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**Paper Title:** Resolution Requirements for Passive Sense & Avoid

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**Abstract:** One of the major hurdles for Unmanned Aircraft Systems (UAS) to achieve routine access to civil airspace (similar to manned aircraft of the same class and category) is compliance with the right of way requirements given in Title 14 Code of Federal Regulations (14 CFR) Part 91, paragraph 91.113. This is commonly referred to as the "see and avoid" requirement. The problem lies in detecting and tracking non-cooperative aircraft – those flying VFR without a transponder. While larger UAS might effectively implement a radar or other active scanning system, such a solution is problematic for smaller UAS. One solution is the use of small passive EO/IR cameras to search the required field of regard and detect the traffic in a manner similar to a pilot's eyes. Such a small, light-weight, low-power system will need to effectively detect and track traffic early enough to avoid conflicts – creating a resolution requirement based on traffic range and the closing velocity. However, the information provided by passive sensors is limited to azimuth and elevation. This paper proposes a means to resolve this problem and define a passive "sense-and-avoid" system's resolution requirement.

# Resolution Requirements for Passive Sense & Avoid

## By

## David E. Grilley

### Introduction

In the United States, all pilots are required to "see and avoid" other aircraft, whether Instrument Flight Rules (IFR) or Visual Flight Rules (VFR), when conditions permit.[1] This extract from Part 91 is the bane of Unmanned Aircraft's ability to operate routinely in civil airspace. Without an onboard pilot, Unmanned Aircraft have no means to "see" other aircraft because "to see" implies human eyes.[2]

The solution to this problem is twofold: 1) provide an official explanatory document (such as an advisory circular) which allows mechanical detection of traffic conflicts as functionally equivalent to "seeing" them, and 2) including appliances capable of detecting and avoiding traffic on unmanned aircraft.

### Problem Statement

The first part of this solution is regulatory in nature. This paper will address only the second part of the problem: the mechanical appliances necessary to meet the requirement. Specifically, this paper will provide a means to determine the resolution requirements of a passive, electro-optical sensor (a visual or infrared video camera) that most closely duplicates the human ability to see. In addition, this paper supports the design of an appliance that complies with ASTM standard F-2411, "Design and Performance of an Airborne Sense-and-Avoid System."

For starters, one needs to review the actual rule Unmanned Aircraft Systems (UAS) are expected to comply with. Here's the rule:

*14 CFR 91.113 Right of way rules: Except Water Operations*

*(a) Inapplicability. This section does not apply to the operation of aircraft on water.*

*(b) General. 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. When a rule of this section gives the right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear.*[3]

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[1] 14 CFR Part 91-113, "Right of way rules"

[2] Webster's New Twentieth Century Dictionary, 2nd Edition, defines "to see" as: *to get knowledge or an impression of [something] through the eyes and the sense of sight; to perceive visually; look at; to view.*

[3] "Well clear" is normally defined as 500 feet separation.

*(c) In distress. An aircraft in distress has the right-of-way over all other air traffic.*

*(d) Converging. When aircraft of the same category are converging at approximately the same altitude (except head-on, or nearly so), the aircraft to the other's right has the right-of-way. If the aircraft are of different categories --*

*(1) A balloon has the right-of-way over any other category of aircraft;*

*(2) A glider has the right-of-way over an airship, airplane, or rotorcraft; and*

*(3) An airship has the right-of-way over an airplane or rotorcraft.*

*However, an aircraft towing or refueling other aircraft has the right-of-way over all other engine-driven aircraft.*

*(e) Approaching head-on. When aircraft are approaching each other head-on, or nearly so, each pilot of each aircraft shall alter course to the right.*

*(f) Overtaking. Each aircraft that is being overtaken has the right-of-way and each pilot of an overtaking aircraft shall alter course to the right to pass well clear.*

*(g) Landing. Aircraft, while on final approach to land or while landing, have the right-of-way over other aircraft in flight or operating on the surface, except that they shall not take advantage of this rule to force an aircraft off the runway surface which has already landed and is attempting to make way for an aircraft on final approach. When two or more aircraft are approaching an airport for the purpose of landing, the aircraft at the lower altitude has the right-of-way, but it shall not take advantage of this rule to cut in front of another which is on final approach to land or to overtake that aircraft.*

Therefore, UAS must be able to detect traffic conflicts and yield the right-of-way when required. Also, all aircraft must avoid creating a hazard[4], even if they have the right-of-way. In the modern air traffic system, there are two types of traffic: cooperative and non-cooperative. Cooperative traffic broadcasts its position using a transponder, while non-cooperative traffic does not broadcast information. The Traffic Collision and Avoidance System (TCAS) has already demonstrated that avoidance of cooperative traffic via an appliance is acceptable to civil aviation authorities. In fact, pilots are required to comply with TCAS resolution advisories. This sets a fine precedence for accepting an appliance that can sense and avoid non-cooperative traffic.

