CONCEPT OF INTEGRATION FOR UAS OPERATIONS IN THE NAS

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Abstract

One of the major challenges facing the integration of Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) is the lack of an onboard pilot that can comply with the legal requirement identified in the US Code of Federal Regulations (CFR) that pilots see and avoid other aircraft. UAS will be expected to demonstrate the means to perform the function of see and avoid while preserving the safety level of the airspace and the efficiency of the air traffic system. This paper introduces a Sense and Avoid (SAA) concept for integration of UAS into the NAS that is currently being developed by the National Aeronautics and Space Administration (NASA) and identifies areas that require additional experimental evaluation to further inform various elements of the concept. The concept design rests on interoperability principles that take into account both the Air Traffic Control (ATC) environment as well as existing systems such as the Traffic Alert and Collision Avoidance System (TCAS). Specifically, the concept addresses the determination of well clear values that are large enough to avoid issuance of TCAS corrective Resolution Advisories, undue concern by pilots of proximate aircraft and issuance of controller traffic alerts. The concept also addresses appropriate declaration times for projected losses of well clear conditions and maneuvers to regain well clear separation.

1 Introduction

The Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) project is a research effort funded by the National Aeronautics and Space Administration (NASA) that addresses the development and integration of concepts and technologies to facilitate public and civil UAS in non-segregated airspace operations. The desire to utilize unmanned aircraft to perform national security, defense, scientific, emergency management, and many civil applications is driving the critical need for UAS to have less restrictive access to the NAS. Access to the NAS is hampered by challenges such as the lack of an on-board pilot to see and avoid other aircraft, the lack of protected civil radio frequency spectrum and reliable infrastructure for command and control links, and the wide variation in UAS size, performance (altitudes, speeds, and maneuvering performance) and missions. The Federal Aviation Administration (FAA) has established a process enabling public agencies to request a Certificate of Authorization or Waiver (COA) to operate UAS in the NAS. The COA process is resource intensive and lengthy; additionally, COAs are restrictive and often lack the flexibility to meet the needs of the entire mission. In order for UAS to integrate seamlessly in the NAS, major technical and regulatory challenges must be resolved. Although some of the abovementioned characteristics are not unique to UAS, the number of aircraft that possess them is expected to increase because UAS will be able to fulfill so many new roles. A large number of these types of operations may impact the efficiency of all aircraft operations as well as the entire airspace by inducing additional delays or increasing air traffic control workload.

The UAS in the NAS project is addressing a number of the technical challenges such as ensuring robust and secure communications technologies and solving the constraints of frequency spectrum allocation, developing robust human systems integration and standards, defining airworthiness and certification standards for a wide range of UAS vehicle types and assessing the impact of "sense and avoid" equipped unmanned aircraft (UA) on both the airspace system and the air traffic control (ATC) environment. This paper focuses on the sense and avoid interoperability challenge.

The lack of an onboard pilot is clearly the most obvious difference between UAS and traditional aircraft and it is this difference that drives the problem of how to deal with the legal requirement identified in the US Code of Federal Regulations (CFR) that pilots see and avoid other aircraft. As a means of compliance with the regulatory requirements to see and avoid the final report of the FAA sponsored Sense and Avoid (SAA) Workshop [1] defines SAA as "the capability of a UAS to remain well clear from and avoid collisions with other airborne traffic. SAA provides the intended functions of self separation and collision avoidance compatible with expected behavior of aircraft operating in the airspace system." Future SAA systems will provide UA pilots with some level of surveillance information about aircraft near the UA and enable the pilot to execute approved procedures for maintaining safe separation ("well clear") from other aircraft with or without controller coordination.

This paper introduces a SAA concept for integration of UAS into the NAS that is currently being developed by NASA and identifies areas that require additional experimental evaluation to further inform various elements of the concept. The concept design rests on interoperability principles that take into account both the ATC environment as well as existing systems such as the Traffic Alert and Collision Avoidance System (TCAS).

The rest of the paper is organized as follows: Section 2 provides a high level description of a concept for integration of SAA-equipped UAS operations and introduces basic SAA terminology and concepts needed to describe the new proposed implementation. Section 3 further describes the new SAA implementation concept as well as the rationale and design principles on which the concept is based. Section 4 provides concluding remarks.

2 SAA Concept of Integration for UAS NAS Operations

This section and section 3 describe an implementation concept for SAA and the fundamental design principles that rest on the interoperability requirements of SAA functionality with the provision of air traffic services, and with existing TCAS equipped aircraft. The specific focus is on determining SAA capabilities required to compensate for the lack of an onboard pilot, and to define an operational concept that will enable such SAA-equipped aircraft to smoothly integrate into an air traffic services environment. The concept builds on and extends a foundation of concepts described by the FAA sponsored SAA Workshop Final Report [1] and by various RTCA SC-203 documents [2, 3].

