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THE USE OF ADS-B INFORMATION FOR AIRBORNE SEPARATION AND COLLISION AVOIDANCE
VYUŽITÍ ADS-B INFORMACÍ PRO ŘÍZENÍ LETOVÉHO PROVOZU A V ANTIKOLIZNÍCH SYSTÉMECH

DOCTORAL THESIS - SHORT VERSION
DIZERTAČNÍ PRÁCE - TEZE

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ABSTRACT

Safety of General Aviation (GA) has always been a concern since lack of harmonized technical standards addressing performance for devices allowing GA aircraft to see and be seen, is major impediment to their widespread use in Europe. The increasing complexity and density of air traffic, when the skies become more crowded with a mix of different airspace users, including unmanned aircraft systems (UAS) trending in the last few years, emphasize the importance of and the need of change.

The aim of this doctoral thesis is to elaborate on the possibilities to improve the operational safety of GA operations in uncontrolled airspace anticipating considerable challenges associated with UAS uptake. With the overall ATM framework being adapted to accommodate these novel airspace users, ADS-B technology is being recognized for its significant potential. This thesis explored the possibilities to improve cooperative surveillance in uncontrolled airspace (starting with but not limiting to ADS-B), and through set of experiments evaluated the acceptability, feasibility and reusability of different existing collision avoidance and situation awareness systems, both tailored and not tailored for GA. Part of the research was also the investigation on possible adaptation of the drone dedicated Remain Well Clear concept for GA operational needs.

The research activities within the scope of this thesis were undertaken in two phases. Within the first phase, spanning from 2015 to 2019, a series of experiments were conducted. The second phase focused on the exhaustive analysis of systems introduced since the last experiment, culminating in the recent months, highlighting the solutions that with appropriate adjustments hold the potential to be effectively tailored for adoption by GA.

Key words: situational awareness, collision avoidance, ADS-B, General Aviation, uncontrolled airspace, remain well clear, see and avoid, TSAA, ACAS X

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ABSTRAKT

Otázka bezpečnosti všeobecného letectva bola vždy problematická. Nedostatok harmonizovaných technických noriem týkajúcich sa výkonu zariadení umožňujúcich lietadlám všeobecného letectva vidieť a byť videný, sa stal hlavnou prekážkou k ich rozšírenému používaniu v Európe. Rastúca komplexita a hustota leteckej dopravy, a skutočnosť, že sa vzdušný priestor s príchodom nových užívateľov (napr. systémov bezpilotných lietadiel, ktoré zaznamenávajú v posledných rokoch rastúci trend) stále viac napĺňuje, zdôrazňujú dôležitosť a potrebu zmeny.

Cieľom tejto dizertačnej práce bolo rozpracovať možnosti zlepšenia prevádzkovej bezpečnosti všeobecného letectva v neriadenom vzdušnom priestore, s prihliadnutím na značné výzvy spojené so zavádzaním bezpilotných lietadiel do vzdušného priestoru. S celkovým rámcom ATM prispôsobujúcim sa týmto novým užívateľom vzdušného priestoru, sa ADS-B technológia so svojim potenciálom stáva významným činiteľom. Táto práca skúmala možnosti zlepšenia kooperatívnej *“surveillance”* v neriadenom vzdušnom priestore (začínajúc od, ale neobmedzujúc sa na ADS-B) a prostredníctvom súboru experimentov hodnotila prijateľnosť, uskutočniteľnosť, a opätovnú použiteľnosť rôznych existujúcich antikolíznych systémov a *“situational awareness”* systémov, či už šitých na mieru pre všeobecné letectvo alebo nie. Súčasťou výskumu bolo aj skúmanie možného prispôsobenia konceptu *“Remain Well Clear”* vyvíjaného pre drony, prevádzkovým potrebám všeobecného letectva.

Výskumné aktivity v rámci tejto dizertačnej práce prebiehali v dvoch fázach. V rámci prvej fázy, ktorá trvala od roku 2015 do roku 2019, sa uskutočnila séria experimentov. Druhá fáza sa zamerala na prehľadnú analýzu systémov zavedených od posledného experimentu, ktorá vyvrcholila v posledných mesiacoch. Práca zdôrazňuje riešenia, ktoré s vhodnými úpravami majú potenciál byť efektívne prispôsobené na používanie vo všeobecnom letectve.

Kľúčové slová: situational awareness, antikolízny system, ADS-B, všeobecné letectví, neřízený vzdušný proctor, Reman Well Clear, see and avoid, TSAA, ACAS X

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CONTENTS

1. INTRODUCTION

Based on European Aviation Safety Agency (EASA) Annual Safety Report [94] [95], EU Member States reported an increase in General Aviation (GA)[1] accidents (fatal by 5%, non-fatal by 14%) and serious incidents (by 61%) in year 2021 compared to 10-year average. This led also to increase in the number of fatalities by 21% (95 in total in 2021) and increase in serious injuries by 12% (47 in total in 2021) compared to 10-year average. The accidents usually occur in the landing phase, but the increase was observed in almost all flight phases. Majority of accidents belong to pleasure flying category and approximately ¼ of all the accidents are caused by human factor or human performance according to incident reports. The second most common reason (right after personnel task performance – 41%) was related to situational awareness issue (39%). The safety data from period 2009-2019 indicate [49] that there were 60 fatal airborne collisions (~6 per year) resulting in 137 fatalities (~13 per year) and all of them occurred in uncontrolled airspace by all small aircraft (many of them rotorcraft).

While general trend in number of aviation accidents (overall) shows decrease, the statistics for GA are experiencing opposite trend, and this trend may even worsen with ongoing massive uptake of uncrewed aircraft systems (UAS) and introduction of Urban Air Mobility (UAM) and Advanced Air Mobility (AAM). Overall ATM framework is adapting to accommodate these novel airspace users and ADS-B technology is being recognized for its significant potential. Active development, not only focusing on the regulatory aspects of integration of these novel airspace users into aviation system, but also on the effective techniques to allow UAS and GA coexistence, is in progress. However, the airborne collision risk involving non-commercial aircraft remains one of the main safety concerns nowadays, as well as key priority for EASA [52].

The main motivation for this thesis was to explore how to improve operational safety of GA operations in uncontrolled airspace anticipating considerable challenges associated with incoming new users – primarily drones. The urgency of this thesis is amplified by the recognition that traditional aviation safety strategies may not suffice in the face of the intricate interactions between traditional GA operations and the increasingly diverse and versatile drone fleet. In this context three main areas were explored:

A. Possibilities to improve cooperative surveillance (or electronical visibility) at that airspace, starting with, but not being restricted to, ADS-B.
B. Through set of experiments, evaluate reusability and suitability of selected existing collision avoidance and situation awareness systems.
C. Investigate adaptations of the drone dedicated Remain Well Clear (RWC) concept for GA systems.

[1] Aircraft with MTOM below 5700kg.

The first part of the dissertation thesis explains the set-up of separation assurance and collision avoidance (CA) in overall ATM concepts, highlighting the role of ADS-B technology in it. Comprehensive overview of “see and avoid” and RWC concepts is provided separately to build solid basis for understanding the research problematics. Second part of the thesis clarify the needs and concerns of today’s GA community and provides a detailed analysis of systems introduced since the initial experiments. The state-of-the-art section provides overview of all the technologies assumed during the research execution. Valuable insights were gained from four experiments demonstrating the potential of ADS-B In applications for GA situational awareness, while emphasizing the need for GA-specific adaptations in collision avoidance systems. Finally, the research is concluded by providing the recommendations on possible industrial solutions for GA to foster safe coexistence between GA and UAS in the evolving aviation landscape.

2. BACKGROUND

In the context of Air Traffic Management (ATM), Separation Assurance (SA), Collision Avoidance (CA) together with Strategic Conflict Management (SCM) are three layers that play crucial roles in ensuring the safety and efficiency of air traffic within the airspace. These concepts are fundamental components of ATM systems that help prevent aircraft collisions and maintain safe distances between aircraft. Both SA and CA are Conflict CMS elements defined by ICAO [12]. The failure of any CMS instance may lead to severe consequences, and for this reason it has been designed as a layered system (Figure 1), where each layer is a function of CMS, but also a system itself.

