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**Characteristics and spectrum considerations
for sense and avoid systems use on
unmanned aircraft systems**

M Series
**Mobile, radiodetermination, amateur
and related satellites services**



International
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Union

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Characteristics and spectrum considerations for sense and avoid systems use on unmanned aircraft systems

(2010)

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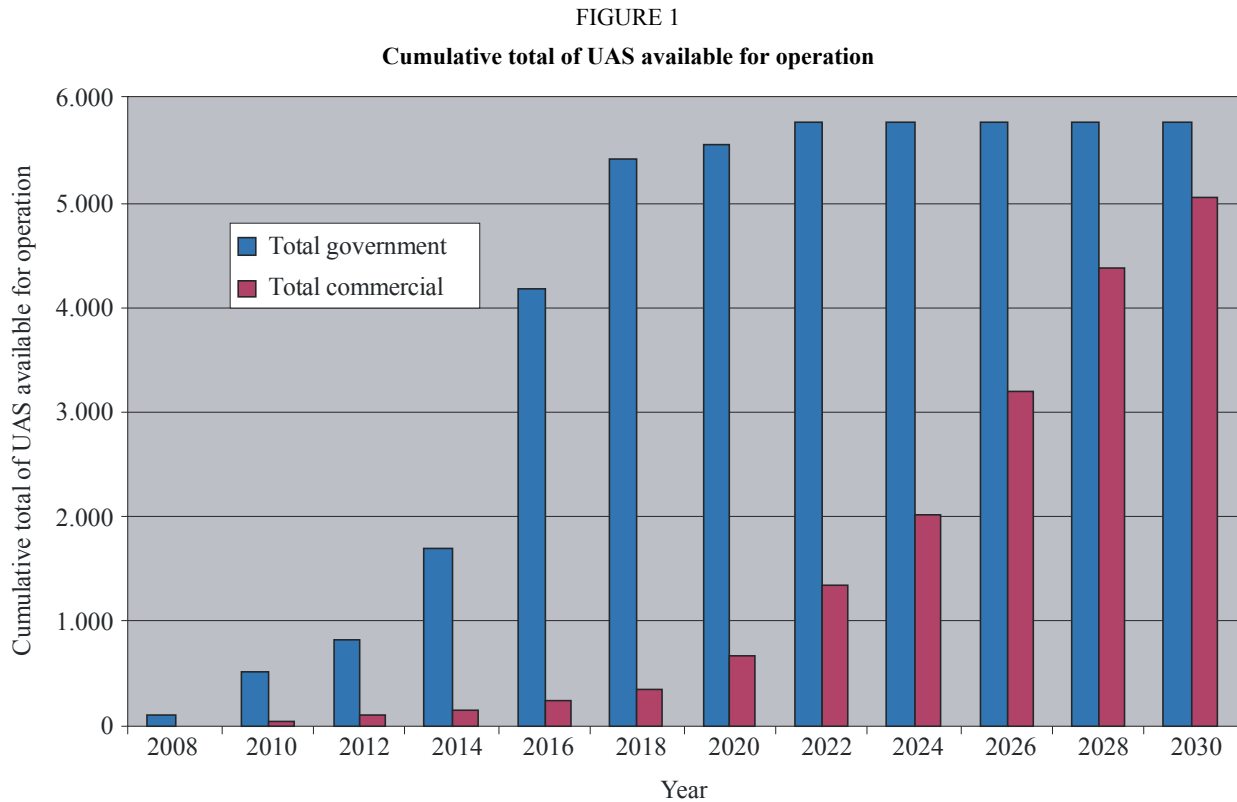
Objective

Numerous unmanned aircraft (UA) applications have been demonstrated or are planned that will dramatically increase the numbers of UA worldwide. With integration of UA into non-segregated airspace very close, it is essential that adequate spectrum be found to support UA operations including the spectrum requirements for UA sense and avoid (S&A) systems.

1 Introduction

Though UA have traditionally been used in segregated airspace where separation from other air traffic can be assured, administrations expect broad deployment of UA in non-segregated airspace alongside manned aircraft in the future. Current and future unmanned aircraft system (UAS) operations may include scientific research, search and rescue operations, hurricane and tornado tracking, volcanic activity monitoring and measurement, mapping, forest fire suppression, weather modification (e.g. cloud seeding), surveillance, communications relays, agricultural applications,

environmental monitoring, emergency management, and law enforcement applications. Thus, significant growth is forecast in the UAS sector of aviation and the projected growth is shown in Fig. 1.



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For an air vehicle to operate in non-segregated airspace there is a requirement to see and avoid other aircraft, properly act and respond to certain weather conditions, and remain well clear of obstacles. Two primary sensor systems are under development to allow a UAS to meet this requirement. The first class comprises sensor(s) or electronic system(s) on the air vehicle and is called aircraft-based sense and avoid (ABS&A). The second class involves sensor(s) or electronic system(s) monitoring the air space from the ground and is referred to as ground-based sense and avoid (GBS&A). It is anticipated that equipage of UA with an ABS&A system or the use of a GBS&A would be dependent on the class¹ of airspace the UA operates.

