D3.3 – Drone Risk Assessment Digital Assistant

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Abstract

In this deliverable, we define a digital assistant supporting drone risk assessment, particularly in beyond visual line-of-sight (BVLOS) operations, by leveraging data intensive algorithms to analyse historical large-scale air traffic data. The Digital Assistant produces drone air risk maps, enabling users to make informed decisions in accordance with safety requirements for drone operations in the specific category according to EU drone regulation.

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1 Introduction

In this deliverable, we define a digital assistant supporting drone risk assessment, particularly in beyond visual line-of-sight (BVLOS) operations, by leveraging data intensive algorithms to analyse historical large-scale air traffic data.

A data intensive tool is adapted to assist drone pilots and mission dispatchers in evaluating safety risks and optimizing mission parameters to mitigate potential losses of separation and mid-air collisions. The tool uses machine learning models and statistical techniques to process data from various sources, including ADS-B, Mode S, and FLARM [AirData2], to generate quantitative air risk assessments. By integrating geographical and trajectory parameters, the tool provides spatially and temporally specific risk evaluations, enabling decision-making to ensure mission safety through pre-tactical mitigations.

The Digital Assistant provides drone air risk forecast, enabling users to make informed decisions in accordance with safety requirements for drone operations in the specific category according to EU drone regulation.

2 Regulatory Context

2.1 Drone Operation Regulations

Over the last ten years Europe has established a regulatory framework [DroneReg1] that deals with drone operations. This framework defines three operation categories: Open, Specific and Certified. The Open category groups low risk operations performed with low mass drones where the remote pilot is always able to visually observe the drone flight and the drone does not fly over people. The Certified category groups high risk operations such as people or dangerous good transportation. In between these two categories, the Specific category addresses medium risk operations. It contains operations where the remote pilot cannot always visually observe the drone flight, the drone could fly over rural, suburban or urban populated areas, the drone could fly in airspaces shared with manned aircraft. Examples of operations that fit in the Specific category are commercial or medical good deliveries (drones transport, for instance, medical samples from one hospital to another one) as well as infrastructure monitoring (drone flies over, for instance, a railway lines and captures images in order to detect degradations).

The EU regulation requires that the drone operator (potentially helped by the drone manufacturer) prepares a Specific Operations Risk Assessment (SORA) [DroneReg2, DroneReg3] for the proposed operation. The aviation authority checks the SORA results in order to decide whether the operation may be authorized.

2.2 SORA

Use-Case 3 Digital Assistant supports a part of the SORA . SORA uses a description of the drone operation and characteristics to assess its main risks, such as the drone colliding with people and infrastructure on the ground of the area of operations (ground risk) or the drone colliding with other aircraft in the area of operations (air risk). The SORA determines a Specific Assurance and Integrity Level (SAIL), which defines the operational safety objectives that the drone, pilot and operating company must satisfy.

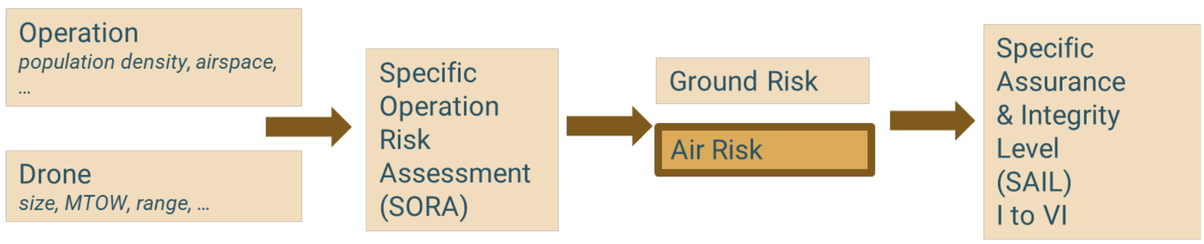

Figure 1 Specific Operation Risk Assessment (SORA)

Various companies developed tools supporting the SORA assessment (see for instance, SORA Tool, SAMWISE or AIRHUB). These tools usually automate the SAIL computation using qualitative assessments of ground and air risks. They also support the justification of operational safety objectives satisfaction by linking these objectives with drone, pilot and operating company documentation. The tools also support the drone operation authorisation process by preparing the required documents.

More recently, researchers have developed tools that quantitatively assess the Ground and Air Risk. In particular, ONERA developed DROSERA [DroneReg4] a ground risk assessment tool that is able to compute the population densities, roads, railways and power lines overflown by the drone. It also produces maps for risk localization and visualization. These results can be used to support SORA Ground risk assessment.

Use-Case 3 investigates a digital assistant that could support SORA quantitative air risk assessment following the ideas developed in [AirRisk4]. In the future, such a digital assistant could be integrated with DROSERA.

2.3 Qualitative Air Risk Assessment

The current SORA air risk assessment is based on a qualitative analysis of the airspace used by a drone operation. The following picture shows an airspace map and a proposed drone operation over a fast railway line between Marseilles and Avignon in France.

