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LETECKÝ ÚSTAV

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

DIZERTAČNÍ PRÁCE

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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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Authors’ declaration

I, as the author, declare that I have written this doctoral thesis titled “The use of ADS-B information for airborne separation and collision avoidance” independently and under the supervision of my university and Honeywell supervisors using exclusively sources of information duly cited and listed in the comprehensive bibliography at the end of the thesis.

Brno, August 31st , 2023

Ing. Eva Jošth Adamová

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Last, but not least, I thank to myself for not giving up.

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.

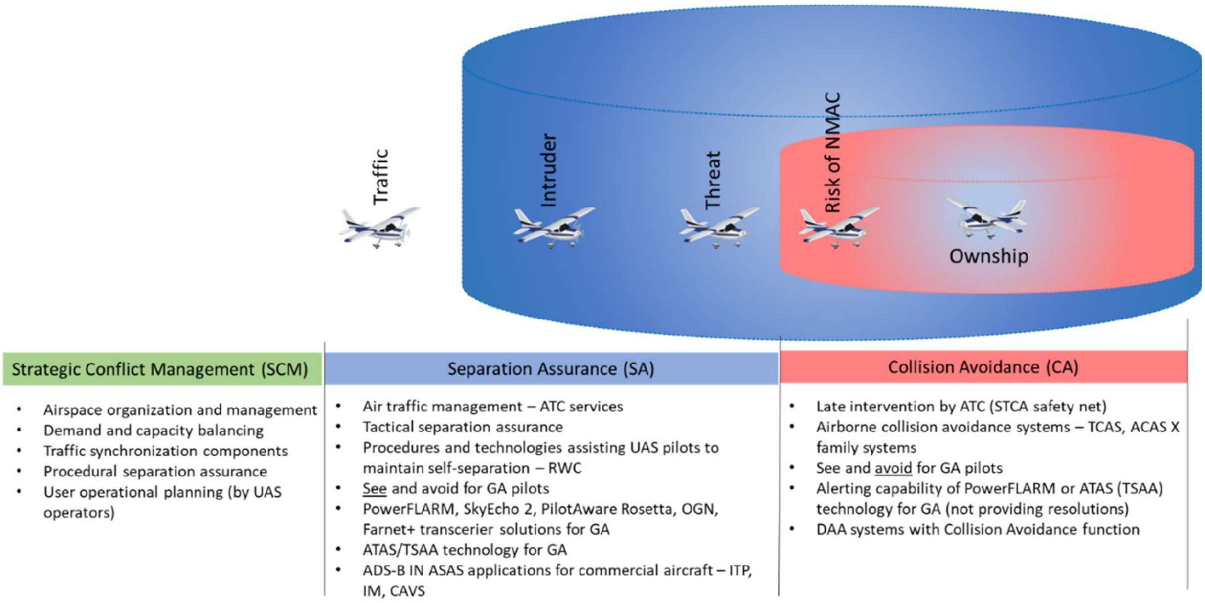


FIGURE 1: ILLUSTRATION OF CONFLICT MANAGEMENT SYSTEM LAYERS

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". Per ICAO [12], SCM is achieved by a combination of [56]:

- Airspace organization and management, which establishes airspace structures (i.e., pre-defined arrival and departure aerodrome tracks), procedures, and other processes that facilitate the organized utilization of the airspace.
- Demand and capacity balancing, including resource scheduling and flow rate restrictions to effectively manage the air traffic flows.

- Traffic synchronization mechanism including optimized sequencing into choke points or aerodromes, 4D trajectory control (i.e., interval spacing or negotiated conflict-free trajectories).

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 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

[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.

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 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

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

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

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 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].

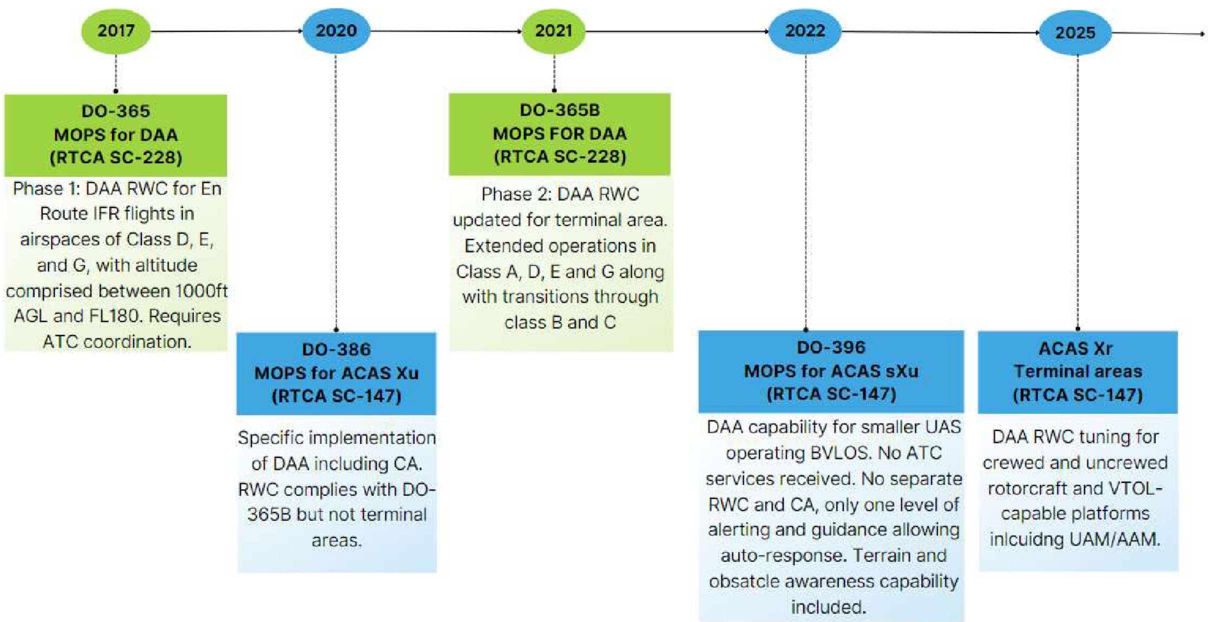


FIGURE 2: RWC PARAMETERS TUNING TIMELINE

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 (section 5.4), 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).

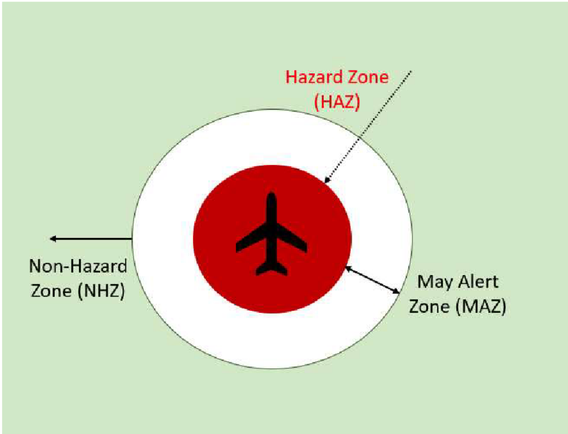


FIGURE 3: ALERTING ZONES USED TO DEFINE RWC ALERTING

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].

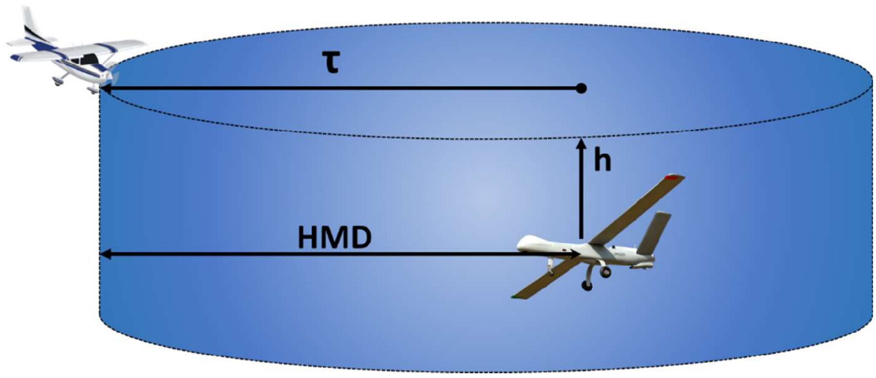


FIGURE 4: A SCHEMATIC REPRESENTATION OF DWC ZONE

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			0		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)	N/A	N/A	30 (prior to HAZ) or 10 (after exiting NHZ)	N/A	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 (see 4.5.1). 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 more details on the existing technologies relevant for the scope of this dissertation thesis. The focus is given 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].

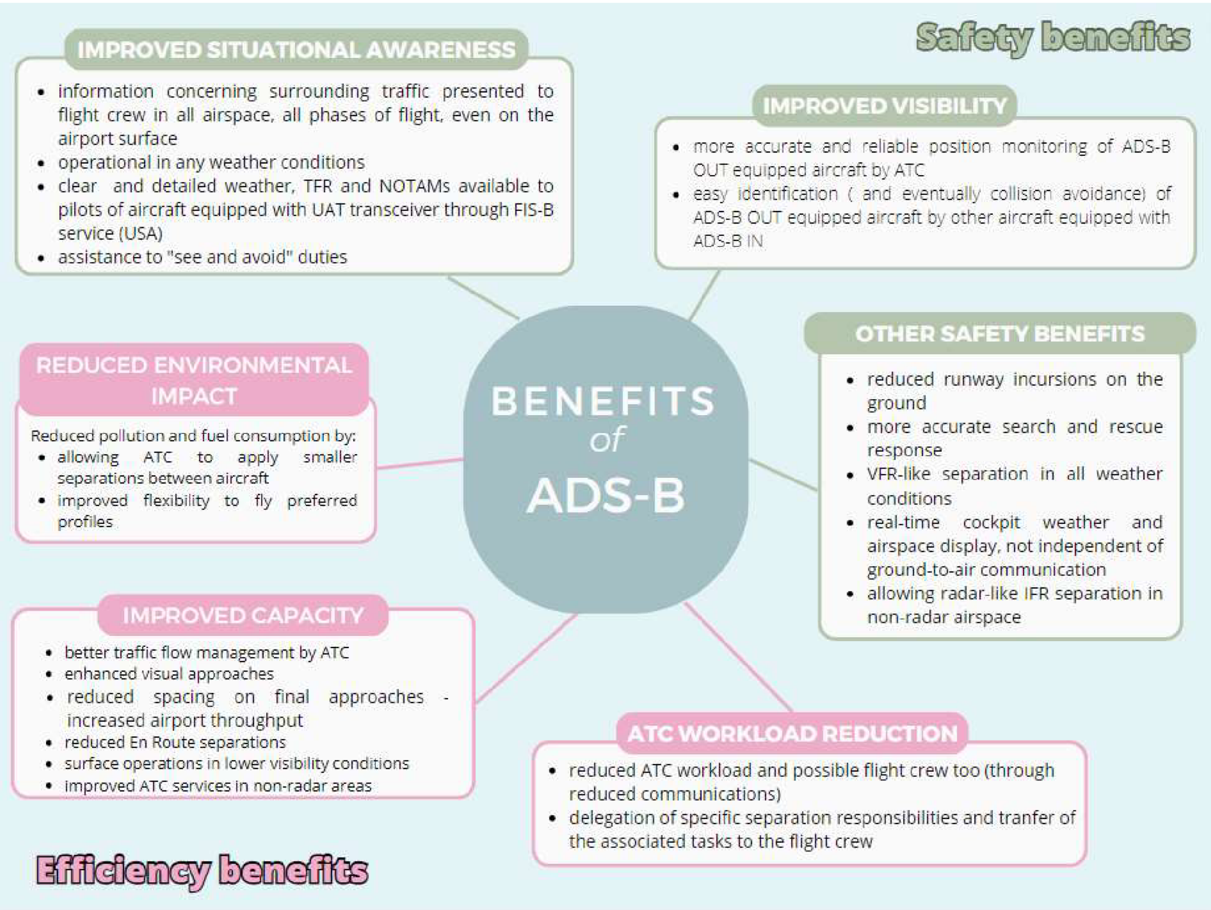


FIGURE 5: OVERVIEW OF ADS-B BENEFITS

While in the US, all powered aircraft that wish to fly in ADS-B rule (transponder required) airspace need to be ADS-B Out equipped since 2020, Europe at the same timeframe mandated for ADS-B Out capability covering only aircraft above 5700kg MTOM, or with maximum cruising speed above 250kt. There is no ADS-B mandate for GA in Europe, just EASA encouraging voluntary adoption amongst GA pilots to improve safety and reduce risk of MAC. However, the decision of individual European GA aircraft owners not to equip with ADS-B Out is influenced by variety of factors:

- Cost: the installation of required avionics equipment can be expensive.
- Aircraft age and lifecycle: some older aircraft might not have the necessary systems or wiring to easily accommodate the ADS-B Out equipment. Also, retrofitting older aircraft with modern avionics can be technically challenging and costly.
- Lack of awareness: some operators still might not be fully aware of the benefits of ADS-B Out, or the regulatory requirements surrounding its use.

In the past, one of the factors was the fact that most of the GA operate in less congested airspace. With the increased number of UAS operations, lower altitude and uncontrolled airspace is becoming more and more congested. This was actually a trigger for EASA iConspicuity initiative.

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 (Figure 6). 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).

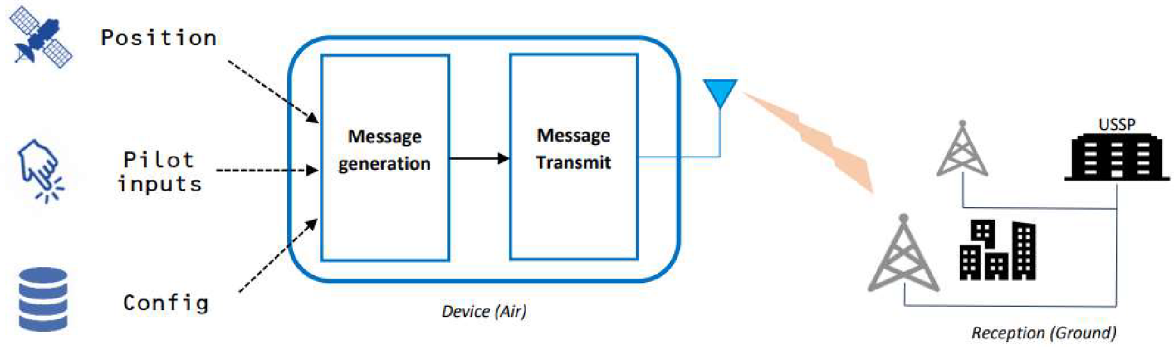


FIGURE 6: ADS-L CONCEPT

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 TSAA equipment was assumed to be less expensive than classical (non ADS-B) Traffic Advisory System (TAS) and TCAS I systems (based on active interrogations of intruder's transponder). It uses different logic to provide similar benefits to airspace users. The cost reduction was believed to attract more GA aircraft owners and operators to voluntarily choose to install TSAA equipment to reduce the risk of mid-air collisions.

4.3.1. SYSTEM OVERVIEW

TSAA is intended to be added to ADS-B IN equipped civil aircraft or rotorcraft that is currently equipped with TAS, or aircraft that are not equipped at all, and would be offered in two equipment classes:

- Class 1, to provide voice annunciation and attention-getting visual cue and is applicable for a/c with limited panel space for new displays or vintage a/c whose owners want to benefit from ADS-B traffic alerting without modifying the instrument panel.

- Class 2, to provide Class 1 capability with TD, therefore an additional assistance with locating possible threat.

TSAA can be used with CDTI or a Cockpit Annunciator for Traffic Information (CATI) and is the only application that is allowed to use CATI instead of CDTI. The system operates in both Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC), therefore in both IFR and VFR conditions and is usable from runway departure on take-off until touchdown on landing in any airspace (controlled and uncontrolled).

An operation of TSAA is based on passive surveillance technologies, therefore does not perform any active interrogations. In U.S airspace, besides ADS-B, TSAA also uses ADS-R and TIS-B information where available and is ADS-B linkage independent (operates with UAT, a 1090 ES or both). Since TIS-B and ADS-R are unique to U.S, so is UAT, the TSAA in European airspace would be based solely on ADS-B through 1090ES. Another aspect to be considered is that published European mandate for ADS-B OUT capability covers only aircraft above 5700kg MTOM, or with maximum cruising speed above 250kt. In Europe, TSAA uptake would only be achieved if the other aircraft are ADS-B equipped and therefore when the European regulation would request all aircraft flying in defined classes of airspace to be equipped by ADS-B OUT.

4.3.2. ADVANTAGES AND DISADVANTAGES OF TSAA

The system potential weaknesses can be summarized as follows:

- TSAA is not intended to alert on conflicts on the surface or runway incursions.
- TSAA is only effective against ADS-B OUT equipped aircraft.
- TSAA does not coordinate with other aircraft or ATC.

On the other hand, following facts seen as advantageous and are believed to be able to convince more GA aircraft owners and operators to equip their aircraft with TSAA:

- TSAA is more accurate than TCAS I or classical TAS (especially in bearing calculation).
- TSAA uses different logic to provide a similar, but not equivalent safety benefit to airspace users.
- TSAA is expected to be less expensive than above mentioned alternatives.

4.3.3. TSAA ALERTING CONCEPT

TSAA alerting is based on the prediction that the position of the target aircraft will be closer than a pre-defined distance to the predicted position of ownship within a defined time horizon. It performs pair-wise evaluations to determine whether a conflict exists between the ownship and a particular target. This is performed in three steps:

1. TSAA algorithm calculates two protected airspace zones around each target. Those are denoted as: Protected Airspace Zone (PAZ), whose dimension decreases with decreasing closure rate and serves as alerting threshold; and Collision Airspace Zone (CAZ) with fixed size at a radius of 500 ft and a height of ±200 ft based on the position uncertainty of two rule compliant ADS-B targets. An alert is received when target's penetration into the PAZ or the CAZ is predicted.

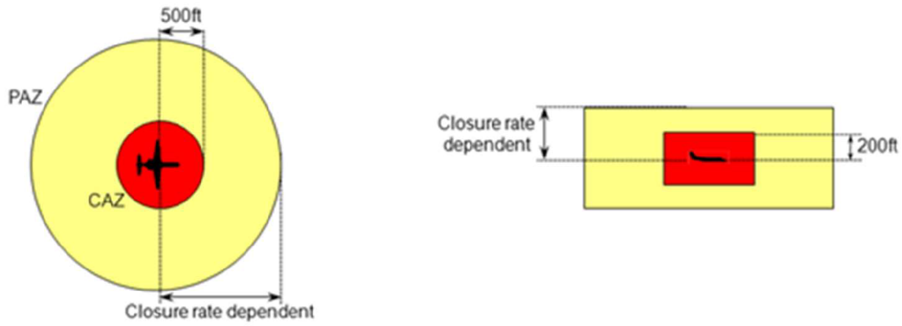


FIGURE 7: TWO ZONES CALCULATED FOR EACH TARGET: PAZ AND CAZ OF TSAA [4]

2. Discrete trajectories are predicted repeatedly for both ownship and intruder at nominal frequency (e.g., once per second). Constant turn rate trajectory propagation is used to predict where the aircraft will be if it were to continue its current maneuver.

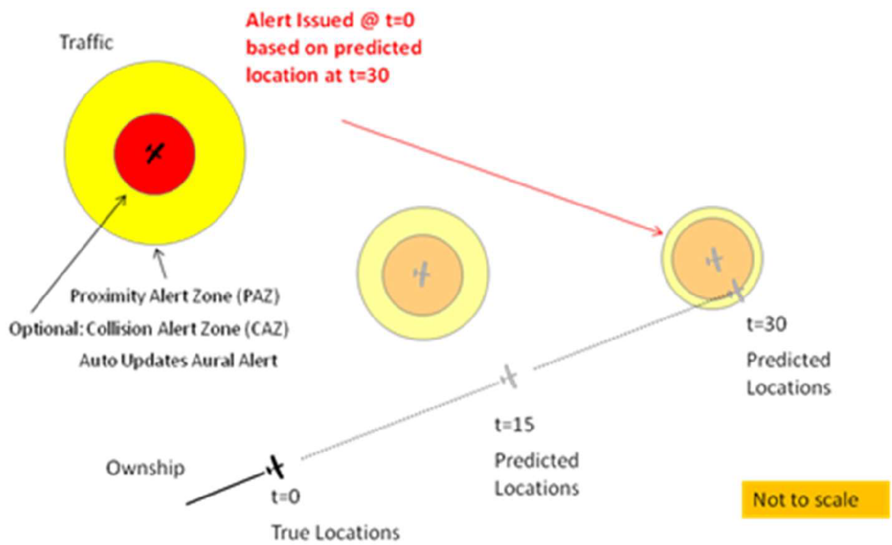


FIGURE 8: TSAA ALERTING LOGIC COMBINING PROTECTED PAZ AND CONSTANT TURN RATE TRAJECTORY PREDICTION [4]

3. Based on the predicted positions of the aircraft and the sizes of the airspace buffer zones along the trajectory, the alerting logic determines whether to issue an alert for a given target or not.

4.3.4. TSAA ALERTS

TSAA provides non-directive alerts (without guidance or commands) similar to TCAS I, TAS or Traffic Information Service (TIS). An alerting logic is optimized for GA flight operations. The two main system outputs are:

- Nearby Airborne Traffic (NAT) displayed on Traffic Display (TD), visually differentiates aircraft within a given range and altitude and supports out-of-window visual acquisition. The traffic shall be identified when an intruder separation is determined to be less than 6 NM and ±1200 ft vertically.

FIGURE 9: TSAA DISPLAY EXAMPLE

This output is available even when the ADS-B data quality parameters are not sufficient for Traffic Caution Alert (TCA), what means that not all traffic shown on TD is capable of generating an alert.

- TCA provides visual and aural cues. An aural cue says “Traffic” + relative traffic bearing, its relative altitude, range and potentially also vertical sense.

FIGURE 10: TSAA TRAFFIC CAUTION ALERT (TCA) EXAMPLE

The annunciations shall alert first at least 12.5 seconds prior to closest point of approach (CPA) when CPA is within horizontal and vertical values defined by MOPS (section 2.2.4.5.3.1.1). The alerts are not of warning type, so an immediate flight crew response is not required (only immediate flight crew awareness). Nominally, the TSAA application is expected to provide the flight crew with adequate time to respond the TCA. During active alerts, TSAA provides updated information on alerted traffic. If the TD is not available, flight crew will be able to update voice annunciation upon manual request, or as a result of a supplemental automatic update function.

Single TSAA TCA should be provided per threatening encounter. Automatic updates of traffic alert when the encounter persists or degrades are optional for TSAA. TCAs are determined by two cylindrical volumes around TSAA, one to specify when alert must be issued, and other to specify when alert must not be issued. The dimensions of the cylinder are based on CPA and differ with operational environment. Figure 11 presents Must and Must Not alert criteria defined for TSAA for CPA.

