Are You Clear About " Well Clear "?

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***Abstract*—Regulations from the ICAO use the term Well Clear without defining it. Now, this definition is needed to design air traffic Detect And Avoid systems. A definition is currently discussed at the ICAO level, with work on the associated Remain Well Clear (RWC) function underway at standardisation bodies level (RTCA, EUROCAE). But many members of the communities impacted by these works are not well aware of their state. To adress this lack of awareness, this paper provides three contributions. First, it derives from ICAO texts the components of a RWC function: boundaries, alerts and guidances. These are linked to essential elements required to define the Well Clear term: a start and end, the actors involved, and the expected actions. Second, it summarizes the current regulatory efforts in RTCA, EUROCAE and ICAO regarding the Well Clear and Remain Well Clear notions. Third, it proposes discussion topics to move forward. From a DAA perspective, the notion of Well Clear is key to unlock RPAS full integration, i.e. operation in all classes of airspaces. Though existing works make good progress, the ressources engaged on this topic seem insufficient when compared with the complexity and importance of the task at hand.**

***Keywords*—Well Clear, Remain Well Clear, Self-Separation, Traffic Avoidance, Detect And Avoid, Sense And Avoid, RPAS, UAS.**

I. INTRODUCTION

Though mentioned ten times in ICAO’s Rules of the Air, the term ”Well Clear” (WC) is never defined in the current ICAO regulation [1]. Until recently, this was not a problem since the interpretation of this term was left to the appreciation of highly trained Air Traffic Control Operators (ATCOs) and pilots. However, with the ongoing effort to integrate Remotely Piloted Aircraft Systems (RPASs) in non-segregated airspaces, providing an objective definition of WC has become urgent.

In many types of operations, the integration of an RPAS in the existing traffic is likely to require the RPA to be equipped with an air traffic Detect And Avoid system (DAA). Depending on the operational and regulatory environment, the DAA system should provide one or both of the following functions: Collision Avoidance (CA) and Remain Well Clear (RWC). The former is a last minute manoeuver to avoid imminent collision with air traffic and reach a safe state. The latter consists in smooth manoeuvers considering multiple factors (e.g. safety, operational, mission) to avoid conflicting traffic. The main differences between CA and RWC are highlighted in Table I.

The notion of CA is built around the precise definition of Collision Volume as defined in [2]. However, there is no such objective definition of a WC volume, thus preventing the definition of a RWC function. Hence the current efforts, reported in this paper, to aggree on a definition for WC and then RWC. The notion of RWC originates from regulatory requirements of the ICAO Annex 2 Rules of the Air [1]. It is strongly linked with the notions of collision risk and right-of-way rules. Hence, coming up with a definition is no easy task. On top of an effort from the ICAO’s Standard and Recommended Practice (SARP) panels, two standardization bodies have taken up the challenge: EUROCAE and the RTCA, along with helper projects.

TABLE I: Main differences between Collision Avoidance (CA) and Remain Well Clear (RWC) functions. CoC is for Clear of Conflict; NMAC is for Near Mid Air Collision.

	CA	RWC
Decision factors	Safety	Safety, acceptability, strategic
Responsibility	Pilot	Depends on airspace (can be shared with pilot’s)
Contact ATC?	If time allows	Yes, notably if under clearance
Start/ End	Collision hazard/ NMAC or CoC	Conflict/ Collision hazard or CoC
Time horizon	Tens of seconds	Few minutes
Manoeuver	Strong	Smooth
Manoeuver constraints	None	Right of Way rules, clearance

The goal of this paper is threefold. First, based on existing definitions form ICAO documents, an operational decomposition of the RWC function is proposed and linked to the definition of WC. Second, an overview of current efforts on the definition of the RWC function is provided. Third, topics are provided to fuel discussions about the possible evolutions around the WC and RWC notions. This paper first describes the RWC function in more details. Then, the current efforts deployed to tackle the WC and RWC definition problems in the ICAO, EUROCAE and RTCA are described, with a stress on the particular contributions and hypothesis of each entity. A discussion is proposed about the paths not being currently explored. This work concludes on the short term objective of current works and ways to go.