## Potential Solutions

While TCAS may, or may not, be suitable for UAS, a transponder based system provides an obvious solution for cooperative aircraft collision avoidance. On-board air-to-air radar is another demonstrated system that provides sufficient information for aircraft collision avoidance. To use a passive system similar to a pilot's vision, one

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[4] 14 CFR Part 91-111.

must first recognize the information available from cooperative and radar based systems.

These systems provide the relative position of the traffic and a velocity indication. This allows the system to predict the traffic's flight path and determine whether a conflict exists. Once the conflict is determined, then the pilot can act to avoid the conflict.

With passive systems however, position and velocity determination are a little more problematic. While there are techniques to resolve both position and velocity, these add significant amounts of time to the entire collision avoidance solution. Time in this respect, greatly increases the resolution required – and consequently the size, weight and power requirements – which adversely affects the overall UAS design.

In order to determine the minimum resolution required of a camera based, passive system there are some important considerations and assumptions to address.

## The Big Picture

First, one should examine the overall geometry of a traffic conflict. Figure 1 presents a "god's eye" view of various collision geometries.

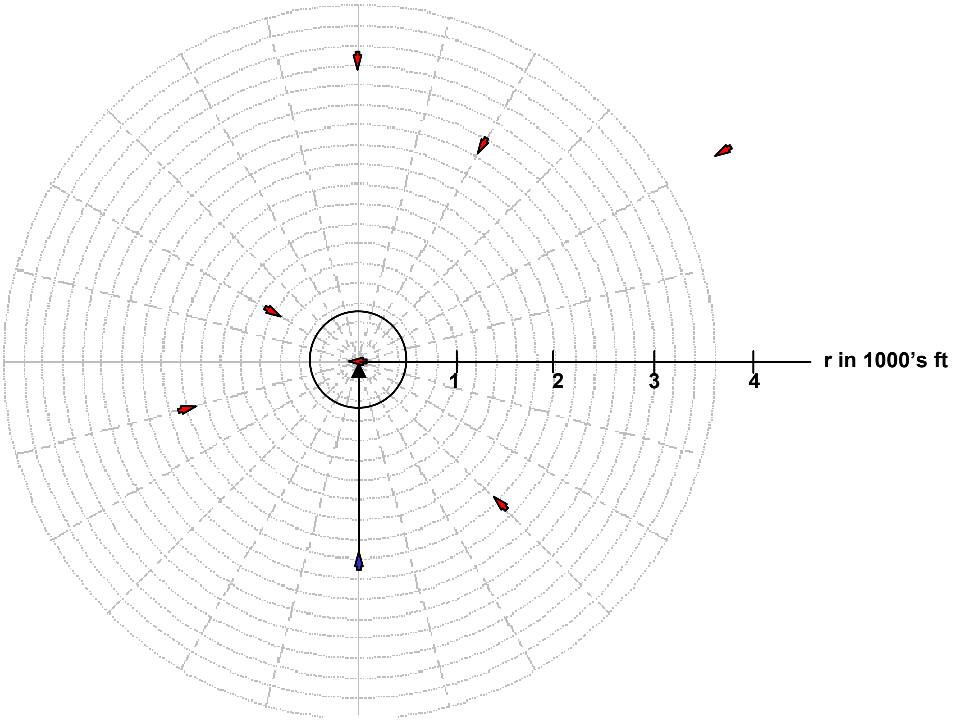

Figure 1: The geometry of collisions

In this diagram, the blue aircraft is traveling up the page towards the origin. All of the red aircraft are also proceeding towards the origin, and a collision will result if the aircraft arrive at the origin at the same time. (One should also note the 500 feet circle in around the origin indicating the "well clear" zone.) Most of the time, we perceive this picture as a static positional relationship between the aircraft (r, $\theta$). However, one can gain a lot more intuitive information if we look at the diagram in terms of velocity and angles. (See figure 2.)

