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COVER SHEET
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Deliverable Number: PD002

Title: Sense-and-Avoid Equivalent Level of Safety Definition for Unmanned Aircraft Systems

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Abstract:
Since unmanned aircraft do not have a pilot on-board the aircraft, they cannot literally comply with the "see and avoid" requirement beyond a short distance from the location of the unmanned pilot. No performance standards are presently defined for unmanned Sense and Avoid systems, and the FAA has no published approval criteria for a collision avoidance system. Before the FAA can develop the necessary guidance (rules / regulations / policy) regarding the see-and-avoid requirements for Unmanned Aircraft Systems (UAS), a concise understanding of the term "equivalent level of safety" must be attained. Since this term is open to interpretation, the UAS industry and FAA need to come to an agreement on how this term can be defined and applied for a safe and acceptable collision avoidance capability for unmanned aircraft. Defining an equivalent level of safety (ELOS) for sense and avoid is one of the first steps in understanding the requirement and developing a collision avoidance capability.

This document provides a functional level definition of see-and-avoid as it applies to unmanned aircraft. The sense and avoid ELOS definition is intended as a bridge between the see and avoid requirement and the system level requirements for unmanned aircraft sense and avoid systems. Sense and avoid ELOS is defined in a rather abstract way, meaning that it is not technology or system specific, and the definition provides key parameters (and a context for those parameters) to focus the development of cooperative and non-cooperative sense and avoid system requirements.

Status:

Access 5-Approved

Limitations on use:
None. The Sense & Avoid ELOS definition has been under review, and some concerns have been raised as to whether the proposed definition and key parameters are sufficient. Some updates to the document were envisioned but not yet accomplished.

ACCESS 5 POSITION PAPER

Project: Access 5 **Paper Number**: SE-1

Regulation Reference: 14 CFR 91.113

Date: January 14, 2005

Status:

Proposal	Draft Position	Closed	SEIT-Approved	Access 5-Approved
			X	

Subject: Sense and Avoid ELOS Definition

Statement of Question/Issue:

All manned aircraft are required to maintain vigilance to "see and avoid" other aircraft when operating in the National Air Space (NAS). Since unmanned aircraft do not have a pilot on-board the aircraft, they cannot literally comply with the "see and avoid" requirement beyond a short distance from the location of the unmanned pilot. Currently, unmanned aircraft are only allowed to operate within the NAS through means of segregation from manned aircraft. One primary reason is due to the lack of an approved/certified collision avoidance system for use on unmanned aircraft. No performance standards are presently defined for unmanned Sense and Avoid systems, and the FAA has no published approval criteria for a collision avoidance system.

Discussion:

Before the FAA can develop the necessary guidance (rules / regulations / policy) regarding the see-and-avoid requirements for Remotely Operated Aircraft (ROA), a concise understanding of the term "equivalent level of safety" must be attained. Since this term is open to interpretation, the ROA industry and FAA need to come to an agreement on how this term can be defined and applied for a safe and acceptable collision avoidance capability for unmanned aircraft.

According to 14CFR 91.113, regardless of whether an aircraft is operating under visual flight rules (VFR) or instrument flight rules (IFR) the pilot in command is to remain vigilant to see and avoid other aircraft. Although this responsibility ultimately rests with the pilot, see and avoid is only one element within the overall traffic avoidance task. Traffic avoidance is accomplished through an integrated, overlapping conflict management process intended to minimize the risk of mid-air collisions. There are two major parts, conflict and collision avoidance. A conflict is any situation involving an aircraft and hazard in which the applicable separation minima may be compromised. A collision is a situation involving the physical contact between an aircraft and an airborne hazard. Airspace procedures and Air Traffic Management are used to create and maintain separation between aircraft to avoid conflict. Collision avoidance is the last layer of conflict management, is not considered part of separation provisions, and must activate when separation has been compromised.

The following document was prepared by a collaborative team through the noted work packages. This was a funded effort under the Access 5 Project.

See and avoid addresses collision avoidance and is the last line of defense used by pilots to avoid collisions with other aircraft and obstacles located in the air and on the surface. This distinction between conflict and collision avoidance, and the focus on collision avoidance will be important as the definition for sense and avoid safety equivalence is developed.

Access 5 Project Position:

The see and avoid requirement for unmanned aircraft must be understood prior to development of systems to provide that capability, and creation of certification criteria/policy to evaluate the adequacy of that capability. Defining an equivalent level of safety (ELOS) for sense and avoid is one of the first steps in understanding the requirement and developing a collision avoidance capability.

Both manned and unmanned aircraft must meet the see and avoid requirement as stated in 14 CFR 91.113. Manned aircraft use human vision, sometimes with cueing assistance, to see and avoid. However, since unmanned aircraft do not have a human on board, they need to have a sense and avoid capability that provides an ELOS to manned aircraft. The question then becomes - what is sense and avoid ELOS to manned aircraft?

The attached document, *Sense-and-Avoid Equivalent Level of Safety Definition for Unmanned Aircraft Systems,* provides a functional level definition of see-and-avoid as it applies to unmanned aircraft. The sense and avoid ELOS definition is intended as a bridge between the see and avoid requirement and the system level requirements for unmanned aircraft sense and avoid systems. The discussions assume that this collision avoidance capability must be provided for both cooperative and non-cooperative traffic. Sense and avoid ELOS is defined in a rather abstract way, meaning that it is not technology or system specific, and the definition provides key parameters (and a context for those parameters) to focus the development of cooperative and non-cooperative sense and avoid system requirements. The ELOS definition, and to a lesser extent the sense and avoid system level requirements, will also provide a recommended set of functional standards to be submitted to the RTCA committee for unmanned aircraft sense and avoid systems. In addition, the system level requirements will be provided to the RTCA committee as a source of information for the development of sense and avoid system equipment requirements. The end goal is sufficient information for both the FAA and industry to develop sense and avoid systems for unmanned aircraft and get a favorable sense-and-avoid ELOS determination by the FAA, thus enabling certification and routine operations of unmanned aircraft in the NAS.

A key point to note is that the complete answer to sense-and-avoid ELOS is a system or systems that address both cooperative and non-cooperative traffic situations. However, under certain conditions (e.g. in Class A airspace or above, with a certain type of control system, and perhaps some other limitations), it may be possible to obtain a favorable sense-and-avoid ELOS determination using a cooperative only system.

The proposed definition and supporting analysis contained in *Sense-and-Avoid Equivalent Level of Safety Definition for Unmanned Aircraft Systems,* provides rationale for establishing objective performance criteria and standards for a sense-and-avoid capability necessary for routine operations in the NAS.

The following document was prepared by a collaborative team through the noted work packages. This was a funded effort under the Access 5 Project.

Project Coordination:

SEIT	ID	PM					

The following document was prepared by a collaborative team through the noted work packages. This was a funded effort under the Access 5 Project.

Sense-and-Avoid Equivalent Level of Safety Definition for Unmanned Aircraft Systems

Revision 9

23 November 2004

Prepared by:

NASA ACCESS 5
Work Package 2, CCA Team
Work Package 1, Policy IPT

The following document was prepared by a collaborative team through the noted work packages. This was a funded effort under the Access 5 Project.

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EXECUTIVE SUMMARY

The ability of a pilot to detect other aircraft and avoid collisions has been the foundation of safe aircraft operations since the beginning of aviation. This process, most commonly known as "*see and avoid*", has become a significant challenge to the routine operation of unmanned aircraft systems (UAS) within civil airspace. Until UAS developers can demonstrate an equivalent capability to sense and avoid other aircraft, UAS flight operations will be restricted to ensure the safety of all aircraft operating in the National Airspace System (NAS).

This paper presents a definition of equivalent level of safety (ELOS) for UAS, as it pertains to see and avoid. The scope of this paper is further limited by only addressing the *aircraft to aircraft* aspect of collision avoidance. Future efforts will address collisions on the *surface* and other situations. The definition described in this paper is based on the functions necessary to sense and avoid traffic that represents a mid-air collision risk. The functions are independent of any particular solution or technology, to allow developers of UAS the ability to determine a sense and avoid solution for their system, considering its' performance characteristics, level of autonomy, and type of airspace intended for UAS operations.

See and avoid is one element of the conflict management process, which addresses the risk of collision between aircraft and hazards. The requirement for see and avoid is contained in Title 14 Code of Federal Regulations Part 91, section 91.113. Without a pilot on-board an UA, an alternative method of compliance with that requirement is necessary, and an equivalent level of safety finding is therefore required for UAS type certification. This means that unmanned aircraft must achieve the same or less risk of collisions as compared to manned aircraft, in order to meet the see and avoid requirement.

The sense and avoid ELOS requirement for UAS is stated as follows:

> The sense and avoid capability of the UAS shall meet the requirements of 14 CFR 91.113, by providing situation awareness with adequate time to detect conflicting traffic and take appropriate action to avoid collisions.

To be useful, this sense and avoid requirement needs to be further defined in terms of functional capabilities and key parameters. The basic functional capabilities of any sense and avoid system are surveillance, avoidance, and system quality. The surveillance and avoidance capabilities are described through functions involving scanning the surrounding airspace for other aircraft, determining if the detected aircraft is on a collision trajectory, deciding what evasive maneuver must be performed if any, and initiating the appropriate maneuver allowing sufficient time for the pilot's own aircraft to respond and maintain separation.

The surveillance capability is further defined by the key parameters of minimum detect time, field-of-regard, and track capability. These parameters define the surveillance volume of the sensing system(s), and description of the ability to provide situation awareness around the unmanned aircraft.

The avoidance capability is further defined by the key parameters of minimum miss distance, miss distance probability, and system reaction time. These parameters address the system collision definition, and the ability of the system to ensure avoidance of traffic in both spatial and time frames of reference.

The key parameters for system quality address the integrity, continuity, and interoperability of the UAS system for sense-and-avoid. While the surveillance and avoidance capabilities address the capability of the system when it is working, the system quality parameters address the ability of the system to be available when needed, provide valid inputs, and work well with other subsystems in the UAS and other systems/users in the NAS.

These key parameters will provide designers with the necessary standards/specifications to build to; and will provide regulators with the necessary standards/specifications to evaluate against. These are the minimum parameters necessary to describe sense-and-avoid system performance for ELOS consideration. These measures must be used in aggregate to properly define sense and avoid ELOS for a UAS and associated subsystems. The exclusion of any one measure will result in an incomplete or very limited sense and avoid ELOS definition. There is no priority order or ranking within the measures.

This sense and avoid ELOS definition is not specific to any one particular solution or technology. The definition provides an approach for UAS manufacturers and the FAA to employ when developing and/or evaluating UAS sense and avoid capability and subsystems. It is the overall project's desire that the content found within this report be referenced and used in establishing the necessary rules, regulations, and policies for UAS regarding sense and avoid.

1.0 INTRODUCTION

1.1 Purpose

The ability of a pilot to detect other aircraft and maintain separation has been the foundation of safe aircraft operations since the beginning of aviation. This process, most commonly known as "*see and avoid*", has become a significant challenge to the routine operation of unmanned aircraft systems (UAS) within civil airspace. The fact that UAS do not carry a pilot to perform this function has been the cause for many to speculate that this will compromise the safety of other airspace users. Until UAS developers can demonstrate an equivalent capability to sense and avoid other aircraft, Federal Aviation Administration (FAA) regulations will continue to place restrictions on UAS flight operations relative to this requirement, to ensure the safety of all aircraft operating in the National Airspace System (NAS). **The purpose of this paper, therefore, is to present a recommended approach for defining an equivalent level of safety (ELOS), as it pertains to see and avoid.**

1.2 Scope

The scope of this paper is limited to the sense and avoid aspect of ELOS. ELOS is much broader than just the sense and avoid topic, and encompasses almost all aspects of a systems operations. However, other safety-related aspects of ELOS that are unrelated to sense and avoid, are reserved for future study. This paper is further limited in scope by only addressing the *aircraft to aircraft* aspect of collision avoidance and leaves the analysis of collisions on the *surface* and other situations to future efforts.

The approach described in this paper is based on the functions necessary to sense, and avoid traffic that represents a mid-air collision risk and is deliberately independent of any particular solution or technology. This independence from any particular technology should therefore allow developers of UAS platforms the ability to determine a final solution unique to their UAS's performance characteristics, level of autonomy, and type of airspace intended for UAS operations.

1.3 Project Sponsor and Participants

The project sponsor for this effort is the National Aeronautics and Space Administration (NASA) Access 5 Project Office located at NASA Dryden Flight Research Center in Edwards, CA. This paper was developed by the Access 5 Policy and Cooperative Conflict Avoidance (CCA) Work Packages, comprised of individuals from Northrop Grumman, Lockheed Martin, General Atomics/Aeronautical Systems, NASA Langley, and Modern Technology Solutions, Inc.

In addition to the above participants, the information contained within this report has been argued and discussed at numerous workshops containing members from industry, government, and academia. The comments and recommendations received during each of these workshops have also helped to shape the current version of this paper.

1.4 NASA Access 5 Project

Access 5 is a national project sponsored by NASA, with participation by the FAA advisors, DoD, and industry, to introduce civil High Altitude Long Endurance (HALE) UAS to routine flight in the NAS. Access 5 commenced in May 2004 and is slated to run for five or more years. While Access 5 is limited to HALE it is intended that this document be developed such that it has general applicability to airspace access and operations for UAS.