II. THE NOTION OF REMAIN WELL CLEAR

As mentioned in the previous section, the notion of Remain Well Clear is directly linked to ICAO’s Rules of the Air [1], ”An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard.". So the primary objective of a RWC function is to prevent collision hazards. Moreover, according to ICAO's Manual on RPAS, RWC is "the ability to detect, analyse and manoeuvre to avoid a potential conflict by applying adjustments to the current flight path in order to prevent the conflict from developing into a collision hazard" [2]. Meaning that the RWC function should start when a conflict is detected, and finish when the conflict is solved (RWC succeeded); or when it developed into a collision hazard (RWC failed), in which case the CA function shall engage, if available. Finally, though this is not clear from the ICAO Annex 2 [1], it seems reasonable to assume that the right-of-way rules apply as soon as a conflict exists.

The previous RWC definition relies on the term "conflict" as a starting point and in its relationship with the right-of-way rules. But the term "conflict" is not defined in these documents. The rest of this paper uses the definition of conflict from ICAO's Air Traffic Services Planning Manual [3] and formulated as a *"Predicted converging of aircraft in space and time which constitutes a violation of a given set of separation minima"*. By relying on the term "conflict", the definition of RWC asks for the definition of separation minima.

These minima are materialised by boundaries which separate the airspace in volumes where different rules apply. Considering there is a Remote Pilot (RP) in or on the loop, such boundaries need to be associated with alerts and guidances. An important thing to consider when reading this section is that WC and RWC are different concepts. WC is an aircraft state influencing the application of the right-of-way rules, while RWC should be understood as a separation minima and the RWC functions is a function aimed at ensuring that the RPAS stays out of the RWC minima. DEBUG

A. Boundaries

According to the Right of Way rules, three states are relevant to describe the level of constraint during an encounter: *in conflict*, *well-clear* and *has right-of-way*. In presence of an intruder, i.e. when in conflict, the RPAS needs to follow the RoW rules. If the ownship has the right-of-way, it needs to maintain heading and speed. If not, it is free to maneuver. When an intruder becomes a threat, i.e. when WC is lost, the aircraft giving way is restricted in its possible maneuvers. For the ACAS community, note that the intruder and threat notions used for RWC are different from the ones in ACAS documents where intruder means under surveillance, and threats require RAs.

The different combinations of these states yield two boundaries which split the space in three volumes (see Figure 2). According to the ICAO's RPAS Manual [2], the two first volumes are called the RWC volume and RWC threshold (see Figure 1). The third one encompasses the space beyond the RWC threshold, we call it the *conflict-free* volume. Recent discussions led to a proposition to rename the "Remain WC volume" into "Regain WC volume" to stress the necessity to be WC at any time. This proposition comes from communities which envision DAA systems with no CA capabilities. In this

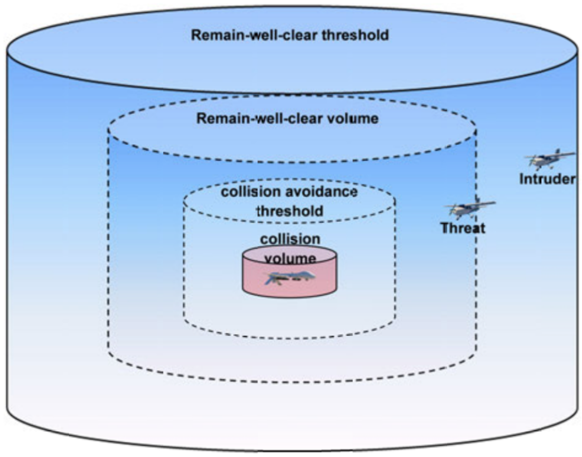

Figure 1: The Remain Well Clear threshold and Remain Well Clear volume as defined in the ICAO RPAS Manual. The collision avoidance threshold and collision volume are not considered here as they are not related to the RWC function but rather to the CA function. (image from the ICAO's RPAS Manual)

case the RWC function is the only safety layer and should continue performing as long as possible. This is similar to a CA function integrated in the RWC function. For simplicity, in the rest of this paper we consider that a separate CA function always exists and will not use the term "Regain WC". The boundaries of these volumes can be defined using time and/or distance measures (e.g. slant range, time to NMAC). These values should be chosen carefully as the volumes they define must ideally remain larger than the CA volumes so as to infringe them before any CA volume and ensure that the RP and/or conflicting traffic pilot are not upset by a sudden high priority alert. DEBUG

The previous boundaries separate the different steps of an evolving encounter depending on the constraints on the RPA motions. With these boundaries defined, the system needs to communicate to the RP the state of the conflict as well as the level of maneuver available. This is done through appropriately timed alerts.