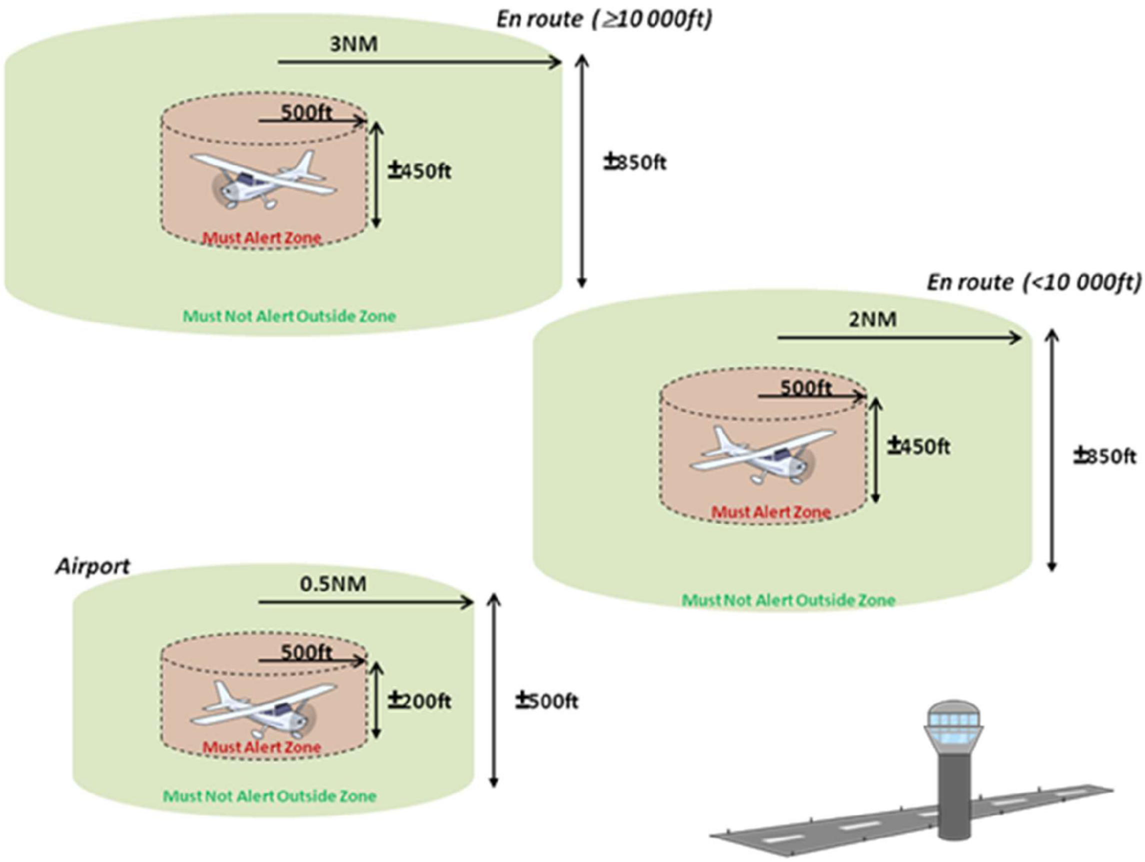


FIGURE 11: TSAA MUST AND MUST NOT ALERTING CRITERIA FOR CPA

4.3.5. TSAA OPERATING METHOD

The flight crew's primary responsibility is to safely fly the aircraft (Aviate, Navigate, and Communicate). As part of the "see and avoid" concept, traffic situation awareness is a major portion of the "Aviate" function. The flight crew develops traffic situation awareness by out-the-window visual scanning, and, when available, cockpit traffic displays and radio communication. In the event of a TCA, the presence of an alert condition is conveyed through attention getting visual cues, voice annunciations, and, if available, TD symbol change. When the TSAA application is operating on a multifunction display, the flight crew will be able to access the traffic display function. When an alert condition is detected by the flight crew, the flight crew will search out the window for alerted traffic or consult the TD, if available, for the relative location of the alerted traffic. Voice annunciations of alerted traffic relative bearing, range, altitude, and optionally vertical sense are provided for caution level alerts which also aid the flight crew to visually acquire the alerted traffic. NAT is available only for those installations that include a TD. No attention-getting mechanism is required beyond the TD symbol change for NAT. As in VFR operations today, if the NAT or alerted traffic or any other aircraft is visually identified, the flight crew decides on whether a "see and avoid" maneuver is the safest course of action. If it is not necessary, the flight crew continues to fly the aircraft as usual. If a maneuver is necessary, the flight crew maneuvers based on visual acquisition of the target aircraft. After the flight crew maneuvers to avoid the alerted traffic, the flight crew returns to the desired flight path and contacts ATC if appropriate. When the flight crew utilizes knowledge about a target aircraft's prior, current, or expected behavior, ATC traffic advisories, or any other information that is relevant to the current situation, to determine that a maneuver is necessary, the maneuver is not made solely on the TSAA TCA or indication (i.e., NAT). If the target aircraft is not visually acquired, and ATC traffic advisories are available and the flight crew would like traffic advisory information, the flight crew may contact ATC. When information received from ATC validates the information from the TD or the TSAA voice annunciation, and the flight crew judges that maneuvering the aircraft under VFR is the safest course of action, then the flight crew may maneuver the aircraft based on the ATC traffic advisory. If information received from ATC does not validate the information from the TD or voice annunciation, or the flight crew judges that a maneuver is not necessary, then the flight crew proceeds on its desired flight path. As in existing operations, if ATC services are being provided to the TSAA-equipped aircraft the flight crew should, time permitting, announce to ATC any intentions to maneuver before undertaking the maneuver. If a target aircraft cannot be visually acquired and ATC traffic advisories are available and desired, the flight crew may request ATC instructions. [5]

TSAA application has been evaluated for European operations within the scope of this thesis (see section 5.1 and [86]).

4.4. ENHANCED TSAA (TSAA+)

Previous studies conducted by MIT [14] showed that if the GA pilot is made aware of the Resolution Advisory (RA) raised by the TCAS equipped intruder, by adopting a responsive coordination strategy the risk ratio would be always lower than when the system only responds to TCAS, and no coordination. In this context, TSAA system would help the GA pilot in triggering attention to potential risk of collisions and TCAS intruder visual acquisition, hence in increasing response rate and reaction time, which are factors contributing positively to risk ratio reduction. For this reason, it is expected that enhancing TSAA application for use of information about intruder RA, and indicate it to pilot, could further reduce the risk of MAC and NMAC. Such capability is referred to as TSAA+.

TSAA+, even though listed as state-of-the-art technology, is still a concept developed by Honeywell, not further standardized nor implemented.

4.4.1. Operational environment

TSAA+ 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 TSAA+ is intended for any civil or military, powered aircraft or rotorcraft which is not under TCAS II mandate. It is intended to operate in any airspace (controlled or uncontrolled) with various traffic density; in IMC or VMC; during IFR or VFR flights; during departure, en-route or approach operations when there is a potential of encounters with commercial, TCAS II-equipped aviation. TSAA+ will only be effective in an airspace where ADS-B OUT equipment is installed and operational.[7]

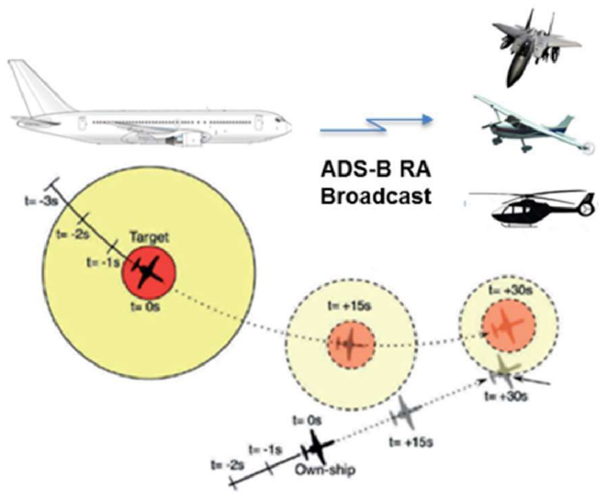


Figure 12: TSAA+ pictorial view

It is expected that safety benefits will be greater in uncontrolled airspace and in airspace where ATS services are limited. It is intended for powered aircraft not under TCAS II mandate, and civil and state airplanes or rotorcraft that operates in non-segregated airspace.

4.4.2. Technical characteristics

TSAA+ permits pilot to know the maneuver planned by TCAS II equipped intruder. In case of collision risk, TCAS II decides a vertical maneuver (climb or descent) which is transmitted into a specific squitter (ADS-B 1090 MHz Extended Squitter) through ADS-B transmitter. With TSAA+, ADS-B receiver can detect this squitter and inform GA pilot about the intruder intention.

TSAA+ would make use of ARA subfield[8] of ME field in ADS-B TCAS RA Broadcast message [58] transmitted by TCAS II equipped aircraft. This RF message (known also as DF=17) is part of 1090ES Aircraft Status Message (Message Type Code=28, Subtype=2) and is initiated within 0.5 seconds after the transponder notification of the initiation of a TCAS RA. Intervals are randomly distributed over the range of 0.7 to 0.9 seconds for the duration of the TCAS RA, and every 5 seconds with RA is not active. Figure 13 illustrates the allocation of RA message to be used by TSAA+.

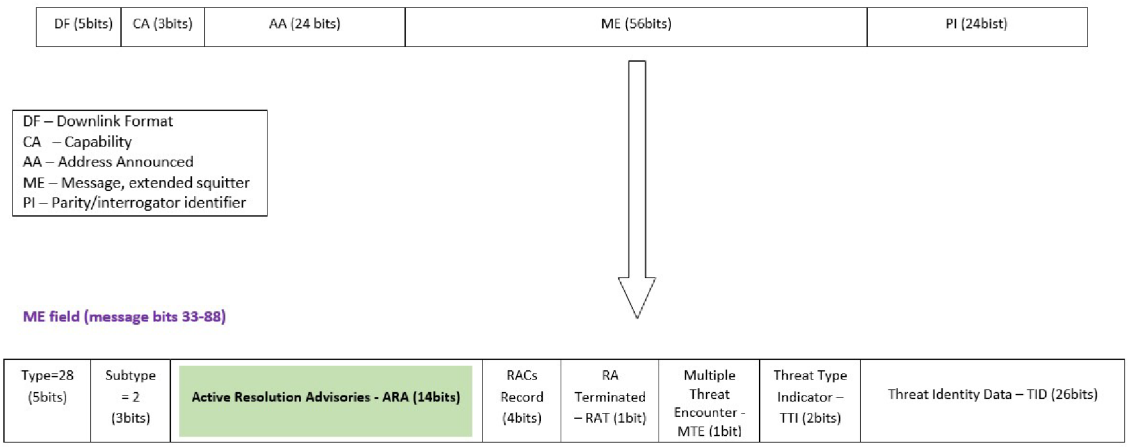


FIGURE 13: ARA SUBFIELD LOCATION WITHIN ADS-B TCAS RA BROADCAST MESSAGE (DF=17)

ARA subfield shall indicate the characteristics of the RA, if any, generated by the ACAS associated with the transponder transmitting the subfield. 14 bits of ARA subfield are defined as shown Table 4.

Figure 14 provides comparison of the current situation versus system overview involving TSAA and Enhanced TSAA (TSAA+).

[8] ARA subfield spears in three other RF messages (RA report, RA Broadcast Interrogation message and Coordination Reply message), but only ADS-B TCAS RA Broadcast is feasible for TSAA+ purposes.

TABLE 4: ARA SUBFIELD DEFINITION [56]

ARA Bit	Values & Definitions	
41	1 = one threat or RA is intended to provide separation in the same direction for all threats)	0 = more than one threat and RA is intended to provide separation below some threat(s) and above other threat(s) or no RA has been generated
42	0 = RA is preventive	1 = RA does not require a correction in the upward sense
	1 = RA is corrective	1 = RA requires a correction in a upward sense
43	0 = upward sense RA has been generated	0 = RA does not require a positive climb
	1 = Downward sense RA has been generated	1 = RA requires a positive climb
44	0 = RA is not increased rate	0 = RA does not require a correction in the downward sense
	1 = RA is increased rate	1 = RA requires a correction in the downward sense
45	0 = RA is not a sense reversal	0 = RA does not require a positive descend
	1 = RA is a sense reversal	1 = RA requires a positive descend
46	0 = RA is not altitude crossing	0 = RA does not require a crossing
	1 = RA is altitude crossing	1 = RA requires a crossing
47	0 = RA is vertical speed limit	0 = RA is not a sense reversal
	1 = RA is positive	1 = RA is sense reversal

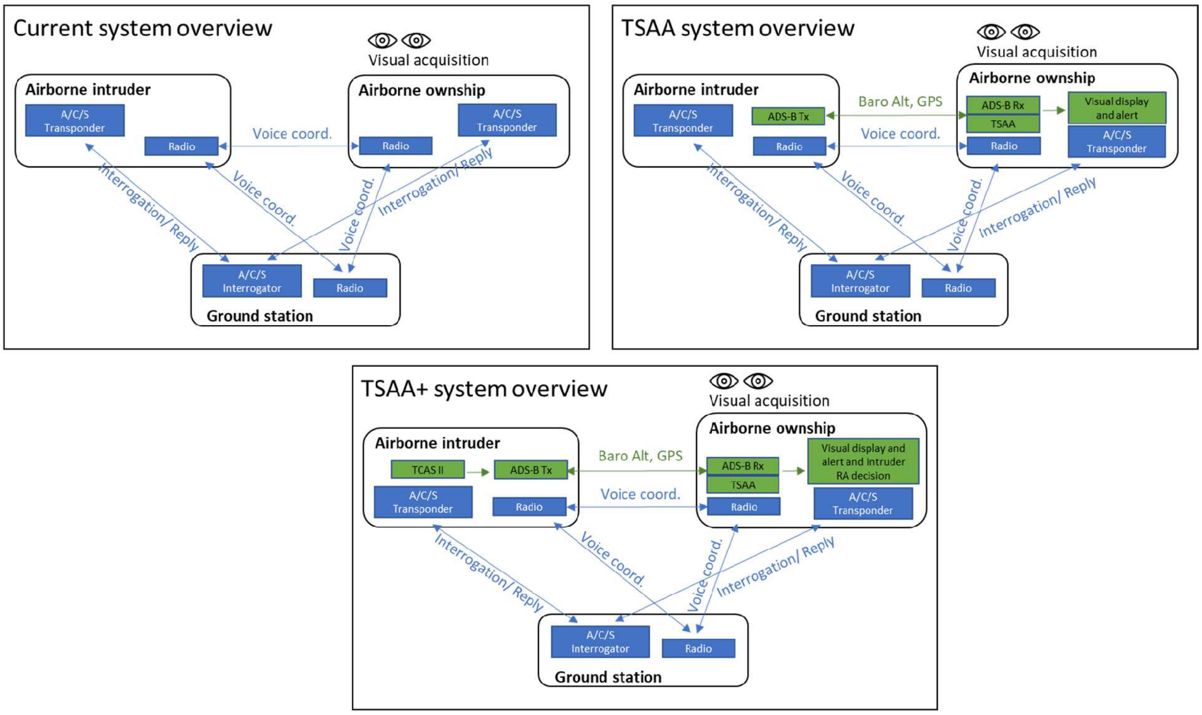


FIGURE 14: SYSTEM OVERVIEW COMPARISON CURRENT SITUATION VS. TSAA VS. TSAA+

4.4.3. OPERATING METHOD

TSAA+ will, in addition to visual cues and voice annunciations already being provided by TSAA, benefit from availability of information about RAs broadcasted by TCAS-equipped aircraft. In Europe, TSAA+ will only use ADS-B information (no ADS-R nor TIS-B since those are not operational in Europe) to provide flight crew with indications of nearby aircraft and if nearby, TCAS II-equipped aircraft is issuing RAs, then also an information about RA issued on-board of TCAS II-equipped threat.

TSAA+ is therefore expected to support see-and-avoid responsibility of the pilot and improve interoperability with TCAS II-equipped aircraft. There is no coordination between TSAA+ application and alerting systems on other aircraft, but TSAA+ can be considered as a first step toward responsive coordination, which strategy requires that intended aircraft knows it is the intruder aircraft for the TCAS-equipped aircraft. TSAA+, as a situational awareness application, will not provide flight crew with maneuver guidance or commands.

Pilot provided with such information, must consider (when deciding for further action to be taken), in addition to information provided by TSAA+, also the following:

- Rule of the Air (SERA.3210, ICAO Annex 2, 14 CFR § 91.113 [12]).
- Proximity of clouds (for VFR).
- Proximity of terrain or ground obstacles.
- Proximity, to other traffic, etc.

TSAA+ system outputs are:

- Nearby Airborne Traffic (NAT, same as TSAA).
- Traffic Caution Alerts (TCA, same as TSAA).
- Information about RA issued on board of TCAS II-equipped aircraft (version 7.1).

4.4.4. EXEMPLAR OPERATIONAL SCENARIOS

The exemplar operational scenario involves TSAA+ equipped aircraft and TCAS II-equipped aircraft.

Such situations can occur:

- En Route[9] – an exemplar situation depicted at figure shows two En Route TCAS II-equipped aircraft during NMAC, and third – TSAA+ equipped military fighter being aware of the situation and ongoing RA of both threats.

[9] En-route phase is considered when both involved aircraft are not in the phase of approach to/departure from the airport.

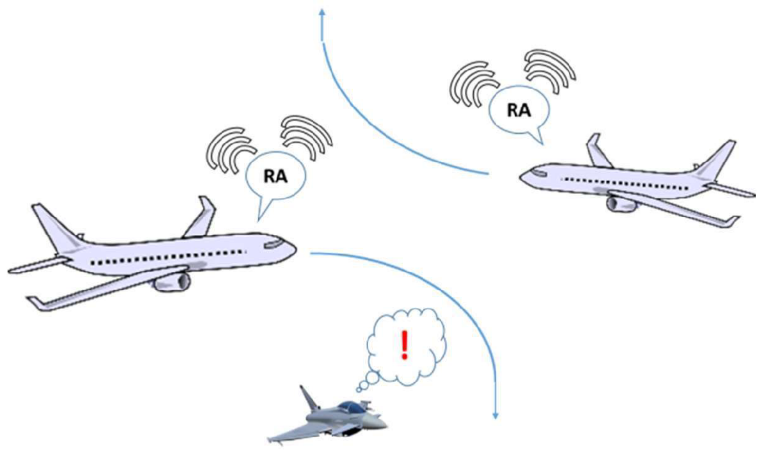


FIGURE 15: EN ROUTE EXEMPLAR SCENARIO

- TMA – most of the use cases are going to be in TMA environment where different types of traffic encounters. Such situations can occur at:
  - Mixed operations at one airport (airliners, rotorcraft, small aircraft).
  - Civil/Military mixed operation at one airport.
  - Large hub airport with smaller regional airports (controlled or uncontrolled) in vicinity where TCAS II-equipped aircraft are approaching hub airport and can encounter with non TCAS II aircraft approaching smaller, regional airport.

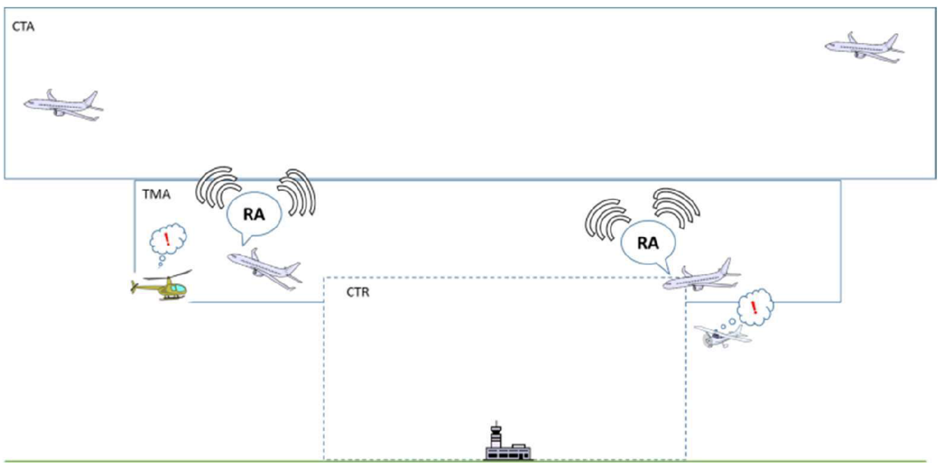


FIGURE 16: TMA EXEMPLAR OPERATIONAL SCENARIO

4.4.5. OPEN POINTS RELATED TO COCKPIT PROCEDURE

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. The initial assumption for the cockpit procedure for GA pilot was NOT to maneuver (in the meaning that GA pilot should maintain his course and speed).

Past studies performed by MIT [14] on the coordination of GA CA maneuver with TCAS RA, and which should be taken into consideration for future cockpit procedure discussions on TSAA+ or even future CA for GA, investigated the performance of varying levels of coordination:

- full coordination where the system directly coordinates with TCAS,
- responsive coordination where the system only responds to TCAS (e.g., no own maneuverer is generated on board of GA aircraft, but GA merely responds to TCAS with the goal of avoiding non-coordinated maneuvering), and
- no coordination at all.

The purpose of the analysis was to help identify the relative benefit on a system's ability to coordinate with TCAS, which can then be used to identify potential technological solutions. There were four different implementations of a responsive coordination tested, assuming that GA aircraft can receive Vertical Resolution Advisory Complement (VRC7) [90] subfield:

- Level-Off (LO) required pilot to maneuver to maintain a vertical speed between +250ft/min and +250ft/min (for both Don't climb and Don't descend).
- Do not descend (DND) / Do not climb (DNC) required pilot to maintain a vertical speed that complies with the VRC code. If the VRC code is Don't climb, then any vertical speed less than or equal to 0ft/min complies with the advisory.
- Descend (D) / Climb (C) required pilot to maintain a vertical speed of at least 500ft/min in the direction that complies with the VRC mode, assuming that aircraft is always able to achieve 500ft/min.
- Maintain vertical speed (MVS) required pilot to maintain the current vertical speed of the aircraft.

The results of the analysis concluded that Descend/Climb strategy which requires the most vertical maneuvering from the GA aircraft, provides the highest level of safety with the lowest probability of NMAC (0.000021 P (NMAC/encounter)).

One of the concerns that study highlighted was the fact that pilot response rate for GA pilots may be so low that equipping with responsive logic might be less safe than not equipping. Different pilot reactions on TSAA+ were assessed in 5.3

4.4.6. USE CASES

Use case N°1

1. Aircraft N°1 which is not equipped with TCAS II is flying under VFR condition in controlled airspace, class D. In accordance with the airspace classification, it

means that ATC service (separation) is not provided to aircraft N°1 flying under VFR condition (ANS provide to aircraft N°1 the traffic information and the traffic avoidance advice on request only). Aircraft N°1 is equipped with TSAA+ and may or may not be equipped with ADS-B OUT. Aircraft N°1 is equipped with transponder.

2. In vicinity of the aircraft N°1 (in the same class of airspace) another aircraft N°2 is flying under IFR condition. ATC provides to this aircraft N°2 ATC service (separation) from other IFR flights, not from VFR flights. Because aircraft N°1 is flying under VFR condition, ATC does not provide ATC service (separation) to aircraft N°2 in relation to aircraft N°1 (ATC provide to aircraft N°2 the traffic information about VFR flights and the traffic avoidance advice on request only). Aircraft N°2 is equipped with TCAS II and ADS-B/ OUT.
3. Aircraft N°1 receives ADS-B information from aircraft N°2. TSAA+ processes this information and if traffic equipped with TCAS II is issuing an RA, then the information about RA is passed to the flight crew and indicated via timely alert. Pilot of aircraft N°1 sees the position of aircraft N°2, tries to reduce risk by reaching visual acquisition and, without maneuvering (i.e., maintain course and speed), waits for the most appropriate solution from side of aircraft N°2 (RA solution from aircraft equipped with TCAS II).
4. Pilot of aircraft N°2 executes maneuver immediately in accordance with TCAS resolution.

Use case N°2

1. Aircraft N°1 and aircraft N°2 are equipped with TCAS II, both are ADS-B Out equipped, and both are flying under IFR conditions. Both aircraft N°1 and N°2 become a threat to each other and receive an RA again each other.
2. Aircraft N°3, flying in the vicinity, is not equipped with TCAS II is flying under VFR condition in controlled airspace, class D. Aircraft N°3 is equipped with TSAA+ and transponder.
3. Aircraft N°3 receives ADS-B information from both Aircraft N°1 and aircraft N°2. TSAA+ process this information, pass to the flight crew and indicate via timely alert. Pilot of aircraft N°3 sees the position of aircraft N°1 and N°2, tries to reduce risk by reaching visual acquisition and, without maneuvering (i.e., maintain course and speed), waits for the most appropriate solution from side of aircraft N°1 and N°2 (RA solution from aircraft equipped with TCAS II).
4. Pilots of aircraft N°1 and N°2 executes maneuver immediately in accordance with TCAS resolution.