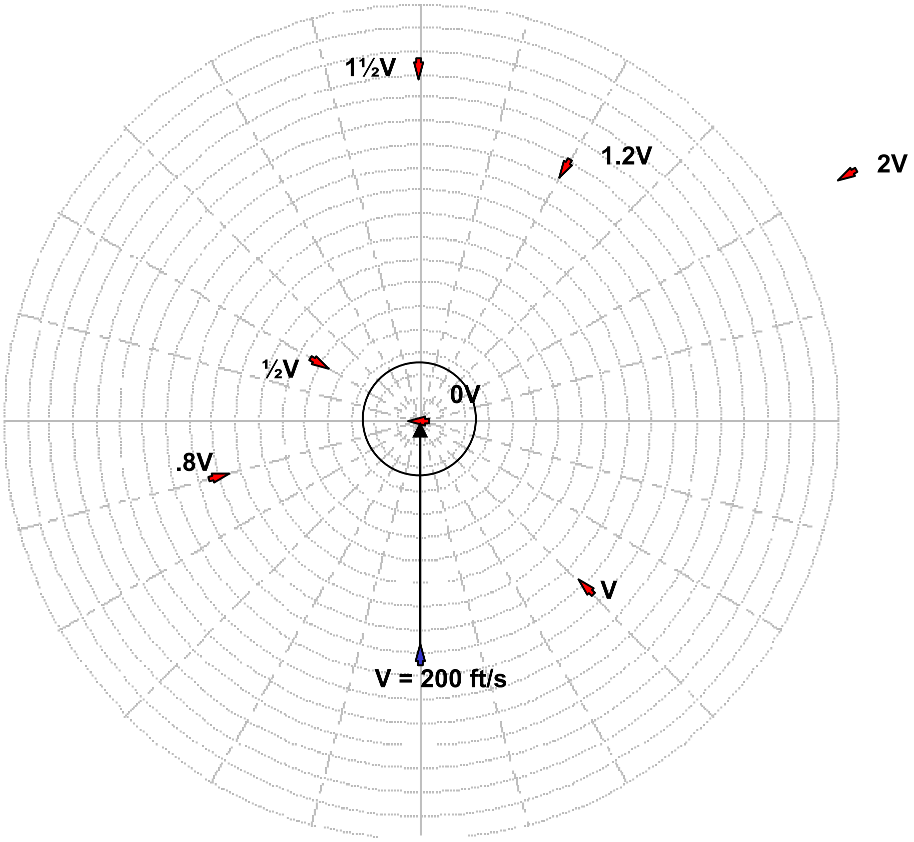

Figure 2: Velocity scale

Here, it becomes apparent how the relative velocity of the traffic determines whether a conflict will occur.

## Avoiding the Collision

Our first assumption is that the traffic will not maneuver. Thus, the UAS will effectively avoid the collision if it avoids the collision point in figure 2 by 500 feet or more. Any given UAS may choose another distance for the calculation, but 500 feet is considered well clear. Both NASA's ERAST study and OSD's MARCAT program have shown that the primary factor in displacing an aircraft is the bank angle. For a given bank angle, the time required to displace the UAS by 500 feet is relatively independent of the aircraft's velocity. (This generalization breaks down at very slow airspeeds. In the extreme, an aircraft with 0 velocity will never move 500 feet….)

For forward aspect conflicts (head-on ± ~60°), this can be shown directly through application of the turn rate and radius equations:

Turn Radius (R) in ft: $R = {V^2}/{g \tan \beta}$ (1)

Turn Rate ($\gamma$) in ${\deg}/{s}$ $\gamma = \left( {g \tan \beta}/{V} \right) \times \left( \frac{360}{2\pi} \right)$ (2)

Where $g$ is the acceleration of gravity, $\beta$ is the bank angle, and $V$ is the aircraft velocity. One can examine the flight path of a turning aircraft a little easier in standard Cartesian coordinates as shown in figure 3. Using a nominal airspeed of 120 knots true airspeed (KTAS ~200 ft/s) a bank angle of 18° gives us (approximately) a standard rate turn of 3°/second and a turn radius of 3927 feet.