As shown in Fig. 1, the number of commercial and government UAS is rapidly expanding. UAS densities vs. altitude and size are shown in Tables 1 and 2. The goal of airspace access for appropriately equipped UA systems is to achieve a level of safety equal to that of an aircraft with a pilot in the cockpit. If UAS operate in non-segregated civil airspace, they must be integrated safely and adhere to current operational rules that provide an acceptable level of safety similar to that of a conventional manned aircraft. Thus it is envisioned that UA will require an S&A system

¹ The world's navigable airspace is divided into three-dimensional segments, each of which is assigned to a specific class. Most nations adhere to the classification specified by the International Civil Aviation Organization (ICAO) in which classes are fundamentally defined in terms of flight rules and interactions between aircraft and Air Traffic Control (ATC). Individual States may also designate Special Use Airspace, which places further rules on air navigation for reasons of national security or safety.

that can maintain simultaneous tracks of nearby aircraft, terrain, weather, and obstacles to replace current functionality and actions performed by the pilot on manned aircraft.

TABLE 1
UAS densities vs. altitude based on Fig. 1 projections

UA density	UA/10 000 km ²
At surface	(3 UA at an airport) 2.395
0-FL50 (1 500 m)	4.017
FL50-FL195 (1 500-6 000 m)	1.560
> FL 195 (> 6 000 m)	0.644
Total density	8.616

TABLE 2
UAS densities vs. size based on Fig. 1 projections

UA categories	Per 10 000 km ²	Per spot-beam*	In regional-coverage beam**
Large	0.440	21	341
Medium	1.950	93	1.515
Small	8.031	385	0
Total	10.421	501	1.856

* 480 000 km²
** 7 800 000 km²

Since the S&A systems will be used to ensure the safety of life and property, a radiofrequency (RF) based S&A system is one of these technologies. These RF systems will need to be designated a safety service and operate in an aeronautical radionavigation service (ARNS) allocation.

2 General descriptions and terminology

Unmanned aircraft are powered, aircraft that do not carry a human pilot, use aerodynamic forces to provide vehicle lift, and may fly semi-autonomously or autonomously, or be piloted remotely. The current state-of-the-art in UAS design and operation is leading to the rapid development of UAS applications to fill many diverse requirements. UAS applications that have been demonstrated or planned come from such areas as agriculture, communications relays, aerial photography, mapping, emergency management, scientific research, environmental management, and law enforcement. The safe operation of UAS outside segregated airspace requires addressing the same issues as manned aircraft, namely integration into the air traffic control (ATC) system. Because the pilot is no longer aboard, a method of replacing the pilot's "see and avoid" responsibilities as well as procedures, are required. While existing onboard systems may be adapted or incorporated to accommodate the S&A requirements for cooperative targets, it is likely that new technologies as well as additional systems will be required for detecting and acting on non-cooperative targets.

2.1 Terminology

Unmanned aircraft (UA): Designates all types of aircraft remotely controlled.

Unmanned aircraft control station (UACS): Facilities from which a UA is controlled remotely.

Control and non-payload communications (CNPC): The radio links, used to exchange information between the UA and UACS, that ensure safe, reliable, and effective UA flight operation. The functions of CNPC can be related to different types of information such as: telecommand messages, non-payload telemetry data, support for navigation aids, air traffic control voice relay, air traffic services data relay, target track data, airborne weather radar downlink data, non-payload video downlink data.

Sense and avoid (S&A): S&A corresponds to the piloting principle “see and avoid” used in all air space volumes where the pilot is responsible for ensuring separation from nearby aircraft, terrain and obstacles.

Unmanned aircraft systems (UAS): Consists of the following subsystems:

- UA subsystem (i.e. the aircraft itself).
- UACS subsystem.
- CNPC subsystem.
- ATC communications subsystem (not necessarily relayed through the UA).
- S&A subsystem.
- Payload subsystem (e.g. Video camera ...).

Intruder: An aircraft (manned or unmanned) that enters the S&A surveillance volume and tracked by the S&A system.

2.2 Airspace

To date, operations have been limited to segregated airspaces designated as “R” (Restricted), “D” (Dangerous) or “P” (Prohibited). For the purposes of this report, the airspace may be grouped into three categories, namely:

- ATC Separation Assurance – Air traffic control is responsible for safe separation of all aircraft. This comprises Classes A, B, and, if the UAS is operated in accordance with Instrument Flight Rules (IFR), Class C airspace.
- Limited or no ATC Separation Assurance– Air traffic control is not responsible for safe separation of all airspace users. This comprises Classes D, E, F and G airspace.
- Segregated – A defined volume of airspace is reserved for exclusive use of a particular UAS. In such airspace there would be no air traffic control service and therefore ATC is not responsible for separation but there are one or more aircraft, under the control of the same operator, in this airspace at a given time.

2.3 Applicability of sense and avoid to overall collision avoidance approach

An important point to consider in the design of a sense and avoid system is how it fits into the total systems approach to collision avoidance. As shown in Fig. 2, the approach to collision avoidance uses a layered approach. Current technologies that may accommodate these layers include ATC procedures, ground and surface ATC surveillance systems, automatic dependant surveillance-broadcast (ADS-B), airborne collision avoidance system (ACAS) also called traffic collision avoidance system (TCAS), and S&A. ACAS (or TCAS) for use on an UA is still being developed and requires modification to the ACAS algorithms not only for the UA, but also on existing manned aircraft prior to implementation. ADS-B is a newer situational awareness system that is currently

being deployed on manned aircraft. It is likely that there will be cases where ADS-B is used without ACAS. In any event, the S&A system is the final layer in case the preceding layers do not provide sufficient separation to avoid a potential collision.

