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Approaches for Autonomous Vehicles in Civil Airspace: Giving Sight to the Blind

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To the Graduate Council:

I am submitting herewith a thesis written by Nicholas Scott Hardman entitled "Approaches for Autonomous Vehicles in Civil Airspace: Giving Sight to the Blind." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Richard J. Ranaudo, Major Professor

We have read this thesis and recommend its acceptance:

Ralph D. Kimberlin, U. Peter Solies

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew_________
Vice Chancellor and
Dean of Graduate Studies

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Approaches for Autonomous Vehicles in Civil Airspace:

Giving Sight to the Blind.

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Nicholas Scott Hardman
December 2005

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Abstract

The growing prevalence of unmanned aerial vehicles (UAVs) brings great potential for public benefit, but in order to fly in civil airspace UAVs must avoid traffic without the benefit of an onboard human. Developing this capability presents many system integration challenges.

This report examines the integration of automated detect, see, and avoid (DSA) systems on aircraft. For context, the need for UAV operations is reviewed. The report then examines how DSA fits into the entire framework for aviation safety. The research, test results, and conclusions that follow provide the necessary information to decide:

- how to test and evaluate new DSA technology;
- what is the necessary performance for installed DSA systems;
- what is currently available and what possibilities are in development.

Finally, after surveying available technologies, recommendations are given for some specific UAV platforms and missions.

This report would be useful for persons engaged in DSA development, acquisition, or testing. It is applicable for all small aircraft because future advances may make DSA technology feasible for the entire aviation community. The emphasis, however, is on enabling safe UAV operation world-wide.

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List of Abbreviations

ACARS	Aircraft communication and reporting system
ACAS	Aircraft collision avoidance systems
ADS-B	Automated Dependent Surveillance, Broadcast
AFRL/SN	Air Force Research Laboratory Sensors Directorate
AIP	Aeronautical Information Publications
ANR	Israeli Air Navigation Regulations
ATC	Air traffic control
ATDSS	Air traffic detection sensor system
ATM	Air traffic management
ATS	Air traffic service
AUVSI	Association for Unmanned Vehicle Systems International
BASI	Former name for Australian Traffic Safety Board
bps	Bits per second
CAAI	Civil Aviation Administration of Israel
CAR	Canadian Aviation Regulations
CASA	Civilian Aviation Safety Authority, Australia
CNS	Communication, navigation, surveillance
COA	Certificate of Authorization
DGAC	Direction General de l'Aviation Civile, France
DOE	Design of experiments
DRA	Defense Research Associates, Inc.
DSA	Detect, see and avoid, (alternatively detect, sense and avoid)
EASA	European Aviation Safety Authority
ECAC	European Civil Aviation Conference
EHS	Enhanced surveillance
ELOS	Equivalent level of safety
ELS	Elementary surveillance
EMI/EMC	Electromagnetic interference/compatibility
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FANS	Future air navigation system
FAR	Federal Aviation Regulations
FOR	Field of regard
FOV	Field of view
GCS	Ground control station
GNSS	Global navigation satellite system
GPS	Global positioning system
HALE	High altitude, long endurance
ICAO	International Civil Aviation Organization
IFR	Instrument flight rules
IMC	Instrument meteorological conditions
INTA	Instituto Nacional de Técnica Aeroespacial, Spain

IR	Infrared
IRST	Infrared search and track
JAA	Joint Aviation Authority
LADAR	Laser detection and ranging
Laser	Light amplification through stimulated emission of radiation
LBA	Luftfahrt-Bundesamt, Germany
LIDAR	Light detection and ranging
LOS	Line of sight
MALE	Medium altitude, long endurance
MMI	Man machine interface
MMW	Millimeter wave
MR	Maintenance ratio
MSL	Mean sea level
MSSI	Multispectral Solutions Inc.
MTBF	Mean time between failures
NAS	National airspace (system)
NASA	National Aeronautics and Space Administration
NfL	Nachrichten für Luftfahrer, Germany
NOTAM	Notice to airmen
NVG	Night vision goggle
OASys	Obstacle awareness system
PANS	Procedures for air navigation services
RA	Resolution advisory
ROA	Remotely operated aircraft
RPA	Remotely piloted aircraft
RPV	Remotely piloted vehicle
RTCA	Radio Technical Commission for Aeronautics
SARPs	Standards and Recommended Practices
SATCOM	Satellite communication
SIVA	Sistema integrado de vigilancia aérea
SSR	Secondary surveillance radar
STDMA	Self-organizing time division multiple access
SUPPs	Regional Supplementary Procedures
TA	Traffic advisory
TAS	Traffic advisory system
TCAS	Traffic collision avoidance system
TIS-B	Traffic information services, broadcast
UAT	Universal access transceiver
UAV	Unmanned aerial vehicle, (alternatively uninhabited aerial vehicle)
UHF	Ultra high frequency radio
UWB	Ultra-wideband
VDL	VHF Data link
VFR	Visual flight rules
VHF	Very high frequency radio
VMC	Visual meteorological conditions

List of Symbols

ϕ	Bank angle
σ	Radar cross section (RCS)
Θ_R	Angular resolution
A	Antenna area
Ψ	Azimuth angle (also AZ)
b	Unalerted straight-line flight path
c	Speed of light
D	Detector aperture diameter
Θ	Elevation angle (also EL)
f	Frequency
$f_{s,\ co}$	Spatial cut-off frequency
g	Acceleration due to gravity
G	Antenna gain
n	Load factor
P	Power
R	Range
ρ	Reflectivity
s	Alerted flight path on an arc
S	Signal energy
t_{c-}	Time before collision
t_f	Final time
t_{ot}	Time on target, dwell time, or integration time
t_p	Propagation time
t_r	Scan time
η	Transmissivity
v	Velocity
λ	Wavelength
W_R	Linear resolution

Introduction

Numerous aviation accident investigations have concluded that unaided pilots are not capable of satisfactorily avoiding each other in today's airspace;[1] therefore, computer assistance in the form of collision avoidance systems are now mandatory on all commercial aircraft.[2] Whether desired or not, computers are very good at helping humans avoid one another. Though the human without the computer may be insufficient, currently the reverse is also true.

The growing prevalence of unmanned aerial vehicles (UAVs)[*] brings great potential for public benefit, but in order to fly in civil airspace[†] UAVs will require the ability to detect, see, and avoid (DSA)[‡] traffic without the benefit of an onboard human. Doing this presents many system integration challenges unique to typical UAV platforms. While there is a very large variety of UAV platforms, most are designed for operations at relatively low speed, low maneuverability, and medium altitude. They are frequently propeller (or rotor) driven with light payloads.

This report examines the integration of DSA systems on such aircraft. The research, test results, and conclusions provide the necessary information to decide:

- how to test and evaluate new DSA technology;
- what is the necessary performance for installed DSA systems;
- what is currently available and what possibilities are in development.

Section 1 examines the motivation for these efforts with a brief look at current and proposed UAV applications needing access to controlled airspace. **Section 2** discusses the four layers of traffic safety and current issues that affect DSA system development.

Discussion of Terms:

[*] Some sources use the alternate terms: remotely piloted vehicles (RPV), remotely piloted aircraft (RPA), remotely operated aircraft (ROA), or un*inhabited* aerial vehicles. In Europe, acronyms for terms translated as "aircraft not crewed" are normal. There is no universal agreement. In this report, the term UAV will be used throughout to mean any airborne vehicle that does not have a human being onboard.

[†] Civil airspace is used to define that airspace under the control of the civil aviation authority of a particular country, sometimes called the national airspace system (NAS), as compared to restricted or special use airspace. NASA has undertaken a similar project called Access 5. Eurocontrol has undertaken a similar project called UAV Safety Issues for Civil Operations (USICO).

[‡] Some sources use the alternate terms: sense-and-avoid (SAA), non-cooperative collision avoidance, or autonomous avoidance systems. "See-and-avoid" is the primary term used in regulatory sources. In this report the term DSA will be used throughout to mean any concept or system in effect for the primary purpose of preventing collisions between aircraft that have not been deconflicted by other means.

Section 3 proposes a complete list of evaluation topics for DSA systems. These are defined in quantifiable terms so that they are useful for requirements documentation and test plan generation. In **Section 4** an assessment of the necessary performance for DSA systems is presented and justified. This is recommended as guidance for the creation of threshold and objective criteria. **Section 5** is an evaluation of the current state of the art[§] and **Section 6** provides some recommendations based on platform type and the necessary requirements presented in Section 4.

[§] The mention of specific companies or products in this report is for illustrative purposes only and does not constitute an endorsement by the author.

1. Background

A review of current and potential UAV applications reveals how important it is to overcome the challenges that currently prevent routine flight operations.

1.1. Demand for UAVs in Civil Airspace

UAVs offer the possibility of operating: for very long periods, at very high altitudes, doing tasks too tedious or repetitive for humans, in environments deemed too dangerous for humans, at a significant cost savings to piloted aircraft or satellites based systems. However, in the same way their autonomous operation makes them very useful, it makes them controversial. Some see them as an unwarranted safety risk. This section is not an attempt to win over critics but to define the public benefit of such operations as a reference when evaluating DSA options. The following missions are the end goals to keep in mind when weighing complex trade offs. If an option makes UAV flight possible but too restricted for the following missions, then it is not a true solution.

1.1.1. Commercial Applications

The most visible and direct public benefit will be commercial applications. Already some UAVs, such as the Rmax in Japan, are being used in agricultural applications. Plantations in Hawaii have also used UAVs in the same way. Other services that may one day be the work of UAVs include: telecommunications, television and radio broadcasting, real time news reporting, and aerial photography. In addition many private companies will be able to make use of the inexpensive flight time for applications such as: urban planning, exploration, surveying, and remote area security/safety.

1.1.2. Civil/Government Applications

The low cost eye-in-the-sky capability promises to increase security and assist government agencies through applications such as: border patrol, counter narcotics, counter terrorism, traffic management, surveillance of infrastructure (pipelines, airports, railways, roads, waterways, etc.), communications relays, and airborne crime reconnaissance. One current example is SIVA (Figure 1). The Spanish government plans to expand the use of these small inexpensive UAVs for many civil and government applications including search and rescue and forest fire patrol.[3] In addition UAVs can contribute to fishing regulation enforcement, animal and environmental monitoring, and atmospheric research.

One specific example of future possibilities is the Altair (Figure 2) made by General Atomics Aeronautical Systems, Inc. It is a civilian derivative of the Predator B now in operation for the military. The company hopes it will be the first UAV to meet all requirements for routine operation in the national airspace. In addition to redundant avionics and flight control systems, Altair has a traffic collision avoidance system and an air traffic control voice relay. The relay allows air-traffic controllers to talk to ground-based Altair pilots through the aircraft.[4]

Figure 1: SIVA (Spain)
(Source: INTA website,
Permission granted)

Figure 2: Altair (USA)
(Source: GA-ASI website,
Permission granted)

1.1.3. Military Applications Requiring Civil Airspace

The militaries of many nations are currently using, and expanding the use of, a plethora of unmanned vehicles on land, sea, air, and space.[5] New UAV platforms are expected to grow at an even more accelerated rate in the next few decades.[6]

Though their wartime operations are much different, these UAVs still have a requirement to integrate into civil airspace for transit and training. Some combat aircraft already possess airborne surveillance systems of some type. This precludes the need for a separate system to be installed just for DSA, but it will require some modification. There may be problems with getting approval for civilian use without compromising the classification of the military application. Also, there are multiple examples in the piloted aircraft world where the lack of accommodation to civil aviation requirements has created tension and safety concerns for military aircraft (e.g. F-15s equipped with UHF-only radios). Also, in keeping with the new mandates on technology insertion, rather than new technology development, many military programs will likely be pressed to pursue commercial off the shelf options. For all these reasons, any attempt to create military-specific DSA requirements or specialized systems should only be done after a complete analysis of alternatives.

2. Layers of Safety

The true solution for safer, and more accessible, skies will be a composite solution consisting of technical advancements and procedural changes that accommodate new technology. As mentioned, this report examines the total framework of air safety. By design, there are four layers that maintain safe operations in aviation. They are:

1. Administrative
2. Air traffic service (ATS)
3. Cooperative avoidance systems
4. Detect, see and avoid (DSA)

Individual aircraft development programs do not have influence over the first two layers, but program managers should be mindful of how new policies will influence the performance requirements of their specific program. Technical changes at any level must be accommodated by regulatory changes to be effective, and those changes need to be global to be truly successful. The proposed evolution of air traffic control into air traffic management would effectively swap roles between layers 2 and 3 as the ground-based staff move away from active control and the networked aircraft perform more automated route deconfliction. Such is the concept called "Free Flight".

2.1. Administrative

The administration of air transportation is the primary method for maintaining the safe and orderly flow of air traffic. This is done by regulating the airspace, air operations, and certification of new systems. Compared to other layers, it is low tech and low cost. Wise changes here save money and reduce demand on all lower levels. However, this layer is neither dynamic (except in the case of NOTAMs) nor flexible.

Most nations have their own agencies to govern air traffic in the airspace they control. These agencies have the authority to enforce the regulations adopted by their respective governments. Table 1 lists the agencies and governing documents for areas with high levels of UAV activity.

Table 1: Chart of Regulatory Agencies and Documents World-wide

Country	Organization	Regulation
Australia	Civilian Aviation Safety Authority (CASA)	Civil Aviation Legislation
Europe (34 Member States)	European Aviation Safety Authority (EASA), European Civil Aviation Conference (ECAC) Joint Aviation Authority (JAA)	European Organization for the Safety of Air Navigation (Eurocontrol), European Organization for Civil Aviation Equipment (EUROCAE)
Israel	Civil Aviation Administration of Israel (CAAI)	Israeli Air Navigation Regulations (ANR)
United States	Federal Aviation Administration (FAA)	Federal Aviation Regulations (FAR)

The International Civil Aviation Organization (ICAO), a United Nations agency, works to harmonize air regulations world-wide through the creation of Standards and Recommended Practices (SARPs). Nations that have agreed to follow the Convention on International Civil Aviation are called contracting states. Almost all controlled airspace in the world falls under the jurisdiction of one of the 188 current contracting states.

