Literature Review on Detect, Sense, and Avoid Technology for Unmanned Aircraft Systems

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16. Abstract

This is a literature review of detect, sense, and avoid (DSA) documentation related or applicable to Unmanned Aircraft Systems that is currently in publication. The literature review focuses on noncooperative technologies and then types of systems, such as active or passive, for those technologies as applicable. Cooperative DSA technologies also are discussed. A summary of the technologies and systems is contained in the appendix C.

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TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

3-D	Three-dimensional
ACSS	Aviation Communication and Surveillance Systems
ADS-B	Automatic dependent surveillance-broadcast
AESA	Active electronically scanned array
AFRL	Air Force Research Laboratory
AGV	Automated Guided Vehicles
AIM	Aeronautical Information Manual
ASC	Aeronautical Systems Center
ASOS	Automated Surface Observing System
ATD	Advanced Technology Demonstration
ATDSS	Air Traffic Detection Sensor System
ATIS	Automated Terminal Information Service
ATTAS	Advanced Technologies Testing Aircraft System
AWOS	Automated Weather Observing System
BHO	Black-hot objects
C^2	Command control
CA	Collision avoidance
CFR	Code of Federal Regulations
CGAR	Center of Excellence for General Aviation Research
CAB	Civil Aeronautics Board
COA	Certificate of Authorization or Waiver
COTS	Commercial off-the-shelf
DAA	Detect and avoid
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DRA	Defense Research Associates, Inc.
DSA	Detect, sense, and avoid
EH101	Elicottero Helicopter Industries-01
EMD	Elementary motion detector
EO	Electro-optical
FAA	Federal Aviation Administration
FOR	Field of regard
GPS	Global positioning system
IAW	In accordance with
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IMC	Instrument meteorological conditions
IR	Infrared
LOAM®	Laser Obstacle Avoidance and Monitoring
MAGICC	Multiple Agent Intelligent Coordination and Control (Bringham Young University)
M^2CAS	Multimode collision avoidance system
MITL	Man-in-the-loop
MWS	Missile warning system

NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NGC	Northrop Grumman Corporation
nm	Nautical miles
NMSU	New Mexico State University
NOTAM	Notice to Airmen
NRTF	National Radar Test Facility
OPEC	Optical encounter
PANCAS	Passive Acoustic Noncooperative Collision Alert System
PSL	Physical Science Laboratory
SAA	Sense and avoid
SAR	Synthetic aperture radar
SARA	Scientific Applications and Research Associates, Inc.
SAVDS	Sense-and-Avoid Display System
SBIR	Small Business Innovative Research
SDD	System development and demonstration
SDT	Signal detection theory
SUA	Special use airspace
SWaP	Size, weight, and power
TAAC	Technical Analysis and Applications Center
TCAS	Traffic Alert and Collision Avoidance System
TRS	ThalesRaytheonSystems
UAA	University of Alaska–Anchorage
UAS	Unmanned aircraft system
UH	Utility helicopter
UND	University of North Dakota
VFR	Visual Flight Rules
VME	Virtual machine environment
WHO	White-hot objects

EXECUTIVE SUMMARY

This literature review of the detect, sense, and avoid (DSA) included technologies and approaches that could be used on an unmanned aircraft system (UAS) and that enable the Federal Aviation Administration (FAA) to understand the types of DSA available for UAS operating in the National Airspace System (NAS). Over 1000 articles were screened and over 150 references and/or citations related to potentially useful technologies were examined for the review.

The ability to operate a UAS on a routine basis in the NAS includes maintaining a safe aviation system. Although discussions are underway within the FAA, Department of Defense, other Federal agencies, and industry, one technology item with a consensus interest is the need for the ability of a UAS to DSA other aircraft or airspace users in the UAS flight-path area. Solutions to the DSA function will enhance the safety of the UAS and eventually provide more immediate access to the NAS.

Likewise, the ability to operate a UAS in the NAS today requires that the DSA function is accomplished. Whether operating with FAA permission as a public aircraft through the Certificate of Authorization process or through the experimental airworthiness certificate for the civil proponent, both approaches require a positive DSA activity by the UAS proponent.

A standard systems engineering approach was used to define and understand the DSA problem and to approach the problem systematically including evaluating DSA requirements and the potential technology solutions. As part of the definition phase, a needs analysis was performed. A functional analysis also was performed, and then the analysis of the literature was conducted. To support the reader, this report provides a review of DSA technology testing starting with the Environmental Research Aircraft Sensor Technology tests of 2003 culminating in the testing conducted by the United States Air Force with a UAS with a single camera system in 2007.

This DSA technology review examined both near-term potential DSA technologies and the manner in which this technology can be implemented. Near-term technologies reviewed included visual, infrared, radar, and a combination of technology systems. A summary of technologies with less maturity were included to illustrate the potential future state of the art that may be applicable to DSA.

DSA technology may be implemented in a passive or an active mode. For example, passive technology could include a visual-based system, whereas active technology may be radar-based. Additionally, a DSA system also may be cooperative or noncooperative. A cooperative system could employ transponders that exchange flight data with other aircraft. A noncooperative system could identify air platforms lacking the equipment or capability for in-flight communication.

Due to environmental constraints, such as weather or night-time operations, one specific noncooperative sensor or method may not be optimal. However, tradeoffs may be significant. For instance, a visual sensor system may not work well in adverse weather. A radar-based system could be a good complement to the visual system, but its size, weight, and power analysis may be high compared to the visual system. Consider whether two DSA systems using the same

technology are better than different technologies. However, even if environmental constraints become a driver for a multisensor approach, consider the advantage of redundant technology for the overall DSA function may be considered.

This report includes a case study on DSA technology (camera-based system) development, a 7-year history of a camera DSA development starting from requirements definition, to design, to UAS integration, and finally to NAS and special-use airspace flight demonstrations.

More than 150 references were examined for this literature review and report. The literature was separated into several categories (passive, active, cooperative, noncooperative, and type of technology) for ease of review and later assessment of the data. This review focused on the detect and sense portions of the noncooperative DSA function, although cooperative technologies and avoidance algorithms and technology also are discussed.

1. INTRODUCTION.

This report covers an unmanned aircraft system (UAS) detect, sense, and avoid (DSA) literature review undertaken by the Center of Excellence for General Aviation Research (CGAR) for the Federal Aviation Administration (FAA). The New Mexico State University Physical Science Laboratory (NMSU/PSL), the University of North Dakota (UND), and the University of Alaska-Anchorage (UAA) conducted the literature review under subcontract to the CGAR administrator, Embry-Riddle Aeronautical University. The UAA acted as the technical monitor.

1.1 BACKGROUND.

The FAA has long relied upon the eyesight of a human pilot as the primary method to avoid midair collisions even when transponders or radar systems are present. Lacking a human pilot, a UAS does not have the advantage of this onboard see safety feature. An increasing number of military, civilian, and commercial applications for a UAS may lead to an increasingly crowded airspace. Sharing this airspace with manned air vehicles, it will be necessary that automated DSA systems provide a level of safety equaling or exceeding that of manned aircraft (Title 14 Code of Federal Regulations (CFR) Part 91.113 and RTCA, 2007). In July 2004, an endeavor to set the standards for this equivalent level of safety was attempted when the ASTM subcommittee released Document F2411-04 (since amended to F2411-04e1) "Standard Specification for Design and Performance of an Airborne Sense-and-Avoid System." Since its release, this document has served as a guideline for developers and researchers working on UASs. In 2005, the United States Department of Defense (DoD) adopted these performance standards for its UAS program.

The scope of Document F2411-04e1 contains two pertinent items of interest. The first of these is to specify the requirements for the detection and safe separation from other aircraft. The second is to set a standard of an equivalent level of safety to the see capabilities of manned aircraft. This standard requires that a UAS be able to DSA other aircraft within a range of ±15° elevation and ±110° azimuth and respond in sufficient time so that a collision is avoided by a minimum of 500 feet. The 500-foot margin of safety derives from what is commonly defined as a near midair collision. Additionally, RTCA (2007) states the responsibilities of the UAS operator.

1.2 GOALS AND OBJECTIVES.

This report systematically examines journals, technical publications, government reports, government agencies, and industry sources to identify DSA systems or related systems that have a benefit to aviation safety and are under development or can be adopted for use in UASs.

The FAA maintains the safe air transportation system. The potential introduction of UAS into the National Airspace System (NAS) is a new type of aircraft system with an undetermined level of risk and no regulatory framework (Hottman, et al., 2001). All aviation systems in the NAS have a see and avoid requirement (14 CFR 91.113). This study provides a review of the state-of-the-art of technologies that could help support the definition of DSA requirements for UAS. This information allows better understanding of a critical enabling technology for eventual UAS NAS access from both a technical and eventually a regulatory requirement perspective.

1.3 INVESTIGATIVE TEAM.

The CGAR team consisted of representatives from the University of Alaska, the University of North Dakota, and the NMSU/PSL subcontractor.

1.4 REPORT CONTENT.

This report provides a review of the technologies currently being used in DSA systems as well as an overview of emerging technologies. Along with a description of how each technology detects and makes avoidance decisions, advantages and disadvantages of each system are discussed. While it is possible that any one of these extant or emerging technologies will provide the equivalent level of safety as outlined by F2411-04e1 or the RTCA (2007), it is probable that technologies will be used concurrently to meet standards.

2. THE DSA SYSTEMS ENGINEERING REVIEW APPROACH.

The authors developed a detailed functional allocation of a DSA system. Information sources included formal literature along with DSA-related NAS and special use airspace (SUA) surrogate and UAS flight demonstrations.

A detailed problem statement came from the Statement of Work and functional requirements, which are listed below.

- Define DSA criteria for UAS using recent technical reports, FAA, and RTCA publications

- Review potential technologies/methods to meet the DSA criteria

- Evaluate DSA requirements for facilitating UAS NAS integration

- Identify qualitative tradeoffs using size, weight, and power (SWaP) for DSA technologies/methods by general UAS class

- Separate/identify near- and mid-term DSA solutions

- Assess the overall utility of single-use and multiple-approach solutions

This problem statement provided the review team with a common set of criteria for the literature review. Although the focus for the review was UAS operation in the NAS, the reviewers recognize that benefits for SUA also will occur.

The decomposition of the requirements then was expanded, relying on a number of assumptions. Since a priori, the system was not defined as noncooperative, the technology could be communicating with both the operator (pilot-in-command) and perhaps other aircraft. The technology is expected to be robust enough to pass an FAA Technical Standard Order process for UAS certification. The system could ultimately be totally autonomous realizing that the

levels of automation could increase over time to a higher autonomous state. Table 1 contains an expansion of the five general functions.

Table 1. Requirements for DSA Systems

Function No.	Function	Requirements	Detect	Sense	Avoid
1.0	Detect conflicting traffic	• Continuously scan for threats	×		
		• Minimizes false alarms	×		
		• Minimizes misses		×	
		• Provides operator threat data		×	×
		• Covers a field of view of 110° horizontal and ±15° azimuth	×		
		• Tracks all threats within a minimum range		×	
		• Determines closure rates		×	
2.0	Determine Right of Way	• Autonomously makes move in accordance with (IAW) FAA/International Civil Aviation Organization (ICAO) regulations			×
		• Operator makes move IAW FAA/ICAO regulations			×
3.0	Analyze Flight Paths	• Determines if target is heading toward danger zone (maintain 500-foot separation)		×	
		• Calculate flight paths based on sensors available information		×	
		• Updates time available for maneuver		×	×
4.0	Maneuver	• Maneuver IAW FAA guidelines			×
		• Allows operator maneuver			×
		• Maneuvers continuously in loss link/loss of command control (C^2)			×
		• Maintains at least 500-foot separation		×	×
		• Returns to original flight path after maneuver		×	
5.0	Communicate	• Continuously reports to ground system; allows operator override		×	×
		• Available bandwidth exists to carry message packets		×	×
		• May use stand-alone telemetry or platform communications		×	×
		• Priority communication to maintain safety of flight		×	
		• Reports targets when threat parameters are met; updates solution until no longer a target		×	×

3. TERMINOLOGY OF DSA.

3.1 HISTORY OF SEE AND AVOID RULEMAKING.

UAS operations in the NAS present a unique challenge to the application of the 14 CFR, which historically envisioned a pilot in the cockpit. The following discussion is a brief historical review of the Visual Flight Rules (VFR) and their basic underlying concept, generally referred to as "see and be seen." Further, the development of the regulations, some case law defining those regulations, and the duty placed on the aircraft operator (historically a pilot) will be reviewed under a second concept. This second concept is a pilot's duty of vigilance, which is to "see and avoid" other aircraft.

Substantive federal participation in the regulation of aviation began with passage of the Air Commerce Act of 1926. This act followed an era of generally unregulated flying that resulted in a rate of 1 fatality per 13,500 hours. In contrast, earlier self-regulation of airmail by the post office experienced only one fatality per 463,000 hours (Adamski and Doyle, 2005). Congress recognized that regulatory oversight would pay dividends, and the Air Commerce Act became welcome law.

For the next 12 years, regulations promulgated under this act put requirements in place for licensing and registration of aircraft, certification and medical qualification of pilots, and penalties to encourage compliance. Also important, these earliest regulations embraced the concept of "see and be seen," which remains the cornerstone of the VFR. Unfortunately, though evidence of the "see and be seen" concept is clear, the use of this phrase has not been used in rulemaking. During this time, agency rulemaking was in its infancy, and the regulatory process and its recordkeeping was weak at best.

By the mid-1930s, it was recognized that this needed to change, and an aviation accident highlighted this need. An accident led to the death of a prominent New Mexico senator. The airline argued that the applicable regulations for air transportation operations were improperly promulgated and were not in force. A Bureau of Air Commerce search for the original copy of the contested rule was unsuccessful. Unfortunately, this was not an isolated instance. In other instances, unsigned copies were all that were located (Adamski and Doyle, 2005). This and other examples of regulatory shortcomings led to the enactment of the Federal Register Act, (Pub. L. 74-220, 49 Stat. 500 (1935)). What were found in the regulations were provisions embracing this concept. For example, the 1937 regulations promulgated under the Air Commerce Act contained numerous provisions relating to VFR operations.

These regulations quickly recognized the impact of weather on the ability for pilots to see other aircraft, and vice versa. Accordingly, ceiling and visibility minimums were established for controlled zones (the traditional 1000 feet and 3 miles was put in place), as well as areas outside these early controlled zones (2 Fed. Reg. 2181, 2184, 1937). Section 60.6, prescribed the intensity of aircraft lighting to ensure adequate visibility (2 Fed. Reg. 2188, 1937). Side lighting was to be visible for at least 2 miles and rear light visible for at least 3 miles. These regulations clearly directed themselves to the "see and be seen" concept and were designed to provide aircraft separation by visual means. In addition to supporting the "see and be seen" aspect, these early regulations imposed a duty on the pilot to be vigilant to "avoid" other aircraft. Specifically,

right-of-way provisions governed which aircraft had the right-of-way during various stages of flight, including during landing, overtaking, or approaching other aircraft (2 Fed. Reg. 2183-2184, 1937).

In 1938, Congress passed the Civil Aeronautics Act of 1938. This act created a separate entity to regulate aviation and included economic regulation of airlines serving a developing passenger industry. Rulemaking under the newly created Civil Aeronautics Authority, later the Civil Aeronautics Board (CAB), continued to recognize the importance of "see and be seen" in the separation of VFR aircraft. In its 1945 amendments to the air traffic rules, the concept was further enhanced with the introduction of cruising altitudes (10 Fed. Reg. 5066, 1945). While the "see and be seen" concept is clearly recognized, the phrase itself had yet to be used in the narrative of formal rulemaking.

The first identified use of the phrase "see and be seen" was found in the preamble to a 1955 rulemaking of the CAB, which stated that "[t]he philosophy behind the Visual flight Rules is that aircraft being flown in accordance with these rules are operated in "see and be seen" weather conditions permitting the pilots to observe and avoid other traffic" (19 Fed. Reg. 6871, 1954). However, the language of the actual rule uses the term "observe and avoid" under section 60.12, Careless or reckless operation (20 Fed. Reg. 6694, 1955). This is a clear pronouncement of a pilot's duty to be vigilant to observe and avoid other aircraft, and failure to do so could constitute careless or reckless operation of an aircraft.

This 1955 phrase "observe and avoid" establishes both the concept behind the VFR (see and be seen) as well as the duty placed on the pilot (observe and avoid). The FAA and its predecessors, the CAB, did not treat this duty lightly. In an early 1950 decision by the U.S. Court of Appeals for the District of Columbia, the court affirmed a CAB decision to suspend the airmen certificate of an Eastern Airlines captain for failure to maintain a proper lookout and colliding with an aircraft he was overtaking (Kahn v. CAB, 1949). The captain argued that the Douglas DC-3 he was overtaking was obscured by a windshield post that created a blind spot. The court refused to accept that a visual deficiency excuses a pilot from his or her duty to maintain a proper lookout. The pilot was expected to move his or her head or body to cope with an obstruction, or at least put the copilot on a heightened lookout. The pilot's duty of vigilance was not excused by this aircraft design limitation.

The duty of vigilance also has arisen in the context of a flight-testing accident. Uniquely, the circumstances of that accident and its remedy closely resemble UAS operations. During flight testing, the pilot can be preoccupied with cockpit duties, which require his or her eyes to be in the cockpit. The result is a compromise of the ability to "see and avoid" other aircraft (22 Fed. Reg. 2575, 1957). Here, the duty of vigilance to see and avoid other aircraft was not excused by the nature of flight operations. Instead, the regulation provides that careless or reckless operation of an aircraft may be found when pilot duties inside the cockpit preclude looking outside, unless the operation compensates for this reduced vigilance by use of an onboard observer, a chase aircraft, or another equivalent arrangement (22 Fed. Reg. 2576, 1957). Clearly, a duty of vigilance is expected of any aircraft operator, whether the operator is a pilot performing test-related duties inside the cockpit but not looking outside, or a pilot operating the aircraft from a

remote location, in the case of a UAS. If this duty cannot be met by the operator, an alternative arrangement is required to compensate for the compromised duty of vigilance.

In 1968, the FAA, having established the new Part 91 from the earlier Part 60 of the Civil Aviation Regulations, published an amendment in the Federal Register to specifically reconfirm that it is the pilot's responsibility to ". . .maintain vigilance so as to see and avoid other aircraft when weather conditions permit" (33 Fed. Reg. 10505, 1968). The amended 14 CFR 91.67(a) (now 14 CFR 91.113(b)), clearly required that each person operating an aircraft under VFR or Instrument Flight Rules (IFR), weather permitting, had a duty to be vigilant to see and avoid, and to give way to other aircraft in accordance with the right-of-way rules of section 14 CFR 91.113. Importantly, this regulation does not excuse pilots who are operating under positive control or instrument flight rules from the duty to be vigilant. Even if operations are under IFR, if operating in visual metrological conditions, operators must see and avoid other aircraft.

The phrase "each person operating" contained in 14 CFR 91.113(b) carries considerable weight. Under 14 CFR 1.1, the term operate "…means use, cause to be used, or authorize to use aircraft, for the purpose…of air navigation including the piloting of aircraft, with or without the right of legal control (as owner, lessee, or otherwise)" (14 CFR 1.1, 2005). This definition appears sufficiently broad to easily encompass UAS operations.