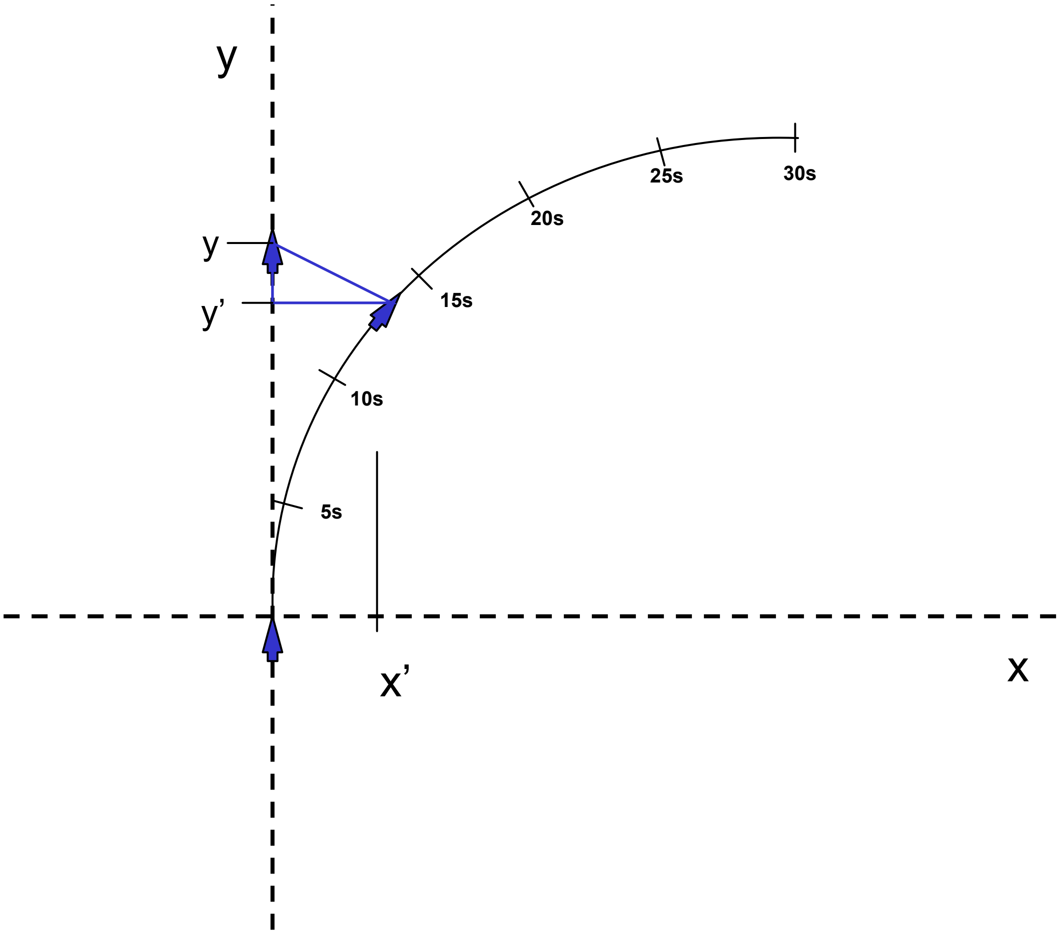

Figure 3: Aircraft maneuver

The position of the non-maneuvering aircraft is simply

$$y = V \bullet t \quad (3)$$

The position of the maneuvering aircraft is

$$x' = R - R \bullet \cos(\gamma \bullet t) \tag{4}$$

$$y' = R \bullet \sin(\gamma \bullet t) \tag{5}$$

The goal of the maneuver is to be 500 feet away from the non-maneuvering position at the point of collision. This distance (d) is the hypotenuse of the right triangle shown in figure 2:

$$d = \sqrt{x'^2 + (y - y')^2} \tag{6}$$

$$d = \sqrt{(R - R\cos(\gamma t))^2 + (Vt - R\sin(\gamma t))^2} \tag{7}$$

$$d = \sqrt{2R^2(1 - \cos(\gamma t)) + V^2t^2 - 2RVt\sin(\gamma t)} \tag{8}$$

If one iterates equation 8 from t = 0 at 1 second intervals, one can find the value of t for which the right side of equation 8 is ≥ 500 feet. The surprising thing we find is that for a given bank angle (in this case, 18°) the time, t, that achieves 500 feet separation is 10 seconds, independent of airspeed, when airspeed is > about 70 KTAS.

A graphical combination of this is shown in figure 4.