2.1 Overview, Assumptions and Scope

One approach to developing and scoping an SAA interoperability concept is to assume that, from an air traffic controller or manned aircraft pilot's point of view, an SAA-equipped UA should behave in and react to air traffic situations in the same or a closely-similar manner as if it were capable of see and avoid. This assumption implies not only the obvious general requirement of safely avoiding proximate aircraft, but outside of Class A airspace may also include the requirement to enable visual separation procedures. Controllers apply visual separation in addition to radar and non-radar (procedural) separation when providing services to aircraft outside of Class A airspace (i.e., below Flight Level 180 or

18,000 feet MSL in the U.S.) [4] and visual separation is needed for orderly and expeditious traffic flow in a visual environment. Controllers expect pilots to maneuver clear of proximate aircraft and to comply with visual separation instructions and clearances in a predictable and efficient manner. Controllers frequently apply visual separation with the instruction to “maintain visual separation” or even to “follow” visually-acquired traffic. It can therefore be argued that see and avoid (and potentially SAA) also serves as a mode of separation provision. The SAA concept described in this paper is designed to address these various see and avoid requirements.

The concept described here assumes the present-day NAS communication, navigation and surveillance (CNS) infrastructure and ATC capabilities, although it does not preclude planned NextGen operational improvements, and additionally assumes that an approved and reliable UAS control link capability will be available between UAs and their respective Ground Control Station (GCS) sites. A means for the UAS operator to communicate with ATC will also be available, such as voice communications relayed through the control link in the present-day environment. It is also assumed that one or more aircraft sensor/tracker capabilities will be available to the UAS, either onboard the UA and/or from ground-based sources, and that these sensor/tracker data will be provided as inputs to sensor fusion and threat detection and/or resolution capabilities. ATC’s assumed expectations are that for normal operations, UAS requesting NAS access will be appropriately CNS-equipped and able to comply with the same ATC clearances and instructions as manned aircraft requesting the same services and airspace access.

Initially, this concept would exclude very limited-performance aircraft or lighter-than-air vehicles. This limited scope implies that the UA: a) would be large enough to be seen by other aircraft; b) would be operating under comparable right-of-way rules with other Airplane and Rotorcraft category aircraft (e.g., aircraft overtaking the UA must give way); and c) are not so performance-limited as to be treated as a “special case” by ATC (e.g., with segregated airspace and/or COA operations).

2.2 Terms, Functions and Allocation

The SAA Workshop Final Report [1] defined SAA terms, functions and sub-functions which are utilized in describing the concept in subsequent sections. The remainder of this subsection provides a brief description of these terms, functions and sub-functions (phrases in quotes are taken directly from reference [1]), as well as a description of how these sub-functions are allocated by the concept.

The two functions of SAA are self separation (SS) and collision avoidance (CA). The SS function is “essential” and “could be the only function provided” if “the target level of safety can be met with SS alone”; it is intended as a means of compliance with the regulatory requirements to remain well clear of other aircraft, compatible with expected behavior of aircraft operating in the NAS. SS maneuvers “are expected to be normal/operational, non obtrusive maneuvers which will not conflict with accepted air traffic separation standards” and made “within a sufficient timeframe to prevent activation of a collision avoidance maneuver.” The maneuvers must be in accordance with regulations and procedures and compatible with TCAS II Resolution Advisories when maneuvering to avoid TCAS II equipped aircraft. The CA function engages “when all other modes of separation fail” and maneuvers are made “within a relatively short time horizon before closest point of approach” (CPA).

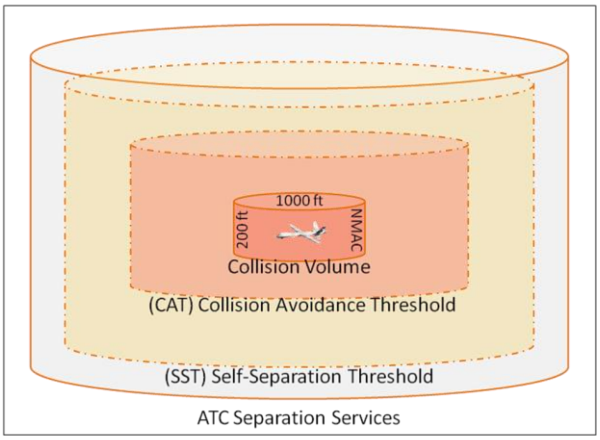

Fig. 1. SAA Airspace Volumes

The SAA functions are based on a set of airspace volumes and thresholds surrounding the UA, as shown notionally in Fig. 1. The Collision Volume (CV) is "a cylindrical volume of airspace centered on the UA with a horizontal radius of 500 feet and vertical height of 200 feet (±100 feet) within which avoidance of a collision can only be considered a matter of chance." An aircraft encounter within the CV is considered a Near Mid-Air Collision (NMAC). The CA function's role is to prevent any aircraft from penetrating the CV, although it should be noted that an aircraft kept just outside the CV may still be dangerously close and could still be affected negatively by wake turbulence and other unforeseen considerations. The Collision Avoidance Threshold (CAT) is "the boundary around the UAS at which the collision avoidance function declares that action is necessary to avoid a collision and prevent the threat from penetrating the collision volume." The CAT is not cylindrical but rather is a variable boundary that depends on time, distance, maneuverability, and other parameters.