FIGURE 2
Layered collision avoidance approach



2.4 Existing aeronautical radionavigation allocations

Currently, there are a number of frequency bands with worldwide ARNS allocations. These ARNS bands could potentially be used to accommodate the UAS S&A applications. These bands are listed in subsequent sections.

3 Technical considerations for S&A

3.1 Aircraft-based S&A

There are a number of factors that drive the performance requirements needed from an RF-based ABS&A sensor as shown in Fig. 3. Indeed, the number of factors that drive the performance requirements for an ABS&A sensor is large resulting in a very difficult multidimensional trade space containing both dependent variables and independent variables. These factors include characteristics of the encounter including near miss aircraft collision (NMAC) volume, the latencies in the actual ABS&A system implementation, and the performance parameters of the radar used as the ABS&A sensor.

FIGURE 3
S&A sensor performance requirement factors

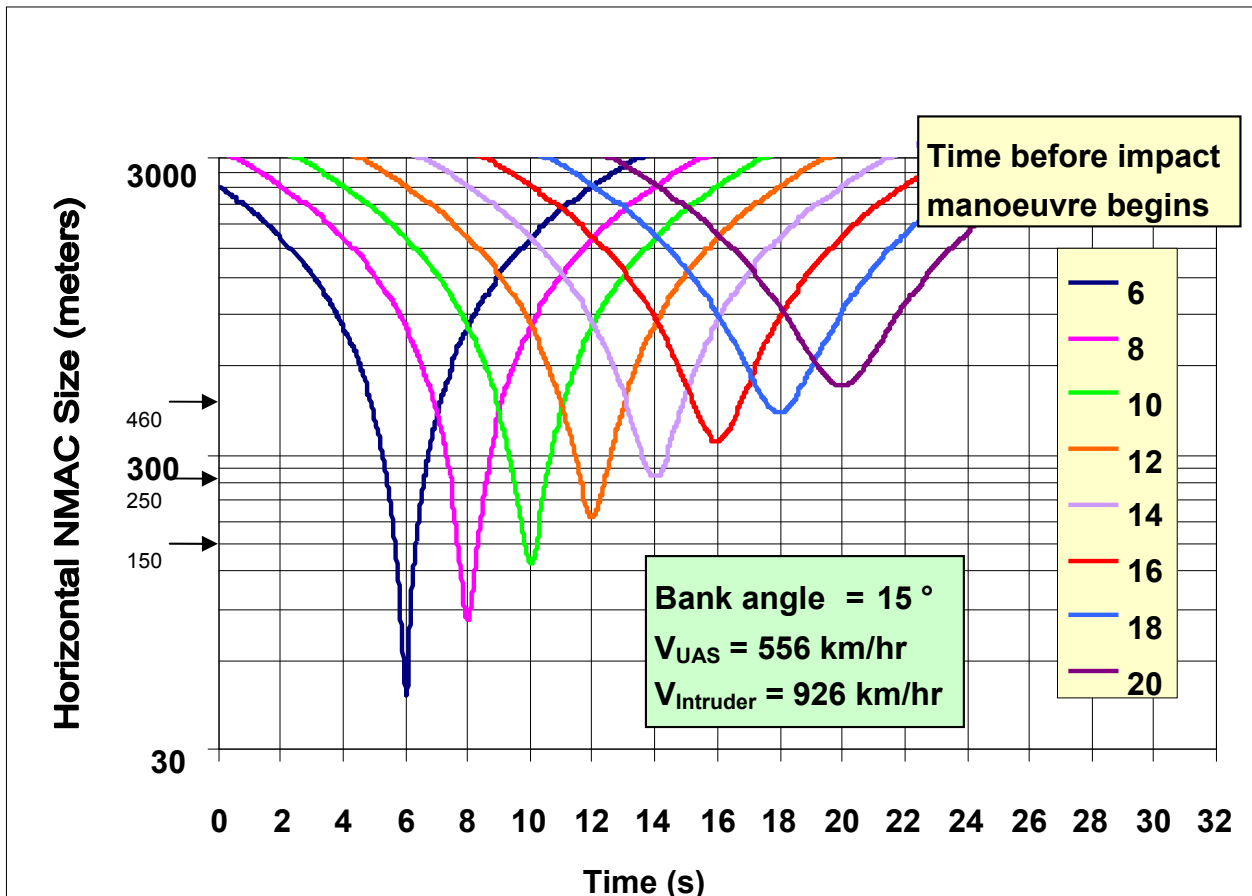
Encounter Characteristics	Time Processing Latency	Radar Performance
<ol style="list-style-type: none"> 1. Encounter Geometry 2. Closing Speeds 3. NMAC Volume 4. Collision Avoidance Zone Size 5. Traffic Density 	<ol style="list-style-type: none"> 1. Detection 2. Track Declaration 3. Algorithm Processing 4. Communications Delay 5. Pilot Response 6. Aircraft Performance 	<ol style="list-style-type: none"> 1. Angular Resolution 2. Frequency 3. Detection Range 4. Track Rate 5. Intruder Radar Cross Section

