

# COMPARISON OF SEE-AND-AVOID PERFORMANCE IN MANNED AND REMOTELY PILOTED AIRCRAFT

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## Abstract

See-and-avoid is the current FAA approved method for pilots to avoid objects and other aircraft while flying in visual meteorological conditions (VMC). Although fully autonomous 'sense-and-avoid' or 'detect-and-avoid' systems are in development, none are currently certified. Thus existing unmanned aerial vehicle (UAV) operations are limited to case-by-case restricted airspace or require escort by manned aircraft [1, 2]. Many UAVs are equipped with at least a forward-looking camera. In the transition between current technology and future fully autonomous, certified sense-and-avoid systems, it seems reasonable to require a ground-based operator to perform the see-and-avoid function.

This paper discusses the flight-testing performed to establish air traffic detection ranges for low-time pilots, and for a low-cost UAV camera system. The system was evaluated to determine if it could provide the equivalent see-and-avoid performance as the tested pilots.

## Introduction

In the past UAV operations have been used almost strictly by the military in restricted airspace. However, as UAV technology has matured many civilian uses have begun to develop. With this subdivision of civil UAVs comes the inherent use of the National Airspace System (NAS) in which to operate them. Heavy restrictions (equivalent to a general aviation aircraft) currently exist on UAV operation outside of restricted airspace [2].

The term see-and-avoid appears in the FAA Right-of-Way Rules (Title 14 CFR 91.113). "When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft." See-and-avoid is often considered the most difficult unmanned aviation

requirement to meet because there are no quantifying numbers included with the regulations, only that UAVs must provide "an equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft" [1,3]. FAA Order 7610.4K goes on to mention several possible methods to achieve this see-and-avoid function. Among those mentioned is "forward or side looking cameras," which we have chosen to implement in our testing.

When flying in VMC, aircraft separation or the see-and-avoid function is primarily the pilot's responsibility [4]. One important objective is to determine if a UAV operator can provide an equivalent level of traffic detection remotely. If this can prove possible, a ground based operator or monitor could be an important intermediary step while future autonomous sense-and-avoid systems are being developed and certified.

The purpose of this project is to compare the obstacle and traffic detection capability of a UAV operator to that of an actual pilot flying a manned aircraft. It may seem obvious that the majority of midair collisions (MACs) and near midair collisions occur with low-time pilots; however, it is surprising to learn that most MACs also occur during daylight hours in VMC [3, 5]. Given this information, we chose to examine low-time pilots flying under the Visual Flight Rules (VFR) and determine their traffic detection ranges.

While the UAV community and RTCA Special Committee 203 are drafting regulations with precious little data available to assist in the decision making process, this is an extremely important area of research. We are anticipating that the data provided in this experiment could benefit the community as UAVs make the transition from restricted-only airspace into the broader NAS.

### ***Current UAV Regulations and Related Research***

RTCA SC-203 is one of the teams designated with the task of quantifying Unmanned Aerial Systems (UAS) performance requirements, which include both the air vehicle and the ground station. Of the already existing rules, Title 14 CFR Part 91 – General Operating and Flight Rules has specifications for unmanned aircraft but the community is having trouble complying with them. One of the most difficult to accomplish is providing an equivalent level of safety to the see-and-avoid requirement.

Detection range and search area are both key components in the overall representation of see-and-avoid. Search area and range are not directly addressed in the FAA regulations, although AC 25.773-1 goes into some detail regarding cockpit visibility guidelines. Search area azimuth guidelines range from  $\pm 60^\circ$  up to  $\pm 120^\circ$ , and elevation guidelines range from no guidelines up to  $+37^\circ$  and  $-25^\circ$  [3].

To avoid a midair collision, a 500 foot altitude separation needs to be maintained between aircraft at all times. In 2005 a study was conducted to determine the minimum detection range needed for a passive sense-and-avoid system to detect a threat and maneuver in order to still maintain the 500 foot altitude separation required. Since this was for a passive system, lag time introduced by a system using a ground station would require additional range to still maintain this separation. It is also assumed that each aircraft is below 10,000 feet and going no more than 250 kts, with the presumption that a system based off of aircraft transponders could be incorporated for higher altitudes. The minimum detection range was determined to be 1.17 miles for the system [6].