SARPs consist of two parts: A *standard* is the specification of anything that is <u>necessary</u> to be uniformly applied for safe and orderly international air navigation. Contracting states are to comply with such standards or notify ICAO why they are unable. A *recommended practice* is the specification of anything that is <u>desired</u> to be uniformly applied for the safe and orderly international air navigation. Contracting states are to endeavor to conform and are invited to inform ICAO of non-compliance. Where needed, Procedures for Air Navigation Services (PANS) are created to amplify SARPs.

Under the Universal Safety Oversight Audit Program, ICAO performs regular mandatory audits to verify safe implementation of all SARPs. Contracting states that chose to not comply with SARPs and PANS are to publish their differences in the Aeronautical Information Publications (AIP). Also, regional supplementary procedures (SUPPs) can be made that have authority for only a particular area.[7]

UAVs currently have to perform the complete coordination process of each country for any airspace they fly through.[8] An ICAO-sponsored standard regarding UAV operations would not only make flight planning much easier, but it would increase aviation safety by creating consistent procedures world-wide.

2.1.1. Airspace

One of the primary ways that the before mentioned agencies aid in conflict avoidance is by defining airspace. Table 2 explains the internationally designated airspace categories. Pilots are required to practice see-and-avoid at all times, but the responsibility for conflict avoidance changes with the type of airspace.[9] In addition, there is a speed limitation of 250 knots below 10,000′ MSL and 200 knots in Classes C & D.

In theory this makes a very straightforward classification of the area above land; however, due to factors ranging from the geographical to political, the actual implementation of airspace is not so straightforward. The airspace over the European continent is quite fragmented.

The ECAC is pursuing a more simplified airspace allocation plan called the Single European Sky proposal. In this proposal, ECAC introduces their plan for creating a Corresponding Traffic Environment which redefins the existing airspace into only three types of airspace by 2010[10]. The types are defined as:

N: Intended Traffic Environment. All traffic position and intentions known to ATS
K: Known Traffic Environment. All traffic position known to ATS.
U: Unknown traffic Environment. Not all traffic is known to ATS.

Table 2: ICAO Airspace Designations and UAV Operations (Source: ICAO Annex 11, Appendix 4)

Class	**Flight Ops**	**ATC equipment & services Provided**	**Com. Required**	**Transponder Required**	**UAV integration problems**
A	IFR only	Radar Conflict resolution & separation	Yes	Yes	None ACAS, data link primary
B	IFR/VFR By permission	Radar Conflict resolution & separation	Yes	Yes	Moderate problem due to high traffic density, ACAS, data link primary
C	IFR/VFR After contact	Radar Separation (IFR), or traffic advisories (VFR)	Yes	Yes	Possible problem due to high traffic density, ACAS, data link primary
D	IFR/VFR After contact	Tower Separation (IFR)	Yes	No	ACAS insufficient, *DSA system primary*
E	IFR/VFR	Separation (IFR)	Yes	No (<10,000′)	ACAS insufficient, *DSA system primary*
F	IFR/VFR	Traffic advisories (IFR)	No (<10,000′)	No (<10,000′)	ACAS insufficient, *DSA system primary*
G	VFR	None	No (<10,000′)	No (<10,000′)	Moderate problem due to lack of ATC coverage, *DSA system primary*

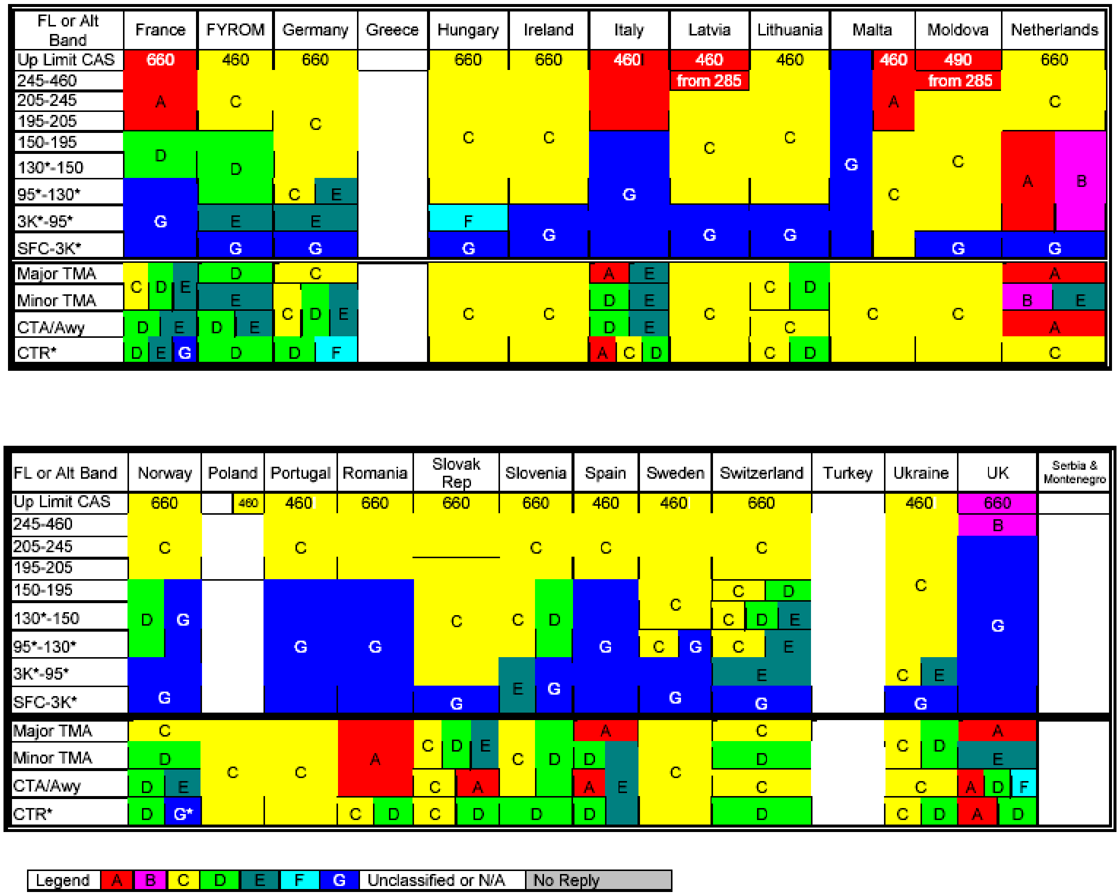
Figure 3 illustrates the lack of standardization in European airspace. In anticipation of the migration from that to the Single European Sky proposal shown in Figure 4, European countries have implemented new requirements. Mode S capable transponders are now required for all new aircraft in Class A, B, or C airspace higher than 5,000′ MSL. They will soon be required for all aircraft except in remote locations. Flying at night or in IFR now requires transponders everywhere and for all aircraft.[11]

2.1.2. UAV Operations

Currently, UAVs are restricted to special use airspace. Permission to fly outside of these designated airspaces requires special notification. In the US, the FAA requires a certificate of authorization (COA) which requires at least a 30-day notice to local administrators, visual meteorological conditions (VMC)[**], a route clear of all populated areas, and constant ground control by a certified pilot.[12]

Military units pushing for more UAV access to civil airspace have recently been helped by advances in the commercial UAV market. This has led to an increased frequency of permitted UAV flights into civil airspace.

[**] Instrument Flight Rules (IFR), Visual Flight Rules (VFR), Instrument Meteorological Conditions (IMC), and Visual Meteorological Conditions (VMC) are defined more completely in FAR 91.



FL or Alt Band	France	FYROM	Germany	Greece	Hungary	Ireland	Italy	Latvia	Lithuania	Malta	Moldova	Netherlands
Up Limit CAS	660	460	660		660	660	460	460	460	460	490	660
245-460	A	C	C		C	C		from 285	C	G A	from 285	C
205-245								C			C	
195-205												
150-195	D	D					G			C		A B
130*-150												
95*-130*	G		C E									
3K*-95*		E	E		F	G		G	G			
SFC-3K*		G	G		G						G	G
Major TMA	C D E	D	C		C	C	A E	C	C D	C	C	A
Minor TMA		E	C D E				D E					B E
CTA/Awy	D E	D E					D E		C			A
CTR*	D E G	D	D F				A C D		C D			C

FL or Alt Band	Norway	Poland	Portugal	Romania	Slovak Rep	Slovenia	Spain	Sweden	Switzerland	Turkey	Ukraine	UK	Serbia & Montenegro
Up Limit CAS	660	460	460	660	660	660	460	460	660		460	660	
245-460	C		C	C		C	C		C		C	B	
205-245												G	
195-205					C			C					
150-195	D G		G	G		C D	G		C D				
130*-150									C D E				
95*-130*								C G	C E				
3K*-95*	G					E G		G	E		C E		
SFC-3K*					G				G		G		
Major TMA	C	C	C	A	C D E	C D	A	C	C		C D	A	
Minor TMA	D						D E		D			E	
CTA/Awy	D E				C A		A		C		C	A D F	
CTR*	D G*			C D	C D	D	D		D		C D	A D	

Legend	A	B	C	D	E	F	G	Unclassified or N/A	No Reply

3K* = FL55/ Alt 1,000 /1,500 /2,000 /2,500 /3,000 /3,500 /5,000 (ft AGL/AMSL)
95* = FLs 75/95/100/ Alt 7,500
130* = FLs 115/125/130/135
CTR* = CTR/ Aerodrome Zone
G* = G or G with special conditions

Figure 3: European Airspace Designation by Country (Source: Eurocontrol website)

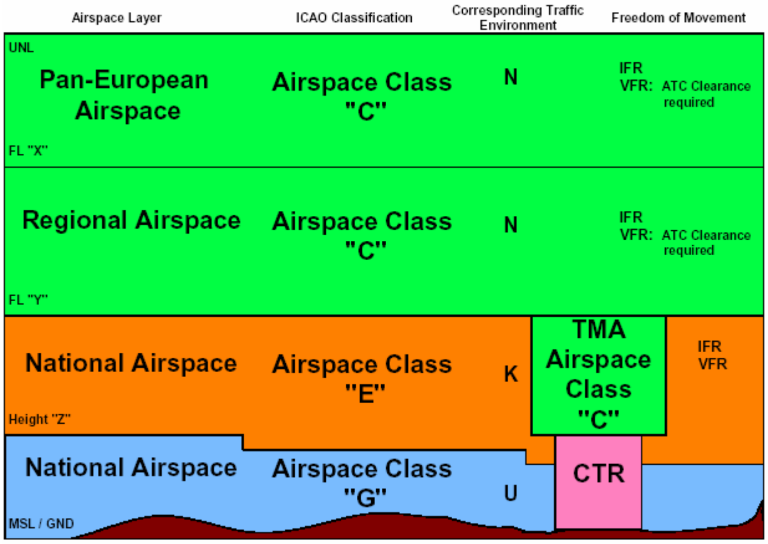


Figure 4: Single European Sky Concept
(Source: Eurocontrol website)

The current policy heavily dampens UAV usage. Some UAV operations will always remain in special use airspace (e.g. experimental tests and target drones), but even specialized UAVs need better access to the air route system for transition to/from areas of operation. UAVs could blend in with traffic operating under instrument flight rules (IFR) with no need for modified regulations. In reality, UAVs would have less impact on airspace congestion than other types of traffic as their automation will make them more precise and predictable than piloted traffic. Their full intentions can be known and deconflicted well in advance. In addition, UAVs, with their different mission, will largely stay clear of high traffic areas.

From a UAV access perspective, Class A does not present a particular difficult problem as air routing solves the problem. The American UAV Global Hawk is already given frequent approval to travel at high altitudes over most of the world and with a minimum of pre-coordination.[13] Even with this, however, Global Hawk must first climb to altitude within restricted airspace.

With an installed collision avoidance system, as discussed in Section 3, safe UAV operation in Class B or C is technically possible. As with other aircraft, they would only be necessary for short transitions. Due to the high traffic volume, however, there is likely to be opposition to granting access to UAVs.

Accommodation in Class D and E, and G (and in Europe, F), is a problem because aircraft flying under VFR at lower altitudes are not required to have transponders. It is the presence of these aircraft, and the freedom that they enjoy, that presents a challenge for UAVs to join the skies. As discussed in Section 2.3, a collision avoidance system is not sufficient for traffic deconfliction. These same areas are the primary operating region for small UAVs. These areas have lower traffic densities, but, except for Class G, they will still have ATS control. Class G is the most problematic as there are no requirements for radar coverage or communication.

Under the proposed European airspace designations there would be little or no difficulty integrating UAVs into Class N and Class K. Class U would present all the same challenges of the current Class E (below 10,000′), Class F, and Class G.

2.1.3. Certification

Another way that aviation agencies increase safety is through their certification processes. As discussed in the previous section, ICAO SARPs and detailed annexes provide commonality for certification, but the individual agencies actually grant the certifications. The multiple approval processes include: registration, airworthiness, aircrew/operator licensing, and facility certification.[14]

Many of the regulations covering these certifications will only require minor changes to accommodate UAVs. The UAV community should make every effort to conform to already established certification requirements; however, there are currently no common airworthiness requirements for UAVs.[15] When creating regulations for UAVs certification and operation, it will be important for UAVs to be categorized by the ICAO definition of aircraft. One near term possibility is to use the restricted category as defined in FAR 21.25 & 91.313 to allow operation but to prohibit some airspace.

It is reasonable for a tiered structure for avionics capabilities based on UAV class. This is analogous to the differences in regulation between crop dusters and transatlantic airliners. The challenge, though, is to make a reasonable classification of the plethora of UAVs. At the Spanish test center in Torrejón, and in other agencies under Eurocontrol (See Table 1), UAVs are grouped similarly to that shown in Table 3.