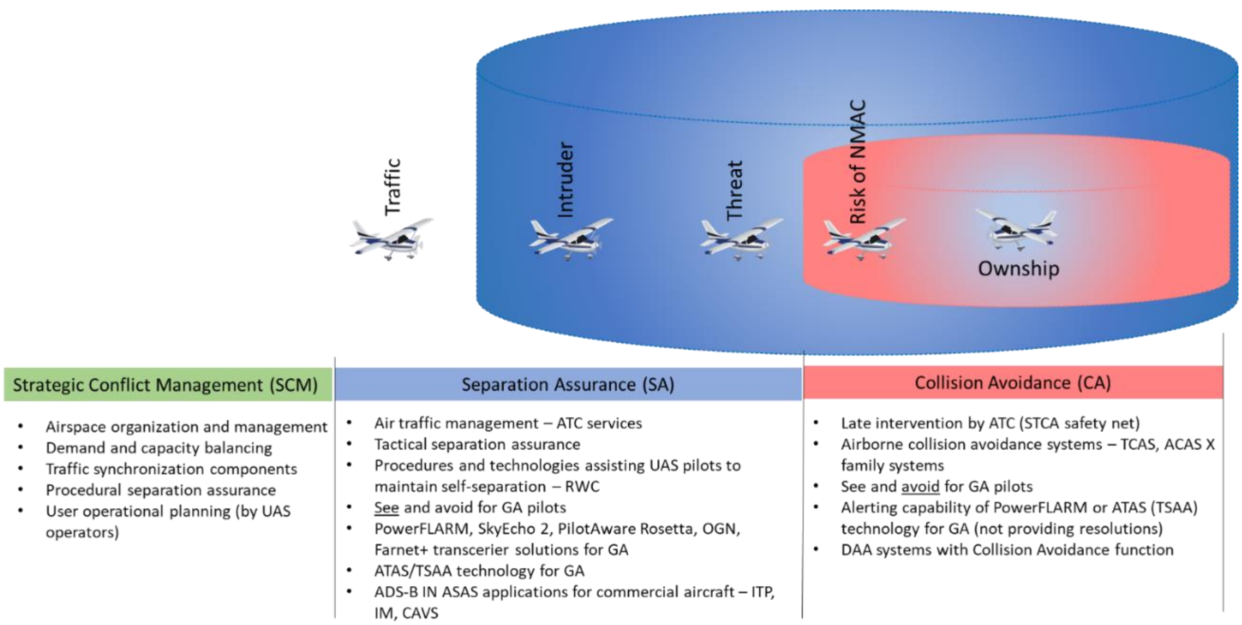

FIGURE 1: ILLUSTRATION OF CONFLICT MANAGEMENT SYSTEM LAYERS

The objective of Strategic Conflict Management (SCM) is to reduce the need to apply SA to an appropriate level [56]. In controlled airspace, SCM ensures that the workload of ATC remains at acceptable level. In uncontrolled airspace it ensures that pilot is capable of providing separation from other aircraft using "see and avoid".

2.1. SEPARATION ASSURANCE AND COLLISION AVOIDANCE AND THEIR ROLE IN ATM CONCEPT

SA and CA are two tactical, supplementing layers of SCM defined by ICAO [12]. SA layer identifies medium term tactical conflicts (5-30 minutes) and performs tactical separation of aircraft. Depending on the airspace class and the flight rules (IFR or VFR), either the ATC or the pilot is responsible for separation. SA is also where ADS-B technology is bringing the most benefits in terms of improved situational awareness for flight crew in all airspaces, during all phases of flight, even on the airport surface by presenting pilots with flight information concerning surrounding traffic, possibly in conjunction with a navigation display or surface map. A number of ADS-B In application concepts, falling under Airborne Separation Assurance/Assistance Systems (ASAS) applications [60] [61], currently exists which can provide pilots with information regarding surrounding traffic, and in some cases, decision supporting tools that aid in providing separation from that traffic. These applications can be based on [60] divided into four categories:

- Airborne Traffic Situational Awareness (ATSA) applications for instance for In-Trail Procedures (ATSA-ITP) [63], [64], [65] supporting desired flight level (FL) changes, or ASTA for airport SURFace (ATSA-SURF) [75] improving safety at airport surface in all weather conditions, or even enhanced ATSA-SURF IA providing pilots with indications and alerts in risky situations (in Honeywell portfolio).
- Airborne Spacing (ASPA) applications including for instance already standardized Flight-deck Interval Management (FIM) [62] allowing improved traffic flow and precise aircraft spacing.
- Airborne Separation (ASEP) applications including already standardized Cockpit Display of Traffic Information (CDTI) Assisted Visual Separation (CAVS) [63], [64], [76], [65] application, which allows safe approaches applying own visual separation from a preceding traffic using Traffic Display (TD) when visual contact is lost.
- Airborne Self-separation (SSEP) applications, which require flight crews to separate their flight from all surrounding traffic, in accordance with the applicable separation standards and rules of flight.

An important element supporting GA pilots improved situation awareness is ADS-B In/Out transceiver (electronic conspicuity devices), like uAvionics SkyEcho [66] or PilotAware Rosetta [67]. Alternative to ADS-B IN/OUT transponder is PowerFLARM [68], which operates on SRD860, but is capable to receive ADS-B In, and except see and be seen capability offers alerting to avoid a potential collision.

Improved situational awareness for GA pilots including alerting on potential conflicts is also standardized ADS-B Traffic Advisory System (ATAS), an ADS-B In application also referred as Traffic Situational Awareness with Alerts (TSAA) [4], [61], [64], which was evaluated within the scope of this dissertation thesis.

CA layer identifies short term (imminent) conflicts of less than 1 minute and performs last-resort measures to prevent collision. CA is always the responsibility of the pilot. See and avoid sitting in the CA layer[2] of conflict management, is considered as one tool that is available regardless of the aircraft equipment or an ATS. The pilot can be however assisted in his task by different on-board systems such TCAS II or ACAS Xa mandated for large commercial aircraft. GA solution aiming to reduce risk of collision by providing appropriate alerting (no resolutions) is TCAS I or PowerFLARM [68], which already utilize

[2] “See and avoid” is by GA used as a CA tool in controlled airspace. In uncontrolled airspace “see and avoid” serves as both SA and CA tool.

benefits of ADS-B. The CA is benefiting from ADS-B through TCAS II with Extended Hybrid Surveillance developed, implemented and validated by Honeywell, where the main benefit aims in reduction on 1030/1090MHz frequency load, which consequently has an impact both on ATC and pilots through decreased risk of secondary radar information loss due to overloaded frequency band.

The validation and benefits assessment of TCAS II with extended hybrid surveillance capability, completed in 2015 under SESAR project 9.47 (part of the scope of this dissertation thesis), showed savings of up to 86.5% on 1090MHz RF load [91] . Considering the fact that recent analysis of 1090MHz spectrum congestion indicates that replies to TCAS interrogations comprise the largest portion of the unmitigated 1090MHz inference environment (~50%), saving 86.5% portion of it indicates that extended hybrid surveillance significantly reduces the 1090 MHz load.

The ICAO definitions of SCM and its layers are, with the introduction of Urban Air Mobility (UAM) and Unmanned Aircraft Systems (UAS), subject to change and are often used as a starting point for any further research and related re-definition of it.

2.2. FROM “SEE AND AVOID” TO “DETECT AND AVOID”

“See and avoid” principle originates in ICAO Rules of the air (Annex 2) [37] even though it is not explicitly mentioned. This regulation is however mirrored in FAA right-of-way rules [27], and European regulation 2018/1139 [36], where direct references were added. “See and avoid” refers to a method for avoiding the collision when weather conditions permit, requiring pilot to actively search for potentially conflicting traffic. This concept requires that vigilance is maintained at all times, by each pilot regardless of whether the operation is conducted under IFR or VFR. See and avoid skills require the application of effective visual scanning, ability to gather information from radio transmissions from ground and other aircraft (“party line” effect of ATM voice communication), building overall situational awareness, and development of good airmanship [29]. The relevance and achievable performance of “see and avoid” method for modern commercial aircraft was questioned already decades ago [30], and several other limitations have been raised by GA community [31]-[34]. Moreover, US National Transportation Safety Board (NTSB) indicate that in 95% of mid-air collisions (years 1991-2000), the probable cause was failure to “see and avoid”, inadequate visual lookout, or failure to maintain visual and physical clearance [32]. European safety data then indicate that airborne collision risk mostly affect pilots of smaller aircraft regardless of the experience and phase of flight [38].