3.1.1 Encounter characteristics

The first major factor driving the sensor performance requirements shown in Fig. 3 is Encounter characteristics, which include collision course geometries, closing speeds between the UA and another aircraft known as “the intruder”, the selected NMAC volume, collision avoidance zone size and overall aircraft traffic density. The second major class of factor driving the needed sensor performance includes the latencies in the system implementation. Specific latency drivers that need to be taken into account are minimum allowable detection/detection times, pilot response latencies, UA communications system latencies, ABS&A sensor data processing delays and expected UA aero-performance characteristics. The last major factor driving ABS&A sensor performance includes the characteristics of the radar such as angular accuracy, available power-aperture (i.e. detection range), radar cross-section of the intruder aircraft and track rate.

Closing speeds between the UA and an intruder and the NMAC volume, on the other hand, do have bearing on the necessary detection range needed to detect, track and perform a collision avoidance maneuver. Obviously, the faster the closing speed between the two aircraft, the longer the detection range from the radar that is needed. What might not be obvious is the impact of NMAC size on needed detection range. Each plot in Fig. 4 shows the distance between the UA and the intruder aircraft as a function of time before a maneuver is needed, and the time at which each curve is at a minimum is the point of closest approach assuming that the UA can perform a turn at a 15° bank angle. Using the minimum as a proxy for horizontal NMAC distance, one can see that a larger NMAC volume drives the system designer to needing a longer detection range.

FIGURE 4
 NMAC size vs. time required to start avoidance manoeuvre



3.1.2 System latencies

The S&A encounter timeline shown in Fig. 5 defines the 8 major elements that need to be accounted for in an ABS&A scenario. Again, as with the considerations associated with encounter geometries, system latencies ultimately drive the radar sensor detection range.

UA performance has a large impact on the system latencies. Obviously, a slower moving aircraft has more time to devote to detecting an intruder, but is often less maneuverable so it will probably have less ability to affect a collision avoidance maneuver in order to avoid a collision. On the other hand, UA that fly faster will have less time to devote to detecting an intruder, but these UA are often more maneuverable so they will probably have a greater ability to turn away from the collision.

FIGURE 6
Probability of missed collision as a function of available angular resolution

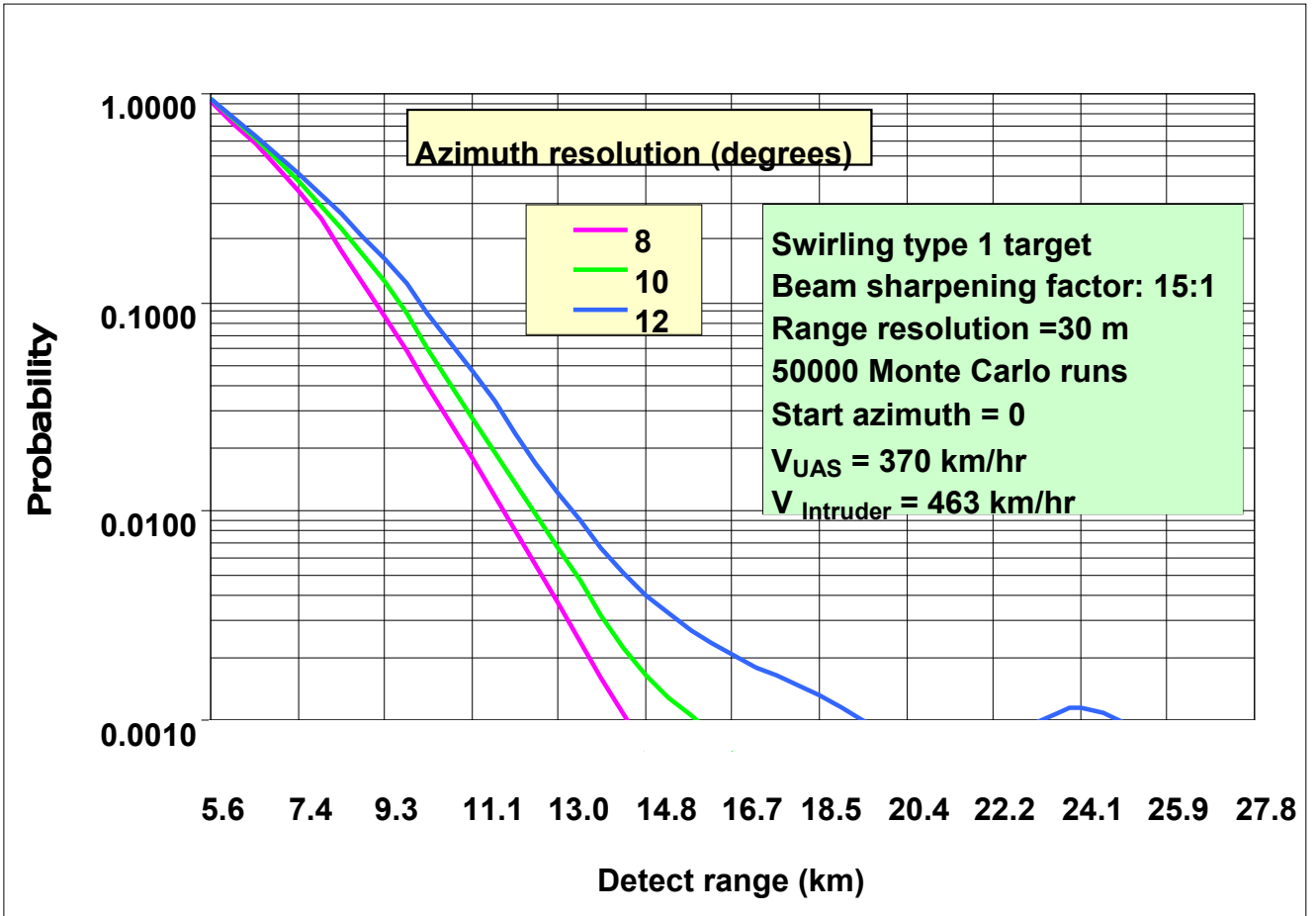
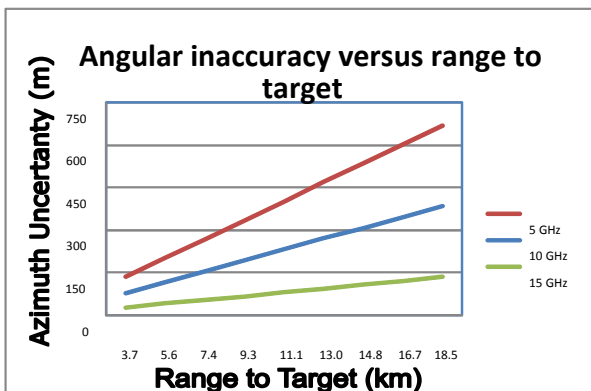
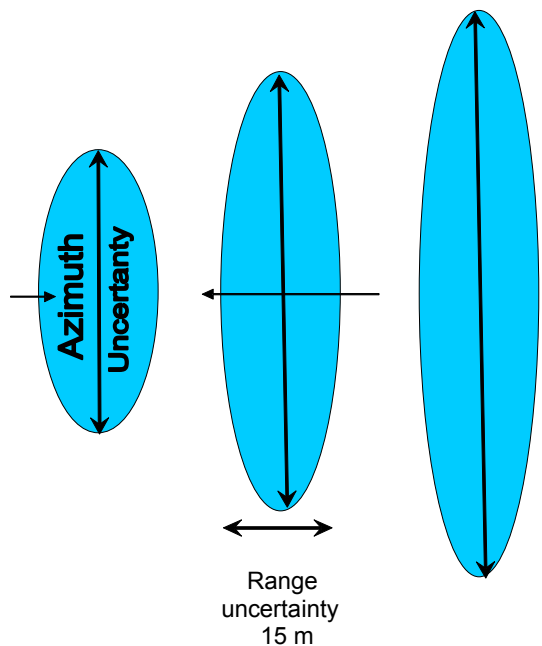