Table 3: Proposed UAV Classification

Class	Description	Current Example	Operating Altitude [ft]	Range Restriction	Cruise Speed [kts]	Max Weight [lb] or [kg]	
3	High Altitude, Long Endur. (HALE); Stratospheric	Global Hawk, Aerosonde	>35,000	Beyond LOS	>250	>4500	>2000
2	Medium Altitude, Long Endur. (MALE);	Eagle, Predator	35,000	Beyond LOS	< 250	4500	2000
1	Short range	SIVA, ALO, Pioneer	18,000	LOS only	< 150	1100	500
0	Mini, and micro	R-Max, MicroStar	<1,000	LOS only	< 100	45	25

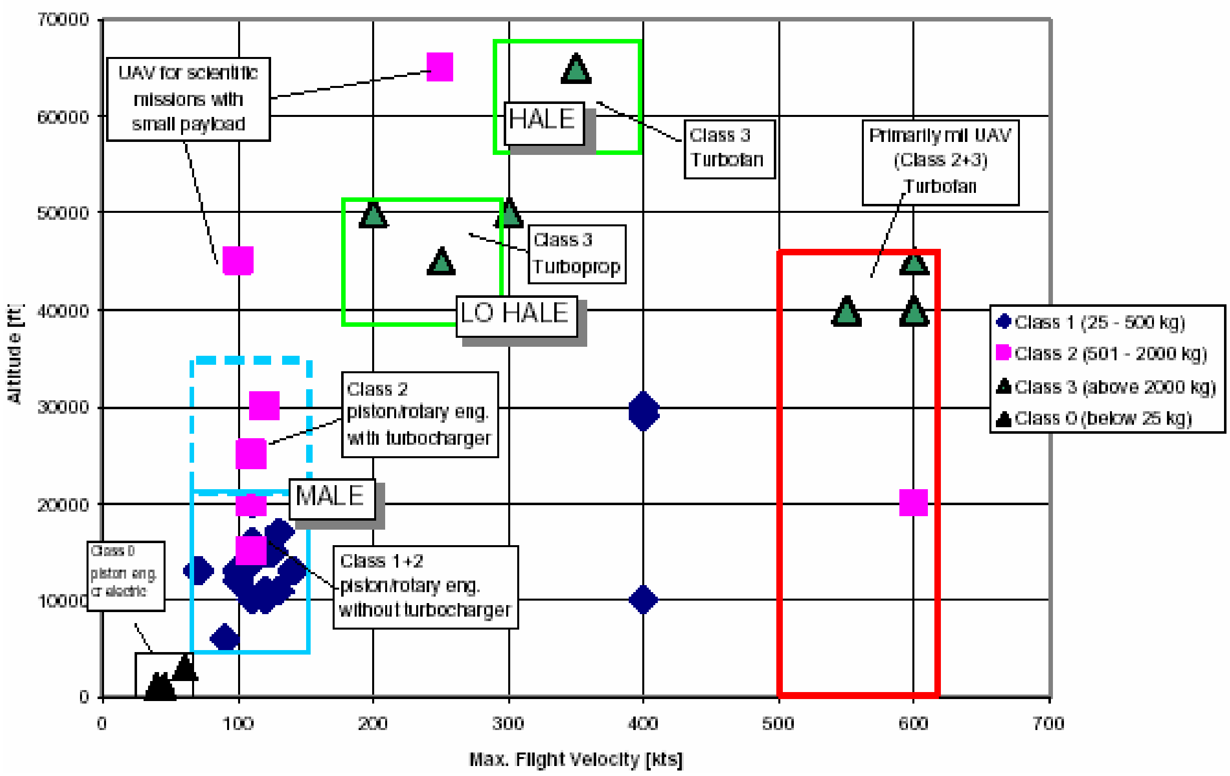


Figure 5: UAV Categorization by Flight Envelope Location
(Source: Eurocontrol IABG Report, 2001)

Other classifications exist, but this grouping emphasizes the significant differences for purposes of airworthiness and air traffic regulations. A UAV should be classified by whatever parameter gives it the highest classification with respect to altitude. Figure 5 is taken from a study sponsored by Eurocontrol which draws a correlation among existing UAVs between weight and the performance envelope. This reinforces that UAVs can be effectively classified as in Table 3. The grouping is important because it allows regulations to be constructed that are realistically safe but not too burdensome for the intended use of the vehicle.

2.2. Air Traffic Service

The second layer of safety for all aviation is the air traffic service or air traffic system (ATS). It has traditionally been referred to as air traffic control (ATC) and is now more frequently being titled air traffic management (ATM) to highlight the eventual evolution towards less controlling and more managing. Whatever the terminology used, this level is active, third party, and higher cost than the first layer. However, it is real time and flexible. Duties range from pre-coordinated flight plan filing to active radar separation. The principle technologies involved are the primary surveillance radar and secondary surveillance radar (SSR). Primary radar detects all traffic by returns of radar energy reflected from the aircraft surface. As such, it is independent but possesses less capability for situational awareness. SSR detects cooperating traffic by receiving the reply signal from the aircrafts´ transponder.

Many technical and regulatory changes are planned for the ATM world. Figure 6 shows the latest system proposal known as future air navigation system (FANS). It is heavily based on satellite communication (SATCOM) and global navigation satellite system (GNSS) technology. It is also planned to rely heavily on some type of data link such as the aircraft communication and reporting system (ACARS). The third layer, cooperative traffic avoidance, is expected to play a much larger role.[16]

How will this affect UAVs? If ever implemented, this would theoretically eliminate the need for a DSA system on UAVs. Instead, UAVs would need to implement the required data links. In reality, the need for DSA systems must still be pursued for several reasons. (1) Mandatory participation in the data link is many years off, and it is not certain. (2) When implemented, there are still likely to be regions in which general aviation aircraft are not required to participate, similar to the current regions where no transponder is required. (3) Finally, all aircraft will still need a backup capability in the event of network failures.

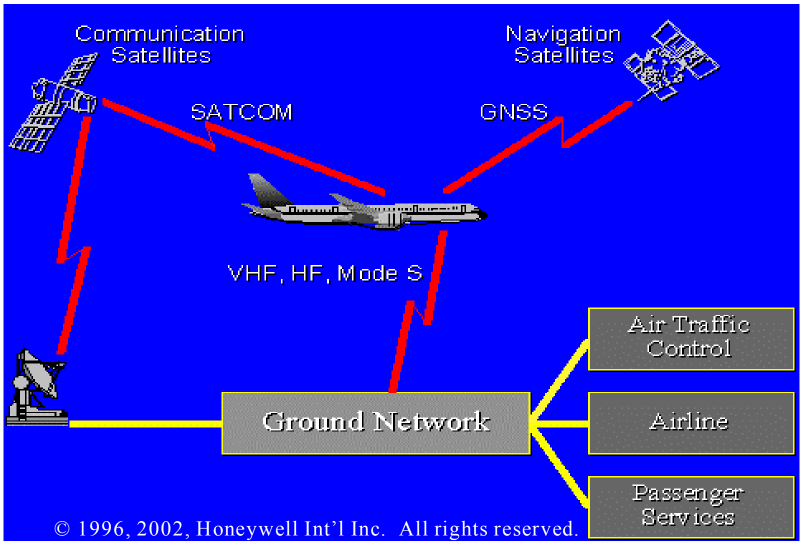


Figure 6: The Future Air Navigation System (Source: Honeywell website, Permission granted)

2.3. Cooperative Traffic Avoidance

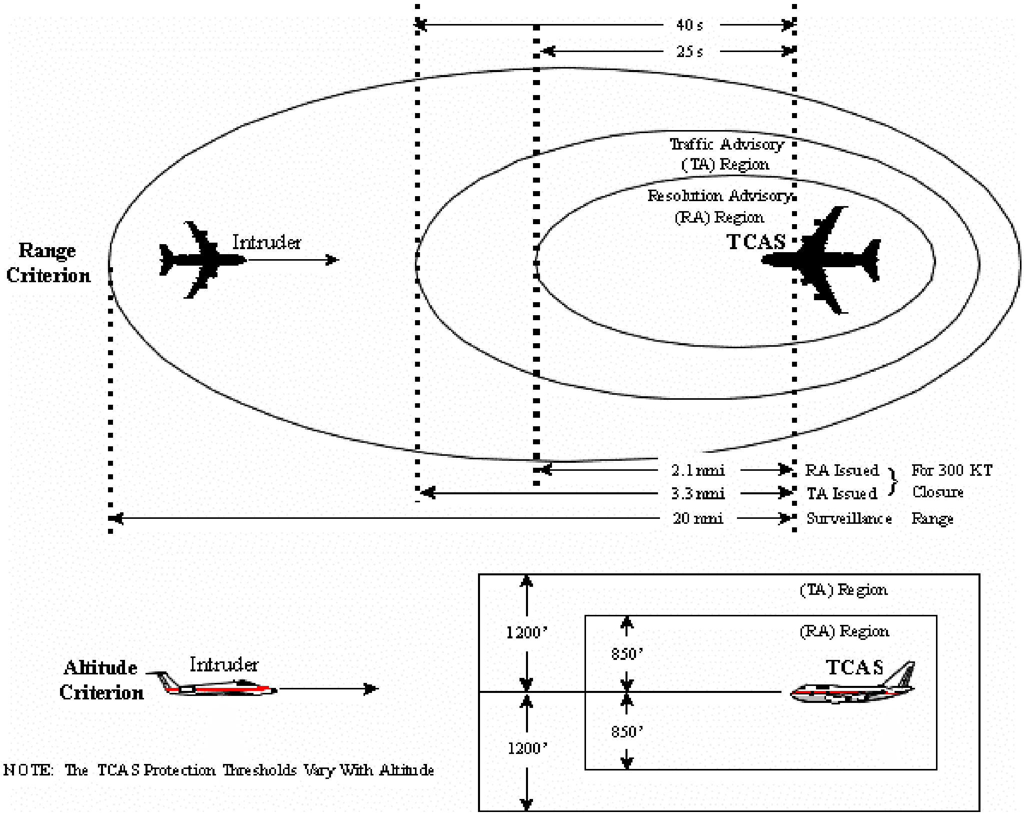
The third layer consists of onboard systems that cooperatively work to deconflict traffic. These systems are independent of, but compatible with, ATM detection systems. Such systems enable aircrews to perform deconfliction on their own. They are active, first or second person but are "high tech" and high cost. The current weakness of cooperative systems is the necessity for all aircraft involved to have a compatible functioning system. As discussed here, multiple proposals are being explored for ways to add information for traffic that is not self reporting. This has great potential as an independent automated traffic control technology.

2.3.1. Aircraft Collision Avoidance Systems (ACAS)

A more advanced system is the ACAS, formerly called traffic collision avoidance system (TCAS). As mentioned earlier they function on the signals from the transponder. The purpose of an ACAS system is to track other aircraft based on their transponder signal as shown in Figure 7. There are currently three versions of the ACAS system in use or in some stage of development; TCAS I, II, and ACAS.

TCAS I is simple and less expensive, primarily for general aviation use. It can interrogate transponders on other aircraft and indicate approximate bearing and relative altitude (for Mode-C transponders). It has a range of about forty miles. If another aircraft becomes a potential collision threat, a traffic advisory (TA) is created to alert the pilot. The pilot must visually identify the intruder and resolve the conflict or receive assistance from an air traffic controller.

TCAS II is more capable, but the cost to integrate it is about $200,000 US. This system has been required on all commercial air carriers in the United States since 1994. In addition to TCAS I capability can issue a resolution advisory (RA) to advise the pilot what evasive maneuver will deconflict the traffic. There are two types of RAs, preventive and positive. Preventive RAs instruct the pilot not to change altitude or heading to avoid a potential conflict. Positive RAs instruct the pilot to climb or descend at a predetermined rate of 2500 feet per minute to avoid a conflict. TCAS II is capable of interrogating Mode-C or Mode-S. In the case of both aircraft having Mode-S interrogation capability, the TCAS II systems communicate with one another and issue deconflicted RAs.



NOTE: The TCAS Protection Thresholds Vary With Altitude

Figure 7: ACAS (TCAS) Advisory Envelopes
(Source: Rannoch Corp. website, Permission granted)

ACAS is virtually the same as TCAS II but will allow pilots who receive RAs to execute lateral deviations as well as climbs/descents.[17]

2.3.2. Mode-S

The Mode-S data link is a related, but separate, technology development. Through this link an aircraft will be able to transmit more aircraft information than the older Mode-C. The basic implementation of this capability is called elementary surveillance (ELS) and enables aircraft identification, altitude, flight status, system capability reports, and resolution advisories. The more expensive enhanced surveillance (EHS) capabilities include reports on velocity, turning, and vertical intentions.[18]

2.3.3. ADS-B

Automatic dependent surveillance, broadcast (ADS-B) is a dependent and cooperative surveillance system that holds great promise. The principle is to automatically transmit various aircraft parameters (identification, position, intended route, and speed) via data link to other aircraft and ground stations. The recipients can then process or reject the messages based on position. While the ADS-B technology is merely a communication means, its application for airspace surveillance and traffic deconfliction is defined in the Radio Technical Commission for Aeronautics publication RTCA /DO-181A. Also, it is being examined for use with automated avoidance maneuver systems. Before implementation it would have to be integrated with current surveillance systems. EUROCONROL´s ADS program and the FAA´s Safe Flight 21 program are currently testing this data link. Three options have been proposed:

- Mode-S "extended squitter" or 1090 data link
- Very high frequency (VHF) Data link (VDL) Mode 4
- UAT (Universal access transceiver)

Mode-S is already in place and the "extended squitter" only requires a software modification whereas the other options require new equipment. For operation, the transponder transmits a data string, or squitter, that is twice as long as the current 56 bit Mode-S squitter. The total ADS-B message requires several squitters which transmit with various update rates. The system is capable of a large traffic volume, and the possible range is between 60 and 100 NM. The extended squitter protocol has been standardized by ICAO and its necessary EUROCAE/RTCA documentation has been published.

VDL Mode 4 is a self-organizing time division multiple access (STDMA) system. It is GPS synchronized, and users transmit during reserved slots based on a reservation map. Each message is 256 bits. For more capacity, a ground station can regulate usage or more frequencies can be added. VDL has very good range (140 and 200 NM), and its protocol has been standardized by ICAO and is detailed in EUROCAE/RTCA documentation. It was developed in Sweden and is supported by the Swedish Civil Aviation; however, it does not appear to be the data link of choice for either the other European or American aviation agencies.