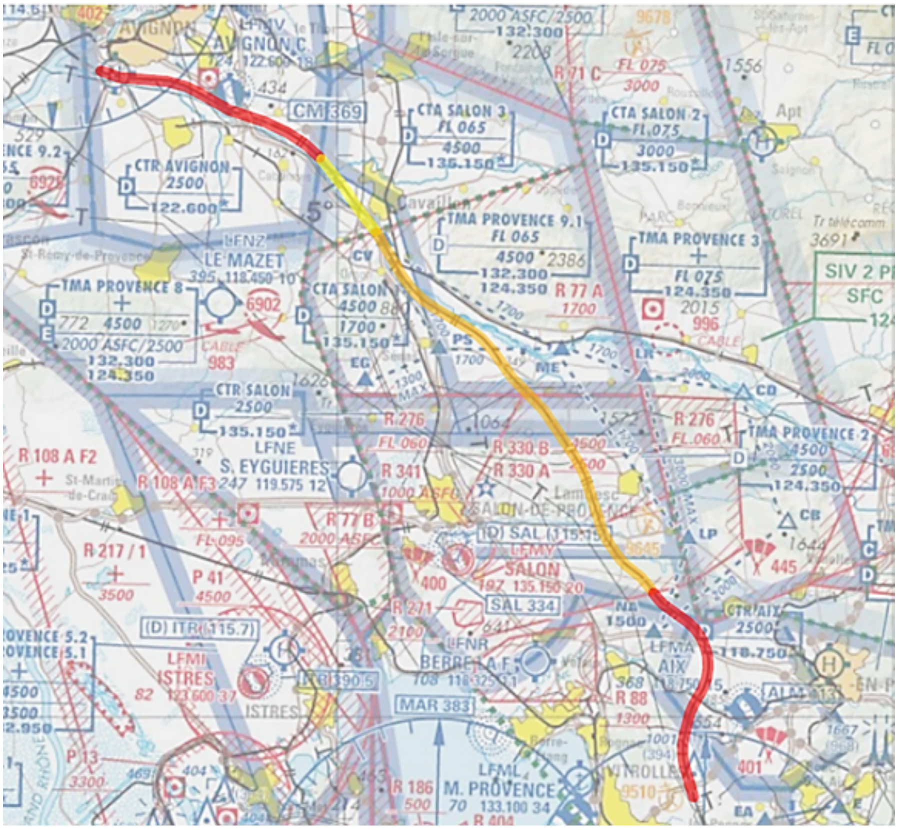

Figure 2 Airspace map used to support SORA Qualitative Air Risk Assessment

The initial air risk assessment is currently performed using a decision tree, taking as inputs the intended operating environment (airport proximity, airspace class, urban vs rural area, etc.) shown in the previous figure. This step determines the airspace encounter category and its associated air risk class (ARC), ranging from ARC-a (lowest risk) to ARC-d (high risk).

Based on the SORA decision tree, an operation following the fast railway line would belong most of the time to the airspace encounter category "*VLL in controlled airspace*" with a medium level of risk (ARC-c). This part of the flight plan is coloured in orange in the picture. Another significant portion of the flight plan belongs to category "*Ops in airport environment in class D airspace*" (ARC-d) because the fast railway line crosses various airport control zones (CTR Provence, Aix and Avignon). This portion is coloured in red. A much smaller portion of the trajectory belongs to category "*Ops over rural area*" (ARC-b). This portion is coloured in yellow. As a result, we could consider applying for a generalized, aggregated, initial air risk ARC-c.

Once the Air Risk and Ground Risk are assessed, a table is used to define the SAIL level of the intended operation. The following SAIL Determination Table would be applicable for a drone with dimension less than 3m, maximum speed less than 35 m/s and equipped with a parachute (this would lead to a Ground Risk Reduction of -1). The precise definition of population densities (Rural, Suburban, Urban, …) used in the table can be found in the SORA document [DroneReg3] and in the next section.

		Air Risk Class (ARC)			
		a	**b**	**c**	d
Ground Risk (Population Densities)	≤ Rural	I	**II**	**IV**	VI
	Rural	II	**II**	**IV**	VI
	Rural Residential	III	**III**	**IV**	VI
	Suburban	IV	**IV**	**IV**	VI
	Urban	V	V	V	VI
	Assemblies of People	VI	VI	VI	VI

Table 1 SAIL Determination Table (applicable when Drone size < 3m, speed < 35 m/s, equipped with parachute)

According to column for ARC-c air risk in the SAIL determination table, a SAIL IV drone should be authorized to perform the fast railway line monitoring operation as long as it does not fly over urban areas or assemblies of people.

Optionally, an applicant may ask for a reduction of the ARC by demonstrating that the actual level of risk is lower than the generalized initial ARC. This demonstration should typically be supported by an analysis of actual traffic data, based on a methodology up to now left to the applicant.

Given the initial ARC-c, the applicant may claim a reduction to ARC-b if the local density can be demonstrated to be similar to the reference environment "*VLL ops over rural area*". This density rating corresponds to an unmitigated Mid-Air Collision (MAC) rate of 10^{-7} per flight hour, that is equal to the target level of safety for general aviation. Consequently, the Digital Assistant should be able to support the computation of the unmitigated MAC for a proposed flight plan in order to justify such an ARC reduction.