FIGURE 7
Range and azimuth uncertainty as a function of range

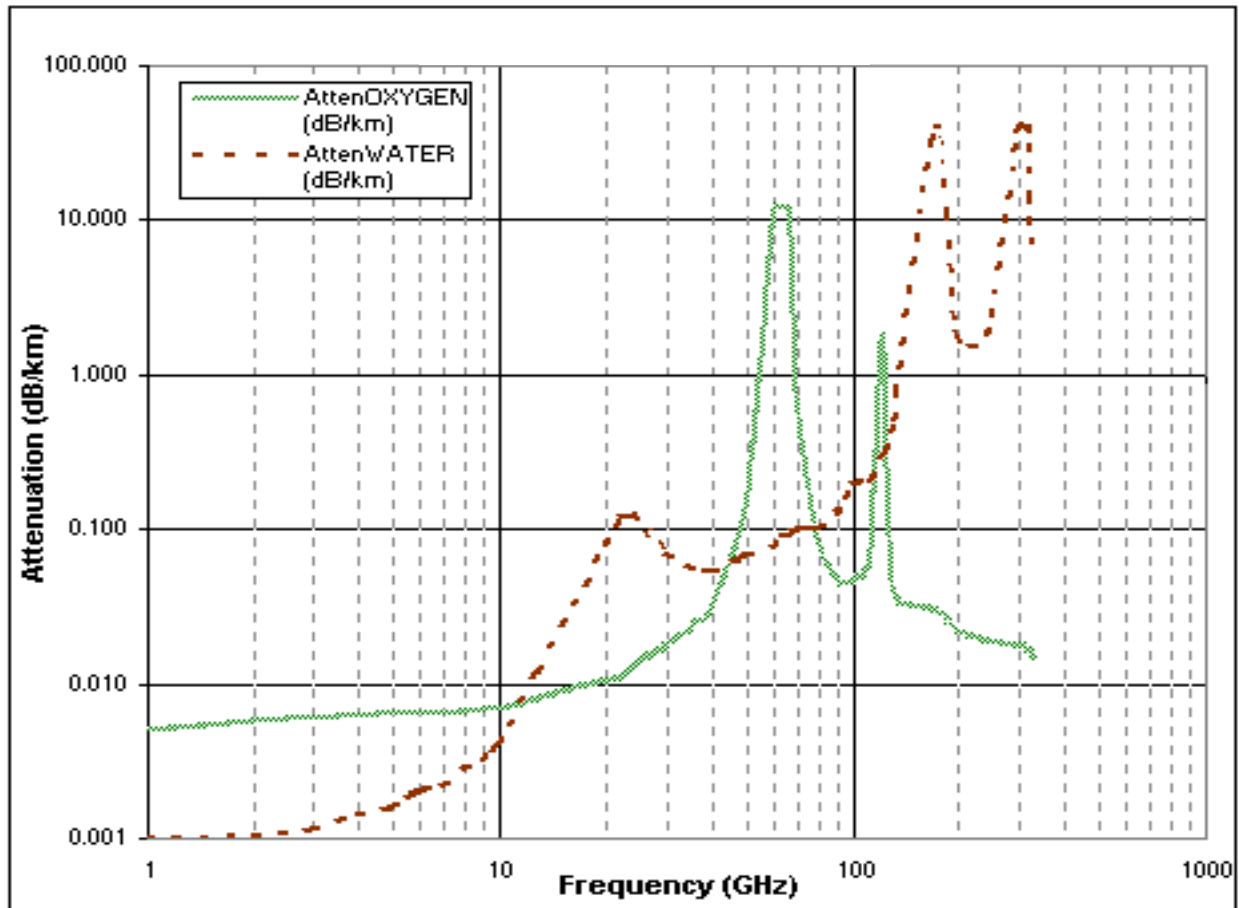


- Assumptions:**
- Angular RMS accuracy = 1°
 - AESA 38 cm x 38 cm array



Collision course geometries and overall aircraft traffic density impact the scan volume needed by an ABS&A radar, and have only indirect impacts on the specific radar frequency used. However, the size and placement of the antenna array are dependent on these. As shown in Fig. 8, the atmospheric attenuation due to rain increases as frequency increases so the lower frequencies would require less power aperture than higher frequencies for a given detection range.

FIGURE 8
Plot of atmospheric absorption at microwave frequencies



According to Fig. 8, lower frequencies are favored over higher frequencies for a given detection range because of the lower attenuation due to rain. Further, in terms of antenna size, higher frequencies are favored over lower frequencies because, in general, smaller antennas can be used at higher frequencies (lower wavelengths).