The UAT was developed in America by MITRE. Unlike VDL Mode 4, the equipment operates on one single frequency and is capable of functioning in any aviation frequency band. It has a data exchange rate of 1 million bits per second (Mbps). In the UAT concept, users transmit a data structure, of about 3200 data slots, every second. UAT does not require synchronization and allows messages of 128 or 256 bits to be transmitted, including all information required by DO-242. The FAA has tested prototypes and has chosen it (along with the Mode-S extended squitter data link) for ADS-B; however, it has not been standardized by ICAO and no RTCA documentation has been created.[19]

Like ACAS, ADS-B requires all traffic to have working transponders. As shown in Table 2, this requirement is met in Class A, B, and C airspace, but it does not provide protection in the rest of the civil airspace where nonparticipating aircraft are allowed. This was the reason for the development of TIS-B, as described in the next section.

2.3.4. Traffic Information Services-Broadcast (TIS-B)

The FAA, as part of Project Safe Flight 21, is evaluating an additional capability called TIS-B. In this system traffic information from ground surveillance sources is broadcast to ADS-B equipped aircraft. Updates will come about every 5 to 20 seconds (as compared to every second for ADS-B broadcasts). This will complete the air traffic picture in airspace where not all aircraft are using transponders. A current advisory-only service is in use.

This system is still limited to the areas that have both radar coverage and an ADS-B broadcast source. Also, more development is needed in the processes that correlate ADS-B reports with corresponding radar returns from the same aircraft.

2.3.5. Cooperative Avoidance Options for UAVs

Small UAVs not originally designed to carry transponders can take advantage of some new developments targeted at the recreational flying community. A class of light aviation transponder has been designed and approved specifically for small aircraft. By definition it is Class 2 equipment restricted to use below 15,000′ and 175 knots, but it will fulfill the requirements of the Eurocontrol ELS and complies with ICAO Annex 10 Amendment 77. Several manufacturers are marketing them with Mode-S capability.

In order to use the information being reported by other participating aircraft, UAVs must be equipped with an ACAS or a traffic advisory system (TAS). L-3 Avionics Systems has developed a TAS, called Skywatch and Skywatch HP, specifically for small aircraft. It is low weight (11 pounds), low power (160 W), and low cost (approx. $25,000 US). It is capable of detecting cooperative traffic at distances in excess of 35 NM and generating corresponding alerts and advisories for transmission to the ground control station (GCS). This system has been tested by NASA and is being considered by the US Navy.[20] This possibility is one of the recommended alternatives discussed in Section 6.

2.3.6. Issues to "See and be Seen"

As an aside, the UAV community must improve their own "seeing and being seen". Due to their generally smaller size and lack of reflective surfaces such as windshields, UAVs make harder visual targets. While this may be desirable for military applications, it is a negative characteristic in civil airspace. Some authors have proposed incorporating things such as sequential lighting flashes and high visibility paint as passive methods to improve visibility. Also, "wing flash" maneuvers and automated radio call outs may be programmed to correspond to traffic advisories from installed DSA equipment. To date, no regulatory agencies have discussed making any of these options mandatory.

2.4. Detect, See and Avoid

The last layer of safety is the independent ability for each aircraft to detect and avoid other aircraft. In uncontrolled airspace, the inherent freedom means that all responsibility for separation lies with the pilot. In other airspace, see and avoid is still required to be practiced to the maximum extent possible. The primary example of DSA is human scanning, but some aircraft (mostly military) augment this with systems using radar or other means of detection. Ironically for UAVs, the fact that other aircraft have pilots makes it necessary for UAVs to have DSA. Relative to other layers of safety, DSA is “high tech” and high cost. Options for use are covered in Section 5.

3. DSA System Evaluations

The following is a list of evaluation topics (also called system performance parameters and system characteristics) that must be considered in order to evaluate the effectiveness and suitability of a DSA system:[21]

1. System Performance
    1.1. Time to collision
    1.2. Tracking accuracy
    1.3. Field of regard
    1.4. Integrity
2. Physical characteristics
    2.1. Size and Shape
    2.2. Weight
    2.3. Physical interference
    2.4. Power and Cooling
3. Interoperability
    3.1. Aircraft interface
    3.2. Electromagnetic interference/Compatibility
    3.3. External compatibility
4. Human factors
5. Logistics

These are quantifiable and should be addressed in any decision making process. While any unsatisfactory result is a problem, these topics are ranked in the normal order of product development. For example, new systems generally must meet performance thresholds in concept demonstrators or prototypes. Then, viable alternatives can be evaluated based on the platform-specific limitations of physical characteristics and other requirements. Evaluating these systems in the most efficient manner requires a sequential test program through laboratory, ground, and flight test phases.

3.1. System Performance

For DSA technology, the ultimate performance requirement is: *provide traffic conflict information in sufficient time to prevent midair collisions*. A test program to fully prove DSA system effectiveness in realistic scenarios would require thousands of flight hours involving many aircraft. Judicious use of design of experiments (DOE) principles can significantly reduce the test matrix while maintaining a high confidence level. Even more reductions can be made by quantifying the critical technical parameters that are necessary to achieve success and using those values as performance requirements. Using these lower-level criteria reduces time and cost because it makes laboratory and ground testing possible and reduces necessary flight testing.

3.1.1. Time to Collision

Defining a sufficient amount of reaction time is not trivial. The DSA system must detect traffic with sufficient time for the remaining evasion steps to occur. The time before collision (t_{c-}) is a function of detection range and aircraft velocity as follows:

$$t_{c-} = R/v_c \qquad 3.1$$

where:

R – Range to target at time t_{c-}

v_c – Closure velocity (or range rate).

In real life v_c is not a constant value and is based on both aircraft velocities (v_1, v_2) and the angles in azimuth (Ψ) and elevation (Θ) between the two aircraft as shown:

$$v_c = dR/dt = ((v_1 \cdot \cos(\Psi_1)\cos(\Theta_1)) + ((v_2 \cdot \cos(\Psi_2)\cos(\Theta_2)) \qquad 3.2$$

For radar systems the maximum Range (R_{max}) is given by Stimson[22] as:

$$R_{\max} = \sqrt[4]{\frac{P_{avg} G \sigma \mathrm{A}_e t_{ot}}{(4\pi)^2 S_{\min}}} \qquad \text{Radar Systems} \qquad 3.3$$

where:
P_{avg} – Average power
G – Antenna gain
σ – Target radar cross section (RCS)
A_e – Effective antenna area. (Product of the physical area and an efficiency factor)
t_{ot} – Time on target, dwell time, or integration time
S_{min} – Minimum detectable signal energy

Except for RCS and dwell time, these parameters are all limitations of the physical system. Increases in range through increases in the power, gain, or area invariably come with consequence in weight, size, power, and money.

The frequency of operation is also a significant factor as it affects the gain, size, and weight of the system. It is also given by Stimson as:

$$G = \frac{(4\pi)A_e}{\lambda^2} \qquad \text{Radar Systems} \qquad 3.4$$

where:
λ – Wavelength (equal to the speed of light (c) divided by frequency (f); $\lambda = c/f$)

Thus, the aperture size decreases or the gain increases proportionally to the square of the frequency. This makes radar systems operating at higher frequencies attractive options for UAV installation where payload is limited.

For target RCS, most specifications use a 3 m^2. To effectively use the dwell time parameter, it is important to design a good scanning technique as discussed later. The optimal dwell time is a trade off with revisit rate and field of regard (FOR). The longer one dwells in any one part of the sky, the longer it takes to view the total area of observation.

For infrared imaging systems, the range is related to angular resolution by[23]:

$$R = W_R/\Theta_R \qquad \text{Infrared Systems} \qquad 3.5$$

where:
W_R – Linear resolution (minimum resolvable distance or diameter of target)
Θ_R – Angular resolution [rad]. The inverse of the spatial cut-off frequency ($f_{s,\,co}$)

For all imaging systems, the resolution is a function of the number of picture elements (pixels). A higher pixels count means dots to fill the image which leads to greater resolution. However, high resolution imaging creates challenges for the processing system because of the large quantities of data that must be analyzed in real time.

For systems using laser technology the maximum detection range is determined by the required power (P_R) which can be determined by the laser range equation given by the U.S. Test Pilot School Handbook[24] as:

$$P_R = \frac{P_{XMTR} D^2 \rho_T}{4R^2} \eta_{ATM}{}^2 \cdot \eta_{XMTR} \cdot \eta_{RCVR} \qquad \text{Laser Systems} \qquad 3.6$$

where:
R – Range to target
P_{XMTR} -- Power in the transmission path of the laser
D – Detector aperture diameter
ρ_T – Target reflectivity
η_{ATM} – Transmissivity, atmospheric
η_{XMTR} – Transmissivity, transmission path of the laser
η_{RCVR} – Transmissivity, receiver path of the detector

Unless a system is capable of simultaneous omni-directional monitoring, this stated t_{c-} is not sufficient. After detection, the DSA system must track the traffic to determine if a conflict exists. This requires at least three scans for accurate determination (real world trajectories will be arcs). Thus the t_{c-} is also a function of revisit rate. It must be assumed that the traffic is just outside of maximum detection range in the previous scan. Thus the distance the traffic can close before being detected and tracked is equal to the closure rate times the time the system takes to perform three complete scans ($3 \cdot t_r$). Substituting this into equation 3.1 yields an actual time to collision of:

$$t_{c-} = \frac{R-(3t_r\ v_c)}{v_c} = \frac{R}{v_c} - 3t_r \qquad 3.7$$

As mentioned before, a longer dwell time increases the range for radar systems. For electro-optical systems, an increase in range requires an increase in sensitivity which also requires a longer dwell time. However, these longer dwell times increase the time required to scan the entire area. Therefore, revisit rate and maximum detection range are conflicting parameters of the time to collision requirement. This necessary trade off is seldom discussed in product literature, but it should be considered for new system evaluation.

Section 4 discusses the necessary performance for the time to collision requirement. From the DSA system perspective, it must complete its detection, tracking, and predicting in adequate time for an avoidance maneuver. For operations that are not LOS the time requirement is lengthened by the necessary relay time. Onboard automated avoidance maneuver systems would be much more responsive, but they add another level of yet unproven technology.

Predicted performance can be obtained from the given equations. The necessary parameters will be available from applicable regulations or manufacturer data. This performance can be evaluated in laboratory tests, but flight tests are still necessary to verify all derived results in a real world environment. Certification will require verification flight tests as well.

3.1.2. Tracking Accuracy

The accuracy of the system must be evaluated in order to determine the level of uncertainty for each track. Once determined, errors for range, range rate, azimuth angle, and elevation angle must be used in the preceding calculations. This is so that, even with errors present, the necessary time to collision requirement would be met. Most errors can be predicted by using the given performance equations and estimating parameter uncertainties.

The minimum ambiguity in range and resolution can be determined through equations specific to the system technology, and these variables can be checked in laboratory testing. The determination of actual system accuracy can only be accomplished through flight test with a proven truth source for comparison.

3.1.3. Field of Regard

The field of view (FOV) is the angular amount a system can observe at one time. Field of regard (FOR) is the complete area that the system can put into its FOV through slewing or other means. For fixed sensors the FOR is equal to the FOV. Some sources use the term scan envelope instead. Limitations such as obstructions and gimbal limits may create an unsymmetrical FOR.

It is necessary for a DSA system to provide coverage in the entire area of responsibility. Ideally, the system would provide +/-180° in azimuth (AZ) and +/-90 ° in elevation (EL); that is, total coverage. As Section 4 discusses, however, total coverage is not required.

The threshold requirement for the FOR must be established by regulation. Installed system ground tests can evaluate the system FOR.

3.1.4. Integrity

System integrity is a measure of how well the data can be trusted. For a DSA system it is the probability for missed traffic, false alarms, or incorrect prioritization of intruders. The technical reasons for these problems include target location ambiguities, improper noise rejection, terrain reflections, and errors by predictive algorithms. The tracking accuracy also plays a part as discussed previously.

Ideally, the system would have a 0 % probability of missed traffic and a 0 % error rate. This is impossible to achieve much less evaluate. Aviation systems already have established threshold levels of safety that apply to these systems. If a DSA system is functioning as the primary method of separation, and traffic on a conflicting flight path is non-cooperative, then a missed or incorrect detection could lead to a midair collision. In this scenario, the chance of a collision is a compound probability consisting of the statistical chance of two aircraft being on intersecting flight paths, both arriving at the same point at the same time, and the DSA system not detecting or predicting it would happen. If a mishap were to occur it would fall under the definition of a catastrophic event and so requires the probability of occurrence to be less than 10^{-9} events/hour.[25] That is once every billion hours of operation. This can only be realistically evaluated in modeling and simulation.

Conversely, a false alarm or incorrect prioritization qualifies as an annoyance factor. Determining an acceptable frequency of occurrence for these requires some subjective analysis, but should be considered a human factors issue as discussed in requirement 4.

System integrity also concerns evaluations of self-monitoring and graceful degradation. A critical system, such as DSA, must detect its own degraded operation and alert the user. It must also be capable of continuing at the best level possible in the presence of partial failures. An example of this is a detection system that loses its vertical scanning capability, but reacts by: detecting the failure, alerting the user, and continuing to report traffic in azimuth only.

Requirements for failure alerts and information reliability will very likely model those developed for other traffic systems such as ACAS. Evaluation and certification must be done in laboratory testing where deliberate failures can be executed.

3.2. Physical Characteristics

The physical characteristics of a proposed DSA system regard the issue of suitability for a particular aircraft. The actual values for these criteria will be platform-specific, but all categories must be considered.

3.2.1. Size and Shape

Is there room? This criterion is the limiting factor on many radar systems. Lower frequencies require larger antennae. The shape is also important as there are possible aerodynamic concerns for the externally mounted sections. A recent C-130 missile detection system encountered unexpected problems in this area and required modification, wind tunnel tests, and multiple additional flight test hours.

For complete size criteria the following limitations must be stated: (1) the maximum available dimensions at all internal installation locations. (2) The external surface area available for mounting, or availability of attachment points.

Determining the external shape requirements is more difficult. There are no textbook answers, but limitations will be encountered from one of two possibilities: either the contribution to parasitic drag, or flying qualities degradation. Wind tunnel tests are required. Flying qualities flight testing may be necessary.