B. Alerts

Through the boundaries, the RP can monitor the evolution of the encounter. However, the RP is already concerned with numerous tasks (aviate, navigate, communicate) and the navigation is not his/her first priority. That is why well located alerts are required to draw the RP attention to the right information at the right time. As proposed by Veitenburger [4], four types of alerts can be considered for a RWC function: information, advisory, caution, and warning. The information alert requests awareness, though no action is needed. The advisory alert requests awareness and possible action. The caution alert requires immediate awareness and possible corrective or compensatory action. The warning alert requires immediate awareness and immediate corrective or compensatory action.

Figure 2: Two boundaries (yellow, orange) separate the different states. Top, the ownship does not have the right of way. Bottom, the ownship does have the right of way. As an encounter evolves, the ownship possible manoeuvers are increasingly constrained: none (clear), maintain heading and speed (darker), constrained according to Right of Way rules (darkest).

Special care should be taken to have coherent alerts between the RWC and CA functions with CA alerts having a higher level of priority than RWC alerts. Their evolution should be progressive along time and contradictory alerts of the same level at the same time should be avoided. The minimum number of alerts required and their timing is still open to discussions.

To be most useful, alerts should come at optimal times to ensure boundaries are not violated. They should be accompanied with relevant information on the situation and, in the case of a RWC function, with avoidance information, it is to say a guidance.

C. Guidances

The type of information associated to an alert level belongs to one of four categories: informative, suggestive, directive, automatic. Informative guidance provides situational awareness; suggestive guidance limits the set of possible actions, e.g. headings, altitudes and speeds to avoid. Directive guidance provides a limited set of actions to execute, e.g. a 3-D trajectory, a vertical direction and/or a heading along with a manoeuver strength. Finally, with automatic guidance, the system informs the RP of its intent and executes a manoeuver, while the RP monitors it and can inhibit the manoeuver at any time. The guidance type should be chosen depending on the alert level and the efficiency of the system to solve the task at hand. In the particular case of the RWC function, directive only guidance should be avoided. Indeed, a RWC maneuver should take into consideration numerous factors (traffic, weather, clearance, etc.) when the system might only consider part of them and propose sub-optimal solutions.

With a general idea of how the fundamental elements of a RWC function are defined, the next section introduces the state of current efforts to provide a definition for the RWC function. The scope is on the contributions of ICAO to provide a WC definition, and EUROCAE's and RTCA's in defining the minimum requirements for a RWC function.

III. Current Work

The greatest effort to define objectively and precisely the notion of RWC is currently carried out by two standardization bodies: the RTCA and the EUROCAE. Each has different hypothesis and, though coordination is strong, their conclusions may differ. In the following, the current state of their efforts regarding the definition of the RWC function is presented, a summary of the main hypothesis and methodologies is available in Table **??**.

A. RTCA

The topic of DAA is tackled by two Special Committees (SCs) of the RTCA, the SC-228 and SC-147. The SC-228 is tasked with developing Minimum Operational Performance Standards (MOPSs) for RPAS, including for the DAA part. Their work considers the DAA problem as a whole and in all operational aspects (airspace classes, equipage, etc.). The SC-147 is tasked with defining and updating the ACAS performance standard. The work on RPAS started with ACAS Xu, the new generation of CA avionics for UAS, and was then extended to the RWC function thus describing a full DAA system. Both RTCA groups rely on a bottom up approach with their work being based on existing implementations, NASA's DAIDALUS + TCAS for SC-228 [5] and Honeywell's ACAS Xu for SC-147 [6]. The MOPSs are written based on the capabilities of these existing systems. In the following, we provide an overview of the state of the work in both groups, and the harmonisation and reconciliation efforts currently taking place.

1) SC-228: The work of the SC-228 is organised in successive phases with a scope increasing at each phase. Phase I considered "en route" IFR flights in airspaces of class D, E and G, with an altitude comprised between 1000ft AGL and FL180, though the lower limit is likely to be higher due to sensor limitations (e.g. around 3000ft for air-to-air radar).

	Airspace classes	Min. altitude	Ownship sensors	Ownship equipage	Companion projects	Methodology
RTCA SC-228	D-G	1000 ft (or sensors min. operational altitude if higher)	ADS-B Active surveillance Air-Air radar	Optional CAS	NASA evaluations	Top-down/Bottom-up
RTCA SC-147	D-G	3800 ft	ADS-B Active surveillance Air-Air radar	ACAS Xu	NASA evaluations SESAR-JU evaluations	Bottom-up
EUROCAE WG-105	A-G	TBD	Cooperative + non-cooperative (not specific)	mandatory CAS	MIDCAS TRAWA MIDCAS-SSP	Top-down

TABLE II: Comparison of RTCA SC-228, SC-147, and EUROCAE WG-105 working hypothesis, support projects and methodologies. CAS is for Collision Avoidance (CA) System.