The CFRs have a specific part set aside for the operation of moored balloons, kites, unmanned rockets, and unmanned free balloons (14 CFR Part 101, 2005). However, there is no counterpart for unmanned aircraft. Until recently, the only document directed at unmanned airplanes, was Advisory Circular 91.57, dated June 9, 1981, a one-page guide addressing operating standards for model aircraft. In September 2005, the FAA issued a memorandum entitled "AFS-400 UAS Policy 05-01." This latest policy guidance is to be used by the FAA to determine if a UAS may be allowed to operate in the NAS. It also acknowledges the problem UAS operations have complying with the duty to "see and avoid" other aircraft. Regardless of these problems, it is clear the FAA is committed to this concept, and operations in the NAS that fall short of this mandate will not be authorized, including UAS operations.

3.2 PILOT'S SEE AND AVOID ROLE.

A pilot has defined responsibilities while in command of an aircraft as detailed in the CFRs and the Aeronautical Information Manual (AIM). One responsibility is DSA, which, in the absence of a pilot on an aircraft (UAS), must be accomplished by a technology solution or a human observer external to the UAS (RTCA, 2007). To help understand DSA, the pilot's see and avoid operational responsibility and requirements are discussed. A direct relationship exists for the UAS DSA function, whether autonomous or with an operator or monitor in the loop.

With the current emergence of UAS operating in the NAS, numerous debates have occurred discussing how they apply in reference to 14 CFR Part 91.113 Right-of-way rules: Except water operations. This regulation 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." Section 14 CFR 91.113 goes on to describe right-of-way rules as they apply to aircraft in distress, converging, approaching head-on, overtaking, and landing.

Seeing and avoiding other aircraft is an extremely difficult perceptual-cognitive task and is no small feat for the average general aviation pilot flying in today's operating environment (AIM, 2006). The general aviation pilot must be a master of many tasks. The pilots must be able to ensure the safety of their aircraft in accordance with 14 CFR 91.113 noted above, monitor flight and engine instruments, tune radios and communicate, tune navigational equipment, read maps and navigate, and fly the aircraft. Many pilots now fly with portable global positioning system (GPS) devices. Although, these devices have provided an increased sense of situational awareness, they also have placed another demand on the pilot and have taken the pilot's attention from outside the aircraft to inside the aircraft. Most pilots realize that they cannot be totally reliable at seeing and avoiding aircraft, contrary to FAA requirements. Therefore, they rely on established procedures to ensure they maintain separation from other aircraft (e.g., East-West altitudes, landing approach patterns, etc.). It seems likely that UASs have the potential to do a better job than human pilots who must rely primarily on visual identification, communication, and operational procedures to avoid other aircraft.

The AIM (2006) discusses several "see and avoid" factors in Chapter 8, Sections 1-6, Vision in Flight. The AIM reiterates that scanning the sky for other aircraft is a key factor in collision avoidance, but acknowledges the fact that the pilot must split time between a visual scan of the surrounding airspace as well as inside the cockpit monitoring flight and engine instruments. Use of a copilot and/or passenger in the right seat adds additional capability to the "see and avoid" task. The AIM further cites that the time a pilot spends on visual tasks inside the cockpit should represent no more than a 1/4 to 1/3 of the time spent scanning for traffic outside the cockpit. This equates to 4 to 5 seconds inside for every 16 seconds outside.

The AIM (2006) also describes a visual scanning technique in which the pilot centers attention on a very small area that focuses the scan to a portion of the eye called the fovea. This allows the eye to send clear, sharply focused messages to the brain. The AIM cites an example in which an aircraft appears in sharp focus at 7 miles within the foveal center of vision, but would have to be less than 1 mile away to be recognized if outside of foveal vision. This technique of foveal scan is only effective if the pilot learns to scan the surrounding airspace in 10° intervals for at least 1 second (AIM, 2006, Sec. 8-1-6). Foveal scanning might be effective while flying straight and level in clear air, but that is also when other aircraft are usually rare. While ascending or descending, which usually takes place in the vicinity of airports, the pilot is engaged in a large variety of activities, and the workload is high. However, this is also when other aircraft are most likely to be present (also ascending or descending) and when avoiding collisions are most likely.

Other sources and information are relevant to the DSA activity. The following are administrative approaches that address the enhanced detectability of a UAS.

- NOTAMs—UAS operations outside of restricted and warning areas are required to issue a Notice to Airmen (NOTAM) for the area and times they intend to conduct operations. A thorough preflight review of the NOTAMs will alert a pilot of possible UAS operations within his or her proposed flight route (current FAA Certificate of Authorization or Waiver (COA) requirement).

- AWOS/ASOS/ATIS—Many UAS operators coordinate with local airport authorities to have the information discussed above in the NOTAM recorded on the local Automated Weather Observing System/Automated Surface Observing System/Automated Terminal Information Service (AWOS/ASOS/ATIS) broadcast (Las Cruces, New Mexico Airport Manager's Practice [Technical Analysis and Applications Center (TAAC), 2006]).

- Flight Following—All UAS operations require the use of a transponder with a discreet code. This code is easily identified by Air Route Traffic Control Center (ARTCC) and/or approach control radar. Pilots requesting flight following can expect to receive VFR traffic avoidance to assist with "see and avoid" (AIM, 2006).

- Passengers—Pilots should include a preflight brief to passengers to scan for traffic, proper terminology to identify suspect aircraft, and scanning techniques (AIM, 2006).

- Giving way—Pilots should not assume that the UAS can see them. If pilots are close to another aircraft, they are expected to give way even if they have the right-of-way (14 CFR 91.113).

- Education—Many UAS pilots are also general aviation pilots. It is recommended that pilots seek out these UAS pilots and learn about their UASs, flight procedures, and safety concerns.

3.3 THE UAS DSA.

COAs currently being issued by the FAA state:

> UAS have no on-board pilot to perform see-and-avoid responsibilities, and therefore, when operating outside of Restricted, Prohibited or Warning Areas, special provisions must be made to ensure an equivalent level of safety exists for operations had a pilot been on board. In accordance with 14 CFR Part 91, General Operating and Flight Rules, Subpart J-Waivers, 91.903, Policy and Procedures, the following provisions provide acceptable mitigation of 14 CFR Part 91.113 and must be complied with:
>
> - Visual Observers, either ground-based or airborne, must be used.
>
> - The applicant and/or its representatives are responsible for collision avoidance with all aircraft, other aviation operations, and the safety of persons or property on the surface.

The act, process, or specified performance for detecting and sensing something in the NAS appears to be potentially simplistically defined. To detect is to ascertain that there is something in the airspace. By detecting, it does not imply that the object has been identified. It could be a large bird nearby, a balloon far away, or an aircraft in a head-on course. For this report, the operating definition of detect, from a UAS, is to determine through some technology (including the human visual system) that something is in the airspace.

The act of sensing is the determination that the object in the airspace is or is not a threat or target to the UAS. Visibility models, such as those shown in figure 1, are relevant to how well an individual or a sensor may be able to detect or sense an object in the airspace. Once detection has happened, a series of algorithms are likely performing numerous calculations to make the decision as to whether or not the detected item is a threat. Part of this process can be compared to what the human operator does when he or she performs a see and avoid function. Table 2 shows a comparison between the human and an autonomous system. Note that in figure 2, part of the decision that is required is the declaration that the detected item is a threat, it is in the airspace, and it is on a potential collision course. Lastly, avoidance is the act of moving the UAS from its flight path to a new heading/altitude and then returning to its original course once a declaration is no longer calculated on a sensed object.
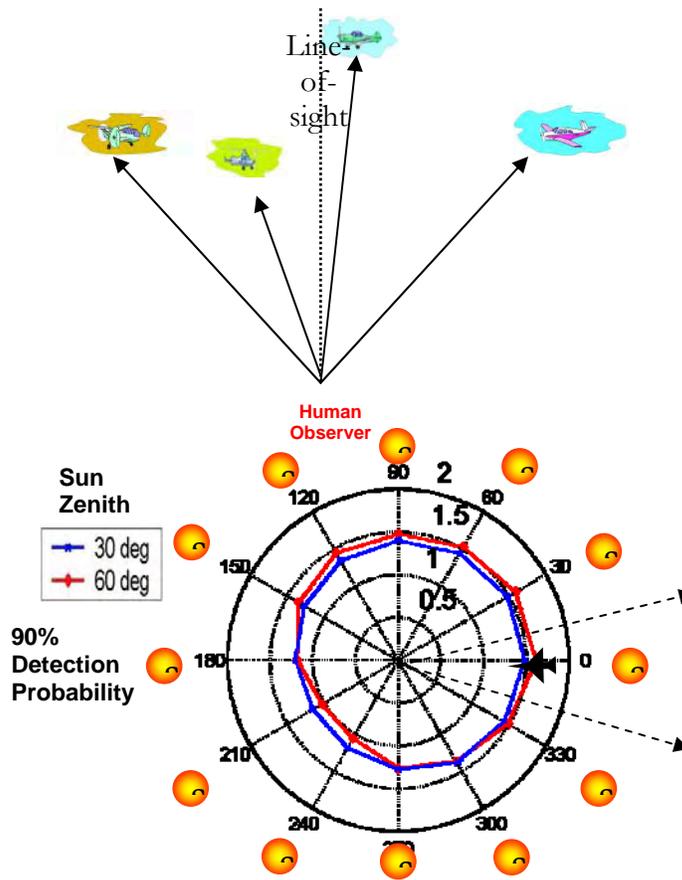
Figure 1. Range and Response Analysis

Table 2. Comparison of Human and Autonomous Systems

Detection Range Requirements (Nautical Miles)				
Scenario (Altitude)	"Manned" RQ-4	Actual RQ-4		
	Nominal Pilot	AUTONOMOUS	LOS	BLOS
Low	2.6	1.1	1.8	1.9
Medium	4.2	1.8	2.9	3.1
High	5.7	2.8	4.1	4.3

LOS = Line-of-sight
BLOS = Beyond line-of-sight
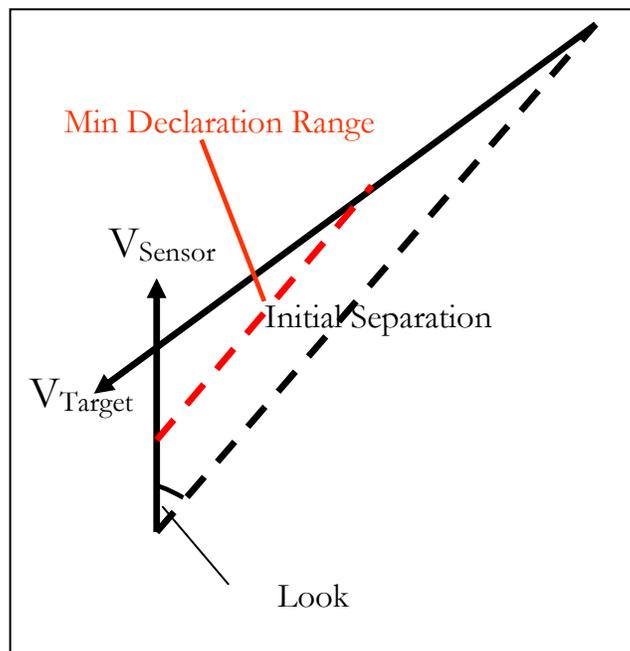
Figure 2. Declaration Decision

Considerable debate exists on how well a DSA system needs to quantitatively function. Figure 3 shows an aircraft with 360° of airspace highlighted around it. The FAA states that an equivalent level of safety to the human pilot onboard an aircraft must be provided by a DSA system for a UAS. However, technology far surpasses the human capability. Is 360° needed, or is a moving half-doughnut shape in front of the UAS sufficient? Is a back-looking view necessary for an overtaking aircraft? Although a DSA system may be described with specifications that exceed the capability of the pilot onboard an aircraft, that same technology migrated back to aircraft with the pilot onboard will have positive safety implications for the NAS.
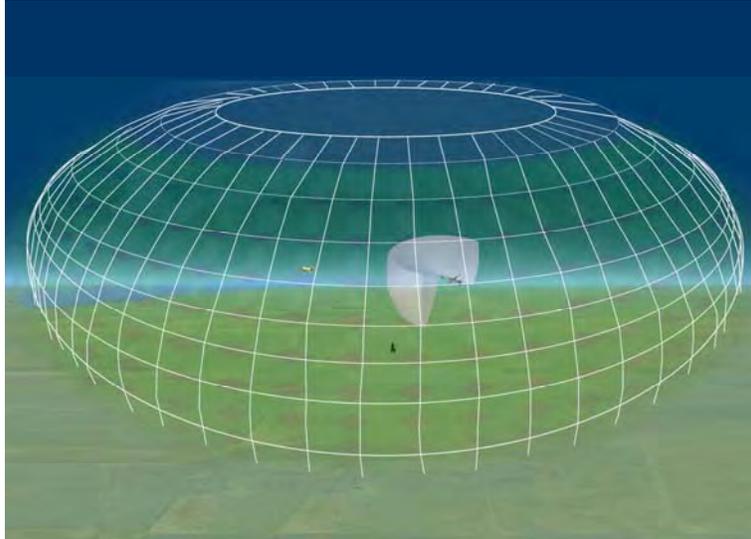
Figure 3. How Much Coverage is Required?

Understanding that DSA has many dimensions, as discussed above, the definition provided in the recent RTCA (2007) UAS publication defines "see and avoid" as:

> The ability of a pilot to see traffic which may be a conflict, evaluate flight paths, determine traffic right-of-way, and maneuver to avoid the traffic. 14 CFR 91.113 directs that "vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft."

A shortened version of the definition and text is:

- detect—is something there?
- sense—is it a threat/target?
- avoid—maneuver to miss.

4. SIGNAL DETECTION APPROACH FOR DSA.

4.1 INTRODUCTION.

The sensitivity of a DSA technology is important so that one will know what will possibly be detected in the NAS and what exists operating in the UAS airspace. The DSA technology should not be designed such that a large number of false targets are inappropriately detected, nor should the sensitivity of the system miss the real targets. Signal detection, then, is an approach to identify and characterize the performance of the sensor system and also to define part of its operating characteristics.

Signal detection theory (SDT) evolved with the development of radar and communications equipment in the early part of the 20th century. In an attempt to understand the human sensory perception system, psychologists grasped upon the model to help describe human behavior when detecting faint or ambiguous stimuli that could not be explained using traditional threshold

theories. A solid foundation was laid by Green and Swets (1966) with their seminal book, "Signal Detection Theory and Psychophysics."

The most logical starting point for any examination of SDT is that there is nearly always some degree of uncertainty in any task requiring reasoning or decision making. For the case of DSA and UAS, the sensors and algorithms as analogous to a decision-making process will be considered. By providing graphic notation and a precise language, SDT allows for the analysis of decision making under uncertainty. A basic assumption of SDT is that the decision maker is not merely a passive receiver of information, but rather an active presence in the environment.

An example of this would be as follows: A person is presented with a stimulus (or signal) that is ambiguous or faint. The difficulty facing this person, causing uncertainty, is that there are any number of other agents present that are similar to the stimulus (or noise). Noise generally falls into one of two categories: external and internal. External noise is noise present in the observer's environment. Examples of external noise could be fog that would serve to partially obscure vision or protective headphones that dampen the strength of an auditory signal. Internal noise is noise created from the observer's own sensory systems in terms of neural responses. Fatigue, drug use, or even blood pressure in a human could be causes of internal noise.

When in this situation, the observer must make a decision—was the signal present or absent? If the signal was indeed present, this judgment leads to either a hit or a miss. If the signal was not present, the observer's decision can lead to either a false alarm or a correct rejection. The four possible outcomes of this decision are commonly presented in a table similar to figure 4.

		Signal	
		Present	Absent
Decision	Present	Hit	False Alarm
	Absent	Miss	Correct Rejection

Figure 4. Outcome of the Presence or Absence of a Signal

To more fully understand SDT, a more complete understanding must be gained in each component of which it is comprised. In the following sections, the Response Bias (Beta or ß), Response Criterion, and Discriminability (d-prime or d′) will be discussed in greater detail.

4.2 RESPONSE BIAS AND RESPONSE CRITERION.

Those studying SDT commonly use a pair of distribution curves, to graphically represent signal, noise, and their relation to one another. An example of these distribution curves is shown in figure 5.
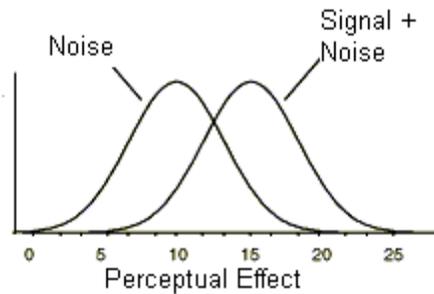
Note:
- The curve on the left represents that signal detection is due to noise alone.
- The curve on the right represents that signal detection is due to the presence of the signal.
- The point where the two signals intersect indicates the point where there is an equal probability that signal detection is due to either the noise or the signal.
- The overlapped area represents where either a false alarm or a miss occurs.

Figure 5. The SDT Distribution Curves

The response bias is a level set by the observer based upon any number of factors, depending upon the situation and the consequences of the outcome. If the sensory input exceeds ß, the observer will say "yes, there is a signal." If it fails to exceed ß, the observer will say, "no, there is no signal." The observer may adopt any one of three basic response criterions, each with its own implications and consequences.