The Self Separation Threshold (SST) is also a variable boundary that depends on time, distance, maneuverability, and other parameters. Reference [1] defines the SST as "the boundary around the UAS at which the self separation function declares that action is needed to *preclude a threat aircraft from penetrating the collision avoidance threshold, thereby maintaining self separation and keeping the aircraft 'well clear' of each other" [emphasis added]*. The concept described in this paper extends the SAA Workshop's SST and well clear definitions. As described further in section 3.1, these definitions do not appear to provide sufficient conditions for maintaining self separation or well clear.

The ATC Separation Services volume surrounding the aircraft represents the airspace where ATC separation services are provided and established legal standards and regulations apply. This volume may or may not be cylindrical and its size will vary, depending on the region of airspace and means of separation applied.

The SAA functions are further divided into a set of sub-functions as shown in Fig. 2 and listed below:

1. **Detect** intruder
2. **Track** intruder (position & velocity)
3. **Evaluate** (assess collision or self-separation risk)
4. **Prioritize** intruder risks
5. **Declare** that some action may be required
6. **Determine** what action(s), if any, to take
7. **Command** determined action, if any
8. **Execute** commanded action

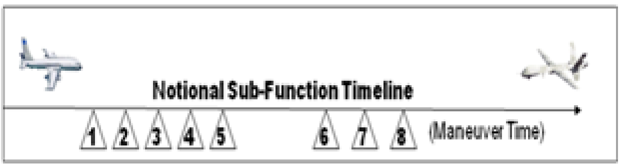

Fig. 2. SAA Sub-functions

The concept described in this paper allocates each of these functions to either automation or humans. There are clear advantages to allocating automation what it does best (sensing, monitoring, calculating) and allocating adaptive decision-making to humans (i.e., UA pilots, controllers), who typically do these functions better and more easily than does automation. This allocation is also more closely aligned with current operations; that is, the SAA automation is basically "restoring intelligent sight" to the remote UA pilot, but leaving the communication and executive-level decisions with the pilot-in-command. Based on that rationale, sub-functions 1-5 are expected to be performed by sensors and algorithms (automation), resulting in information elements/decision aids being provided to the UA pilot. Sub-functions 6 and 7 are, in normal conditions, performed by the UA pilot who evaluates information elements, queries or responds to ATC as necessary, and commands action if needed. Sub-function 8 is executed by UA systems. One additional sub-function, "return to mission" is under consideration that will ensure that the vehicle will efficiently return to its mission.

2.3 Sense and Avoid Concept of Use

At an overview level, SAA systems notionally consist of one or more surveillance sensors, trackers and/or surveillance data fusion logic, data communications architecture (between UA & GCS), threat detection and/or resolution (TD&R) computer logic, and potentially the display of traffic information and/or resolution guidance/advice. The SAA concept of use described here starts with the sensing and tracking of aircraft within the surveillance volume and the provision of these intruder data to an onboard TD&R capability. The TD&R capability is able to detect situations where intruders have become threats – that is, they have violated defined self-separation and/or collision avoidance thresholds or are projected to violate them within a specified look-ahead time – and to compute resolution maneuvers intended to resolve these threat situations. In normal operations the intruder and threat data, and recommended resolution maneuver(s), if any, are displayed to the UA pilot at the GCS. The UA pilot will consider the displayed data relative to the operations being conducted, negotiate and/or coordinate as necessary with ATC if receiving services from them, and then either command one or more UA maneuvers to resolve any threat situations (using either the TD&R-recommended maneuvers or alternate maneuvers negotiated with ATC) or take no action if the pilot determines or ATC coordination assures none is necessary. These UA pilot actions are analogous to those that would be taken by the pilot of a manned aircraft in visual meteorological conditions (VMC) who would see (i.e., detect and track) proximate aircraft, determine if they (will) possibly conflict with the current flight path, coordinate as needed with ATC if receiving services, and then maneuver (or not) as necessary to remain well clear and resolve the conflict if it exists. Similarly, the UA pilot may use the displayed data to identify and follow, or maneuver relative to, traffic called out by ATC, at a safe distance as indicated by the TD&R capability, in an analogous manner to a pilot of a manned aircraft visually performing these functions.

In situations where the UA-GCS link is assumed to be lost (e.g., link heartbeat timers have exceeded defined thresholds), the UA may take autonomous action to remain well clear of threats identified by the TD&R capability to have violated a defined self-separation threshold. The autonomous self-separation threshold may be different than the self-separation threshold used when the link is still functional. This UA behavior is analogous to a manned-aircraft pilot in VMC who has lost communication with an air traffic service provider, but continues to remain clear of other detected traffic. Similarly, if the UA's SAA capability includes collision avoidance (which it may or may not have, as described previously) and the computed time-to-collision falls below a defined threshold, then the UA may autonomously maneuver to avoid collision, regardless of lost-link status. These actions are analogous to the last-moment maneuvers that a pilot of a manned aircraft would take to avoid collision with an intruder.

3 SAA Concept Extended

A key element of the concept development approach is to understand the design space for SAA interoperability. This can be accomplished by starting with the assumption that completely accurate and reliable surveillance data are available to the TD&R logic of the SAA system. This assumption allows for the determination of practical separation and alert-time minima and maxima for optimal interoperability with the airspace system, independent of surveillance performance.