The goal of Access 5 is to assist in the development of policies and procedures, demonstrate the enabling technologies, and identify infrastructure to promote a robust civil market for HALE UAS. Access 5 will address UAS airworthiness certification, flight operations, and crew certification. Project efforts will also include the development of appropriate standards, working where appropriate, through existing national standards groups. The project products are policy and procedure recommendations on UAS system airworthiness certification, UAS flight operations, UAS pilot certification, and appropriate standards. The project will identify mature technologies in several areas, including conflict avoidance and communications, and will also provide recommendations on maintenance for continued airworthiness, currency for pilots, and guidelines/processes for safe operation.

Access 5 plans call for integrating HALE UAS into the NAS through a four-step process:

Step1 - Routine operations of HALE UAS above Flight Level (FL) 400 (40,000 feet) with takeoff and landing within pre-coordinated/restricted airspace. Plus, proposals/guidance for an initial level of certification (experimental airworthiness) will be developed.

Step 2 - Routine operations above FL180 (18,000 feet) with takeoff and landing within pre-coordinated/restricted airspace. A type certification basis for HALE UAS will also be developed.

Step 3 - Routine operations above FL180 and access to UAS designated airports with emergency landings in restricted areas. In addition, the guidance/proposals for restricted airworthiness certification will be developed.

Step 4 - Routine operations above FL180 and access to UAS designated airports, including emergency landings (i.e., true "file-and-fly"). The primary difference in operations between Steps 3 and 4 from an operating perspective, is the ability to handle emergencies or contingency landings in non-restricted airspace. In addition, the guidance/proposals for standard airworthiness certification of HALE UAS will be developed, along with guidance for an air operations certificate.

2.0 BACKGROUND INFORMATION

2.1 Current Operational Environment for UAS

The demand to operate HALE UAS within the NAS is expected to increase significantly in the near future. This demand is being fueled by federal, non-DOD markets and emerging civil opportunities. The growth of the HALE UAS industry requires technology standards and regulatory criteria (certification of aircraft and the individuals who fly them) and operating standards (flight rules) that provide for the safe integration of this new aviation technology into the mainstream of airspace users. Because there currently does not exist any regulatory or procedural guidance for unmanned aircraft, the governing FAA authorities directly manage the ability to operate UAS within the NAS. Since most UAS are currently operated by the military, operations within civil airspace are treated as exceptional, one time events and authorization to fly is granted on a per mission basis in accordance with procedures contained within FAA Order 7610.4K *[1]*. This FAA Order requires that the UAS operator apply for a Certificate of Authorization (COA) at least 60 days prior to the proposed commencement date.

Under the COA process, UAS are allowed to operate within the NAS, but only through means of segregation. Even with a valid COA, UAS are unable to routinely operate with the same flexibility as manned aircraft and are subject to numerous restrictions prohibiting simple activities such as operating above populated areas of the country or taking off and landing outside special use airspace (SUA). Regardless of the mission or role, UAS are restricted as to *how, when*, and *where* they can operate.

By not having routine access to the NAS, the civil and commercial viability for UAS is severely limited. The manufacturers often have difficulty in attracting investment capital, as well as difficulty in obtaining flight insurance; both of which lead to high operating costs. The UAS industry must take several steps forward to become more attractive to the civil and military sector. Routine operations within civil airspace are essential to their ability to thrive in the marketplace, both domestically and internationally.

2.2 Current Process used for Preventing Mid-Air Collisions

According to 14CFR 91.113, regardless of whether an aircraft is operating under visual flight rules (VFR) or instrument flight rules (IFR) the pilot in command is to remain vigilant to see and avoid other aircraft *[2]*. Although this responsibility ultimately rests upon the pilot's shoulders, other factors assist him/her in safely performing this task. To increase aviation safety, the FAA has established an integrated, overlapping process intended to minimize the risk of mid-air collisions. *Figure 1* depicts the layered approach that is currently in place for manned aviation and what the UAS industry should adopt if they desire to integrate into the NAS.

Airspace Procedures
The first line of defense in the prevention of mid-air collisions are existing rules, regulations, and procedures. If adhered to, these procedures should prevent most accident scenarios from ever occurring.

Air Traffic Management
The second line of defense is the services provided by Air Traffic Management (ATM). If an aircraft is under positive control, it will receive separation services from ATM for other participating aircraft within the surrounding airspace. The air traffic authority assumes responsibility for providing separation for all IFR traffic and directs the participating aircraft to either maintain or change their flight path, including providing traffic advisories on other aircraft, time permitting.

Figure 1: Current Process for Avoiding Mid-Air Conflicts/Collisions

See and Avoid / Cooperative Traffic Avoidance
See and avoid is the last line of defense used by pilots to avoid collisions with other aircraft and obstacles located in the air and on the surface. The use of on-board traffic advisory systems to provide situational awareness concerning all cooperative traffic within a certain range and altitude, can enhance the ability of the human pilot inside the cockpit to detect and track potential collision threats. These systems, mandatory on all aircraft that carry 10 or more passengers, also provide a traffic advisory to the pilot of an impending collision and some can even provide a resolution advisory directing an avoidance maneuver. While technology such as cooperative traffic avoidance systems can cue a pilot to the presence of conflicting traffic, the use of human eyesight to see-and-avoid airborne hazards, has been the ultimate collision avoidance tool contributing to safe flight since the beginning of aviation. The discussions contained within this paper focus on on-board and/or off-board sensing means and aircraft control required for UAS to provide the airborne aircraft to aircraft segment of this layer of collision avoidance without an on-board pilot. The discussions assume that this collision avoidance capability may be provided for both cooperative or non-cooperative traffic (see section 2.3.2).

Conflict Avoidance vs Collision Avoidance
The overall process described above is one of conflict management, which according to RTCA, is the limiting of the risk of collision between aircraft and hazards, to an acceptable level. However, the distinction needs to be made between avoiding *conflicts* with other traffic as opposed to avoiding *collisions* with other traffic (Figure 2). A conflict is any situation involving an aircraft and hazard in which the applicable separation minima may be compromised. A collision is a situation involving the physical contact between an aircraft and an airborne hazard. Conflict management involves all of the layers shown in Figure 1, including collision avoidance. Collision avoidance is the last layer of conflict management, and must activate when the separation mode

has been compromised. Airspace procedures and ATM represent the separation layers of conflict management. Collision avoidance is not part of separation provisions, and collision avoidance systems are not included in determining the calculated level of safety required for separation provision *[34]*. Sense and avoid is therefore part of collision avoidance as distinguished from maintaining separation minima for conflict avoidance. This distinction and focus on collision avoidance will be important as the requirement for sense and avoid safety equivalence is developed.

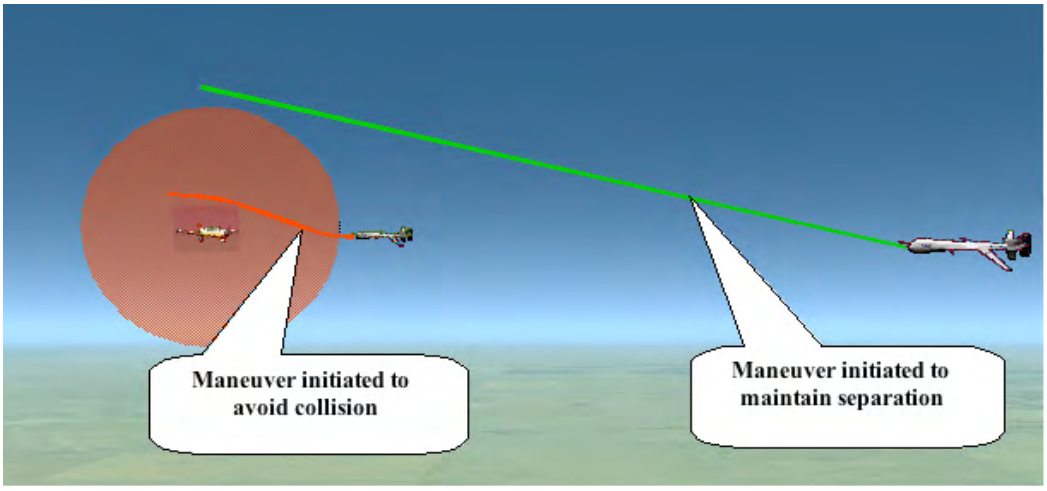

Figure 2: Collision Avoidance versus Conflict Avoidance

2.3 Collision Avoidance Challenges

There are several external elements that make collision avoidance challenging. Some of these elements include: various classes of airspace, different types of aircraft, and environmental conditions; as well as independent maneuvers of aircraft, competition for resources (airport, VOR, etc.), and ability to detect other aircraft. Each of these will be briefly discussed below.

2.3.1 Types of Airspace Operations

The first of these elements is the type of airspace and existing manned operations where the UAS will be operating. There are several different classes of airspace through which the UAS may have to transition in order to accomplish the desired mission. Within each of these classes of airspace (designated Class A – Class G), the FAA has established specific guidelines and constraints to reduce the collision

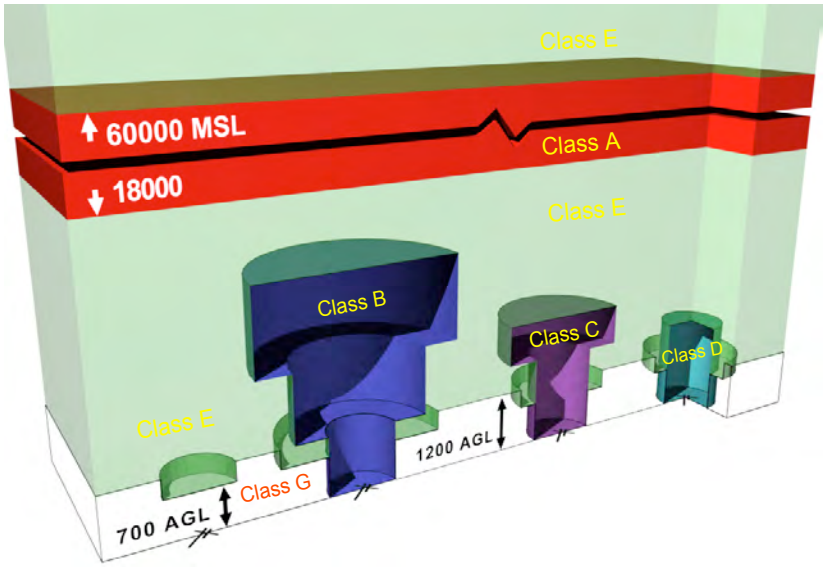

Figure 3: Airspace Example

potential. For example, traffic above FL180 (18,000 ft) is required to be under FAA positive control and must abide by instrument flight rules (IFR) for that airspace. With respect to conflict avoidance, air traffic control (ATC) accepts the responsibility for providing separation between aircraft operating at these altitudes. Actually, all IFR aircraft are normally required to use an approved transponder, regardless of the airspace they are operating in, which enables the FAA to track the aircraft and provide traffic separation information to the pilot. Traffic maneuvers above FL180 also tend to be more constrained than maneuvers at lower altitudes. Aircraft operating below FL180 may or may not be under ATC control. In fact, at these lower altitudes there may be both ATC controlled and un-controlled air traffic transitioning within the same class of airspace with varying surveillance avionics equipage. This mix of aircraft type and capabilities can create a challenging operational environment for an unmanned aircraft to transition. *Figure 3* shows a depiction of the many different classes of airspace found within the NAS.

2.3.2 Cooperative vs. Non-cooperative Aircraft

Essentially, two types of traffic must be detected for collision avoidance: *cooperative and non-cooperative*. Cooperative aircraft, which comprise most of the total air traffic, are those aircraft that have an onboard transponder or other means to "cooperate" with normal air traffic surveillance systems. One of the most common situational awareness tools used to detect and locate cooperative aircraft is the Traffic Alert and Collision Avoidance System (TCAS), required on all aircraft in the United States capable of seating 10 or more passengers. The transponder signal from a cooperative aircraft is received by other aircraft possessing the TCAS equipment and is used to display the cooperative aircraft's position and altitude information. Non-cooperative aircraft do not "cooperate" with air traffic surveillance systems and therefore need to be detected through alternative surveillance means such as human vision for see and avoid. Some small general-aviation airplanes, gliders, and balloons, with very few exceptions, fall into this category of traffic. Therefore, a truly robust sense and avoid system must be capable of detecting both non-cooperative and cooperative aircraft to avoid a potential collision. Candidate on-board technologies capable of detecting non-cooperative objects include electro-optical (infrared or visible), radar, and ladar. Off-board technologies such as broadcasting FAA primary or secondary radar information may also be useful in detecting non-cooperative objects.

2.3.3 Detection Characteristics

The ability to detect other aircraft largely depends upon the relative size, background contrast, structural materials, propulsion system, and intercept geometry. These characteristics can obviously present challenges to different sensor technologies that may be employed for such an application. For example, a visible sensor like the human eye can detect a brilliant orange colored aircraft much better that it could detect a camouflage one. Radar, or other radio frequency (RF) type sensors on the other hand, would not differentiate between aircraft coloring schemes. The material with which an aircraft is made can also drastically affect how easily it may be detected using RF and infra-red (IR) sensors. For example, cloth and composite aircraft are much more difficult to detect with radar than a metal aircraft would be; while an infrared camera could detect a hot-air balloon much easier than radar could. Similarly, the type of propulsion system (none, single prop, dual prop, jet engine) used by an aircraft can affect how easily it can be detected. These different propulsion types can have a wide range of radar cross-sections and heat signatures. The final aircraft characteristic to be mentioned is that of aircraft aspect. The geometry, at which

the intruder aircraft is approaching, can also make detections more or less difficult because of the cross-section of the aircraft presented to the pilot or sensor.