Traffic detection ranges have also been the subject of several other studies. The Air Force Research Labs Operational Encounter model calculated the expected pilot detection range to be between 1.7 and 2.3 miles for an alerted pilot [3]. Research from the MIT Lincoln Laboratory in the 1980's found recognition ranges of 1.14 miles for un-alerted pilots and 1.61 miles for alerted pilots trying to detect a Cessna 421 aircraft in the open sky [7]. Several other see-and-avoid options exist, such

as the Amphitech OASys radar used in the NASA ERAST project in 2003, which was able to detect most intruder aircraft an average of 5.18 miles away [8]. Evasive action time related to see-and-avoid for a manned aircraft is discussed in Advisory Circular 90-48C Appendix I, where it shows a total time of 12.5 seconds between obstacle detection and a subsequent course change.

### **Testing**

With all of the above information in hand our goal became to independently verify the traffic detection ranges for low-time pilots, as well as determining the detection ranges for a low-cost three camera UAV system (each camera <\$200). To accomplish this we used one of our flying laboratories at Ohio University to house most of the test equipment. A Piper Saratoga (Figure 1 below) was used as the test aircraft and the Ohio University Department of Aviation's Piper Warrior III (Figure 2 below) was used as the traffic aircraft.



**Figure 1. Ohio University's Piper Saratoga**



**Figure 2. Ohio University's Piper Warrior III**

### ***Equipment and Installation***

The three cameras used were Arm Electronics C600 cameras (Figure 3 below), each having a resolution of 600 TV lines. All of the cameras were installed behind the test aircraft windshield, on pan-tilt mounting brackets. This setup allowed us to adjust the positioning of the cameras if initial testing revealed any overlap or other errors associated with the camera positions.



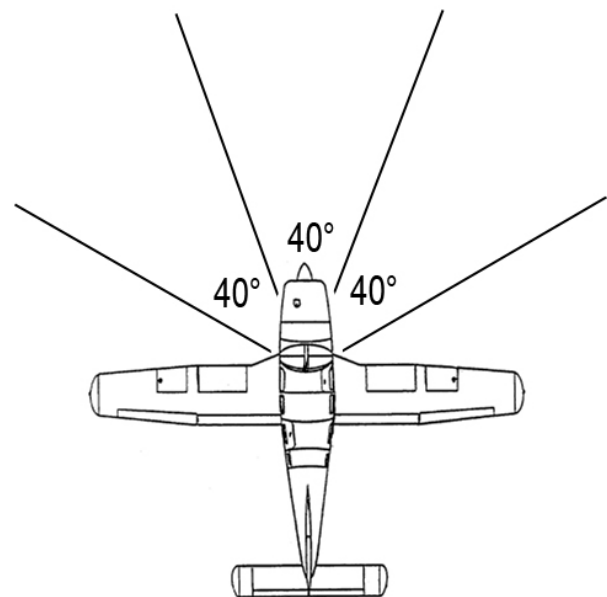
**Figure 3. Three Camera Installation**

The three cameras installed on the Saratoga each provide a  $40^\circ$  horizontal by  $30^\circ$  vertical field of view, totaling  $120^\circ$  horizontal field of view from the three cameras together. The field of view provided by these cameras meets the  $\pm 60^\circ$  horizontal and  $\pm 10^\circ$  vertical scanning guidance set forth by the FAA with regard to a pilot avoiding a midair collision [9]. This field of view does not meet the  $\pm 110^\circ$  azimuth guidance from the ICAO Rules of the Air Section 3.2; however, more cameras could be added to increase the horizontal field. Since this is a controlled experiment, we ensured that all of the target aircraft fell within the horizontal field in order to maintain accuracy in the data. The horizontal field of view captured by the cameras is demonstrated in Figure 4 below.

In order to calculate the range between the test and traffic aircraft the location of both aircraft must be known at the time of detection. To do this we installed a Novatel OEM4 GPS unit onboard the test aircraft. This unit is WAAS enabled and provides position and UTC data at 20 Hz. Onboard the traffic aircraft we installed an Eagle Tree

eLogger v3 with GPS expander module behind the windshield. This unit is also WAAS enabled, and provides position and UTC data at 5 Hz.

To record the video feeds coming from the three cameras, we chose a computer PCI card with BNC video input connections. This card is typically used for security or surveillance applications, but the features also worked well for our project. The card was a Netpromax NDRx204 DVR card, recording at 30 FPS total between the three cameras. The video was recorded at  $704 \times 480$  pixel resolution per camera. Onboard the test aircraft was a rack-mounted computer, which had the PCI card installed, as well as serial connections to record the GPS output from the Novatel unit. The complete rack installation can be seen in Figure 5 below.