While the limitations of “see and avoid” for large commercial aircraft were addressed through TCAS II mandate [45]-[48], GA pilots are still largely relying on established procedures [35] complemented with seeing and avoiding other aircraft in today’s operating environment. Worldwide initiatives are undertaken to supplement visual observation by electronic means. The advantages of such systems over human vision are seen in their ability to scan larger volume of airspace at once and continuously, fast, and efficiently [13]. Nevertheless, one should not forget the nature of GA, when power, weight, size, and cost of any electronic equipment plays crucial role. On the other hand, many GA aircraft are already equipped with portable GPS devices.

This situation seems to be finally untenable with the ongoing massive uptake of uncrewed aircraft systems (UAS) and introduction of Urban Air Mobility (UAM), which further increase the need for replacement or complementing “see and avoid” principle with additional means to handle separation and collision avoidance in uncontrolled mixed traffic environment. Active development is in progress to ensure safe and sustainable integration into the aviation system. The development focus not only on the regulatory aspects, but also on the effective techniques to allow UAS to “electronically see” other aircraft in different environments, at higher altitudes and beyond visual line of sight (BVLOS) of the pilot operating them.

“Detect and avoid” (DAA) capability allows to see, sense, or detect conflicting traffic or other hazards and take the appropriate action. This capability aims primarily to ensure the safe execution of UAS flight and to enable full integration of UAS in all airspace classes with all airspace users [25], however spin-offs of the development of DAA systems [26], [80], [79] for UAS also introduce new means for augmentation of visual observation feasible for GA operations. DAA is thus believed soon to replace the “see and avoid” as the main method to ensure safe separation between aircraft in airspace where ATC does not provide a separation service [39].

The key gap is currently represented by a lack of suitable onboard sensors capable to reliably detect all surrounding traffic. There are two conceptual approaches: cooperative and non-cooperative. While with the cooperative surveillance (TCAS, PowerFLARM, ADS-B IN applications…) it is typically easier to achieve necessary performance, it requires that all users are equipped with some interoperable technologies to be electronically visible (or iConspicuous using the EASA terminology). It requires setup of a suitable regulatory framework, availability of suitable industrial solutions for different users (respecting their SWPC limitations) and wide deployment. Non-cooperative surveillance (cameras, radar, LIDAR, acoustic sensors...) is to large extent independent of the eco-system, however, there are clear performance (and SWAP) limitations of existing technologies.

2.3. REMAIN WELL CLEAR AND ITS EVOLUTION

The concept of staying “well clear” from manned aviation is linked with “see and avoid” principle applied for SA in uncontrolled airspace, thus also originates in ICAO Rules of the Air (Annex 2) [37], but lacks exact definition. It applies to flying under VFR, and referring to aircraft state, it does not require any quantification of the separation minima, since “well clear” is a subjective assessment of a pilot and his subjective feeling of being in a safe distance from the hazard[3]. Most of the established separation minima that ATC

[3] Except the situations when ATC is separating the IFR traffic from VFR traffic.

must nowadays apply, relates to radar separation under IFR, and procedural separation applied in airspace where surveillance coverage is not available (ocean, sparsely populated areas) or during departures and arrivals in some TMAs and CTRs.

Remain Well Clear (RWC) concept was introduced in ICAO Manual on RPAS [25], defining the RWC function as "the ability to detect, analyze and maneuver to avoid the potential conflict by applying adjustments to the current flight path in order to prevent the conflict from developing into a collision hazard." It should be understood as a function aimed at ensuring that aircraft stays out of the RWC minima [69], provided by DAA system. By utilizing the term "conflict", the RWC definition calls for quantitative definition of separation minima, since based on the ICAO [12] definition of conflict as "any situation involving aircraft and hazards in which the applicable separation minima may be compromised".

The applicable separation minima in todays' world of manned aviation differ depending on subject of conflict (other aircraft or any other object, weather, or airspace) and various conditions (including available surveillance means). RWC minima are materialized by boundaries which divide the airspace in volumes where different rules apply. These boundaries are associated with alerts and guidance. As of today, several RWC parameters were defined dependent on the airspace user to be equipped with DAA system and associated type of operations.

RWC thresholds, referred as DAA Well Clear (DWC) thresholds, were for the first time defined within standard for DAA systems, DO-365 [26], and provided En Route DWC definition not considering take-off and landing in the terminal areas. This standard defined DAA system minimums that enable IFR operations for UAS that can meet prescribed equipage and performance requirements. It also required ATC coordination for caution level or RWC maneuvers[4], while warning level RWC and CA maneuvers have no ATC coordination requirement [80]. Such system was, however, expected to produce excessive nuisance alerting during normal operations in terminal airspace, what resulted in development of DO-365B [79], which defined the terminal area DWC parameters. In parallel of the redefinition DWC within DO-365 owned by RTCA SC-228, EUROCAE WG-75/RTCA SC-147 developed a standard for airborne collision avoidance system ACAS Xu designed for UAS, ED-275/DO-386 [23], a specific implementation of DAA, which complies with all the applicable requirements of DO-365. However, DO-386 being published 3 months before DO-356B, the refinement of the fixed-wing terminal DWC was not implemented in ACAS Xu standard. Terminal DWC requirements for specific DAA implementation will be addressed through development of ACAS Xr (for manned and unmanned rotorcraft, Advanced Air Mobility (AAM) and UAM) standard planned for 2025.

The gap for smaller UAS operations (below 25kg, or those above 25kg but not meeting equipage or performance requirements of DO-365B), was addressed through ACAS sXu

[4] See the section 3.2 for further explanation of these terms.

standard, DO-396 [80], as a DAA solution for small UAS. Since this category of UAS is not receiving ATC services, only one level of alerting is provided, with two sets of alerting thresholds – one against larger unmanned aircraft, and second volume against smaller UAS. Also, since many small UAS use cases are envisioned to require automatic response to guidance, all ACAS sXu DAA guidance is directive, what allows for automatic response without the need to wait for pilot response. For this reason, ACAS sXu provides only one level of alerting and guidance with the protection volume scaled based on intruder type, not a separate RWC and CA functions. In addition, since small UAS are expected to operate at low altitudes, ACAS sXu also incorporates terrain and obstacle awareness capability [23].