2.3.4 Weather and Environment

The last challenge affecting collision avoidance is the environmental conditions in which an aircraft will be operating. Aircraft come in many different shapes and sizes and are capable of flying at a wide range of altitudes. Some are designed to fly along the nap of the earth, while others travel at very high altitudes. Depending upon the UAS operational environment, the sense and avoid sensor may need to operate under a variety of altitudes, temperatures, pressures, and forms of precipitation (snow, rain, mist, or fog).

A sensor's performance may also depend upon when it is used, as well as where it is used. If an aircraft is intended for both day and night operations, the collision avoidance system should have limited degradation resulting from the ambient lighting conditions. Furthermore, the ability to detect conflicting aircraft will vary significantly with the object's background. For example, an aircraft with the blue sky as a background can be much easier for an electro-optic sensor to detect compared to an aircraft with ground clutter as its background.

3.0 UNDERSTANDING ELOS

3.1 The Basis for an ELOS Requirement

UAS intending to routinely operate within the NAS must demonstrate that they can meet the existing rules and regulations currently in place for manned aircraft. If any of these standards cannot be met, then the shortcoming must be addressed using the procedures established by the FAA for meeting such deficiencies.

One of the precedents for having to meet an equivalent level of safety for routine operations within the NAS is found in 14CFR 21.21, paragraph (b) *[3]*. This regulation states that an applicant is entitled to a type certificate for an aircraft, if the type design, test reports, and computations necessary to show that the product to be certificated meets the applicable airworthiness requirements of the Federal Aviation Regulations. However, upon examination of this information, if any airworthiness provisions are not complied with then they must be "*…compensated for by factors that provide an* ***equivalent level of safety***" *[3].*

The FAA process for demonstrating that a deficiency meets an equivalent level of safety is identified in Paragraph (g.) of FAA Order 8110.4B *[4]*. This order identifies the responsibilities and procedures for FAA aircraft certification personnel responsible for the certification process required by Title 14 of the CFR for civil aircraft, aircraft engines, and propellers necessary before granting a Type Certificate. When required, the basis may include *an equivalent level of safety* finding when literal compliance with a certification regulation cannot be met and compensating factors exist that can be shown to provide an equivalent level of safety. [1]

3.2 Need for UAS to Meet an ELOS for See and Avoid

Not only is see and avoid a vital element of safe aircraft operations, but it is also required by Title 14 of the Code of Federal Regulations (CFR). Paragraph 91.113 (b) states:

> *14 CFR 91.113(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*

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[1] **FAA Order 8110.4B; Paragraph (g.) Equivalent Level of Safety Finding**

(1) Equivalent level of safety findings are made when literal compliance with a certification regulation cannot be shown and compensating factors exist which can be shown to provide an equivalent level of safety (reference § 21.21(b)(1) and Order 8100.5, paragraph 408.)
(2) The applicant submits to the ACO the proposed equivalent level of safety. The ACO then submits to the directorate the proposed equivalent level of safety with recommendations. The accountable directorate makes all equivalent level of safety findings.
(3) In documenting an equivalent level of safety:
  (a) List the applicable regulation;
  (b) Describe the features of the design that require the equivalent level of safety findings;
  (c) Describe any design changes, limitations, or equipment imposed to make the equivalency; and
  (d) Provide an explanation of how the actions taken provide an equivalent level of safety to that intended by the regulation.
(4) All equivalent level of safety findings must be listed on the TCDS or on the STC.

> *see and avoid other aircraft. When a rule of this section gives another aircraft 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.*

Part 91 of Title 14 CFR specifically identifies 14 CFR 91.113 as an operating regulation. Without a pilot on-board an UA, an alternative method of compliance with that requirement is necessary, and an equivalent level of safety finding is therefore required for a UAS type certification process. Developers of unmanned aircraft intended to operate in the NAS, must have an approach that can be used to demonstrate to the appropriate regulatory agencies that the UAS system design meets an equivalent level of safety to that of a manned aircraft.

A similar requirement can be found in Section 12-9-2, of FAA Order 7610.4K, Special Military Operations *[1]*, which addresses the operation of military UAS outside Restricted Areas and Warning Areas. Sub-paragraph a.4 states that all requests to operate UAS must provide the FAA with the "method of pilotage and proposed method to avoid other traffic." In a note, this sub-paragraph goes on to state:

> *Approvals for UAS operations should require the proponent to provide the UAS with a method that provides an* ***equivalent level of safety****, comparable to see-and-avoid requirements for manned aircraft. Methods to consider include, but are not limited to; radar observation, forward or side looking cameras, electronic detection systems, visual observation from one or more ground sites, monitored by patrol or chase aircraft, or a combination thereof.*

Although the ELOS phrase found in FAA Order 7610.4K is quite vague, it can be used as a starting point for exploring civil UAS type certification. To do this however, it is incumbent upon the UAS industry and the FAA to come to a consensus approach for demonstrating ELOS, which must include an acceptable definition of ELOS for sense and avoid. Ultimately, this approach should be sufficient enough to provide industry with a set of functional capability requirements that could be used to derive sense and avoid subfunction performance requirements for UAS collision avoidance systems. The FAA could also use this established approach and definition as a means to derive the certification requirements for such a system.

3.3 Dissecting the See and Avoid ELOS Phrase

Before an attempt is made to define ELOS, it is beneficial to first dissect the phrase into its three key elements: (1) equivalence, (2) safety, and (3) see and avoid requirements for manned aircraft. Each of these elements will be discussed in the following paragraphs to ensure a common understanding before addressing the definition of the phrase as a whole.

3.3.1 Equivalence

Equivalence, simply defined, means "same." So the question becomes one of "the same as what?" Equivalence should be with respect to the desired end result of see and avoid based collision avoidance and not the individual processes leading up to that result. The see and avoid responsibility of the pilot is an important element of collision avoidance, but primarily provides a last line of defense if airspace procedures, air traffic management, and cooperative traffic

avoidance measures break down or are not available. See and avoid limitations placed on a pilot by workload, cockpit design, human vision, and other factors all suggest that equivalence should not be applied directly to the processes that a pilot performs when avoiding another aircraft. For example, a see and avoid system designed to mimic a human pilot would need to stop detecting for several seconds every few minutes to account for the time that a human pilot must routinely check the cockpit avionics instruments and flight map. It might be reasonable to expect an actual improvement in detection performance over a human pilot's ability to spot other traffic since electronic sense and avoid systems are not distracted, fatigued, or affected by physiological limitations. Equivalence should therefore be applied to a sense and avoid system's ability to permit the successful completion of a collision avoidance maneuver when required.

3.3.2 Safety; as it Applies to See and Avoid

UAS operations must be shown to be "safe" if they are to be successfully integrated into the NAS. This will require those who design, build, operate, and maintain UAS to convince the regulators and the public that UAS are "safe" *[5]*. In this context, "safe" represents an acceptable level of risk of damage or injury to persons or property in the air or on the ground. Some might suggest that the UAS system be "absolutely safe". However, this implies zero risk and is therefore an unobtainable state. An alternative definition for safe is "acceptably safe". The question then becomes: what is an acceptable level of safety or risk.

Historically, manned aviation has achieved a relatively high level of safety. With this threshold and the requirement of transparence in mind, UAS operations must be as safe as manned aircraft operations insofar as they must not present or create a hazard to persons or property in the air or on the ground. The methods required by the civil aircraft certification process have played a major role in achieving the high safety levels evident in aviation *[5]*. There is, however, a distinction that must be made concerning overall system safety and safety as it pertains to see and avoid only. As mentioned in Section 1.0, this paper is intended to define the "equivalent level of safety, comparable to see and avoid" as opposed to the much broader topic of "equivalent level of safety to that of a manned aircraft". This document focuses on the level of safety value for see and avoid only. This level of safety should support the overall ELOS value that will be used for the UAS system. The remainder of this document will discuss where this line for collision avoidance safety gets drawn.

3.3.3 See and Avoid Requirements for Manned Aircraft

With respect to see and avoid, the foremost requirement contained within the Federal Aviation Regulations (FAR) is 14 CFR Part 91.113, entitled Right of Way Rules: Except Water Operations *[2]*. Sub-paragraph (b) states: "*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.*"

Similarly, a requirement within ICAO regulation is Annex 2, entitled Rules of the Air *[6]*. Section 3.2 of this annex, which is entitled Avoidance of Collision, states: "*It is important that vigilance for the purpose of detecting potential collisions be not relaxed on board an aircraft in flight, regardless of the type of flight or the class of airspace in which the aircraft is operating, and while operating on the movement area of an aerodrome.*"

It should be clear from these references that the operator cannot rely solely upon ATC for providing separation if weather permits visual detection of conflicting traffic. Since UAS do not possess a pair of human eyes onboard the aircraft, some other means for providing a sense and avoid capability is necessary. This capability, regardless of what it is, should be able to achieve an "equivalent level of safety, comparable to see and avoid requirements for manned aircraft", so as not to pose a hazard to persons or property, both in the air and on the surface.

The term "sense," as in "sense and avoid," will be used to denote detection capability provided by means other than human vision. The term "see" will be used when referring to human vision.

In summary, the phrase "equivalent level of safety, comparable to see and avoid requirements for manned aircraft," means that unmanned aircraft must achieve the same or less risk of collisions as compared to manned aircraft, in order to meet the Federal Aviation Requirements concerning see and avoid (14 CFR 91.113).

4.0 APPROACH FOR SENSE AND AVOID ELOS

4.1 Approaches for Defining Sense and Avoid ELOS

There are two general approaches that may be used to determine whether an unmanned aircraft is as safe as a manned aircraft. The first approach compares the ***statistics*** of a manned system to that of the unmanned system, whereas the second approach compares the ***performance*** of the manned system and the FAA regulatory requirements, to that of the unmanned system. While both approaches can provide meaningful insight, only the performance approach defines ELOS using *leading indicators* to measure UAS capability. The statistics approach, on the other hand, relies upon *lagging indicators* that can only be validated after a sufficient amount of UAS operations statistics are collected. Although statistics by definition are always lagging indicators they can still be an important element of identifying a need for tradeoffs between the performance-based parameters, if required, in order to ensure routine access to the NAS.

Both the statistical and performance-based approaches have a variety of different methods that could be used to achieve an ELOS definition for sense and avoid. A detailed description of each potential approach and methodology, including their strengths and weaknesses, is contained in *Appendix A* at the end of this paper.

4.2 Recommended Approach for Defining Sense and Avoid ELOS

The suggested approach for defining sense and avoid ELOS for sense and avoid actually combines portions of the statistical and performance based approaches, which are discussed in detail within *Appendix A*. **The <u>sense and avoid ELOS definition (Section 5)</u> should be used as basis for establishing the leading indicators needed to gain initial access to the NAS for UAS, while the <u>Target Level of Safety Method</u> should be used to establish the top-level measure of effectiveness.**

This approach establishes a set of well-defined, measurable parameters that can be used to evaluate a sense and avoid system design through simulation, analysis, demonstration, and test. Using a performance-based approach will result in a greater level of confidence that a proposed sense and avoid design meets the necessary safety criteria. These parameters will provide the FAA with a "*leading indication*" that the UAS system is capable of maintaining safe separation and is suitable to fly within civil airspace. This should therefore also result in a higher probability of approval by the regulatory agencies responsible for ensuring the safety of the NAS.

Even though the performance-based approach is proposed for creating the initial ELOS definition and gaining approval to operate, the statistical approach still plays an important role in this combined approach. A certain amount of simulations and analysis should also be used to show how the sense and avoid system will be able to achieve a high degree of reliability and safety, necessary to achieve ELOS to that of a manned aircraft. If problems are identified, changes to the performance-based approach would then be required to ensure that only UAS with an equivalent level of safety were gaining approval to operate.

5.0 DEFINING SENSE AND AVOID ELOS

It is important to recognize that a "one size fits all" approach to performance of a UAS sense and avoid system may not be possible, nor desirable, since UAS operations can vary widely. For instance, while both a high-speed, high-altitude and low-speed, low-altitude UAS must provide an equivalent level of safety for see-and-avoid, the sense and avoid system used in each aircraft may be different. The selected performance parameters should be allowed to be different, to account for the environments in which each system operates. The definition of ELOS for sense and avoid will start with the basic requirement followed by the fundamental capabilities, and finally a breakout of the measures or parameters that describe the attributes of the system will complete the definition. The measures should represent all of the critical elements which define any sense and avoid system's ability to provide an ELOS for sense and avoid. This sense and avoid ELOS definition should adequately address cooperative traffic, non-cooperative traffic, autonomous and non-autonomous situations and implementation. In addition, the definition should account for UA maneuvers as well as straight and level situations.

5.1 Sense and Avoid ELOS Requirement

The sense and avoid ELOS requirement as stated in Section 3, is based on 14 CFR 91.113 "*Right-of-way rules: Except water operations*", which is the genesis of the "see and avoid" requirement. Using this definition as the starting point, the sense and avoid ELOS requirement for UAS is as follows:

> The sense and avoid capability of the UAS shall meet the requirements of 14 CFR 91.113, by providing situation awareness with adequate time to detect conflicting traffic and take appropriate action to avoid collisions.