Use case N°3

1. Aircraft N°1 is not equipped with TCAS II is flying under VFR condition in controlled airspace, class D. Aircraft N°1 is not equipped with TSAA+ either but is equipped with ADS-B Out.

2. Aircraft N°2 is not equipped with TCAS II is flying under VFR condition in controlled airspace, class D. Aircraft N°2 is equipped with TSAA+ and may or may not be equipped with ADS-B OUT. Aircraft N°2 is equipped with transponder.
3. Aircraft N°3, flying in vicinity, is equipped with TCAS II and ADS-B OUT.
4. Aircraft N°2 receive a Caution Alert against aircraft N°1. Consequently, pilot of aircraft N°2 decides to maneuver, but by doing so, he become a threat for aircraft N°3.
5. Aircraft N°3 issue an RA against aircraft N°2. An RA information is broadcasted and received by aircraft N°2.
6. TSAA+ process this information, pass to the flight crew and indicate via timely alert. Pilot of aircraft N°2 sees the position of aircraft N°3, tries to reduce risk by reaching visual acquisition of both aircraft N°1 and N°3 and, without maneuvering (i.e., maintain course and speed), waits for the most appropriate solution from side of aircraft N°3 (RA solution from aircraft equipped with TCAS II).

4.4.7. TECHNICAL AND OPERATIONAL ASSUMPTIONS FOR TSAA+

TABLE 5: GENERAL AND ENVIRONMENTAL ASSUMPTIONS FOR TSAA+

Type	#	Assumption
General	1	The TSAA+ equipment will be installed on and provide alerts to flight crews of airplanes not under ACAS mandate, rotorcraft, and non-ACAS equipped military aircraft.
	2	The TSAA+ application and TCAS II (or other ACAS systems) will not operate on the same aircraft simultaneously.
	3	Integration of the TSAA+ application with any other airborne traffic alerting capability will not compromise the intended function of the TSAA+ application or the other alerting capability.
	4	The TSAA+ application will not change roles or responsibilities for ATC.
	5	The TSAA+ application will require no change in existing ATC or flight crew phraseology.
Environmental	1	The TSAA+ application will be used in controlled, uncontrolled, and Special Use Airspace.
	2	The TSAA+ application will be installed on aircraft operating under IFR and VFR.
	3	The TSAA+ application will be used under both IMC and VMC.
	4	Not all aircraft within the environment in which the application is operating will be equipped with ADS-B OUT, transponders for TIS-B broadcast, the TSAA, or TSAA+ application.
	5	No ground infrastructure changes will be required to support the TSAA+ application.

TABLE 6: ASSUMPTIONS FOR TSAA+ EQUIPPED AIRCRAFT AND RA BROADCASTING AIRCRAFT

Type	#	Assumption
TSAA+ equipped aircraft	1	To be consistent with guidance on caution alerts, TSAA+ Traffic Caution Alerts will include voice annunciations and attention-getting visual cues.
	2	As in existing operations, before any maneuver, the flight crew will perform a visual scan to check if the area they want to maneuver towards is free of traffic, obstacles, and hazardous weather.
	3	The TSAA+ application will not change roles or responsibilities for flight crews.
	4	ATC radio communications will be independent from TSAA+ voice annunciations.
	5	If TSAA+ installation include display, the location of this Traffic Display is sufficient for TSAA+.
	6	The TSAA+ application will be hosted on ownship with no coordination with other aircraft or with air traffic control. No additional data is required to be transmitted as part of this application.
	7	The TSAA+ application in European airspace will be based only on a 1090 MHz Extended Squitter (1090ES) ADS-B receiver. *NOTE: Performance of the TSAA+ system would likely be maximized on aircraft with dual [top/bottom] antennae capable of receiving ADS-B messages.*
	8	The TSAA+ application will utilize the same Airborne Surveillance and Separation Assurance Processing (ASSAP) and Traffic Display if other ASA applications are installed in the same aircraft.
RA Broadcasting aircraft	1	TSAA+ targets will be any emitter category except surface vehicles or obstacles as described in DO-338 [4]

4.4.8. TSAA+ REQUIREMENTS

Since TSAA+ is an enhancement of TSAA, in many cases the same requirements that apply for TSAA also apply for TSAA+. In this case a reference to DO-348 [5] is provided, in which TSAA should be read as TSAA+. Changed or additional requirements are stated fully.

TABLE 7: TSAA+ OPERATIONAL REQUIREMENTS

#	TSAA+ Operational Requirement
1	The flight crew shall use the TSAA+ application only as a supplement to existing traffic avoidance procedures (e.g., see-and-avoid, radio communications).
2	After a TSAA+ Traffic Caution Alert, the flight crew shall attempt to visually acquire the Alerted Traffic out-the-window using the alert information as appropriate.
3	The flight crew shall not undertake any maneuvers relative to Alerted Traffic based solely on the TSAA+ Traffic Caution Alert or indication (i.e., NAT).
4	As in existing operations, upon out-the-window visual detection of a Target Aircraft, the flight crew shall take appropriate measures to ensure the safety of the operations.

TABLE 8: TSAA+ INFORMATION EXCHANGE REQUIREMENTS

Category	#	Requirement
Information exchange	1	The TSAA+ application shall use ADS-B surveillance reports on one or more ADS-B links as specified in the TSAA+ interoperability requirements.
	2	The TSAA+ application shall provide RA information if and only if received in ADS-B report from a Traffic Aircraft.
	Following requirements can be adopted for TSAA+ from DO-348 [4] without change for information exchange: SPR.6, SPR.7, SPR.9, SPR.10, SPR.11, SPR.12, SPR.13, SPR.14, SPR.15, SPR.16, SPR.17, SPR.18, SPR.19, SPR.20, SPR.21, SPR.22, SPR.23, SPR.25. For system reliability and integrity requirements: SPR.26 and SPR.27. Timing requirements: SPR.28 to SPR.33. Data quality requirements: SPR.34 to SPR.41.	

The Interoperability Requirements specify technical exchange of data between all relevant participants of the TSAA+ application. This exchange of data focuses primarily on the ADS-B surveillance data. Specific ADS-B link technology requirements are not addressed. Requirements are specified at the ADS-B system level. TIS-B and ADS-R data usage is out of scope of this research.

TABLE 9: TSAA+ INTEROPERABILITY REQUIREMENTS

Category	#	Requirement
Interoperability	1	The Receive Participant shall be capable of receiving surveillance messages containing at least the following parameters, which allow the avionics to interpret and format the required surveillance reports and associate the surveillance data with own surveillance data: ➢ Horizontal position. ➢ Vertical position. ➢ Horizontal velocity. ➢ Identity (e.g., Aircraft Identification and 24-bit aircraft address). ➢ Horizontal position quality indicators. ➢ Horizontal velocity quality indicator. ➢ Resolution Advisory. ➢ Resolution Advisory Termination.
	2	The Receive Participant shall be capable of determining the surveillance message type for ADS-B messages as specified in EUROCAE ED-102A/RTCA DO-260B [56].
	3	The Receive Participant shall be capable of determining the resolution advisory information from ADS-B message.
	4	The Receive Participant shall be capable of determining the termination of the resolution advisory from ADS-B message.
	The following requirements of EUROCAE DO-232 [4] also applies to TSAA+ system: IR.3 (version number), IR.5 (time of applicability), IR.6 (24-bit address), IR.7 (horizontal position reception), IR.8 (horizontal position interpretation), IR.9 (horizontal position quality), IR.10, IR.11, IR.12, IR.13, IR.14, IR.15, IR.16 (quality indicators), IR.17 (air/ground status), IR.18 (horizontal velocity), IR.19 (horizontal velocity interpretation), IRec.2 (vertical rate), IR.20 (latency).	

TSAA+ application has been for the first time defined in [7], and evaluated through Fast Time Simulation (FTS) [8] and human-in-the-loop validation [88] (see section 5.2 and 5.3).

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].

To achieve these benefits, several significant changes with respect to existing TCAS II were introduced, such as:

- new functional architecture,
- new type of logic which uses probabilistic information about intruder’s state, and
- new surveillance functions which allow enhanced use of ADS-B information when available.

The development of ACAS X started with version intended to replace TCAS II, named ACAS Xa. MOPS published as DO-385 [21] and ED-256 [22] in 2018 was jointly developed by RTCA and EUROCAE standardization working arrangements (RTCA SC-147 and EUROCAE WG-75), and addressed also ACAS Xo functionality, which is an optional extension to ACAS Xa, tailored for specific operations, such as closely spaced parallel approaches, where ACAS Xa might generate a large number of nuisance alerts.

ACAS Xo is integrated with ACAS Xa systems, but activation of the ACAS Xo functionality is optional. It provides additional collision avoidance logic modes designed to support closely spaced flight operations (CSPO) and allows specifically designated traffic to be monitored by an alternative ACAS logic more compatible with the flight operation than the standard ACAS Xa logic. ACAS Xa/Xo MOPS [21] specifies two modes for ACAS Xo:

- Closely Spaced Parallel Operations down to 3,000ft runway separation mode (CSPO-3000) which provides designated traffic with modified Collision Avoidance System (CAS) logic monitoring more appropriate for parallel operations; applicable in both visual and instrument conditions. ACAS Xa protection is maintained on all other cooperative traffic.
- Designated No Alerts mode (DNA) which suppress all alerts and guidance (except during multi-threat encounters) on the specifically designated traffic; requiring flight crew to visually acquire the desired traffic before designating it and then maintaining visual separation from the DNA-designated aircraft. This mode is

intended for use in closely spaced operations on visual conditions, where ACAS Xa alerts would otherwise be a nuisance, ignored, and/or disruptive. DNA mode may be used instead of placing ACAS Xa into TA-only mode, preventing alerts on the designated traffic but still allowing full ACAS Xa protection from all other cooperative traffic.

Part of ACAS X family are also DAA implementations:

- ACAS Xu designed for large UAS, standardized through RTCA DO-386 [23] in 2020,
- ACAS sXu, an extension to ACAS Xu intended for small UAS with wingspan up to 15 meters standardized through in [80], and
- ACAS Xr intended for rotorcraft and Advanced Air Mobility (both manned and unmanned), currently under development and standardization with MOPS planned for 2025.

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

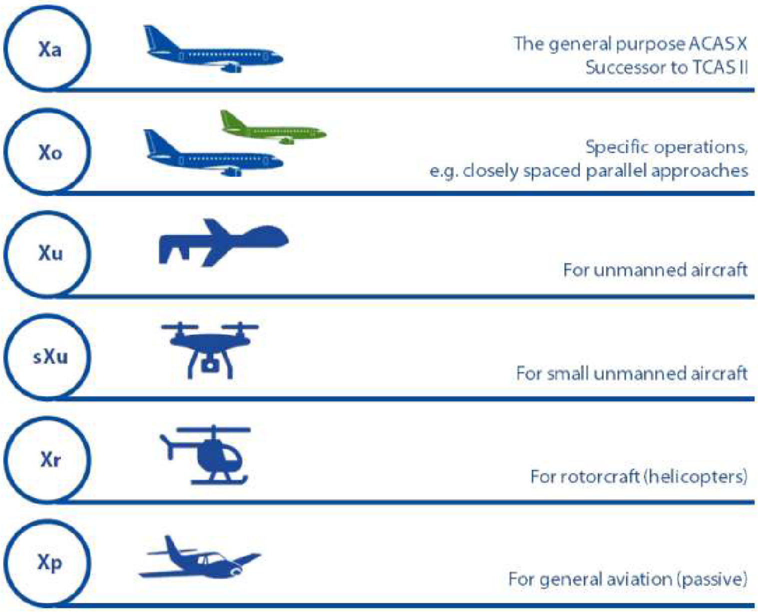


FIGURE 17: ACAS X VARIANTS [18]

4.5.1. ACAS X ALERTING CONCEPT

The approach to collision avoidance logic differs a lot from legacy TCAS II. It is based on the ability to predict future trajectories of aircraft given its current state (which includes position and velocity information) of the aircraft. To issue an advisory, a full spectrum of possible future trajectories and their likelihood is taken into account as ACAS X uses a probabilistic approach to the prediction (Figure 18).

At first, ACAS X detects and tracks aircraft by receiving sensor measurements from onboard surveillance systems and estimates the relative position and velocity of nearby aircraft using advanced tracking algorithms. To compensate for imperfect sensors, a surveillance and tracking module explicitly takes measurement and dynamic uncertainty into account by representing relative positions and velocities as a probabilistic state distribution. To assess potential collision risks, ACAS X uses computer-optimized logic lookup tables that capture each possible state in the probabilistic state distribution. Dynamic programming is used to solve Markov decision processes in the creation of these tables. The tables provide a cost for each potential action—no alert, a traffic advisory alerting pilots about nearby aircraft, or a resolution advisory directing pilots to increase or maintain their existing separation from threat aircraft. This cost is combined with the weighted states to provide a single, optimal action. If a collision avoidance alert is necessary, this information is sent to the flight deck displays and aural annunciators are triggered to provide pilots with the guidance corresponding to the optimal action. [1]

For more detailed explanation of ACAS X logic refer to [17], [18],[22] and [21].

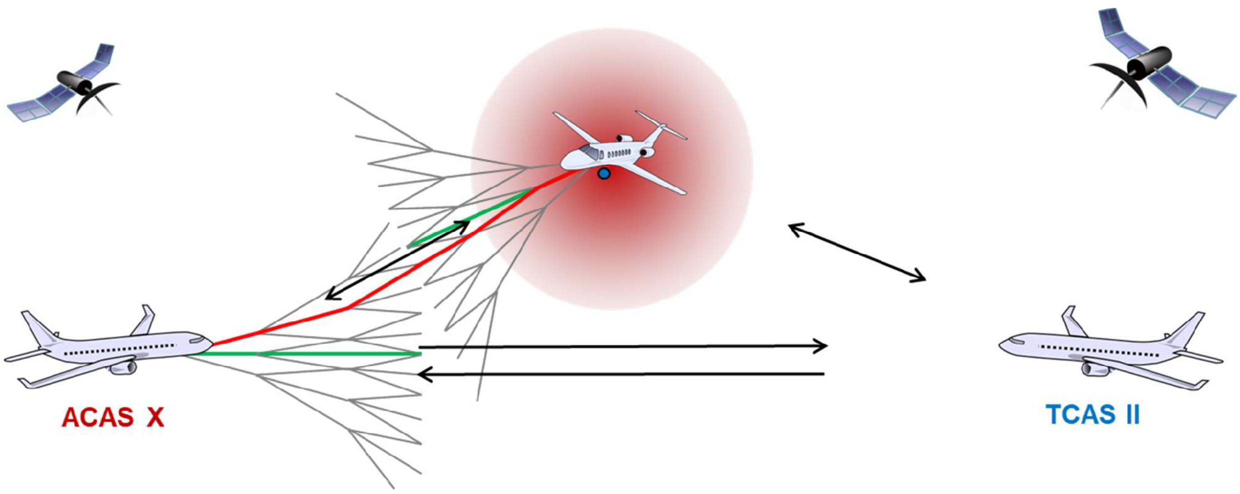


FIGURE 18: IMPROVED ROBUSTNESS OF ACAS X BY TAKING INTO ACCOUNT THE RELATIVE LIKELIHOOD OF ALL POSSIBLE FUTURE TRAJECTORIES

4.5.2. ACAS X DAA SOLUTIONS

DAA systems [81] [79] provides UAS remote pilot with the information about surrounding traffic, alerts, and maneuvering aids to avoid potential collisions.

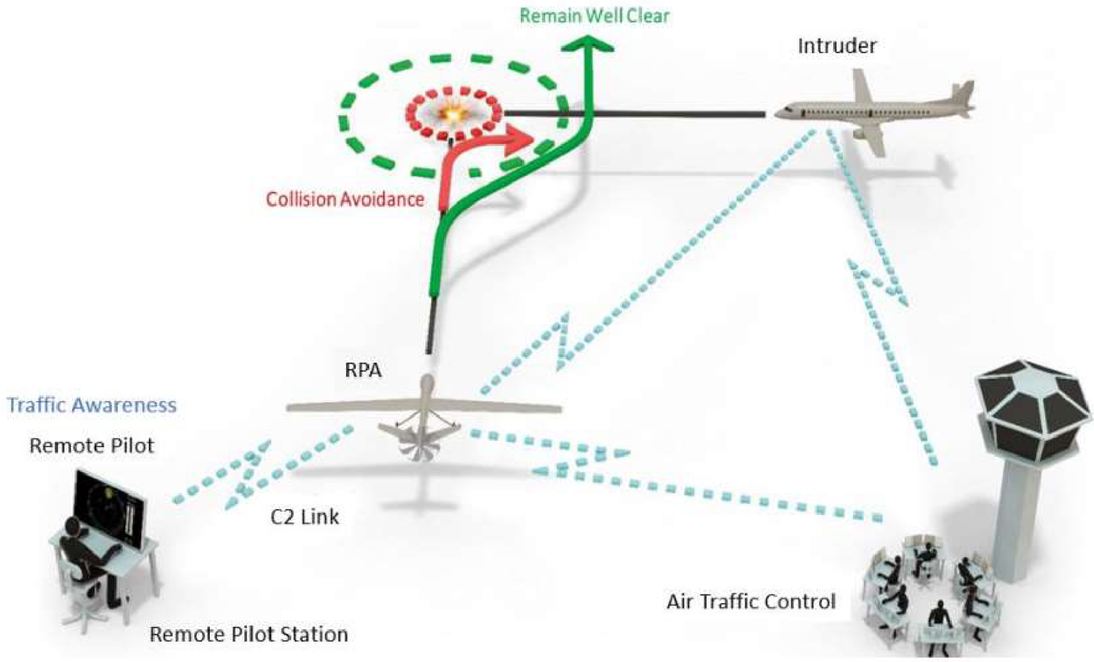


FIGURE 19: DAA CONCEPT [81]

ACAS Xu is an extension of the ACAS Xa/Xo system which is designed for vehicles with new surveillance technologies and different characteristics, such as UAS. It is a DAA solution that provides both DAA Well Clear (DWC) compliant with DAA MOPS [26] and CA) functionality compliant with MASPS for the Interoperability of Airborne Collision Avoidance Systems [27].

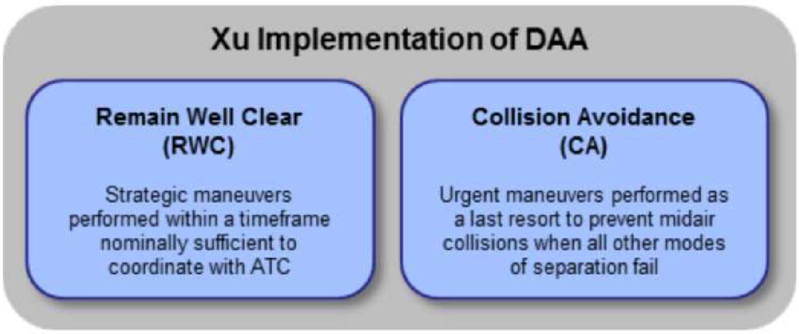


FIGURE 20: ACAS XU IMPLEMENTATION OF DAA [5]

In comparison to existing collision avoidance system for manned aviation (TCAS II or ACAS Xa), for ACAS Xu, Traffic Advisories (TAs) have been replaced by DWC alerting and guidance, and RAs are considered to be a combination of the DAA Warning Alert and Directive Guidance (continue to be referred as RAs to keep terminology consistent with ACAS Xa/Xo standards). RAs are indications given to the flight crew recommending maneuvers intended to avoid collisions with all threats or restrict maneuvers to maintain existing separation. In case of collision risk (intruder poses a threat), a recommended course of action is selected and provided to the pilot. That action can be in both vertical and horizontal plane. Vertical and horizontal maneuvers are guidance and are depicted independently of one another on the display and their timing may not coincide. However, if the timing does coincide, the pilot responds to both recommended maneuvers, resulting in a blended maneuver (a combination of both vertical and horizontal response).

ACAS sXu is a solution, is an extension to ACAS Xu addressing smaller UAS (sUAS) operating BVLOS. DAA capability of ACAS sXu is provided by accepting surveillance sources available to sUAS and adapting to performance requirements to their operations [96]. The system does not apply a strict altitude threshold (unlike other ACAS X variants) and is applicable for UAS that are not equipped with ADS-B Out and which does not assumes ATC services in their operations.

The last variant of ACAS X which is currently under development is ACAS Xr [83], which address the surveillance difficulties of manned and unmanned rotorcraft and VTOL platforms. It will be capable of providing scaled separation volumes to provide alerting and guidance against different types of intruders.

5. EXPERIMENTS

This chapter summarizes four experiments addressing situational awareness and CA solutions for GA undertaken between years 2015 and 2019.

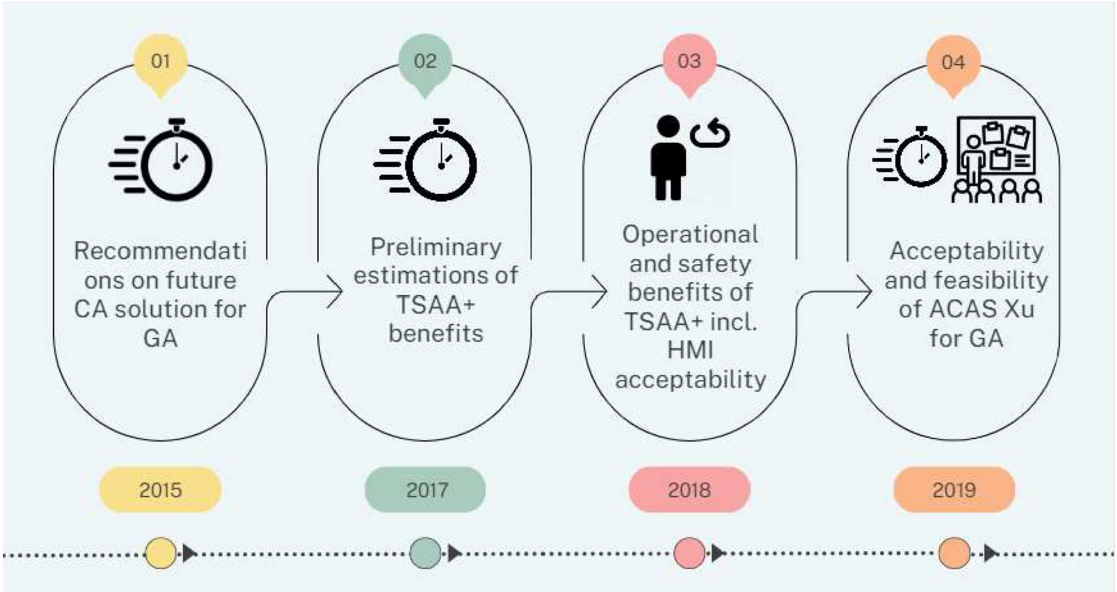


FIGURE 21: EXPERIMENTS TIMELINE

5.1. EXPERIMENT #1: COMPARISON STUDY OF TSAA AND ACAS X PERFORMANCE ON GENERAL AVIATION (2015)

The experiment has been performed within the scope of SESAR 9.47 project as part of work package addressing GA solution, and the results of the experiment has been published in [86].