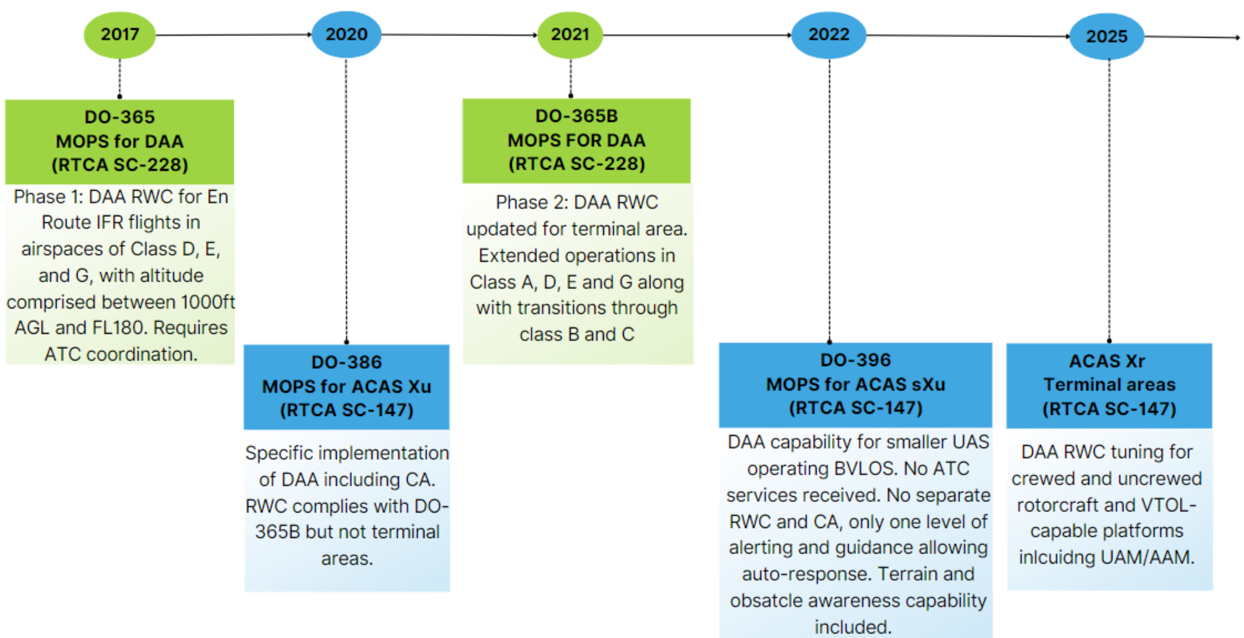

FIGURE 2: RWC PARAMETERS TUNING TIMELINE

3. GENERAL AVIATION NEEDS AND CONCERNS

As already stated in introduction, safety of GA has always been a concern since lack of harmonized technical standards addressing performance for devices allowing GA aircraft to see and be seen, is major impediment to their widespread use in Europe. The increasing complexity [49] and density of air traffic, when the skies become more crowded with a mix of different airspace users, including UAS aircraft trending in the last few years, emphasize the importance of and the need of change.

The challenges which GA community is currently facing can be summarized as follows:

- Uncontrolled airspace where GA aircraft are predominantly flying VFR applying “see and avoid” is now being shared with increasing number of UAS. This leads to congestion in uncontrolled airspace, what introduces high risk of situations which can potentially lead to collision.
- Various electronic situational awareness and collision avoidance systems and applications exist, but only small number of aircraft are equipped with such system. The reasons for this can be SWAP limitations, i.e., GA aircraft being limited in terms of size, weight and power consumption, but also cost and lack of harmonized regulatory framework. Recent EASA survey indicated that main barrier in bigger uptake of TA or CA system for GA pilots is high cost of devices (48%) [49].
- The diversity of existing systems/applications means implies they are not always interoperable with each other, thus aircraft may or may not be visible to each other. This leads to ineffective sharing of traffic information and lack of full protection against collision. The second biggest barrier in bigger uptake of the TA and CA systems are thus, according to EASA, their interoperability issues (30%) [49].

It seems that desire to accelerate the deployment of UAS BVLOS operations in Europe made regulatory bodies to propose an acceptable solution for GA (iConspicuity) operating in airspace shared with UAS (U-space).

3.1. ELECTRONIC CONSPICUITY REGULATIONS

Based on the SERA.6005 (c) regulation [54] starting from January 2023, all manned aircraft operating in U-space airspace, which are not provided with ATC services, shall continuously make themselves electronically conspicuous to the U-space service providers (USSP). Driven by this regulation EASA developed a proposal for solution [52],[54] how to comply with this requirement in practice, keeping in mind that the solution needs to:

- be affordable to all airspace users,
- be a technology available now, with minimum standardization needs,
- allow one single device to comply with the requirement,
- be a device with simple and straightforward installation,

- support broader airborne collision risk mitigations for manned aircraft, even beyond U-space in a longer term.

iConspicuity, sometimes referred also as e-conspicuity, falls under cooperative surveillance, and refers to in-flight capability to transmit position and/or to receive, process and display information about other aircraft, airspace, weather, or support to navigation in a real-time with the objective to enhance pilots' situational awareness [49]. The proposed means of transmission are:

1. certified ADS-B Out on 1090 MHz frequency, so that existing certified aircraft are conspicuous to other traffic,
2. devices that are transmitting on SRD 860 frequency band (FLARM, OGN, FANET+, PilotAware) using new ADS-L specification – the existing devices will therefore need to be adapted for ADS-L,
3. mobile/fixed communication network (MFCN) transmitting information in compliance with new ADS-L specification.

Part of EASA proposal is also a potential use of technically suitable 789 MHz (UAT) frequency band for certified ADS-B, considered as one of the transmission means, if the spectrum will once become available for this purpose in all Europe, especially for cross borders.

The use of mobile telephony, or MFCN, as a non-aviation technology potentially useful for very minimalistic aviation use by user equipment installed either on board of UAS or GA, has been under assessment since 2018. In 2022, Electronic Communications Committee (ECC), approved the use of aerial user equipment for communications based on the LTE and 5G [55].

iConspicuity is believed to be a key to increase safety by reducing the likelihood of mid-air collisions, especially in class G airspace, helping other airspace users to be more aware of any aircraft operating in the same airspace. It is also expected to have an impact on possible choices of GA pilots regarding the installation of electronic conspicuity devices.

3.2. DAA RWC ALERTING

As already mentioned in previous sections, the spin-offs of the development of DAA systems [26] [79] for UAS also introduce new means for augmentation of visual observation feasible for GA operations. In other words, GA can potentially benefit from various adaptations of RWC functionality aiming to address different type of operations and different airspace users. The usability of ACAS Xu installation on the GA aircraft was also assessed through one of the experiments within the scope of this thesis, although the focus of the experiment was given on the CA, not RWC functionality of ACAS Xu. The CA functionality was during the experiment shown not to be compatible with GA operations since maneuvers provided were not often compliant to rules of the air, sometimes in contradiction to what GA pilot would otherwise do in such situation. Nevertheless, suitable RWC functionality, if tuned for GA, would minimize the need for collision avoidance action.

Definition of when an RWC alerting algorithm may or may not alert, is typically driven by so called alerting zones (Figure 3). The alerting zones are used to generate timing requirement for the various types of RWC alerting (alerting requirements).

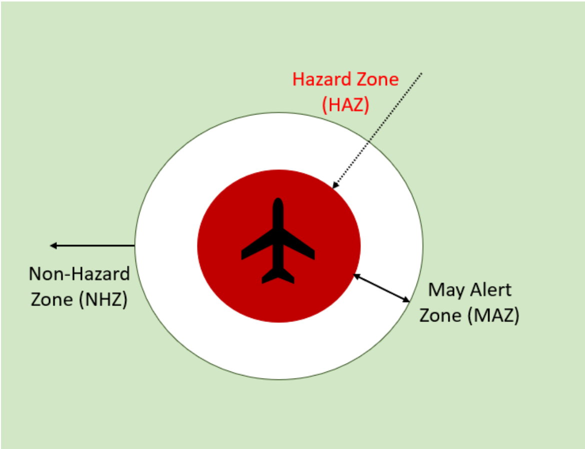

FIGURE 3: ALERTING ZONES USED TO DEFINE RWC ALERTING

DAA MOPS [79] defines three types of alerts:

- Preventive – applied En Route, drawing the remote pilots' attention to traffic that would trigger a corrective alert of warning alert if no action is taken.
- Corrective – applied En Route, intended to get the remote pilots' attention, and indicates that his response is required (incl. coordination with ATC).
- Warning – intended to inform remote pilot that immediate action is required to remain DWC and is thus prompting ownship to maneuver.

The alert types are in [79] classified into two alert levels:

- caution type of alert requires immediate pilots' awareness and a subsequent response, and
- warning type of alert requires immediate pilots' awareness and immediate response.

The three types of alerts for RWC functionality as defined by DAA MOPS [79] are combined with suggestive guidance, while CA consists of warning alert type with directive guidance. Suggestive guidance provides pilot with a range of actions for manual execution to avoid a hazard, such as altitudes or headings to favor or avoid ("don't go there"). Directive guidance provides specific recommended action or range of actions ("go there") to avoid a hazard with manual or automated execution. Third possible type of guidance is called automatic, when the system informs pilot about its intent and executes the maneuver ("I go there").