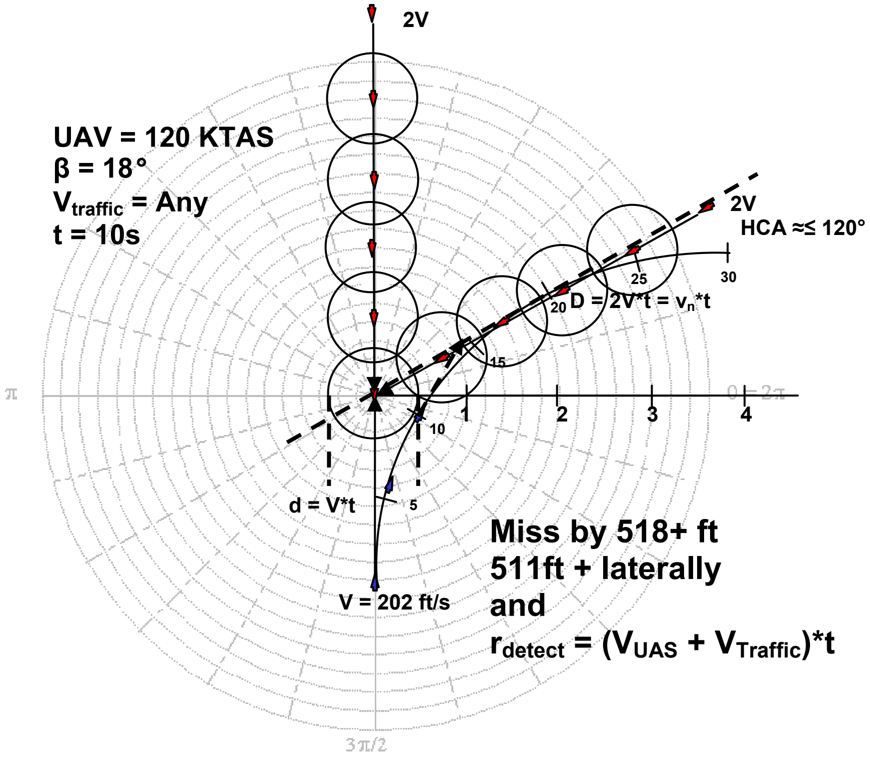

**Figure 4: Polar plot plus the maneuver**

Any operator can input his specific variables for airspeed and bank angle for the maneuver and determine the amount of time needed to remain "well clear" of the collision. Using this t, one can calculate the range needed to detect a conflict by adding the velocities and multiplying by t. One can also add any computational delays or pilot response time to t in order to improve the margin of safety.

$$r_{detection} = \left(V_{UAS} + V_{traffic}\right) \bullet t \tag{9}$$

For traffic conflicts along the wingline, the UAS will need to perform a check turn away from the aircraft, or maneuver much sooner than t prior to collision. For reference, see the shaded area in figure 5. In either case, the distance for detection needed is less than the maximum for a head-on collision.[5]

## Finding the Threat

According to the rules, overtaking aircraft have to yield to the UAS. 14 CFR Part 91 does not define "overtaking", but ICAO does. ICAO Annex 2 defines overtaking as within ± 70° of the tail – or outside ± 110° of the nose. This field of regard requirement is shown in figure 5. The circles in the figure represent ½, 1, 1½, 2, and 3 times the velocity of the UAS out from the collision point. (Figure 2 transposed to this reference frame.) There is a 500 ft. bubble shown on the traffic at 90 right.