Thus the proper selection of frequency is critical to the success of the ABS&A radar. If the selected frequency is too low, the antenna will become too large for the UA and if the frequency is too high, the atmospheric attenuation will require more power than is available onboard the UA and increase the size and weight of components required for the ABS&A radar.

3.1.4 Other technical considerations

Another factor that must be taken into account in the determination of a suitable frequency for an airborne radar sensor is electromagnetic interference (EMI) compatibility, both local compatibility on the UA, as well as compatibility with co-primary users of the spectrum. For example, if a UA is carrying another radar as part of its mission payload, one would prefer that

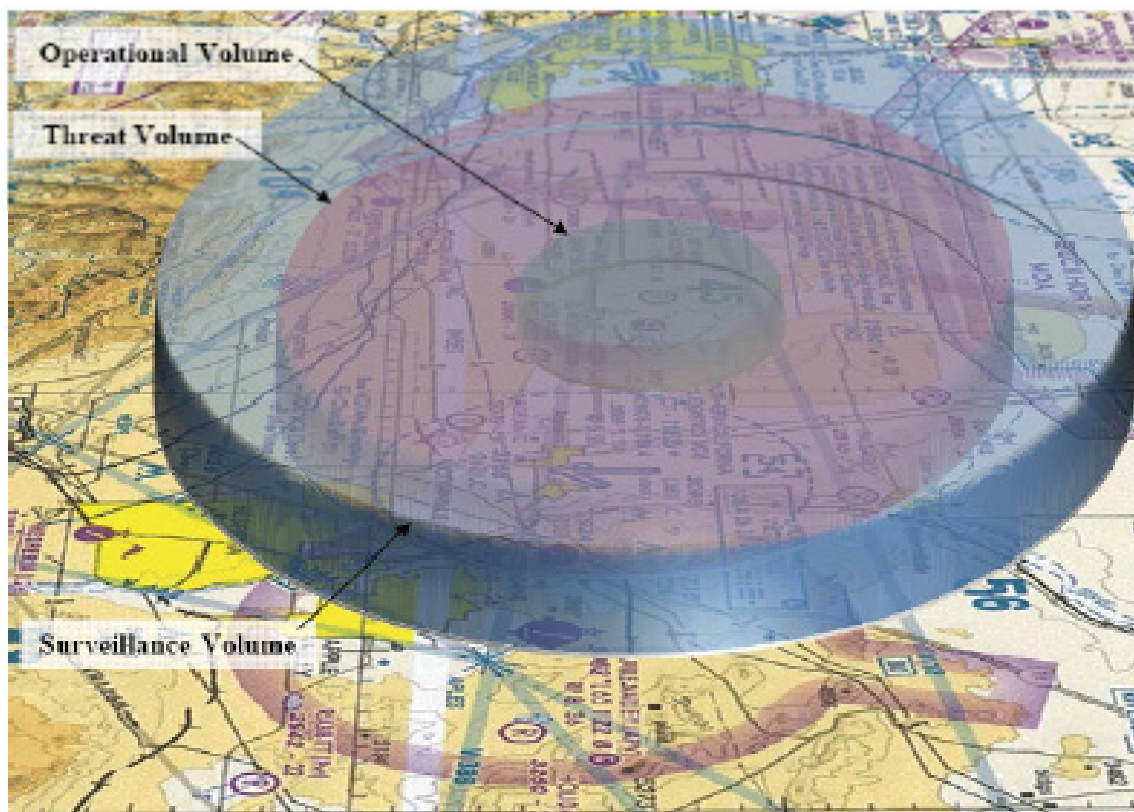
the S&A sensor frequency be out-of-band from the mission payload radar in order to minimize interference between the two radars. In addition, the prevalence of other radars (e.g. weather radars) in a certain band may impact the use of that band for ABS&A.