With a neutral bias (or perhaps more accurately, no bias, as shown in figure 6), the ß level is at or about 1.0. There is an equal probability of getting either a false alarm or a miss. This would represent a situation where there are equal consequences for getting either a hit or a miss.
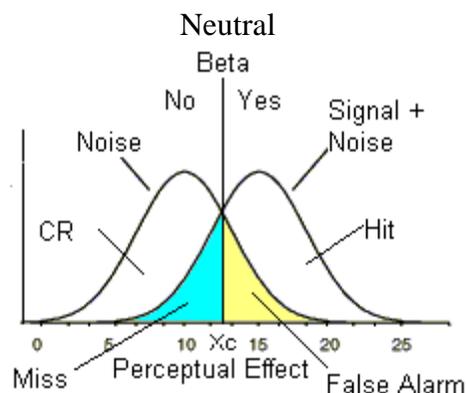
Figure 6. Neutral Beta Strategy

With a conservative bias (as shown in figure 7), ß is set at a level greater than 1.0. The observer is more inclined to say, "no, there is no signal," leading to a lower number of hits and a higher number of misses, but a fewer number of false alarms. A conservative bias would likely be adopted in situations where the consequences for a false alarm outweigh the rewards of getting a hit. An example of this can be found in the criminal justice system. It is thought to be better for

13

a guilty person to go free (a miss) than for an innocent person to be convicted of a crime they did not commit (a false alarm).
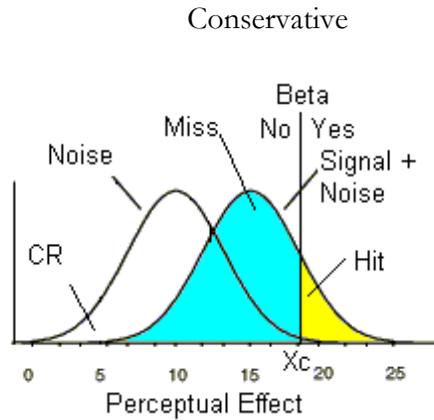
Conservative

Figure 7. Conservative Beta Strategy

The ß level for those with a liberal bias is set to lower than 1.0. The observer is more inclined to say, "yes, there is a signal," leading to a lower number of misses and a higher number of hits, but also a higher number of false alarms. A liberal bias (depicted in figure 8) would likely be adopted in situations where the consequences of failing to detect a hit outweigh the consequences of a false alarm. A typical example of this would be airport security screeners being more likely to search a scanned piece of luggage if there is anything even remotely suspicious (a false alarm) rather than take the risk that a dangerous object might be brought on board an airplane (a miss).
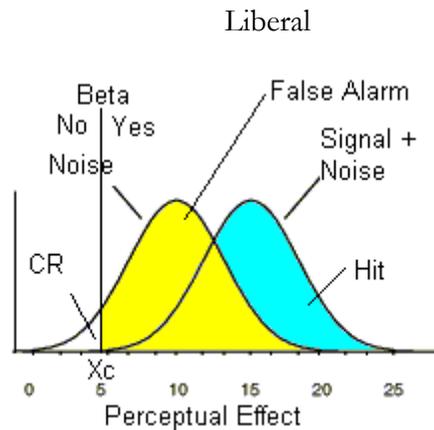
Liberal

Figure 8. Liberal Beta Strategy

4.3 DISCRIMINABILITY.

The standard deviation of the noise distribution is the basis for measuring the distance between the means of the noise and signal distributions. Measurements of the hit and false alarm rates can be used to estimate discriminability (or d'), as shown in figure 9. A higher d' indicates a greater amount of sensitivity on the part of the observer that leads to greater ability to detect the signal.
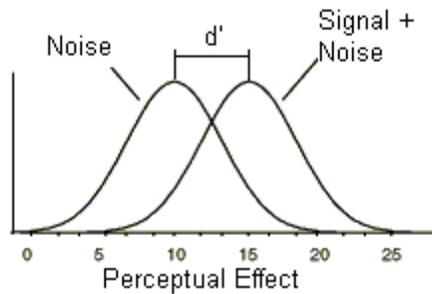
Figure 9. Discriminability

The greater the distance between the two means, the higher value of d′, indicating a greater level of sensitivity on the part of the observer.

As d′ and the level of sensitivity of the observer increase, so does the probability of making an error. Keeping in mind that the area of overlap between the two distribution curves (figure 10) represents the probability of error, it is readily apparent that the area of overlap decreases as d′ gets larger, reducing the chance that an error will occur.
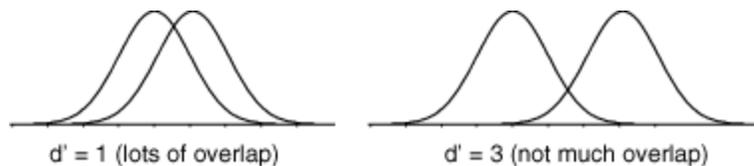
Figure 10. Discriminability and Sensitivity

4.4 SUMMARY OF SDT.

A DSA system should be conservative in its generation but with sufficient discriminability to not overwhelm the DSA processor. A DSA technology, that in part replicates the pilot's actions on board the aircraft, can have its sensitivity and other features described by SDT. SDT should be considered as a tool or method to communicate about different technology attributes related to DSA.

5. THE DSA TECHNOLOGY REVIEW.

The two types of technologies reviewed relative to performing a DSA function on the UAS are cooperative and noncooperative. The discussion of noncooperative systems includes active and passive sensor systems. Additionally, alternate approaches are described to enhance the visibility of the UAS.

15

5.1 COOPERATIVE TECHNOLOGIES.

5.1.1 Traffic Alert and Collision Avoidance System.

Collision avoidance is a primary concern to the FAA regarding aircraft safety (AIM, 2006). UASs are seen as potential key airspace users in the future of air transportation, which necessitates additional research and study of safety measures for DSA.

Currently, the traffic alert and collision avoidance system (TCAS) is the primary cooperative collision avoidance system and is in use by a variety of airspace users. TCAS transmits information via a transponder. The black box relays information back-and-forth and to-and-from other aircraft with a transponder to avoid collision with the aircraft. Simply, all aircraft designed with the transponder permit for communication with other aircraft. On the other hand, aircraft without a transponder may not recognize when other transponder aircraft are near, which may result in conflict. In sum, the transponder coordinates air traffic between other transponder-equipped air traffic, which "lets other air-traffic know their intent" (Wolfe, 2006) of air travel.

A major design issue of UAS is that any black box is additional weight, and weight restrictions for some smaller UASs may restrict UAS functionality or the inclusion of cooperative systems (RTCA, 2007). Although it seems plausible that the TCAS III is the forerunner in TCAS, another issue may be in integrating the UAS TCAS III auditory transmission into the remote location. In fact, verbal communication between operators, ground pilots, and air traffic control is difficult to comprehend and should first be mastered before adding a fourth dimension of communication between the UAS automation system and the UAS operators. Further issues with this system include imperfect or unreliable system automation. For an example of imperfect system automation, see Doyle and Bruno, 2006.

5.1.2 Automatic Dependent Surveillance-Broadcast.

Automatic dependent surveillance-broadcast (ADS-B) is a relatively new technology that allows both pilots and ground-based stations to detect other similarly equipped aircraft in the airspace with much more precision than previously has been possible. Making use of the satellite-based GPS, ADS-B determines an aircraft's precise position. The aircraft's position, along with other information such as altitude, speed, flight number, type of aircraft, and whether it's turning, climbing, or descending, are then converted to a digital code. This digital code, which is updated as frequently as several times per second, is then broadcast via a discrete frequency via a datalink through a universal access transceiver. Ground stations and other aircraft within about a 150-mile radius can receive these datalinks, which are then displayed on computer monitors in a user-friendly format. Pilots are able to see a representation of these datalink signals on a cockpit display of traffic information. Ground-based stations can use regular traffic display screens to see ADS-B targets in addition to other radar targets (Garmin, 2007).

ADS-B has several advantages, many of which are relevant for UAS DSA applications (Garmin, 2007; Hidley, 2006; Sensis, 2006a; and Sensis, 2006b):

- ADS-B allows pilots and ground-control personnel access to more accurate and reliable traffic information, which is updated on a near-constant basis.

- Pilots and ground-control personnel will not only be able to see the current position of other aircraft, but also the speed, heading, and altitude. As these variables change, ADS-B provides immediate information as to whether other air traffic is climbing, descending, turning, or accelerating.

- ADS-B provides pilots with far more information than was previously available to them. Because of ADS-B's wide range (near 150 miles), more time is available for conflict detection and resolution than with other systems.

- ADS-B improves approaches and separation standards in bad weather or low-visibility situations by providing ground controllers much more information than traditional radar technology.

- Because it makes use of satellite technology, ADS-B is effective even in areas where radar is unavailable or ineffective.

- The technology used in ADS-B can be scaled and adapted not only to improve safety in the air, but also on the ground, providing effective surveillance on runways and taxiways.

- Through automation, ADS-B can provide further levels of safety through such features as warnings of imminent runway collision and automatic traffic call-outs.

- Because it uses proven digital communication technology, ADS-B can be implemented more rapidly than developing technologies and at a much lower cost.

- ADS-B allows for more rapid and effective search and rescue operations.

- ADS-B datalinks can be used by general aviation to receive flight information services, such as flight advisories and graphical weather updates, which were previously cost prohibitive for broad use in general aviation.

- ADS-B allows for a very flexible software structure, ensuring an ability for adaptation and incorporation of future technologies.

At the forefront of ADS-B technology is the joint industry and FAA initiative being conducted in Alaska known as Capstone. For almost 7 years, the Capstone program has been working to improve aviation safety in Alaska, a region with very limited radar coverage. The Capstone program has reduced the accident rate, and has provided invaluable data necessary for moving forward with a national program. Implementation of ADS-B in other parts of the United States is underway or planned.

5.1.3 Traffic Advisory System.

The traffic advisory systems process limited amounts of information via a cooperative system design. These systems are somewhat outdated and provide limited knowledge regarding air traffic information. This is similar to the TCAS I because they provide information to the pilot when the intruder aircraft is within a certain time of collision (Wolfe, 2006). Although some

technologies are advancing to provide more information, TCAS is the more accepted product of use and, thus, should be recognized as superior (especially the TCAS III) and should be considered first when selecting collision avoidance (CA) systems for UAS and other aircraft.

5.1.4 Implications of Using Cooperative Technologies on UAS.

Cooperative technologies are widely used in manned aircraft and have a reliable track record in regards to reducing the number of midair collisions. When considering the use of cooperative technologies in UAS sense and avoid (SAA) systems, the advantages of their use must be weighed against the disadvantages inherent in such a unique flight environment.

The very fact that cooperative technologies have been used for some time in piloted aircraft leads to a couple of important advantages. The first and most obvious advantage is that these are established technologies and have proven to be reliable systems. These systems are less prone to unexpected results that might lead to a failure in the SAA system. Additionally, most of these systems have already been certified and approved for use. The current cooperative technologies have gone through their trial phase and have proven themselves though years of service.

Perhaps not quite as apparent, but at least as important to consider, are the disadvantages of relying on cooperative technologies for UAS SAA systems. These systems tend to be cost prohibitive for some users. Another consideration is that cooperative technologies only work when all aircraft that share airspace possess and use them. In addition, cooperative technologies provide no SAA capabilities against collisions with ground-based obstacles such as terrain features, towers, or power lines. However, modern GPS does provide location data for ground-based obstacles. While not an element of a cooperative DSA technology, the rapid advance in GPS technologies generally provides accurate information for terrain and obstacle avoidance. Perhaps negating the advantage of using an already established and certified system is the fact that these technologies were developed assuming that a human operator would be in the loop, verifying warnings, and taking the appropriate measures to avoid collision. If these technologies were to be modified for use in UAS, recertification would most likely be needed to be certain that the equivalent level of safety was maintained.

5.2 NONCOOPERATIVE TECHNOLOGIES.

Some promising technologies that are being investigated for use in UAS SAA systems are noncooperative technologies, which do not rely on other aircraft possessing cooperative technology. These technologies include radar, laser, motion-detection, electro-optical (EO), and infrared (IR). These technologies differ from cooperative technologies because they do not require usage by other aircraft sharing the same airspace to avoid collisions. Noncooperative technologies benefit from the fact that they can be used to detect ground-based obstacles as well as those that are airborne. These noncooperative technologies can be divided into two basic systems: active and passive. Active systems transmit a signal to detect obstacles in the flight path. Some examples of these active systems are radar and laser. Passive systems do not transmit a signal, but rather rely upon the detection of signals emanating from the obstacles themselves. Motion-detection, EO, and IR systems are all examples of passive systems.

5.2.1 Active Systems.

5.2.1.1 Radar.

Radar is an active detection system that operates in a similar fashion to sonar, but uses waves in the electromagnetic spectrum, rather than sound waves. Differences in the time of arrival of the reflected radar signal create variations in waves which, when combined, can create an image of objects.

Currently in use, and of particular value to UAS (especially for ground-based objects) due to their small size, is the synthetic aperture radar (SAR). This technology uses a calculated integration of multiple radar pulses to create an image much greater than could be achieved with normal radar. SAR is unique to aerial vehicles because it relies on the movement of the aerial vehicle to record data. In essence, the movement of the vehicle creates a synthetic aperture, or window, through which pulses can be sent and collected. Without movement, a very large antenna would be needed to gather the returning frequencies. The distance traveled by the vehicle acts as the synthetic aperture. The result is a miniaturization of the needed antenna, and finer resolution than with normal radar (Sandia National Laboratories, 2005). As well, low-frequency SAR has the capacity to penetrate foliage and certain depths of soil.

Applications and abilities of SAR technology currently are being developed and improved (Sandia National Laboratories, 2005). These include three-dimensional (3-D) SAR, which uses more than one antenna to create a 3-D image, and change detection, which looks for changes in ground objects by comparing images from separate passes of the same area. A new application is the ability of SAR to be used for motion detection. This application can determine the location, speed, and size of moving ground targets.

Radar systems are ideal for situations when normal optical vision is occluded due to weather or lack of light, such as nighttime. The radar pulses can penetrate through storms and other inclement conditions, delivering an accurate image of the terrain. Disadvantages include the large size of traditional radar systems, the high cost of radar, and the fact that radar technologies do not offer the degree of real-time imagery that a standard EO system would.

These radar systems appear to be relevant to the issues of SAA in terms of avoiding obstacles in the landscape and can be used to avoid the risk of all types of midair collisions. Some radar technologies are focused primarily on ground imagery. While this downward focus may not be important when cruising, it may be of importance during landing and takeoff, because the majority of midair collisions occur within 3 miles of airports, with 50% being below 1000-feet altitude (Narinder and Wiegmann, 2001).

5.2.1.2 Laser.

The recent decision by the Danish Air Force to equip its Elicottero Helicopter Industries-01 (EH101) Search and Rescue Helicopters with the SELEX Communications Laser Obstacle Avoidance and Monitoring (LOAM®) system has pushed laser technology to the forefront of SAA solutions (The Society of British Aerospace Companies, 2006). It was announced that Lockheed-Martin will be working in collaboration with SELEX on new SAA solutions for

civilian and military applications, including the U.S. Army's Utility Helicopter-60 (UH-60) Black Hawk (Lockheed Martin, 2005). Though it currently is being employed primarily on rotary-wing platform aircraft, the potential for cross-platform usage in UAS is readily apparent.

Laser systems, such as LOAM, use eye-safe lasers operating similar to that of conventional radar systems. Laser scans of the immediate airspace are taken at regular intervals and processed through echo-analysis software. Obstacles in the flight path of the aircraft result in a warning, alerting operators to the hazard (SELEX Communications, 2006). While a UAS does not have the benefit of human operators to respond to these alerts, standardized avoidance protocol software based upon established FAA regulations could be created to avoid collisions in the absence of a pilot.

Other applications currently employing laser detection systems include those manufactured by Sick Inc., of Minneapolis, Minnesota, for Automated Guided Vehicles (AGV). These systems use optical sensors that scan the immediate area with IR lasers. Upon detecting an obstacle based upon reflected light, the sensor system signals the AGV to reduce speed or stop, if necessary, to avoid collision without making contact. These systems can add significantly to the cost of the AGV; users cite reduced maintenance costs, increased productivity, and lower accident rates as overwhelmingly sufficient compensation (Iversen, 2006).

There are many benefits to laser-based SAA systems. Due to the nature of lasers themselves, the scan beams are of sufficient return power to detect even nonperpendicular surfaces at a high resolution. Additionally, in conjunction with echo analysis software, laser systems can differentiate between several different types of obstacles such as perpendicular objects like poles and trees, wires up to 5 mm in diameter, and large obstacles such as buildings and bridges (SELEX Communications, 2006). Laser systems are also highly configurable, allowing them to compensate for varying atmospheric conditions. This leads to system optimization and an elimination of the probability of false signal detection. This low false alarm rate, along with high scan resolution, makes laser systems both comprehensive and efficient.

5.2.1.3 Sonar.

The use of sonar technology in UAS SAA systems is not ideal due to the nature of sound as a medium of detection (Lee, et al., 2004). Sonar only works in close proximity to the UAS. Sonar originally was developed for use as an active underwater detection system. In this system, sounds, which are referred to as pings, are transmitted, and an image is formed based on the time it takes for the echo of the sound to return to the sensors. Due to issues of stealth, a passive sonar system has been developed that uses detection of sound information already present underwater. Nevertheless, the application of sonar to aircraft is unreasonable because sound does not travel fast enough through air to be detected accurately by a moving aircraft. In fact, sonar is more adept in water because sound travels faster in water than in air. As well, variations in temperature can affect the speed of sound greatly, and atmospheric temperature is far more variable than temperature variation in the sea. Thus, sonar is better suited for its original application, underwater.

5.2.2 Passive Systems.

Appendix D contains an entire case study of the development of a passive noncooperative SAA system for the DoD. This technology is also usable by civil UAS and provides a near-term solution for DSA.

5.2.2.1 Motion Detection.

Typical motion detectors in use by consumers for security purposes simply detect the presence of movement, but motion detection technologies for aircraft are designed to sense direction and velocity of specific objects in the sensing field. Current technologies are varied, but most used the same basic principles. The basic format of the technology is to use multiple cameras placed at different angles to create multiple views that, when combined, can allow for calculation of object vectors (Shah, et al., 2006). In other words, the images are compared to each other and, when certain pixel difference thresholds are met, a vector is calculated for movement. The challenge of motion detection in these technologies is the fact that the UAS itself is moving. Due to this challenge, numerous companies, laboratories, and academics have developed their own formulas and algorithms to deal with making the distinction between the movement of one's own plane and the nature of the movement of objects it is detecting (Lee, et al., 2004; Netter and Franceschini, 2004; Nordberg, et al., 2002; Shah, et al., 2006). In effect, these algorithms cancel the movement of the UAS, including movement based on vehicle trajectory, as well for vibrations from the UAS. Also, numerous formulas have been developed that make the sensors able to identify objects based on physical characteristics and vectors to deal with occlusions (appendix D).

An emerging technology uses biotechnology with the eyes of flying insects as a model for sensing (Netter and Franceschini, 2004). This technology is referred to as neuromorphic motion detection, and attempts to copy the optical flow that is used by flying insects. Optical flow in insect eyes detects relative motion of contrasts through multiple eye sensors called lenslets. The combined contrast data of the lenslets creates patterns that are discerned as movement. For the signals from the lenslets to be perceived accurately, cells in the medulla of the insects, called elementary motion detectors (EMD), compute the velocity of the contrasts. Researchers have duplicated these EMDs electronically and connected them to photoreceptors to create a contrast-oriented visual system of motion detection.

5.2.2.2 Electro-Optical.

EO systems are IR-type sensors that require light for detecting objects. However, EO cannot detect target intensity and rate of change of target intensity, whereas IR sensors can. Nonetheless, EO algorithms make it so that the visual display of the images show differences with regards to night and day viewing, whereas the IR sensor does not. The major overall drawback to the EO system is that light is required for these systems to operate; with an IR system, light is not required.

Currently, Australian planners are discussing future radar systems that permit the use of a particular radar and EO system working simultaneously (Kopp, 2007). The name of this system is the active electronically scanned array (AESA) radar-based system. Although AESA is

radar-based, it allows the EO system to scan and record imagery while the radar is shifting through its various modes. Another feature of the AESA is that the surveillance sensors can be transformed to reconnaissance sensors by simply modifying the code. The pitfalls of a system such as this are that the UAS is required to have a payload weight of 3000 lb and a minimum airspeed of 200 knots. Additionally, there would be need for large areas of antenna separation, because essentially these UASs also would be considered low-flying satellites.

5.2.2.3 Infrared.

Many UAS platforms use IR technology on their payloads that detect heat in two forms: white-hot objects (WHO) and black-hot objects (BHO). IR requires heat from an object for object detection, which is most beneficial for night-time use. The BHO and WHO systems rely on the principle that objects that emit heat are colored black and white on the monitor, respectively. Further, for the WHO view, objects that do not emit any heat are colored black; and with the BHO view, objects that do not emit heat are gray and light gray. These onboard sensors have been considered a possible tool for DSA. Research and application in UAS IR technology refers to air-to-ground surveillance and reconnaissance, which relays information from the ground to the UAS, and then to the UAS operator. For instance, with border control issues, night surveillance by humans is almost impossible given the amount of area that needs to be covered. However, border surveillance in Arizona operations has benefited from UAS (with IR sensors) use with an increase in drug seizures and capture of illegal immigrants.