3.2.2. Weight

The system weight limitations are derived from more that just payload capacity. If the weight and balance of the aircraft are significantly altered, it is an issue for stability and control. Also, there may be structural issues due to increased loads in specific areas. Analysis must be performed for each proposed installation location to determine the maximum permissible weight. Threshold limitations can probably be established by deduction with the aid of aircraft manufacturer data; however, some of the flying qualities data may need to be re-verified by wind tunnel and flight test.

3.2.3. Physical Interference

The physical interference challenge is the most significant limitation of propeller-driven aircraft. The propeller and engine greatly limit options for systems that require unobstructed forward views with a high FOR. Many small UAV designs are incorporating pusher-type propulsion systems which frees up the front, but it inhibits rear traffic detection. Mounting systems on the wings is possible, but structures limitations often make this option difficult as well.

3.2.4. Power and Cooling

The power and cooling limitations are determined by evaluating excess capability of the system. All electronics use power and produce heat, so if available aircraft capabilities are insufficient, DSA installation will have to be accompanied by an upgrade in the power system and/or cooling system. This may significantly increase total cost.

Power requirements can be satisfactorily determined from manufacturer data and laboratory testing. Cooling requirements can be estimated in the same manner, but normally require installed ground tests for more accuracy.

3.3. Interoperability

DSA systems, by definition, are independent of other layers of safety however; they must operate as a "system of systems", both among other onboard systems as well as in the surrounding airspace.

3.3.1. Internal Interfaces

The DSA system will need ownship data (velocity, altitude, heading, and rates) in order to calculate and display traffic information. It must be able to get this information by interfacing with the other onboard systems. This means being properly integrated into the aircraft bus, if one exists, or being wired to other systems and using the proper communication protocols.

This requirement can be evaluated in laboratory tests.

3.3.2. Electromagnetic Interference/Compatibility

All new developmental efforts that emit or receive emissions must be concerned about the effect of operating among other systems. Unexpected problems in this area have cost the recent Link-16 data link development effort millions of dollars. In addition to added expense, problems with electromagnetic interference/compatibility (EMI/EMC) can have critical safety and legal implications. Changes are much cheaper to make before aircraft installation, so a detailed evaluation of the possible risks is paramount.

EMI/EMC testing requires specialized equipment during ground tests.

3.3.3. External Compatibility

In addition to EMC, DSA systems will have to demonstrate that they do not degrade the integrity of information for other traffic control systems. For example, if queried by another aircraft using an ACAS or ADS-B system (as discussed in Section 3), the UAVs must be able to properly respond with valid data in a compatible format.

This requirement can be evaluated in laboratory tests and verified concurrently with other flight tests.

3.4. Human Factors

Human factors evaluations examine the suitability of the system for real world use. Since DSA systems are not a part of the primary mission, it needs to operate with the minimum of operator attention. Inputs and responses must be able to be performed while taking a very small percentage of the operator's time.

To achieve this, the controls and displays must be evaluated for clarity and logical man machine interface (MMI). In addition, any algorithms used to aid operator decisions must be timely and accurate. Standardized symbology should be used to the maximum amount that such exists. The system should be capable of accurate prioritizing and correlating of traffic. The operator should have the ability to selectively declutter or adjust display settings. Finally, all warnings and alerts must be clear and sufficiently intrusive.

No generic values can be given for the evaluation of these requirements, but they are not totally subjective. Many studies have attempted to quantify acceptable human factors. The applicable regulations should be used. Human factors evaluations require flight time as they must be used in the actual operational environment, however, they should be performed concurrently with other activities.

3.5. Logistics

The logistical considerations for any new technology are the things that decide if a good concept can actually be a good product. The three main issues for logistical considerations are reliability, maintainability, and availability.[26] For DSA systems they can be quantified as:

Reliability = hours of operation / operational failures [hours]
    - known as mean time between failure or (MTBF)
Maintainability = maintenance hours / operating hours
    - known as Maint. Ratio (MR). Function of MTBF and required servicing.
Availability = MTBF / (MTBF + maintenance time) [%]
    - the amount of time the system will be available for use.

The last two issues are concerns for their cost and operational impact, but reliability is a safety of flight concern. As such, a regulatory value must be established for this issue. Logistics evaluations are conducted concurrently with other testing and for the duration of the test program.

4. DSA Necessary Performance

Governing agencies have required UAVs to demonstrate an "equivalent level of safety" (ELOS) to manned aircraft[27]. A complete definition of exactly what that is would offer an answer to the question of, "How good is good enough?" for DSA systems on UAVs. If that were done, airworthiness requirements could be directly derived from that definition. Unfortunately, no such definition has been endorsed by any regulating agency. While many vendors present their proposals as "how much better than nothing", many critics emphasize "how much less than perfect".

4.1. Equivalent Level of Safety

While ICAO regulations do not define the required level of DSA performance, they have established see and avoid areas of responsibility.[28] Studies from multiple research agencies are listed in Table 4 as technical answers to the equivalent level of safety of a human pilot; however, those same studies also note that this level is not adequate.[29]

As shown in the notes, the warning time needed prior to a potential collision is based on two things. The first component is the reaction time to the collision threat. Research for this component has been performed by the Australian Traffic Safety Board (formerly BASI). Their results are listed in Figure 8. These values are generally accepted by the aviation community and have been cited in multiple accident investigations and subsequent research. Since they apply to piloted aircraft, they require modification for UAV operations (see Section 4.2.1).

Table 4: Required Performance and Human Ability

Parameter	Required Performance	Source of requirement	Human performance	Source
Time to Collision Warning	No value given Sufficient for a safe miss distance (>500'). Speed dependent	FAA-P-8740-51. FAA Order 8700.1, Ch. 169	Requires greater than 18.2 sec. [1]	1991 BASI report & calculations
Detection Range	No value given Sufficient to achieve warning time requirement	N/A	1.14 to 1.84 NM for 90% confidence	Lincoln Labs test, 1989. AFRL Study, 2002
Revisit Rate	Sufficient to achieve tracking within warning time requirement	N/A	16 sec	FAA-P-8740-51
Resolution	Sufficient to achieve tracking at required range.	N/A	0.3 mrad	"Modern Optical Engineering" W. Smith
Field of Regard	+/-110° Azimuth +/-30° Elevation	(ICAO Annex 2) "Rules of the Air"	+/-180° AZ +/-30° EL	N/A
Traffic Volume	Sufficient for most crowded airspace (up to 12)	Derived from EUROCONROL website statistics link	Up to 5	FAA-P-8740-51

Note: 1: That is, 12.5 seconds for pilot and 5.7 seconds for avoidance maneuver (non fighter or aerobatic).

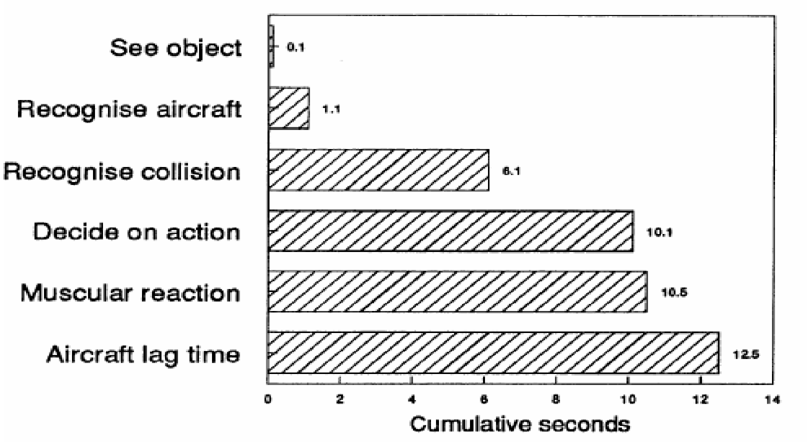


Figure 8: Time to React to a Collision Threat (Source: BASI Report, 1991)

The aircraft lag time of two seconds is the one component of the reaction time that is system dependent. Both the time for aircraft systems to respond to the control input, and the time to reach the desired flight attitude are included in this time. Evaluations done at INTA confirmed that this value is appropriate for aircraft that are not designed for high agility operations.

The second component is the time required for the aircraft to complete the avoidance maneuver. Engineers at INTA did not find any prior research for determining the required maneuver time for a given speed and bank angle. A study was undertaken to define this component for all aircraft including UAVs. The conclusions are explained below.

4.1.1. Conclusions of INTA Study on Avoidance Maneuvers

Due to the closer proximity of traffic, avoidance maneuvers for DSA systems will have to be much more abrupt than those programmed for cooperative systems such as ACAS. An aircraft will avoid a hazardous incident, as defined by the FAA, if it is able to alter its flight path in order to remain at least 500 ft from the traffic.

In the vertical plane, the UAVs tested at INTA operate with too little excess thrust or airspeed for a zoom maneuver (rapid climb) to be a viable option. This is true for most all small aircraft. A dive would yield the most rapid change in trajectory, but it is an undesirable option due to the effects of negative g-forces on the systems and payloads. Furthermore, unapproved changes in altitude while on an IFR flight plan may unsafely complicate the scenario for both controllers and operators.

For these reasons, avoidance through a change in the horizontal plane is preferred. Analysis was performed to calculate the time necessary to complete a horizontal

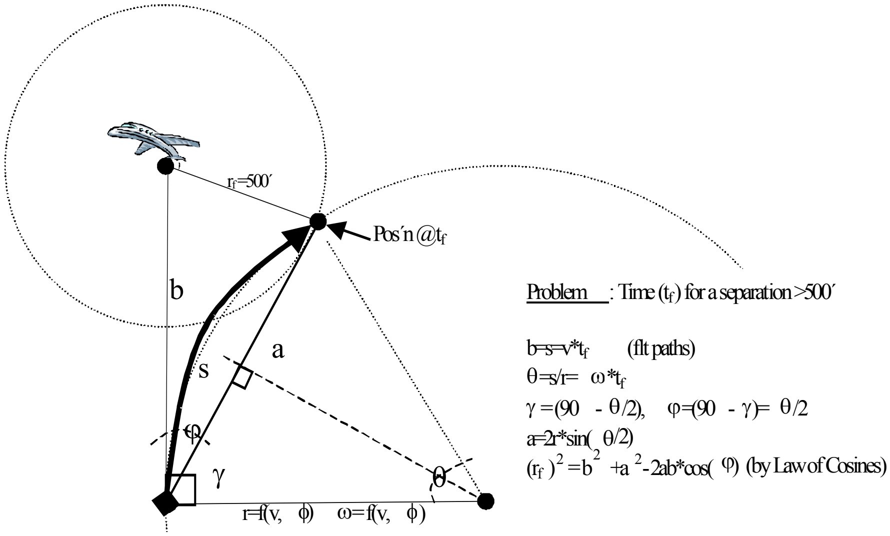


Figure 9: Avoidance Maneuver, General Solution

maneuver. Figure 9 shows the geometry for the generalized (no specific velocity or bank angle) worst case scenario. In this scenario, a warning was given at the minimum alert time based on a predicted collision at time (t_f) if the aircraft continued on flight path (b). The time (t_f) is measured from the conclusion of the reaction time mentioned previously. The aircraft miss distance (r_f) must be a minimum of 500' as defined by the FAA. The aircraft's actual trajectory (s) is based on the maximum response performed during the reaction time which results in the bank angle (ϕ). For illustration a right turn is used, but it is done so without any loss of generalization. The solution is achieved using the Law of Cosines, the derivation of which can be found in any geometry textbook. Any changes in altitude or reductions in airspeed will improve the separation distance.

The turn radius and the turn rate of an aircraft in level flight can be solved using the following equations derived by the USAF Test Pilot School[30]:

$$r = \frac{v^2}{g\sqrt{n^2 - 1}}; \quad \text{and} \quad \omega = \frac{g\sqrt{n^2 - 1}}{v} \qquad 4.1 \ \& \ 4.2$$

where
v – velocity
g – force of gravity
n – load factor; which is equal to the inverse of the cosine of the bank angle.
r – turn radius
ω – turn rate

Combining the equations of the generalized solution with equations 4.1 and 4.2 yields the following:

$$r_f^2 = \left(v\,t_f\right)^2 + \left(2r\sin\left(\frac{\omega t_f}{2}\right)\right)^2 - 2\left(2r\sin\left(\frac{\omega t_f}{2}\right)\right)\left(v\,t_f\right)\cos\left(\frac{\omega t_f}{2}\right) \qquad 4.3$$

with all values defined as in Figure 9 and equations 4.1 and 4.2 listed previously.

The INTA study sought to deduce the proper values for the variables in the above equation. It concluded that a maximum bank angle (ϕ) of 45° should be used for several reasons. First, many UAVs and small aircraft are limited in bank angle to 60°. A maximum rate turn should not be performed to the maximum allowable bank angle due to the consequences overshooting the bank angle limit. Secondly, the short timeline limits the amount of time available to execute the maneuver. The study found that the UAVs were capable of roll rates between 20 and 30° per second; these are common values of normal small aircraft. At these roll rates, higher bank angles would require more time than allotted for the execution of the maneuver. Thirdly, as the bank angle increases beyond this value, the viewing geometry (for pilot or sensor) becomes a factor. At some angle, dependent on aircraft type and viewing position, it will not be possible to keep the traffic in sight throughout the turn. Finally, g-force, and the proportional accelerated stall speed, increase inversely to the cosine of ϕ which means the rate of increase becomes very high at high angles.

Since some aircraft may have other factors which require using a different value for the maximum bank angle, the general equation was solved for a range of ϕ and is presented in Figure 10.

One example of additional limitations is that satellite links frequently limited UAVs to $\phi = 15°$ during beyond LOS operations. The INTA study found that this should be programmed as a "soft stop", but, if necessary, the DSA system should be allowed the maximum ϕ. The maneuver duration will be very short, so the link may not be lost. If it is lost, automated procedures for re-establishing the satellite connection are possible once the aircraft has returned to level flight.

A fact that is not intuitively obvious, but that falls out of the calculations, is that the warning time requirement is not speed dependent. The required detection distance is proportional to the closure velocity, but the turn rate is *inversely* proportional to closure velocity. In the time to collision calculations these two factors cancel out the speed dependence.

Based on the above study, and using equation 4.3, the time necessary to complete the avoidance maneuver with a $\phi_{max} = 45°$ is $\underline{t_f = 5.7 \text{ seconds}}$.