3.2 Other technical issues

There are scenarios that occur when traditional existing ground-based surveillance radars are unable to detect the UA when they are flying at low altitude. These scenarios are caused by terrain, man-made structures, flight below normal radar coverage and lack of a transponder. A ground-based radar that can fill this gap would be an ideal GBS&A system.

One approach has been developed utilizing a GBS&A system. This approach involves self separation that requires the UAS operate in airspace inside a fixed threat detection airspace with no other air vehicles. If an aircraft enters the threat detection airspace, a ground-based surveillance system warns the operator. The operator will then execute the second phase and fly the UAS to a safe state. A safe state exists when the UAS lands, exits from its operating area into a safe area, or controlled or restricted airspace.

FIGURE 9
Ground-based sense and avoid



It is anticipated that GBS&A may be a critical component to the overall S&A solution, because many operations are conducted with relatively much small classes of UAS that do not have the power, cooling and physical space to accommodate the currently projected size and weight of current onboard ABS&A systems. In addition, an ABS&A system may add significant cost and may therefore not be affordable for all UAS. Therefore, GBS&A may be the predominant solution to support all classes of UAS to operate in non-segregated airspace.

There are currently no standards for GBS&A, so standards will need to be developed.

4 Spectrum considerations for UAS sense and avoid system

To ensure safe flight operations with other aircraft in non-segregated airspace, UAS S&A may require operation in multiple ARNS bands. Allocations for ARNS can be grouped in three general categories; airborne radars, ground-based radars, and other ARNS allocations. Thus, ABS&A may not use bands reserved for ground-based ARNS systems and GBS&A may not use bands reserved for airborne ARNS systems.

The sections below summarize the status of the ARNS bands from the Radio Regulations without prejudice to a specific band. It should be noted that there may be exceptions to this categorization that could be considered when selecting an appropriate band. For example, the bands from the other ARNS allocations category may also be appropriate for airborne S&A radars. Consideration should also be given to the need for ABS&A radars to use worldwide ARNS allocations rather than allocations for a single Region. Conversely, GBS&A radars only require allocations within regions and areas of the world where they will be used and allocations for GBS&A radars may be best considered within individual administrations.

4.1 Aeronautical radionavigation spectrum currently allocated for airborne radars

There are currently five frequency bands allocated to ARNS that are used to support airborne aeronautical radionavigation radar systems worldwide. These bands are listed in Table 3. There are currently existing standards for these airborne radars in all of these bands.

TABLE 3
ARNS allocations for airborne radars

Band	Status	Applicable RR (Edition of 2008) footnotes	Example of Aviation Standards	ITU-R Recommendations
4 200-4 400 MHz	primary	5.438, 5.439, 5.440	C67 ⁽¹⁾ , C92c ⁽²⁾	
5 350-5 470 MHz	primary	5.449, 5.448B, 5.448C, 5.448D	C63c ⁽³⁾	M.1638
8 750-8 850 MHz	primary	5.470, 5.471	C65a ⁽⁴⁾	M. 1796
9 300-9 500 MHz	primary	5.474, 5.475, 5.475A, 5.475B, 5.476	C65c ⁽³⁾	M. 1796
13.250-13.400 GHz	primary	5.497, 5.498A, 5.499	C65a ⁽⁴⁾	

⁽¹⁾ Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C67, Airborne Radar Altimeter Equipment (For Air Carrier Aircraft), 15 November 1960.

⁽²⁾ Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C67, Airborne Ground Proximity Warning Equipment, 19 March 1996.

⁽³⁾ Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C63c, Airborne Weather and Ground Mapping Pulsed Radars, 18 August 1983.

⁽⁴⁾ Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C65a, Airborne Doppler Radar Ground Speed and/or Drift Angle Measuring Equipment (for Air Carrier Aircraft), 18 August 1983.

4.2 Aeronautical radionavigation spectrum currently allocated for ground radars

There are currently six frequency bands allocated to ARNS that are used to support ground-based aeronautical radionavigation radar systems worldwide. These bands are listed in Table 4.