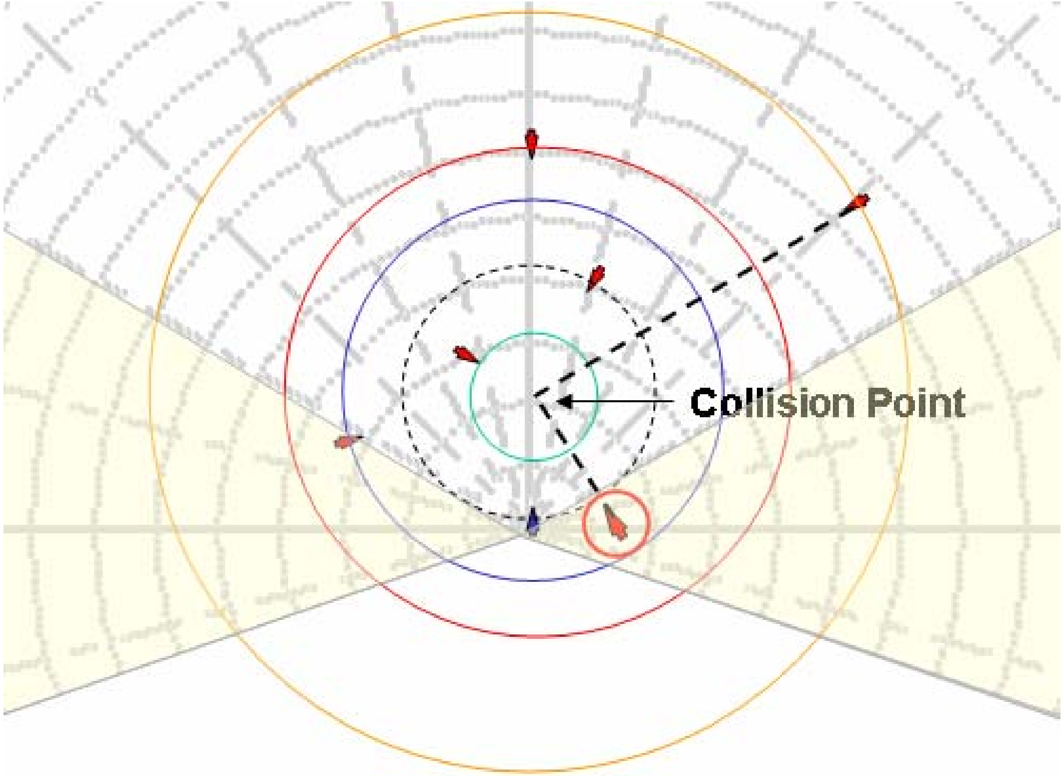

**Figure 5: Field of Regard for Right of Way Rules**

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[5] For further analysis, please review NASA's ERAST Study.

Additionally, NASA ERAST has empirically shown that ± 15° coverage in elevation is sufficient to detect the vast majority of climbing and descending aircraft.[6] Therefore, the cameras used in our passive sense and avoid system must be able to detect and resolve a traffic conflict at the range determined in equation 9. In order to detect the traffic, the camera must have sufficient resolution. For focal plane array cameras, the instantaneous field of view (IFOV) per pixel is the cameral field of view divided by the number of linear pixels in the focal plane array. The IFOV is an angular measurement and the resolution of a pixel is determined by $r \times \theta$. The United States Army uses a four pixel detection requirement (based on the square root of the cross-section); however, there are systems under development that can detect the traffic conflict in a single pixel based on the absence of any line-of-sight motion in the collision geometry. Either way, the camera has to meet the resolution requirement. As shown above, faster aircraft must be detected farther away – giving one the requirement to detect the smallest, fastest aircraft that could be a traffic conflict.

## What Exactly is the Traffic?

This begs the question: "Is there a relationship between the size and speed of aircraft?" For an answer, the author referenced *Jane's All the Worlds Aircraft.* Sample aircraft were chosen based on representative frontal cross-section and speed. The reference aircraft are listed in Table 1.

| **Manufacturer** | **Model** | **Square root of frontal area** | **Maximum Airspeed** | **Type** |
|---|---|---:|---:|---:|
| AIRTRACTOR | AT-500 | 4.47 | 150 | Agricultural |
| AVIAT | PITTS S1-T | 3.46 | 161 | Aerobatic |
| AYRES | THRUSH S2R-R1820 | 3.87 | 138 | Agricultural |
| BEECHCRAFT | BONANZA | 4.00 | 182 | Recreational |
| BEECHCRAFT | BARON | 4.12 | 203 | Recreational |
| BEECHCRAFT | KING AIR | 5.00 | 247 | Commuter |
| BEECHCRAFT | BEECHJET | 5.48 | 468 | Bizjet |
| CESSNA | CARAVAN | 4.69 | 184 | Cargo |
| CESSNA | CITATION II | 4.47 | 262 | Bizjet |
| FAIRCHILD | SA227-CC | 5.00 | 293 | Commuter |
| LAKE | RENEGADE | 4.00 | 148 | Amphibious |
| LANCAIR | LANCAIR | 3.87 | 195 | Recreational |
| LEARJET | 31A | 4.58 | 325 | Bizjet |
| MOONEY | MSE | 3.87 | 168 | Recreational |
| PIPER | CHEYENNE | 4.47 | 305 | Commuter |
| PIPER | MALIBU | 4.00 | 232 | Recreational |
| TAYLORCRAFT | F22 | 3.74 | 108 | Recreational |
| MUSTANG | M-II | 3.61 | 195 | Homebuilt |
| BELL | Cobra | 5.29 | 123 | Helicopter |
| BELL | Kiowa Warrior | 4.47 | 128 | Helicopter |
| BOEING | 737-400 | 8.49 | 480 | Passenger |

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[6] IBID.

| | | | | |
|---|---|---|---|---|
| BOEING | 757 | 9.17 | 530 | Passenger |
| McDONNELL | MD-11 | 10.00 | 450 | Passenger |

**Table 1: Aircraft Cross-Section and Speed**

There is, in fact, a distinct relationship between size and speed as shown in figure 6.

So how does the combination of size and airspeed affect the resolution requirement? To do this one has to determine the required detection range for the reference aircraft and compare range vs. cross-section and the range vs. airspeed plots.