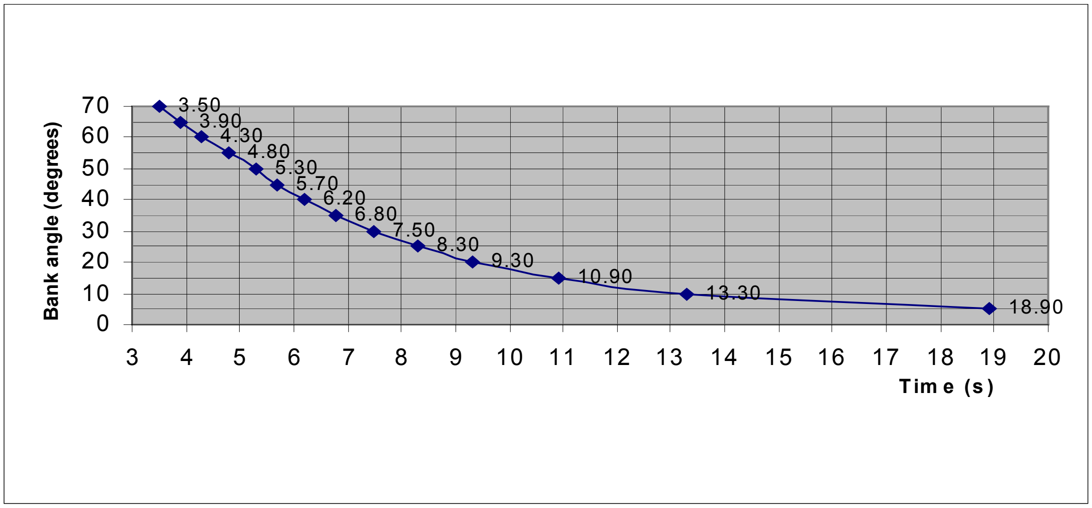


Figure 10: Time to Clear Traffic (by Bank Angle)

As already mentioned, studies show that the human level of safety is not sufficient.[31] To illustrate this, we use equation 3.1:

$$t_{c-} = R/v_c \qquad (3.1)$$

as defined in Section 3. Using the optimal human performance values listed in Table 5 (R=1.84 NM and necessary t_{c-} = 18.2 sec), the maximum closure velocity (v_{c_max}) safely protected by human see and avoid is:

v_{c_max} = 364 knots Human ability, optimal.

This does not take into account the human scan rate. The FAA recommends that pilots rescan every 16 seconds. More frequent complete area scans are a worthy goal but difficult to achieve during high task operations. At this recommended rate, any particular area of view is only observed once every 16 seconds. With this necessary time to collision (t_{c-} = 34.2 sec), the maximum safe closure velocity is:

v_{c_max} = 194 knots Human ability, practical.

GA aircraft are normally performance limited to less than 150 knots, so the optimal value would seem to be sufficient; however, aircraft can legally fly at speeds of 200 knots in airport areas and 250 knots elsewhere (refer to Section 2.1.1) below 10,000´. This means aircraft below 10,000´ in Class E or higher airspace must be able to prevent against collisions with closure velocities up to 500 knots (two aircraft traveling head on at 250 knots). This corresponds to a required visual detection range of 4.8 NM. Even considering the speed limited aircraft mentioned before (150 knots ownship means closure velocity up to 400 knots), the required visual detection range is 3.8 NM or twice that of the human ability! These results are compared to those for UAVs in Section 5.2.1.

Due to the geometry, off angle traffic will have significantly lower closure velocities as shown by Equation 3.2. The required time to collision reduces proportionally which means a DSA system capable of non-uniform scanning could be programmed to do a weighted distribution of scan time and increase effective system performance.

Above 10,000′ there is no speed restriction except for those prohibiting supersonic flight. With only the Mach limitation, closure velocities can theoretically be over 1200 knots true air speed. However, at that altitude working transponders are required which means cooperative avoidance systems can be used. As discussed, even in the absence of any ATS radar assistance systems such as ACAS are capable of deconflicting traffic at distances sufficient for all closure velocities of subsonic aircraft.

4.2. Necessary Performance for UAVs

ICAO provides two ways to determine if a new system is acceptably safe: (1) comparison to a reference system, and (2) evaluation of system risks against a threshold. The first method is a relative method in that all the characteristics of the new system are compared with the corresponding characteristics of a reference system that is already determined to be sufficiently safe. The second method requires the advocating party to quantify the system performance and compare against an approved risk level.[32]

Using method one, advocates of UAV operations have compared their systems against human performance. This approach has been ill fated because of the evidence that discredits the sufficiency of the reference system (namely, accident reports that find unaided human performance legal but insufficient for some conditions). Therefore, UAVs will ultimately have to prove their safety by method two.

In reviewing the data of Table 5 with this approach in mind, the following adjustments must be made to the performance requirements.

4.2.1. Revised Time to Collision

As discussed previously, the time to collision capability of a system is a function of revisit rate, detection range, and/or resolution. For determining what DSA system performance is necessary, the required performance should be modified to consider several factors. At the time an alert is issued, the detection and recognition stages have already occurred. This leaves 6.4 seconds of the timeline shown in Figure 8.

UAVs being operated by satellite link (Class 2 and 3) will have a transmission time which must be added to the reaction time twice, once for the alert and once for the control message. While the traffic speeds will be the same, UAVs will be limited by Class.

The transmission time delay consists of a propagation component and a relay processing component. Propagation time is the result of transmission range divided by the speed of light. This results in a time delay of 6.18 μsec per nautical mile. Processing of the message will be negligible because the message size is small enough to be completely transmitted in a single transmission. A total of one second for one-way transmission time is sufficient for world-wide coverage. Autonomous DSA operation will not need this additional time except for operator override. Modifying Figure 8 with these considerations results in the Figure 11.

Using the equations given in Section 3, an automated system with the capability of resolution advisories and a revisit rate of 1 Hz could provide the necessary alert time to a pilot with a detection range of only 2.0 NM. This improvement over the values quoted in Section 4.1 are due to the higher revisit rate and the reduction in time to react as shown in Figure 11. A comparison of the human and automatic requirements is made in Figure 12.

4.2.2. Field of Regard

By ICAO regulation, all aircraft are responsible for taking action to avoid traffic in an area consisting of +/-110° in azimuth and +/-30° in elevation. This means that UAVs must be able to do their part of deconfliction with any aircraft that enters this region. Additional coverage is desired from a "defensive driving" perspective, but meeting this FOR requirement satisfies the law.

4.2.3. Traffic Volume

This parameter insures that a DSA system would be able to cope with the highest traffic densities likely to be encountered. Modern computers have no problem far exceeding this number of simultaneous predictions, but the system must be able to also prioritize in order to advise of the highest threat at all times.

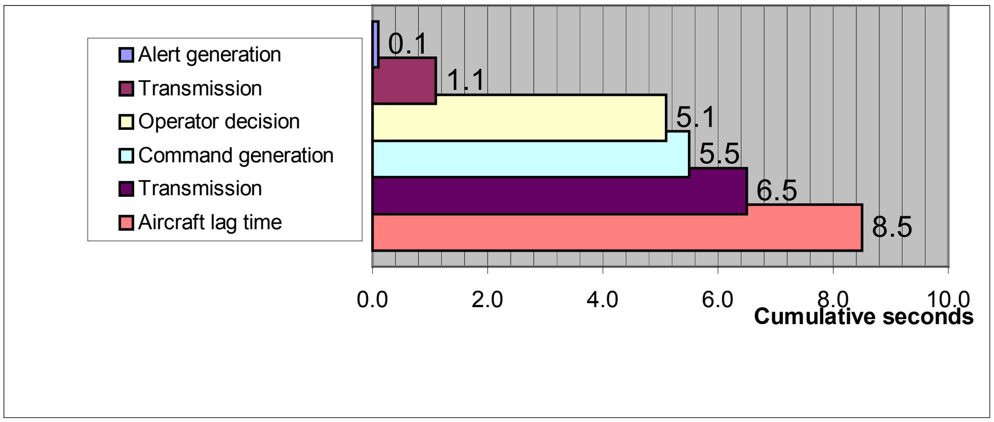


Figure 11: Time to React to a Collision Threat, UAV Version

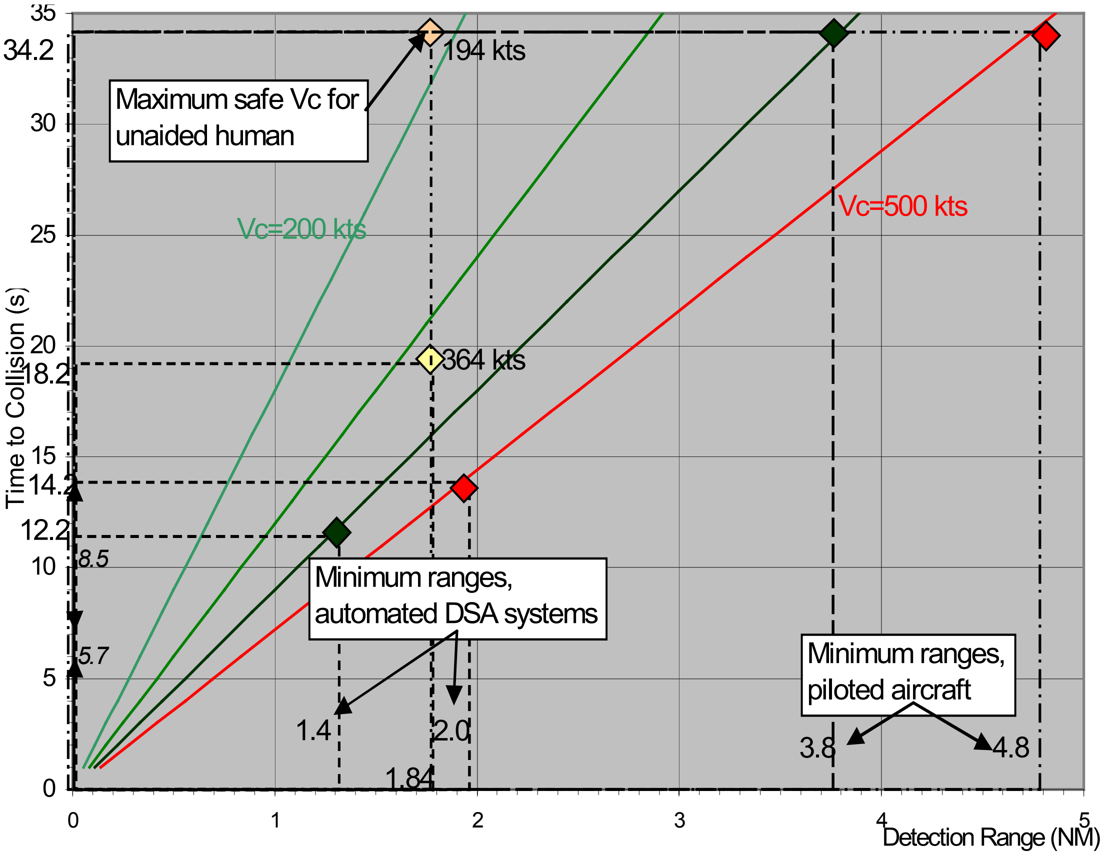


Figure 12: Detection Range versus Time to Collision

4.3. Proposed UAV Requirements

Based on the preceding sections, some basic requirements become apparent for all UAVs regardless of operation. The following is a proposed list of requirements that should be met for all UAV flights within civil airspace:

Certification: Be certified for flight in civil airspace. This certification should state that, in addition to meeting applicable existent airworthiness requirements, UAVs demonstrate fault-tolerant flight control, data link, and flight termination systems.

Approved airfields: Operate only out of airfields approved for UAV operations.

Preflight: File an IFR flight plan in accordance with all IFR requirements. Flight plan will indicate UAV status and secondary method for contact (e.g. land line).

Communications: Maintain communication with applicable ATS at all times.

Navigation: Maintain a contingency flight plan in the event of loss of communication. The contingency plan will be dynamically updated to remain in accordance with procedures for radio out (NORDO) IFR throughout the flight.

Identification: Broadcast and receive a Mode S transponder signal regardless of airspace requirements for piloted aircraft.

The first two requirements are reasonable and most sources are in consensus. This gives the national authority control over what is approved. Once the requirements are specified, the advocating organization will have a clear process for securing approval. Being on an IFR flight plan is reasonable since, in essence, the operator is flying IFR. The communications requirement can be met in one of two ways as discussed below. The requirement for a loss of communication procedure that meets IFR NORDO requirements is a logical extension of the requirements for piloted aircraft. The contingency flight plan must be dynamic because the proper course of action will vary based on stage of flight and what ATS clearances have been received prior to communication failure. The Mode S requirement may soon become a requirement for all powered flight in controlled airspace. For now, it should alleviate concerns among the commercial community as they will be able to detect and avoid all UAVs at great distances.

In addition to those overarching requirements, the necessary equipment by UAV Class is listed in Table 5. With the implementation of these modifications, the derived necessary level of performance for DSA systems to be used on UAVs is listed in Table 6.

As demonstrated in Section 4.1, these requirements provide a greater level of safety than what is required of piloted aircraft. This is in order to meet the *necessary* level of safety. Due to their ability to travel beyond LOS, Class 2 and 3 UAVs must have satellite links. Their radio communications will also have to be relayed to the GCS via satellite as ATS will not be LOS with the GCS. Class 1 UAVs are not required to have a satellite link for control and can provide the link through some means other than onboard radios.

Table 5: UAV Proposed Requirements

Class	Description	ATS Communication	ACAS	DSA	DSA autonomous operation allowed
3	HALE	Onboard radio & Sat. data link	Yes	Yes	Yes
2	MALE	Onboard radio & Sat. data link	Yes	Yes[3]	No
1	Short range	GCS com. with ATS [2]	No [4]	Yes [3]	No
0 [1]	Mini and micro	No	No	No	---

Notes:

1. Class 0 will not operate in civil airspace except by the COA process already in place.
2. Class 1 UAV communication requirement may be met through direct link between ATS and GCS.
3. In airspace with full radar coverage and operational TIS-B: DSA requirement may be met by ACAS system capable of ADS-B. Radar coverage can be general ATS or specific UAV support.
4. Except operations above 10,000′ require ACAS due to increased traffic speeds.