5.2 Sense and Avoid ELOS System Capabilities

Although the basic goal is to define an equivalent level of safety to that of a manned aircraft, it would be unreasonable to establish sense and avoid system requirements based solely upon human parameters. In addition to ensuring that collision avoidance requirements are adequate for UAS to operate routinely in civil airspace, the requirements must not be overly burdensome. Since UAS have a wide variety of performance characteristics, the values for each performance parameter could vary substantially between the various UAS types. What is essential for a high performance UAS may be unnecessary and impractical for a less capable UAS. Any requirement more stringent than one that is derived from the existing aviation regulations should be considered as *exceeding* "an equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft". If a more stringent requirement is to be imposed on UAS, the rationale for the additional capability, exceeding that required for manned aviation, should first be substantiated.

Once see and avoid ELOS has been defined, requirements can then be proposed for collision avoidance systems. These parameters will provide designers with the necessary standards/specifications to build to; and will provide regulators with the necessary standards/specifications to evaluate against. Before discussing any specific numbers or values, these parameters and appropriate Measures of Effectiveness (MOE) to evaluate a system against those parameters must first be determined. After the MOEs are determined, then the appropriate

measures of performance (MOP) may be determined, if necessary, to establish collision avoidance standards.

Regardless of the technology selected for implementation of a collision avoidance solution, it should be able to meet certain functional capabilities that are measurable and together provide the required goal of achieving an equivalent level of safety.

The six sense-and-avoid functions listed below were derived from a human model for mid-air collision avoidance, but they are applicable to any collision avoidance system. These functions involve scanning the surrounding airspace for other aircraft, determining if the detected aircraft is on a collision trajectory, deciding what evasive maneuver must be performed, if any, and initiating the appropriate maneuver allowing sufficient time for the pilot's own aircraft to respond and maintain separation. To avoid collisions, these six essential functions must be performed by a UAS collision avoidance system. It is also important to note that these functions may occur within the aircraft element, control element, or both. The six sense-and-avoid functions are shown in Figure 4.

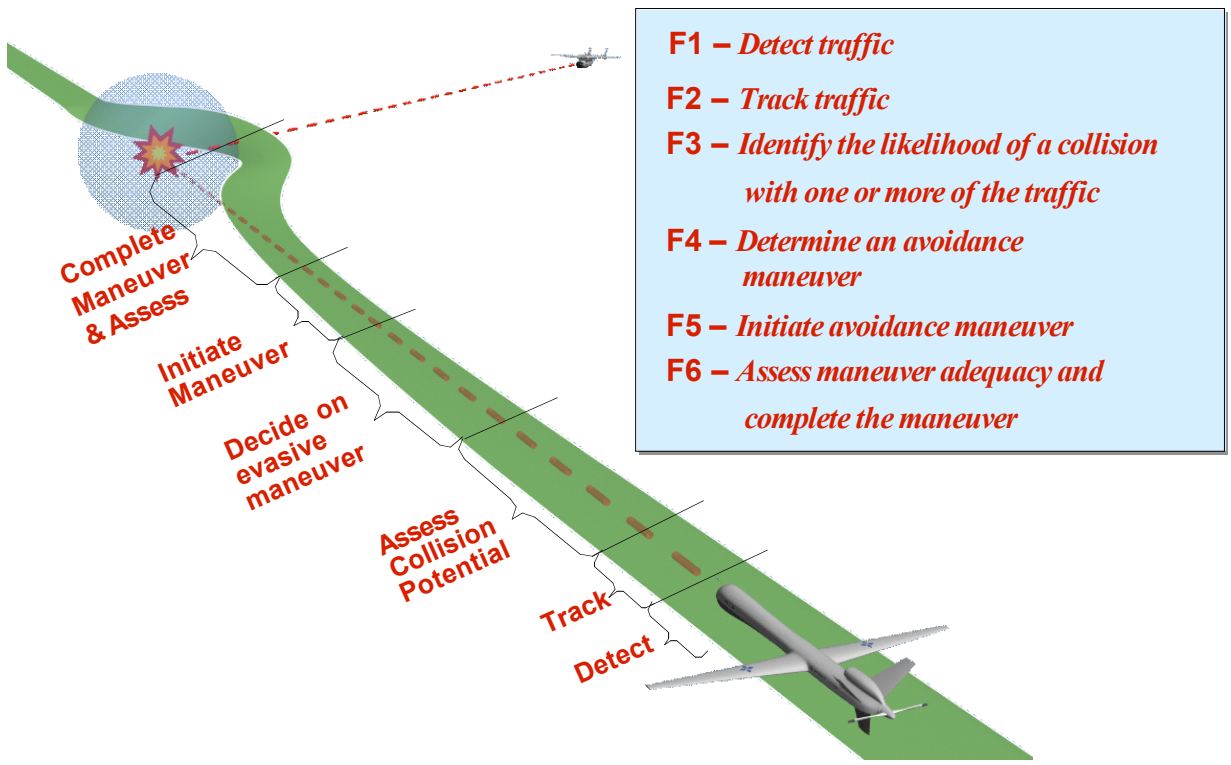

Figure 4: Sense-and-Avoid Functions

These functions support the top-level function of a sense and avoid system to meet the requirements of 14 CFR 91.113 by providing situational awareness with adequate time for the UAS system to detect conflicting traffic and take appropriate action to avoid mid-air collisions and provide a framework for defining measures that can be used to determine the adequacy of a system

design. The sense and avoid requirement contains several important words/phrases which outline some of the capabilities of any system to meet the requirement. The following paragraphs expand on the key capabilities of a sense and avoid system for UAS.

5.2.1 Surveillance Capability

The phrase "situation awareness" in the sense and avoid requirement, implies a surveillance capability to detect and track traffic with sufficient resolution to give dynamic perspective to the traffic picture. The dynamic aspect of the situation awareness is necessary to present an accurate picture of the traffic flows, especially in situations where the UAS or the traffic, or both are maneuvering. This surveillance capability can be defined with the functions of detect and track (F1 and F2 above). The detect function can be defined using the measures of minimum detect time and field of regard of the system. The track function can be defined using the measures of field of regard and track capability. Each of these measures are defined below.

5.2.1.1 Minimum Detect Time

Minimum detect time is defined as the time from detection of an intruder until the completion of an evasion maneuver (functions F2 through F6 in section 5.2). In other words, the system must provide sufficient time after intruder detection for performance of all remaining collision avoidance functions resulting in successful execution of an avoidance maneuver if necessary.

$$MDT > F2 + F3 + F4 + F5 + F6$$

A system meeting this requirement is shown in Figure 4.

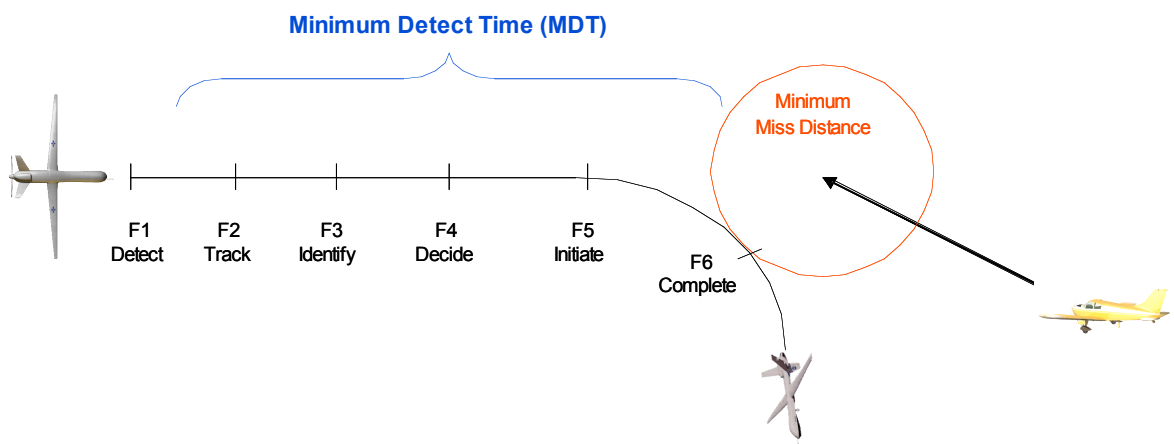

Figure 5: Minimum Detect Time Definition

The greatest distance that traffic would need to be detected would be in a head-on collision at maximum speed. In order for minimum detect time to be realistic, a maximum closure speed between the UAS and traffic should be defined relative to the capability of the UAS and potential traffic in the operating environment. Minimum detect time in effect, provides the range or depth aspect of the surveillance volume.

5.2.1.2 Field of Regard

Field of Regard (FOR) is the azimuth and elevation aspects of the surveillance volume within which the collision avoidance system is able to detect and track other aircraft (Figure 6). The elevation limits should be broad enough to include climbing and descending traffic. The azimuth limits should be wide enough to detect converging traffic, and to clear the area ahead of a turn. The field of regard volume is centered on the UA flight path vector and aligned along the horizon.

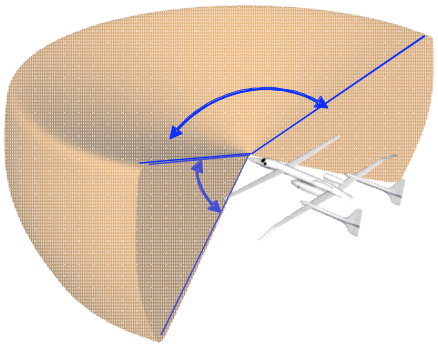

Figure 6: Field of Regard

5.2.1.3 Track Capability

Track capability addresses the track function. This measure includes track probability, probability of false alarm, and the total number of intruder aircraft tracks that the sensor is capable of simultaneously tracking and managing. Figure 7 shows an example of a display providing the track of several traffic objects.

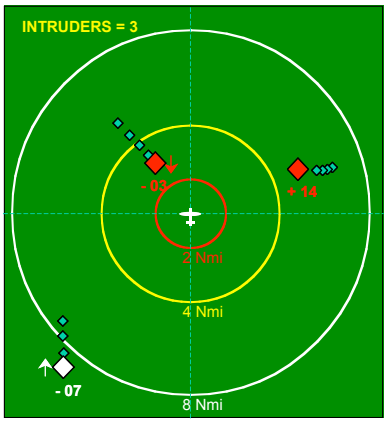

Figure 7: Track Capability

5.2.2 Avoidance Capability

The phrase "adequate time" in the sense and avoid requirement, means there is a critical time element in the definition. The phrase "appropriate action" implies that the system, including the pilot or autonomously, must be able to decide on the appropriate maneuver to provide the avoidance of a collision along with the correct right-of-way in a particular situation. Finally, the phrase "avoid collisions" means the focus is on avoiding a collision with the conflicting traffic versus avoiding a conflict with the traffic. The traffic avoidance capability can be defined using the four remaining functions – identify conflicting traffic, determine avoidance action, initiate avoidance maneuvers, and finally, assess and complete the avoidance maneuver. The avoidance functions can be defined by using the track capability measures under surveillance, along with a definition of a minimum miss distance, the miss distance probability, and a system reaction time.

5.2.2.1 Minimum Miss Distance

Minimum miss distance (MMD) addresses the assumption that any traffic flight path that intersects the UA flight path within a specified distance (horizontal and vertical) will result in a collision. The goal of the sense and avoid system is to prevent actual contact between the UA and any traffic. However, any practical implementation of a sense and avoid system will have to decide when a maneuver must occur to avoid a collision. This minimum miss distance or "collision definition" is a prerequisite for determining minimum detect time (described above) and miss distance probability (described below), and must be tailored to the specific UAS. Figure 8 provides an example of how a minimum miss distance might be calculated. In this example, the MMD is defined as the sum of one-half the wingspan of the traffic plus one-half the wingspan of the UA. Note that this is an example for only one dimension of the MMD. An actual MMD would be defined in three dimensions.

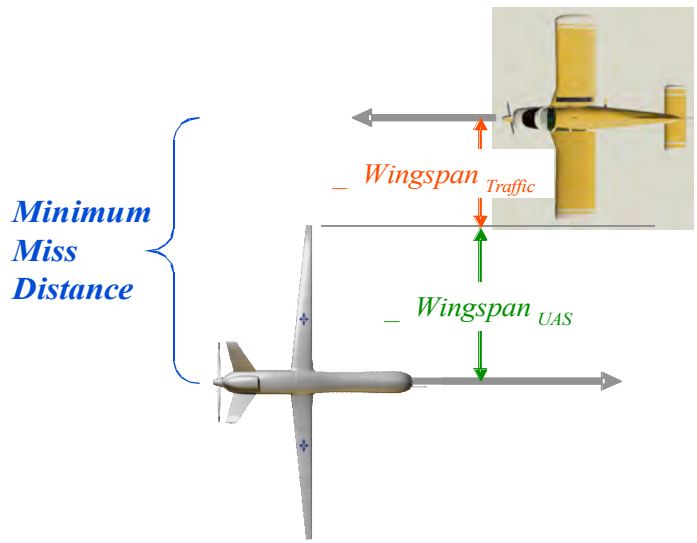

Figure 8: Example Minimum Miss Distance

5.2.2.2 Miss Distance Probability

Miss distance probability (MDP) defines the probability that a UAS will avoid an intruding aircraft by the MMD. In order for a system with uncertainties to achieve a desired MDP, the UAS must have a target miss distance that is greater than MMD, as shown in Figure 9.

For instance, a miss distance with a three sigma level probability would mean that the sense and avoid UAS system would have to plan to miss all traffic by a distance large enough to ensure that it would miss in 99.7% of collision encounters. A system with large uncertainties would be required to achieve a greater miss distance on average in order to ensure the required miss distance probability. Even a system with small uncertainties would still have a target miss distance greater than MMD.