5.2.2.4 Acoustic.

Scientific Applications and Research Associates, Inc. (SARA) developed a compact acoustic sensor system for use on small UASs, as shown in figure 11. The Passive Acoustic Noncooperative Collision Alert System (PANCAS) provides a means of detecting aircraft on a collision course by detecting and tracking the sound of their engines, propellers, or (helicopter) rotors. The PANCAS sensor array consists of a number of microphones mounted in a configuration to provide bearing information for sound at each frequency. The microphone array takes advantage of phase differences at the microphones to determine bearing angle in both azimuth and elevation. Based on a geometric analysis, if both the UAS and opposing aircraft are traveling at constant speed, regardless of range or bearing angle, a collision will occur only if the bearing rate of change is 0. However, bearing measurement will include fixed and random error sources from atmospheric effects, the effects of winds, and signal processing errors. A proprietary algorithm is applied to determine a threshold decision on whether the target is on a collision course, and to minimize false alarms in the presence of signal error sources. Since the system is able to detect potential collisions from all aspects in azimuth and elevation, coverage is available even for scenarios where a piloted aircraft would be blind to other air traffic and for potential collisions where an aircraft is overtaken from behind (Milkie, 2006).
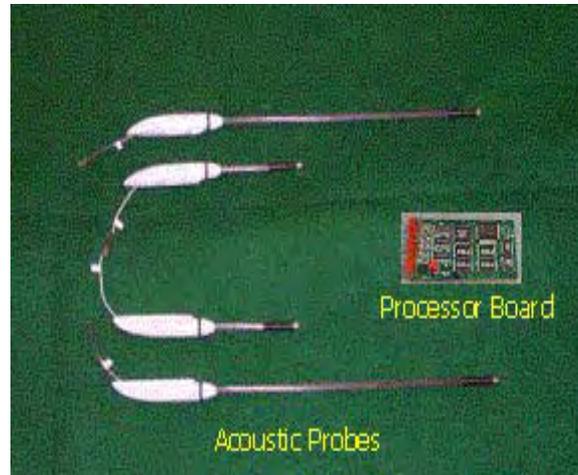
Figure 11. The Pancas Acoustic Sensor Probes and Signal Processor

5.2.3 Passive Systems and Ranging.

Traditionally, a passive system in a simplistic application may not be thought of as having significant ranging capabilities. Several papers described making minimal position movement of the UAS that can result in helping to produce ranging information.

An intriguing concept of determining range with a passive EO sensor was proposed in an Air Force Research Laboratory (AFRL) report (Raska, 2004) in November 2004. The assumption is that the fixed sensor is on a UAS avoiding collisions with noncooperative objects, on a steady course, in the near airspace. On detecting the target, the UAS maneuvers to establish a baseline and allow the EO sensor processor to calculate angles and determine a range to the target by triangulation. This type of processing and vehicle control technique combined with some active sensors, like in the Stanford 2005 Defense Advanced Research Projects Agency (DARPA) Challenge Vehicle (Stanford, 2005), would appear to efficiently fill a gap in detecting noncooperative aircraft and, at the same time, making a UAS maneuver that lessens the chance of collision and provides more data to make further safe decisions.

A paper describing resolution requirements for passive SAA maneuvers (Grilley, 2005) provides many details needed to determine what type of baseline maneuver might be made and which timing consideration is needed to also process a range solution by triangulation.

A theoretical paper presented in August (Kim, et al., 2007) has the potential of contributing to the issue of eliminating UAS overtaking collisions with noncooperative targets. The paper pertains to cars or ground vehicles and presumes that range data to the vehicle being overtaken is available. With a UAS in this situation, overtaking another aircraft at the same altitude, making a maneuver to determine range with a passive EO sensor would potentially avoid the collision and simultaneously provide range data to the target vehicle.

The recent literature does not reveal whether the passive ranging concept described in the AFRL November 2004 report was implemented and/or tested since that time.

5.3 ADAPTING TECHNOLOGIES.

A variety of technologies that were not originally developed specifically for DSA may be adapted to solve the DSA issue. A few examples are listed here; note that not all technologies were originally airborne applications.

Using the concept of the compound eye of a fly, the Swiss created an optical sensor to avoid fixed obstacle collisions with a very small UAS (Zufferey and Floreano, 2006). This is a unique and relatively simple adaptation of a biological sensor for a very small UAS. The simplicity of the sensor and the minimal processing requirement would appear to make this type of sensor very attractive in a fusion autonomous sensor system for helicopters or UASs flying within visual range of the ground or ground-based structures.

The multi-sensor-based 2005 DARPA Challenge Vehicle (Stanford, 2005) produced by the Stanford Intelligence Laboratory also provide technologies and processing algorithms applicable for UAVs flying close to the ground and needing autonomous DSA capability.

The most innovative use of existing technology for a different purpose was found in the Brigham Young University Multiple Agent Intelligent Coordination and Control (MAGICC) UAS (Saunders, et al., 2005; McLain, 2004), where an optical computer mouse sensor was adapted to provide a collision avoidance function on a small lightweight autonomous UAS. This team also used a commercial video camera sensor and a commercial range finding laser for a fusion sensor system in special purpose, small, light-weight UASs. The unique aspect of these sensors and their use in UASs demonstrated the likelihood of a wide range of currently commercially available sensors and technologies from science research, the medical fields, household appliances, and manufacturing for specific applications in the field of DSA with smaller UASs.

5.4 THE DSA DEMONSTRATION AND TESTING.

The variety of sensors, technologies, and concepts for DSA recently demonstrated or tested covers a broad area of academia and industry. The Advanced Technologies Testing Aircraft System (ATTAS) (Friehmelt, 2003) is a full-sized commercial jet used in Germany in a "pseudo-UAV" mode to test and analyze systems and procedures. The aircraft can house a wide range of systems to test or exercise both for UAS flight applications and DSA applications. The optionally piloted aircraft called the Proteus, is a similarly sized vehicle used in the U.S. for the Skywatch (Wolfe, 2002a; Wolfe, 2002b; Hottman, 2004) tests. On the other side of the size spectrum is the 30-gram UAS flown by the Swiss (Zufferey and Floreano, 2006), which tests the ability of a very simple optical sensor to enable this vehicle to avoid obstacles.

For their acoustic-based DSA system, SARA has collected acoustic signatures from a number of general aviation piston-engine aircraft and typical turbine-powered helicopters. Sound at low frequencies has little atmospheric absorption, so an R-squared reduction with range was modeled in a number of collision scenarios, using acoustic signal levels and self-noise levels from actual test data. The range at which detection occurs was computed in the worst-case scenario, with aircraft traveling head-on at maximum speed. This range was further decreased due to the effect of the small time delay for the sound to reach the UAS. A 3-second allowance was also provided for data computation and decision time and time for the flight computer to initiate (but not

complete) a flight maneuver. The remaining time before collision is available for the execution of the avoidance maneuver. The results of these calculations for a number of cases are presented in table 3 (Milkie, 2006). The data reveal that detection is achieved with considerable warning time expected by small UASs.

Table 3. Time Available to Execute an Avoidance Maneuver

UAS Type	UAS Cruise Speed (kts)	Approaching Aircraft Type	Aircraft Speed (kts)	Range When Sound Reaches UAS (m)	(Head on) Time for Maneuver (s)
MiTEX BUSTER	40	UH-60 Black Hawk	155	6030	57.2
MiTEX BUSTER	40	UH-60 Black Hawk	78	6980	112.1
MiTEX BUSTER	40	UH-60 Black Hawk	0	7950	383.7
MiTEX BUSTER	40	Cessna 172	120	3640	41.3
L-3 Tern	50	UH-60 Black Hawk	155	1380	10.1
L-3 Tern	50	UH-60 Black Hawk	78	1560	20.7
L-3 Tern	50	UH-60 Black Hawk	0	1780	66.3
L-3 Tern	50	Cessna 172	120	814	6.3

The AFRL EO system described in a number of papers (Utt, et al., 2002; Utt, 2003; McCalmont and Utt, 2005; McCalmont, et al., 2005; Utt, et al., 2005; Copeland and Hill, 2005) has gone through a full developmental period resulting in a sensor system suitable for integration into one of the United States Air Force High-Altitude Long Endurance (HALE) UASs in the near future. Although the AFRL EO System does not meet the full set of requirements for a DSA system for UASs flying in the U.S. NAS, it lessens the risk of collision during the operation of this vehicle.

In academia, with support from federal funding, Brigham Young University has developed and successfully flown small UASs with innovative commercially available sensors (Sauders, et al., 2005; Theunissen, et al., 2005), which will peak the interest of developers of DSA systems. The sensors and algorithms used by these university students illustrate novel approaches toward addressing the DSA issues.

The Stanford Artificial Intelligence Laboratory (Stanford, 2005) multisensored and sophisticated 2005 DARPA Challenge Vehicle successfully demonstrated the ability to DSA in a ground-based exercise with potential applications to UASs. This vehicle required input from several sensors being processed in a system combining these data and a vehicle objective to autonomously navigate from point to point.

Another academic project demonstrating DSA application was the Carnegie Mellon University autonomous helicopter using a TI-C40-based vision system for autonomous operation. While limited in capability, the potential of this system is apparent for enhanced applications in UASs.

The Sense-and-Avoid Display System (SAVDS) active ground-based radar system (Zajkowski, et al., 2006) is an existing system with a computer-driven display system suitable for certain small UAS applications to monitor and detect aircraft within a limited range and altitude. While this type of system is not suitable for autonomous UAS operations, it has been demonstrated to provide a DSA function for ground-based operators of UASs.

The sensors and systems demonstrated for DSA in UASs have been primarily based on single types of sensors. Several papers (Taylor, 2005; Suwal, et al., 2005; Flint, et al., 2004) have described concepts of multisensor systems and a mixture of cooperative and noncooperative systems to provide a fuller spectrum of DSA capability. While these types of systems have not yet been demonstrated, or at least papers have not yet reported on any test or demonstration results, it appears that for large UASs to operate safely within the U.S. NAS from takeoff to 60,000 feet, no single type of sensor likely will provide adequate DSA coverage. Demonstration and testing of multisensor systems also will require GPS and other information to adequately collect data for performance analysis.

A review of all the work being performed to test and demonstrate DSA systems, as found by this literature search, illustrates the fact that the performance standards of any DSA systems vary greatly with the performance specifications of the UAS. Additionally, there are no baseline performance standards for any UAS DSA system flying in the NAS, nor is there any laboratory or testing area with calibrated support systems to unambiguously provide data on systems performance. The development of DoD weapons systems has required the advent of highly instrumented ranges to collect performance data. The analysis and development of DSA systems for UASs require these same types of resources.

5.5 ALTERNATE APPROACHES TO VISIBILITY.

So far, this report has focused on technology that can be applied directly onto the UAS platform, for instance, cooperative or noncooperative technologies. However, other technology approaches that are not located on the aircraft or perhaps procedural approaches should also be given some consideration that may either enhance the visibility or the awareness that the UAS is in the NAS.

The DoD has had a number of research and aircraft application programs that can be characterized as low observable. That is, the specific design, materials, or countermeasures were employed to make the aircraft less visible to radar systems. In addition, the DoD has identified paint schemes that make detection by the human visual system difficult. For UAS operating in the NAS (especially considering civil, non-law enforcement mission), the desired state of a UAS is not low observable.

Whether observability is enhanced or processes and procedures are implemented, the goal of DSA is to increase the likelihood of detecting and sensing the UAS. Sections 5.5.1-5.5.4 describe candidate approaches including increasing the radar cross section, increasing the visual

discrimination of the aircraft, ground-based radar systems, and processes and procedures related to air traffic.

5.5.1 Electromagnetic Visibility Enhancement.

A premier Federal organization that understands radar visibility of aircraft is the National Radar Test Facility (NRTF) located within the 46th Test Group at Holloman Air Force Base, New Mexico. The NRTF is tasked with characterizing the radar visibility of DoD aircraft using a variety of large electromagnetic test equipment on several size ranges. At times, the DoD goal is to minimize, or at least understand, the aircraft cross section. For civil UAS, the goal is to increase the cross section for a particular platform without adversely adding to external geometry. Simplistic approaches to impacting the radar detectability are to minimize the use of any radar absorbent material, add reflective edges internal to the platform, and, when not adversely impacting the aerodynamics, include designs that are more radar visible.

5.5.2 Visibility Enhancements.

The DoD also has considerable expertise in developing and applying camouflage paint schemes on aircraft. This painting approach can be optimized for geography and other environmental factors if desired. Considering the optical encounter (OPEC) model discussion in section D.2.1 of appendix D of this report, the detectability of a UAS potentially can be impacted by its paint scheme.   Therefore, a consideration to aid the detection of UAS is to suggest that the manufacturers include paint schemes that visibility models indicate provide earlier detection, sensing, or identification.

In addition to paint schemes, optimized lightning may also potentially provide a greater awareness of the UAS platform to other airspace users. The FAA now requires UAS to operate with lights onboard the platform. However, do the various platforms under operation today use aircraft-specific lighting, and if so, is its location in concert with general aviation practices? The best or brightest lighting with the appropriate transmitting field of view could help the visible detection of the UAS platform to the human or certain types of DSA sensors.

5.5.3 Ground-Based Radar.

5.5.3.1 The SAVDS and Sentinel.

Radar coverage from the ground is primarily used for secondary track of the aircraft. Until 2004, ground-based radar was allowed by the FAA as a means to perform the SAA function for UAS flights in the NAS. An example of newer development in ground-based radar applications is the SAVDS, integrated with certified, high-performance, ground-based Air Defense Radar Systems such as the Sentinel manufactured by ThalesRaytheonSystems (TRS).

The Sentinel is a highly mobile, high-performance X-Band pulse Doppler radar (figure 12) using advanced 3-D pencil beam antenna technology. With precision tracking of 0.2° angle accuracy and a scan rate of 2 sec (30 rpm), the Sentinel provides 360° surveillance volume coverage of all airborne targets, with a 45-mile detection range over a -10° to +55° elevation range.

Figure 12. Transportable TRS Sentinel Radar

The SAVDS is an integrated hardware and software system that fuses location and state vector data streams from ground-based radar and UAS ground control stations in real-time for immediate viewing on high-definition displays. Georeferenced background maps that correspond to the area of radar coverage are overlain by colored icons that show the location and ground heading of the UAS in relation to the radar target returns. The tracks of the UAS and the radar-detected airborne vehicles persist on the display to show their flight paths (figure 13). An adjoining elevation profile display window shows the flight heights of the UAS and the radar-detected targets.
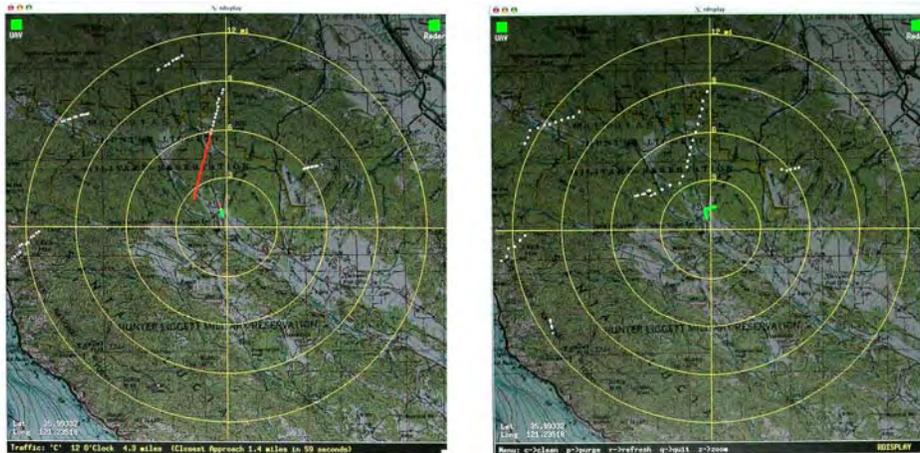
Figure 13. The SAVDS Showing Air Traffic Conflict Detection and Abatement

With the SAVDS display colocated at the UAS ground control station, the UAS operator is immediately warned of the need to change the UAS flight path to maintain safe separation distances. The SAVDS automatically provides visual and audible proximity warnings of any potential air traffic conflict. These warnings provide the UAS operator with the situational awareness needed to safely perform conflict avoidance maneuvers.

5.5.3.1.1 Validation Program.

SAVDS, Inc. and TRS are actively engaged in a Validation Program that is systematically demonstrating and documenting the functionality of the SAVDS-Sentinel System. This program

is driven by the growing need to satisfy the FAA's equivalent level of safety SAA requirement for UAS operations in the NAS. The current FAA requirement for UAS flights beyond the visual range of the UAS operator is either ground observers or chase aircraft.

The Validation Program is divided into four phases: Phase 1 (completed in December 2006) involved simulated UAS flight and live SAVDS-Sentinel detection of manned aircraft. Phase 2 (completed in April 2007) involved actual UAV flight and live SAVDS-Sentinel deconfliction with manned aircraft compared to deconfliction recommendations from ground observers. Phase 3 (currently in progress) involves actual UAS flight and live Sentinel-SAVDS deconfliction with all airborne vehicles (manned aircraft, hot air balloons, ultralights, and gliders) compared to deconfliction recommendations from a chase aircraft. The strategy for Phase 4 will involve working with the FAA, compiling and analyzing the results of Phases 1-3, and providing the documentation and additional validation testing needed for system certification.

The Validation Program, thus far, has demonstrated that the SAVDS-Sentinel detection of approaching air traffic is more effective than technologies that only provide a forward-looking view comparable to a pilot's cockpit-based eyes. Frontal views (120º laterally, 20º vertically) from inside the cockpit may not provide UAS operators with adequate air traffic detection range. SAVDS-Sentinel provides UAS operators with the capability of viewing the entire range of front, side, rear, above, and below conflicts with airborne vehicles.

5.5.3.2 Ground-Plane Array.

Another example of ground-based radar has been proposed by the UND (Tribune, 2007). UND's proposal is to use a network of ground-based, phased-array radar systems in a triangular area roughly from Nekoma to Devils Lake to Lakota, North Dakota. The intention is to use this network of digitally steered radars to provide a comprehensive situational awareness of all objects flying within the covered area. The multiple radar systems will provide a 3-D solution, and the inherent capability of phased-array systems will provide a much larger area of simultaneous coverage. UND researchers claim that this system will eliminate the need to use airborne visual observers to realize an effective SAA capability.

5.5.4 Processes and Procedures for Visibility Enhancement.

Today, for many aircraft operations (e.g., high-speed, low-altitude, military training routes) where there would be no opportunity to detect and sense the low speed or other unique noncooperative aircraft, procedures do exist to protect other airspace users. These procedures are primarily based upon segregation that provides a mechanical separation of the airspace users. This could mean that UASs are encouraged or required to operate in certain prescribed routes for high-density traffic flow between airports. Although free flight concepts will bring greater autonomy to pilots, the notion of UAS routes (similar to jet ways) would be a procedure for, in part, segregating UAS traffic.