Concept implementations will subsequently have to account for real-world surveillance data uncertainty and sensor performance, informed by the interoperability concept of the operational design space available, and by safety analyses of the required sensor performance to operate within this design space to a specified target level of safety.

SAA concepts and their implementations must address at least three questions:

- What proximate traffic situations may require a change to the current

trajectory, or modification of a new trajectory under consideration?
- When should such a possible change be declared to the pilot?
- What trajectory changes are acceptable?

Each of these questions is addressed in the following subsections; the first question is closely related to the issue of "well clear."

3.1 "Well Clear"

The regulatory requirement to remain well clear of other aircraft is most directly addressed in 14 CFR 91.113 (b) which states, "When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the right of way, the pilot shall give way to that aircraft and may not pass over, under or ahead of it unless well clear." If a UA is projected to be less than well clear from an intruder for which it should yield right of way, either on its current trajectory or on a new trajectory under consideration, then the SS function must detect this condition. The challenge is to determine what is well clear.

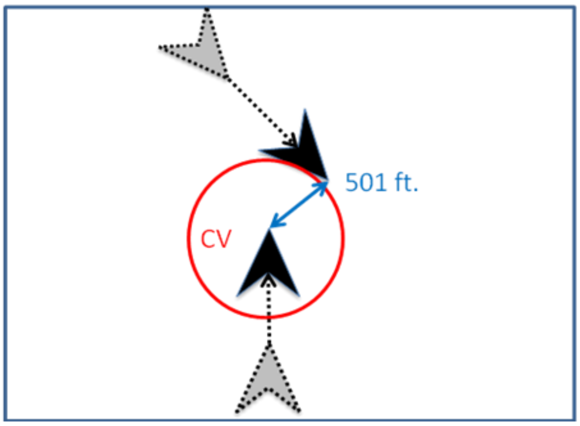

Fig. 3. No NMAC but also not Well Clear!

There is no precise regulatory definition of well clear, but at a minimum it should provide enough separation to avoid collisions. Specifically, 14 CFR 91.111 (a) states that "no person may operate an aircraft so close to another aircraft as to create a collision hazard." The SAA Workshop Report considers aircraft to be well clear if they remain outside of each others' respective collision avoidance thresholds (i.e., prevent activation of their collision avoidance functions), but while necessary this does not seem a sufficient condition to be well clear. For example, consider one co-altitude aircraft crossing just in front of another (Fig. 3) and missing by 501 feet (that is, passing just outside the CV).

A hypothetical CA function with perfect surveillance data and trajectory calculations would not necessarily activate, since it would calculate that technically an NMAC will not occur (i.e., the intruder trajectory would remain outside the CAT). By the workshop definition these crossing aircraft would be well clear, even though at CPA they would be less than a second apart if each was traveling at 600 knots! The condition is also difficult to specify in abstract terms: if the UA's SAA capability does not include a CA function then there is no CAT defined for which the SS function should remain outside. Additionally, the SS function has no knowledge of the intruder's CA function, if any, and thus no defined way to prevent its activation. The Workshop Report recognizes this last issue as a challenge and states that the SS function should calculate well clear so as not to initiate a CA maneuver by either the UA or the intruder, but does not provide a mechanism for doing so.

To address the aforementioned difficulties, the concept described here requires that a well clear determination is large enough to avoid: 1) corrective resolution advisories (RAs) for Traffic Alert and Collision Avoidance System (TCAS) II Version 7 (or higher) equipped intruders; 2) undue concern for proximate see and avoid pilots; and 3) traffic alert issuances by controllers. Each of these well clear requirements will be further described in subsequent subsections, but most importantly they all indicate the need for a "self separation volume" (SSV), larger than the CV and designed to provide a minimum practical separation distance between the UA and any intruder as shown in Fig 4. The SSV size will vary with operational area and needs – smaller in the vicinity of airports and larger in en route airspace – but in all cases should be sufficient to compensate for unexpected maneuvers by intruders as well as to provide a well clear "comfort factor" for pilots and controllers.

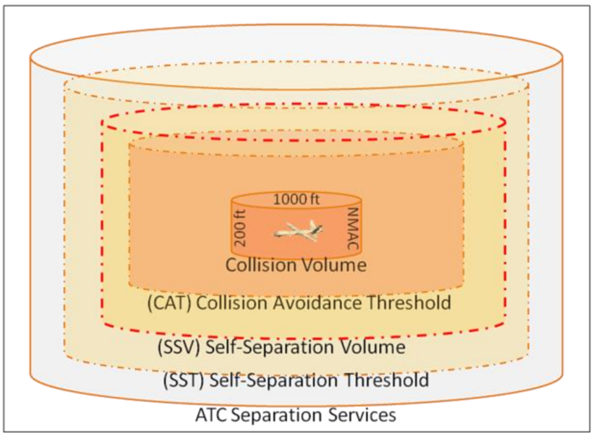

Fig. 4. Self-Separation Volume (SSV)

The SSV's significance for SS function design is analogous to the CV's significance for CA function design: it provides a performance goal. That is, an ideal SS function would prevent all SSV incursions just as an ideal CA function would prevent all CV incursions. Occasional SSV incursions will inevitably occur with SS implementations in actual operations and the SS implementation should recognize such cases and provide guidance for optimally recovering from the SSV incursion. Safety analyses will ultimately determine acceptable SSV incursion rates and inform the selection of SS design parameters (sensor performance, activation thresholds, maneuver selection, etc.) necessary to sufficiently detect and avoid SSV incursions, in the same way that similar safety analyses have informed the design of CA functions such as TCAS.

