | N/A | N/A | .28 | .75 | -.47 | | | | .18 | .5 | -.32 | | | |
| 17 | | | | | | | .15 | .19 | -.04 | | | | .86 | .095 | .77 |
| 18 | | | | | | | | | | .13 | .038 | .09 | .78 | N/A | N/A |
| 19 | | | | | | | | | | | | | 1.36 | 1.0 | .36 |
| 20 | | | | | | | | | | | | | 1.17 | .25 | .92 |

Note: (Act = Actual UAS Distance; Est = Pilot Estimated UAS Distance; Δ = Difference between Act & Est distance/pilot estimation error). Lack of data available to perform calculation or no pilot distance estimate indicated by “N/A” in dataset. All distances presented in statute miles (SM). Positive numbers in the delta column indicate the pilot *underestimated* the actual distance between the UAS and aircraft; Negative numbers in the delta column indicate the pilot *overestimated* the actual distance.

Table 5 shows each flight, organized by intercept passes 2-6. The table contains the manned aircraft’s GPS-measured distance from the UAS at the time of sighting, followed by the pilot’s distance estimate, and the overall difference. Distance estimates for the Anaconda deviated by an average of 0.25 statute miles from the actual UAS distance: distance estimates for the Iis deviated by 0.20 statute mile. Generally, pilots tended to *overestimate* their distance to the smaller Iris UAS and *underestimate* distances to the larger Anaconda UAS.

## Visual Data

The externally mounted GoPro electro-optical camera provided several video and still images of the intercepts. Researchers selected a representative sample of the images to include in this report for illustrative purposes.

During the experiment, the experimental aircraft encountered a large-winged bird, believed to be a turkey vulture. Presented in Figure 6, this image provides a convenient comparison between a pilot's visual depictions of a bird encounter vs. an encounter with a similarly sized Anaconda UAS platform, such as the one presented in Figure 7. Figure 8 shows another encounter with the Anaconda UAS, estimated at 0.5 SM. At further distances, it appears that the only visible discernable portion of the UAS is the large wingspan. Figure 9 depicts the small Iris platform operating at relatively low-level transition to landing. The platform shows up as an almost indiscernible white speck in the photograph.

Visual contrast between the UAS and surface vegetation clearly has an impact on visibility. It is fairly easy to discern both the flying bird and Anaconda UAS in both Figures 6 and 7, as they are both presented against a reasonably homogeneous surface background. Conversely, the UAS craft presented in Figures 8 and 9 show how difficult it can be to detect and discern a UAS against a complex, heterogeneous background.

## Qualitative Data

The observations of the safety observer and recorded participant comments were collected and analyzed for common themes. Five common themes emerged from the qualitative data:

**Size estimation error.** Many participants were surprised to learn the actual size of the fixed wing Anaconda platform. Most participants underestimated the size as a 2-3 foot wingspan craft [actual wingspan was 6.75 feet]. As previously mentioned, participants also underestimated the distance to the Anaconda platform. Since participants were not shown the platforms in advance of the experiment, this finding may help to explain the distance estimation error. Personal assumptions of the UAS size may influence the distance perception.

*Figure 6*. Visible bird encounter (Turkey Vulture).

**Parallax error.** Parallax error describes how an object, when perceived from the observer's position demonstrates an apparent displacement from its actual location. Despite the experimental pilots being aware of the positive vertical separation engineered into the experiment, several participants reported still perceiving the UAS to be in such proximity that they felt a collision was imminent. One participant even performed an evasive climbing maneuver to avoid the UAS. This finding seems to indicate that pilots experienced a form of parallax illusion in the vertical plane.

**Reaction time estimation error.** Contrary to the telemetry data, most participants reported they could avoid a UAS collision. This observation was reflected in the comment of Participant 18 who stated, "passes where UAVs were spotted [we] had ample time to avoid a collision."

**Limited scanning width.** The safety observer noted that Participants 19 and 20 were not scanning the full range of visibility. Participants primarily scanned between the 11:00-2:00 positions. The safety observer also noted that a tendency of the participants was to look almost straight down rather than just below the window level to observe the UAS craft. The safety observer noted that in these cases the UAS was actually flying higher than the angle the pilots were scanning

**Fixed-wing platform readily identifiable.** Participants indicated the fixed-wing Anaconda platform was much easier to spot than the Iris quadcopter. Participant 14 remarked, “was able to see fixed wing aircraft straight away…vehicle was coming at the manned aircraft and initiating a turn underneath…the size and movement of the UAV made a difference.” Additional comments recorded by the safety observer reflected this sentiment. Participants 1 and 3 both indicated the Anaconda became visible after the platform maneuvered, producing a visible “wing-flash.”