Research also has been accomplished in the past with investigating ways to inform air traffic control personnel that a particular aircraft in their sector is a UAS. Hottman and Sortland (2006) modified data blocks and the flight progress strip to add information to the controllers so they understood (in the simulations) that something unique existed regarding these particular aircraft

(UAS). This methodology of providing information to the controller that the aircraft was a UAS (and the type) was no different from informing air traffic control personnel that a conventional aircraft was a "heavy" (thus, having a slower airspeed than expected) or the specific type of an engine on a Boeing 737, because the engine version translated to a slower or faster aircraft.

5.6 SUMMARY.

To safely operate UASs in the NAS and to minimize the risk of midair collisions, UAS operators must be able to detect and track air traffic to a level of safety equal to or better than that required by the FAA Document 7610.4 K "Special Military Operations" and 14 CFR Part 91. Most manned general aviation aircraft, which operate under VFR and lack collision avoidance systems, rely on the pilot's eyesight and radio contact with air traffic controllers to track approaching airborne vehicles.

Equipping UASs with TCAS transponders to communicate with other transponder-equipped aircraft reduces the possibility of midair collisions; however, TCAS reduces conflict only with cooperative aircraft. Noncooperative aircraft that are not equipped with CA transponders continue to pose a significant risk when flying under VFR. For this reason, UAS operators must be equipped with an SAA system that can locate and track both cooperative and noncooperative airborne vehicles at sufficient range to maintain safe separation distances.

Table 4 offers a summary of the technology approaches that have been discussed. The color green indicates where the particular technology would satisfy the individual DSA requirement (e.g., instrument meteorological conditions (IMC), day, night, etc.), and the color yellow is where short falls exist.

Table 4. Technology Attributes for DSA

Technology	Detects Noncoop Targets	Discerns Range	Detects in IMC	Day/ Night	Detects Multiple Targets	Full Time	Multiple Sectors	Detection Rng, NM	Constant Azimuth Issue	Co-alt Issue	Supports Due Regard	Asym Covert	Sym Covert
Search													
EO	Yes	No	No	No	??	Yes	Yes	4?	Yes	No	No	Yes	Yes
Human Visual	Yes	No	No	No	No	No	No	2	Yes	No	Yes	Yes	Yes
IR Search and Trk	Yes	Yes	No	Yes	Yes	Yes	Yes	22+	No	Yes	??	Yes	Yes
Passive IR	Yes	No	No	Yes	Yes	Yes	Yes	22+	No	Yes	Yes	Yes	Yes
Radar	Yes	Yes	Yes	Yes	Yes	Yes	Yes	22+	No	No	Yes	Yes	No
Cooperative Surveillance													
TCAS/ACAS	No	Yes	Yes	Yes	Yes	Yes	Yes	22+	No	No	No	Yes	No
ADS-B	No	Yes	Yes	Yes	Yes	Yes	Yes	22+	No	No	No	Yes	No

Notes: With onboard processing, search technologies may be able to disseminate resolved targets across C2 links. TCAS is a related but separate requirement. ADS-B is in a demonstration phase of development.

Cooperative technologies for DSA have been developed, tested, and are fielded. The best examples of cooperative technologies are TCAS and ADS-B. These technologies have been developed for manned aircraft with direct applicability for DSA but with capability for unmanned aircraft systems.

Some airspace users, such as aircraft, parachutists, and balloons, may not have cooperative or functional systems onboard. Additionally, ground-based threats to aircraft also exist. In those cases, a noncooperative technology will be required to detect, sense, and avoid these other airspace users although modern GPS dutifully can provide information for terrain avoidance.

Cooperative technologies applicable to UAS have an inherent SWaP. Depending on the SWaP requirement to operate the cooperative system, this technology may not be applicable to smaller UASs.

There are multiple constraints on noncooperative systems, including environmental, SWaP, and operational. These constraints limit the application of a particular technology based upon the size or class of the UAS. For instance, IMC places an operational limitation on EO technology, whereas day or night places no such restriction. The SWaP on a radar system is generally much higher than technologies such as a camera-based system. Operational limitations also are imposed by the existing design of UASs, which may not accommodate an additional system due to space or configuration. Additional weight could affect center of gravity of aerodynamics, and excess power capacity may not be available.

Additional visibility approaches were discussed that did not involve adding a technology to the actual UAS platform. Examples included paint schemes, lighting, and increasing the radar observability of the platform. Also, segregation of the UAS in the airspace may have value. Notifying air traffic controllers through the data block or flight progress strips would also raise the awareness of the type of airspace user.

One single approach may not be adequate for the DSA requirement on a UAS. Where the UAS is operated, its size, and the SWaP of the technology, along with the technology capabilities should be considered when determining a DSA suite.

The vocabulary associated with signal detection theory, such as the number of false hits and sensitivity of the system, will provide a mechanism to communicate among constituents and users on part of the DSA specification or requirement.

6. RECOMMENDATIONS FOR FUTURE RESEARCH.

The investigators recommend a number of further actions.

- Tangential technologies were not reviewed in depth. These technologies should be further examined for potential applications, perhaps specifically by UAS class.

- A DSA specification should be developed and endorsed by the FAA. Considerable work has been accomplished on candidate systems, but developers and manufacturers require minimal performance thresholds. In developing a specification, both cooperative and noncooperative technologies need to be considered, as well as mixes of those technologies.

- A variety of technologies have been demonstrated on UAS including cooperative and noncooperative as well as ground-based radar. Upcoming demonstrations are planned and should be observed by FAA management, researchers, and contractors to more fully understand the DSA function for UAS. Existing system performance mapped to candidate DSA specifications may also help perform "reality checks" between technology capability and the DSA for the human onboard a manned aircraft.

- A number of DSA specific and related research and development activities are ongoing within the USA and internationally. This study should be maintained to collect new information to maintain currency. Additionally, literature reporting DSA information that is older than 2-3 years should be updated so that the state-of-the-art for the particular application or technology is known.

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Zufferey, J.-C. and D. Floreano (2006), "Fly-Inspired Visual Steering of an Ultralight Indoor Aircraft," *IEEE Transactions on Robotics*, Vol. 22, No. 1.

APPENDIX A—INVESTIGATIVE TEAM

Stephen Hottman—New Mexico State University/Physical Science Laboratory
      Associate Dean for R&D
      Director, UAS Technical Analysis and Applications Center
      PhD in process, Engineering Psychology, New Mexico State University
      MS Industrial Engineering, Texas A&M University
      BS Psychology, Texas A&M University
      Certified Human Factors Practioner
      30 years optimizing human performance in systems
      Current lead on research and applications of UAS: operator requirements, trust in
          automation, see-and-avoid integration and demos, reliability and availability,
          handling qualities, integration to NAS
      Teach Aviation Psychology

Kathryn Hansen—Arrowhead Center, owned by NMSU
      Chief Financial Officer
      PhD coursework Ag Economics, Texas A&M University
      MA Sociology UTEP
      BA Sociology UTEP
      Deputy Director of Aerospace and Autonomous Systems Laboratory, NMSU
      Environmental Research Aircraft Sensor Technology UAV project manager coordinating
          regulatory roadmap and issue papers
      Coordinator of UAS TAAC Conference
      Economic development, technology maturation and transfer focused on unmanned
          systems and other aerospace platforms with domain expertise to New Mexico
      Support State level technology pursuits including National Lab involvement

Dr. James McDonald—PI—New Mexico State University
      Head, Department of Psychology
          Teaches courses in Aviation Psychology, Human Computer Interaction,
          Experimental Methodology, Statistics, History of Psychology
      PhD in Engineering Psychology
      Extensive experience in Human Factors, Usability, and basic Cognitive research
          Human Factors Engineer, IBM
          Vice President Interlink, Inc.
             Software development
          Vice President ThoughtWare Solutions, Inc.
             Usability research for hi-tech companies such as HP, IBM, Cisco, Oracle,
             Microsoft, and Intel
      Private Pilot certification

Bawcom

Michael Berry—New Mexico State University
      Research Assistant, Physical Science Laboratory

BA Psychology, New Mexico State University

Leonard Kirk—PI—University of Alaska, Anchorage
      Assistant Director, Aviation Technology Division
      Capstone Coordinator
      Program Development Specialist
      Over 40 years of comprehensive aviation experience
            Pilot, Chief Pilot
            Director Flight Operations,
            Dispatcher
            Coordinator Planner
            Director of Training
            Operations Management
            Vice President of Operations and Maintenance for FAR 121 Air Carrier
      Airman Ratings:
            Commercial Pilot #1649203   Airplane, Single Engine Land & Sea
                                    Airplane, Multi-engine Land Instrument Airplane
            Flight Instructor Certificate # CFI1649203
            Ground Instructor Certificate # 568624362
            Aircraft Dispatcher Certificate # 568624362
            Designated Examiner for Aircraft Dispatcher
      Specialized Aviation Education:
            Boeing Commercial Airplane Company, Seattle, Washington
            Operations Engineer
            Performance Engineer

George Frushour—University of Alaska, Anchorage
      Research Analyst, Aviation Technology Division
      BS Engineering Management, United States Air Force Academy, Colorado
      MA International Relations, University of Southern California, London Campus
      40 Years in Aviation
            FAA Air Transport Pilot Rating (SEL/SES/MEL)
            FAA Flight Instructor (SE/ME/INST)
            FAA A&P with IA
            Aviation operations analysis and planning
            Aviation facility analysis and planning
            Aviation/Airport Management
            Aviation Security Management

Doug Marshall—University of North Dakota
      Associate Professor
      Director, UAS Program Development
      Director, Aviation Graduate Program
      BS Political Science, University of California, Santa Barbara
      JD Law, University of California Hastings, College of Law
      28 Years Law Profession

20 Years Representing Major Airlines
Counsel in Major Air Disaster Litigation
FAA Enforcement Matters
President, Regional Airline
9 Years Teaching Aviation Management, Economics and Law Courses
Commercial/Instrument Rated Pilot

Ben Trapnell—University of North Dakota
Assistant Professor
Director, UAS Technology Integration and Education
BS Physical Science, United States Naval Academy, Annapolis, Maryland
MAS Aeronautical Science, Embry Riddle Aeronautical University
Graduate, Aviation Safety Programs Management, Naval Postgraduate School, Monterey, California
Naval Aviator, Carrier Aircraft Plane Commander, Aviation Safety Officer, Squadron Landing Signal Officer

APPENDIX B—DEVELOPERS

The following organizations are involved in research and/or development of detect-, sense-, and avoid-related systems.

Radar

Amphitech Systems, Inc. (http://www.amphitech.com/english/index.html)
Customer Support
Amphitech Systems Inc.
3440 Francis-Hughes, Suite 120
Laval, Quebec, Canada H7L 5A9
Telephone: (450) 663-4554
Toll free: 1-866-657-4554
Fax: (450) 663-7134
abrowne@amphitech.com
Published Papers
http://www.amphitech.com/english/product/uav-papers.html
Product Specifications
http://www.amphitech.com/english/product/uav-dsa.html

Flight Safety Technologies (http://www.flysafetech.com/)
Mystic, Connecticut Headquarters
28 Cottrell Street
Mystic, CT 06355
Phone (860) 245-0191
North Kingstown, Rhode Island
1130 Ten Rod Road, E102
North Kingstown, RI 02852
Contact:
http://www.flysafetech.com/contact/onlineForm.asp
UNICORN™ System Description
http://www.flysafetech.com/advancing_technologies/unicorn.asp
Product Specifications
http://www.flysafetech.com/images/customer-files/FST-UNICORN-website-v3.pdf

General Atomics Aeronautical Systems (http://www.ga-asi.com/index.php)
Aircraft Systems Group:
General Atomics Aeronautical Systems, Inc.
16761 Via Del Campo Ct.
San Diego, CA 92127 USA
(858) 455-2810
(858) 455-4247 (fax)
Reconnaissance Systems Group:
13322 Evening Creek Drive North
San Diego, CA 92128
(858) 964-6700

pr-asi@uav.com
Product Specifications
http://www.ga-asi.com/products/lynxSAR.php

Sandia National Laboratories (http://www.sandia.gov/)
Sandia media contact:
Chris Burroughs, coburro@sandia.gov, (505) 844-0948
Sandia technical contact:
Kurt Sorensen, kwsoren@sandia.gov , (505) 845-9583
News Releases
http://www.sandia.gov/news-center/news-releases/2004/def-nonprolif-sec/minisar.html
http://www.sandia.gov/radar/sarapps.html

Telephonics (http://www.telephonics.com/index.asp)
Command Systems Division
Phone: (631) 755-7569
Fax: (631) 755-7644
Email: CommandSystems@telephonics.com

Obstacle Awareness and Collision Avoidance Radar Sensor System for Low-Altitude Flying Smart UAV
http://ieeexplore.ieee.org/iel5/9579/30281/01390837.pdf
Young K Kwag and Jung W Kang, Avionics Dept. AERC, Hanhk Aviation University, Seoul, Korea

Laser/LADAR
Elbit Systems Electro-Optics ELOP Ltd. (http://www.el-op.com)
Headquarters
Advanced Technology Park
P.O. Box 1165
Rehovot 76111, Israel
Tel: 972-8-9386211
Fax: 972-8-9386237
lasers@el-op.com
ODAM Obstacles Detection and Avoidance Module Info:
http://www.el-op.com/files/PDF/IntegratedSights/UN_ODAM.pdf
Surveillance & Warning Obstacle Ranging and Display (SWORD) Info:
http://elop.pionet.com/files/PDF/Lasers/UN_SWORD.pdf

Goodrich Corporation (http://www.goodrich.com/Main)
Sensor Systems
Goodrich Corporation
14300 Judicial Road
Burnsville, MN 55306-4898
Phone: (952) 892 4000
Fax: (952) 892 4800

LOAS Product Description and Specifications
http://www.sensors.goodrich.com/literature/lit_pdfs/4109_LOAS.pdf

Monterey Technologies, Inc. (http://www.montereytechnologies.com)
Corporate Headquarters
24600 Silver Cloud Court, Suite 103
Monterey, CA 93940
Phone: (831) 648-0190
Fax: (831) 648-0191

Electro-Optical
Foster Flight (http://www.fosterflight.com)
Contact Information
1691 Snow Eagle Ct.
Loma, CO 81524
scott@fosterflight.com
Operations Handbook
http://dwp.bigplanet.com/fosterflight/nss-folder/publicfolder/POH.doc

Electro-Optics Center (http://www.electro-optics.org)
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Sensor Technology
Division Head
Ken Freyvogel

Electro-Optics Center Northpointe
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Freeport, PA 16229
Phone: (724) 295-7000
Fax: (724) 295-7001

Electro-Optics Center South
559A Freeport Road
Freeport, PA 16229
Phone: (724) 295-6600
Fax: (724) 295-6617

See and Avoidance Behaviors for Autonomous Navigation
http://www.ee.byu.edu/faculty/djlee/Publications/SPIE_SeeAvoid_102004.pdf
Dah-Jye Lee, Randal W. Beard, Paul C. Merrell, and Pengcheng Zhan
Department of Electrical and Computer Engineering
Brigham Young University, 459 CB
Provo, Utah 84602
Phone: (801) 422-5923
Fax: (801) 422-0201
Email: djlee@ee.byu.edu

Neuromorphic Motion Detection For Robotic Flight Guidance
http://www.ini.unizh.ch/~tnetter/papers/NetterFranceschini-04-INE-NeuroEng1-1.pdf

A Robot That Flies With A Neuromorphic Eye
http://www.ini.unizh.ch/~tnetter/papers/NetterFranceschini-03-SPIE-Robotics12-2.pdf
Thomas Netter and N. Franceschini

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Institute of Neuroinformatics
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tnetter@ini.unizh.ch

Vision For A UAV Helicopter
http://www.imt.liu.se/mi/Publications/pdfs/ndffgmw02.pdf
Klas Nordberg, Patrick Doherty, Gunnar Farneback, Per-Erik Forssén, Gosta Granlund, Anders Moe, Johan Wiklund

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Computer Vision Laboratory
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SWEDEN
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Fax: +46 13 138526
Email: klas@isy.liu.se

Detection And Tracking Of Objects From Multiple Airborne Cameras
http://www.cs.ucf.edu/~vision/papers/SPIE06.pdf
Mubarak Shah, Asaad Hakeem, and Arslan Basharat

Mubarak Shah
Agere Chair Professor
Computer Vision Lab
School of Electrical Engineering and Computer Science
University of Central Florida
4000 Central Florida Blvd.
Orlando, FL 32816
Phone: (407) 823-5077
Email: shah@cs.ucf.edu

Others

Defense Advanced Research Projects Agency (DARPA) (http://www.darpa.mil/)
Micro Air Vehicle (MAV) Advanced Concept Technology Demonstration (ACTD)
Program Manager:
Mr. Daniel Newman
E-mail daniel.newman@darpa.mil
Phone: (571) 218-4219
Fax: (703) 696-8401
DARPA Tactical Technology Office
3701 N. Fairfax Drive
Arlington, VA 22203-1714
Working with:
Allied Aerospace (http://www.alliedaerospace.com/)
>   *Home Office*
>   703 Middle Ground Blvd.
>   Newport News, VA 23606
>   Phone: (757) 873-1344
>   Fax: (757) 873-2183

>   Athena Technologies, Inc. (http://www.athenati.com/)
>   *Contact Information:*
>   6876 Watson Court
>   Vint Hill Tech Park
>   Warrenton, VA 20187
>   Phone: (540) 428-3300
>   Fax: (540) 428-3301

>   Sagem (http://www.sagemavionics.com/)
>   *Contact Information:*
>   2701 Forum Dr.
>   Grand Prairie, Texas USA 75052
>   Toll-Free: (800) 585-8106
>   Phone: (972) 314-3600
>   Fax: (972) 314-3640

>   Harris (http://www.harris.com)
>   *Headquarters*
>   1000 Charles J. Herbert Drive
>   Palm Bay, FL 32905
>   Phone: (321) 727-4000
>   Fax: (321) 409-7058

Scientific Applications & Research Assoc., Inc. (http://www.sara.com)
        (UAV Acoustic Collision-Alert System)
        Headquarters
        6300 Gateway Drive
        Cypress, CA USA 90630-4844
        Phone: (714) 224-4410
        Fax: (714) 224-1710

Magnetic UAV Trajectory Design Using Total Field Collision Avoidance
http://acl.mit.edu/papers/Field_gnc03.pdf
Karin Sigurd and Jonathan How
        Jonathan P. How
        Associate Professor
        Department of Aeronautics and Astronautics
        Aerospace Controls Laboratory
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        Fax: 617-253-7397
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APPENDIX C—CAPABILITY MATRIX

This appendix includes three different matrices. The first two list cooperative followed by noncooperative technologies relevant to detect, sense, and avoid. The third matrix lists general information from relevant articles from the literature survey.