This Fast Time Simulation (FTS) experiment compared two dedicated systems intended to reduce the number of MAC and NMAC involving GA aircraft: the TSAA and ACAS X modified to use passive surveillance only. The original intention of this experiment was to compare TSAA with ACAS Xp system, i.e., an ACAS X version intended for GA community. However, ACAS Xp was, at the time of experiment execution, still at the stage of concept development, so an alternative approach was applied, using up to date (while still not final) implementation of ACAS Xa system (Run13), modified to use passive surveillance only.

5.1.1. OBJECTIVES

The aim of this experiment was to compare the behavior (in terms of alerting performance) of the TSAA and ACAS X (modified to use only ADS-B surveillance) alerting logics in the scenarios defining expected operational behavior during typical GA operations, tailored for TSAA logic. The goal was to indicate points that should be considered for further ACAS

Xp system definition and development, in particular how big the differences resulting from the fact that ACAS Xa logic is tuned for commercial air transport (CAT) operations and different aircraft performance characteristics are.

5.1.2. Approach to experiment

TSAA was implemented based on sample algorithm provided in TSAA MOPS, DO-317B [4]. Core ACAS Xa algorithm was implemented according to most recent release of ACAS X Algorithm Design Description document [3], and was modified based on the assumptions listed in 5.1.3.

The comparison of ACAS X and TSAA was based on simulated flights using the same input data. The focus of this experiment was to compare alerting performance of the two systems. Scenarios used for this comparison study were selected from TSAA MOPS [4] Appendix U and are tailored for TSAA testing. These MOPS test tracks were derived from multiple sources (study of NTSB Mid-Air Collision reports, Aviation Safety Analysis and Sharing (ASIAS) reports) giving a focus on geometries and locations where the system would need to operate reliably.

Each MOPS test scenario contains a pair of trajectories: a trajectory of the ownship and the intruder. In addition to the real flown trajectories (denoted as “truth”), MOPS test vectors also contain variants of 1090ES and UAT based trajectories from three different surveillance sources: ADS-B, ADS-R and TIS-B with surveillance error. For this experiment, only 1090ES ADS-B data were used (see assumptions in 5.1.3).

The comparison overview is presented in Figure 22. Two systems on two types of inputs (truth data and data with surveillance error) yield four types of results, which enables four comparisons.

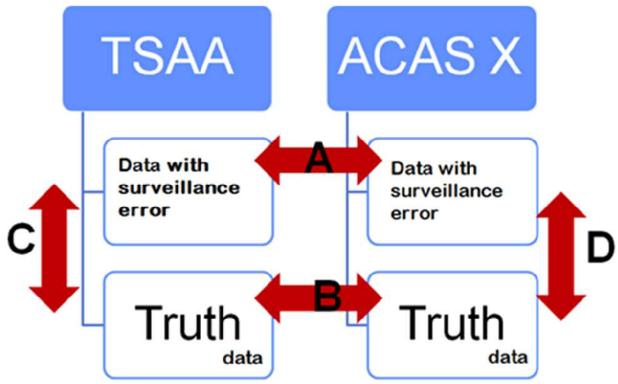


FIGURE 22: EXPERIMENT #1 COMPARISON OVERVIEW

Comparison of the two systems on trajectories based on data with surveillance error (labelled A) provided a useful insight into expected behavior in real flights. Comparison B, i.e., simulations of ACAS X and TSAA on truth data, was useful insight into the impact of noise. The influence of noise on each system (C and D) provided information on the robustness of each system to surveillance error.

The test tracks are split into two categories:

1. Must Alert scenarios test the alerting capabilities of the system for a range of aircraft encounters that have historically occurred in both airport and En Route environments in which an alert must be issued.
2. Must Not Alert scenarios have modified CPA, to separate aircraft such that alerting should not occur according to pilot and industry experts.

Each scenario is defined by the relative state parameters (Figure 23): Intersect Angle (IA), Relative Vertical Velocity (RVV), and Relative Horizontal Velocity (RHV), which define relative velocities between ownship and target aircraft, and aims to fully test the capabilities of the system implementation.

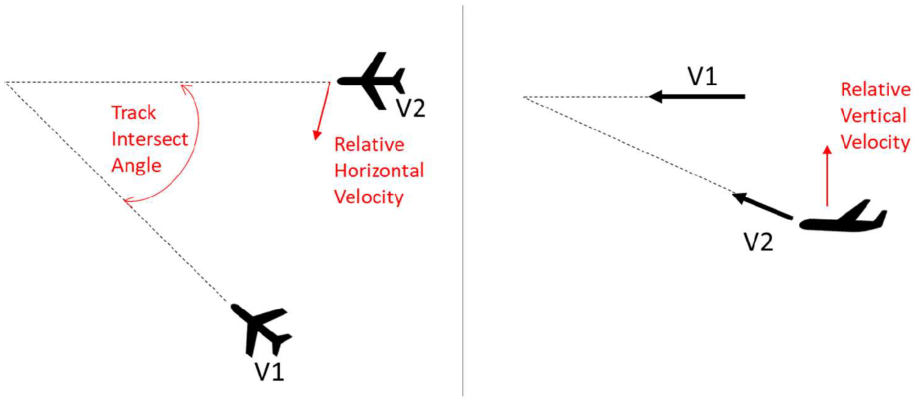


FIGURE 23: EXPERIMENT #1: SCENARIOS RELATIVE STATE PARAMETERS

A data source (1090ES ADS-B) was simulated by degrading the idealized truth trajectory with real world position and velocity errors, and noise based on the parameters listed in Table 10[10], all based on definition available in [4].

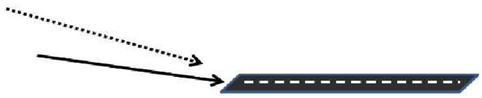
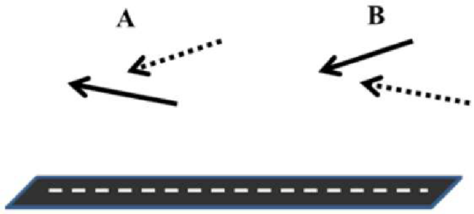
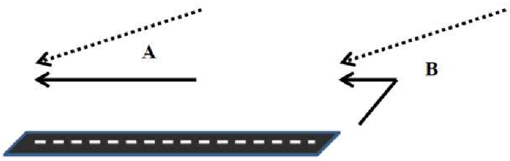
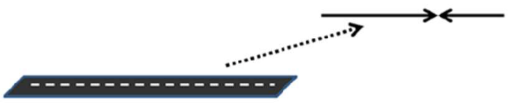
TABLE 10: EXPERIMENT #1: TSAA VS. ACAS X COMPARISON - DEGRADER PARAMETERS

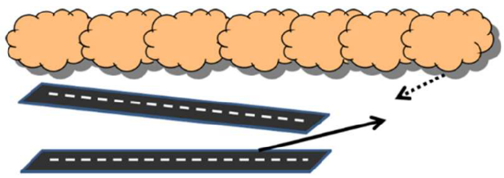
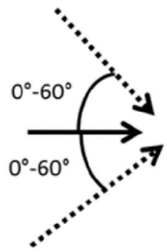
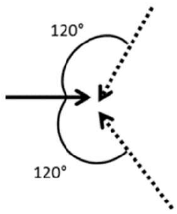
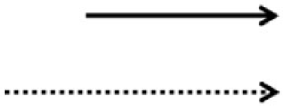
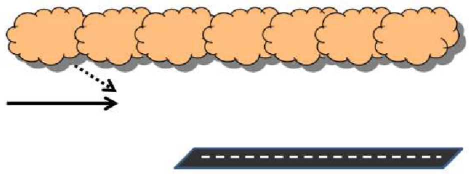
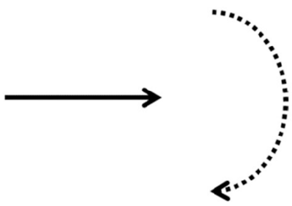
	Ownship	ADS-B
NACp	8	8[7]
NACv	1	1
Altitude Quantization [ft]	25	25 and 100
Update Rate [s]	1	1
Probability of Receipt [%]	N/A	95
Latency [s]	3.5	5
Latency Error [s]	0.78	0.78

[10] Note that according to SPR, for TSAA, the horizontal position for both traffic and ownship aircraft shall meet a 926m accuracy level or better at 95% probability what corresponds to NACp=5.

Following types of scenarios were selected for both Must and Must Not Alert situations:

TABLE 11: EXPERIMENT #1: OVERVIEW OF SCENARIOS CONSIDERED

Environment	Illustration	Description
Airport		Convergence on final to same runway when target aircraft is also attempting to land on the runway. Target is situated either above or behind the ownship (limited out-the-window view).
Airport		Convergence on same leg of airport pattern in different flight phases. Ownship is either departing/climbing through the pattern (A) or descending into the pattern (B) such that the target is either descending (A) or climbing (B) through the pattern on the same leg.
Airport		Convergence in airport pattern with target entering via standard procedure. Ownship altitude and speed are constant while either following the traffic pattern downwind leg (A) or turning from crosswind to downwind (B) with target entering the downwind leg from above and behind the ownship.
Airport		Convergences in airport pattern with target entering via non-standard procedure such as direct final (A) or opposite turn (B). Ownship continually turns; altitude and speed are constant while following the traffic pattern base to final leg or crosswind-to-downwind leg.
Airport		Convergences with departing target jet with VFR ownship cruises (both parallel to and perpendicularly towards the runway) above the traffic pattern altitude and encounter a target jet aircraft departing from a nearby airport. Ownship altitude and speed are constant. The target departs ascending at 3000 ft/min.

Environment	Illustration	Description
Airport		Convergence with approaching target jet to the same airport. The ownship climbs on the upwind leg while a target jet on IFR approaches a different runway.
En Route		Convergence with target aircraft at angles greater than zero and less than 60 degrees. Both the ownship and target can be cruising, descending, or ascending.
En Route		Convergence with target aircraft at an angle of 120 degrees. Both the ownship and target can be cruising, descending, or ascending.
En Route		Ownship and target pair in a head-on encounter (180°IA). Both the ownship and target can be cruising, descending, or ascending
En Route		Encounters when ownship is being chased or overtaken by a target. Both the ownship and target can be cruising, ascending, or descending as well as turning.
En Route		IFR convergence with jet. Ownship is under IFR conditions cruising at 4 000 ft through Class C airspace while arrival jet is descending at 3000 ft/min to the primary airport within the Class C airspace.
En Route		Convergence with aircraft performing maneuvers (such as circling or flight training). The ownship may be cruising, ascending, or descending.

Additionally, 15 Non-Accelerating encounters were run to test basic alerting for CPA that occurs at 0 ft horizontal and 0 ft vertical separation over a range of relative vertical and horizontal velocities that would be encountered in both Airport and En Route environments.

A total of 144 scenarios were run (consisting of 67 Must Alert tracks, 15 Non-Accelerating tracks, and 62 Must Not Alert tracks).

Since TSAA and ACAS X are based on completely different alerting logic, a common reference has to be defined in order to enable comparing performance of these two systems. The core element for quantitative assessment in this experiment was the time between alert and reaching the CPA. In the following sections, this time will be referenced as alert to CPA[11] time. Truth trajectories of ownship and intruder were used for reference CPA computation in all cases.

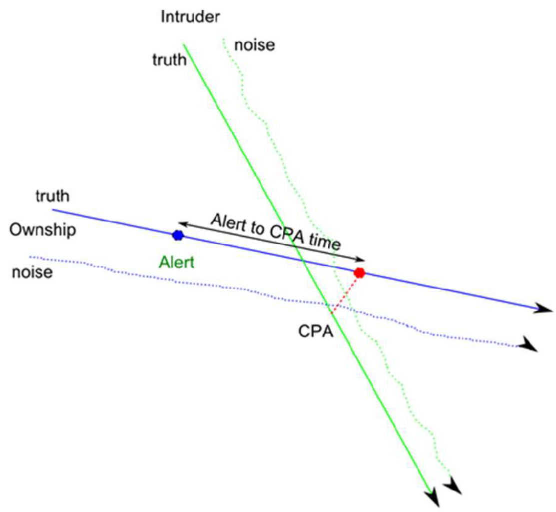


FIGURE 24: EXPERIMENT #1: ALERT TO CPA TIME

For TSAA, the first alert issued is considered (MOPS [4] allows a repeated alert, however, since this is an optional feature, repeated alerts are not considered for this study). For ACAS X, an RA rather than TA was relevant alert for this experiment since the purpose of TA is to provide only a situation awareness to the crew. It is an RA that requires an immediate action by the pilot. ACAS X RA has therefore operationally comparable role to the alert in TSAA.

The result analysis of this experiment was conducted from two perspectives.

1. First, qualitative assessment aimed to show whether TSAA and ACAS X issue alerts in the same situations. In situations where differences were observed, more

[11] The concept of CPA used by TCAS is in this study applied for a reference only. In ACAS X, no CPA is computed nor defined.

detailed analysis were done aiming to justify the behavior. For each system and each group of scenarios, the following metrics are evaluated:

- Outlying alerts - number of situations when the system alerts during Must Not Alert scenarios.
- Missed alerts - number of situations when system does not alert during Must Alert scenarios.

2. For the second, quantitative assessment focused on alert to CPA time and its differences between the two systems as well as its comparison between different time of inputs (e.g., data with surveillance error, truth), the following approach was applied:
   - For cases in which both systems performed alerted, the alert to CPA time differences were analyzed to see if one of the systems was likely to issue alerts earlier than the other one.
   - Alert to CPA times were also compared for input with surveillance error and truth input into the same system. The result of this assessment was the robustness of each system to noise.

In the final step, noise impact analysis was performed to evaluate the robustness of both systems to surveillance noise.

5.1.3. ASSUMPTIONS

For the purpose of the experiment, it was assumed that following characteristics describe ACAS X model used:

- The ACAS X model used for this experiment had the same functional architecture as ACAS Xa so as was expected for future ACAS Xp.
- The ACAS Xa logic used for this experiment was not tuned for GA aircraft operations. It is assumed that ACAS Xp will use different set of logic tables, tailored for GA aircraft performance characteristics, and GA operations (and probably using a reduced set of maneuvers).
- Since in Europe no TIS-B or ADS-R data are being used; only ADS-B data (both truth data and data with surveillance error) were used as an input.
- The ACAS X model used for this experiment was simulated in both airport and En Route environment.
- The comparison of alerting capabilities was performed primarily between TSAA alerts and ACAS X RAs since both of them encourage pilot to take an action in order to avoid a potential collision.

5.1.4. RESULTS ANALYSIS

Table 12 provides an overview of the qualitative assessment for both the truth trajectories and trajectories-based data with surveillance error. The values in columns “TSAA Alerts”, “ACAS X TA” and “ACAS X RA” state the number of scenarios (out of the total number of scenarios in each group) in which an alert (or an advisory) was issued by the given system. The values in parentheses represent results for input without surveillance error.

TABLE 12: EXPERIMENT #1: ALERTING RESULTS OF TSAA AND ACAS X ON TEST SCENARIOS WITH INPUT WITH SURVEILLANCE ERROR

Type	Number of scenarios	TSAA Alerts	ACAS X TA	ACAS X RA
Must Alert - Airport	44	44	44	27
Must Alert – En Route	23	23	23	23
Non-Accelerating	15	15	15	14
Must Not Alert - Airport	41	0	37 (39)	7 (5)
Must Not Alert – En Route	21	0	7 (6)	0

It can be seen that TSAA alerts were issued in all situations in which an alert is required (Must Alert – Airport, Must Alert – En Route, and Non-Accelerating) and it does not alert when alert is undesirable (Must Not Alert – Airport and Must Not Alert – En Route). Since MOPS test tracks were tailored for TSAA, this assessment only confirmed that TSAA behaves as is required according to TSAA MOPS.

Numbers in the table also indicate that there were several scenarios in airport environment[12] where ACAS X alerted differently than TSAA by issuing a TA, but RA was missing. To assess whether such behavior is correct (RA was inhibited due to low altitude at or below 1,000 ft) additional analysis was performed:

Must Alert (airport) situations where ACAS X issues TA only

Out of 44 scenarios where system should issue an alert, ACAS X issues 44 TAs but only 27 RAs. This behavior is correct, since all 17 scenarios where RA was not issued, occurred in the altitude at or below 1,000 ft. ACAS Xa (just as TCAS II) will inhibit all RAs below 1,000 ft AGL (± 100 ft). Refer to 4.5.1 for more details. One Non-Accelerating scenario with missing RA had the same reason (i.e., aircraft flying in 100 ft altitude).

Must Not Alert (airport) situations where ACAS X issues RAs

As shown in Table 12, there were many Must Not Alert scenarios where ACAS X issued alerts. The fact that most of them occurred in airport environment may indicate that the system was not tuned for low altitude airport environment with GA operations.

Two out of seven scenarios where RA was issued, while TSAA would not issue an alert at all, occurred during scenarios testing convergence on final to same runway:

[12] There were 17 cases in Must Alert – Airport category and 1 case in Non Accelerating category which was also at low altitude.

1. Scenario verifying no alert will be issued for target approaching at a 2°intersect angle (IA) with relative vertical velocity (RVV) of 190 ft/min and relative horizontal velocity (RHV) of 19 kts.
2. Scenario verifying no alert will be issued for target turning from base-to-final ahead of ownship, with RVV of 190 ft/min and varying RVV.

The rest of RAs (five scenarios) were issued during encounters including high performance business jet targets during convergence with departing (one scenario) and approaching target jet (four scenarios).

3. Scenario verifying no alert will be issued when departing jet target passes behind ownship with RVV of 3,000 ft/min, RHV of 500 kts and IA 180°.
4. Scenario verifying no alert will be issued when jet target approaching at RVV of 3,100 ft/min, RHV of 250kts, and IA 120° such that minimum horizontal separation is 0,5 NM.
5. Scenario verifying no alert will be issued when jet target approaching at RVV of 3,100 ft/min, RHV of 430 kts, and IA 120° such that minimum horizontal separation is 0,5 NM.
6. Scenario verifying no alert will be issued when jet target approaching at RVV of 6,000 ft/min, RHV of 430 kts, and IA 120° such that minimum horizontal separation is 0,5 NM.
7. Scenario verifying no alert will be issued when jet target approaching at RVV of 3,100 ft/min, RHV of 498 kts, and IA 170° such that minimum horizontal separation is 0,5 NM.

It should be noted that ACAS X, as described previously, is not based on hard-coded rules (such as TCAS II) so it is very difficult to discover why there was an alert in some situations. However, some observations and discussion could still be made.

Results for scenarios no.3 to no.7 (e.g., ACAS X system alerting during encounters with jet target when TSAA would not alert) might reflect the fact that ACAS X model is not yet tailored for GA aircraft performance characteristic. Looking at these scenarios more into detail, following observations were made:

- For two of these scenarios (no. 2 and no. 6), ACAS X did not issue alert when truth input was used. It can be derived that the conditions with noise input (with surveillance error) were „at the boundary“ of condition set for which ACAS X issues an alert (in other words, for a slightly different input, the alert is not issued).
- ACAS alert duration (see Table 13) was very short for scenario no. 3. This could be another case of „boundary“ conditions.

TABLE 13: EXPERIMENT #1: ACAS X ALERT DURATION IN TSAA VS. ACAS X COMPARISON

Scenario No.	ACAS X alert duration [s] Input with surveillance error (noise)	ACAS X alert duration [s] Truth input
1	17	0
2	51	41
3	7	8
4	22	21
5	24	23
6	15	0
7	28	20

➢ On the other hand, ACAS X alert duration in scenario no.2 (Figure 25 and Figure 26) was quite long and relatively stable with respect to noise/truth input change. Here, with the assumption that MOPS test tracks were tailored for TSAA, an open question could be raised whether this alert should be considered as nuisance or further analysis should be recommended to re-evaluate this track in terms of safety and concerning possible uncertainty in intruders' intent. Another interpretation of the result can be that in similar cases, a specially tuned ACAS X logic table for GA would be needed.

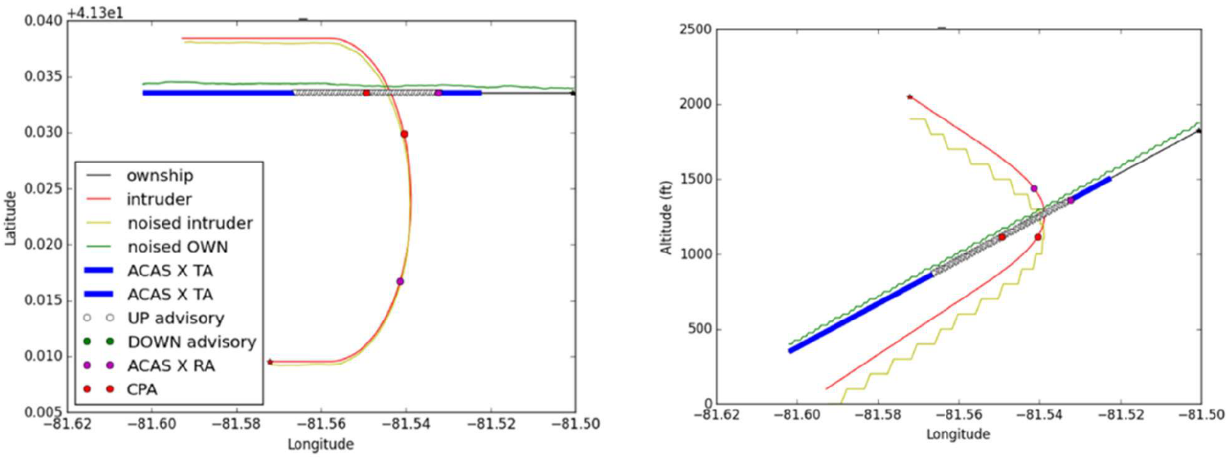


FIGURE 25: EXPERIMENT #1: TWO VIEWS AT SCENARIO NO.2.

At Figure 25, asterisks denote beginning of the trajectories. Magenta circles show positions of both aircraft at the time of ACAS X alert (i.e., RA).

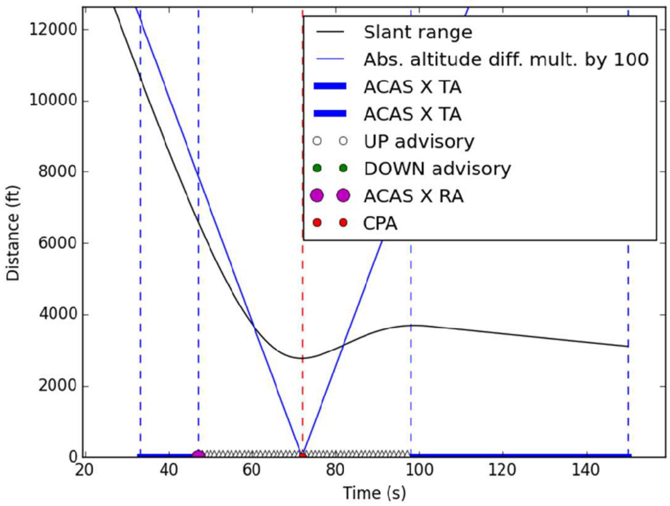


FIGURE 26: EXPERIMENT #1: SLANT RANGE AND ABSOLUTE ALTITUDE DIFFERENCE (MULTIPLIED BY 100 FOR BETTER PLOTTING) EVOLUTION IN PART OF SCENARIO NO.2.

For quantitative assessment, the alert to CPA time for trajectories with surveillance error are presented in histogram in Figure 27. It shows that alert to CPA times of ACAS X RA tend to be lower than those of TSAA, but the ACAS X RA is always preceded by a TA.

There was a significant peak close to the value of 80 s for ACAS X values. The reason is that in many scenarios ACAS X issues TA (and in some cases RA follows immediately) at the beginning of the simulation, which often starts 80 s before CPA. Had these trajectories begun at more distant positions, ACAS X would very probably have issued advisories even earlier.