**Figure 4. Horizontal Field of View of the Three-Camera Setup**



**Figure 5. Rack Unit Installation**

### ***Testing Procedure***

The crew onboard the test aircraft consisted of three members: a subject pilot performed the traffic detection; a safety pilot assisted the subject with navigation and observation guidelines; and a data collector recorded the crucial information. Before the flight the safety pilot provided the necessary flight path details to the subject pilot, and described what the subject believed to be the focus of the research and their part in the experiment. Along the flight the subject searched for and identified landmarks such as bodies of water and electrical towers which the safety pilot had marked on a flight map, as well as identified any air traffic that entered his or her field of view. The purpose of identifying landmarks was to provide a sufficient distraction to the pilot as to not skew the data with an unrealistic amount of traffic scanning.

The subject pilot notified the safety pilot and data recorder as he or she identified the different landmarks and air traffic along the flight, although only information that pertained to the target aircraft

was recorded. When the target aircraft was identified the data collector marked the exact time. Along the entire flight the test aircraft and traffic aircraft recorded time and position using the GPS units mentioned above. This allowed the data recorder (after the flight) to look up the positions of both aircraft at the identification time, and compute the range between the two aircraft.

While the flight took place, we also had the three cameras behind the test aircraft windshield which captured approximately what the pilot was able to see. The cables from the cameras fed to the onboard computer which recorded the 120° by 30° field of view. When the flight was complete, we were able to replay the recorded video and determine the various detection ranges for the cameras given the limited resolution and field of view. Time was overlaid on the video, which allowed the same method to determine position and range as mentioned above for the subject pilots.

When the flight-testing was complete, we were able to look at the ranges from both the subject pilot and camera methods. This allowed us to determine if the cameras could provide an equivalent level of detection capability as the human eyes used by the subject pilots. If the cameras could provide superior detection capability, we could then add an approximate lag time to account for the latency that would be present between the video transmission and a ground-based operator performing the see-and-avoid function. This would allow us to compare a theoretical active see-and-avoid system to the currently approved pilot see-and-avoid used in all manned aircraft today.

### **Preliminary Results**

As of August 2008, seven subject pilots have gone through the experiment and provided very useful data regarding their ability to detect air traffic during daylight VMC. Originally the test was designed to record both pilot detection ranges and camera ranges on the same flight, so both could be compared on a single detection with the same sun angle and cloud conditions et cetera. However, after initial testing revealed a noticeably lower detection range for the cameras, not all of the traffic passes were at a close enough proximity to capture the target on camera. Thus, a later test was

conducted without a subject pilot, and was designed specifically to ensure the target aircraft would be captured on camera. This secondary test allowed the necessary range calculations to be performed. In this experiment the same Saratoga test aircraft was used, and a Cessna 210 Centurion was used as the traffic aircraft.

Each subject pilot was presented with two aircraft conflicts. The first pass was set up with the target aircraft crossing the flight path of the test aircraft at a 90° angle. The second involved the traffic aircraft approaching the test aircraft from straight ahead. This is said by pilots to be the most difficult position to detect traffic because of the illusion that the traffic aircraft is not moving, paired with the empty field myopia occurrence when attempting to focus in an empty visual field [10]. In both cases the test aircraft was kept at approximately 3000 feet altitude, and the traffic aircraft 500 feet above or below.

### ***Subject Pilots***

The subject pilots were able to detect the traffic aircraft somewhat faster than the camera setup, with an average detection range of 1.275 miles. In all but one case, the 90° intersect detection was noticeably better than the oncoming detection. In one of the tests, the oncoming traffic aircraft passed within 500 feet of the subject pilot without any detection. Table 1 on the next page shows the ranges for the seven subject pilots, as well as the mean detection ranges. The average intersect detection range was 1.511 miles, while the average oncoming range was just over a mile at 1.038 miles. When comparing both the average ranges, the mean 90° intersect detection range is almost half a mile greater (0.473 miles) than the mean oncoming detection range.

All of these ranges fall right around the detection ranges from the other research mentioned above. Between the Air Force Research Labs Operational Encounter model and MIT’s Lincoln Laboratory research a nominal detection range of 1.14 to 2.3 miles was to be expected, depending on whether the pilot was anticipating seeing any air traffic.