3.1.1 TCAS Interoperability

It is highly desirable that SAA implementations be designed in a way that minimizes issuance of corrective RAs by TCAS equipped intruders. RAs are alerts with recommended vertical escape maneuvers, to maintain or increase vertical separation with intruders that are collision threats. Corrective RAs that cause evasive maneuvers are disruptive to the air traffic system and are intended as a last resort maneuver when all other means of separation have failed. TCAS uses various mechanisms for collision avoidance that have implications for the appropriate sizing of the SSV.

The SAA concept described in this paper is designed to detect encounter geometries that will cause an RA [5], so that action may be taken early enough to avoid the RA. Determination of these encounter geometries requires a more detailed understanding of TCAS operations and functions; this subsection provides a description of TCAS collision avoidance logic and subsequently describes well clear requirements for compatibility with TCAS operations.

TCAS is a family of airborne devices that are designed to reduce the risk of mid-air collisions between aircraft with operating transponders [6]. TCAS II provides RAs and is mandated in the U.S. for aircraft with greater than 30 seats or a maximum takeoff weight greater than 33,000 pounds, and is also installed on many turbine-powered general aviation aircraft. TCAS has evolved through extensive development and a number of versions since its initial operational evaluation in 1982; Version 7.0 is the current operationally mandated version of TCAS II, and Version 7.1 has been fully specified [7].

TCAS uses the concept of tau (τ), defined as range over the negative of range rate (i.e., closure rate), or $\tau = -r/\dot{r}$, to estimate the time to closest point of approach (CPA) between the own aircraft and an intruder. Both range and range rate are derived from TCAS interrogations of the intruder's transponder, nominally at one-second intervals when the intruder's range and tau are below specific threshold values.

Tau is the actual time to CPA only when the aircraft are on collision courses and not accelerating (tau will be zero at collision). If the aircraft will merely pass near each other then tau is only an approximation of time to CPA. In this case, tau will decrease to a minimum value shortly before actual CPA and then increase. Since the ratio of range and range rate will be lower with closer approaches, this minimum value of tau varies directly with the nearness of the encounter.

This property of tau means that selection of a minimum tau value at which to alert for a collision threat determines not only the *time* to react to the threat, but also the *size of protected airspace* within which a given threat encounter will cause an alert. TCAS computes both a range-based tau, as described above, and also a "vertical" tau (altitude separation divided by vertical closure rate) to estimate time to co-altitude.

Effective TCAS logic requires a tradeoff between necessary protection and unnecessary advisories [6]. This tradeoff is accomplished by controlling the sensitivity level (SL), which among other things controls the tau thresholds for RA issuance, and therefore the dimensions of protected airspace around each TCAS-equipped aircraft. The higher the SL, the larger the amount of protected airspace and the longer the alerting times, with SL selection generally controlled by the aircraft's altitude (higher SL for higher altitudes, where generally speeds are higher and separations are larger).

Table 1 (at the end of the paper) shows the altitude bands for each SL and the associated (range and vertical) tau thresholds for RA issuance (values are also shown for TA issuance, which are not discussed here). For example, when a TCAS-equipped aircraft is between 20000 and 42000 feet (SL 7), the tau threshold for RA issuance is 35 seconds, and generally an RA will be issued if both range and vertical tau fall below this value. An RA will also be issued for low vertical rate encounters if the current altitude difference is less than the vertical threshold (ZTHR) value of 700 feet.

Once TCAS determines that an RA is required then it must determine the type of RA needed. In order to do this, TCAS estimates the altitude difference at CPA for various RA types; if the altitude difference will be less than the ALIM value (600 feet in this example) then the RA will be corrective (e.g., "Climb" if level), requiring a trajectory change to regain at least ALIM feet of vertical separation; otherwise the RA will be preventive (e.g., "Don't Descend" if level), requiring no trajectory change.

Two problems arise with use of the simple definition of range tau ($\tau = -r/\dot{r}$). The first problem involves threat encounters with low range closure rates, and the second problem involves high closure rates with large miss distances. To address these problems, TCAS employs modifications to the definition, and these modifications are instructive for SAA's well clear challenge and for the determination of TCAS-compatible SSV sizes.

Fig. 5 illustrates these two problems. The figure shows four co-altitude intruders with various encounter geometries, but all at an RA-threshold tau (for SL 7) of 35 seconds from the own aircraft. Intruder A is a head-on collision encounter with a 1200-knot closure rate, resulting in an RA-threshold tau at a large range (11.7 nmi). Intruders B and C illustrate the low-closure-rate problem: the ranges are only 0.1 and 0.3 nmi, respectively, before the RA-threshold tau value is reached. If either intruder accelerates (in the general sense, including turns) there will be little or no collision protection. Intruder D's parallel fly-by encounter illustrates the high-closure-rate problem: a "nuisance" RA will be issued even with a horizontal miss distance of nearly 6 nmi because of the high closure rate.