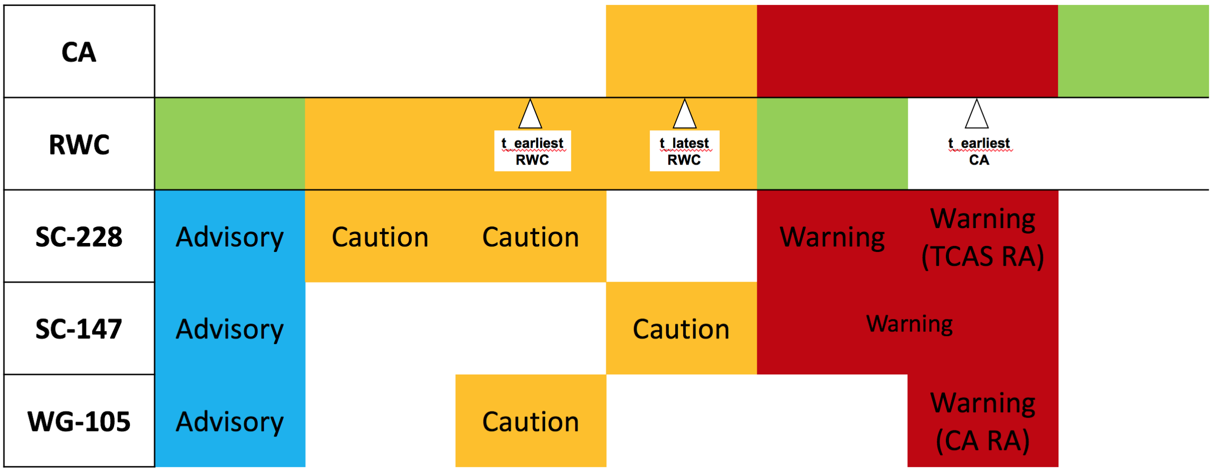

Figure 3: The alerting timeline has three main events: earliest time to make a Remain Well Clear (RWC) manoeuver, latest time to make a RWC manoeuver, and earliest time to make a Collision Avoidance manoeuver. The alerts for each of the systems envisioned by RTCA SC-228, SC-147 and EUROCAE WG-105 are distributed with respect with these milestones.

Both cooperative (i.e. transponder or ADS-B equipped) and non-cooperative intruders were considered, equipped with any type of CA system or DAA, and with the following maximum performances: speed 600knts, vertical rate 5000ft/mn, horizontal acceleration 1.5g. One of the crucial hypothesis of the SC-228 work is that an RPA might fly without a CA function, and rely solely on a RWC function. In this context, the DAA system was required to have a RWC function and optionally a ACAS II system for CA. But the focus of this work was on the RWC part. Based on models and experiment results provided by the NASA, AFRL and MIT, the SC-228 selected a fixed definition for the RWC volume based on time and distance values (see Figure 4). The experiments leading to this choice are described in detail in [7]. A RWC threshold around this volume is considered to provide an alert when LoWC is predicted.

Because CA is optional, three alert, with two different levels, have been used for the RWC function alone: preventive (=caution), corrective (=caution) and warning; additionally, ACAS II, if equipped, provides a second warning alert in the form of a Resolution Advisory (RA), note that Traffic Advisories (TA) are not issued. Guidances include showing headings leading to a loss of well clear (suggestive) and

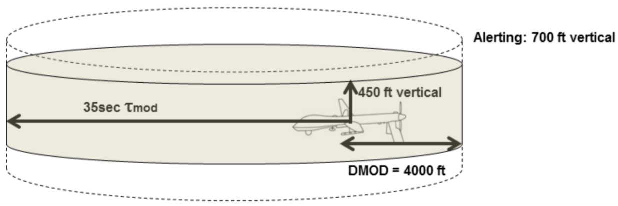

Figure 4: The Regain Well Clear volume defined by the RTCA SC-228.

providing instructions to regain well clear (directive) (cf. Figure 3). Automatic execution of RWC manoeuvers are not considered in Phase 1, though the CA maneuver can be automatic. These manoeuvers can be performed in the vertical or horizontal dimensions. With the start of Phase 2, efforts aim at looking into operations in more airspaces and in cases which require new definitions of RWC boundaries. Specifically, low cost, size, weight, and power sensors will have limited range so appropriate RWC boundaries should be chosen; and terminal area operations will require reduced separation distances asking for suitable RWC boundaries.