Table 6: DSA Necessary Performance for UAVs

Parameter	Required Performance		Notes
Time to Collision Warning	Class 3 & 2	14.2 sec	Sufficient for a safe miss distance (>500’) below 10,000′.[1]
	Class 1	12.2 sec	Value is for head-on traffic. Less for off angle traffic.
Detection Range & Revisit Rate	Minimum to achieve time requirements above:		Sufficient to achieve tracking within warning time requirement.
	Class 3 & 2	2.0 NM	
	Class 1	1.4 NM	
Resolution	--		Sufficient to achieve tracking at required range including worst case scenario ambiguities.
Field of Regard	+/-110° Azimuth +/-30° Elevation		Required performance: Those dictated in the ICAO “Right of Way rules”. Desired performance: Total spherical area.
Traffic Volume	> 10		Busiest airspace densities for UAV operation

Note:
1: Includes transmission, reaction, and maneuver time; also, for Classes 2 & 3, propagation time.

The International Technical Committee on Unmanned Air Vehicle Systems (ASTM F38) has created a standard for DSA systems, Standard F 2411-04. It was created after input from many segments of the aviation community. It is still unclear if aviation regulatory agencies will embrace this new standard for certification purposes.[33]

5. DSA Analysis of Alternatives

To meet the requirements specified in Section 4, multiple possibilities exist. Figure 13 shows several key regions of the electromagnetic spectrum. Any feasible DSA solution will likely operate in one of these regions due to their atmospheric transmissivity, which is important for achieving the range requirement.

Studies by Amphitech have ranked the performance requirements for possible technologies that would operate in those areas of the spectrum.[34] Their conclusions are shown in Table 7. They refer to the FOR as the scan envelope but otherwise use the same proposed requirements mentioned above.

This information is not complete, however. The higher ratings for systems in the lower frequencies like millimeter wave (MMW) radar are based on the effect that moderate rain and fog have on higher frequency systems. By definition, these weather conditions are instrument meteorological conditions (IMC). By regulation, IMC requires all aircraft to operate under IFR. Being able to protect against possible traffic that is not on an IFR flight plan, not using a transponder, and flying through fog might be nice, but it has never been mandatory.

In addition, as discussed in Section 4, there is a trade off between FOR, revisit rate, and range (or resolution in the case of electro-optics). Thus, technologies with inherent abilities in one area can make trade offs for improvement in others to make an affordable alternative that still meets the time to collision warning requirement. Given this, a new analysis of these technologies is listed in Table 8 rearranged by order of their place on the electromagnetic spectrum.

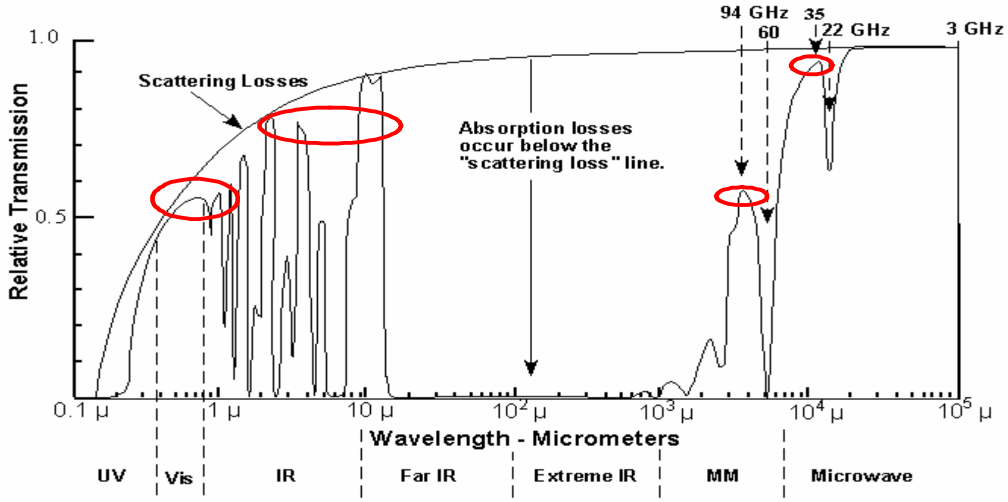


Figure 13: Atmospheric Transmission per NM (Sea Level) (Source: NAWCWPNS Handbook TP 8347)

Table 7: Amphitech Evaluation of DSA Technology Performance

Sensor technology	Scan envelope	Time to Collision	Revisit rate	Resolution	Adverse weather
Laser Radar	Excellent	Fair	Poor	Excellent	Poor
35 GHz MMW radar	Excellent	Excellent	Fair	Excellent	Fair
94 GHz MMW radar	Excellent	Fair	Fair	Excellent	Fair
Visible Imaging	Excellent	Poor	Excellent	Fair	Poor
IR Imaging	Excellent	Poor	Excellent	Fair	Poor
Passive MMW imaging	Excellent	Poor	Fair	Poor	Excellent

Table 8: Revised Evaluation of DSA Technology Performance

Sensor technology	Time to Collision	Accuracy	FOR
Visible Imaging	Marginal due to range	Satisfactory	Satisfactory
IR Imaging	Marginal due to range	Satisfactory	Satisfactory
Laser Radar	Marginal due to revist	Satisfactory	Satisfactory
Passive MMW Imaging	Unsat. due to range	Unsat. due to resolution	Satisfactory
MMW radar	Satisfactory	Satisfactory	Satisfactory

The following sections will evaluate all known DSA proposals and applicable technologies in order of spectral region. System performance and physical characteristics can be estimated, but other requirements such as interoperability issues, human factors, and logistical concerns require evaluations on a specific product.

5.1. Visual Imaging

This technology consists of using some form of camera arrangement to establish situational awareness. It is the most analogous process to that of piloted see and avoid. Visual imaging is a semi-passive system in that no onboard illumination is needed for detection. Modern camera technology holds great possibility for small, low power cameras with very good zoom capabilities. In the future, a virtual reality system could theoretically give the remote operator the same visual scan as an onboard pilot, but the bandwidth and equipment requirements would not justify its use simply for DSA. A more realistic option is using image processing and a target recognition algorithm to analyze the input for the operator. Several options discussed below have taken this route. The operator could still be in the loop by cueing cameras to focus on places interest.

The primary weakness of these systems is that they are limited in the same way as the human vision. Some technologies (such as those used for night vision goggles, NVGs) will give satisfactory performance at night, but visual systems degrade greatly in the presence of water vapor such as rain and fog. As mentioned before, this may not exclude their use as a DSA system since other cooperative systems can be made the primary for IMC.

Another inherent difficulty with electro-optical imaging systems is that, unlike radar, they do not have the capability to directly measure range. This is a big drawback for DSA systems as this is the primary parameter for calculating traffic avoidance. One possibility is stereoptic vision with sensors on the wing tips. This would use the same principle as the human brain to discern the distance of an object by simultaneously viewing it from two different angles. Unfortunately, this method is only effective at short distances. Beyond those distances the human being uses assessments of the apparent size of an object to determine distance.[35] A computer could do this as well, but it must know the actual size of the object. Range rate can be determined simply by measuring the rate of change in apparent size, but requires very high resolution systems as the apparent size of an object does not change rapidly until the distance is very small. A more probable solution to the range problem is to combine the electro-optical system with an eye-safe invisible laser range designator as discussed in the section for lasers.

There are currently no visual imaging DSA systems in use. The following are reviews of applicable technologies and proposals.

5.1.1. Panospheric Cameras

Athena and Carnegie-Mellon University have developed a 4 million-pixel, panospheric, (that is, 360-degree view) electro-optical camera with a vertical FOR of +10° and -80°.[36] Panospheric imaging is a technology developed by a Panoramic Viewing Systems, Inc. in Canada. This level of resolution and FOR is excellent for DSA applications, but it creates difficulties for the onboard image processing system and data link bandwidth. Also, there are processing challenges to correct the distorted image created by the sensor's spherical mirror.

By review, this system will be able to meet the FOR requirement and fit within the physical limitations. Revisit rate would also not be a limitation. There still remain the possible critical limitations on range and accuracy.

5.1.2. Detection Algorithms

Graduate students at The Royal Institute of Technology in Stockholm are doing thesis work on creating efficient detection algorithms for DSA systems. They point out that current algorithms suffer greatly by factors such as light conditions and the background clutter. Also, current common market video cameras do not have sufficient resolution to meet both the range and FOR requirements. This problem is expected to be reduced as high resolution cameras become sufficiently miniaturized in the future.[37]

A review of their research indicates that, at this time, these algorithms are not mature enough for use in actual systems. It is still not certain if better image processing alone will be sufficient to overcome the limitations of this area of the spectrum.

5.1.3. Optical TCAS for UAVs

Aurora Flight Sciences Corporation has proposed to combine low-cost visual image processing devices from the automotive market and the encounter logic developed for ACAS to create an "Optical TCAS". The company plans to use panospheric mirrors to achieve 360° coverage without complex scanning systems. The visual image processing devices are currently being developed by Mercedes-Benz as automotive collision avoidance devices. To test this system, they propose to use their "Chiron" optionally piloted aircraft, which, similar to Proteus, can operate as a UAV, but with a safety pilot onboard.[38]

By paper analysis, this system, if developed, will be a lightweight alternative that will meet the FOR and revisit requirement. Still, there is no mention of how to overcome the physical limitation on range as discussed above.

5.1.4. Modified Missile Detection Technology

The US Air Force Research Laboratory Sensors Directorate (AFRL/SN) is addressing the see and avoid challenge with an initiative called the Air Traffic Detection Sensor System (ATDSS). They have funded Defense Research Associates, Inc. (DRA), to pursue a passive moving target detection system using low cost optical sensors, processors, and DRA's proprietary software originally developed for missile detection systems. [39]

No initial analysis is possible, but all the same inherent limitations make this a technical high risk alternative.

5.1.5. Ranger Cameras

A similar system called Ranger was proposed at the AUVSI 04 conference. It would use 4 cameras and an algorithm using image processing to detect traffic. No further details are available.

5.2. Infrared

As shown in Figure 12, the infrared (IR) region is just lower in frequency (higher in wavelength) than the visible spectrum. This technology takes advantage of the fact all objects radiate energy at a quantity proportional to their temperature. Aircraft will have a temperature contrast with the surrounding sky. Unless used with an IR illuminator, these systems are passive; their detection is based on received energy only. IR systems are in the electro-optical area of the spectrum and share many of the same properties and limitations of systems in the visible range. They also have the physical limitations in the presence of water vapor such as rain and fog, but not as significantly as visible imaging.

A typical IR system requires a signal to clutter ratio greater than 19 in order to achieve a 99% probability of detection.[40] Also, these systems must have target recognition algorithms to analyze the information.

Though IR search and track (IRST) systems have been used by the military, there are currently no IR DSA systems in use. The only known proposal is a NASA and US Navy effort to develop a supplementary IR-based DSA system with a FOR of +/-105° in azimuth and +/- 35° in elevation.[41]

5.3. Laser Radar

This technology operates in the visible and near-IR spectrum. A laser (light amplification through stimulated emission of radiation) is a system capable of generating an intense coherent beam of light. This beam is less susceptible to the atmospheric attenuation of other electro-optical systems. When reflected this beam can be sensed by a detector which can determine the distance of the reflected object. A laser detection and ranging (LADAR) system takes advantage of this feature to make accurate range measurements at long distances. Since the range is a part of each sensed beam, the system is capable of providing a three dimensional perspective of the reflection. Some sources also used the term light detection and ranging (LIDAR) and include the use of ultraviolet lasers as well. Figure 14 shows the various lasers currently available and their spectral positions.

The advantages and limitations of LADAR systems are both related to their very precise focused beam. LADAR systems provide high resolution in range and angle, but to cover a sufficient FOR they require very fast scanning, and real time signal processing.

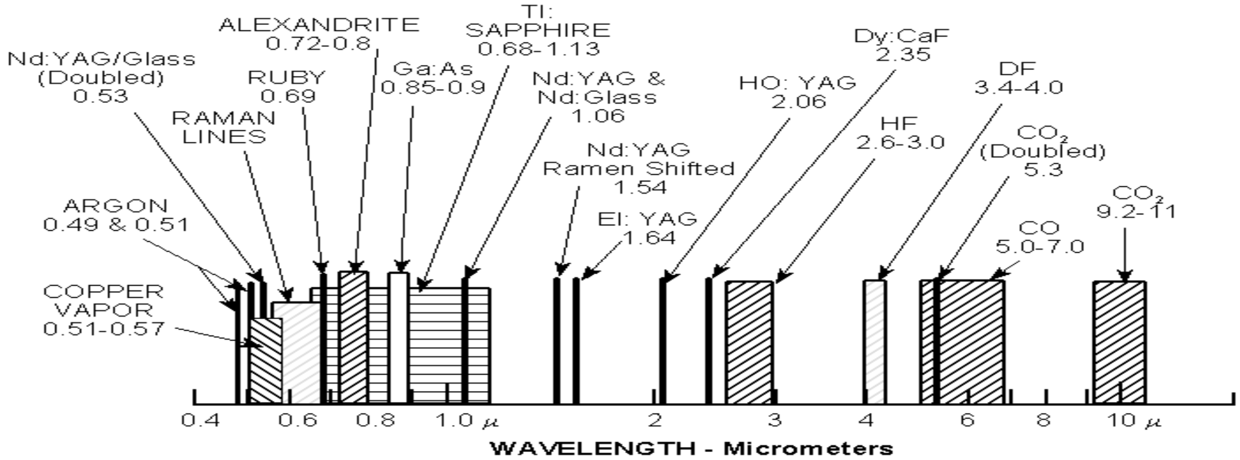


Figure 14: Laser Materials by Spectral Position (Source: NAWCWPNS Handbook TP 8347)

5.3.1. LIDAR and Fish-eye Lenses

Engineering 2000 has proposed to use LADAR technology to detect obstacles within a full 360 degree sphere. Their proposed system would first use what they call fish-eye optics imaging systems to identify potential collision threats and then a LADAR system to acquire range and closure rate. [42]

There are no performance specifications to analyze with this system, but it appears to take advantage of the strengths of the two technologies reviewed so far. That is, the wide FOR of visual imaging systems with the precision of LADAR. This has the possibility of achieving all performance goals while still being within limits of cost and size for small UAVs. Though not yet mature, this option is recommended for further investigation (See Section 6).