**Color scheme matters.** While not specifically studied during the experiment, 16 participants indicated that the white color of the UAS platforms aided in their detection. Conversely, Participants 3 and 5 thought the white color made the UAS more difficult to spot. Participant 2 commented that the “white color made it [UAS] a little easier to spot.” Participant 8 echoed the observation stating, “the white color helped make it [UAS] stand out.”

**Comparable or more difficult to detect than birds.** Ten participants reported that the UAS craft was more difficult to detect than birds. Seven participants reported detecting the UAS craft was comparable to spotting birds. Participant 5 commented, “The white color blended with the background and was harder to see, very similar to seeing birds…at first I thought the UAV could have been a bird.”

## Conclusions

### Research Question 1

*What is the mean distance in which an aware pilot can reliably visually detect a converging sUAS platform under visual meteorological conditions?*

The results do not support clear conclusions to this research question. Seemingly, UAS platforms with a small visual surface area are extremely difficult to detect. Quadcopter platforms like the Iris and comparable, popular DJI Phantom series are not likely to be seen by pilots until within 0.10 SM. Even inside this range, detection varies considerably between 26.3% and 57.9%. Larger platforms such as the Anaconda are much easier to detect, with detection rates reaching 84.2% and a mean detection distance of 0.493 SM. It is likely that this higher detectability and longer detection range is partially due to the larger UAS platform visual surface area, and in part due to the head-on intercept type. Further research is required to determine the exact reason for this substantial difference in detection range.

### Research Question 2

*Is there a substantial difference in detectability of fixed-wing vs. quadcopter UAS platforms?*

The data did not conform to normality requirements to perform a valid correlated *t*-test to parametrically determine significant differences between detection of fixed-wing and quadcopter platforms. Moreover, several data points would need to be excluded from the data such as Flight 8 in which all passes were flown with the Anaconda and Flight 9 in which no telemetry data was recorded for the fixed-wing platform. Additionally, long-distance sightings of the Anaconda in intercept 6 would have to be removed as outliers to preserve test integrity. As a result, the researchers did not elect to perform data transformation or conduct non-parametric testing. The authors recommend statistical analysis of the data after conducting further iterations of the experiment to collect additional data points.

*Figure 7*. Visible overhead encounter of fixed-wing Anaconda UAS.

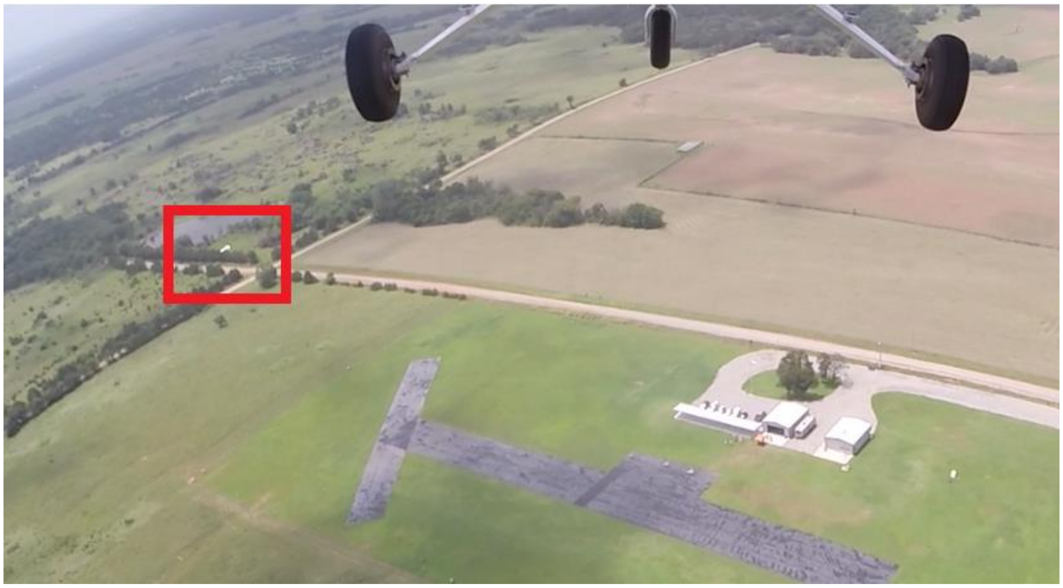

*Figure 8.* Visible encounter of fixed-wing Anaconda UAS

*Figure 9.* Visible encounter of Iris quadcopter UAS.