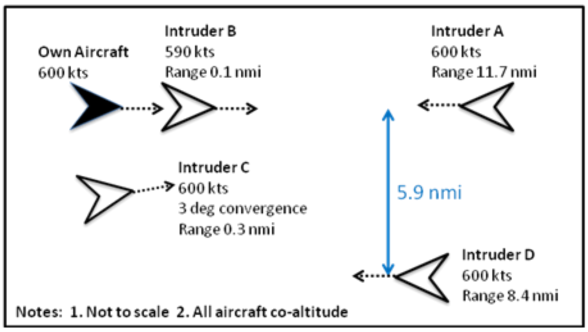

Fig. 5. Intruders at Tau=35 seconds

TCAS addresses the low-closure rate problem by using a modified tau definition [7]:

$$\tau_{mod} = -(r^2 - DMOD^2)/(r\dot{r}) \quad (r > DMOD)$$

$$\tau_{mod} = 0 \quad (r \leq DMOD)$$

DMOD is a distance modification that varies with sensitivity level (see Table 1) and was designed to provide approximately an RA-threshold amount of reaction time for an intruder that accelerated toward the own aircraft at a sustained 1/3 g [8]. Modified tau values are nearly identical to "true" tau at large ranges and range rates but are smaller (more conservative) for smaller ranges and rates, and will be zero if an intruder is within a distance of DMOD from the own aircraft, even with no closure rate.

TCAS Versions 7.0 and higher address the high-closure-rate, nuisance-RA problem by employing a horizontal miss distance (HMD) filter [9]. The HMD filter employs a parabolic range tracker to provide projected range acceleration as well as projected range and range rate, and uses the range acceleration to detect horizontal miss distances that are sufficiently large as to not be a collision threat (range acceleration will be zero for non-accelerating aircraft on a collision course, but will monotonically increase if the encounter has a miss distance). The HMD filter employs numerous noise filters and maneuver checks whose explanations are beyond the scope of this paper, but the end result is that the filter will suppress RA issuances for horizontal miss distances at CPA that are approximately equal to the DMOD values.

TCAS's use of modified tau and the HMD filter has implications for defining minimum acceptable sizes for the SSV. That is, the lower lateral and vertical limits for a TCAS-compatible SSV size are approximately the DMOD and ALIM values in Table 1, respectively (exact values are contained in the pseudocode volume of [7]). Encounter geometries that would result in an intruder entering this SSV will cause issuance of a corrective RA, because the HMD filter will not suppress RA issuance and also because modified tau will eventually drop below the threshold value (and will be zero when the intruder is within this SSV). Conversely, if the aircraft are not maneuvering toward each other (as defined by the HMD maneuver checks) then encounter geometries that will clear the SSV as defined here should not cause RA issuance.

3.1.2 See and Avoid Pilot Expectations

Determining minimum well clear requirements that meet see and avoid pilots' expectations is not straightforward. The determination is subjective and pilot-specific, and may even be different for UA and manned aircraft intruders. That is, an encounter geometry that a pilot would consider "well clear" if the intruder is a manned aircraft might be judged as "too close" by the same pilot if the intruder is a UA. Human-in-the-loop (HITL) studies are needed to further inform such subjective assessments, but lacking such studies some general observations can still be made. It should be noted that these observations are focused only on pilots' perceptions of what is well clear when an intruder (such as a UA) passes ahead, across, over, under or abeam their flight path, and not on perceptions of appropriate intruder following or pass-behind distances. Determination of these latter distances depends on numerous additional operational factors such as wake vortex avoidance, sufficient spacing for runway arrivals, etc. and is arguably a distinct, additional issue, involving informed judgment by the intruder pilot, than that of the well clear challenge.

Except for formation flight, which is beyond the scope of this initial concept, pilots generally expect to have the least separation from airborne intruders in the immediate vicinity of airports, more separation in a terminal area, and the most separation in the en route environment. This expectation is consistent with the TCAS use of larger DMOD, HMD, ZTHR and ALIM values for higher altitudes, i.e., higher SL, and in fact these values may serve as a starting guideline for pilot minimum well-clear expectations during transitory (non-following) encounters. The DMOD/HMD values vary from 0.2 nmi below 2350 feet AGL (i.e., typical of operations near an airport) to 1.1 nmi above 20000 feet MSL (typical of en route operations) with values of 0.35-0.8 nmi in between (0.35 nmi below 5000 feet, typical of terminal operations). ALIM values are 300-400 feet below 20000 feet MSL (pressure altitude) and 600-700 feet above this level, which is compatible with the vertical separations of 500 and 1000 feet in use below and above Flight Level 180, respectively, and are set slightly smaller than the vertical separation values to minimize disruptive "nuisance" RA maneuvers.