Because of harmonisation constraints, choices made by the

SC-228 affect the ACAS Xu definition work lead by the SC-147. Indeed, the ACAS Xu MOPS is expected to comply with the Phase 1 DAA MOPS, as is explained below.

2) SC-147: The SC-147 focuses on the whole ACAS family, especially on most recent one: ACAS X. In the RPAS case, they are in charge of writing MOPSs for the ACAS Xu system. Though ACAS Xu was initially planned to perform only the CA function, it evolved into a full DAA system integrating both RWC and CA functions. Thus, the work of SC-147 on ACAS Xu has been extended to RWC. The work from SC-147 is different from the one developed in SC-228, but the ACAS Xu RWC definition strives to support SC-228 DAA MOPS requirements. The evolution of ACAS Xu is organised around successive validation Runs (spirales) followed by tuning phases. In parallel, the SC-147 MOPS redaction is organised in Phases, just like for SC-228. The hypothesis of this group's work are similar to the ones of SC-228 except that the minimum considered altitude is 3800ft. Though the RWC and CA functions are mixed into a single function, we only consider here the information relative to the RWC part of this function. The ACAS Xu RWC function considers two boundaries: a look-ahead boundary, whose role is similar to the RWC threshold; and a RWC boundary, the limit of the RWC volume. Unlike in SC-228 definition, these two boundaries are not defined by a geometrical description but rather described in the ACAS Xu tables and optimized with each successive Runs. These boundaries are associated with three levels of alerts: preventive (=advisory), corrective(=caution) and warning (cf. Figure 3). The advisory and caution alerts are accompanied by a suggestive guidance while the warning alert gives a directive guidance. It is interesting to note that the warning alert can be given both as a part of RWC or CA sub-functions, but there is only one warning alert. In Run 3, guidance is only in the horizontal direction. Vertical manoeuvers are planned to be added in Run 4. In the meantime, Phase 2 will see timeline adjustments to improve the integration of the RWC and CA functionalities. Writing of the ACAS Xu ConUse is planned to be finished by the end of 2017 while writing of the ACAS Xu MOPS is planned to end by 2020 with harmonisation with SC-228 Phase 2 work. Resulting SC-147 ACAS Xu MOPS will try to comply as much as possible with the more general SC-228 DAA MOPS.

3) Harmonisation: With the extension of ACAS Xu to provide a RWC functionality, overlapping between the SC-228 and SC-147 scopes became a risk and led to the creation of three joint harmonisation groups, so called Tiger Teams, for surveillance, threat, and metrics and modelling. These three groups include members from SC-228 and SC-147 as well as members from EUROCAE's WG75 and WG105 (see below) for international harmonisation. The TTs have three goals: organise the work on the ACAS Xu MOPS, deal with scoping and design decisions thrown by the SCs, and deal with scoping overlap between the DAA and ACAS Xu MOPSs.

B. EUROCAE

In EUROCAE's history, three work groups have been involved in the standardisation effort for DAA systems, or parts of it. First, the WG-73 has been tasked with developing support documents for a CA function in airspaces A-C. The output of the group has been a CA function OSED. The WG-73 has since been reshaped to create the WG-105, described in the following. Second, the WG-75 focuses on ACAS systems, and lately on the ACAS X family. Their work is supported by external projects like Eurocontrol's CAFE simulator and the development of an encounter model for CA systems evaluation. This model could later be extended to evaluate RWC systems as well, though this is a difficult task that will ask for time and effort. The last, and largest, group dealing with DAA in EUROCAE is the WG-105, a counterpart to RTCA's SC-228. It tackles RPAS related standardisation efforts (C3, DAA, design and airworthiness, SORA, ERA; and more recently UTM and RPS). The DAA focus team is separated in three sub-groups: DAA airspaces A-C (CA only); DAA airspaces D-G (RWC + CA); and DAA airspaces Very Low Levels (VLL). The RWC definition is in the scope of the DAA D-G sub group, as there is no mandatory ATC separation services in these airspaces, thus requiring a self-separation function: the RWC function. As opposed to the RTCA, work done by EUROCAE adopts a top-down approach and actively seeks to avoid limiting future implementation choices.