In this instance, however, the descriptive statistics clearly indicates a notable difference in detectability between the Iris quadcopter and fixed-wing Anaconda platforms. The Anaconda's mean detection distance of 0.493 SM far exceeded that of the Iris platform, by more than 500%. As discussed in the previous research question, it is likely that this variability is in part due to the difference in platform surface area, and partially due to the differences in intercept aspect. Additionally, fixed-wing UAS platforms seem to become more visible when maneuvering, since the large surface area of the wing becomes exposed producing a recognizable *wing flash* to searching pilots.

### Research Question 3

*Is there variability between a pilot's perceived visual distance from a UAS and their actual distance?*

The data shows that pilots generally underestimated their distance to the large Anaconda UAS by 0.25 SM. Pilots overestimated their distances to the small Iris UAS by a mean distance of 0.20 SM. This finding is significant. Small platforms make up the vast majority of hobby platforms and many commercial operations, as well. If the finding is broadly true, pilots that visually spot such small UAS platforms in flight are likely to assume they have more distance and subsequent reaction time to respond before a potential collision. This problem may be further complicated by the fact that small UAS platforms like the Iris are already difficult to detect.

### Research Question 4

*Based on the FAA's model for Aircraft Identification & Reaction Time, would pilots have adequate time to evade a UAS collision?*

According to the FAA's Aircraft Identification and Reaction Time model presented in Table 1, pilots require at least 12.5 seconds to detect, process, and perform required evasive maneuvers to avoid an airborne collision threat. Based on the mean detectability distances demonstrated by the participants in this study, 0.493 SM for the Anaconda and less than 0.10 SM for the Iris, the researchers reverse-applied a conservative general aviation cruise speed of 100 knots to estimate available reaction times to each platform.

The simple equation of Time = Distance / Speed, yielded the following results:

Table 6

*Available Reaction Time to a sUAS Collision Threat Based on Visibility Distance*

| Platform | Detection Distance | Speed | Available Reaction Time |
|---|---|---|---|
| Anaconda | 0.493 SM | 115.08mph (100 kts) | 15.42 seconds |
| Iris | 0.10 SM | 115.08mph (100 kts) | 3.12 seconds |

Note: This estimation assumes the UAS platform is stationary and the convergence speed is limited to the cruise speed of the aircraft.

Based on this estimate, a pilot would likely have adequate time to recognize and respond to a larger fixed-wing platform like the Anaconda, but would be unlikely to have adequate time to recognize and respond to a smaller platform like the Iris.

## Researcher Comments

It is important to note that the results of this experiment are based on the most ideal of conditions. First, each pilot was made acutely aware of the presence of UAS operations. These results may not represent realistic distributions of a pilot's divided attention between external scanning and internal flight deck workload. Alert pilots are likely to divert increased attention to see-and-avoid scanning than during normal flight operations. Additionally, this experiment was conducted under clear, daytime, visual meteorological conditions. UAS detectability and visual range are not likely to be valid when a pilot encounters visually-hindering conditions such fog, mist, haze, snow, or other similar phenomenon. Succinctly, the researchers believe the results presented in this study represent the most optimistic visibility conditions that may not necessarily be reflective of normal operations in the National Airspace System.

## Recommendations

The researchers recommend the following operational considerations when flying in proximity to unmanned aircraft:

**Full-range scanning.** Full-range scanning is critical to ensuring safety in the visual environment. The authors recommend employing the scanning procedures and concepts outlined by the FAA in Advisory Circular, AC 90-48D, *Pilots' Role in Collision Avoidance.*

**Enlist others to assist in UAS detection.** Enlist the aid of other crewmembers or passengers to assist in UAS visual detection by putting more eyes on more sky, particularly in areas proximate to UAS operations.

**Realize the limitations of vision.** It is important to understand the physical limitations of vision as a mechanism of collision detection. Visual illusions such as the aforementioned parallax error and size estimation error can lead to poor aeronautical decision-making regarding UAS avoidance and evasion. Pilots should check NOTAMs for UAS flight activity, monitor ATC frequencies for traffic alerts, and exercise a vigilant visual scanning pattern to ensure early awareness to a potential UAS encounter or collision threat.

**Do not delay evasion.** The study results indicate pilots are consistently poor at estimating UAS distance. The authors recommend pilots actively maneuver to avoid or evade close encounters with UAS platforms, provided the maneuver can be performed without compromising flight safety.

## Suggestions for Further Research

The authors recommend repeating this study to gather additional data points for statistical analysis. Furthermore, the authors recommend the creation of spin-off research projects to include analysis on the visibility of UAS lighting and night operations, UAS markings, and color contrast. Finally, the authors recommend additional testing of the proprietary uAvionix ADS-B system to determine the viability, effectiveness, and reliability of large-scale use.

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