The airport operational encounter geometry with both the closest expected lateral spacing and a high closure rate would likely occur during simultaneous opposite-direction operations to parallel runways; controllers can approve such operations in daylight visual conditions when the runway centerlines are as close as 1400 feet (slightly over 0.2 nmi) apart ([4], Section 3.8.4). A more typical close-range, high-speed traffic pattern encounter would occur with one aircraft on an extended downwind leg and the other on final approach; these may result in fly-by encounters of as close to one-half mile without undue concern by the pilots, who understand the structure of the encounter, although generally the spacing is a mile or more. Low-closure-rate operational encounters can be much closer with same-direction parallel runway operations; controllers can approve these operations with runway centerline separations of as little as 300-700 feet, depending on the aircraft category, although typically the aircraft are also staggered longitudinally for increased separation. Such small separations, if the aircraft are abeam on approach, are less than the DMOD RA threshold when above 1000 feet AGL (RA issuance is suppressed below 1000 feet AGL), and may be too small for "comfort factor" use by SAA-equipped UAs in mixed operations.

Well clear distances that are acceptable to pilots in in the airport vicinity would generally be smaller than in terminal airspace and in turn those would be smaller than acceptable distances in en route airspace. This is partly due to the progressively higher "surprise" factor of encountering a proximate aircraft in these regions and also the visual impact of higher encounter speeds. Often the encounters involve crossing geometries, which can add to the perceived need for more separation. As with airport-vicinity operations, the TCAS RA DMOD/HMD values may serve as a starting guideline for pilot lateral well-clear minimum expectations, but HITL studies are needed to determine average "comfort factor" minimums, which are likely somewhat larger based on an informal sampling of a few pilot subject matter experts.

3.1.3 Controller expectations

Air traffic controllers' expectations for minimum safe distances between visually separated aircraft also have a subjective component, as they do for pilots, and can be informed by HITL studies; such studies are planned within the next two years by NASA's UAS in the NAS project and results will be reported in future publications. In addition to their subjective expectations of minimum safe visual separations, controllers are also equipped with a variety of conflict alert tools [4] to detect and alert for encounters with potentially unsafe separation between visually-separated aircraft. Work is underway within the project to quantify minimum SSV sizes that will avoid issuance of these alerts.

Unlike pilots, controllers also have expectations for *maximum* well clear distances. That is, pilots are generally unconcerned by an intruder that avoids them by an excessively large distance, unless it personally delays them, but for a controller such actions have the potential to disrupt overall traffic flow. For example, an en route aircraft that deviates a mile from an airway centerline to avoid traffic with or even without a prior request to ATC is unlikely to cause concern to the controller, but a five-mile deviation would most certainly get the controller's attention. These expectations, in both en route and terminal airspace, will also be informed by the HITL studies planned by the project. Controllers also have expectations for visual following distances, since it directly impacts the efficiency of visual separation operations, and HITL studies can shed light on these expectations as well.

3.2 Declaration Times

As discussed in the previous subsection, SAA implementations must detect projected losses of well clear distances with intruders, but they must also determine when to declare that some action may be necessary to avoid these losses. A simple answer might be, "declare as soon as a projected (future) loss of well clear separation is detected," but if surveillance capability enables intruders to be detected at large ranges then such immediate declarations may cause frequent nuisance alerts and be inappropriate. Conversely, very limited surveillance range may provide too little declaration time to successfully avoid a loss of well clear separation or issuance of a TCAS RA. From a concept perspective, the declaration times should be at least large enough to avoid TCAS corrective RAs and to allow time for pilot reaction, ATC queries and execution of normal operational maneuvers to avoid SSV incursions, but small enough to avoid nuisance queries. Determining appropriate declaration times will both enhance SAA interoperability and inform sensor range requirements.

One approach to determining appropriate declaration times is to observe the steps that a see-and-avoid capable pilot would take in the presence of an intruder, and to construct a "time budget" required to complete each of these steps (which are analogous to SAA *sub-functions*). The time budget can then be used to determine appropriate declaration times. For example, the pilot of a manned aircraft would initially see (*detect*) an intruder, observe it for a short time to ascertain its relative *track*, and then *evaluate* that track for any projected loss of well clear separation. If the pilot decides that well clear separation may be lost at some future time, but the intruder is still a long distance away or has a small closure rate, then the pilot is likely to continue to *track* and *evaluate* the intruder (for example, to see if it changes direction or altitude), but at some point will decide (*declare*) that some action may be necessary, *determine* what action (if any) to take, and *command* and *execute* the action. The total time required between deciding that some action may be necessary and completing the execution of an avoidance maneuver that will miss the SSV is the declaration time.

The declaration time will be influenced by many factors and in general will not be a fixed time. If the aircraft is receiving air traffic services then one of the factors is the allowance of sufficient time for the pilot to query ATC about the situation. If the controller knows the intruder's intent and can advise the pilot that no separation loss will occur, then no action will be required; if the controller has no knowledge of intent then the pilot must determine and negotiate an appropriate action, and time must be allowed for this factor. Once an action is determined it must then be commanded through avionics over a control link, which raises another time factor particular to UAS. Executing the commanded avoidance maneuver is an additional time factor that will vary significantly with encounter geometry and aircraft maneuver performance.

Quantifying each of these time factors will require further studies which are ongoing within the project. For example, batch simulations are being conducted using the Prototyping Aircraft-Interaction Research Simulation (PAIRS) aircraft performance evaluation application [10, 11] to determine required distances and execution times for various aircraft encounter geometries, maneuvers, miss distances and UAS performance characteristics. HITL studies will also be performed to assess controller perceptions of appropriate declaration times, and to evaluate concepts and procedures for late detection of intruders.