Each alert has own threshold for horizontal proximity in time (τ)[5] [s], predicted horizontal miss distance (HMD)[6] in [ft], and vertical separation (h)[7] [ft]. The alerting zone for a particular alert is violated when all three thresholds have been met [5].

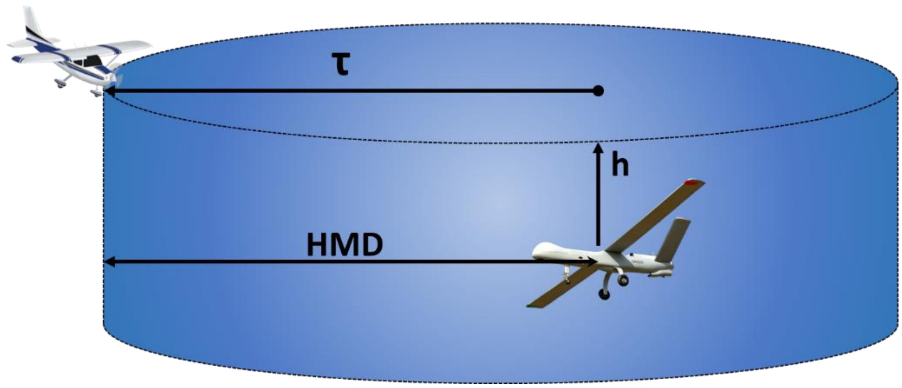

FIGURE 4: A SCHEMATIC REPRESENTATION OF DWC ZONE

First DAA RWC parameters (DWC) were defined in DAA MOPS [26] addressing En Route IFR UAS operations, with the aim, to limit excessive nuisance alerting onboard of TCAS II/ACAS Xa equipped aircraft. These were later complemented (via MOPS update [79]) with parameters tuned to support UAS approach and departure operations near VFR traffic patterns and in close proximity to the ground, terrain and obstacles, i.e., smaller HAZ was applied to avoid generating excessive nuisance alerts during this terminal area operations.

For terminal area alerting on cooperative traffic, no preventive alerts (they would result into high nuisance alerting) and no corrective alerts are generated (they would not provide enough time to coordinate with ATC prior to necessity to execute a missed approach procedure and thus are considered as operationally unsuitable). For terminal area intruders tracked solely by non-cooperative sensors, no preventive alerts are generated (due to altitude uncertainties of the sensors), but corrective alerts are generated to address the issue of their lack of visibility to ATC. For non-cooperative intruders, a slightly higher HAZ therefore needs to be applied, but not as high as for En Route areas.

[5] Tau - time taken for the two aircraft to get horizontally close to each other (CPA).
[6] HMD – predicted minimum horizontal distance (in the future) assuming constant velocities.
[7] h – two aircrafts' current altitude difference.

TABLE 1: DO-365B RWC PARAMETERS

		En Route DWC (DO-365)			Terminal Cooperative DWC (DO-365B)			Terminal Non-Cooperative DWC (DO-365B)		
	Alert type	Preventive	Corrective	Warning	Preventive	Corrective	Warning	Preventive	Corrective	Warning
	Alert level	Caution	Caution	Warning	Caution	Caution	Warning	Caution	Caution	Warning
	Guidance									
HAZ	τ [s]	35	35	35	N/A	N/A	0	N/A	0	0
	HMD [ft]	4000	4000	4000			1500		2200	2200
	h [ft]	700	450	450			450		450	450
Alert Times	Minimum Average Time to Alert [s]	55 (prior to HAZ)	55 (prior to HAZ)	25 (prior to HAZ)			45 (prior to HAZ)		55 (prior to HAZ)	25 (prior to HAZ)
	Late Threshold [s]	20 (prior to HAZ) or 5 (after NHZ)	20 (prior to HAZ) or 5 (after HAZ)	15 (prior to HAZ) or 5 (after HAZ)			30 (prior to HAZ) or 10 (after exiting NHZ)		20 (prior to HAZ) or 5 (after HAZ)	15 (prior to HAZ) or 5 (after HAZ)
	Early Threshold [s]	75 (prior to HAZ) or 110 (prior to CPA)	75 (prior to HAZ) or 110 (prior to CPA)	55 (prior to HAZ) or 90 (prior to CPA)			70 (prior to HAZ or CPA)		110 (prior to HAZ or CPA)	90 (prior to HAZ or CPA)
NHZ	τ [s]	110	110	90			75		110	90
	HMD [ft]	1.5	1.5	1.5			2000		1.5	1.2
	h [ft]	800	450	450			450		4000	4000

RWC volumes showed in Table 1 serve as a baseline for development of various DAA implementations targeting different UAS airspace users listed in Table 2. Each implementation has different target platform and thus also performance, different operational environment, and different needs, so the timing and types of RWC (and CA) alerting and guidance, as well as separation volumes were optimized to provide safe and operationally suitable DAA solution meeting the UAS needs.

TABLE 2: OVERVIEW OF EXISTING DAA IMPLEMENTATIONS AND APPROACH TO RWC

DAA Solution	ACAS Xu (2020)	ACAS sXu (2022)	ACAS Xr (work in progress, MOPS expected in 2025)	
Target platform	large UAS, potentially UAM/AAM (if equipped with transponders) in controlled airspace	Low performance UAS Low size, weight and power (SWAP) sUAS	Manned and unmanned rotorcraft, UAM (air taxi), AAM	
Target operations	IFR, high altitudes where manned aircraft and other large UAS operate	Uncontrolled airspace, low altitudes	From low altitude VFR to IFR at higher speeds and altitudes	
Novelty	Providing also horizontal maneuvers Protection against non-cooperative traffic Supports automated and manual responses	Dynamically scaled protection volume based on type of an intruder Increased flexibility in terms of minimum required surveillance equipage Terrain and obstacle awareness capability	Will support ground-based surveillance from USSP	
			Unmanned	**Manned**
RWC Alerting level	Caution ("be aware")	Warning ("act") **- considered as RA-**	Caution ("be aware")	No RWC but TA
RWC Guidance	Suggestive ("don't go there")	Directive ("go there") **-considered as RA-**	Suggestive ("don't go there")	N/A
Gap	Alerting logic not tailored for terminal area -> i.e., would generate nuisance alerting in TMA No terrain or obstacles awareness capability	Intended platform limitations (no passengers on board)	N/A yet	

First considered implementation of DAA, ACAS Xu, standardized in 2020 [23], was developed as a primary tactical mitigation of collision risk with manned aircraft and larger

UAS. It provides RWC and CA functionality. It does not have a separate warning alert for RWC (suggestive) and CA (directive), but ACAS Xu combines the warning alert and directive guidance to regain DWC into single event known as Resolution Advisory (RA), part of CA functionality. Before RA, a RWC caution alert level is applied with suggestive guidance.

Second explored implementation of DAA, ACAS sXu standardized in 2022 [80], is a solution for platforms with reduced performance, typically low size, weight, and power (SWAP) small UAS operating in uncontrolled airspace at low altitudes. With ACAS sXu, all RWC alerts are of warning level with directive guidance since no coordination with ATC is required prior to executing the avoidance maneuver.

Third DAA implementation, ACAS Xr is currently under development and standardization, with MOPS planned for January 2025, therefore information provided here may change in the final version. ACAS Xr is being tailored for rotorcraft type of operations traditionally involving “see and avoid” (with or without ATC coordination) ranging from local, low level VFR flights for medical emergencies to IFR sorties at higher speeds and altitudes to offshore oil rigs [83]. Xr will also serve to autonomous unmanned EVTOL vehicles with passengers (UAM) or cargo (AAM) on board.

The protection volume of ACAS sXu and ACAS Xr is scaled based on intruder type, automatically determining the size of an intruder separation volume based on the information provided explicitly via identification bits. ACAS sXu provide only one level of alerting with two sets of alerting thresholds. All (Xu, sXu, Xr) provide horizontal, vertical and blended maneuvers, supporting automated and manual responses. Only sXu and Xr can provide terrain and obstacle awareness capability.