5.3.2. Strategic Defense Initiative Application

New Vistas International has proposed a system using radar and electro-optical/infrared sensors. The small gimbaled system leverages radar technology developed in the strategic defense initiative program and later adapted for helicopter obstacle avoidance systems made by Canada's Amphitech International. [43]

No initial analysis is possible; the biggest issue of doubt is how a system requiring so much sensor equipment will be able to fit within the physical limitations of most UAVs and small aircraft.

5.4. Passive MMW

Like IR systems, this technology takes advantage of the fact that all objects radiate as a function of their temperature. As a passive system, it has the advantage of being low power, but it suffers in range and accuracy performance. Most likely due to these limitations, no known systems are being investigated to exploit this technology for the purposes of DSA.

5.5. Radar

Radar (radio detection and ranging) systems have been used to detect aircraft for decades. Their processing systems are very mature and their performance in all conditions is very well known. Like LADAR, which was derived from radar principles, it is an active system that sends strong pulses of energy and analyzes the returned signal. Two locations of interest in the radar area of the spectrum are at 35 and 94 GHz.

The need for large external apertures makes radar systems difficult to implement on small UAVs. Propeller driven aircraft have an even more difficult time dealing with the interference issues that the propeller and engine can cause. Pusher propeller configurations allow for the installation of radar in the nose, but the size, weight, and power requirements make them still currently unfeasible.

5.5.1. OASys Ka-band Radar

NASA´s optionally piloted aircraft, the Proteus, has performed tests with a 35 GHz (Ka band) radar based DSA system developed by Amphitech. The OASys (Obstacle Awareness System) radar detailed in Table 9, and shown in Figure 15, is mounted on the chin of the Proteus. Designers set a range objective requirement of 6 NM. Initial NASA tests found the system was capable of detection ranges between 2.5 to 6.5 nautical miles, but there were some complete misses. The system is currently being redesigned by Amphitech.

Based on NASA´s flight test results, this system comes close to meeting all necessary performance requirements listed in Section 5. These are shown in Table 10. Regarding physical characteristics, the total weight is about 55 pounds and the externally mounted antenna is 16”x16”x22”. The system requires 250 W and costs $170,000. One potentially critical problem is in the area of physical interference. Aircraft with forward propellers will have a very difficult time finding a place to mount a complete radar and gimbaled platform. This option is recommended for larger aircraft (Class II and III UAVs) that can afford the cost and weight penalty and require the autonomous DSA performance that this system offers (See Section 6)**.**

5.5.2. Ultra-wideband Radar

Multispectral Solutions Inc. (MSSI) has engineered an ultra-wideband (UWB) radar prototype. It is lightweight and employs standard, printed circuit board packaging, the device radiates about 0.25 watt instantaneous peak power. The primary application for this system is micro-UAVs whose main concerns are flying amongst trees and buildings at very close range. This system is not capable of the ranges necessary for aircraft traffic avoidance.

Table 9: Evaluation of OASys 35 GHz Radar

Parameter	System Performance	Notes
Time to Collision based on: -- Detection Range & -- Revisit Rate	2.5 –6.5 NM 150°/sec	Generally sufficient for UAVs
Resolution e	1.7 mrad	Sufficient to achieve tracking within warning time requirement
Tracking Accuracy	Range: <5 m	Sufficient to achieve tracking at required range including worst case scenario ambiguities.
Field of Regard	Typical: AZ: +/- 30°, EL: +/- 11° Max: AZ: +/- 90°, EL: +25° & - 85°	Less than the ICAO requiremnet.
Other	Altitude limitation of 20k´	Problem for most UAVs

Figure 15: OASys Radar on Proteus

(Source: NASA website, Permission granted)

5.6. Off Board Assistance

Performing DSA through off board assistance is attractive for several reasons including cost, weight penalty, and minimized integration issues. In this approach, ground-based systems perform the detection operations. This information is then sent to the aircraft by a data link system such as TIS-B discussed in Section 2.3. In areas where ATS supports TIS-B, the traffic data can be received from the TIS-B system in the same way as other aircraft. For areas of desired UAV operation that are not serviced by a TIS-B system, new systems would have to be installed.

This option exceeds all requirements, is very light, and relatively inexpensive. These reasons make it seem perfect for the DSA function, except that is fails to meet the primary assumption of see and avoid; that is, independence. Advocates of this option as the sole means of DSA are facing a very challenging approval task because the fundamental purpose of DSA in modern aviation is to be able to maintain safe operations even when all outside systems fail. (See Section 6).

6. UAV Type-Specific Recommendations

Given the complete requirements as listed above, and after a through examination of the available technology, the following are recommended approaches for particular UAV scenarios:

For small propeller-driven UAVs, there are currently no solutions that are fully satisfactory. The most promising is the use of an off board system such as TIS-B discussed in Section 2.3. This system is not fully proven, and has not been approved as a primary DSA system. The obvious advantages, as discussed in Section 2.3.5, are low size/weight and low cost. In addition, installation on existing UAVs will require much less integration than other options. The US Navy is investigating this option. No information is currently available regarding their plan on development. Test agencies in Spain are lobbying their aviation authority for approval to use this option for both their military and national police. If approved, this would at least allow the beginnings of UAV operations in civil airspace while other technologies mature. The disadvantage of this option is that it is not independent. This limits where a UAV could operate and forces dependence on another organization. The Spanish have relatively few areas of interest and many small UAVs. For a situation such as this, the expense and logistical challenges of such construction will ultimately be less difficult than outfitting every UAV with expensive and heavy equipment as is required for other options.

For aircraft that must have fully independent DSA, such as those used in tactical military applications or to cover large distances, the best onboard alternative is a combined visual and LADAR system as mentioned in Section 5.3.1. Such systems are currently only in development, but they hold great promise. In addition to having the possibility of meeting the evaluation requirements listed in this report, these systems would have the military advantage of inherent low probability of interception (LPI).

At this time, radar systems such as the OASys are the most mature. For larger UAVs tasked with strategic or high loiter missions, a radar system is a good selection. The Spanish are looking into a multi-function radar option that could fulfill the tasks of ground tracking, weather tracking, and DSA. The expense and weight of such systems is still prohibitive for most classes of UAVs, but future developments promise to bring both the price and the weight down.

Conclusion

As it has been shown, UAVs bring the potential for enormous public benefit. The market for their use in the plethora of possibilities is driving the revisions of all aspects of aviation safety. Regulations will always lag behind what available technology makes possible, but, as shown, their careful modification must be a part of any solution for safe UAV operation in public skies. Also, developments in ATM such as ADS-B and TIS-B come at a very good time for the UAV community.

The test and evaluation guidance given in this report is independent of the technology being tested and can be used as a guide for all future DSA testing. That section is very similar in format to typical avionics test plans, but the unique DSA function requires the key differences. Unlike the timeless nature of the test guidance, the recommendations section depicts the best options for the present time. The currently available options leave much to be desired, but as these technologies mature they should compare more favorably against the necessary requirements listed herein.

If the predictions of most aviation leaders come true, the next decade will see an explosion in the number and variety of DSA systems. To prepare for this, regulatory agencies must be knowledgeable of the necessary performance of these systems, and UAV developers must be ready to quantitatively evaluate the options. This report aims to have provided the necessary information for both.

Bibliography

Bibliography

[1] "Report #A95H0008, Investigation of Air Collision," Toronto: Transportation Safety Board of Canada, May 1995.

[2] "Order 91.221," Federal Aviation Administration, 1994.

[3] "Technical Report: Aviones no Tripulados Desarrollos del INTA," Torrejón, Spain: National Institute of Aerospace Technology (INTA), Aug 2003.

[4] "Altair Product Specifications," General Atomics Aeronautical Systems, Inc., 15 Apr 2005, <http://www.uav.com/ products/Altair.html>.

[5] Tirpak, John, "The Robotic Air Force," *Air Force Magazine,* Sept 1997, Vol. 80, No. 9.

[6] Aldridge, E.C., and J.P. Stenbit, "Unmanned Aerial Vehicles Roadmap: 2002-07," Office of the Secretary of Defense, May 2003.

[7] "Article 8," Convention on International Civil Aviation, 1944.

[8] "Article 8," Convention on International Civil Aviation, 1944.

[9] "Part 91.113" and "Part 91.11(a)," *Federal Aviation Regulations,* Federal Aviation Administration, 2005.

[10] "Luftrecht Online," European Aviation Center, 20 Apr 2005, <www.luftrecht-online.de/ english/ecac.htm>.

[11] "LBA Company Home Page," LBA Company, 20 Apr 2005, <http://www.lba.de/>.

[12] "Order 7610.4," Federal Aviation Administration, 2002.

[13] "Global Hawk System Description," Northrop Grumman, 28 Mar 05, <www.is.northropgrumman.com/products/ usaf_products/global_hawk>.

[14] Marsters, G.F. and Mac Sinclair, "Integrating UAVs with Conventional Air Operations: Some Regulatory Issues," AeroVations Associates, 20 Apr 2005, <http://www.aerovations.com /downloads/pub3.doc>.

[15] "Integration of UAVs into Future ATM," *CARE Innovative Action Study,* IABG, Dec 2001.

[16] "Air Traffic Management Strategy," Eurocontrol, 20 Apr 2005, <http://www.eurocontrol.int/activities/ atm-strategy/index.html>.

[17] "Understanding ACAS/TCAS II," Honeywell, 2 Apr 2005, <http://www.honeywelltcas.com/support_pages/whitepapers/tcasoperationaldescription.pdf>.

[18] "Annex 10 Amendment 73 – 77: Comparison for SSR Mode S System," International Civil Aviation Organization, 2003.

[19] "ADS-B Review," STNA, 20 Apr 2005, <www.stna.aviation-civile.gouv.fr>.

---

[20] "Collision Warning Systems," L-3 Avionics Systems, 20 Apr 2005, <http://www.as.l-3com.com/ pdfs/Collision_Avoidance.pdf>.

[21] "Regulation 5000," Department of Defense, 2003.

[22] Stimson, G.W., *Introduction to Airborne Radar,* 2d ed., New York, SciTech Publishing, 1998, p. 136.

[23] *Systems Phase Handbook,* Edwards AFB, CA,USAF Test Pilot School, 2000, p. 4-41 and 4-189.

[24] *Systems Phase Handbook,* Edwards AFB, CA,USAF Test Pilot School, 2000, p. 4-113.

[25] *System Safety Handbook,* Federal Aviation Administration, Dec 2000, p. 3-8.

[26] *DoD Test & Evaluation of System Reliability Availability and Maintainability.* DoD #3235.1-H, Department of Defense, Mar 1982, p. 2-1.

[27] "Order 7610.4J*,"* Federal Aviation Administration, Jul 2001, Chap. 12, Sec. 9.

[28] "Annex 2: Rules of the Air*,"* International Civil Aviation Organization, 1962.

[29] Wolfe, R., "Is Meeting an Equivalent Level of Safety for See & Avoid Adequate for ROA Operations within Civil Airspace?" EuroUVS Conference, 3 Dec 2003.

[30] *Performance Phase Hadbook,* Edwards AFB, CA, USAF Test Pilot School, 2000.

[31] "BASI report: Limitations of the See-and-Avoid Principle," Sydney, Civil Aviation Authority, 1991.

[32] "Annex 11: Air Traffic Services, Appendix 4," International Civil Aviation Organization, 1967.

[33] "Standard F 2411-04: Specification for Design and Performance of an Airborne Sense-and-Avoid System*,"* F38 committee, ASTM International, Jan 2005.

[34] Bernier, R., Bissonnette, M., et al., "DSA Compliance using 35 GHz Radar for unmanned vehicles operating in national airspace*,"* Amphitech, Jun 2004.

[35] *USAF Physiological Training Handbook,* Edwards AFB, CA, Medical Group Publication, 2001.

[36] Adams, C., "UAVionics in the US," *Aviation Today,* Feb 2005.

[37] Rydergard, D., "Image Processing Algorithms for See and Avoid," The Royal Institute of Technology, Apr 2005.

[38] "Proposal #98-149*,"* U.S. Navy, 1998.

[39] "UAV Initiatives 2005," US Air Force UAV Battlelab, 20 Apr 2005, <www.nellis.af.mil/UAVB/ uavbinitiatives.asp>.

[40] *Systems Phase Handbook,* Edwards AFB, CA, USAF Test Pilot School, 2000, p. 4-20.

[41] Adams, C., "UAVionics in the US," *Aviation Today,* Feb 2005.

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[42] "Contract #98-150," U.S. Navy, 1998.

[43] Lopez, R., "Avoiding Collisions in the Age of UAVs," *Aerospace America,* June 2002.

Vita

Nicholas Hardman is currently an American exchange officer with the Spanish Air Force at the National Institute for Aerospace Technology (INTA), Torrejón, Spain. He is working in the department for unmanned aerial vehicle development.

Nick was born in Pendleton, Oregon. He graduated from Colville High School, WA and entered Seattle Pacific University in 1992. He graduated in 1996 with a degree in electrical engineering. He was commissioned into the U.S. Air Force and went on get a master's degree from the University of Washington. His thesis work was in the control of elastically coupled systems under a research fellowship in the Boeing Control and Robotics Systems Laboratory.

He then transferred to Edwards AFB, California where he worked on the B-1B upgrade program as an avionics test engineer. Nick went on to work on the B-2A and F-22 defensive electronic warfare systems. During the same time period he began flight operations with the B-52H test team and became mission qualified as an airborne test instrumentation operator.

Nick was selected for the USAF Test Pilot School in 2000. After graduation, he began work at Eglin AFB, FL as the lead engineer for the advanced data links test team. After moving to flight commander of the Tactical Communications and Surveillance Test Flight, Nick oversaw Link-16 developmental programs on the F-15E, AC-130J, KC-10, and B-1B. In 2004, Nick was accepted for a flight test engineer exchange program with the Spanish Air Force. He is currently pursuing a master's degree in aviation systems from the University of Tennessee, Space Institute.