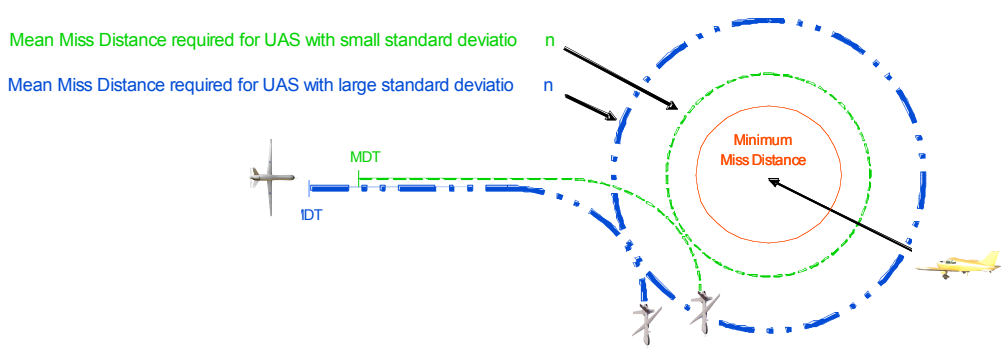

Figure 9: Miss Distance Probability Example Encounters

5.2.2.3 System Reaction Time

System reaction time is measured from point at which a collision potential has been identified, to the completion of the avoidance maneuver (Figure 10). It is everything after detection and track, and includes the time to decide on an avoidance maneuver, plus the time to initiate and accomplish the avoidance maneuver. In a human based collision avoidance system, system reaction time includes the recognition time, decision time, psychomotor reaction time, aircraft control system time lags, and the time for the aircraft to move the minimum miss distance away from the collision point. System reaction time must be less than the minimum detect time plus track time.

$$MDT > F2 + SRT$$

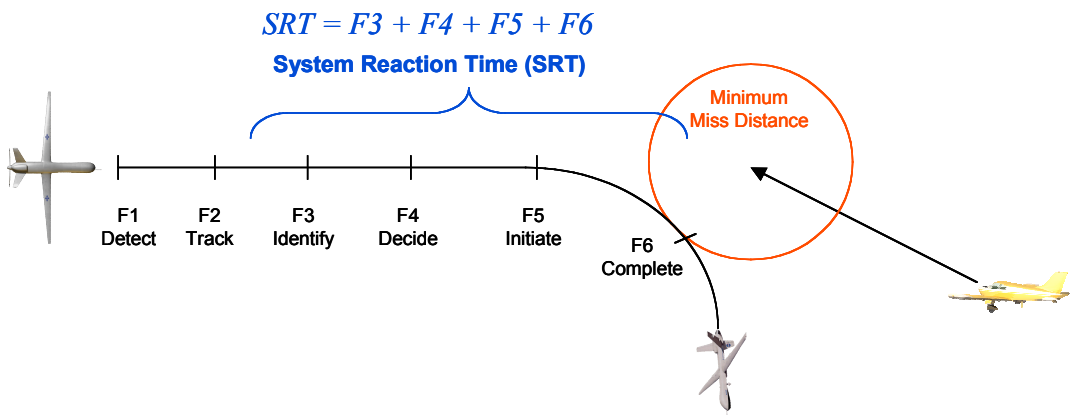

Figure 10: System Reaction Time

5.2.3 System Quality

The surveillance and avoidance capabilities describe the performance capabilities of a sense and avoid system. In addition, there must be measures identified to describe how well the system performs its functions. The measures identified to define the sense and avoid system quality are miss distance probability, integrity, continuity, and interoperability.

5.2.3.1 System Integrity

Integrity is defined as the ability of a sense and avoid system to identify degraded input data or system functionality and continue sense and avoid operations within the limitations of the degraded system *[32]*. Integrity includes the following lower-level measures of performance: fault tolerance (including software integrity management), and false maneuver rejection. It also includes the issuance of timely and valid warnings when the system cannot be reliably used.

5.2.3.2 System Continuity

System Continuity is a measure of the systems ability to complete a sense-and-avoid process once initiated *[32]*. This includes availability, reliability, and persistence.

5.2.3.3 System Interoperability

System interoperability is a measure of the level of degradation of other systems, including the National Airspace System (NAS) and the UAS, caused by sense and avoid system operation. This

includes nuisance to the NAS and operability, or ease of use for operators of the UAS. System interoperability also includes the ability of the UAS to provide right-of-way as necessary according to Federal Aviation Regulations.

System interoperability also relates to disruption of the Air Traffic Control (ATC) System if the UAS sense and avoid system reacts early and maneuvers wide of potential conflicts. While operating under ATC, the regulations specify that a manned aircraft will not maneuver unless there is an absolute necessity.

> CFR 91.123(a) *When an ATC clearance has been obtained, no pilot in command may deviate from that clearance unless an amended clearance is obtained, an emergency exists, or the deviation is in response to a traffic alert and collision avoidance system resolution advisory…*

Though not stated, there is an implication that failure to adhere to this principle will not just disrupt ATC, it will compromise the safety of the air traffic system. Early activations or alarms by a sense and avoid system could negate the instructions that ATC was about to issue and force him or her to reroute other traffic unnecessarily. Early sense and avoid activations could also conflict with resolution advisories issued by other aircraft TCAS. Therefore, in order for a sense and avoid system to achieve ELOS to a manned aircraft, it must not force a maneuver unless it is absolutely necessary.

5.3 Sense and Avoid ELOS Definition

Using the requirement for sense and avoid described above, and the measures of capability which describe any sense and avoid systems ability to provide an ELOS to manned aircraft, the definition of sense and avoid ELOS is therefore the following:

Equivalent level of safety to manned aircraft see-and-avoid for UAS, is the providing of situation awareness with adequate time to detect conflicting traffic and take appropriate action to avoid collisions. This sense-and-avoid capability is described by measures addressing surveillance, avoidance, and system quality. The following measures describe the sense-and-avoid system capability:

1. Minimum Detect Time
2. Field-of-Regard
3. Track Capability
4. Minimum Miss Distance
5. Miss Distance Probability
6. System Reaction Time
7. System Integrity
8. System Continuity
9. System Interoperability

These are the minimum measures necessary to describe sense-and-avoid system performance for ELOS consideration. These measures must be used in aggregate to properly define sense and avoid ELOS for a UAS and sense and avoid subsystem. The exclusion of any one measure will result in an incomplete or very limited sense and avoid ELOS definition. There is no priority order or ranking within the measures. Additional measures for a specific system may also be used to provide a more complete description of a proposed implementation.

The definition presented here is qualitative in nature, in order to retain maximum design flexibility for sense and avoid system developers. The definition includes measures as leading indicators, to permit understanding and evaluation of proposed systems, in support of an overall requirement which can only be validated after the fact (a lagging indicator of performance).

6.0 SUMMARY

The discussion of the sense and avoid requirement and the associated capabilities and measures provide the definition of what equivalent level of safety means for sense and avoid as it applies to UAS. The definition is qualitative in nature, in order to retain maximum design flexibility for sense and avoid system developers.

UAS are currently allowed to operate in the NAS through a process of precoordination and segregation of UAS from manned aircraft. Defining an ELOS for sense and avoid for UAS would be a key factor in the eventual integration of UAS in the NAS. The current process for preventing mid-air collisions for manned aircraft in the NAS utilizes a layered approach consisting of both conflict avoidance and collision avoidance techniques. The conflict avoidance techniques for UAS will be identical to manned aircraft conflict avoidance, so the sense and avoid ELOS definition is focused on the collision avoidance portion of preventing mid-air collisions.

The requirement for a sense and avoid capability is contained in 14 CFR 91.113. Since UA do not have a human pilot onboard, the UAS needs to provide other means to provide an ELOS to manned aircraft for the see and avoid capability. The ELOS phrase can be partitioned into its three key elements: 1) "equivalence", 2) "level of safety", and 3) "see-and avoid requirements for manned aircraft," in an attempt to better understand the phrase as a whole. A combined approach has been developed for defining sense and avoid ELOS and for verifying the system is performing safely and reliably. The performance-based capability measures defined will provide "*leading indicators*" to describe to the FAA the systems ability to meet an equivalent level of safety for sense and avoid. These leading indicators could also be supported with a sufficient amount of simulation and analysis showing that a sense and avoid system, which contains the performance-based characteristics, can achieve the necessary safety level. Once the FAA has confidence that the proposed system will provide an ELOS and has permitted the system to operate within the NAS, the performance of this system should then be evaluated to ensure the overall reliability and safety numbers are being met. This later evaluation is what is referred to as the "*lagging indicator*" that an equivalent level of safety has been met.

Throughout this paper, a conscious effort was made to define ELOS for sense and avoid in a logical order and in a manner that does not specify any one particular solution or technology over another. It is important to keep an adequate amount of flexibility for the developers of UAS platforms since the final solution could be unique to an UAS. The results address the phrase "equivalent level of safety" which has been impeding the UAS industry for several years, and provide an approach for UAS manufacturers and the FAA to employ when developing/evaluating UAS sense and avoid subsystems. It is the project's desire that the content found within this report be referenced and used in establishing the necessary rules, regulations, and policies for UAS regarding sense and avoid.

7.0 ACRONYMS

ADS-B	Automatic Dependent Surveillance - Broadcast
ATC	Air Traffic Control
CFR	Code of Federal Regulations
COA	Certificate of Authorization
DSA	Detect, Sense, and Avoid
ELOS	Equivalent Level of Safety
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation (Title 14 Code of Federal Regulations)
fpm	Feet per Minute
GA	General Aviation
GCS	Ground Control Station
GPS	Global Positioning System
HALE	High Altitude, Long Endurance
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
LOS	Line-of-Sight
MOE	Measure of Effectiveness (Black Box… Top Level)
MOP	Measure of Performance (White Box… Lowest Level)
NAS	National Airspace System
Nm	nautical miles
NMAC	Near Midair Collision
OPEC	USAF Optical Encounter Model
OTH	Over-the-Horizon
RA	Resolution Advisory (assoc. w/ TCAS)
ROA	Remotely Operated Aircraft (synonymous w/ UAS)
SUA	Special Use Airspace
TA	Traffic Advisory (assoc. w/ TCAS)
TCAS	Traffic Alert Collision Avoidance System
TtC	Time-to-Collision
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
USAF	United States Air Force
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

8.0 BIBLIOGRAPHY

1. FAA Order 7160.4K, "*Special Military Operations"*, Effective Date: February 19, 2004.
2. FAR 91.113, "*FAA Right of Way Rules*". Federal Aviation Regulations General Operating and Flight Rules.
3. 14CFR 21.21 (b) "*Issue of type certificate: normal, utility, acrobatic, commuter, and transport category aircraft; manned free balloons; special classes of aircraft; aircraft engines; propellers*". FAA, U.S. Dept. of Transportation.
4. FAA Order 8110.4B. Type Certification, Paragraph (g.) "*Equivalent Level of Safety*."
5. Marsters, G. & Sinclair, M. "Integrating UAVs w/ Conventional Air Operations: Some Regulatory Issues"; March 2003.
6. ICAO Annex 2, Rules of the Air, "*Right of Way Rules*". International Civil Aviation Organization, Ninth Edition, July 1990.
7. "*2001 Nall Report*". AOPA Air Safety Foundation, 2002.
8. ICAO Doc 9869 "*Manual on Airspace Planning Methodology for the Determination of Separation Minima", First Edition, 1998*.
9. "*2003 Nall Report*". AOPA Air Safety Foundation, 2004.
10. Accidents, Fatalities, and Rates, 1984 through 2003, U.S. General Aviation http://www.ntsb.gov/aviation/Table10.htm
11. "*Mid-Air Collision Avoidance Document*", Tyndall Air Force Base. 18 June 2001.
12. Wiener, Earl and Nagel, David, "*Human Factors in Aviation*". Academic Press.
13. Edwards, Gerald. Harris, James. "*Visual Aspects of Air Collision Avoidance*", University of California, San Diego. February 1972.
14. Suzler, R.L. "Visual Attenuation of Private Pilots, the Proportion of time Devoted to Outside the Cockpit", FAA report. May 1976.
15. Orlady, H.W. 1969, "Selected Visual Problems of an Airline Pilot Committee on Vision, Visual Factors in Transportation Systems, National Research Council.
16. Bureau of Air Safety Investigation, "Limitations of the See-and-Avoid Principle", April 1992.
17. Andrews, J.W., "Modeling of Air to Air Visual Acquisition", The Lincoln Laboratory Journal, Vol.2, No. 3, 1989, pp475-482.
18. McCalmont, J. "*See And Avoid For UAVs".* AUVSI Unmanned Systems 2002 presentation. Lake Buena Vista, FL. July 2002.
19. *"Non-cooperative DSA Flight Test Report".* Written for NASA ERAST program by Modern Technology Solutions, Inc. Alexandria, VA. July 2003.
20. White, C.T. "Ocular Behavior in Visual Search", Applied Optics, vol. 3, 1964..

21. *Civil Aero-Medical Institute (CAMI), "Pilot Safety Brochure". http://www.cami.jccbi.gov/aam-400A/400brochure.html, Revised 9/13/2002.*

22. Crosby, Sarah. "See and Avoid", Air Transportation Safety Board website. http://www.atsb.gov.au/aviation/editorial/cavoid/index.cfm

23. Smith, Warren J., "*Modern Optical Engineering"*, 3rd Ed., pp258.

24. Liebowitz, H.W. & Appelle, S. 1969, "The Effect of a Central Task on Luminance Thresholds for Peripherally Presented Stimuli", Human Factors, vol. 11, pp387-392.