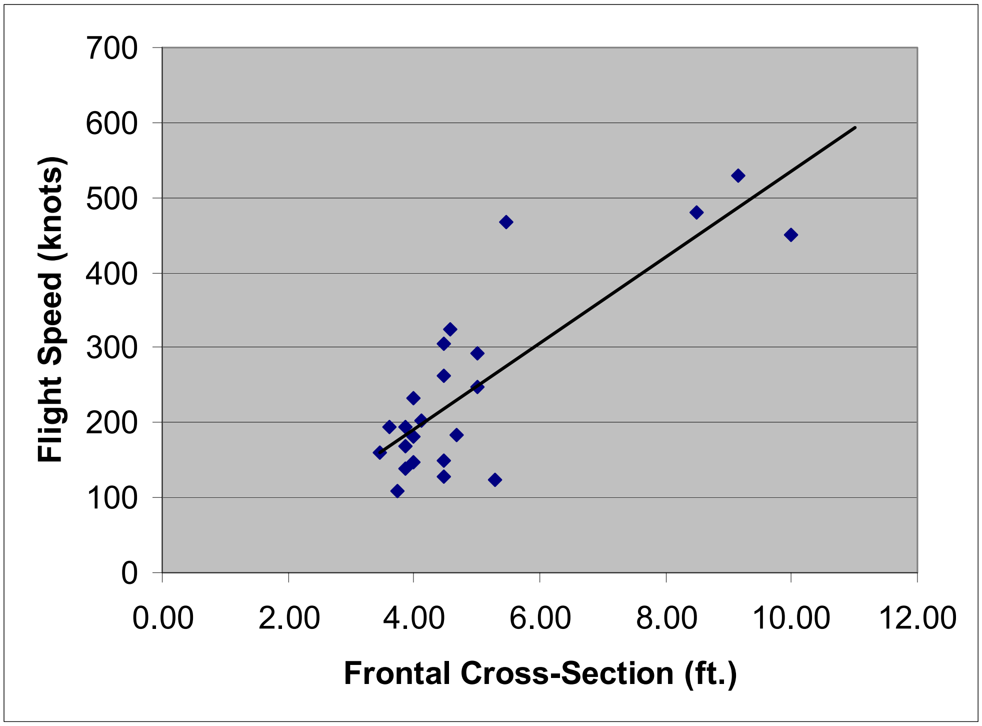

**Figure 6: Plot of Table 1**

For the calculations, this paper will use a UAS flying at 120 KTAS, and a maneuver of 18° of bank. Also, the head-on case represents both the maximum range required for detection and the smallest cross-section: the worst case scenario.

## Running the Numbers

Based on the above assumptions, one can determine the range at which to begin the avoidance maneuver. The range calculation, equation 9, for the reference aircraft in table 1 is displayed in figure 7. Additionally, the milliradian resolution requirement to detect each aircraft at the required maneuver range is shown in figure 8. These numbers will vary depending on the UAS airspeed and bank angle input into the calculation. The yellow line indicates the minimum slope that will include all of the aircraft in the sample set.

The final discussion involves a couple more rules. According to 14 CFR Part 91, all aircraft are required to do two things: 1) remain below 250 kts below 10,000 feet mean sea level, and 2) use a transponder above 10,000 feet mean sea level. *Fast aircraft only fly >250 kts above 10,000 feet where they are required to use a transponder – allowing a transponder based system to provide the additional detection range needed for aircraft >250 kts.*

This means that we can limit the non-cooperative requirement to 250 kts for all aircraft. This corresponds to a maneuver range of 6167 feet. Using this as input in figure 8, one intercepts the minimum resolution slope at 0.67 mrad. (The diagram shows ~0.63 mrad. This is an artifact of the drawing. 0.67 is the calculated value.)