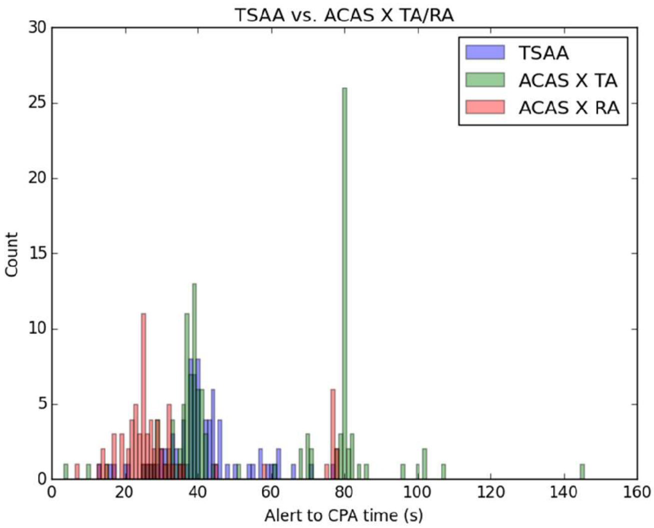


FIGURE 27: EXPERIMENT #1: HISTOGRAM OF ALERT TO CPA TIMES FOR TSAA AND ACAS X WITH INPUT BASED ON DATA WITH SURVEILLANCE ERROR

Therefore, the median – rather than the mean – was selected as the most appropriate characteristic. Also, minimum, and maximum[13] alert to CPA times were investigated.

Detailed results provided in Table 14 suggest that TSAA tends to issue alerts much earlier than ACAS X (i.e., RA), as observable from the median values (compare 40 s vs. 25 s).

Closer investigation of RA values that form a peak around 80 s in Figure 27 showed that there were 9 cases for which ACAS X alert to CPA time (RA) was higher than 70 s. The related TSAA alerts for these cases were distributed in an interval between 38 s and 77 s (Figure 28). The most extreme case was the scenario with convergence on final to the same runway, thus when a target aircraft was also attempting to land on the runway and ownship being behind the target was chasing it. Both aircraft descended on a nominal 3°glideslope with relative vertical velocity of 10 ft/min, relative horizontal velocity of 3 kts and intersect angle of 2°.

TABLE 14: EXPERIMENT #1: QUANTITATIVE ASSESSMENT RESULTS BASED ON ALERT TO CPA TIME.

Type	Median TSAA	Median ACAS TA	Median ACAS RA	Min TSAA	Min ACAS TA	Min ACAS RA	Max TSAA	Max ACAS TA	Max ACAS RA
Must Alert - Airport	39 (40)	80	25	13 (19)	28 (26)	13 (12)	77 (78)	107	78
Must Alert – En Route	40	40	27 (26)	21 (26)	25 (31)	14 (18)	66 (47)	80	77 (76)
Non Accelerating	40	39	28	36	38 (39)	23	44	80	36
Must Not Alert - Airport	–	75 (68)	22 (21)	–	4 (13)	7 (8)	–	145	25 (24)
Must Not Alert – En Route	–	33 (36)	–	–	29 (32)	–	–	37 (36)	–
All	**40**	**41 (40)**	**25**	**13 (19)**	**4 (13)**	**7 (8)**	**77 (78)**	**145**	**78**

[13] Please note that maximum was biased due to the issue described above.

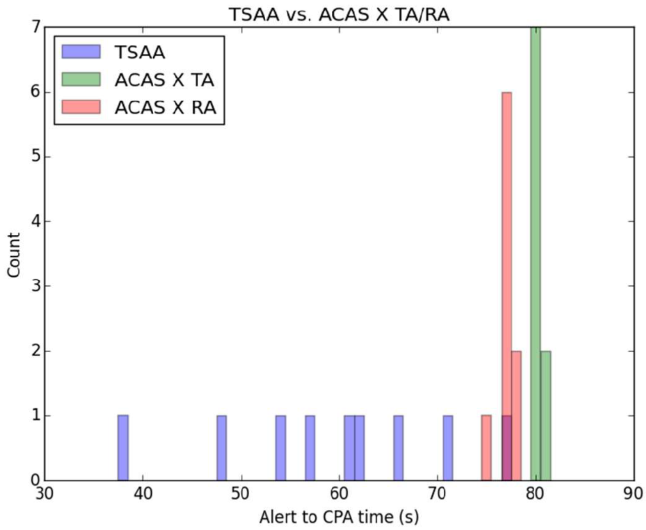


FIGURE 28: EXPERIMENT #1: ALERT TO CPA TIMES FOR NINE SELECTED CASES

The results presented so far were cumulative: one value (e.g., median) represented a large set of scenarios, from which only global picture can be derived. Individual quantitative assessment comparing alert to CPA time of TSAA and ACAS X on each scenario individually (Figure 29) confirmed the preliminary observations: although there were exceptions, in majority of the cases ACAS X issued alert later than TSAA.

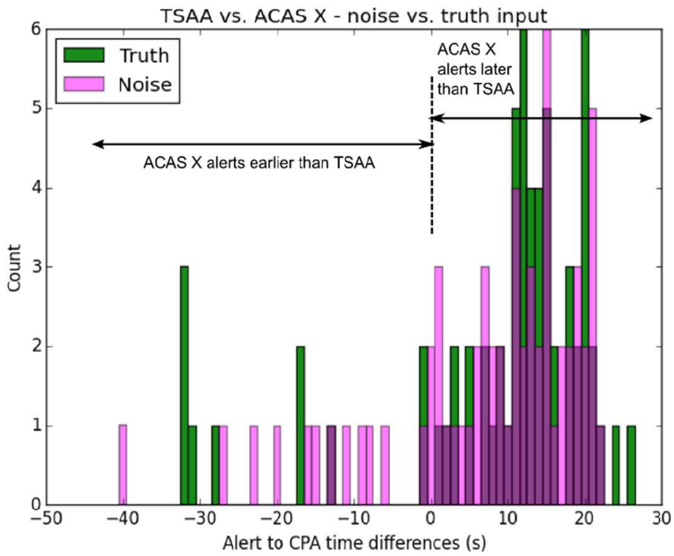


FIGURE 29: EXPERIMENT #1: HISTOGRAM OF ALERTING INTERVAL DIFFERENCES[14] BETWEEN TSAA AND ACAS X: BOTH TRUTH AND INPUT WITH SURVEILLANCE ERROR

[14] A difference is defined as alert to CPA time for TSAA X minus alert to CPA time for ACAS X. Therefore, positive result are obtained for cases in which TSAA alerts earlier, and vice versa

It should be emphasized that due to bias (shortening) of some ACAS X alerting intervals, some negative values could be even lower. However, 84 % of the results for input with surveillance error (and 78 % for truth input) were positive, which means that in these cases TSAA alerted earlier.

Although in most of the cases ACAS X TA precedes TSAA alert, there are cases in which TSAA is issued earlier than TA (and, of course, also RA – if any). Specifically, TA is issued later than TSAA in approx. 30 % cases (see Figure 12). Note that some of the extremely small values presented in Figure 27 do not appear in this comparison. These are the cases of ACAS X alerts in Must Not Alert scenarios which do not have their TSAA counterpart.

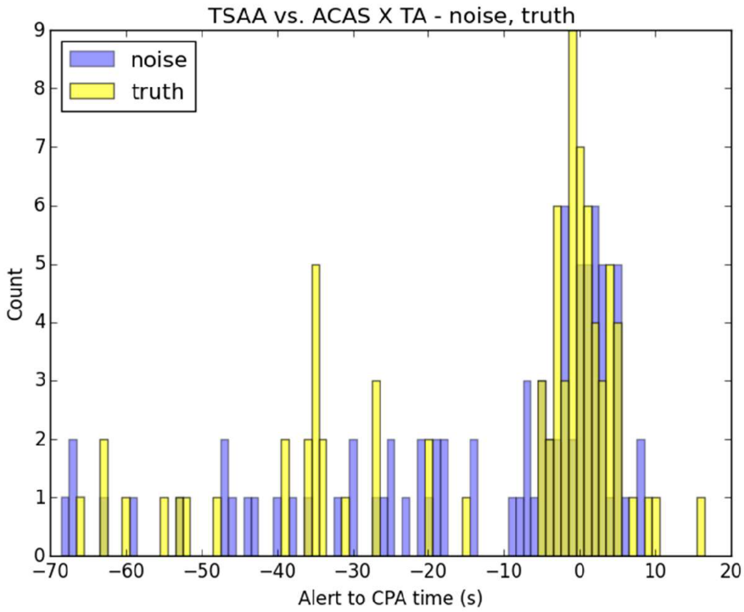


FIGURE 30: EXPERIMENT #1: ALERT TO CPA TIMES COMPARED FOR TSAA AND ACAS X TA (BOTH TRUTH AND DATA WITH SURVEILLANCE ERROR).

Mixed equipage encounters could have been simulated through one pair of test tracks in MOPS [4], in which ownship and intruder trajectories are interchanged (Figure 31). In both scenarios there was an ACAS alert issued (and it both situations the ACAS X RA alert was issued earlier than TSAA alert). This was used for simulation of two encounters in which one of the aircraft was equipped with TSAA and the other one with ACAS X, and vice versa. In this example, an input with surveillance error was used.

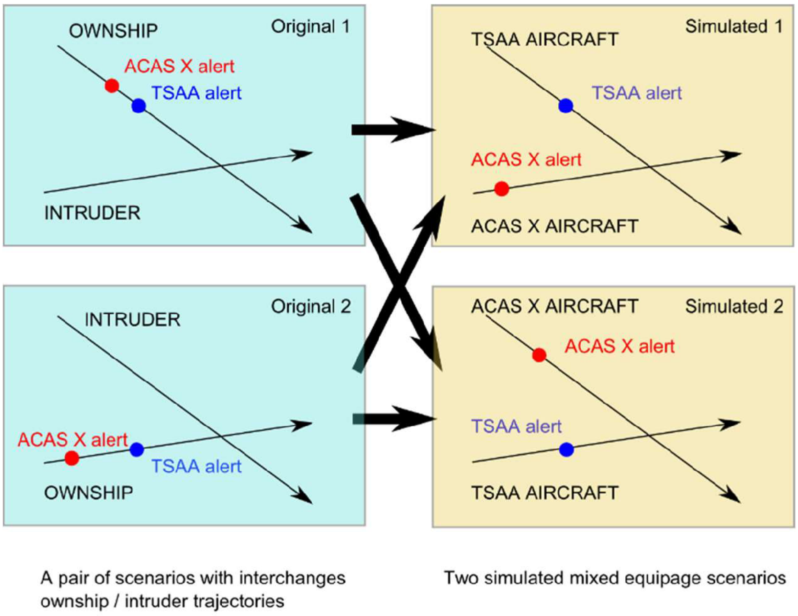


FIGURE 31: EXPERIMENT #1: MIXED EQUIPAGE ENCOUNTERS SIMULATED USING SYMMETRIC PAIRS OF SCENARIOS

Table 15 provides the results for original and simulated scenarios. The first two rows simply summarize the results for different systems for the two original scenarios. We can see that ACAS X issues TA/RA at equal alert to CPA times (80 s / 77 s) regardless of the trajectory at which the ownship approached the conflict. TSAA issues alerts later than ACAS X and the alert to CPA times were slightly different (62 s and 71 s). The last two rows of the table show values for the simulated mixed equipage scenarios. In the 1st simulated scenario, ACAS X and TSAA equipped aircraft approach to each other. A pilot with ACAS X obtains TA first. After, an RA follows, and 15 seconds later also the pilot with TSAA system gets an alert.

This simulation, however, included no maneuvering in response to alerts. In reality the pilot of the ACAS X equipped aircraft would take an action immediately (within 5 seconds) after receiving the RA. There is a chance that the pilot of TSAA equipped aircraft would receive no alert at all since the conflict would be resolved by the ACAS X aircraft.

In the second simulated scenario the situation was similar but the difference between alerts was only 9 seconds. In this case it is less likely that the TSAA alert would not be issued: the ACAS X pilot has less time to react.

TABLE 15: EXPERIMENT #1: MIXED EQUIPAGE SCENARIOS RESULTS

Scenario	Alert to CPA time [s]		
	TSAA	ACAS X TA	ACAS X RA
Original 1	62	80	77
Original 2	71	80	77
Simulated 1	62	80	77
Simulated 2	71	80	77

5.1.4.1. NOISE IMPACT ANALYSIS

This section provides the noise impact on each system individually. The impact of noise is observable when comparing the two systems, ACAS X and TSAA, to each other.

Histograms of alerting differences between results with and without surveillance error as an input are shown in Figure 32. Although median of the differences is 0 s for both systems, results indicated ACAS X is more robust to noise. There is zero difference between the results for 36 % of the cases for ACAS X, but only 18 % for TSAA. And even though the maximum difference values were detected for ACAS X, 83 % of ACAS X differences were less than 5 s (comparing to 62 % for TSAA).

Better noise robustness of ACAS X is caused by ACAS X accounting for uncertainty of intruder intent while TSAA calculates CPA deterministically.

For a complete picture, alerting differences for ACAS X TA are shown at Figure 33. As in the previous cases, median is 0 s. More than half (52 %) of all the cases, had zero difference between the data with surveillance error and truth input. Difference of less than 5 s was observed in 94 % of the cases. Outliers, although only a few, were of high values (maximum absolute difference is 43 s). These extreme values may be biased due to simulation limitations, as discussed previously.

These histograms show only scenarios in which ACAS X provides alerts for both inputs - with and without surveillance error. However, there are cases in which only one type of input generates an alert, while the other one does not, and vice versa (Table 12). These five scenarios were all from the Must Not Alert category. The duration of these alerts (TA or RA) was between 15 s and 23 s.

On Figure 32 (right), an isolated case with large difference in alert to CPA times for truth and input with surveillance error can be seen. In this case the altitude difference at CPA was 250 ft (truth), but data with surveillance error indicated only 125 ft. Although the lateral (and as a result also three-dimensional) distance between ownship and intruder was larger for input with surveillance error (approx. 1700 ft for noise vs. 560 ft for truth), ACAS X issued alert 35 s earlier for the input with surveillance error than for the truth input. Specifically, for input with surveillance error, alert to CPA time was 58 s, while for truth input it was 23 s.

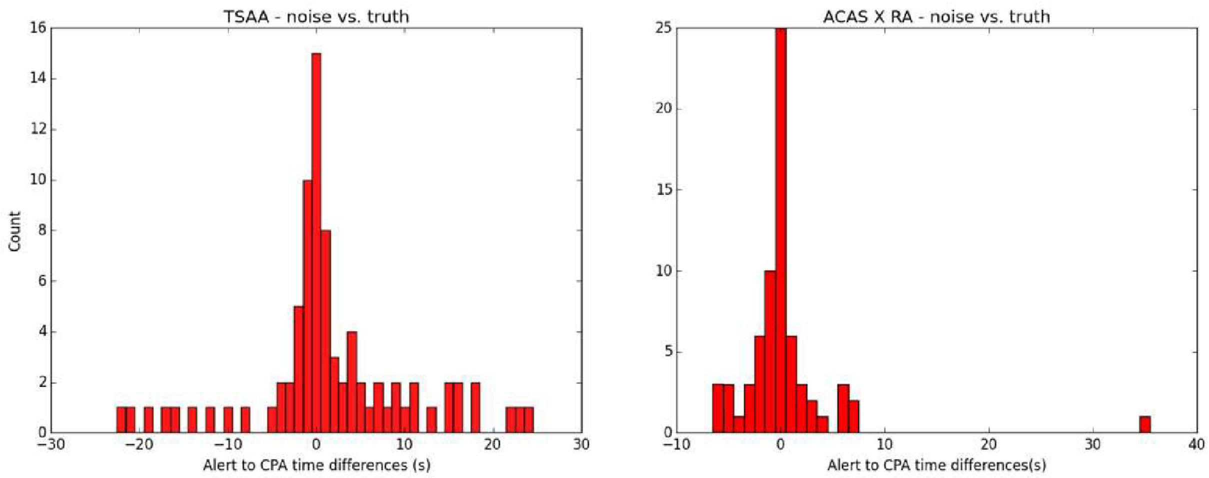


FIGURE 32: EXPERIMENT #1: TSSA (LEFT) AND ACAS X (RIGHT) - ALERT TO CPA TIME DIFFERENCES FOR INPUT WITH (NOISE) AND WITHOUT (TRUTH) SURVEILLANCE ERROR

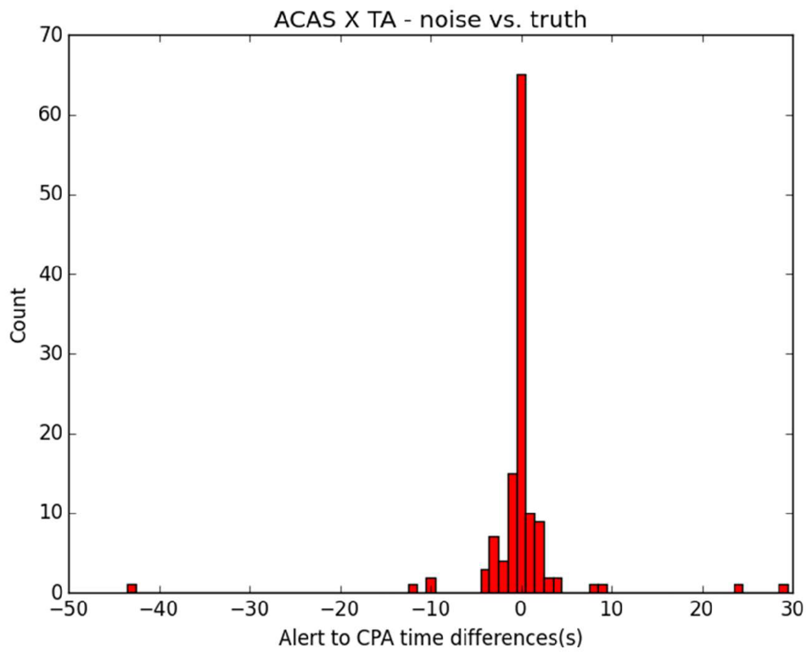


FIGURE 33: EXPERIMENT #1: ALERT TO CPA TIME DIFFERENCES FOR INPUT WITH (NOISE) AND WITHOUT (TRUTH) SURVEILLANCE ERROR

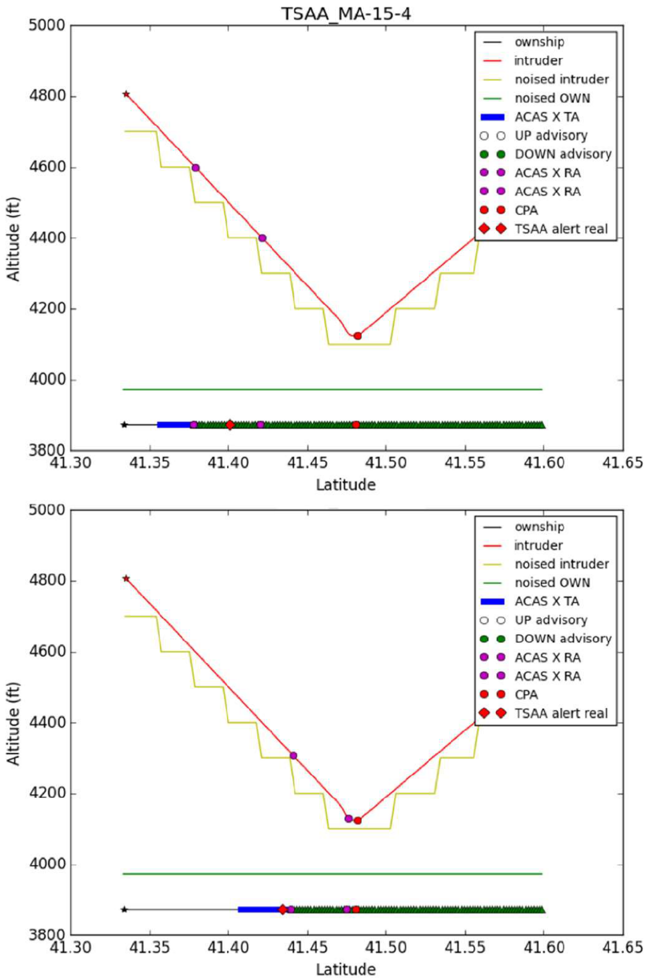


FIGURE 34: EXPERIMENT #1: A SCENARIO WITH THE LARGEST DIFFERENCE IN ALERT TO CPA TIME FOR INPUT WITH SURVEILLANCE ERROR (TOP) AND TRUTH INPUT (BOTTOM)

5.1.5. EXPERIMENT CONCLUSIONS

This experiment compared the performance of GA-intended system TSAA and its alerting capabilities with modified model of ACAS Xa system, which was developed for CAT aircraft operational needs but the modification of using only passive surveillance it had the same functional architecture as is expected for future ACAS Xp (targeting GA operations). Selected TSAA-tailored MOPS [4] test vectors were run through both TSAA and ACAS X models, and the results of the simulations can be concluded as follows:

- Used ACAS X model does not meet operational criteria for TSAA by alerting in situations where alerts are not expected.
  - Most of these situations occurred in airport environment, indicating that ACAS X was not tuned for low altitude airport environment with GA operations.

    - Must Not alert RAs generated against jet targets corresponds to fact that ACAS X model was not yet tailored for GA aircraft performance characteristics.
    - On the other hand, generating a TA only during Must Alert scenarios proved to in accordance with altitude inhibit rules implemented in ACAS X, avoiding RA at altitudes below 1,000ft.
- ACAS X issues RAs later than TSAA in 84% (with surveillance error) and 78% (without error) of the cases. TAs are issued earlier than TSAA alert in 30% of the cases.
- Noise impact analysis showed that ACAS X tempts to be more robust to surveillance noise than TSAA. This is very likely caused by different approach to ACAS X logic in general, which accounts for uncertainty in target intent, while TSAA calculates CPA deterministically.
- This assessment also confirmed that TSAA behaves as is required according to MOPS, but since the entire test tracks were tailored for TSAA, it cannot be considered as a kind of TSAA validation. In any case, for scenarios where ACAS X issued an alert, but TSAA would not, an open question was raised whether it should be considered as nuisance alert or should the TSAA test track be re-evaluated in terms of safety.

The results of this simulation and associated report were provided to RTCA SC-147 committee responsible for ACAS X development. Results were also used as prerequisite for planned SESAR2020 activities, in particular for project PJ11-A4 (Airborne Collision Avoidance for General Aviation), within which the operational and system requirements addressing GA were refined, and under which the next three experiments have been performed.

5.1.6. EXPERIMENT RECOMMENDATIONS

The results clearly pointed out to the importance of GA specific operational acceptability to be considered for further ACAS X definition and development. This should be addressed primarily by tailoring the system for GA specific operations, as well as GA aircraft performance characteristics.

At this point, a recommendation for further ACAS X development was made as part of SESAR 9.47 project:

- A need to define operational acceptability criteria for GA was identified.
- A criterion of operational acceptability should be tailored for GA and the results should be shared with RTCA SC-186 to further investigate interoperability of TSAA and ACAS X.
- Impact of performance characteristics on alerting logic should be further investigated.

5.2. EXPERIMENT #2: EVALUATION OF TSAA ON REAL EUROPEAN MIXED-EQUIPAGE ENCOUNTERS INVOLVING GA/R (2017)

The experiment has been performed within the scope of SESAR2020 project PJ.11-A4. Two project publications are linked with this experiment: the validation plan [87] and validation report [8]. Three independent FTS have been performed in this phase of the project by different project partners (Honeywell, Thales and Leonardo). Each partner used different simulation platforms and addressed different objective. This section provides only details of experiment performed by Honeywell.

The focus of this FTS experiment was the evaluation and analysis of incremental benefits of TSAA+ compared to TSAA.