Cooperative															
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Perform-ance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
Traffic alert and collision avoidance system (TCAS)															
Skywatch HP															
Goodrich	Avoiding collisions in the age of UAVs	55	Lopez, Ramon	Jun-02	Proteus	×									A web article discussing the testing done at Las Cruces with Proteus aircraft using the Goodrich Skywatch HP system
Traffic advisory system (TAS)															
N/A	Detect, See and Avoid Systems For Unmanned Aerial Vehicles	144	Stephen B. Hottman	2004											A .ppt giving the pilot's responsibility, DSA flight tests, surrogate UAS results, requirements for UASs, avoiding other aircraft, planned file and fly demonstrations.
N/A	Cooperative DSA & OTH Communication Flight Test	138	Russell Wolfe	2002											A .ppt given at the 2002 TAAC Conference. Many slides incorporated in previous presentation.
ADS-B															
FAA-SBS	Surveillance and Broadcast Services- Industry Day #3	116	Vincent Capezzuto	Nov-06											A .ppt on status and activities related to ADS_B implementation from a number of SBS offices
FAA-SBS	Surveillance and Broadcast Service Program Overview -NWAAAE 2006 Annual Conference	124	Bobby Nichols	Oct-06											A .ppt on ADS_B implementation with ATM impacts associated with Colorado mountain airports
FAA-SBS	Surveillance and Broadcast Services- Industry Day #2	129	Vincent Capezzuto	Aug-06											A .ppt on status and activates related to ADS_B implementation from a number of SBS offices
Honeywell Intl	ADS-B Industry Day	120	Tom Henderson	Aug-06											A .ppt with emphasis on Honeywell related products and capabilities
NBAA	ADS-B Industry Day	123	Bob Lamond	Aug-06											A .ppt on NBAA viewpoint that ADS-B "Out" must be tied to ADS-B "In" for benefit to operators

Cooperative																
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Perform-ance			Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy		
Rockwell Collins	ADS-B Industry Day Rockwell Collins Perspectives	127	na	Aug-06												A .ppt on Rockwell viewpoint on ADS-B implementation, future, and global perspective
UPS	Dramatically Improving Gate-to-Gate Operations	131	Bob Hi	Aug-06												A .ppt reporting on improving aircraft flight operations and scheduling with ADS-B as one of several systems utilized
RAA	FAA ADS-B Industry Day	125	Scott Foose	Aug-06												A .ppt presenting RAA viewpoint on aspects of modernization, no direct ADS-B discussion
Garmin	Garmin AT SBS Briefing	119	na	Aug-06												A .ppt briefing on Garmin involvement in ADS-B testing and their product line
ACSS	SafeRoute ADS-B Program Briefing	113	Cyro A. Stone	Aug-06												A .ppt briefing on the ACSS SafeRoute product capabilities for ADS-B
RTCA	Overview of RTCA Activities for ADS-B	128	Harold Moses	Jun-06												A .ppt on RTCA Special Committee (SC) - 186, structure, documents, and work plan identifying points of contact.
JPDO-NGATS	The Role of ADS_B in NGATS	121	na	Jun-06												A .ppt on the positive impacts ADS_B will have on ATM in NGATS
FAA-SBS	Surveillance and Broadcast Services-Industry Day	117	Vincent Capezzuto	Jun-06												A .ppt on status and activities related to ADS_B implementation from a number of SBS offices with an introduction by John Scardina - JPDO
Dimensions International	ADS-B Data Monitoring	118	David Dougherty	Jun-06												A .ppt with observation from nearly two years of ADS-B fixed point data collection and analysis from 11 US locations. Approximately 9x10 to the 6th flights monitored

Cooperative														
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Perform-ance	Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
AOPA	ADS-B Industry Day The General Aviation Perspective	114	Andy Cebula	June 2006 (?)											A .ppt on AOPA viewpoint on ADS-B implementation and needs of general aviation
Rannoch	ADS-X Extended ADS-B Surveillance	126	Alex Smith	Jun-06											A .ppt on Ronnoch designed ground equipment and system to extend ADS-B into FAA-ATM system
MITRE-CAASD	Surveillance and Broadcast Services Coverage	122	Rob Strain	Jun-06											A .ppt providing ADB-S coverage review and analysis
Boeing	Boeing Perspectives on ADS-B Surveillance	115	na	na											A .ppt from Boeing with analysis on enhancements and issues
Other															
AFRL/Northrop Grumman	SeFAR Integration Test Bed for See and Avoid Technologies	23	Suwal	Sep-05				x							This paper describes a TCAS simulator, a vision simulation system, a radar simulator for the AFRL system to test and evaluate procedures and algorithms for safe UAS testing and operation.
Alion Science and Technology	Resolution Requirements for Passive Sense and Avoid	79	David E. Grilley	Jan-05				x							A proposal involving both regulation change and sensors to detect a potential collision without having to quantify the human pilot's ability to "see" a potential colliding object.
Lockheed Martin, UC-Berkeley, ONR	An Overview of Emerging Results in Cooperative UAV Control	45	Allison Ryan, Marco Zennaro, Adam Howell, Raja Sengupta, J. Karl Hedrick	Dec-04											An overview based on looking at a few selected projects. Not a comprehensive overview. Formation flying and flocking was described along with a case study.

						Cooperative									
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Perform-ance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
Univ. of Cincinnati/ DARPA	Efficient Bayesian Methods for Updating and Storing Uncertain Search Information for UAVs	49	Mathew Flint, Emmanuel Fernandez, Marios Polycarpou	Dec-04				x							A theoretical study using cooperating UASs to find and detect a target along with a simulated test case
GMU/MITRE	UAS Safety: Unmanned Aerial Collision Avoidance System (UCAS)	97	Jose Asmat, Brett Rhodes, Jesica Umansky, Chris Villavicencio, Amir Yunas,	na				x							This proposed flight system utilizing TCAS and sensors utilizes a simulation to create model. An existing case study is used to demonstrate the value of the model

Noncooperative															
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Performance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
Active Systems															
Radar															
Amphitech International	Avoiding collisions in the age of UAVs	55	Lopez, Ramon	Jun-02	Proteus	×									A web article discussing the testing done at Las Cruces with Proteus aircraft.
Ground-based															
SAVDS															
Tom Zajkowski	Small UAS Communications Mission	3	Tom Zajkowski, Steve Dunagan, Jim Eilers	Apr-06	RnR APV-3										This ground based NASA radar system is used to support USDA operations using a small UAS to monitor forest fires
Laser															
Fibertek, Inc.	By air, land and sea, the unmanned vehicles are coming	66	Richard Bloss	2007	Not specified	×							See notes		Can detect 6 mm wire at 75 m; larger wire at up to 200 m
Small UAS															
Opti-Logic															
BYU	Static and Dynamic Obstacle Avoidance in Miniature Air Vehicles	20	Jeffery B. Saunders, Brandon Call, Andrew Curtis, Randal W. Beard, Timothy W. McLain	Sep-05	BYU MAV	×			fixed pointer			2 watts	400 meters		This small laser system and tested and successfully flown demonstrating real time avoidance of fixed obstacles and maintaining independent flight to a programmed waypoint.
Laser Radar															
Selex Communications	Laser Obstacle Avoidance System	41		2006	Manned	×			40°H - 30°V	320×239 ×419 mm	24 kg	+28V DC			Measurements are for the largest of four units.

Noncooperative															
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Performance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
Selex Communications	LOAM® Laser Obstacle Warning System to be Equipped on Denmark's EH101 Search and Rescue Helicopters	42		2006	Manned	×									Supporting document to above.
Selex Communications	Lockheed Martin and SELEX Communications Pursuing Obstacle Avoidance Technology Opportunity for UH-60 Fleet	43		2006	Manned	×									Supporting document to above.
Brigham Young University	Static and Dynamic Obstacle Avoidance in Miniature Air Vehicles	20	Jeffery B. Saunders, Brandon Call, Andrew Curtis, Randal W. Beard, Timothy W. McLain	2005	Small UAS - Miniature air vehicles			×				12 watts	400 m - 10 Hz		
N/A	Threading the maze: GPS/INS, landmark sensing, and obstacle avoidance	47	Rui Hirokawa, Kenji Nakakuki, Koichi Sato, Ryuichi Ishihara	2004	Autono-mous ground vehicle		×								Laser scanner with 35-mm range accuracy and 1 degree angle resolution
Other															
Optic Flow															
Centeye	Biomimetic Visual Sensing and Flight Control	27, 124	Geoffrey L. Barrows, Javaan S. Chahl, Mandyam V. Srinivasan	???	Mini and micro air vehicles	x	x				<100 grams		100-8000 frames/ second		Optic flow sensor based on artificial insect vision

Noncooperative															
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Performance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
Univ. of Central Florida	Detection and tracking of objects from multiple airborne cameras	53	Mubarak Shah, Asaad Hakeem, and Arslan Basharat	2006	Various		x							90% detection; 1-3% false alarm	Computer vision techniques using COTS to be used on multiple mobile platforms
Royal Netherlands Naval College and Delft University of Technology	Feasibility of Using Synthetic Vision Technology for UAV Operator Support	22	J. Tadema, E. Theunissen	2003	General UAS			x							Combination of radar, visual, TCAS, AWACS for synthetic vision to increase situational awareness
Passive Systems															
Sound Navigation and Ranging (SONAR)															
Motion Detection															
Laboratoire de Neurobiologic	A Robotic Aircraft that Follows Terrain Using a Neuromorphic Eye	49	Thomas Netter & Nicolas Franceschini	2002	Micro air vehicles		x								MAV flown on test bed. Worked well. Proceedings of the 2002 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems EPFL, Lausanne, Switzerland, October 2002
Electro-optical															
DAA															
1024x1024 Dalsa CA-D7-1024T															
AFRL/DRA	Detect and Avoid Technology Demonstration	9	Mr. James Utt, Dr. John McCalmont, Mr. Mike Deschenes	May-02	Helo/ Bonanza	x			30° H, 30° V	na	na	na	4 nm	100% target detection	This report describes the initial testing of a limited FOV sensor to passively detect air traffic with the "same level of capability as a human pilot. The test meet or exceeded range requirements for the two UAVs considered in the study, Global Hawk and Predator
	Detect and Avoid (DAA) for Global Hawk and Predator	135	James Utt	Oct-03		x				4x4x3 inch pro-cessor					Reporting completion of a flight processor and plans for 2004

Noncooperative															
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Develop-ment			Specifications					Performance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
	See and Avoid (SAA) Passive Ranging Concepts	137	Maj. Vince Raska	Nov-04											Concept of using rate of pixel intensity change for ranging information
	Sense and Avoid	138	Dr. John McCalmont	May-05	Aerostar/Aero Commander	x			100°az 30° el	12x7x15 inches (bay only)	56 lb	462 watts			Reporting on ATDSS I and announcing plans for ATDSS II
	Sense and Avoid, Phase I (Man-in-the-Loop) ATD	1	John McCalmont, Mr. James Utt, Mr. Mike Deschenes, 2Lt. Michael Taylor	Sep-05	Aero Commander	x			100°az 30° el						Specifies Global Hawk and Predator SAA requirements and describes ATD system
	Development of a Sense and Avoid System	5	Mr. James Utt, Dr. John McCalmont, Mr. Mike Deschenes	Sep-05	Aerostar/Aero Commander	x			100°az 30° el						Aero Commander flight test results, plans for Aerostar testing
	Initial test flights for UAV collision-avoidance system	152	Phil Copeland	Dec-05	Aerostar	x									News release reporting on flight testing the integrated SAA flight system without targets
FAA	Authorizing Operations in the National Airspace System	140	John Timmerman	Oct-05											A .ppt on status of FAA addressing UAS flights in the NAS, SAA is not an ATC function
	Nallatech FPGA solution provides platform for Defense Research Associates, Inc. UAV Detect and Avoid application	96		Mar-05											Advertisement showing the Nallatech products used in the DRA tests
	A passive optical detect, sense and avoid system for tactical UAVs	60	Arndt, Martin (Bodenseewerk Geratetechnik GmbH [BGT])	Jun-05	Ranger UAV										Abstract from Proceedings of 2004 AUVSI's Unmanned Systems North America

Optic Flow Sensor

2610 Optical Mouse Sensor

						Noncooperative									
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Develop-ment			Specifications				Performance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
Agilent/BYU	Autonomy and Cooperation for Small Unmanned Aircraft	129	Tim McLain	na	COTS-ZAGI	x			1.2 FOV lens	1x1x1.5 inch	22 grams	na	80 meters	na	2300 frames/sec processing outputs optical flow over computer bus, cheap
Fixed Sensor															
TI C40															
TI/CMU	CMU's autonomous helicopter explores new territory	19	John Charles	Oct-88	Yamaha R Max helicopter	x			na	na	na	na	na	na	Fast video processor to successfully control helicopter flight
4 ea Basler															
OUSD (AT&L)	Status of OUSD (AT&L) Sense and Avoid Demo	143	Peter Lewis	Dec-06	Spyder II	x			±75°, ±15° vertical	27 ft^3	280 lb	800 watts			This .ppt report describes the existing SAFD EO based detection system and the plans to fly this system with cooperative targets
Northrop Grumman/ AFRL	Passive Ranging for UAV Sense and Avoid Applications	10	Omid Shakernia, Won-Zon Chen, Maj. Vincent M. Raska	Sep-05				x							This paper describes a technique of making a fixed EO sensor maneuver to generate range information. The technique is tested in a simulator
Infrared															
Engineering 2000	Avoiding collisions in the age of UAVs	55	Lopez, Ramon	Jun-02	Proteus	×									A web article discussing the testing done at Las Cruces with Proteus aircraft.
Camera															
UC Berkeley	Obstacle Detection for Small Autonomous Aircraft Using Sky Segmentation	31	Timothy G. McGee, Raja Sengupta, and Karl Hedrick	Apr-2005	Fixed wing aircraft	×			62°						A Sig Rascal model aircraft with 2.8 m wingspan; control by Piccolo avionic package; CCD camera with 320x240 pixels and 62° field of view.

Noncooperative															
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Develop-ment			Specifications				Performance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
NASA Ames Research Center	UAV See and Avoid Systems: Modeling Human Visual Detection and Identification	118	Andrew B. Watson	2005 or later											A report describing simulation of an existing subjective data set using the Spatial Standard Observer (SSO) and development of a web-based application for demonstrating SSO-based visibility calculations. Preliminary results indicate the utility of both elements.
MAGICC															
Panasonic KX-141															
BYU	Autonomy and Cooperation for Small Unmanned Aircraft	129	Tim McLain	na	COTS ZAGI	x			2 axis gimbal	na	7.4 oz	na			Small NTSC fixed focal length video camera with BYU designed gimbal system using RC servos
BYU	See and avoidance behaviors for autonomous navigation	36	Dah-Jye Lee, Randal W. Beard, Paul C. Merrell, and Pengcheng Zhan	Sept-2004	Small UAS		x								A novel computer vision algorithm for collision detection and time-to-impact calculation based on feature density distribution analysis.
Wallenberg Laboratory															
Sony FCB-EX470LP Color Composite															
Linköping University, Sweden	Vision for a UAV Helicopter	50	Klas Nordberg, Patrick Doherty, Gunnar Farnebäck, Per-Erik Forssén	2002	Modified Yamaha RMAX	x									A long-term study on integrating software and hardware systems on a helicopter to be used for autonomous applications such as traffic monitoring, emergency services, photogrammetry, and surveying.
Other															
Autopilot															
Gyros, accel															

Noncooperative														
Developer	Title	Ref.	Author(s)	Date	Platform	Phase of Development			Specifications				Performance		Notes
						Flight unit	Prototype	Concept / Simulation	Field of View	Size	Weight	Power	Range	Accuracy	
Kestrel Autopilot 2.1/BYU	Autonomy and Cooperation for Small Unmanned Aircraft	129	Tim McLain	na	COTS ZAGI	x			n/a	2x1.5 inches	17 grams		n/a	n/a	Small COTS autopilot used for Army TAC-MAV and AF BATCAM and Night Hawk
Vision Processing															
Helios/BYU	Autonomy and Cooperation for Small Unmanned Aircraft	129	Tim McLain	na	COTS-ZAGI	x				2.5x2.5x 0.5 inches	2 oz	3 watts	na	na	Small vision processing board for UAS

General				
Title	Ref.	Author	Date	Discussion
Algorithm				
Transfer time complexity of conflict-free vehicle routing with no communications	76	Vikrant Sharma, Michael Savchenko, Emilio Frazzoli, and Petros G. Voulgaris	2007	What is the minimum time needed to transfer each vehicle from its source to its destination, avoiding conflicts with other vehicles?
Image processing algorithms for UAV "sense and avoid"	63	Carnie, Ryan (Australian Research Centre for Aerospace Automation, Queensland University of Technology); Walker, Rodney; Corke, Peter	2006	Two algorithms processed image streams featuring real collision-course aircraft against a variety of daytime backgrounds. Preliminary analysis of first detection times was at distances ~35-40% greater than those of the alerted human observer.
Probabilistic mapping for UAV using point-mass target detection	59	Kang, Yeonsik (University of California Berkeley); Caveney, Derek S.; Hedrick, J. Karl Source	2006	The proposed algorithm uses a well-known Interacting Multiple Model (IMM) based target formulation and tracking method to first process the noisy measurement data. The outputs build the probabilistic occupancy map.
An investigation into the next generation avionics architecture for the QUT UAV project	12	Robert Ellen, Peter Roberts, Duncan Greer	2005	Discussion of options for avionics architectures with respect to design requirements and experiences with their physical implementations. Conclusions are drawn and recommendations made on the optimal standardized architecture for UAS research at QUT.
Obstacle Avoidance with Sensor Uncertainty for Small Unmanned Aircraft	121	Eric Frew, Raja Sengupta	Dec 2004	An approach to obstacle avoidance in the context of a multilayered, multi-objective control architecture that considers both the aircraft dynamics and sensor limitations in an integrated framework.
Conflict Alerting Functionality For Autonomous Vehicles	17	Yiyuan J. Zhao, University of Minnesota, and Dennis Rock, The Boeing Company	2002	Two fundamental approaches to the design of alerting algorithms—the kinematic approach and the dynamic approach.