Though starting their work on the topic somewhat later than the SC-228, current work from EUROCAE WG-105 tackles a broader scope than RTCAs phase 1. Indeed, it considers "en route" phases of the flight in airspaces A-G + VLL. Intruders hypothesis are the same as for SC-228. For ownship, minimum equipage includes a CA system, plus a RWC system in airspaces D-G. Even if the CA and RWC functions belong to two different systems, it is considered that the CA system engages as soon as WC is lost. Pilots acceptability studies have been carried out to propose RWC boundaries [8]. Such boundaries would allow to provide advisory and caution alerts with continuous guidance being displayed and updated as long as the CA does not provide a warning, as in [9]. The hypothesis that all RPAS will have a CA function led to the absence of warning alert in the RWC function (cf. Figure 3). This represents a difference with the RTCA approach, as there is no alert when the Right of Way rules start constraining the RPA manoeuvres (LoWC). Current work focuses on the choice of guidance type at the different levels of alert with the possibility to have semi-automatic execution of the RWC guidance. More generally, an Operational Service and Environment Description (OSED) is being developed to bring forward requirements and assumptions for the DAA system, including the RWC function.

C. ICAO

The ICAO is currently pressured into proposing a useful definition for WC. Discussions in the DAA SARP panel are centered around the formulation of such definition. It should be precise enough to be useful but have a large enough scope to allow a diversity of solutions answering the problem. Their output is crucial as this will provide a definition on which EUROCAE and the RTCA will continue to build their work. According to the previous decomposition of a RWC definition, a formal definition from their part can be expected to define the events which start and end the RWC function (related to boundaries) as well as the actors involved (related to alerting) and possibly the actions expected (related to guidance). Care need to be taken not to enter into too much details so as to not limit possible solutions.

On all sides, the work on defining WC and RWC is advancing and coordination between the entities will ensure a coherent result. The main situations are being addressed, still some topics are not part of the discussions. The next section mentions some of them and proposes some discussions.

IV. Discussions

This section aims at fueling discussions on some topics which are not yet covered by existing efforts: non-binary loss of well clear, CA vs Regain Well Clear, RWC for low performance RPAS.

To begin with, the loss of WC (LoWC) is currently being considered as a binary value: an aircraft is well clear or not. Though, metrics to measure the severity of a LoWC have been proposed [10] and are already used in Verification and Validation simulations [11]. Though, including them in the current discussions would increase the difficulty of an already difficult task, it could be beneficial for the safety of a RWC function. Indeed, allowing low severity LoWC could allow a RPA to lose WC momentarily in order to avoid a potentially dangerous situation later.

Some approaches do not consider a CA function, but they do consider a Regain Well Clear (RegWC) sub-function. The difference between RegWC and CA is not clear, so we propose three differentiating elements. First, some regulatory bodies ask for the RWC and CA functions to be independent, which would not be the case in a RWC/RegWC system. Second, the RWC/RegWC system implies that a LoWC would immediately trigger the RegWC, which would not be necessarily the case for a CA function which could trigger some time after LoWC. Third, the end of a CA event is indicated by a Clear of Conflict (CoC) related to a collision volume, the end of a RegWC event would be linked to a WC volume. From a coordination point of view, it is not clear if a RegWC manoeuver would be required to be interoperable with existing ACAS systems. As the RegWC solutions is being pushed, a clear definition of RegWC will become necessary.

Current definitions associated to the notion of RWC are being developed for integrated airspace operations with RPAS performances at least close to those of General Aviation (GA). However, as lower performances RPAS will ask to enter integrated airspace, there will be a need to adapt existing definitions for their performances in terms of RPA dynamics and sensors capabilities. To allow low performance RPAS into airspace will ask for a delicate balance between safety and performance requirements.

V. Conclusion

Many RPAS integration efforts are currently focused on quick wins, mainly integration in controlled airspace. However, complete integration will only be accomplished when RPAS will be able to fly in any class of airspace. For this purpose, the definition of WC and its associated DAA functionality, the RWC, are crucial elements. Current efforts from RTCA and EUROCA, with helper projects from NASA and SESAR-JU, are progressing in this aspect, but the available resources does not seem to match the complexity of the task at hand. In the meantime, work from the ICAO's SARPS, generic as it may be, will provide strong foundations on which regulators will be able to lean when defining country specific rules. Even if the basis for nominal operation are not established yet, one can see that there is still more work to do e.g. for closely spaced operations and terminal manoeuvering areas. From the point of view of our work, future leads include gathering elements to propose a formal definition of the Regain Well Clear function and assessing low power sensors capabilities for RWC.

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