Results of this experiment were used as a basis to SESAR definition and consolidation of initial European operational and technical recommendations for ACAS Xp development.

5.2.1. Objectives

The aim of this experiment was to identify and analyze the scenarios where the alerting of different type of systems may potentially increase risk of conflicting maneuvering; and to evaluate in how big portion of scenarios the availability of RA Broadcast (introduced by TSAA+ concept) could potentially help.

5.2.2. Approach to experiment

The overview of validation approach is depicted at Figure 35. Real-environment mixed-equipage European radar data tracks involving GA/R provided by EUROCONTROL (8090), collected from three Air Navigation Service Providers (ANSP), were initially filtered to eliminate equipped-equipped encounters caused by incorrect initial correlation of the tracks. Such filter eliminated 55.2% of the encounters, leaving a sample of 3622 encounters. In addition to initial raw data filtering, following data modifications were needed before simulations:

1. Removal of inconsistent information: some files did not display an alternating pattern of the rows (probably missing data). Standalone rows have been thus removed to restore the alternating rows format.
2. Interpolation: since the flight information was given every 4 seconds, an interpolation has been applied to estimate the flight data every 1 second.
3. Extracting additional information: other quantities such as latitude, longitude, ground speed, vertical rate, East-West and North-South speed have been calculated.
4. Generating of the input files: the data for each aircraft has been reshaped to fit the input file format for TCAS and TSAA simulation.

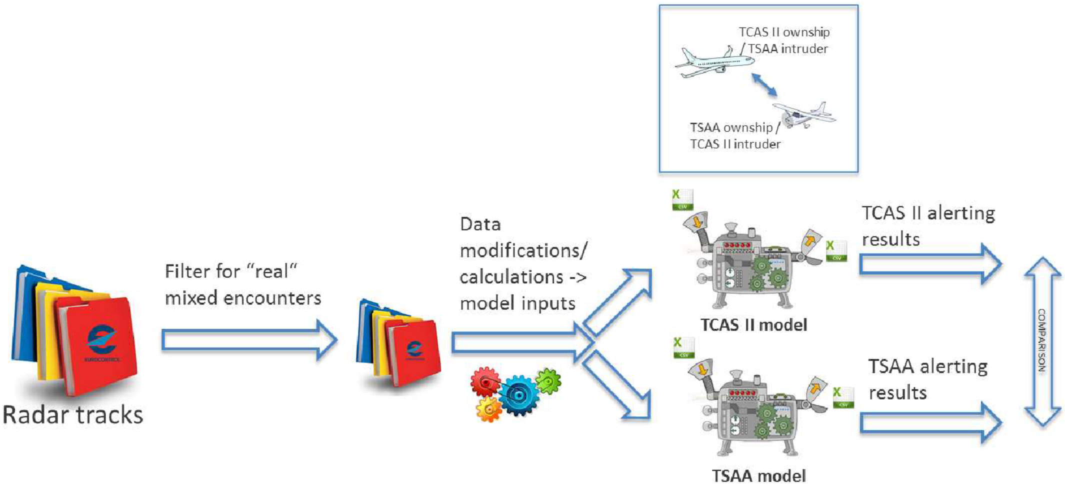


FIGURE 35: EXPERIMENT #2 APPROACH

Then, two platforms were used to perform the simulations:

- First, CASCARA (Collision Avoidance Simulation Components And Runtime Analysis) simulation platform was used to simulate TCAS II-equipped intruder (TCAS II, version 7.1). CASCARA is extensible modular simulation platform developed by Honeywell to support simulation of various ACAS builds (e.g., TCAS II or different versions of ACAS X). It supports range of I/O data types and execution modes for development, testing and analysis.
- Second, development TSAA simulation platform was used to simulate non-TCAS-equipped ownship.

Once the encounters were processed by both models, the alerting performance of TCAS II and TSAA was compared, introducing results that could have been divided into several different groups.

5.2.3. ASSUMPTIONS

For the purpose of the experiment, following assumptions have been applied:

- The preliminary encounter set provided by EUROCONTROL consists of encounters including GA and R encountering TCAS II equipped intruders. No military aircraft were assumed to be part of the encounter set.
- Simulations will only include one intruder, not multiple of them.

5.2.4. RESULTS ANALYSIS

The results have been firstly analyzed to identify the number of encounters which raised TA and/or RA by TCAS II. The encounters have been categorized based on the type and number of alerts raised, and results were provided for each ANSP separately:

TABLE 16: EXPERIMENT #2: ENCOUNTERS CATEGORIZATION BASED ON TCAS ALERTS

Encounter category/ANSP	ANSP1	ANSP3	ANSP6
Only TA (no RA)	222	678	1455
Only RA (no TA)	0	0	0
TA or TA& RA	328	858	1932
TA and RA with anomalies	106	180	477
TA and RA without anomalies	104	170	453

Several TCAS outputs have shown some anomaly behavior due to the time when TA and/or RA have been raised with respect to the CPA. Specifically, an anomaly was identified in case RA and/or TA (and/or SA) are raised after the CPA. Possible combinations of anomalies are depicted at Figure 36 and numbers of different anomalies per ANSP are listed in Table 17.

FIGURE 36: EXPERIMENT #2: ANOMALY BEHAVIORS

TABLE 17: EXPERIMENT #2: NUMBERS OF ANOMALIES

Anomaly type/ANSP	ANSP1	ANSP3	ANSP6
RA > TA > CPA	-	1	-
CPA > TA or CPA > RA	1	2	12
CPA > TA or CPA > RA and RA > TA	1	4	3
RA = CPA	-	3	9
SA = CPA	-	-	1

Additional analysis showed that possible reasons which can be associated to these anomalies are the following:

- The global CPA was selected instead of the local one at which the alerts are raised.
- Missing/jumping[15] data may cause the wrong calculation of the CPA, thus positioning TA and/or RA after or at the same time of the CPA.
- Differences in CPA calculation between the implemented approach (time at which slant range is minimum) and TCAS/TSAA estimation.
- Insufficient flight data before CPA may just be enough to raise RA but not TA.

Near collision situations which may raise RA before CPA followed by TA, would require more detailed analysis which were out of the scope of this experiment. A possible

[15] Missing data: information about aircraft is not given every 4 seconds as from file format. Jumping data: information about aircraft is given every 4 seconds, but positional coordinates are not consistent thus causing extreme displacements.

explanation could be related to the presence of helicopter data which could cause unexpected behavior during TCAS and TSAA simulations.

Even though the anomalies are rather realistic, and most probably caused by simulation limitations, they did not fall into any of the four categories (Figure 37), which were further analyzed in order to evaluate the added value of the TSAA "+" feature, and therefore were excluded from next steps of analysis.

In the next step, TSAA simulations were performed to investigate how many situational awareness (denoted as SA for the purpose of this experiment) alerts have been raised throughout the encounters.

TABLE 18: EXPERIMENT #2: NUMBER OF ENCOUNTERS WITH TSAA ALERT

	ANSP1	ANSP3	ANSP6
No. TSAA alerted	92	113	398

TCAS and TSAA results were then compared in order to determine which flights have raised TA, RA and SA alerts during the encounter aiming to obtain encounters in which both systems alerted. The goal of this step was to obtain a statistical distribution of the alert times before the CPA. Based on the time when alerts were issued, 4 categories were used to interpret the data:

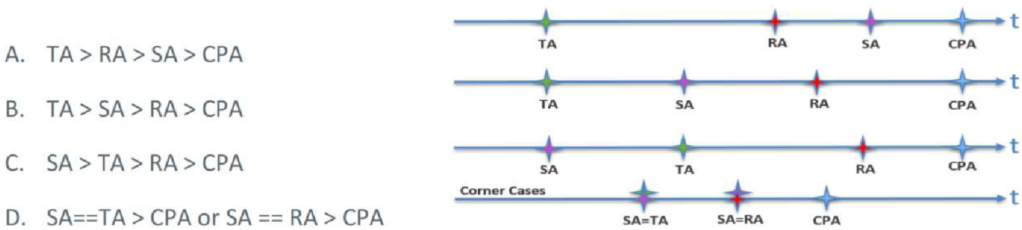


FIGURE 37: EXPERIMENT #2: TSAA ALERTING CATEGORIZATION

Following table summarizes alerting results for different data sets:

	Ansp1				Ansp3				Ansp6			
N° of encounters by Eurocontrol	992				3473				3625			
N° of mixed encounters	354				1023				2245			
TSAA [SA] | TCAS [TA-RA] Analysis		TSAA		TCAS		TSAA		TCAS		TSAA		TCAS
	Paz: True / Caz: False	70	only TA alerts	222	Paz: True / Caz: False	86	only TA alerts	678	Paz: True / Caz: False	318	only TA alerts	1455
	Paz: False / Caz: True	0	only RA alerts	0	Paz: False / Caz: True:	0	only RA alerts	0	Paz: False / Caz: True:	0	only RA alerts	0
	Paz: True / Caz: True	22	TA and RA alerts	106	Paz: True / Caz	27	TA and RA alerts	180	Paz: True / Caz	80	TA and RA alerts	477
	SA alerts	92	TA and RA and no anomalies	104	SA alerts	113	TA and RA and no anomalies	170	SA alerts	398	TA and RA and no anomalies	453
N° of encounters rising SA (TSAA), TA and RA (TCAS) without anomalies	67				76				244			

FIGURE 38: EXPERIMENT #2: OVERVIEW OF ENCOUNTER ALERTS

Out of all mixed encounters, 73,2% of encounters did not issue any alert. In 10,2% of the cases only TCAS alerted, and in 5,8% of cases only TSAA alerted. Both systems alerted in 10,8% of encounters, i.e., 387 mixed encounters were post processed and divided into A, B, C or D groups for further analysis with the distribution as depicted on Figure 39. In most of the cases (47%) where both systems alerted, it was the TSAA which alerted first, followed by TCAS TA and RA Figure 39. In 32% of the cases, first a TCAS TA was issued, followed by TSAA alert and then TCAS RA. Only in 14% of analyzed scenarios, first the TCAS TA and RA was issued, and then TSAA system alerted. Corner cases where TA or RA was issues at the same time as TSAA alert represented 7% of the analyzed scenarios.

Analysis for objective: To identify and analyze scenarios where the alerting of different type of systems may potentially increase risk of conflicting maneuvering.

The goal of TSAA+ is to:

- increase pilot situational awareness of threats and so to assist the pilot in when and where to look out the cockpit to acquire the approaching aircraft,
- increase the performance of the detection and support the decision making as regards a making a successful sense and avoid maneuver, and
- reduce the failure of TCAS RA with GA involvement due to GA pilot misunderstanding of the TCAS equipped aircraft intentions.

Based on that, it is clear that TSAA with "+" feature showing RA information from another aircraft, can introduce significant benefits in situations where:

- only TCAS alerted (so GA pilot is aware of RA issued nearby even before TSAA alert occur), but also
- all the other situations when both TCAS and TSAA alerted regardless of the alert sequence, or corner case situation.

In the TA-SA-RA (group B) or SA-TA-RA (group C) cases, GA pilot was having an alert on TCAS-equipped aircraft earlier than TCAS RA was issued, what would give GA pilot a chance to solve potential conflict early enough to even avoid TCAS to issue an RA. The same was true also for scenarios where only TSAA alerted. Such situations can be considered as TSAA-only benefit, regardless of "+" functionality being implemented or not, and they represent 52.6% of all alerting scenarios (where at least one system alerted). This approach should be considered as a first approximation as probably some scenarios of this type would still evolve in RA and there may be some benefits related to "+" capability.

Objective: To evaluate in which portion of scenarios the availability of RA broadcast could potentially help.

The above-identified scenarios where availability of RA broadcast can potentially help represents 21% from whole data sample, what represents 78.4% from all scenarios where at least one system alerted.

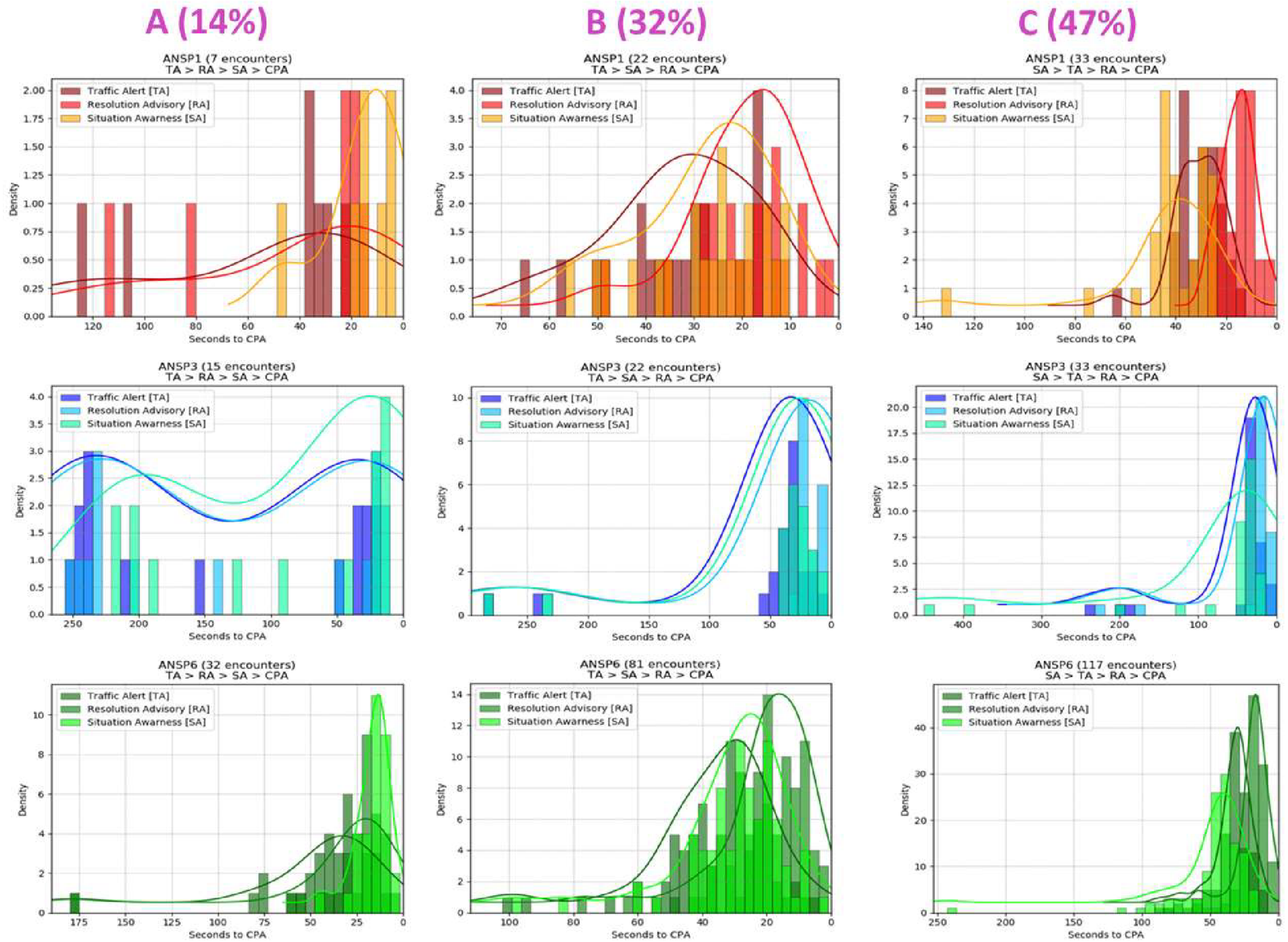


Figure 39: Experiment #2: TCAS II vs. TSAA alerting results

5.2.5. EXPERIMENT CONCLUSIONS

A sample of 3622 mixed-equipage encounters from real European environment was used as an input to simulation involving TSAA (for unequipped trajectories) and TCAS II (for equipped trajectories) models. Such simulations showed that out of the cases where both systems alerted, in 47% it was TSAA which alerted first, in 32% TCAS TA was issued first, followed by TSAA alert, and in 14% TCAS TA was followed by TCAS RA and TSAA alert came at last.

It is assumed that TSAA with "+" feature, i.e., providing pilot with RA information from another aircraft, can potentially bring benefits in situations where:

- Only TCAS alerted (so GA pilot is aware of RA issued nearby even before TSAA alert occur), but also,
- all the other situations when both TCAS and TSAA alerted regardless of the alert sequence, or corner case situation.

Experiment results indicate that such situations represent 78.4% of all alerting scenarios[16]. Performed analysis however also envisage that even TSAA without "+" functionality has a potential to help in 52,6% of all alerting scenarios. That means, that "+" functionality of TSAA can potentially improve safety by 49%.

Note, that this approach should be considered as a first approximation as probably some scenarios of this type would still evolve in RA and there may be some additional benefits related to "+" capability.

These results shall be considered as initial as they are based on real but limited European data set, aiming to estimate opportunity for potential benefits. To estimate real safety benefits of the system, HF study should be performed to assess pilot performance.

5.2.6. EXPERIMENT RECOMMENDATIONS

It is recommended to assess feasibility of providing not only RA broadcast for pilots, but also equipage status of intruder aircraft in future research. Such information may be beneficial in situations, when only TSAA alerted (5.8%). In case, only TSAA alert is issued, even information whether intruder is or is not equipped might be considered useful for GA pilot.

[16] By alerting scenario, scenario in which at least one system alerted is meant.

5.3. EXPERIMENT #3: OPERATIONAL EVALUATION OF TSAA+ (2018)

This experiment has been performed within the scope of SESAR2020 project PJ.11-A4. Two publications are directly linked with this experiment: the validation plans [88], [89] and validation report [9]. The results were used as a basis for SESAR definition and consolidation of initial European operational and technical recommendations for ACAS Xp development.

The experiment was a real-time human-in-the-loop (HITL) cockpit simulation using TSAA+ system prototype assessing safety benefits and HMI acceptability of the system by GA and rotorcraft pilots.

5.3.1. OBJECTIVES

The high-level objective of this experiment was to evaluate operational and safety benefits of SA+ during mixed equipage encounters. This was addressed by defining following lower-level objectives:

TABLE 19: EXPERIMENT #3: OVERVIEW OF LOWER-LEVEL EXPERIMENT OBJECTIVES

Objective no.	Objective	Success criterion	Category
1	Assess pilot performance on the tasks when he has the option to consult the system display for the traffic information as opposed to looking OTW.	Using TSAA+ (as opposed to no TSAA) did not lead to the degradation of pilot performance.	Human Performance
2	Assess pilot's workload coming from the need to intermittently check TSAA+ information.	The potential changes to the level of workload/task demands and/or cognitive demands and the mitigation identified are acceptable.	Human Performance
3	Assess if pilot's information needs regarding the surrounding traffic are met with TSAA+.	There is no discrepancy between system-provided information and user required information.	Human Performance
4	Assess whether the pilot understands each system state (symbols, alerting information and their combinations).	1. End user experiences integrated interface including any new system components as sufficiently usable. 2. Pilot can clearly interpret all the system states (based on the symbols and the information provided by TSAA and TSAA+)	Human Performance
5	Assess the potential for errors occurring.	The number or severity of errors in the solution scenarios are not greater than in the reference scenario.	Human Performance
6	Assess pilot's SA.	End user is able to perceive and interpret task relevant information and anticipate future events/actions.	Human Performance
7	Assess the acceptability of SA with TSAA+.	Level of individual situation awareness within acceptable limits ('acceptable limits' to be defined with regard to the tool used for the assessment).	Human Performance
8	Assess whether pilots find the application and associated operations acceptable.	And users do not predict negative impact with regard to changes in roles and responsibilities or means for mitigating negative impacts are identified.	Human Performance
9	Assess whether training for pilots will be needed.	Where possible, initial knowledge, skill and experience requirements are identified.	Human Performance
10	Demonstrate that see and avoid failures involving GA aircraft were reduced by about 3% (which is about half of the IFR/GA 6% cases where see and avoid currently fails)	See and avoid failures involving GA aircraft were reduced by about 3%.	Safety
11	Demonstrate that GA pilot induced conflict situation identified during scenarios (if any) shows improvement when using TSAA+ system.	GA pilot induced conflict situation identified during scenarios (if any) shows improvement when using TSAA+ system.	Safety

5.3.2. APPROACH TO EXPERIMENT

Tools and equipment used for experiment were as depicted at Figure 40. Simulations were performed in Honeywell laboratory which consists of curved projection screen with 240° view and 7m x 1.5m in dimension that is lit by four short throw projectors with resolution of 1280 x 800 each, and a flight simulator. Input data with scenarios descriptions were provided both to V&V platform and to TSAA+ SW prototype for synchronization purposes. Real-time trajectories were provided to TSAA+ prototype to provide its intended function. Surveillance data including TSAA+ alerts were provided to tablet (experimental mock-up) display via wi-fi.

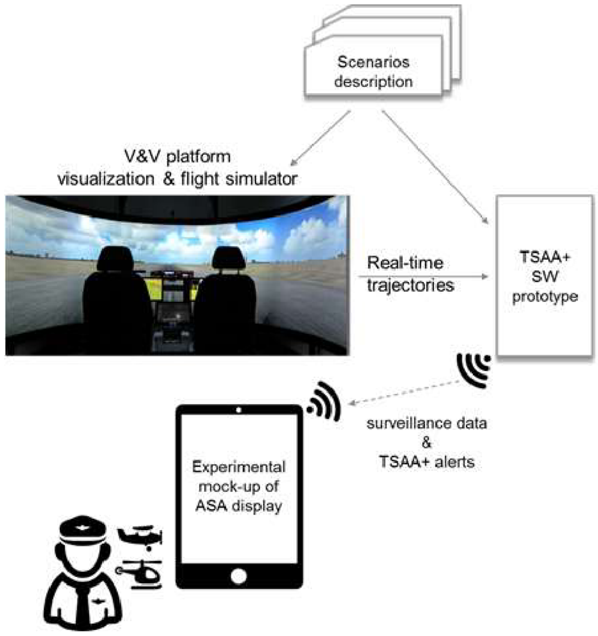


FIGURE 40: EXPERIMENT #3: OPERATIONAL EVALUATION OVERVIEW

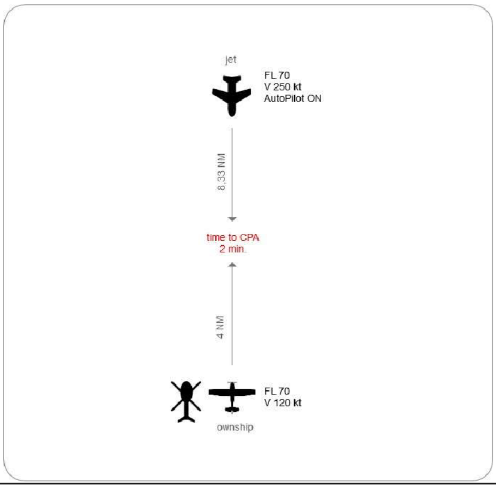
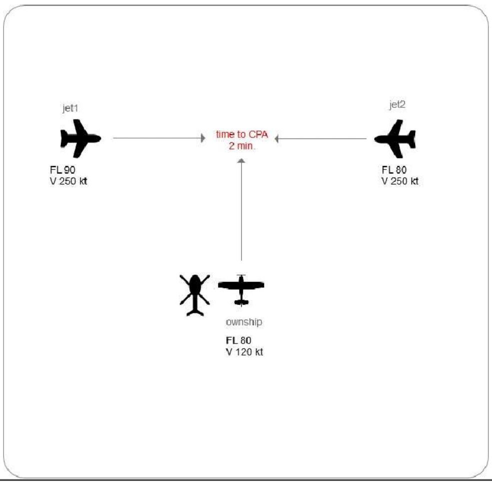
Three types of scenarios have been used based on the ownship equipment:

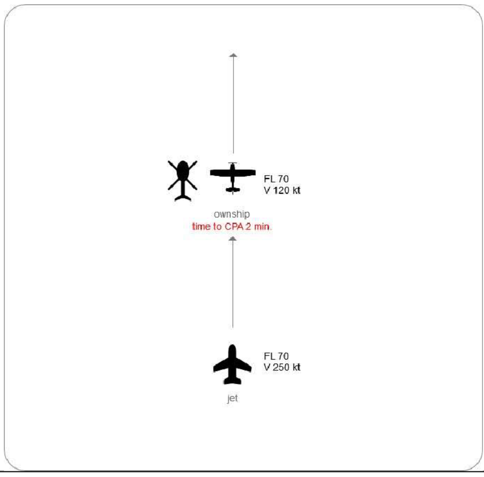
1. Baseline: ownship not equipped with any transponder, meaning that TCAS II intruder does not identify threat (ownship), and therefore does not generate RA against the ownship. GA/R ownship applied "see and avoid" only.
2. Reference: ownship equipped with ADS-B IN/OUT capability and TSAA technology. TCAS II equipped intruder identifies threat (ownship) and generates RA. Ownship had TSAA application with TSAA functionality – mainly alerting when threat is identified, but ownship had no information about the RA that was generated by intruder.
3. Solution: ownship equipped with ADS-B IN/OUT capability and TSAA+ technology. TCAS II equipped intruder identifies threat (ownship) and generates RA. Compared with only TSAA technology, ownship had information about the RA that was generated by intruder.