25. FAA-P-8740-51, FAA Accident Prevention Program, "*How to Avoid a Mid Air Collision".*

26. Advisory Circular AC 90-48C "*Pilots' Role in Collision Avoidance*", FAA, U.S. Dept. of Transportation

27. FAA Order 8020.11, "*Aircraft Accident and Incident Notification, Investigation, and Reporting*".

28. FAA Order 8700.1, Ch. 169. "*Investigate a Near Mid-Air Collision".*

29. FAR 91.155, "*Basic VFR Weather Minimums".* Federal Aviation Regulations General Operating and Flight Rules.

30. Advisory Circular AC 25.773-1, "*Pilot Compartment View Design Considerations",* FAA, U.S. Dept. of Transportation.

31. *"Non-Cooperative Detect, See & Avoid (DSA) Requirements for ROA Operations within Civil Airspace".* Written for NASA ERAST program by Modern Technology Solutions, Inc. Alexandria, VA. 30 September 2003.

32. RTCA SC-186, 2003, Airborne Surveillance Applications (ASA) Minimum Aviation System Performance Standards (MASPS), RTCA/DO-289, Washington, DC, RTCA, Inc.

33. Ebdon, D. & Regan, J., "*Sense and Avoid Requirement for Remotely Operated Aircraft*" HQ ACC/DR-UAV SMO, June 2004

34. ICAO Eleventh Air Navigation Conference, "*ATM Operational Concept Document*," ICAO AN-Conf/11-WP/4

APPENDIX A: POTENTIAL APPROACHES FOR DEFINING ELOS

This appendix provides a survey of potential methods to examine the see and avoid issue, and to derive measures for use in defining an ELOS see and avoid capability for unmanned aircraft systems.

There are two general approaches that may be used to determine whether an unmanned aircraft is as safe as a manned aircraft. The first approach compares the ***statistics*** of a manned system to that of the unmanned system, whereas the second approach compares the ***performance*** of the manned system to that of the unmanned system. While both approaches can provide meaningful insight, only the performance approach defines ELOS using *leading indicators* to measure ROA capability. The statistics approach, on the other hand, relies upon *lagging indicators* that can only be validated after a sufficient amount of ROA operations statistics are collected. Both approaches will be discussed in the following sub-sections.

A.1 Statistical Approach

A statistical approach attempts to quantify ELOS by using the manned-aviation collision statistics gathered over the past decade or more. The assertion is that an "equivalent level of safety" can be achieved if the total rate of manned and unmanned aircraft mid-air accidents, with ROA operating in the NAS, does not increase above the rate of just manned aircraft accidents prior to the introduction of ROA into the NAS.

A.1.1 Statistical Approach Methodologies

The following sections discuss two methodologies within the statistical approach for establishing an ELOS definition. The first methodology is based on the target level of safety number established by ICAO for separation minima and the second methodology is based on general aviation mid-air collision statistics. Either methodology could be used as part of a risk ratio to compare manned aircraft see and avoid requirements to UAS sense and avoid requirements.

A.1.1.1 Method 1: Overarching Target Level of Safety Number

Supporters of this method suggest a single number defining the overarching target level of safety for the air traffic management system is all that is needed to define ELOS for see and avoid. The target level of safety (TLS) number that would be used for this methodology is 2.5×10^{-9}, which is derived from ICAO Doc 9689, Manual on Airspace Planning Methodology for the Determination of Separation Minima [8].

According to ICAO Doc 9689, collision risk in a given airspace is directly affected by the capability of ATC to detect aircraft on conflicting tracks and to correct the situation before a collision can occur. In order to evaluate the estimate of collision risk, it must be compared to a maximum tolerable collision risk for the entire system. This maximum tolerable risk is normally expressed in terms of a target level of safety expressed in terms of the number of fatal accidents per flight hour. Section 6.14 of Doc 9689 states that: for the North Atlantic airspace, the TLS for reduced vertical separation minimum (RVSM) levels is 5.0×10^{-9} and 2.0×10^{-9} for non-RVSM levels. Both of these values take into account the risk of collision associated with performance of the onboard equipment as well as that associated with ATC or pilot errors (operational errors).

Section 6.15 of Doc 9689 then arbitrarily sets a TLS of 2.5 $x10^{-9}$ fatal accidents per flight hour for the risk of collision associated with performance of the onboard equipment. This smaller TLS value does not include the risk arising from either ATC or pilot errors, and is one-half of the original TLS number ($5.0x10^{-9}$) proposed for RVSM levels.

It should be noted, that since RVSM levels have only been implemented between FL290 and FL410, the TLS value of $2.5x10^{-9}$ would only apply to aircraft capable of RVSM and operating within that altitude range. For aircraft operating above FL410 or below FL290, the overall TLS value of $2.0x10^{-9}$ would apply. If the same arbitrary value of ½ is applied to the equipment performance as was done for the RVSM levels, then it could be inferred that $1.0x10^{-9}$ should be attributed to the non-RVSM aircraft's onboard equipment.

A.1.1.2 Method 2: General Aviation Mid-Air Collision Statistics

This proposed methodology for defining ELOS uses the historical midair collision statistics for manned aviation. Since it is not envisioned that ROA will initially be used for transporting personnel, as commercial airliners do, this method specifically looks at the collision statistics for general aviation (GA) aircraft. *Figure A1* and *Table A1*, published within the 2003 Nall Report *[9]* and NTSB Aircraft Accident report *[10]*, provide the U.S. general aviation accidents per 100,000 flight hours for the 10 year period from 1993 to 2002. Using this approach, an equivalent level of safety could be achieved if the average number of midair collisions per 100,000 hours did not increase for the year that ROA are allowed to fly within civil airspace. Using the data provided in *Table 1*, one would expect an equivalent level of safety to be achieved if the rate of mid-air collisions, using manned and unmanned collision statistics, remains at or below 0.052 mid-airs per 100,000 flight hours.

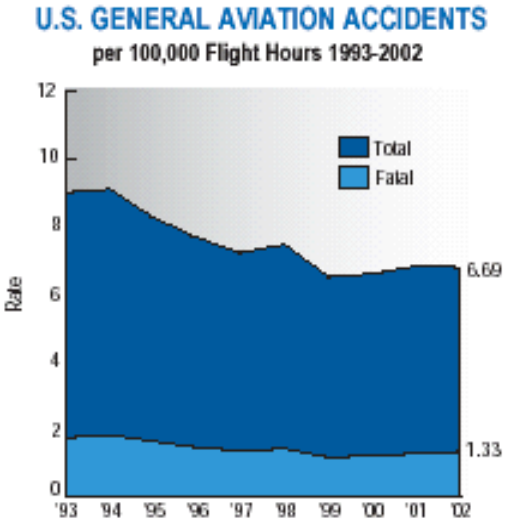

Figure A1: GA Midair Collision Statistics, 1993 - 2002

Table A1: General Aviation Mid-air Collision Statistics, 1993 to 2002

	Mid Air Collisions			Mid Airs per 100,000 Flight Hours	
Year	**All**	**Fatal**	**Flight Hours**	**All**	**Fatal**
1993	13	7	22,796,000	0.057	0.031
1994	11	7	22,235,000	0.049	0.031
1995	14	8	24,906,000	0.056	0.032
1996	18	6	24,881,000	0.072	0.024
1997	13	11	25,591,000	0.051	0.043
1998	14	11	25,518,000	0.055	0.043
1999	15	7	29,246,000	0.051	0.024
2000	19	11	27,838,000	0.068	0.040
2001	5	3	25,431,000	0.020	0.012
2002	9	5	25,545,000	0.035	0.020
AVG	13.10	7.60	25,398,700	0.052	0.030

A.1.2 Benefits of using the Statistical Approach

This approach attempts to assist regulators in establishing the minimum operational performance standards and specifications for a collision avoidance system in a simple measure. The only measure to be made is whether or not the total number of mid-air accidents per year increase after ROA have been introduced into the NAS. The benefit, therefore, would be a lesser workload on regulators since there wouldn't be a need to generate numerous standards and specifications other than the single statistical number used to define ELOS.

Another benefit of this approach is that it could be used to verify or validate an ELOS definition based on leading indicators such as performance-based items discussed in section A.3. In this capacity, the statistical number could be used as a lagging indicator to either confirm the performance-based ELOS indicators are satisfactory or if there is a need for performance tradeoffs in a previously approved design.

A.1.3 Drawbacks with the Statistical Approach

One concern with the statistical approach is that the final value, which gets proposed as being an equivalent level of safety to manned aviation, will be difficult to validate prior to the insertion of ROA into the NAS. Reliability and statistical numbers, by definition, require data to be gathered over a long duration of time. Prior to collection of data over a statistically meaningful period of time, one can only predict results through analysis, simulation, or demonstration through similarity.

Another concern with this approach is the complexity of mid-air collision statistics. Results can be skewed by a number of factors, e.g. ROA encounter scenarios may be different from those of manned aircraft, evolution of the NAS, and variability of mid-air collision statistics from region to region. As an example of the different encounter probabilities, the AOPA Air Safety Foundation 2001 Nall Report *[7]* says that 80% of all mid-air collisions are within 10 miles of an airport while in the traffic pattern, 77% occurred at or below 3,000 feet AGL, and 49% occurred at or below 500 feet AGL. With automated takeoff and landing and no requirement for proficiency training in the traffic pattern, ROA operating in this airspace far less frequently than manned aircraft could mask a higher ROA mid-air collision rate in other flight regimes if only the overall rates are examined.

A.2 Performance-Based Approach

A performance-based approach for defining ELOS could have a higher chance of success for being used by the FAA to establish collision avoidance requirements for ROA. Collision avoidance requirements derived from a performance-based approach can also provide ROA platform developers and sensor designers with a set of measurable performance parameters that could ultimately be used to verify that their proposed system has an equivalent level of safety to that of a manned aircraft. Establishing these measurable parameters will provide the FAA with a "*leading indication*" the ROA system is suitable to fly within the NAS; thereby giving them greater confidence the system will be capable of maintaining safe separation.

A.2.1 Performance-Based Approach Methodologies

A performance-based approach attempts to quantify ELOS by using either 1) the physical and mental limitations of the human pilot or 2) the existing see and avoid rules and guidelines already in place for manned aircraft. The assertion is that an equivalent level of safety can be achieved by developing a see and avoid system that meets or exceeds the capabilities of a human pilot or complies with the existing FAA rules and guidelines for avoiding midair collisions in manned aircraft. Both of these methods are further described below.

A.2.1.1 Method 1: Human Pilot Limitations, Regarding See and Avoid

The first performance-based method attempts to bound the problem by focusing on the physical and mental limitations common to all human pilots as they perform the task of collision avoidance. Over the past several decades, many individuals and groups have attempted to quantify the temporal and visual capabilities of humans as they relate to see and avoid. In addition to modeling and simulation work, many of these results have also been substantiated over the years through various tests and experiments that have focused on several parameters. A discussion of several of these human pilot see and avoid limitations follows.

In order for pilots to avoid midair collisions, they must perform a number of steps. These steps involve scanning the surrounding airspace for other aircraft, determining if the detected aircraft is on a collision trajectory, deciding what evasive maneuver must be performed, if any, and initiating the appropriate maneuver allowing sufficient time for the pilot's own ship to respond and maintain separation. This process of detecting and avoiding other aircraft is comprised of six essential functions, which must be performed in the appropriate order to lessen the chance of a mid-air collision occurring. These six DSA functions are depicted below and listed in Figure A2.

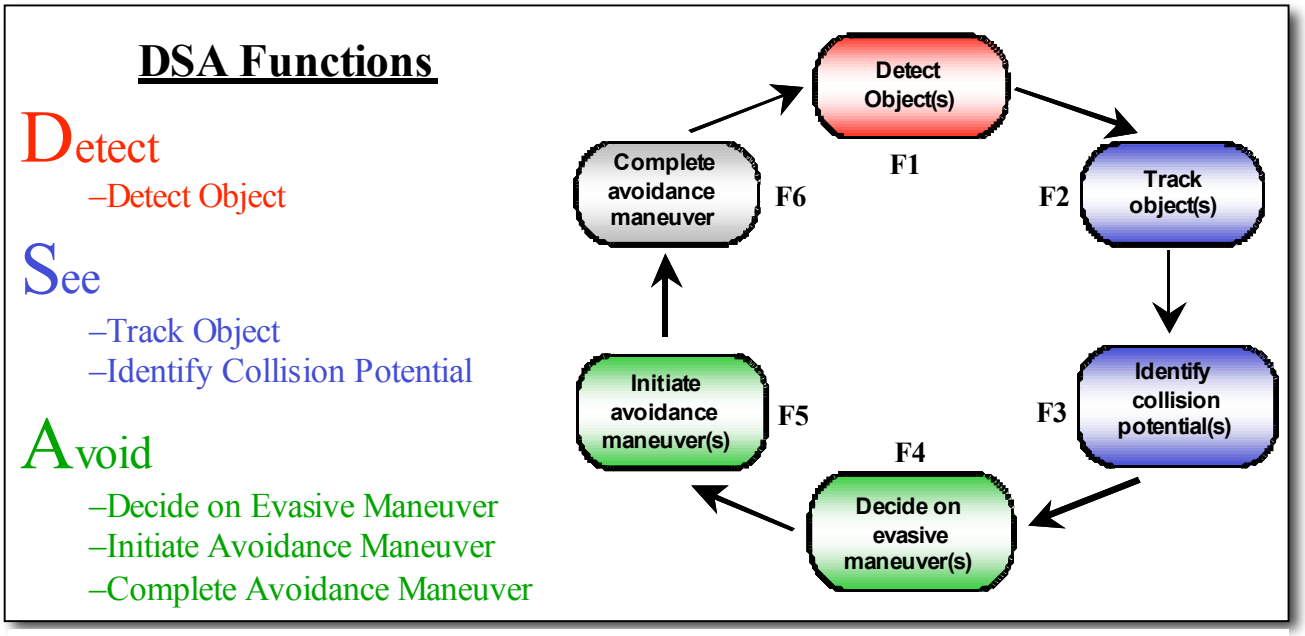

Figure A2: The Functions Comprising Detect, See, and Avoid

It is necessary to always think of collision avoidance, as a process comprised of these six functions, regardless of whether it is for a manned or unmanned aircraft. Each of these functions performs a critical role toward providing an overall collision avoidance capability essential to maintaining safe and reliable operations as a function of see and avoid.