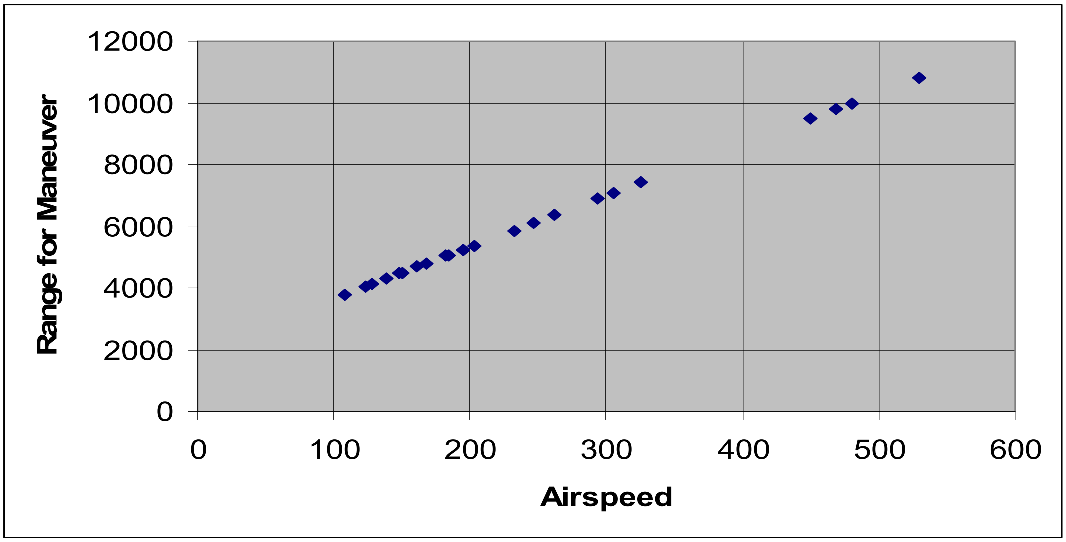

**Figure 7: Maneuver Range**

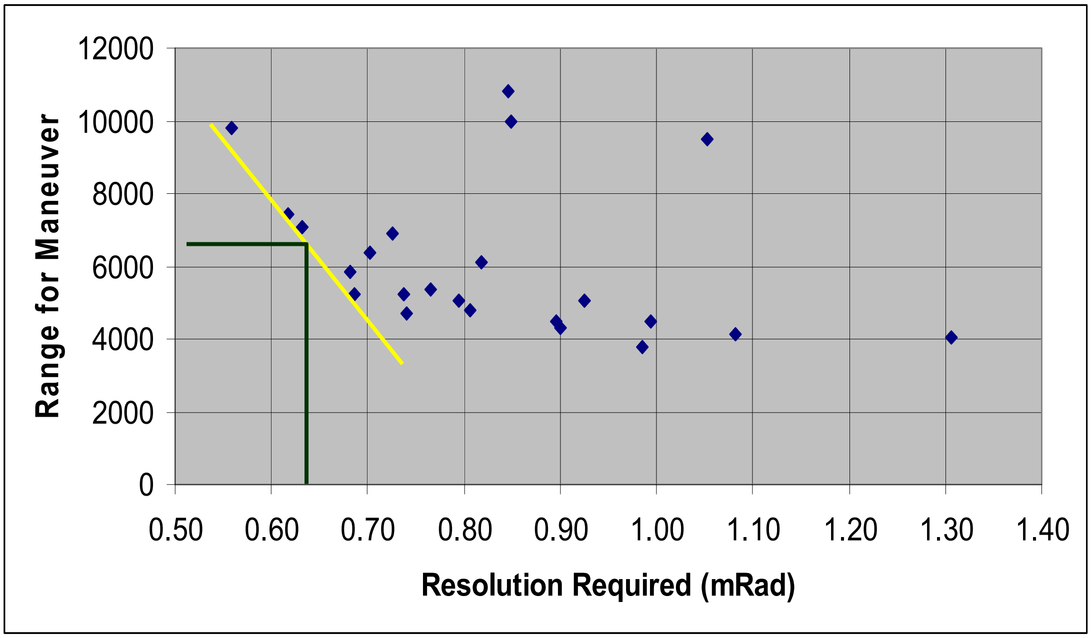

**Figure 8: Resolution Requirement**

## Added Benefit of this Method

Earlier, this paper pointed out that “techniques to resolve both position and velocity, add significant amounts of time to the entire collision avoidance solution.” This method allows one to make two initial assumptions about the traffic. First, it is at 250 kts; second, it is at 6167 feet. (Or other range depending on the specific design specs.) Since the passive system gives good azimuth information, this allows us to initiate the algorithms for position and velocity with an assumed position and speed. The result will be both faster resolution of the position and speed, and a pre-determined response in the event the system does not resolve prior to the need to maneuver.

## In Summary

There are several ongoing efforts to build sense and avoid systems. In these efforts there is a lot of work attempting to quantify the human pilot’s ability to “see” in an attempt to achieve equivalence. This isn’t necessary. An analysis of the rules, combined with the assertion that a UAS needs to remain well clear of traffic conflicts, allows us to develop a straightforward method to determine the resolution requirement of a passive sense and avoid system.

The specific resolution requirement will vary for each UAS. It can be calculated by using the turn rate and radius equations to find the time required to achieve 500 feet separation. Next, the user needs to calculate the resolutions for the sample set, and set the minimum slope to cover all the aircraft. Then, using the time, and the 250 kt speed limit, one can determine the intercept for the resolution line, and the resolution requirement for the system.

Finally, this method establishes a means to initiate the ranging and velocity determination algorithms while providing an assured maneuver.