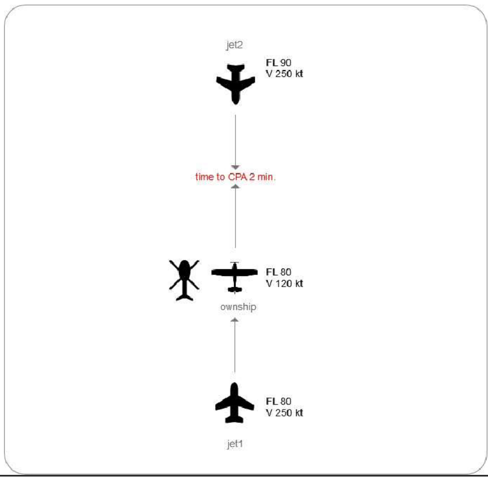
The scenarios have been designed by Honeywell flight operations experts/pilots and included one or two intruders equipped with TCAS II. Ownship scenarios were designed to fit both GA and helicopter operations supported by simulator allowing to simulate both GA and helicopter performance. To allow ownship aircraft to fly precise trajectory as defined below, ownship had an autopilot mode turned on from the simulation initialization up to the time when the pilot decided to maneuver.

All scenarios were initiated approximately 2 minutes before the potential collision. Pilot should have maneuvered after identifying the intruder. There were six solution scenarios in each type (Baseline, TSAA, TSAA+ technology) defined, applicable for both GA and rotorcraft. With one exception – scenario 3 was not performed as Baseline because spotting the intruder flying from behind is almost impossible without avoidance technology.

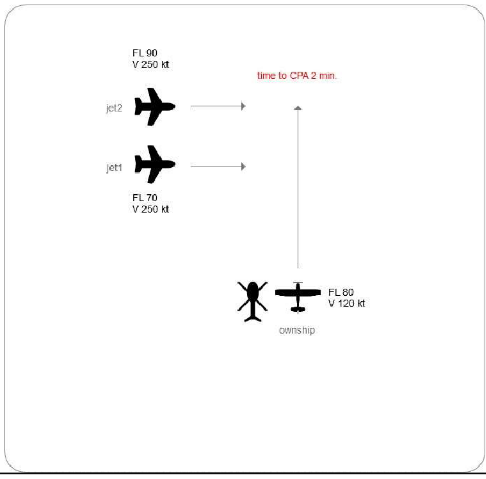
TABLE 20: EXPERIMENT #3: OVERVIEW OF SCENARIOS

Scenario no.	Illustration	Description
1		Head-on encounter of two aircraft. GA/R ownship flies at FL=70, at speed 120 kts. TCAS II equipped intruder is flying at the same FL (FL=70), speed 250 kts.
2		Encounter involving three aircraft converging on each other with an angle of 90 degrees between their tracks. GA/R ownship flies at FL=80, speed 120 kts. One TCAS II-equipped intruder is flying at FL=90, speed 250 kts, the second TCAS II-equipped intruder is flying at FL=80, speed 250 kts.

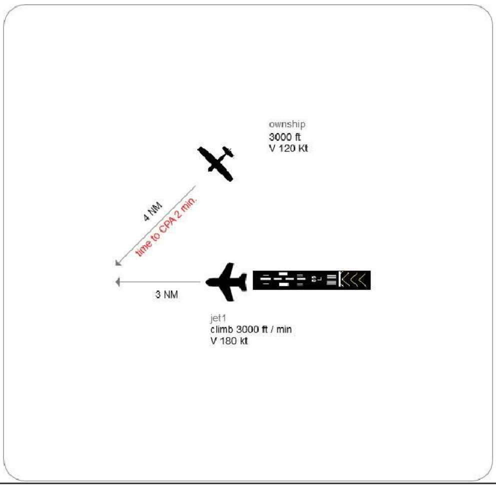
<table>
<tr><th>Scenario no.</th><th>Illustration</th><th>Description</th></tr>
<tr><td>3</td><td>
</td><td>Overtaking encounter involving two aircraft in the same flight phase. GA/R ownship flies at FL=70, speed 120 kts.

TCAS II-equipped intruder is flying behind ownship at the same FL (FL=70), speed 250 kts.</td></tr>
<tr><td>4</td><td>
</td><td>Overtaking and head-on encounter involving two TCAS II-equipped intruders and GA/R ownship in between the intruders on the same track. Ownship flies at FL=80, speed 120 kts.

First intruder is following the ownship at the same FL (FL=80), speed 250 kts.

Second intruder is flying against ownship at FL=90, speed 250 kts.</td></tr>
<tr><td>5</td><td>
</td><td>Encounter involving three aircraft with two TCAS-equipped intruders are converging on GA/R ownship trajectory from the same direction with an angle of 90 degrees between their tracks. GA/R ownship flies at FL=80, speed 120 kts.

Both intruders are flying from the same direction, with the same speed of 250 kts, one flying at FL=70 and second one at FL=90.</td></tr>
</table>

Scenario no.	Illustration	Description
6		Encounter involving GA/R ownship and TCAS II-equipped intruder representing airport environment situation when a departing TCAS II-equipped intruder is climbing out at 3000 ft/min from a nearby airport and encounters the cruising GA/rotorcraft ownship cruising at 3000 ft, speed 120 kts.

To validate the experiment objectives, following data collection methods were applied:

- Qualitative collection methods which were based on:
  - Over the shoulder observations performed by operational and HF experts during each run. The aim was to take note of the behavior of the pilot during encounter situations, to get the idea of their situation awareness as well as their appraisal of the relevance of the TSAA+ system and information available when using it. The observations were also an opportunity to identify unexpected pilots' behavior during simulations. The key points observed were used in support to the discussions during the debriefing sessions.
  - Questionnaires on the validation objective / success criteria.
  - Debriefing sessions held at the end of simulation. The pilots had the opportunity to discuss any issues / particular situations they experienced during the run. The observations and questionnaire answers were used to further discuss the pilots' HMI acceptability, and feedback on TSAA+ system in general.
- Quantitative collection methods which consisted mainly of system data logs.

5.3.3. Assumptions

Following assumptions have been applied for this experiment:

- To be able to create conflicting encounter causing RA on-board of TCAS II-equipped aircraft, ownship aircraft will fly on autopilot until pilot decided to maneuver due to collision risk.

- TCAS II aircraft will not issue reverse RAs against ownship, i.e., TCAS II-equipped intruder trajectory will be fixed and won't change during the scenario due to simulator capabilities.
- No ATC communicate on will be simulated (uncontrolled airspace is assumed during evaluation).
- Simulator environment behavior is sufficiently realistic.
- VMC weather conditions will be simulated, i.e., the simulation will consider good weather conditions to allow pilot easily to identify surrounding traffic.
- TSAA+ display will be implemented on mobile device. Ownship pilots will be for solution scenarios provided with tablet or mobile (as preferred) to display traffic situation.
- TMA operating environment will be addressed in this experiment. TMA environment is considered as the most relevant for TSAA+ applicability.
- Intruder will be always commercial aircraft with ADS-B OUT and TCAS II since TSAA+ is expected to bring benefits during mixed equipped encounters.

5.3.4. RESULTS ANALYSIS

Detailed analysis of the results including exact HF questionnaires are available in the official validation report [9]. Following table summarizes results per each lower-level objective. For success criterions applied refer to [9]. Status field indicate whether success criterions were met or not.

TABLE 21: EXPERIMENT #3: OVERVIEW OF RESULTS

Objective	Result	Status
Task allocation changes: Assess pilot performance on the tasks when he has the option to consult the system display for the traffic information as opposed to looking OTW.	Pilots have considered displayed TSAA+ information beneficial, especially when it was difficult to spot traffic out of the window (OTW). TSAA+ informed about traffic sufficiently in advance. Compared with the baseline, pilot's time to recognize the traffic and time to start maneuver have improved (avg. difference ~68sec with baseline, + ~0.3 sec with TSAA). Information from TSAA+ influenced the ongoing maneuver of pilot and resulted in satisfactory separation.	OK
Pilot workload: Assess pilot's workload coming from the need to intermittently check TSAA+ information.	Bedford workload scale (BWS) rating resulted in "enough spare capacity" (1 -3 on BWS) and "reduced spare capacity" (4 – 6 on BWS). The workload of pilots using TSAA+ has slightly increased (meaning 0,23 on BWS scale) in comparison with baseline. However, based on the questionnaires, pilot's workload should decrease or stay the same with TSAA+ application.	OK
Pilot information requirements: Assess if	TSAA+ provided sufficient information to predict	OK

Objective	Result	Status
pilot's information needs regarding the surrounding traffic are met with TSAA+.	aircraft´s trajectory and avoid the collision. The set of RA was intuitive and adequate for GA pilot maneuvering. The presentation of TSAA+ data required minor HMI adjustments.	
User interface usability: Assess whether the pilot understands each system state (symbols, alerting information and their combinations).	Pilots have considered the position of RA message acceptable. RA message was not easily detected on the display and the color of RA message was unaccepted. Pilots objected on confusion between TSAA and TSAA+ displayed data that seemed to be contradictory. TSAA shows current vertical trend of aircraft (↑↓) and TSAA+ displays issued RA (i.e., CLIMB).	NOK
User interface vs. human errors: Assess the potential for errors occurring.	Pilots occasionally missed the RA message visualized near the intruder symbol when it appeared later than with the symbol. Until pilots are familiar with TSAA+, they could misinterpret the RA of the intruder as a command to ownship. The RA message, presented as a symbol, was repeatedly misunderstood, or missed.	OK
Level of situation awareness: Assess pilot's SA.	During the simulation, pilots were aware of the situation with only minor errors. From 75 situational cases only 11 errors have been made in total. Pilots stated that evaluation of situation during the simulated flight has been easier in case of TSAA+ in Comparison with no TSAA+.	OK
Acceptability of SA with TSAA+: Assess the acceptability of SA with TSAA+.	The situation awareness with TSAA+ will increase or will likely stay in acceptable limits. Overrating of TSAA+ traffic display could lead to decreased situational awareness, since any traffic not equipped with ADS-B could appear in the air but may not be displayed.	OK
Roles and responsibilities: Assess whether pilots find the application and associated operations acceptable.	Based on the questionnaires, TSAA+ application was acceptable for GA purposes. We presume that TSAA and TSAA+ will have impact on GA operations and VFR flying rules. Gradual penetration of TSAA+ may limit the acceptance of this technology in GA environment. Usage of TSAA+ in GA requires understanding of TCAS functionality.	OK
Knowledge, skill, and experience: Assess	Special license for TSAA+ in GA aircraft is unnecessary.	OK

Objective	Result	Status
whether training for pilots will be needed.	Training on TSAA+ would be needed in a form of theory and practice (simulator, e-learning, video demonstration).	
Improved see and avoid failures: Demonstrate that see and avoid failures involving GA aircraft were reduced by about 3%[17]	Compared with baseline, see and avoid failures were decreased by 20 % with TSAA+ technology and by 32 % with only TSAA technology. This was probably caused by the pilot's unfamiliarity with TSAA+.	OK
GA pilot induced conflict situations: Demonstrate that GA pilot induced conflict situation identified during scenarios (if any) shows improvement when using TSAA+ system.	Based on the separation throughout the scenarios of every type, TSAA+ shows improvement from baseline.	OK

5.3.5. EXPERIMENT CONCLUSIONS

The overall concept (providing RA information to pilots) was assessed as beneficial and useful. However, the expansion of TSAA+ to GA will have impact on current GA operations and procedures. Current rules for GA pilots when in proximity of TCAS equipped traffic could be affected by the expansion of TSAA+ (i.e., GA pilot that is used to not to maneuver when in proximity of TCAS equipped traffic is – due to TSAA+ - able to avoid maneuver that is in contradiction to RA).

GA pilots are often not very familiar with TCAS behavior and following operations and advisories (TA, RA) that are common for non-GA aircraft crew. For GA pilot with no previous TCAS experience it took some time to accommodate the rules of TCAS and use it for decision on appropriate maneuver. Information from TSAA+ influences the maneuver already performed by GA pilot. Ought to say, that in many cases the maneuver performed by GA pilot is not focused on having largest separation between ownship and traffic but to perform maneuver that keeps the traffic always in sight to meet the VFR rules. This maneuver is also often driven by the type of aircraft and various conditions of view from cockpit.

Pilots would need to be informed of how to use TSAA+ at least in a means of e-learning/ how-to or video demonstration on simulator. The use of TSAA+ would not expect any special license for GA pilots.

[17] SESAR-given general target.

Since TSAA+ operational concept addressing information on RA was still not fully "frozen", expert opinions differ in whether:

- all active RAs are to be displayed to GA pilot, even though they are not issued against TSAA+ a/c, or
- Only RA issued against TSAA+ aircraft should be displayed, or
- for some pilots, only information that intruder is TCAS equipped is sufficient.

From the technical feasibility perspective, TSAA+ would bring certain benefits to pilots. The benefits of TSAA+ may be pronounced together with other ADS-B data (at least position, altitude, and vertical speed of traffic) and potentially the whole TSAA logic. Potential contradiction between current vertical trend of aircraft taken from ADS-B data as part of TSAA logic (↑↓) and issued RA (i.e., CLIMB) as part of TSAA+ logic must be considered in design stage.

In comparison to no device in GA cockpit, the benefit of TSAA+ was significant. The penetration of ADS-B in GA environment is crucial for the credibility of TSAA+ device in GA cockpit.

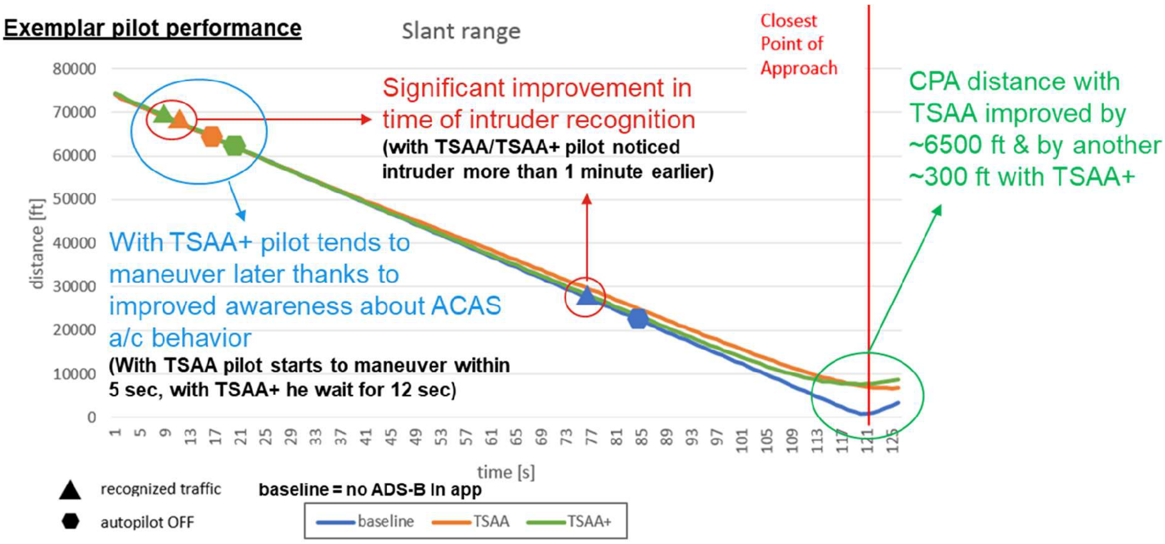


FIGURE 41: EXPERIMENT #3: EXEMPLAR PILOT PERFORMANCE WITH TSAA, TSAA+ AND WITHOUT ANY APPLICATION (BASELINE)

The content of information provided by TSAA+ on display was enough to determine the future path of aircraft to take proper/correct action to avoid collision. The GA pilot´s information needs have been filled by TSAA+ (but involving also other ADS-B data such as position, altitude, and vertical speed of traffic). The form of presentation of TSAA+ content however needs minor HMI adjustments. There was no significant discrepancy between system-provided information and user-required information. Pilot´s interpretation of all system states (based on the symbols and the information provided by TSAA and TSAA+) brought some questions and concerns (see next section).

We have detected several issues with other traffic RAs, that have been classified by GA pilot as a command to ownship. An increased workload of pilots might be expected due to the novelty and amount of TSAA+ information in comparison to baseline (no device).

5.3.6. RECOMMENDATIONS

Even though the overall concept of providing RA information to pilots was assessed as beneficial and useful, future work on HMI development would be necessary. Particular aspects that would need to be addressed on the experimental application HMI are:

- More striking color of RA.
- The list of RAs included in TSAA+ for GA pilots could be limited to these RAs: climb, descent, do not climb, do not descent and level off.
- Both textual and graphical representations of RA to be considered to avoid confusion over the meaning.

More human performance experiments would be useful to identify which pieces of information (existence of anti-collision system; RA to ownship only; any RA) should be presented to the crew of TSAA+ equipped aircraft.

5.4. EXPERIMENT #4: OPERATIONAL ACCEPTABILITY OF ACAS XU FOR GA/R OPERATIONS (2019)

This experiment has been performed within the scope of SESAR2020 project PJ.11-A4. Three publications are directly linked to this experiment: the validation plans [88], [89] and validation report [8].

The results were used as a basis to SESAR definition and consolidation of initial European operational and technical recommendations for ACAS Xp development.

5.4.1. OBJECTIVES

The aim of this experiment was a FTS assessing, in terms of interoperability and reusability aspects, the operational acceptability of ACAS designed for remotely piloted aircraft (ACAS Xu) for GA/R operations. The goal was to get the first impression whether GA pilots accept ACAS Xu RA instructions and find them feasible, and whether they find acceptable when an ACAS Xu equipped drone follows the ACAS Xu RAs.

5.4.2. APPROACH TO EXPERIMENT AND DATA SET

Honeywell FTS platform called CASCARA with ACAS Xu Run4.2 integrated was used for both simulations using EUROCONTROL real European encounters and set of artificial encounters as an input.

This exercise was performed in three consecutive steps:

1. First, a FTS with ACAS Xu-equipped GA/R ownship encountering cooperative intruder using set of real European encounters provided by EUROCONTROL. In this step alerting performance of ACAS Xu when installed on board of GA/R was evaluated.
2. Second, a FTS with unequipped GA/R ownship encountering ACAS Xu equipped intruder using set of theoretical encounters based on geometrical considerations of possible conflicts among any aircraft (worst cases). In this step, alerting performance of the two systems was evaluated.
3. Then, results of the first two steps were consolidated and representative sample (18) of the encounters was presented to Honeywell internal GA pilots on a dedicated workshop in order to obtain feedback on ACAS Xu acceptability and feasibility from operational point of view.

For the 1st step of FTS, real European mixed-equipage encounters provided by EUROCONTROL were used. The same set of encounters was already used experiment described in 5.2. The total set of 3628 mixed equipage encounters was simulated.

Passive surveillance only, based on receiving ADS-B messages, was considered as a surveillance input for ACAS Xu installed on board of GA/R.

Based on results obtained in 1st step of FTS, nine scenarios (Figure 42) were selected as candidates for the workshop discussion. The decision has been made based on first 5 seconds of the RA, which are the most relevant since in normal operation it is expected that pilot would react within 5 seconds.

For the 2nd step of FTS, theoretical collision avoidance "worst case" scenarios created by Honeywell (within different project) were re-used for this purpose. The total set of 110 scenarios with different variables were simulated applying ACAS Xu model on drone intruder side.

Basic scenario was a head-on encounter, ownship flying with speed of 200kt at 3000ft altitude to the north. Intruder was at the same altitude, same speed flying to the south. The other scenarios were derived from this basic one by changing some parameter, adding vertical or horizontal maneuvers of ownship and/or intruder.

Alerting performance of ACAS Xu was assessed by focusing on the number of generated RAs and type issued RA. Since simulations were not dynamic (trajectories did not change based on given RA on either ownship or intruder side), focus was given on:

- the type of 1st RA (assuming that pilot would react, what would in reality change the sequence of all other potential RAs), and
- type & sequence of RA during first 1 seconds of the advisory (assuming that standard pilot reaction duration is 5 seconds).

Based on results obtained in 2nd step of FTS, eight scenarios were selected as candidates for the workshop discussion. Set of scenarios was selected based on expert judgement, to allow various types of possible RAs, including both nominal (which pilot might find to be straightforward) and worst-case situations (when rather unexpected, or combination of more different RAs is given by the system within a short time). In particular, the goal of the scenario set was to include:

- Scenarios with horizontal RA,
- Scenario with vertical RA,
- Reverse scenario which changes RA sense within first 5 seconds (both horizontal and vertical),
- Scenario where provided RA does not comply with rules of the air.

In the 3rd step of experiment, a workshop with GA pilots was performed at Honeywell premises and lasted 2 hours. There were 8 participating GA pilots. First, pilots were introduced to TSAA+ solution, got explained the situations (scenarios) and received paper questionnaires. Then, each scenario was presented as a video and plots with trajectory and RA details. Experiment was concluded based on the feedback received from participating pilots.

To allow pilots to better understand the encounter and ACAS Xu suggested behavior, selected scenarios were simulated in Cesium ion, a scalable and secure platform for streaming 3D geospatial data. With each scenario, workshop participants were asked to fill the questionnaire prepared by HF experts.