General				
Title	Ref.	Author	Date	Discussion
Adapting Technologies				
Stable Control of Vehicle Convoys for Safety and Comfort	64	Peter A. Cook	March 2007	A single dimension theoretical study based of linear system theory including bi-directional control
Hierarchical Longitudinal Controller for Read-End Collision Avoidance	56	Dae-Jin Kim	August 2006	This is a theoretical study and computer simulation using ground vehicles as a model to prevent rear end collision within a certain safety zone.
Fly Inspired Visual Steering of an Ultralight Aircraft	62	Jean-Christophe Zuffery	April 2005	An autonomous ultralight (30 gram, 86 cm wingspan) microflyer of balsa, carbon fiber, and film with a duel compound lens optical system was developed and flown (2 watt LiPoly battery, 30 min flight time) in a small room demonstrating the capability of avoiding obstacles. There is no range input, no altitude data, and the motion was very jerky. There were attitude control issues and the system needs additional development.
Monitoring of gas pipelines - a civil UAV application	22	Dieter Hausamann	2005	A conceptual paper for using a UAS with multispectral sensors and radar to monitor the status and condition of above ground and underground pipelines
Stanford Racing Team's Entry In The 2005 DARPA Grand Challenge	109	Michael Montemerlo	2005	A report describing the vehicle, sensors, and systems as well as the successful performance over 140 miles of uninterrupted autonomous travel.
Unmanned Aerial Vehicle Operations in UK Airspace -Guidance	77	Directorate of Airspace Policy	2002	This government report describes the regulations involved in flying military and civil UASs in the UK airspace and provides points of contact in the government for each of these areas.
Alternative Visibilities				
Risk				
See What's Sharing Your Airspace	97	Flight Safety Foundation	May 2005	An article in Flight Safety Digest that provides an overview on the UAS community and the risk issues with many literature references

General				
Title	Ref.	Author	Date	Discussion
A Standards Based Approach to See and Avoid Technology	7	Ryan J Schaefer	Sept 2004	Proposes to use ASTM Std F2411 for flying UAS in the NAS meeting the manned aircraft collision rate of 8.57x10to the minus 6.
Index of Risk and Safety Objectives for Civil UAVs	16	M. Lega, A.F. Accardo	Sept 2003	This is a theoretical study to determine a comparative index of risk with other UASs
UAS Safety: Unmanned Aerial Collision Avoidance System (UCAS)	99	Jose Asmat	n/a	Abstract— Lack of safety and regulatory framework currently prevent the routine use of unmanned aircraft systems (UAS) within the U.S National Airspace System (NAS). Demonstrating a level of safety equivalent to that of manned aircraft will allow UAS to f
Demo/Testing				
Detect, See and Avoid Systems for Unmanned Aerial Vehicles	98	Steve Hottman	May 2007	This .ppt report provides results from the plans described in Ref 96 Proteus-OPV platform testing of a radar system
Sense and Avoid for Small Unmanned Aircraft	105	David Maroney	2006	This MITRE .ppt reports provides a general overview of the UAS Sense and Avoid issues with no specific future plans
An Integrated Approach to Evaluating Risk Mitigation Measures for UAV Operational Concepts in the NAS	4	Roland Weibel	Dec 2005	This paper proposes a methodology of evaluating risk mitigation measures to obtain a specified level of safety for UAS operations
Multi-Mode Collision Avoidance System M^{2}CAS)	102	Michael Taylor	Oct 2005	An AFRL project .ppt report on using DAA (noncooperative) and TCAS (cooperative) combined fusion system to provide outputs to a TCAS display. Limited initial testing reported.
Integrated UAV Technologies Demonstration in Controlled Airspace Using ATTAS	31	Holger Friehmelt	August 2003	A paper that describes the ATTAS capability. ATTAS is a full sized manned commercial aircraft flown as a "pseudo-UAV" for communications and sensor testing
NASA avoids crashes with UAVs	59	na	June 2003	This Thomson Gale PowerSearch cites Aerospace Engineering 23.5 (June 2003) p30(2)

General				
Title	Ref.	Author	Date	Discussion
Feasibility of Using Synthetic Vision Technology for UAV Operator Support	21	J. Tadema	2003	This paper describes how SV can be used to support ATC operators for vehicle separation
Cooperative DSA and OTH Communications Flight Test	94	Russell Wolfe	October 2002	A .ppt report using the Proteus aircraft as a platform for SkyWatch, Inmarsat, and ATC communications as a pseudo UAV platform
Noncooperative DSA Flight Test	96	na	October 2002	A NASA ERAST .ppt report on using the Proteus-OPV for a radar based collision avoidance flight test using cooperative manned aircraft
USCG UAV's See and Avoid - A Roadmap to FY2006	104	na	na	A general .ppt report with no specific systems identified about what the USCG will develop for UAS capability
Research, Development and Commercialization of an Unmanned Aerial Vehicle Traffic Avoidance System	81	Richard Schultz	na	This abstract proposes a Univ. of North Dakota project to develop and test a prototype Mode S transponder and radar system in a UAS for commercial aircraft avoidance

APPENDIX D—CASE STUDY

D.1 INTRODUCTION.

Defense Research Associates, Inc. (DRA) has worked with the Air Force Research Laboratory (AFRL) and Aeronautical Systems Center (ASC) over the past 7 years to develop and deploy sense and avoid (SAA) technology, as shown in figure D-1. The work that DRA has accomplished provides the reader with an understanding of the effort required for this technology development. The ultimate objective of this program is to develop a technological solution to the SAA problem that meets the guidance given by the Federal Aviation Administration (FAA) to operate Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS).

The development of this technology has been conducted in a phased approach, as portrayed in figure D-1.
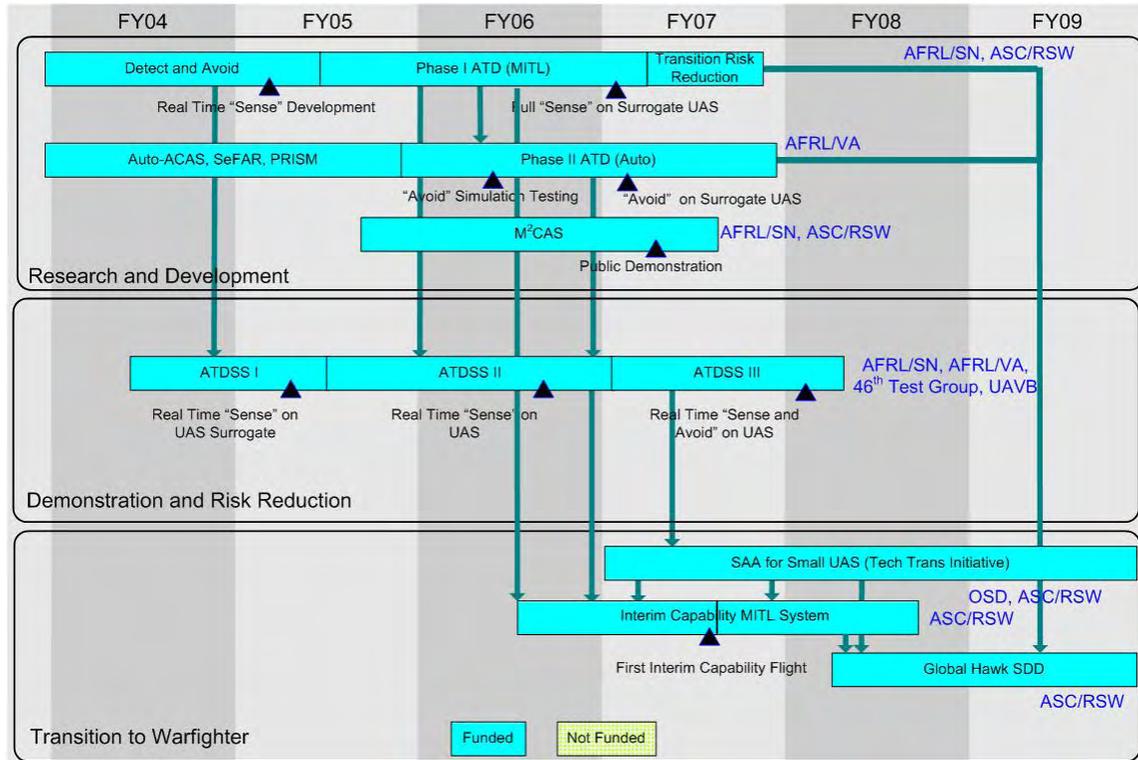
Figure D-1. The SAA Roadmap

D.2 DEVELOPMENT HISTORY.

In 2000, DRA was under an AFRL Small Business Innovative Research (SBIR) contract to develop a low-cost missile warning system (MWS). This system used electro-optical (EO) sensor technology and detection and tracking algorithms to discriminate and track 4-inch-diameter Man Portable Air Defense System missile launches from the background image. In 2001, under a SBIR enhancement funded by ASC, DRA began applying technology developed under the MWS SBIR to the UAS DSA problem. This program was the first of several SAA

technology development and demonstration programs. This appendix describes the various phases of development undertaken by DRA to date as a case study of a DSA development effort.

D.2.1 DETECT AND AVOID I.

Guidance for UAS operating in the NAS is given in FAA Order 7610.4K with the intention that UAS operations provide an equivalent level of safety to that intended by Title 14 Code of Federal Regulations (CFR) Part 91 requirements for manned aircraft SAA. The first DRA program, called Detect and Avoid Phase I (DAA I), was executed in 2001 to define "equivalent level of safety to a human pilot" in terms of detection range and probability. Specific program objectives were to:

- Conduct an in-depth analysis of detection range requirements for Global Hawk.

- Conduct a proof-of-concept demonstration to show that commercial off-the-shelf (COTS) technology could meet those detection range requirements.

Defining "equivalent level of safety" was accomplished by using the optical encounter (OPEC) model. OPEC was developed by AFRL to model human detection ability. It takes into account differing backgrounds, lighting conditions (to include sunshine, earthshine, and skyshine), aircraft designs, and atmospheric transmission. It was calibrated using 937 human trials. OPEC analysis is now required for any paint-scheme changes on U.S. Air Force inventory aircraft. It has been in use since 1980, and the model has been applied to a variety of aircraft, including the F-16, the F-22, and the Predator. Figure D-2 shows OPEC results for an example scenario. It was determined that on average, a human pilot detects an F-16 (used because it had the smallest optical signature in the OPEC database) at 1.6 nautical miles (nm). The results of this study were subsequently verified in SAA flight tests conducted by DRA and independently by the National Aeronautics and Space Administration (NASA).
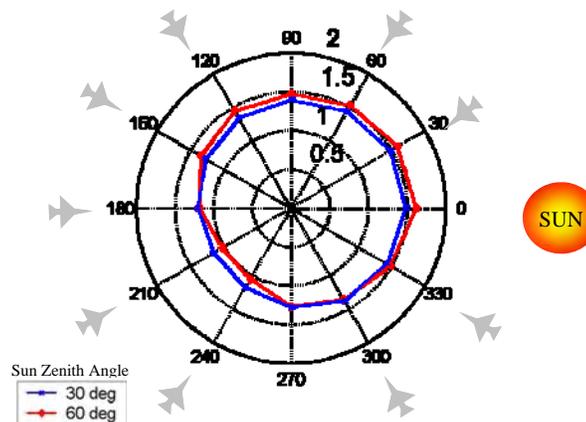

Figure D-2. OPEC Analysis Showing Human Detection Ranges in Nautical Miles

DRA then developed parametric software, which determines detection range requirements. This model calculated closure velocities as a function of the sensor and target aircraft velocities and the look angle (the angle of approach of the target aircraft off the centerline of the sensor

aircraft). The model includes estimated communication latencies, operator decision time (whether human or autonomous), and the time required for any maneuver required to avoid the target aircraft (based on air vehicle performance data). This model also assumes a minimum miss distance for a safety factor. For the results shown in figure D-3, 500 feet, the distance at which a near-miss becomes an FAA-reportable incident, was chosen as this miss distance. Separate analyses by NASA and the Air Force 452nd Flight Test Squadron independently verified this model. For further information on this phase of development, see McCalmont, et al., 2002; and McCalmont and Utt, 2003.
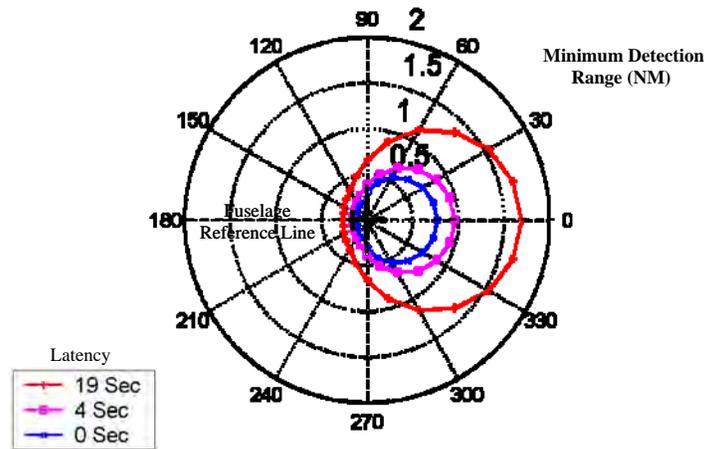
Figure D-3. Detection Range Requirements Software Example Results

D.2.2 THE DAA II.

Under DAA Phase II in 2002, DRA's specific objectives were to:

- Complete a multisensor brassboard system design.
- Complete the initial build of the detection and tracking algorithm suite.
- Demonstrate a real-time implementation of the detection algorithms.
- Characterize system performance under various lighting and background conditions.

All program objectives were successfully executed, and real-time performance of the detection algorithms met all criteria for further development.

D.2.3 THE DAA III.

In Phase III, conducted in 2003 and 2004, DRA refined system requirements based on feedback from the Global Hawk and Predator Program Offices (Bryner, et al., 2003), developed a brassboard design of the SAA system, and implemented the brassboard design to build a system ready for demonstration. Specific objectives of this program were to:

- Refine SAA system requirements, explore alternative SAA technologies.
- Design and fabricate a brassboard system based on the best technology available.
- Demonstrate the SAA system in a virtual environment.

- Design a prototype SAA system for development under a future program.

The alternative technologies evaluated (other than visible EO sensors) were radar, infrared, line scan sensors, and light detection and ranging. Comparing the performance of each of these technologies, the visible EO sensor solution was deemed to be the best solution due to reduced size, weight, and power (SWaP), no moving parts, lower cost, and its nonemitting functionality. Based on the results from this research program, the DAA III design concept was determined to be sound, and continued research and development was warranted under the next phase of the DAA program.

The brassboard system fabricated under this program was demonstrated under a concurrent development program, the Air Traffic Detection Sensor System Phase I (ATDSS I).

D.2.4 THE ATDSS I.

This demonstration was undertaken in 2004 (Deschenes, et al., 2004). Specific program objectives were to:

- Prove the complex algorithms needed to detect, track, and declare intruder aircraft could be implemented in real-time.

- Collect data to use as an indicator of system performance and to assist in future system development.

These objectives were accomplished by flying a half-field of regard (FOR) Man-in-the-Loop (MITL) SAA system on a surrogate UAS (Aero Commander) against a general aviation intruder. As shown in figure D-4, three EO sensors with a resolution of 1004 x 1004 pixels were installed in the nose of the surrogate UAS (Aero Commander). These sensors resulted in a system with a horizontal FOR of -15°/+85°, and a vertical FOR of ±15°. These sensors transmitted data to the detection and tracking processors located at the operator's console inside the cabin of the Aero Commander, as shown in figure D-5.

The real-time implementation of the detection, tracking, and declaration algorithms was successfully demonstrated in flight tests, meeting the prime objective of the program. As mentioned above, DRA also collected data to facilitate further system development. The declaration range results from this demonstration are shown in figure D-6. Declaration range is defined as the range when the intruding aircraft is "declared" as a collision threat by DRA's system. It is at this point when the collision alert would be sent to either the UAS remote pilot or to autonomous collision avoidance algorithms. In previous phases of development, this parameter was referred to as detection range (see figure D-3). This is the critical parameter that is used to conduct a successful collision avoidance. As long as the declaration range is sufficiently far enough out (depending on closure velocities), there will be sufficient time to execute a collision avoidance (CA) maneuver.

Figure D-4. The ATDSS I Sensor Installation in the Aero Commander

Figure D-5. The ATDSS I Data Recorders and Detection and Tracking Processors
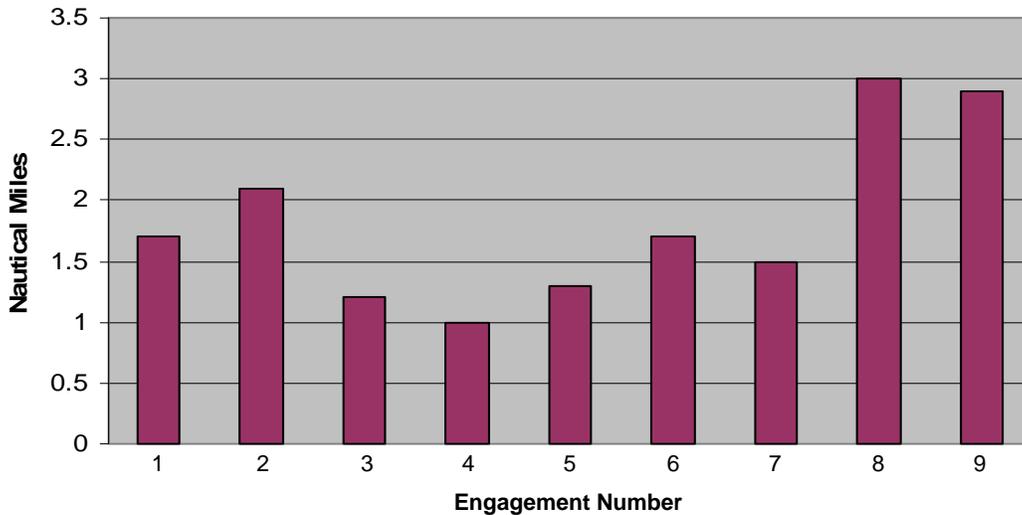in the Aero Commander Cockpit

Figure D-6. ATDSS I Declaration Range Results

Because the primary focus of SAA efforts to this point was on developing and demonstrating algorithms that could process the volume of sensor data in real time, not on improving declaration performance, a very high false alarm rate was observed. As a takeaway, it was learned that over 95% of these false alarms were due to system sensitivity settings. These were eliminated by simply altering system parameters at the expense of adding approximately 1 second of latency to the declaration process.

D.2.5 THE DAA IV.

In 2004, DRA was tasked to mature the DAA system beyond what was demonstrated in ATDSS Phase I. The primary technology areas addressed were:

- Increasing the system FOR to meet the requirement of ±110° azimuth by ±15° elevation. This was accomplished by upgrading the sensors to a model with a 4 times larger focal plane array.

- Upgrading the detection processor hardware to handle the upgraded sensors.

- Enhancing the detection algorithm implementation in the detection hardware.

The DAA IV program successfully accomplished all objectives and laid the groundwork for further development and demonstration under the Advanced Technology Demonstration (ATD) SAA Phase I (Man-in-the-Loop) program.

<u>D.2.6 ATDSS II</u>.

Phase II of ATDSS was undertaken in 2005 and 2006 principally to demonstrate that an integrated sensor system installed on a UAS could detect, track, and declare intruder aircraft. Specific objectives of this program were to:

- Quantify performance of SAA technology (including declaration range, false alarm rate, and real-time operation).

- Address issues specific to UAS operations (including remote control of the SAA system on UAS and down-linking CA data to the remote pilot).

- Support the ATD programs by providing lessons learned and risk reduction.