TABLE 4
ARNS allocations for ground radars

Band	Status	Applicable RR (Edition of 2008) footnotes	Aviation standards	ITU-R Recommendations
1 215-1 240 MHz	primary	5.329, 5.330, 5.331, 5.332	N/A	M.1463, M.1479
1 240-1 300 MHz	primary	5.282, 5.329, 5.330, 5.331, 5.332, 5.335, 5.335A	N/A	M.1463, M.1479
1 300-1 350 MHz	primary	5.337, 5.337A	N/A	M.1463, F.1584
1 350-1 370 MHz	primary	5.334, 5.338	N/A	M.1463, F.1242
2 700-2 900 MHz	primary	5.337, 5.423, 5.424	N/A	M.1464-1
9 000-9 200 MHz	primary	5.337, 5.471, 5.475A	N/A	M. 1796

4.3 Other aeronautical radionavigation spectrum

There are currently twelve other frequency bands allocated to ARNS that are used to support a variety of ARNS applications. These bands are listed in Table 5. There are existing standards for the ARNS systems in many of these bands. It should be noted that some of these bands may be appropriate for ABS&A or GBS&A radars.

TABLE 5
Other ARNS allocations

Band	Status	Applicable RR (Edition of 2008) footnotes	Example of Aviation Standards	ITU-R Recommendations
190-285 kHz	primary	5.68, 5.69, 5.70, 5.71	C41d ⁽¹⁾	
325-405kHz	primary	5.72	C41d ⁽¹⁾	
415-435 kHz	primary	5.72	C41d ⁽¹⁾	
510-535 kHz	primary	5.72	C41d ⁽¹⁾	
74.8-75.2 MHz	primary	5.180, 5.181	C35d ⁽²⁾	
108-117.975MHz	primary	5.197, 5.197A,	C36e ⁽³⁾ , C40c ⁽⁴⁾	
328.6-335.4 MHz	primary	5.258, 5.259	C34e ⁽⁵⁾	
960-1 215 MHz	primary	5.328, 5.328A	C66c ⁽⁶⁾	
5 000-5 030 MHz	primary	5.367		

TABLE 5 (*end*)

Band	Status	Applicable RR (Edition of 2008) footnotes	Example of Aviation Standards	ITU-R Recommendations
5 030-5 150 MHz	primary	5.367, 5.444, 5.444A, 5.446, 5.447, 5.447B, 5.447C	C104 ⁽⁷⁾	
5 150-5 250 MHz	primary	5.367, 5.444, 5.444A, 5.446, 5.447, 5.447B, 5.447C		M.1454, S.1426, S.1427
15.400-15.700 GHz	primary	5.511A, 5.511C, 5.511D	C63c ⁽⁸⁾	S.1340, S.1341

- (1) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C41d, Airborne Automatic Direction Finding (ADF) Equipment, 6 May 1985.
- (2) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C35d, Airborne Radio Marker Receiving Equipment, 5 May 1971.
- (3) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C36e, Airborne ILS Localizer Receiving Equipment Operating within the Radio Frequency Range of 108-112 Megahertz (MHz), 25 January 1988.
- (4) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C40c, VOR Receiving Equipment Operating within the Radio Frequency Range of 108-117.95 Megahertz (MHz), 25 January 1988.
- (5) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C34e, Airborne ILS Glide Slope Receiving Equipment Operating within the Radio Frequency Range of 328.6-335.4 Megahertz (MHz), 15 January 1988.
- (6) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C66c, Distance Measuring Equipment (DME) Operating within the Radio Frequency Range of 960-1215 Megahertz (MHz), 18 January 1991.
- (7) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C93, Microwave Landing System (MLS) Airborne Receiving Equipment, 22 June 1982.
- (8) Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, Washington DC, Technical Standard Order TSO-C63c, Airborne Weather and Ground Mapping Pulsed Radars, 18 August 1983.

5 Conclusions

This Report provides an explanation of the requirements for S&A sensors to support UAS operations as well as the current status of allocations that allow this usage. Tables 3 through 5 provide alternative bands that have allocations for airborne and ground-based applications of UAS S&A. As discussed in § 3, ABS&A systems are constrained by UA SWaP. Also, weather or atmospheric attenuation must be considered when choosing spectrum for ABS&A because of the impact in meeting the operational requirements of the S&A function described in § 2. GBS&A on the other hand is largely free from SWaP considerations and are less constrained by weather and atmospheric attenuation. Thus, selection of the most suitable band for any particular UAS S&A

application must consider performance aspects, which may be constrained due to available technology. Many of the existing ARNS are already in use and the existing users of these bands will need to be considered when selecting ARNS bands for S&A applications.

Glossary

ABS&A	Aircraft-based sense and avoid
ACAS	Airborne collision avoidance system
ADS-B	Automatic dependant surveillance broadcast
ARNS	Aeronautical radionavigation service
ATC	Air traffic control
BLOS	Beyond line-of-sight
CNPC	Control and non-payload communications
EESS	Earth-exploration satellite service
EMI	Electromagnetic interference
FSS	Fixed-satellite service
GBS&A	Ground-based sense and avoid
ICAO	International Civil Aviation Organization
IFR	Instrument flight rules
ITU-R	International Telecommunications Union Radiocommunications Sector
MSS	Mobile-satellite service
NMAC	Near-miss aircraft collision
RF	Radio frequency
RNSS	Radionavigation-satellite service
S&A	Sense and avoid
SWaP	Size, weight and power
TCAS	Traffic collision avoidance system
TSO	Technical standard order
UA	Unmanned aircraft
UACS	Unmanned aircraft control station
UAS	Unmanned aircraft system
WRC	World Radiocommunication Conference