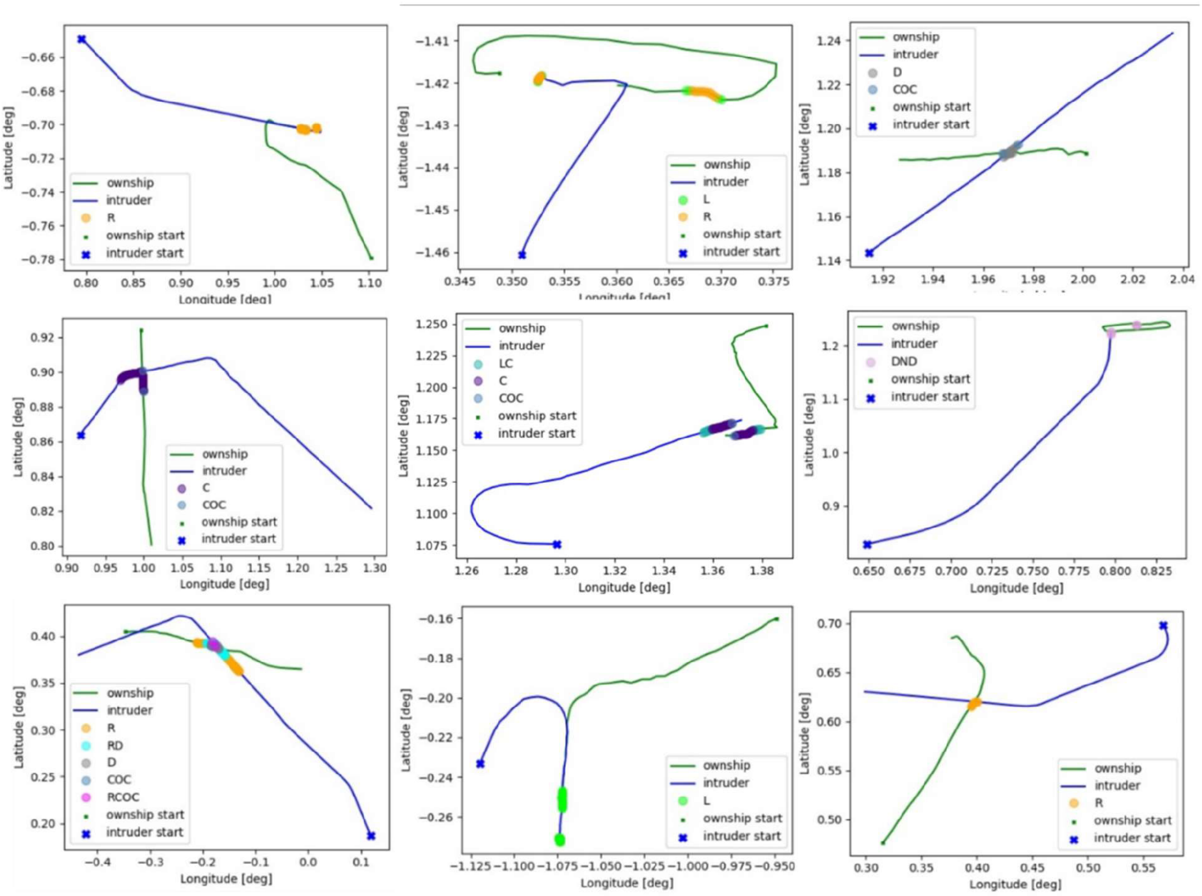


FIGURE 42: EXPERIMENT #4: OVERVIEW OF FTS SCENARIOS SELECTED FOR WORKSHOP WITH PILOTS (1ST STEP)

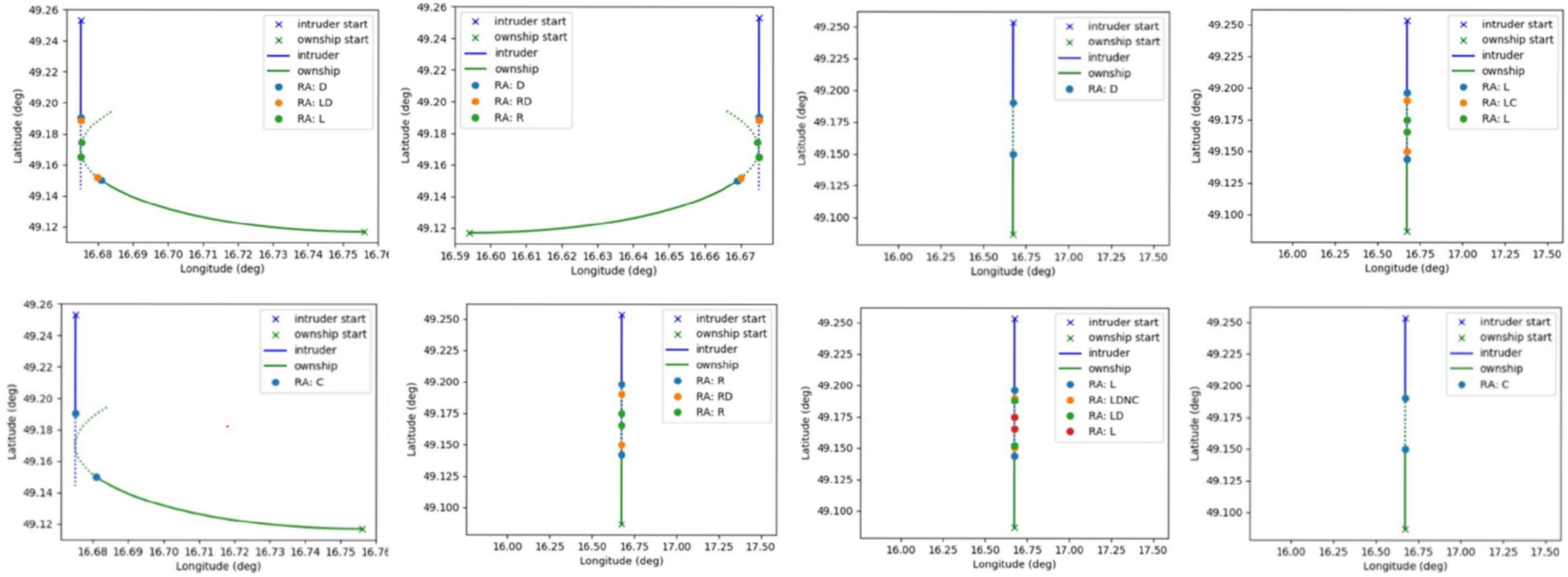


FIGURE 43: EXPERIMENT #4: OVERVIEW OF FTS SCENARIOS SELECTED FOR WORKSHOP WITH PILOTS (2ND STEP)

5.4.3. ASSUMPTIONS

Following assumptions have been applied for this experiment:

- Encounter set will consist of real European encounters involving GA/R encountering TCAS II- equipped intruders.
- Simulation will involve only one intruder.
- Surveillance errors won't be considered within this exercise. This is initial analysis of ACAS Xu logic behavior and its applicability for GA/R aircraft in terms of operational acceptability of conflict resolutions.
- No pilot reaction model is to be used during simulations for GA aircraft. Feasibility of RAs to be consequently discussed with real pilots.
- Maneuvering based on RWC is not considered within the operational scenarios. RWC function has rather traffic advisory character, at this stage the objective of the exercise is interested in RAs.
- No state aircraft encounters will be addressed in this experiment.

5.4.4. RESULTS ANALYSIS

Detailed analysis of the results including charts and graphs for FTS outcomes is available in official validation report of this experiment [9].

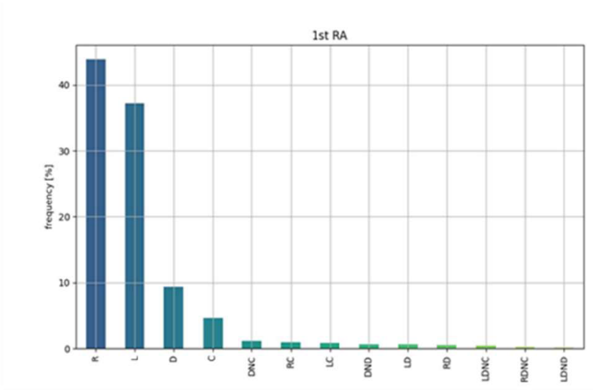
1st Step: FTS of ACAS Xu equipped GA/R ownship vs. cooperative intruder

The purpose of these fast-time simulations was to evaluate alerting performance of ACAS Xu when installed on board of GA/R, during encounters with cooperative intruders. From the obtained results, representative set of scenarios was selected and presented to pilots with the goal to assess/discuss how acceptable and feasible ACAS Xu Resolution Advisories (RAs) are for GA pilot.

In 1270 (35%) of cases out of 3628 encounters, ACAS Xu generated an RAt. Results of the 1st step FTS indicated that majority of RAs issued on board of ACAS Xu equipped GA/R ownship were horizontal and of "right" sense (~43%), i.e., compliant with rules of the air (see left graph of Figure 44). Approximately 80% of all issued RAs were of horizontal sense. This result was influenced by the altitude and corresponded to lower altitude operations, which are typical for mixed-equipage encounters.

Right graph on Figure 42 shows sequence of RA issued during first 5 seconds of the maneuver. It confirms that in most of the cases, the horizontal sense was consistent (pure R, pure L), then third most common maneuver was horizontal reversal followed by consistent, purely vertical senses.

Based on the results obtained in 1st step of FTS, nine scenarios were selected for pilot workshop (see Figure 42).



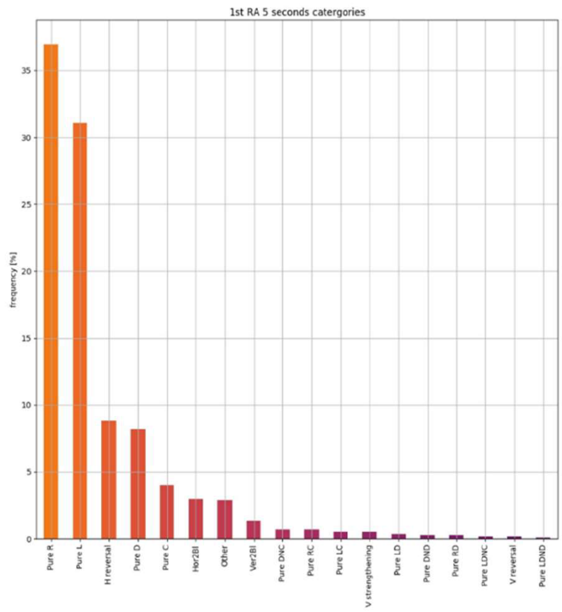


FIGURE 44: EXPERIMENT #4: 1ST STEP RESULTS – TIME AND SEQUENCE OF RA DURING FIRST 5 SECONDS

TABLE 22: EXPERIMENT #4: LEGEND FOR THE EXPERIMENT GRAPHS

Type of RA (1s) abbreviation	Meaning of the abbreviation	Type of 5sec category abbreviation	Meaning of the abbreviation
R	Right	Pure R	Right only
L	Left	Pure L	Left only
D	Descend	H reversal	Right -> Left, Left -> Right
C	Climb	Pure D	Descend only
DNC	Do Not Climb	Pure C	Climb only
RC	Right Climb	Hor2Bl	Horizontal changing to blended manoeuvre (i.e., vertical sense added)
LC	Left Climb	Ver2Bl	Vertical changing to blended manoeuvre (i.e., horizontal sense added)
DND	Do Not Descend	Pure DNC	Do Not Climb only
LD	Left Descend	Pure RC	Right & Climb blended manoeuvre
RD	Right Descend	Pure LC	Left & Climb blended manoeuvre
LDNC	Left Do Not Climb	V strengthening	Vertical only, strengthening manoeuvre
RDNC	Right Do Not Climb	Pure LD	Left & Descend blended manoeuvre
LDND	Left Do Not Descend	Pure DND	Do not Descend only
-	-	Pure RD	Right & Descend blended manoeuvre
-	-	Pure LDNC	Left & Do Not climb only
-	-	V reversal	Climb -> Descend, Descend -> Climb
-	-	Pure LDND	Left & Do Not Descend only

2nd Step: FTS of unequipped GA/R ownship vs. ACAS Xu equipped drone intruder

The purpose of these fast-time simulations was to evaluate alerting performance of ACAS Xu when installed on drone during encounter with unequipped GA. From the obtained results, representative set of scenarios was selected and presented to GA pilots with the goal to assess/discuss how acceptable is for them the RAs issued ACAS Xu equipped drone.

Figure 45 indicate the type of first RA (left), and type and sequence of RAs during first 5 seconds of RA.

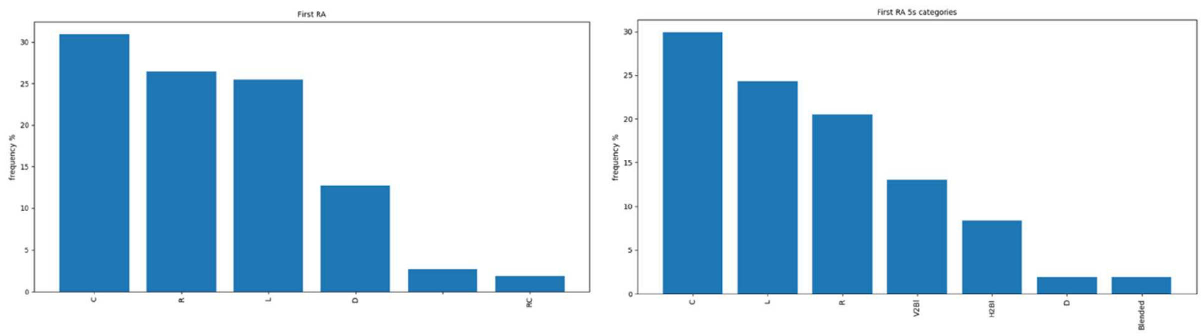


FIGURE 45: EXPERIMENT #4: TYPE OF FIRST RA (LEFT) AND TYPE AND SEQUENCE OF RAS DURING FIRST 5 SECONDS OF RA

Around 35 cases (~31%) of cases out of 110 artificial encounters, ACAS Xu installed on drone intruder issued vertical - climb RA against GA. It is assumed that this result was to big extent driven by the low altitude at which the encounter occurred. More than 50% of the scenarios then generated horizontal maneuver (~26% issued Right RA, ~25% issued Left RA).

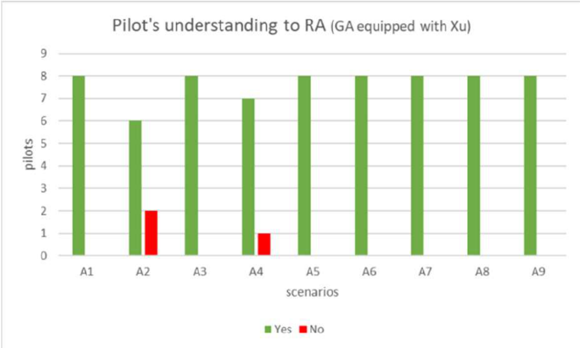
Results of 2nd step FTS indicate that if horizontal maneuver is issued by drone, Right (Right + blended Right Climb) sense RA is given more often than Left sense, however, the left sense still occurs quite often (25% or all the alerts), what introduces a safety risk since it does not comply with rules of the air, that GA pilot involved in the encounters might execute to avoid the collision. Moreover, the amount of Left sense RAs is even higher than Right sense RAs during first 5 seconds of the issued RA.

3rd Step: Internal Workshop with GA pilots

The aim of the workshop was to obtain GA pilots' feedback to acceptability and feasibility of proposed ACAS Xu maneuvers from two perspectives:

- ACAS Xu being installed onboard of GA ownship (nine selected scenarios from 1st step, see Figure 42),
- ACAS Xu installed on UAV intruder, when ownship is not equipped with any traffic awareness or collision avoidance system (eight selected scenarios from 2nd step, see Figure 43).

For the first part of workshop, nine candidate scenarios from 1st step of FTS, shown in Figure 42, were used. Although the suggested ACAS Xu RAs were mostly assessed as understandable, some RA were not provided sufficiently in advance according to the pilots (Figure 46).



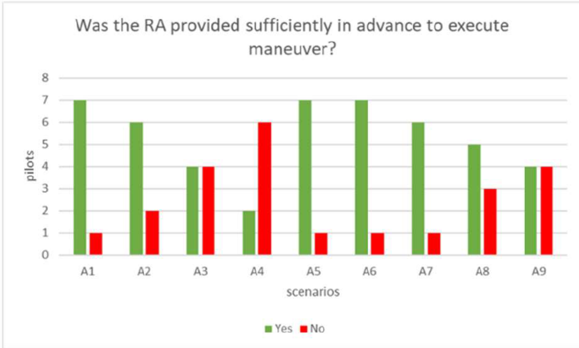
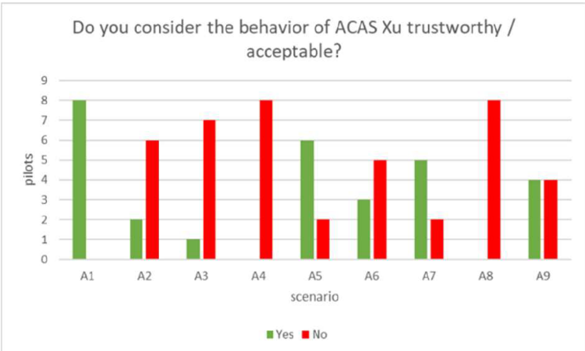


FIGURE 46: EXPERIMENT #4: PILOTS' UNDERSTANDING OF RA (LEFT), RA PROVISION PROVIDED SUFFICIENTLY IN ADVANCE (RIGHT)

Moreover, in several cases the maneuvers were not compliant with the rules of the air, which was also recognized by the workshop participants. Thus, the main outcome of the exercise is that ACAS Xu is not currently trustworthy and acceptable for the use on GA aircraft Figure 47.



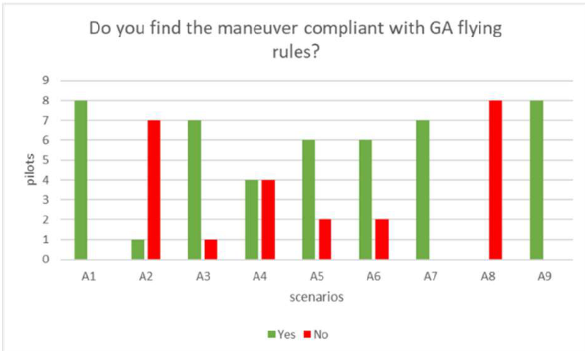


FIGURE 47: EXPERIMENT #4: TRUSTWORTHINESS AND ACCEPTANCE OF ACAS XU

For the 2nd part of the workshop, eight artificial scenarios selected during 2nd step of FTS were used, as shown on the Figure 43. The main questions to the participating pilots were targeting predictability, acceptability, and compliance with the rules of the air Figure 48. The low results of acceptability and predictability of the intruder maneuvering are again related to the non-compliance with rules of the air, i.e., in some scenarios issued horizontal maneuvers were in opposite sense than required by rules of the air.

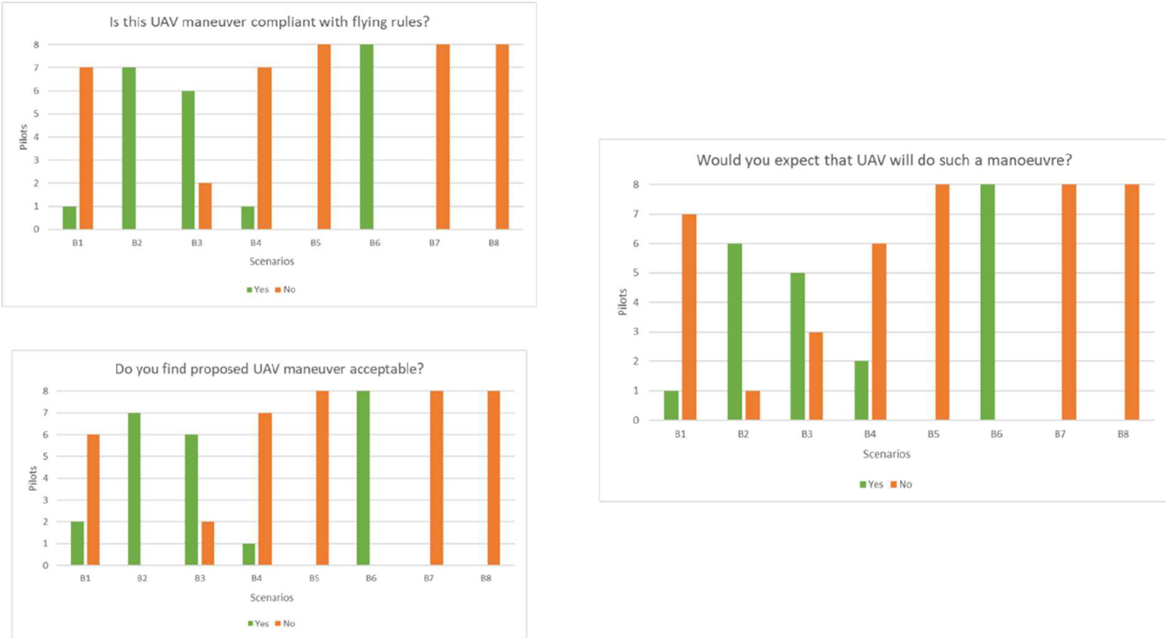


FIGURE 48: EXPERIMENT #4: ACAS XU PREDICTABILITY, ACCEPTABILITY AND COMPLIANCE WITH THE RULES OF THE AIR

5.4.5. EXPERIMENT CONCLUSIONS

The results of ACAS Xu workshop indicated that using ACAS Xu Run 4.2 was for majority of pilots not trustworthy/acceptable for the use on GA aircraft, with following justifications:

- GA pilots understood the meaning of ACAS Xu RA, however, there were cases when the maneuvers proposed by ACAS Xu has been in contradiction to what would GA pilot do in this situation without advisory (maneuvers that were not in line with existing rules of the air).
- In some cases, the ACAS Xu RAs have not been provided sufficiently in advance to GA pilot to be able to decide the maneuver.
- It was also observed, that whenever the proposed maneuver has been considered obsolete (too late or too soon), the GA pilot tended to lose confidence to ACAS Xu logic.

ACAS Xu Run 4.2 was also shown not to be interoperable with GA when equipped on board of an unmanned aircraft (intruder), when for example issued an RA in opposite sense than required by rules of the air.

It should be stated that Run4 version of ACAS Xu was still development release, not fully mature for operational evaluations.

5.4.6. RECOMMENDATIONS

In this context, it was recommended to verify the above conclusions with MOPS version of ACAS Xu.

Compatibility with rules of the air was recommended as a key factor that should be considered for the future development of collision avoidance system for GA.

The concept of operations for ACAS Xu should be refined with focus on interoperability between piloted aircraft and unmanned system with ACAS Xu on board.

6. 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. Table 23 summarizes performed experiments, their scope, goals, and high level conclusions.

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.

TABLE 23: 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.

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 24. 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 24: 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

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.

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 (4.4.2)
- Definition of which ADS-B message and which field shall be used for the "+" functionality. (4.4.2)
- Contribution to definition of exemplar operational scenarios for TSAA+. (4.4.4)
- Definition of three potential use cases for TSAA+. (4.4.6)
- Definition of technical and operational assumptions for TSAA+ derived from TSAA Safety Performance and environment Requirements (SPR). [5] (4.4.7)

Experiment #1

- Definition of validation set-up/approach and validation objectives. (5.1.1 and 5.1.2)
- Selection of scenarios to be used for validation. (Table 11)
- Definition of simulation assumptions. (5.1.3)
- Review of analysis results and drawing the conclusions and recommendations based on analysis results. (5.1.5. and 5.1.6)
- Validation report preparation. [86]

Experiment #2

- Validation plan preparation. [87]

- Contribution to definition of validation objectives. (5.2.1)
- Review of analysis results and drawing the conclusions and recommendations based on analysis results (5.2.5 and 5.2.6)
- Validation report preparation. [8]

Experiment #3

- Validation plan preparation. [87]
- Definition of high-level experiment objective. (5.3.1)
- Contribution to 5.3.2definition of approach to experiment. (5.3.2)
- Review of proposed scenarios to be used. (table 20)
- Contribution to definition of validation assumptions. (5.3.3)
- 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 (5.3.5)
- Review and contribution to experiment recommendations. (5.3.6)
- Validation report preparation. [9]

Experiment #4

- Validation plan preparation. [87]
- Contribution to objectives and approach to experiment definition. (5.4.1 and 5.4.2)
- Definition of experiment assumptions. (5.4.3)
- 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. (5.4.5 and 5.4.6)
- 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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<u>Project CAPITO PJ.11-A4 (TSAA+) - SESAR2020</u>

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