These objectives were accomplished by flying a single-sensor MITL SAA system on a UAS (Aerostar) against a general aviation aircraft intruder. This system used the same technology as that for the ATDSS I program; however, the data recorder and detection and tracking processors were installed in an industrial computing chassis to fit within the SWaP constraints of the Aerostar UAS. Declaration range results from these engagements are shown in figure D-7. Note the first three engagements were with the intruder 500 feet above the UAS, while the second set of three were with the intruder 500 feet below the UAS, against a mountain range, which accounted for the lower declaration ranges. This is because of the inherent increased difficulty in distinguishing a target from a land-based background due to reduced contrast between the target and the surrounding image.
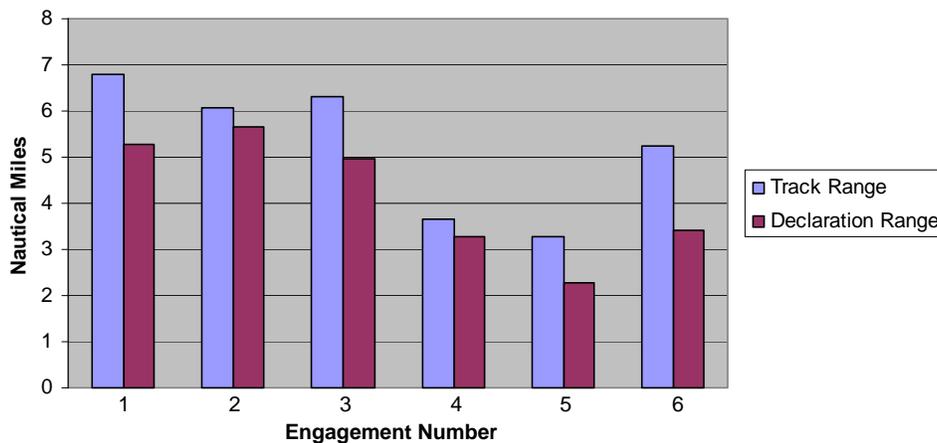

Figure D-7. ATDSS II Declaration Range Results

During this demonstration, 54 false alarms were observed (totaled over all engagements). Careful analysis of the data revealed bad detectors in the detector array. All detector arrays have bad pixels; i.e., detectors that give a response largely independent of the scene viewed. Target detection systems using imaging sensors typically include logic to eliminate bad pixels from the detection process. All false alarms observed in ATDSS II testing were due to bad pixels. Time-lapsed traces of alarm tracks shown in the sensor image plane (i.e., not corrected for ownship

maneuvers) illustrate this point. An example of this is shown in figure D-8. A point on the ground or a distant aircraft would oscillate wildly with aircraft pitch, roll, and yaw in this type of display, but bad pixels appear as points fixed in the image plane. Accordingly, DRA developed bad-pixel algorithms to eliminate this false alarm source. Subsequent testing with the same recorded data showed 100% of the false alarms were eliminated using this improvement. This reflects only one background, albeit a difficult one. The ATDSS II program provided many valuable lessons learned regarding SAA system development. These lessons were incorporated into subsequent development programs.
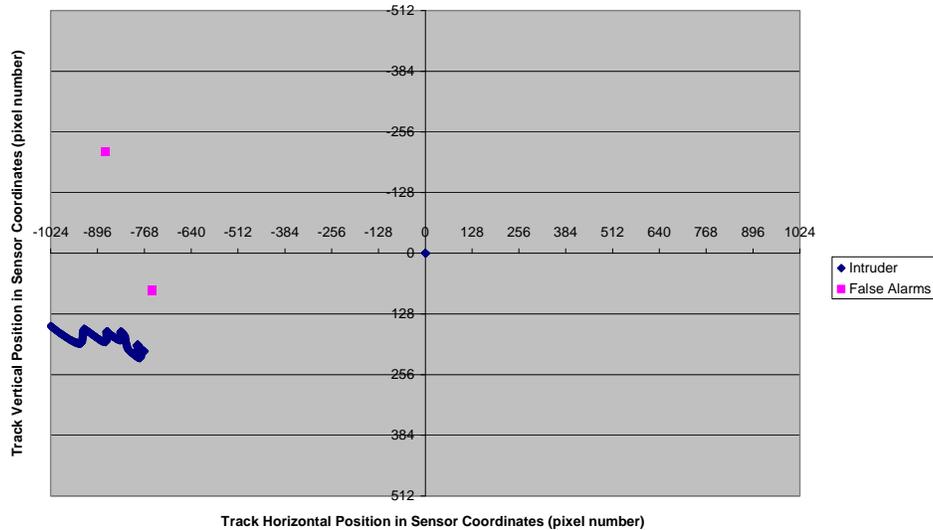

Figure D-8. False Alarm Analysis

D.2.7 THE SAA ATD PHASE I (MITL).

Upon successful completion of the DAA IV program, the next phase of SAA development was commissioned as an ATD program. The objective of the SAA ATD Phase I program, managed by AFRL/Sensors Directorate (SN), was to design, develop, and demonstrate a SAA system to meet the key performance parameters (KPPs) for the program (McCalmont, et al., 2005; Utt, et al., 2005; and McCalmont, et al., 2006).

Under the SAA Phase I ATD program, the DRA fabricated a prototype system suitable for demonstration on surrogate UAS. A block diagram of this system is shown in figure D-9. The system consists of several major components, including sensors, detection and tracking processors, and data recorders. All system hardware consisted of strictly COTS products. The sensors, shown in figure D-10, are charge-couple device digital video cameras, with an available resolution of 2048 by 2048 pixels, and an output rate of 20 hertz.
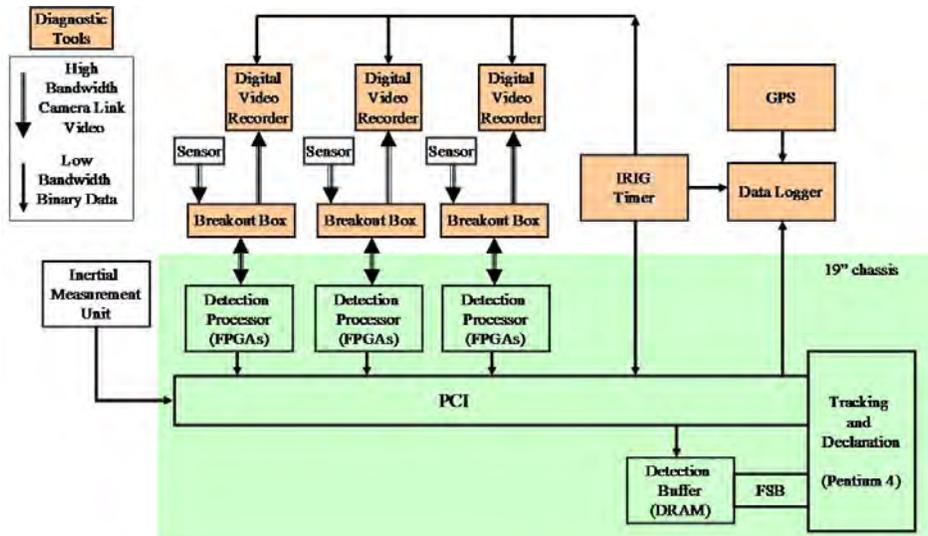
Figure D-9. The MITL SAA ATD Block Diagram

Figure D-10. SAA ATD Sensors

The detection and tracking processor, shown in figure D-11, used field programmable gate arrays based on reconfigurable computing hardware. One detection processor was paired with each sensor. The detection processor accepted sensor input (in the form of pixel intensities) and identified detections by measuring motion against the local background.

Figure D-11. Detection Processor

The tracking processor (figure D-12) was hosted in the same chassis as the detection processors, and accepted detection maps from the detection processor. It then stabilized detections into inertial space using inertia measurement unit data to correlate detections to form sensible tracks. These tracks were monitored over time, with those tracks exhibiting sufficiently low line-of-sight rates being declared as CAs.

Figure D-12. Chassis Enclosing Detection and Tracking Processors

Figure D-13 shows the average track and declaration ranges for several engagements with two different intruder types. The lower pair of bars reflects the average range when the MITL SAA system first began tracking the intruder. The upper pair of bars shows when those tracks were declared as alarms. Obviously, the larger intruder (Convair) was tracked and declared (on average) before the smaller intruder (King Air).
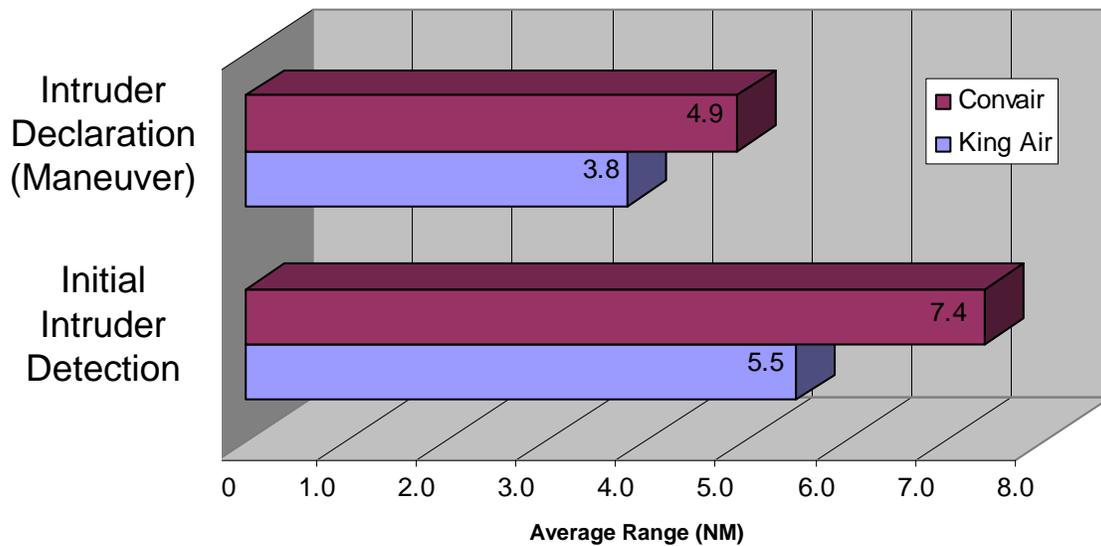

Figure D-13. Average Intruder Track and Declaration Ranges

D.2.8 THE SAA ATD PHASE II.

The purpose of the SAA Phase II ATD, managed by AFRL/Air Vehicles Directorate (VA), was to demonstrate autonomous collision avoidance of both cooperative and noncooperative intruders. Major components of the SAA Phase II ATD were an early version of the prototype MITL SAA system from DRA and the passive ranging and CA system software from Northrop Grumman Corporation (NGC). To permit communication between DRA's system and NGC's system, DRA added an ARINC 429 avionics communication bus to the output side of the tracking processor. Information about intruding aircraft detected by the MITL SAA system were

passed across this communication bus to allow an appropriate avoidance maneuver to be selected by the NGC algorithms.

D.2.9 MULTIMODE CA SYSTEM.

DRA is also executing additional related programs to further develop an overall SAA system. In March 2007, the multimode collision avoidance system (M^2CAS) program was demonstrated in conjunction with Aviation Communication and Surveillance Systems (ACSS), by joining the cooperative traffic alert and collision avoidance system (TCAS) and noncooperative (SAA) CA technologies (Taylor and White, 2005). CA data was accepted by the M^2CAS prototype from both systems. This data was correlated and then displayed on a TCAS-like display, shown in figure D-14, using TCAS-derived symbology. The result was a system that provided a more robust source of CA data to the operator, using an already-proven display method and reducing operator workload. The system was housed in a TCAS-type chassis, shown in figure D-15.

Figure D-14. The M^2CAS Demonstration Display

Figure D-15. The M^2CAS Chassis Housing TCAS and Data Fusion Functions

D.2.10 THE ATDSS III.

Phase III of the ATDSS III program is ongoing and involves a demonstration on the Aerostar UAS. This demonstration will be of a complete SAA capability with auto-airborne collision avoidance system (ACAS) algorithms for autonomous collision avoidance. Funded by the 46th Test Group and jointly executed with New Mexico State University (NMSU), demonstration flights for this program were scheduled for December 2007. For the demonstration, intruder

range is conservatively assumed rather than measured or estimated. This means the avoidance maneuver will be earlier than necessary, but it demonstrates feasibility and provides hooks for a range estimation capability, which can be either active or passive. Specific program objectives are to:

- Demonstrate autonomous DSA

    - Quantify performance of autonomous SAA

        - Avoidance maneuver effectiveness
        - Real-time operation

    - Address issues specific to autonomous operations

        - Autonomous SAA on a UAS
        - Downlink alert and maneuver data to remote pilot

- Support ATD and other transition programs

D.2.11 SMALL UAS SAA SYSTEM.

DRA was awarded a contract in January 2007 to miniaturize its SAA technology. This contract is a multiservice initiative sponsored by the Office of the Secretary of Defense to potentially duplicate SAA operations in the National Airspace in a system with significantly reduced SWaP. The vehicle selected for this system is the Shadow UAS. This is a 3-year development program with demonstrations occurring in 2009. Specific program objectives are to:

- Duplicate SAA "sense" operations while achieving significant SWaP reductions to be compatible with UAS smaller than Predator UAS.

- Seamless integration of SAA data into UAS ground control station.

- Minimal UAS modifications.

- Document small UAS SAA performance requirements and system specifications.

- Determine the feasibility of this technology on a variety of airframes.

D.2.12 PREDATOR INTERIM CAPABILITY.

In 2005, DRA received a contract to further develop their SAA ATD system to fabricate "strap-on" SAA kits for the MQ-1 Predator UAS. This is a 3-year program, with kit delivery in the final year. Specific program objectives are to:

- Integrate the SAA ATD system on a MQ-1 Predator UAS.

- Demonstrate the system using a combination of simulation and flight tests on a Commander and MQ-1 Predator UAS.

- Initiate an operationally suitable design for transition to fielded UAS.

D.3 SYSTEM DEVELOPMENT AND DEMONSTRATION.

The baseline Global Hawk SAA system is scheduled to begin development in 2008 with flight testing in approximately 2010-2011 and other Department of Defense (DoD) platforms (i.e., Predator B, Mariner, etc.) potentially have similar timing. Global Hawk's baseline SAA system will provide DRA's passive sensing capability combined with an active sensor, an integrated pilot display, and traffic warning consisting of a fused solution from noncooperative and cooperative collision avoidance equipment.

Integration of automatic avoidance algorithms to the SAA system will provide avoidance decision and maneuvering cues to the aircraft system to support autonomous CA capability. A notional system architecture, which similarly applies to Predator and other platforms, is shown in figure D-16.

At all phases, this SAA system will assist in easing restraints on access to civil airspace and collection of data necessary to support eventual certification of SAA capability. All design efforts will attempt to comply with anticipated civilian certification requirements, with the prospect of delivering a system certifiable for routine NAS operations in the year 2013-2015 timeframe, dependent on standards targeted for FAA publication in 2013.
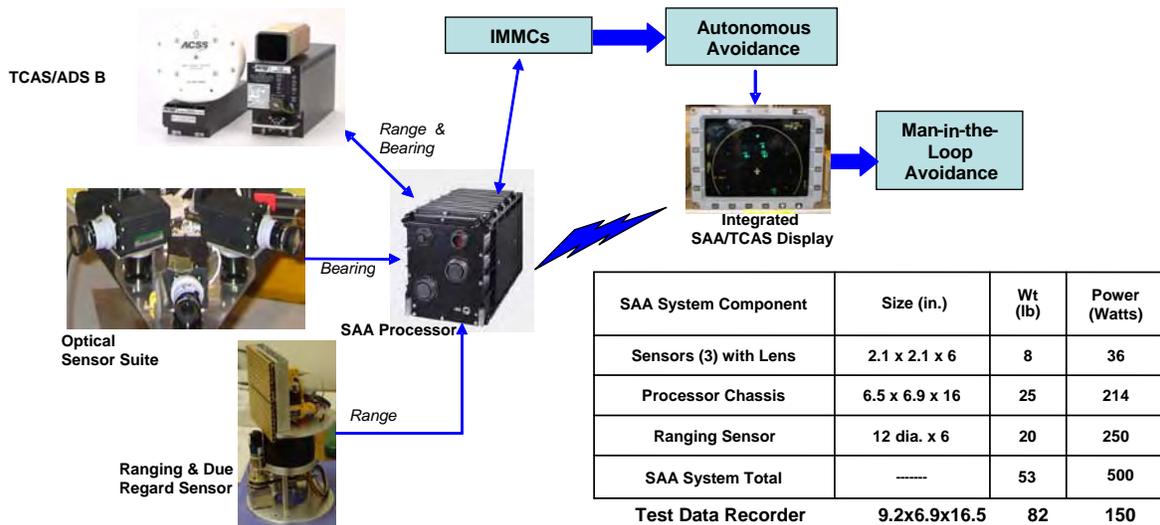

SAA System Component	Size (in.)	Wt (lb)	Power (Watts)
Sensors (3) with Lens	2.1 x 2.1 x 6	8	36
Processor Chassis	6.5 x 6.9 x 16	25	214
Ranging Sensor	12 dia. x 6	20	250
SAA System Total	-------	53	500
Test Data Recorder	9.2x6.9x16.5	82	150

Figure D-16. Global Hawk Integrated SAA

<u>D.3.1 SAA CONFIGURATION FOR SYSTEM DEVELOPMENT AND DEMONSTRATION</u>.

The SAA configuration at system development and demonstration (SDD) entry uses a virtual machine environment (VME) detection processor, shown in figure D-17, and a VME single-board computer. These two boards are installed in a dedicated chassis or a larger chassis housing other functions, depending on platform needs, but using a dedicated chassis eliminates the need for recertification of current platform processors (see figure D-16 for initial SWaP information.) SDD design includes addition of a pressurized sensor enclosure and associated heating elements necessary to meet environmental requirements. These environmental control components are excluded from the above SWaP table.

Figure D-17. The VME Detection Processor Card

Integration of SAA with the active radio frequency sensor provides the added benefits of dissimilar sensor redundancy (increased reliability through assured data availability), continued sense capability under many failure conditions, decreased likelihood of false alarms, improved traffic awareness to the operator through a single display/warning capability, and increased accuracy of SAA avoidance logic. Integration of M^2CAS functionality supports fusion of noncooperative data (passive and active SAA sensors) and cooperative (TCAS and/or automatic dependent surveillance-broadcast (ADS-B)) data. All are positives in supporting eventual certification of SAA capability.

With consideration for environmental qualifications, COTS technology will be leveraged to package the system, using components and enclosures typical to commercial and aerospace applications. Based on platform-provided environmental data, DRA's system will complete environmental qualification testing to provide a flight-ready capability in time to support fiscal year 2010 flight demonstration.

D.4 PREDICTED SYSTEM PERFORMANCE.

DRA's SAA hardware and software are predicted to meet all defined requirements given the maturity path and risk reduction program outlined above. Sensor implementation provides a FOR of ±110° horizontally and ±15° in elevation, and a bearing accuracy of ±1° is achieved for target detection. Recent test data (though limited, and analysis is ongoing) indicates a probability of declaration of 1.00 for the scenarios flown within visual metrological conditions. The above risk reduction program will improve track declaration range to approximate the average 6.3-nm track range, depicted in figure D-14, above predicted requirements. Data fusion will also benefit declaration range.

DRA risk reduction efforts will continue to reduce the false alarm rate (internal to the DRA system) balanced with the need to assure sensitivity sufficient to achieve adequate detection range. One of these efforts includes adding a priority score for existing tracks so that false alarms are differentiated from intruder alarms. Only those tracks with a priority score in the intruder class will be sent to the autonomous algorithms for maneuver consideration. Fusion of data from TCAS, ADS-B, active sensor component, etc. will also assist in reducing the false alarm (or false maneuver) rate to a level sufficient to meet system operational requirements.

D.5 SUMMARY.

DRA's efforts in the field of SAA for UAS has resulted in a capability on the brink of readiness for transition and use on DoD platforms. Programs executed through AFRL and the 46th Test Group from 2001 though the present have aided the UAS community in determination of SAA requirements as well as the development and demonstration of a real-time, noncooperative passive sensor/processor SAA system. Multiple efforts continue to evolve SAA technology for common application to small and large UAS, for seamless integration of cooperative and noncooperative collision avoidance, and to demonstrate improved performance in an autonomous mode of response.

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