ACAS X does not have a strictly defined protection volumes. To issue an advisory, a full spectrum of possible future trajectories and their likelihood is taken into account based on ACAS X probabilistic approach to the prediction. Nevertheless, ACAS sXu [80] and ACAS Xr [83] documentation states that following volumes for the RWC alerting and guidance are assumed for tunning of the logic behavior.

Table 3: Tailored protection volumes for ACAS sXu and Xr

		ACAS sXu (RA)		ACAS Xr		
Alert level		Warning		Caution		
Guidance		Directive		Suggestive		
Airspace		Low altitudes		En Route		Terminal
Type of intruder		Large UAS and manned aircraft	Small UAS	Large UAS and manned aircraft	Small UAS	TMA traffic
HAZ	τ [s]	35	0	N/A	35	0
	HMD [ft]	2000	50	4000	2000	1500
	h [ft]	250	15	450	250	450

4. STATE OF THE ART – EXISTING SYSTEMS

This section provides only very high-level list of existing technologies relevant for the scope of the dissertation thesis. The list focuses on technologies directly used in experiments, as well as cooperative surveillance enablers (ADS-B and novelty ADS-L), which play a major role for GA.

4.1. ADS-B

ADS-B is a cooperative surveillance technique providing continuous broadcast of aircraft information (identity, position, and other data) to other aircraft and ground stations. Such transmission functionality is called ADS-B OUT. The ability to receive this information is known as ADS-B IN. It introduces numerous benefits in terms of safety and flight efficiency. In comparison to radar, ADS-B provides unlimited coverage, and consistent accuracy throughout the range. ADS-B has been already widely explained, documented [70], and standardized [57]-[74].

4.2. ADS-L

ADS-L is a novelty protocol, introduced for the first time in 2022 [78] with initial technical specifications delivered in 2023, within the scope of EASA iConspicuity project [52]. ADS-L is considered as an alternative to ADS-B Out 1090ES, recognized by EASA as a feasible and available technology to support transmissions over SRD-860 frequency band, which was by the time used by more than 50 000 airspace users of specific users' groups (i.e., FLARM).

The goal of ADS-L is to be "as light as possible", compatible with low-cost devices and mobile phones. It is based on simplified ADS-B and uses only GNSS based parameters. Devices compliant with ADS-L specification assumes two main functions: message generation and transmit. The message generation function specification and minimum set of parameters to be transmitted are detailed in Appendix 1 to AMC1 SERA.6005(c) [54]. Initial ADS-L technical specification [50] were developed aiming to provide accurate description for ADS-L messages transmissions using SRD860 allowing manned aircraft operating in U-space to be conspicuous to USSP.

The ADS-L data are assumed to be accessible not only to USSP, but also to any other entity without any proprietary limitations or royalties [50]. The device supporting ADS-L will use three types of inputs: a GNSS sensor data (position source), pilot inputs (i.e., optional emergency status) and configuration data (such as aircraft identifier, address type, or aircraft category).

ADS-L is beyond the conspicuity objective foreseen as a technology supporting future traffic awareness applications enhancing the safety of GA.

4.3. TRAFFIC SITUATIONAL AWARENESS SYSTEM WITH ALERTS (TSAA)

Traffic Situational Awareness with Alerts (TSAA), nowadays rather referred as ADS-B Traffic Advisory System (ATAS), is a traffic situation awareness application developed by MIT with partner Avidyne, based on contract from FAA. It is an airborne ADS-B IN application that is intended to reduce the number of MAC and NMAC involving GA aircraft. This surveillance application has been studied by FAA, and its specifications are contained in RTCA MOPS DO-317B [4], Safety and Performance Requirements (SPR) defined in DO-348 [4] and their EUROCAE equivalents ED-194A and ED-232 respectively.

The full version of doctoral thesis discusses more in detail the TSAA system overview, its advantages, alerting concept, and operating method.

4.4. ENHANCED TSAA (TSAA+)

TSAA+, even though listed as state-of-the-art technology, is still a concept developed by Honeywell, not further standardized nor implemented. It aims to address mixed equipage encounters, e.g., encounters involving TCAS-equipped and non TCAS-equipped aircraft which are one of the remaining sources of MAC risks. TSAA+ is intended to provide timely alerts of qualified airborne traffic in the vicinity of ownship to increase flight traffic situation awareness, and if TCAS II-equipped traffic is issuing an RA (against ownship or any other traffic), then the information about RA will be passed to the flight crew. TSAA+ application is intended to reduce the risk of NMAC or MAC by aiding in visual acquisition, and to avoid TSAA+ pilot to maneuver against RA of TCAS II-equipped aircraft (e.g., idea is NOT to maneuver). [7]

The full version of doctoral thesis provides more details on technical characteristics, operating method as well as exemplar scenarios, use cases and performance requirements.

4.5. ACAS X AND ITS VARIANTS

ACAS X represents a family of next generation collision detection and avoidance systems that can be optimized for specific applications. The concept of ACAS X was for the first time introduced in 2008 as part of FAA funded research program. A new approach to CA was expected to bring important benefits including safety improvement, reduction of “unnecessary” (nuisance) advisories leading to improvement in operational acceptability, improved adaptability to future operational concepts through functional decoupling of the collision avoidance logic from the surveillance and flexibility with respect to use of different surveillance sensors [19]. More details and overview of expected benefits of ACAS X are summarized in [20].

Last, ACAS X variant, ACAS Xp was intended to be solution for a GA, but its development is on hold since 2018.

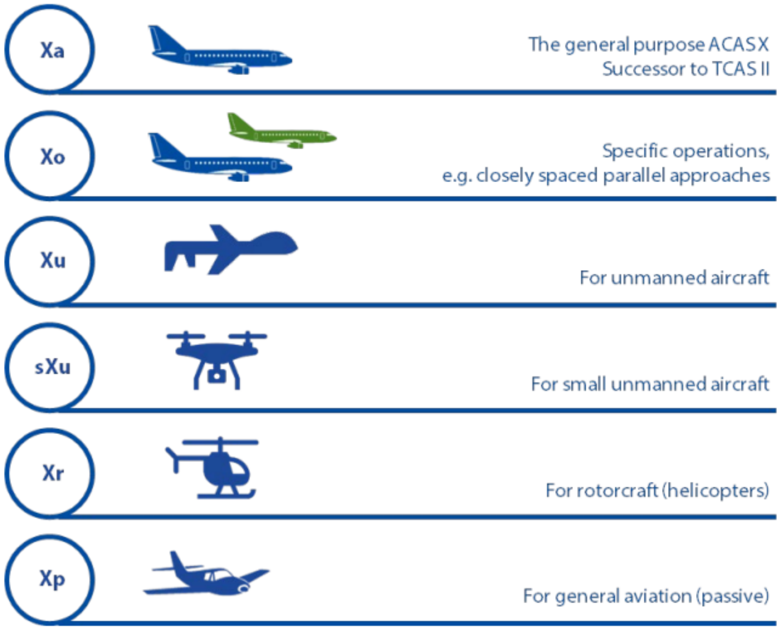

FIGURE 5: ACAS X VARIANTS [18]

The full version of doctoral thesis provides more details on the alerting concept, and different ACAS XDAA solutions (ACAS Xu, sXu and Xr).

5. CONCLUSION

Main motivation for this thesis was to explore how to improve operational safety of General Aviation (GA) operations in uncontrolled airspace anticipating considerable challenges associated with incoming new users – primarily drones. In this context three main areas were explored:

A. Possibilities to improve cooperative surveillance (or electronical visibility) at that airspace, starting with, but not being restricted to, ADS-B.
B. Through set of experiments, evaluate reusability and suitability of selected existing collision avoidance and situation awareness systems.
C. Investigate adaptations of the drone dedicated Remain Well Clear (RWC) concept, for GA systems.

Timewise, the thesis activities can be split in two sequential blocks. In its initial phase, spanning from 2015 to 2019, a series of experiments associated with the above-mentioned point B were conducted. By examining the existing systems (relying to a large extent on ADS-B and potentially interrogation of aircraft's transponder) in various perspectives and configurations, valuable insights have been garnered regarding the feasibility of existing solutions for GA. Figure 6 provides the overview of performed experiments and Table 4 summarizes their scope, goals, and high level conclusions.