**Table 1. Subject Pilot Detection Ranges**

<b>Subject Pilot</b>	<b>(statute miles)</b>	
	<b>Intersect</b>	<b>Oncoming</b>
Pilot 1	1.294	No Detection
Pilot 2	1.178	0.309
Pilot 3	1.898	1.127
Pilot 4	1.710	1.202
Pilot 5	1.167	2.336
Pilot 6	1.773	1.258
Pilot 7	1.559	1.034
Mean	1.511	1.038

### ***UAV Camera System***

In the testing involving the UAV three-camera system, we were searching for a Cessna 210 Centurion somewhere in the sky. After the flight we replayed the recorded video using three displays. Though not real-time, this served as our simulation of a UAV operator designated with the task of obstacle and traffic detection. Circled below in Figure 6 is a screenshot of one of the traffic aircraft identifications from the right camera on an intersect detection, followed by a screenshot of an oncoming detection from the center camera circled in Figure 7 below. The target aircraft is approximately 0.4 miles away in Figure 6, and 0.49 miles in Figure 7. This gives an idea of how much earlier or later an actual remote pilot in the loop system may provide detection of the air traffic.



**Figure 6. Intersect Detection on Camera**



**Figure 7. Oncoming Detection on Camera**

The following UAV camera detection ranges found in Table 2 and 3 below are what we determined to be the fastest detection times possible with the limited camera resolution and field of view. The detection ranges could potentially be even smaller if latency was introduced for the video feeds to transmit to the ground and allow a ground operator to identify the intruder aircraft. The average range for the overall camera system is just over half a mile at 0.521 miles. The mean camera intersect detection range of 0.651 miles is approximately 2.3 times worse than the mean intersect detection range established for the subject pilots. The mean camera oncoming detection range of 0.417 miles is approximately 2.49 times worse than the mean oncoming detection range for the subject pilots.

**Table 2. Intersect Camera Detection Ranges (statute miles)**

Detection	Intersect
1	0.717
2	0.582
3	0.638
4	0.665
Mean	0.651

**Table 3. Oncoming Camera Detection Ranges (statute miles)**

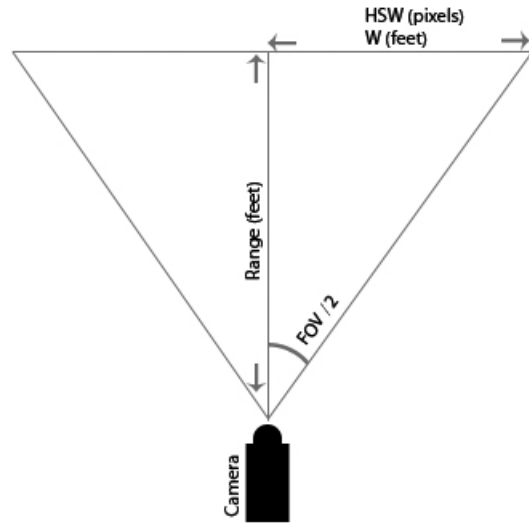
Detection	Oncoming
1	0.372
2	0.424
3	0.494
4	0.319
5	0.475
Mean	0.417

## Resolution and Detection Ranges

With the above camera ranges in hand and a known recording resolution (704 x 480 pixels), we were able to make basic approximations regarding the applicability of a camera system at higher resolutions as well as detection capabilities for larger or smaller aircraft. Using the equations below with the 704 pixel horizontal resolution and 40° horizontal field of view (FOV) at the mean detection range of 2201.76 feet (0.417 miles), we found a ratio of 2.2766 feet per pixel for the cameras. This value implies the 39 foot wingspan for the target aircraft would occupy approximately 17 pixels in an oncoming detection.

To verify this value we took an oncoming detection screenshot and digitally zoomed in to 3200% in order to see the individual pixels of the image. Counting the approximate number of pixels the target aircraft occupied, revealed values near 17 pixels as well. This 17 pixel value became our threshold for the occupied pixels variable in the equations below. Figure 8 below shows where the different variables used in the equations originate, such as width in feet (W) and half screen width in pixels (HSW).

$$Range = \frac{HSW \times Wingspan}{Occupied\ Pixels \times \tan\left(\frac{FOV}{2}\right)}$$