3.3 Acceptable Trajectory Changes

SAA implementations which appropriately detect and declare projected losses of well clear distances should also assist the UA pilot with determining appropriate action after the declaration. Under the concept described in this paper the UA pilot has similar pilot-in-command authority as the pilot of a manned aircraft, and is responsible for safely maneuvering the UA consistent with right-of-way rules and other applicable aviation regulations, but will not have the same immersive visual cues as a see-and-avoid pilot. SAA implementations can aid the pilot by displaying appropriate information elements from proximate traffic and encounters, although use of a conventional traffic display for maneuvering and collision avoidance poses many challenges [12]. In general much development, simulation and validation work remains in order to develop safe and effective displays for use in maneuvering relative to proximate traffic.

One decision aid which may be useful for maneuvering relative to proximate traffic is the use of "maneuver bands" [13,14] with a UA's traffic display and primary flight instrumentation. Maneuver bands are computed by the SAA implementation's TD&R capability and show tracks/headings, airspeeds and vertical speeds that will (or will not) result in loss of well clear distance with identified intruder(s) within the declaration time. The TD&R capability computes and regularly updates the bands with knowledge of the UA's standard maneuvering rates (of turn, climb, etc.) in the current flight environment, so that the UA's performance into or out of a given band is taken into account. The bands provide three decision aiding functions to the pilot: 1) a well-clear threat "declaration," when a band moves over the UA's current track, airspeed or vertical speed; 2) a situation rate-of-change, indicated to the pilot by the rate at which the bands change; and 3) a planning tool, by showing tracks, airspeeds and vertical speeds which can be commanded without projected loss of well clear distances within the declaration time.

Special consideration must be given to appropriate maneuvers when late detection of an intruder occurs (i.e., within the declaration time). A pilot capable of see and avoid is likely to respond to a late detection in one or more ways, depending on the time and equipment available: 1) maneuver first and then inform ATC; 2) maneuver in a more aggressive way, up to a maximum operational rate; and/or 3) respond to a TCAS corrective RA if so equipped and the RA is issued. These responses should also be available to a UA pilot, but optimal means for conveying the urgency of the situation to the pilot, relative to which of these responses are appropriate, are still under development. A principle of the concept is that, if detection occurs too late to avoid penetration of the SSV, the TD&R capability will continue to provide guidance to clear the SSV, but do so in a manner that is TCAS-compatible. That is, once an RA threshold is crossed, the TD&R capability will either "freeze" vertical guidance at the current altitude or rate while continuing to indicate lateral escape tracks, or it will relinquish vertical guidance to the TCAS II logic (and its active-coordination vertical maneuver capability) if TCAS use for UAS is approved in the future and the UA is so equipped.

A final consideration concerns acceptable SAA trajectory changes when the control link to the UA is lost. In this case the UA might have on-board capability to command TD&R-compatible maneuvers in order to remain well clear of proximate aircraft, but such automated UA operations raise many conceptual issues which are yet to be fully articulated, explored and resolved. From an interoperability perspective, one approach might be to autonomously maneuver for an intruder at the declaration time minus the time budget allocated for UA pilot query and negotiation with ATC; that is, the automation would delay maneuvering to the minimum time where a well-clear distance could still be maintained with normal operational maneuvering. This approach might minimize autonomous maneuvering that is disruptive to ATC and proximate see and avoid and/or TCAS-equipped aircraft, but many other questions inevitably remain unanswered when attempting to replace a pilot's decision authority with automation.

4. Conclusions

UAS will need a means to replace an onboard pilots' ability to see and avoid other traffic, and the SAA systems that are expected to provide these means will need to do so in a manner that preserves the safety level of the airspace and the efficiency of the air traffic system. The SAA concept for integration of UAS into the NAS described in this paper is based on interoperability principles that take into account both the ATC environment as well as existing collision avoidance systems such as TCAS. Specifically, the concept addresses the determination of well clear values that are large enough to avoid issuance of TCAS corrective RAs, undue concern by pilots of proximate aircraft and issuance of controller traffic alerts. The concept also addresses appropriate declaration times for projected losses of well clear conditions and maneuvers to regain well clear separation. NASA is currently implementing the concept in simulation for evaluation and to further inform appropriate well clear and declaration time values.

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Table 1: TCAS Sensitivity Level Definition and Alarm Thresholds [6]

Own Altitude (feet)	SL	Tau (Seconds)		DMOD (nmi)		ZTHR (feet) Altitude Threshold		ALIM (feet)
		TA	RA	TA	RA	TA	RA	RA
< 1000 (AGL)	2	20	N/A	0.30	N/A	850	N/A	N/A
1000 - 2350 (AGL)	3	25	15	0.33	0.20	850	600	300
2350 – 5000	4	30	20	0.48	0.35	850	600	300
5000 – 10000	5	40	25	0.75	0.55	850	600	350
10000 – 20000	6	45	30	1.00	0.80	850	600	400
20000 – 42000	7	48	35	1.30	1.10	850	700	600
> 42000	7	48	35	1.30	1.10	1200	800	700