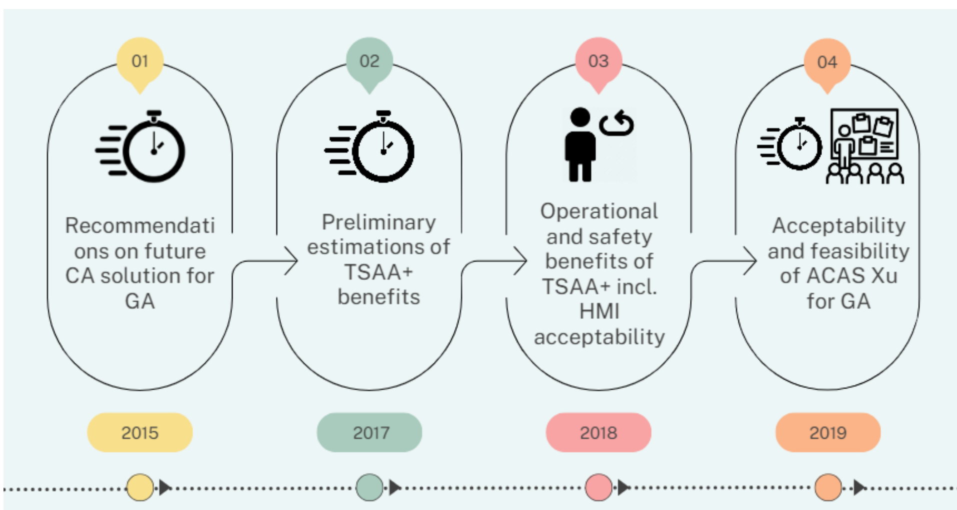

FIGURE 6: EXPERIMENTS TIMELINE

Set of fast-time and real-time simulations as well as workshops with GA/Rotorcraft pilots indicated significant preliminary safety benefits when using ADS-B In situational awareness applications (TSAA or TSAA+). At the same time, experiments confirmed that CA solutions available at that time are not acceptable for GA without their tailoring for GA operations and aircraft performance.

With regard to points A and C, the most significant evolutions appeared during the recent years due to intensive work on drones' integration, Detect and Avoid standardization, and U-space regulatory environment. These updates are reflected in the second phase of this thesis, culminating in recent months, and involves an exhaustive analysis of systems introduced since the last experiment, aiming to highlight the solutions that, with appropriate adjustments, hold the potential to be effectively tailored for adoption by GA.

Concerning electronic visibility (point A), beyond the use of ADS-B considered within the above-mentioned experiments, the introduction of ADS-L and iConspicuity using two additional technological means (SRD 860 MHz and cellular network) by EASA represents the biggest evolutionary step. Although iConspicuity is required at this stage only for GA operating within U-space [92][93], it has a potential to bring significant safety benefits also in other types of airspaces especially if complementary traffic information sharing services will be successfully deployed.

Detect and Avoid systems designed for different types of unmanned aircraft represent another promising candidate to support GA operations. In particular, their RWC function as a sensor-based alternative to the Well Clear concept used during visual separation seems to fit well within GA pilots' way of working. However, provided overview of already existing RWC parameters and their implementations does not encompass the specific needs of GA pilots. This gap can be partially addressed through lens of TSAA system and its alerting criteria, as examined in the conducted experiments and showed in Table 5. Unfortunately, the alerting criteria of TSAA and RWC thresholds of ACAS X cannot be well compared since the two systems (ACAS X and TSAA) are based on completely different alerting logic. While ACAS X is tuned to reflect the alerting thresholds based on current and probabilistic future positions of the two aircraft, TSAA thresholds are distances predicted for the time of CPA. Also, given that TSAA does not provide specific maneuvers, the relevance of the alerting criteria for the fine-tuning of RWC parameters for GA comes into question. Considering the fact that Terminal Area RWC parameters of ACAS Xr, which is currently under development, are tuned to address the interactions with other fixed-wing aircraft, rotorcraft, sUAS and future airspace entrants (UAM, AAM) operating at low altitudes, it is assumed that they might be the best choice as starting point for GA RWC parameters tuning.

TABLE 4: OVERVIEW OF EXPERIMENTS AND THEIR CONCLUSIONS

Experiment	Method	Systems used	Data used	Aim & Goal	Conclusion
#1	FTS	TSAA vs. ACAS Xa (passive surveillance only)	Selected TSAA MOPS – DO-317B test vectors (ADS-B 1090ES data only)	**Aim:** Compare TSAA vs. ACAS X alerting performance during typical GA operations. **Goal:** Indicate points that should be considered for further ACAS Xp system definition and development.	ACAS X not meeting the operational criteria for TSAA (GA) by alerting in situations where alerts are not expected. -> need for GA specific operations and performance tailoring. Majority of ACAS X alerts were issued later than TSAA alerts. ACAS X is more robust to surveillance noise than TSAA – due to different ACAS X logic accounting for target intent uncertainty.
#2	FTS	TSAA vs. TCAS II	Set of European real-environment mixed equipage encounters involving GA/R provided by EUROCONTROL	**Aim:** Identify and analyze the scenarios where the alerting of the two systems may potentially increase risk of conflicting maneuvering and evaluate the amount of potential help of RA Broadcast availability for TSAA+. **Goal:** Preliminary estimation of TSAA+ benefits.	Initial results based on real but limited European data set indicate that providing GA pilot with RA information from another aircraft can potentially bring benefits in 78.4% of all alerting scenarios. TSAA without "+" functionality has a potential to help in 52.6% of all alerting scenarios. That implies that "+" functionality of TSAA can potentially improve safety by 49%.
#3	RTS HITL	TSAA+	Six TMA/Airport environment encounters defined by Honeywell flight operations experts / pilots	**Aim:** Pilots' acceptability of TSAA+ technology integration through human-in-the-loop validation. **Goal:** Assess operational and safety benefits and HMI acceptability of TSAA+ by GA/R pilots.	TSAA+ feature as part of experimental application was very well accepted by all pilots. "See and avoid" failures decrease by 20% with TSAA+ and by 32% with only TSAA technology – safety benefits. Significant improvement in time of intruder recognition (>1 min) HMI improvements are needed. Useful pilots concerns and confusions were collected for future TSAA+ development.
#4	FTS + Pilot workshop	ACAS Xu	Set of European real-environment mixed equipage encounters involving GA/R provided by EUROCONTROL + Set of artificial encounters	**Aim:** Assess interoperability, reusability and operational acceptability of ACAS Xu for GA/R operations. **Goal:** Get the first impression on acceptability and feasibility of ACAS Xu RA instructions by GA pilots (when both ownship and intruder are equipped).	Evaluated ACAS Xu version installed onboard of GA aircraft was not acceptable as the system frequently generated maneuvers that were not in line with rules of the air. From the same reason, ACAS Xu installed on board of unmanned intruder did not seem to be interoperable with GA.

In summary, the analysis and experiments completed within this thesis, aiming to explore potential industrial solutions for GA that would allow safe coexistence of GA and UAS in the near future, showed that Situation Awareness stands as one of the most straightforward applications that GA can readily adopt and derive advantages from. Another option lies in the domain of CA, a system that inherently encompasses situational awareness but demands a significantly higher level of criticality and places increased demands on pilots' skills and training. Unfortunately, performed experiments clearly demonstrated that neither of the existing systems really copes with todays' and future operational needs of GA community.