Pilot Reaction Time

One of the most widely accepted studies attempting to quantify how long it takes a human pilot to perform these six functions was performed by Tyndall Air Force Base in 2001 and is documented within their Air Force - Mid-Air Collision Avoidance (AF-MACA) Document *[11]*. This study was performed using military pilots flying military jet aircraft with closing speeds up to 1,100 mph. According to this study, a duration of **12.5 seconds** is typically required for a pilot to detect an intruding aircraft, track the intruder aircraft's flight path, determine the collision potential with the other aircraft, decide upon an evasive maneuver, and then actually initiate the evasive maneuver. *Figure A3* depicts all 6 of the DSA functions and the time allocated to each within the study. Note that the 12.5 seconds is only for the first five functions. These are the functions that are dependent upon the human pilot, whereas, the time to complete the maneuver is dependent upon the performance capability of the aircraft, the type of maneuver

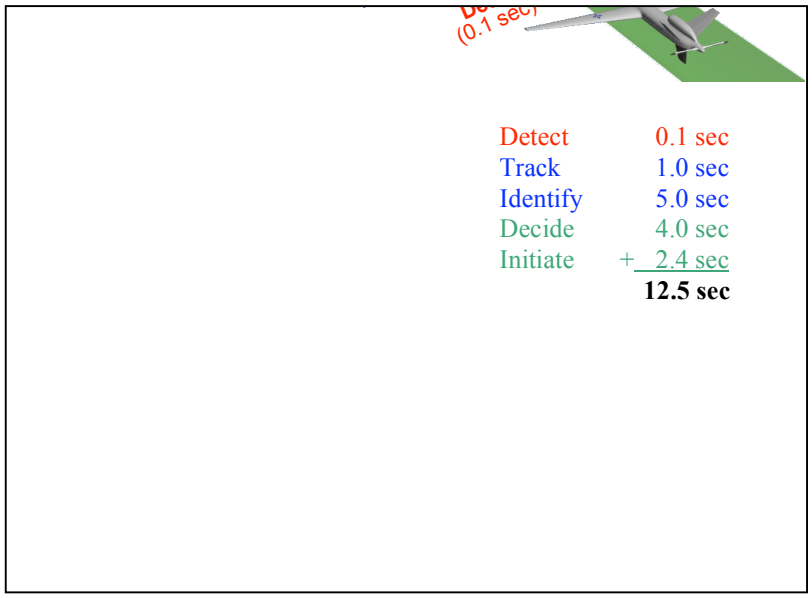

Figure A3: Human Pilot Collision Avoidance Timeline

performed (i.e. climb or dive, heading change, or combination of these two), and the aggressiveness of the maneuver.

A second source for these times was found after discussions with the Air Force personnel involved in the Tyndall AFB test. From this conversation, a book called Human Factors in Aviation *[12]* was mentioned. Upon reviewing this book, a statement was found which said: "*Estimates of the time required to recognize an approaching aircraft and take evasive action range from* ***5.0 to 12.5 seconds***…" However, no supporting analysis was provided other than it was based on military tests previously performed.

A third study performed by the University of California in 1972, alluded to the time necessary to perform collision avoidance as **10 seconds**. This study, Visual Aspects of Air Collision Avoidance [*13*], states: "*Ten seconds has sometimes been stated as the minimum required time for visual acquisition if successful evasive action is to result*."

Regardless of whether 10 seconds or 12.5 seconds is used to begin quantifying the time it takes a human pilot to perform collision avoidance, the total time needed to avoid must also include the aircraft response time. For an ROA this will not only depend upon the maneuverability of the aircraft, but also upon the latency and availability of the command and control link.

Visual Scan Persistence

Obviously, see and avoid will only work if the pilot is looking outside the cockpit. According to a study performed in 1976, U.S. pilots on VFR flights spend about **50 percent** of their time in outside traffic scan *[14]*. Even more disturbing, are the results from a similar study done regarding commercial airline pilots. This study suggests airline pilots spend about **20 percent** of their time in outside scan *[15]*. Of course, the time spent scanning for traffic is likely to vary with traffic density and the pilot's assessment of the collision risk *[16]*

Detection Range

As discussed in Section 2.3, several factors can make visually detecting other aircraft more or less challenging. Some of these factors may include: the relative motion of the approaching aircraft; the aspect of the aircraft; or the approaching aircraft's contrast against its background. Factors such as aircraft color, lighting color, and strobe lighting can all aid a pilot in his/her ability to make an initial detection. Several studies have been done to assess the detection range at which a pilot is first able to detect aircraft on a collision approach. Four of these studies are discussed below.

One of the first analytical studies performed on this topic was conducted at the University of California in 1972. This analysis used a Cessna 180 and a Douglas DC-8 for determining probability of detection based upon time until impact for a variety of collision geometries. The nominal human detection range resulting from this analysis was **2 nautical miles** (nm). In addition, this study showed overwhelming proof that the visual detection performance of a pilot can be significantly improved if he knows when and where to look. *[13]*

In the late 1970s through mid 1980s, MIT Lincoln Laboratory developed an independent see and avoid model in support of the TCAS initiative. This model was based upon several series of flight experiments, which produced a database of pilot visual acquisition performance for a variety of near collision encounters. These experiments, which involved a Cessna 421 and Beech Bonanza, found that the median acquisition range for **"un-alerted pilots" was 0.99 nm** and **1.14 nm when pilots were alerted** to the approximate bearing of the target *[17]*. This model was able to also show that the probability of acquiring an intruder was largely dependent upon the workload devoted to the search and the uncertainty in the approach bearing of the target aircraft.

A third study exploring human detection range was performed by the Air Force Research Laboratory (AFRL) in 2002, using the Optical Encounter (OPEC) model. This model emulates the human ability to detect aircraft under a variety of environmental conditions, and has been validated by 937 trials under all different lighting conditions and aspect scenarios. The results of this study indicated that the human detection range for an alerted pilot was an average of **1.6 nm, +/- 0.2 nm** *[18]* against military aircraft, assuming a 90% detection probability and a +/- 15 degree search cone.

The fourth and final activity to be discussed here was performed by the NASA Environmental Research Aircraft and Sensor Technology (ERAST) Project. Over a two year period, between 2001 and 2002, The NASA ERAST project sponsored several collision avoidance flight demonstrations intended to assess the feasibility of multiple technologies for see and avoid. The NASA ERAST Non-cooperative DSA Flight Test Report states, "*the typical detection range for two human pilots was between* ***1.0 and 1.5 nautical miles***" *[19]*. This detection range was the result of nearly 50 collision scenarios, in which both pilots onboard the aircraft knew the exact time and direction from which the intruder aircraft would be approaching.

It is important to note, that all four of these completely independent tests achieved surprisingly similar values for human detection range for alerted and un-alerted pilots. Also noteworthy is the fact that two of these studies involved analytical modeling tools and two involved actual flight tests.

Probability of Detection

What is the likelihood that a pilot will detect another aircraft approaching on a collision trajectory? The probability of detection (Pd) for a given collision scenario will largely depend upon the workload and attentiveness of the pilot, the approaching aircraft's contrast with the background, and whether or not the pilot was previously alerted regarding when and where to look. With respect to the Lincoln Labs flight test (discussed earlier), the pilots, who were **un-alerted**, detected the approaching aircraft in thirty-six out of sixty-four encounters, or **56%** *[17]*. With respect to NASA ERAST flight tests, the pilots were **alerted** when and where to look. As a result, the ERAST pilots were able to visually acquire the approaching aircraft prior to the 1 nm "call-off" distance in 46 of the 50 encounters, or **92%**. This value is similar to a study performed by AFRL, where they indicate that a 90% Pd is reasonable and comparable to human performance when the pilot is alerted about the approaching intruder aircraft *[18]*.

Update Rate

The individual eye movements associated with visual search takes a small but significant amount of time. According to Applied Optics *[20],* the most updates the human eye can make are **3 fixations per second**. This can, however, substantially increase if the pilot is scanning a complex scene.

Visual Acuity

There are times when the approaching aircraft will be too small to be seen because it is below the eye's threshold of acuity. According to the book Modern Optical Engineering by Warren Smith *[23],* "*The normal, healthy, unaided human eye has a resolution of about* ***0.3 milliradians*****"**; or about 0.02 degrees. This high level of acuity, however, only applies to the foveal 1° cone, where vision is the best. Outside of a 10° cone, concentric to the foveal 1° cone, human vision acuity decreases to one-tenth of it's foveal value [21]. In terms of an oncoming aircraft, if a pilot is able to see an aircraft at 4,000 feet within his/her foveal field, with peripheral vision the aircraft wouldn't be detected until it was only 400 ft away.

While aircraft on converging tracks will appear larger as they get closer, it can be said that the apparent size of an on-coming aircraft doubles with each halving of that aircraft's range. Imagine the case in which a general aviation aircraft and a military jet are approaching each other head-on at speeds of 150 knots and 450 knots respectively, a closing speed of 600 knots. At about 20 seconds before impact, the two aircraft might be about 3200 ft apart and each will present a target to the other of only around $1/16^{th}$ of a degree. Ten seconds from impact, the distance will be halved and the target size will have increased to all of $1/8^{th}$ of a degree; at 5 seconds, the size will have again doubled but will still be only about 1/4 of a degree. In other words, the oncoming aircraft remains extremely small until very late, and then it suddenly expands into something that fills the windscreen. Figure A4 illustrates this concept *[22].*

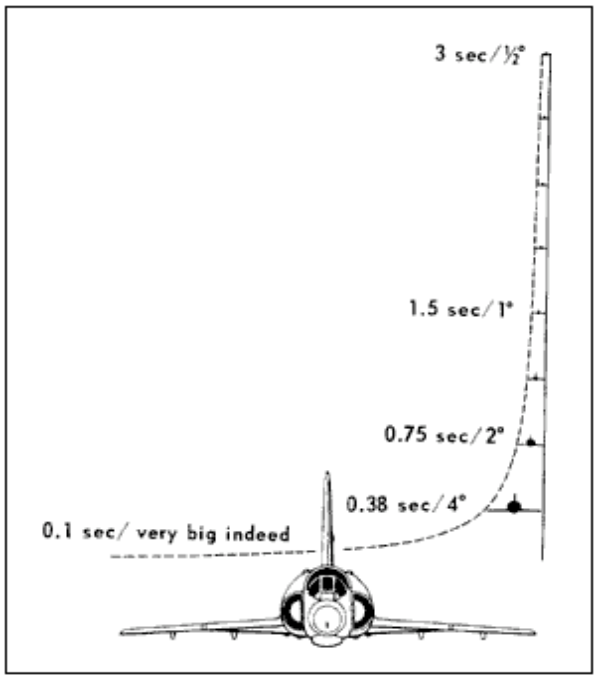

Figure A4: Time to impact and angular size of oncoming aircraft Timeline [ASTB]

Field of Regard

Field of regard (FOR) is the volume of sky that a human can see, in both the horizontal and vertical positions. According to the Civil Aero-Medical Institute (CAMI), the **normal vertical vision field is 135°, 60° up and 75° down**. The **horizontal vision field**, according to CAMI, is **+/- 100° left and right**. Both of these volumes are for a stationary head, using both eyes. Obviously, by moving one's head left/right or up/down, the total FOR can greatly be increased. However, the aircraft cockpit and structure usually restrict the benefits of this substantially (unless of course it is a fighter jet with a large transparent canopy).

Another source for horizontal FOR is the Bureau of Air Safety Investigation (BASI), which states that "*The average person has a field of vision of around **190 degrees**...*" which equates to +/- 95° azimuth. Regardless of the FOR being scanned, some areas of the visual field receive close attention while other areas are neglected. For example, areas of the sky near the edges of the windscreen are generally scanned less than the sky in the center of the windscreen *[20]*.

Field of View

Although a human's field of regard covers a rather large volume of sky, he/she is likely only to detect aircraft that they are directly looking at. According to BASI *[16],* a human can only focus on a **10° to 12°** area at a time. On both sides of this area, all human eyes have blind spots which greatly prohibit viewing anything within a 6° region between 12° and 18° to the left and right of the foveal 1° cone.

Workload

The limiting mental processing capacity of the human pilot can present problems when there is a need to attend to two or more sources of information at the same time. This obviously pertains to performing in-cockpit related activities such as monitoring the instruments and out-of-cockpit activities such as scanning. However, even if pilots could spend 100% of their time looking for traffic, they can get overwhelmed if multiple aircraft are detected and each need to be tracked for determining collision potential. A number of researchers have shown that peripheral stimuli are more difficult to detect when attention is focused on a central object or task *[23]*. For example, while a pilot is concentrating on one aircraft, a second aircraft could enter their peripheral vision and never be detected until too late.