**Figure 8. Camera Range Diagram**

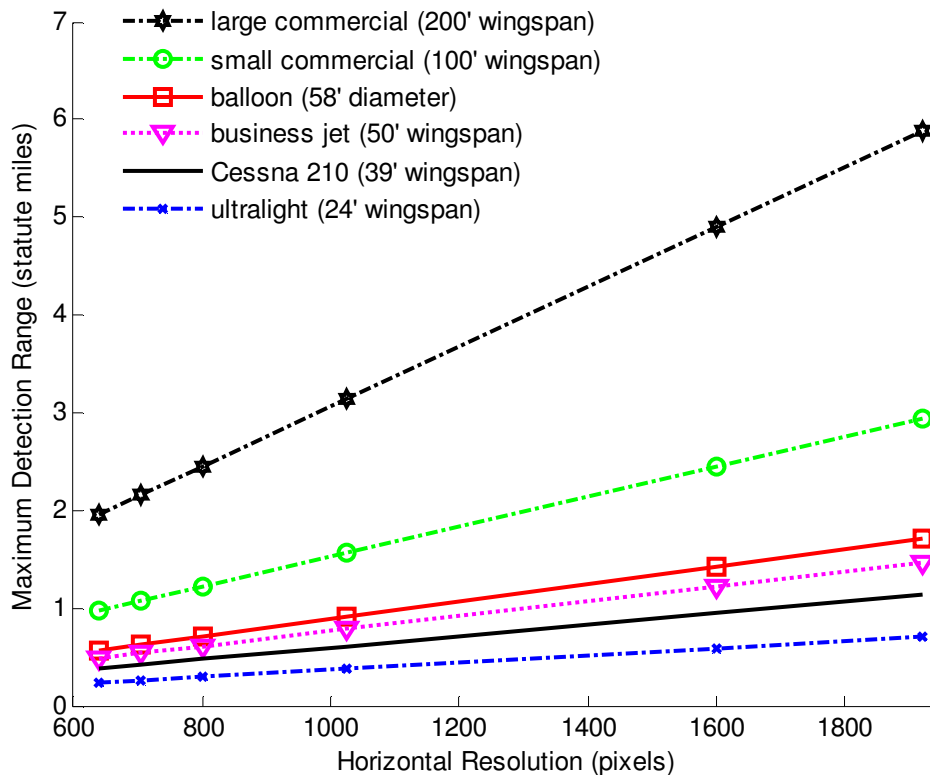
$$W = HSW = Range \times \tan\left(\frac{FOV}{2}\right)$$

Rearranging the above equation and setting it equal to the ratio of occupied pixels to the aircraft wingspan yields the equation below.

$$\frac{Occupied\ Pixels}{Wingspan} = \frac{HSW}{Range \times \tan\left(\frac{FOV}{2}\right)}$$

Rearranging the equation above, we can easily find the detection range. The range equation below is a function of half screen width, wingspan, occupied pixels required for detection, and the field of view of the camera.

This idea can be applied to other resolutions or aircraft with different wingspan lengths. The results of our analysis are shown in Figure 9 below for the listed aircraft types at other typical resolutions (640x480, 800x600, 1024x768, 1600x1200, and 1920x1080). From this graph it shows that 1920x1080 high definition video (HD) or above is required to accurately identify a Cessna 210 traffic aircraft at ranges greater than 1 mile. However, even with HD video, aircraft with wingspans smaller than 34 feet will be difficult to detect at this range with a 17 pixel threshold.



**Figure 9. Range vs. Resolution (Assuming 17 Pixel Minimum Detection Threshold)**

## Conclusions

After several subject pilots had gone through the experiment, it became evident that the pilots were consistently identifying the traffic aircraft before the camera system. Many of the traffic aircraft were not visible on the cameras during the initial subject pilot testing. This required us to create a secondary set of test scenarios with the sole purpose of capturing the traffic aircraft on the camera system. This flight configuration involved much more communication between the safety pilot and the traffic aircraft pilot, in order to pass each other at a closer proximity than in the previous testing. An important theme noticed throughout the subject pilot testing is the pilots' earlier detection of the intersecting traffic over the oncoming traffic. The preliminary results of this study give a good

indication of the ability of a pilot flying VFR to identify general aviation air traffic.

Using our camera data to determine a minimum pixel threshold required to detect a traffic aircraft, we were able to approximate detection ranges for different length wingspan aircraft as well as for various camera resolutions. The result of this analysis led us to hypothesize that an HD resolution camera would be the minimum resolution usable to detect most air traffic at ranges similar to a pilot's detection ability.

## Future Work

Seven subject pilots have completed the experiment so far. We would like to run several more subjects through the testing in order to reduce any anomalies or errors introduced into the data. For example, the oncoming detection for subject 5 being over twice

the range of the subject's intersect detection may turn out to be an irregularity, and could be one of the things we would like to smooth out in the mean values by accumulating more numbers into the average. In the end we would like to have performed the test with a sufficient number of subject pilots to achieve statistical significance within the data. We also plan to run the camera test using a 1920x1080 pixel HD camera to detect oncoming traffic. This test will be performed at various hours of the day with different sun angles, to determine the effects of the sun on the detection ranges. This would enable us to test our hypothesis regarding an HD camera as a minimum detection resolution usable for ranges greater than one mile.

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