TABLE 5: RWC AND TSAA ALERTING THRESHOLDS COMPARISON

		ACAS sXu (RA)		ACAS Xr (RWC)			TSAA	
Alert level		Warning		Caution			Caution	
Guidance		Directive		Suggestive			No guidance	
Airspace		Low altitudes		En Route		Terminal	En Route	Terminal
Type of intruder		Large UAS and manned aircraft	Small UAS	Large UAS and manned aircraft	Small UAS	TMA traffic	All ADS-B Out equipped aircraft	
HAZ	τ [s]	35	0	N/A	35	0	28	25
	HMD [ft]	2000	50	4000	2000	1500	N/A	N/A
	h [ft]	250	15	450	250	450	N/A	N/A
HAZ	HMD* [ft]	*TSAA thresholds predicted for CPA, cannot be directly compared with ACAS X thresholds					500	500
	h* [ft]						450	200

Within the spectrum of capabilities lying between CA and Situation Awareness applications, the RWC concept emerges as a promising intermediary choice, offering a balanced blend of functionalities. Moreover, the RWC application goes a step further by introducing an array of diverse guidance types that can be potentially extended to GA pilots, enhancing the overall safety landscape. However, existing RWC definitions do not seem to be suitable for GA pilots, and therefore a tailored design of the RWC alerting thresholds will need to be developed to satisfy GA operational acceptance. In this context, the ongoing development of ACAS Xr system may address a considerable part of identified operational needs.

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ABBREVIATIONS

AAM	Advanced Air Mobility
ACAS	Airborne Collision Avoidance System
ACAS X	neXt generation Airborne Collision Avoidance System
ACAS Xa	ACAS X Active
ACAS Xp	ACAS X Passive
ACAS Xr	ACAS X Rotorcraft
ACAS Xu	ACAS X Unmanned
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-R	Automatic Dependent Surveillance - Rebroadcast
AGL	Above Ground Level
ANSP	Air Navigation Service Provider
ASA	Airborne Separation Assurance
ASAS	Airborne Separation Assurance System
ASEP	Airborne SEParation
ASIAS	Aviation Safety Analysis and Sharing
ASPA	Airborne SPAcing
ASSAP	Airborne Surveillance and Separation Assurance Processing
ATAS	ADS-B Traffic Advisory System
ATM	Air Traffic Management
ATS	Air Traffic Service
ATSA	Airborne Traffic Situational Awareness
BVLOS	Beyond Visual Line of Sight
BWS	Bedford Workload Scale
CA	Collision Avoidance
CAS	Collision Avoidance System
CASCARA	Collision Avoidance Simulation Components And Runtime Analysis
CAT	Commercial Air Transport
CATI	Cockpit Annunciator for Traffic Information

CAVS	CDTI Assisted Visual Separation
CAZ	Collision Airspace Zone
CDTI	Cockpit Display of Traffic Information
CMS	Conflict Management System
CPA	Closest Point of Approach
CSPO	Closely Spaced Parallel Operations
CTR	aerodrome ConTRol zone
DAA	Detect and Avoid
DF	Downlink Format
DNA	Designated No Alert
DNC	Do Not Climb
DND	Do Not Descend
DWC	DAA Well Clear
EASA	European Aviation Safety Agency
ECC	Electronic Communications Committee
EVTOL	Electric Vertical Take-Off Landing
FAA	Federal Aviation Administration
FIM	Flight-deck Interval Management
FL	Flight Level
FTS	Fast Time Simulations
GA	General Aviation
HF	Human Factor
HITL	Human In The Loop
HMI	Human Machine Interface
HP	Human Performance
IA	Intersect Angle
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
ITP	In-Trail Procedure
LO	Level-Off

MAC	Mid Air Collision
MASPS	Minimum Aviation System Performance Standards
MFCN	Mobile Fixed Communication Network
MIT	Massachusetts Institute of Technology
MOPS	Minimum Operational Performance Requirements
MTOM	Maximum Take Off Mass
MVS	Maintain Vertical Speed
NAT	Nearby Airborne Traffic
NMAC	Near Mid Air Collision
NTSB	National Transportation Safety Board
OTW	Out of The Window
PAZ	Protected Airspace Zone
RA	Resolution Advisory (ACAS)
RAC	Resolution Advisory Complement
RHV	Relative Horizontal Velocity
RPAS	Remotely Piloted Aircraft System
RTCA	Radio Technical Commission for Aeronautics
RVV	Relative Vertical Velocity
RWC	Remain Well Clear
SA	Separation Assurance
SCM	Strategic Conflict Management
SPR	Safety and Performance Requirements
STCA	Short Term Conflict Alert
sUAS	small UAS
SWAP	Size Weight And Power (not cost)
SWPC	Size Weight Power consumption and Cost
TA	Traffic Advisory (ACAS)
TAS	Traffic Advisory System
TCA	Traffic Caution Alerts
TCAS	Traffic Collision Avoidance System with alerts

TD	Traffic Display
TIS	Traffic Information Service
TIS	Traffic Information System
TIS-B	Traffic Information Service - Broadcast
TMA	Terminal Movement Area
TSA	Traffic Situational Awareness
TSAA	Traffic Situational Awareness system with Alerts
UAM	Urban Air Mobility
UAT	Universal Access Transceiver
UAS	Unmanned Aircraft Systems
USSP	U-Space Service Provider
VFR	Visual Flight Rules
VLOS	Visual Line of Sight
VMC	Visual Meteorological Conditions
VRC	Vertical Resolution advisory Complement

APPENDIX A – AUTHOR'S CONTRIBUTION TO RESEARCH RESULTS

Based on the fact that this dissertation thesis has been prepared as part of my employment at Honeywell, and results presented in this thesis were a collective effort of myself and the project team, this appendix explains my direct contribution to research results more in detail.

The contribution can be split into two parts: the TSAA+ concept definition and experiments execution. As mentioned in the thesis, the four experiments summarized in this thesis have been performed within two SESAR projects: SESAR (1) project P9.47 (TCAS Evolution), and SESAR 2020 CAPITO PJ.11-A4 project. At both projects I was in a role of project manager and technical lead. I have been therefore responsible for successful project execution (involving external consortium partners), execution validation activities (experiments), delivering the results captured in deliverables (publications), and presenting the results to SESAR JU.

TSAA+ definition

TSAA+ concept is a novelty concept defined within this research (SESAR CAPITO PJ.11-SA4) project.

Author’s research contribution:

- Definition of general assumptions for ACAS X tailored for GA (ACAS Xp). [1]
- Proposal of the approach to fast time simulations. [1]
- Definition of technical TSAA+ characteristics.
- Definition of which ADS-B message and which field shall be used for the “+” functionality.
- Contribution to definition of exemplar operational scenarios for TSAA+.
- Definition of three potential use cases for TSAA+.
- Definition of technical and operational assumptions for TSAA+ derived from TSAA Safety Performance and environment Requirements (SPR). [5]

Experiment #1

- Definition of validation set-up/approach and validation objectives.
- Selection of scenarios to be used for validation.
- Definition of simulation assumptions.
- Review of analysis results and drawing the conclusions and recommendations based on analysis results.
- Validation report preparation. [86]

Experiment #2

- Validation plan preparation. [87]

- Contribution to definition of validation objectives.
- Review of analysis results and drawing the conclusions and recommendations based on analysis results.
- Validation report preparation. [8]

Experiment #3

- Validation plan preparation. [87]
- Definition of high-level experiment objective.
- Contribution to definition of approach to experiment.
- Review of proposed scenarios to be used.
- Contribution to definition of validation assumptions.
- Organization of human-in-the-loop (HITL) evaluation (including inviting & selection of participating pilots).
- Oversight over the HITL evaluation execution.
- Review of collected inputs from pilots.
- Contribution to experiment conclusions
- Review and contribution to experiment recommendations.
- Validation report preparation. [9]

Experiment #4

- Validation plan preparation. [87]
- Contribution to objectives and approach to experiment definition.
- Definition of experiment assumptions.
- Review of analysis results & review of selected set of scenarios for the workshop.
- Pilot workshop organization.
- Drawing the experiment conclusions and recommendations based on analysis results.
- Validation report preparation. [9]

APPENDIX B - LIST OF AUTHORS' PUBLICATIONS AND PATENTS

United States patents

US10102760 B1: Maneuver prediction based on audio data (2018)

Filled US patents

H230874: Method for Vehicles Handover and Roaming using Ground Control Station (2023)

H227892: Adjustable system for displaying Required Actions and Notification items for Urban Air Mobility ground station HMI (2023)

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