Other limiting factors

Other factors known to affect vision include alcohol, tobacco, stress, sleep deprivation, low barometric pressure, windscreen haze, improper illumination of the cockpit and/or instruments, and dirty instruments *[21]*.

Summary

Table A2 summarizes the results discussed in this section.

Table A2: "Equivalent Level of Safety" Based Upon a Human Pilot's See & Avoid Limitations

Parameter	Value	Reference/Source
Pilot Reaction Time	10 sec 12.5 sec	"Visual Aspects of Air Collision Avoidance" [13] "Mid-Air Collision Avoidance" [11]
Percent of time spent scanning	GA: 50% Airline: 20%	"Visual Attenuation of Private Pilots, the Proportion of time Devoted to Outside the Cockpit" [14]
Detection Range for Alerted Pilots	1.14 nm 1.6 nm 1.5 nm	Lincoln Labs TCAS Flight Tests [17] AFRL OPEC Model "See & Avoid for UAV's" [18] NASA ERAST See & Avoid Flight Test [19]
Probability of Detection (Pd)	Un-alerted: 56% Alerted: 92%	Lincoln Labs TCAS Flight Tests [17] NASA ERAST See & Avoid Flight Tests [19]
Update Rate	3 fixations/sec	"Ocular Behavior in Visual Search" [20]
Visual Acuity	0.3 mrad	"Modern Optical Engineering" [23]
Field of Regard (FOR)	Vertical: +60°, -75° Horizontal: +/-100°	"Pilot Vision Brochure" [21]
Field of View (FOV)	10° – 12° cone	"Limitations of the See & Avoid Principle" [16]

A.2.1.2 Method 2: Existing Aviation Regulations

The second performance-based method for defining equivalent level of safety relies on the FAA and ICAO guidelines that have already been established for the safe operation of manned aircraft. Many of the requirements imposed on manned aviation could potentially be used to establish the requirements for a ROA collision avoidance system initial capability. This approach adopts the existing rules and guidelines that pertain to see and avoid. If a sensor can provide a similar capability for detecting and avoiding collisions, then it could be argued that an equivalent level of safety for see and avoid has been reached. The following paragraphs will identify what some of these existing rules and guidelines state with respect to pertaining to see and avoid.

Pilot Reaction Time

With respect to time-to-collision, the FAA guidelines support the analysis and studies mentioned above in the human-limitation discussions. According to FAA-P-8740-51, FAA Accident Prevention Program *[25]*, "*It takes a minimum of **10 seconds** for a pilot to spot traffic, identify it, realize it is a collision threat, react, and have his aircraft respond*."

Similarly, Advisory Circular (AC) AC 90-48C, entitled Pilot's Role in Collision Avoidance shows a graphic supporting the Tyndall AFB-MACA number of **12.5 seconds**. This graphic allocates 0.1 sec to seeing the object, 1.0 sec to recognizing the aircraft, 5.0 sec for becoming aware of the collision course, 4.0 sec for the decision to turn left or right, 0.4 sec for muscular reaction, and 2.0 sec for aircraft lag time *[26]*.

Separation Minima

All aircraft must be capable of maintaining adequate separation with other traffic. FAA Order 8020.11 identifies a Near Mid Air Collision (NMAC) as an "*incident*" *[27]*, and FAA Order 8700.1 sets out guidelines for classifying the hazard level of NMACs *[28]*. According to 8700.1, the hazard level based on miss distance is as follows:

Critical Hazard:	*<100 feet*
Potential Hazard:	*100 – 500 feet*
No Hazard:	***> 500 feet***

Therefore, to ensure a NMAC or incident does not occur, all aircraft must maintain a 500-foot radius safety bubble around their vehicle.

Visibility

The minimum visibility requirements for operating an aircraft under visual flight rules (VFR) conditions are established in 14 CFR 91.155. According to this source, the visibility requirement to operate **below 10,000 ft is 3 statute miles** and **5 statute miles when above 10,000 ft** *[29]*. It is important to note that these visibility requirements are not intended to identify a range for detecting approaching traffic, but rather are simply a minimum visibility distance. Although visibility and detection range are not equivalent, these visibility requirements could be used to establish the maximum required by the FAA to operate within the NAS under VFR conditions.

Azimuth Field of Regard (FOR)

The FAA does not require a specific azimuth of visibility from the cockpit, but in general, a pilot would need to see beyond 90 degrees right and left, especially to check the airspace prior to a turn. Also, the FAR right-of-way rules [2] require the converging aircraft to deviate to the right to avoid head-on conflicts, or deviate to the right to pass behind a conflicting aircraft approaching from the right. It is also the responsibility of an overtaking aircraft to avoid a slower air vehicle.

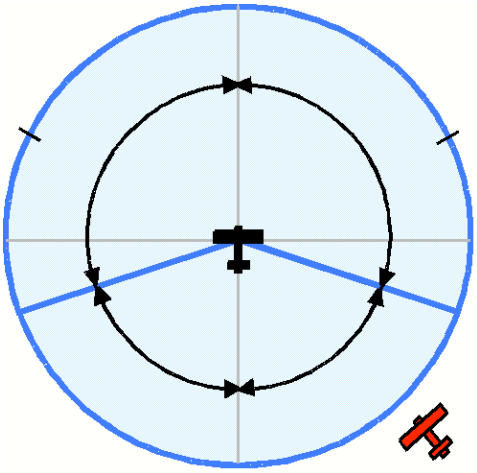

Figure A5: ICAO Annex 2, Azimuth FOR Responsibility

The ICAO Right of Way Rules (Annex 2) *[6]* state that "*an aircraft intercepting from an aspect angle +/- 70 degrees from the tail, must give way to the other aircraft*" A graphic of this is shown in *Figure A5.* The inverse of +/- 70° from the tail is obviously +/- 110° from the nose of the aircraft. Therefore, a Field of Regard azimuth of **+/- 110 degrees** should be sufficient to provide equivalent detection relative to a manned aircraft.

The FAA Air Safety Foundation pilot information pamphlet, How to Avoid a Midair Collision also provides guidance on azimuth FOR. This pamphlet suggests that "*looking **+/- 60 degrees** off the nose would catch the vast majority of conflicting aircraft*" *[25].*

A third reference that discusses azimuth FOR is AC 25.773-1, Pilot Compartment View Design Considerations. This Advisory Circular states: "*vision through the transparent areas should provide the following pilot compartment view ...120° left to ... and 120° right"[30].* It is important to note, however, that this document is only intended to provide guidance on cockpit design, and not to provide guidance for avoiding collisions. In fact many aircraft do not adhere to this AC, while others exceed the suggested amount of transparent material for cockpits.

Elevation Field of Regard (FOR)

Although the FAR does not require a specific elevation of visibility from the cockpit, it does require that climbing/diving aircraft give way to air vehicles above/below [2]. The practical requirement for vertical visibility is dependent on aircraft climb/dive performance and operation where an aircraft that operates with high rates of vertical maneuver would require a higher elevation scan capability than an aircraft with a slower rate of vertical maneuver. The FAA and Air Safety Foundation pilot information pamphlet, How to Avoid a Midair Collision, states that "*looking **+/- 10 degrees** in elevation would catch, virtually all conflicting aircraft*" *[25]. Figure A6* depicts this elevation field of regard.

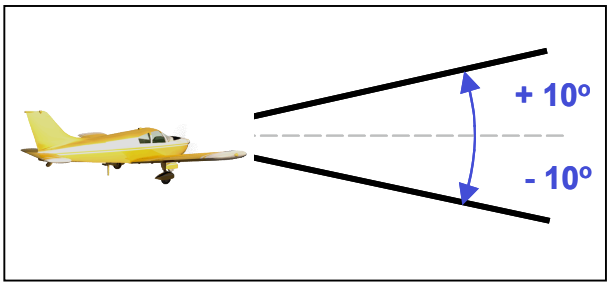

Figure A6: FAA Recommendation for Elevation FOR

Lastly, AC 25.773-1, Pilot Compartment View Design Considerations, also discusses the elevation FOR. This Advisory Circular states: *"Vision through the transparent areas should provide the following pilot compartment view…forward and up 35 degrees… to forward and down 27 degrees"[30]. As* noted previously when this reference was cited in the azimuth FOR section, these values are intended for cockpit design, not collision avoidance constraints.

Field of View (FOV)

The FAA Accident Prevention Program document, How to Avoid a Midair Collision *[25]*, provides insight into the ability of a human to focus on an area of airspace while searching for approaching aircraft. This document states: "*The human eye is limited to a relatively narrow area, approx.* ***10-15 degree****, in which it can actually focus and classify an object*".

Update Rate

Based upon the 10° – 15° field of view limitation for the human eye, which was discussed in the previous paragraph, the FAA established guidelines for scanning to detect approaching aircraft. FAA-P-8740-51 states*: "By fixating every 10 – 15 degrees, you should be able to detect any contrasting moving object in each block. This gives you 8 to 12 blocks in your scan area, each requiring a minimum of one to two seconds for accommodation and detection*." *[25]* Since this same document also suggests a scan area of +/-60 degrees azimuth by +/-10 degrees elevation, the suggested update rate can therefore be determined. If the suggested search volume is comprised of 12 blocks, and if one to two seconds are spent in each block, then the total amount of time needed to scan this volume once would be **between 12 seconds and 24 seconds** depending upon whether one or two seconds were spent searching in each block.

Summary

Table A3 summarizes the results discussed in this section.

Table A3: "Equivalent Level of Safety" Based Upon FAA & ICAO References

Parameter	Value	Reference/Source
Pilot Reaction Time	10 sec 12.5 sec	FAA-P-8740-51 "How to Avoid a Midair Collision." [25] AC 90-48C "Pilots' Role in Collision Avoidance" [26]
Missed Distance	> 500 ft is considered "No Hazard"	FAA Order 8700.1 "Investigate a Near Midair Collision" [28]
Visibility	3 mi, below 10K ft 5 mi, above 10K ft	FAR 91.155 "Minimum visibility for VFR flight" [29]
Azimuth FOR	+/- 60° +/- 110° +/- 120°	FAA-P-8740-51 "How to Avoid a Midair Collision." [25] ICAO Annex 2 "Right of Way Rules" [6] FAA AC 25.773-1 "Pilot Compartment Design" [30]
Elevation FOR	+/- 10° $+37^o$ to -25°	FAA-P-8740-51 "How to Avoid a Midair Collision." [25] FAA AC 25.773-1 "Pilot Compartment Design" [30]
Scan Rate	12 sec to 24 sec	FAA-P-8740-51 "How to Avoid a Midair Collision." [25]

A.2.2 Benefits of using the Performance-Based Approach

This approach attempts to quantify equivalent level of safety at a level that contains technically meaningful and/or more verifiable data. Establishing performance-based criteria would entail the development of collision avoidance requirements which could then potentially be used by the FAA in establishing minimum aircraft system performance standards (MASPS), minimum operational performance standards (MOPS), or technical standard orders (TSO) for see and avoid systems.

The major benefit to using this approach is that a performance-based ELOS definition will provide a leading indication to operators and regulators that the proposed system will in fact meet or exceed a human's capabilities. For example if a certain field of regard and detection range were required to meet an equivalent level of safety, then an adequate number of simulations and flight tests could be performed to verify the sensor could in fact meet these requirements. If these parameters were successfully met within the simulations and flight tests, the regulators would have a high degree of confidence in the see and avoid system before ever permitting it to operate within the NAS.

A.2.3 Drawbacks with the Performance-Based Approach

One concern with a performance-based approach is that multiple parameters may need to be specified, as opposed to a single number proposed under the statistical approach. Each of these parameters could not only require a substantial amount of analysis to derive the necessary requirements, but could potentially conflict with each other if appropriate trade offs are not made.

The biggest concern with this approach is that the requirements will not take into account the unique maneuverability characteristics of each ROA. If the unique characteristics of ROA are not considered when developing the requirements, all ROA could be required to carry the identical see and avoid sensor, which would have the capability to avoid collisions based on the worst case scenario for the fastest moving, least maneuverable aircraft. If all ROA were required to carry an identical see and avoid sensor to operate within the NAS, there would be a high probability that some ROA wouldn't be able to carry such a system due to size, weight and power constraints. Supporters of this approach, therefore, obviously desire to have the ROA's unique characteristics be taken into account when developing requirements so as not to over-specify the see and avoid sensor necessary for that vehicle to operate within the NAS. What is needed by one ROA to ensure collision avoidance may be over-specified for a slower moving, more maneuverable ROA.

A.3 Summary of the Potential ELOS Approaches

As one can see from the information provided within the previous sections, the term "equivalent level of safety" can be defined using several different approaches and methodologies, each based on a different premise. The statistical approach advocates using one number to define ELOS. This number is either the overarching safety number (5.0x10-9) or the average number of mid-air collisions for manned general aviation aircraft (average of 13.1 mid air collisions per year over past ten years) provided in Table A1. The performance-based approach, on the other hand, advocates establishing the ELOS definition that is based upon either human pilot's physical and

mental limitations or upon the existing manned aviation regulations found within the FAR, ICAO Annex2, and various FAA Orders and Advisory Circulars. Several performance parameters and their potential values for these two methodologies have been provided within Tables A2 and A3 above.