The possibility to reduce the Air Risk Class to ARC-b would allow to perform the fast railway monitoring operation with a SAIL III drone in Rural areas. Furthermore, if this is combined with another ground risk reduction justified by a ground risk quantitative assessment then it could be possible to use a SAIL III even in Suburban areas. In that case a majority of the railway line between Marseilles and Avignon could be monitored with SAIL III drones that should be more affordable than SAIL IV drones.

The SORA is an evolving framework that adapts itself using the feedback from the drone community. EASA and member states have been applying SORA 2.0 and they are now transitioning to SORA 2.5 that was published in 2024. SORA 2.5. mainly focused on clarifications needed to perform Ground Risk assessments. JARUS experts are currently defining SORA 3.0. This is SORA next version that will focus on a more accurate air risk model, enabling better airspace integration. The definition of SORA 3.0 includes work on quantitative assessment of Air Risk. Consequently, people involved in the definition of Use-Case 3 interact on a regular basis with JARUS experts.

2.4 Drone Operation Authorisation Process

Once the SORA assessment is performed, its results are used by the drone operator to request a drone operation authorisation to the aviation authority. Existing SORA tools help the drone operator to collect all the requested information and send formal authorisation requests.

Quite often, especially when ground or air risk class reductions are requested, a dialogue between the drone operator and the aviation authority is established in order to reach an agreement about the results of the ground and risk assessments. Justifications about the underlying hypothesis, tools, data that were used for the assessment are exchanged between the drone operator and the authority. Tool support for this dialogue is currently rather limited.

Recent experiments of DROSERA by drone operators and DGAC, the French aviation authority, showed that using a common ground risk assessment tool could have a positive impact on the dialogue between operators and authority. The conclusion of the experiments stressed the importance of the explainability of the assessment. Tools supporting risk assessment should be able to provide clear explanations about aspects such as quality of data sources, justification of hypothesis, explanation about algorithm accuracy and uncertainty, …

More generally, EASA is promoting the idea of an automated SORA process based on shared assessment tools. This initiative is called eSORA. According to [AirRisk15], a team of researchers from Queensland University together with Boeing Australia have defined a quantitative risk assessment approach that enables the automatic processing of drone flight authorisation request. Unfortunately, as it is covered by a patent there is limited public information about this approach.

A digital assistant that implements and explains quantitative air risk assessment could support the authorisation dialogue and contribute to an increased automation of the drone operation authorisation process.

3 System description

3.1 Digital Assistant General Principles

The main functionality of the system is to produce an Air Risk Map that shows the air risk index in each cell in a buffer around the intended flight plan.

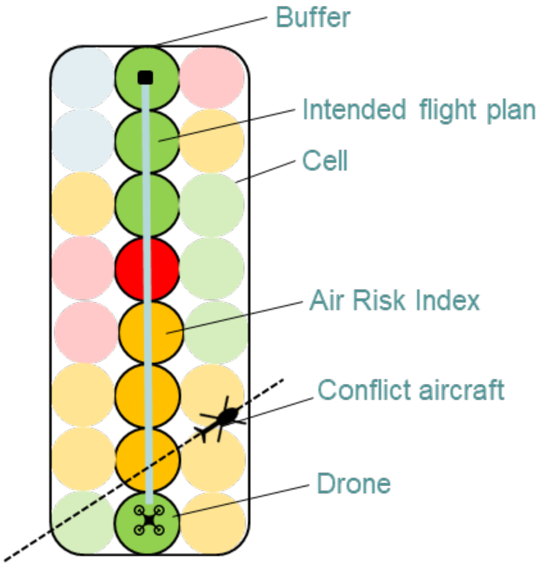

Figure 3 Air Risk Map

The main interactions between the SafeTeam Digital Assistant and the users are:

1. The user defines an intended flight plan, its buffer as well as the number and size of cells.
2. Digital Assistant (DA) uses collected air traffic data to compute the risk index in each cell and produces an Air Risk Map
3. DA computes whether the intended flight plan is safe according to the Air Risk Map. Other mission performance and uncertainty metrics are also computed at this step.
4. If the flight plan is not safe then the DA should recommend alternative flight plans that improve safety, mission performance and uncertainty metrics.

For all steps (1-4), DA should provide the user with explanations about the required inputs and about the methods used to compute the outputs (e.g. air risk index, air risk maps, safety, mission performance and uncertainty metrics).

The idea of producing maps to support air risk assessment was recently investigated by several teams in Italy, Sweden and Australia [AirRisk6,7,8,9]. One novelty of the approach explored in this document is that, when the assessment of the intended flight plan is not successful, the digital assistant explores strategies in order to produce alternate acceptable flight plan.

3.2 Air Risk Maps

3.2.1 Computation

We provide here a summary of Air Risk computations; a more detailed description may be found in the Air Risk Computation Appendix.

To produce an Air Risk map, we have to compute the air risk index for each of the cells in the buffer of the flight plan. The following picture shows three air risk situations: Well-Clear Violation, Near Mid-Air collision (NMAC) and Mid-Air collision.

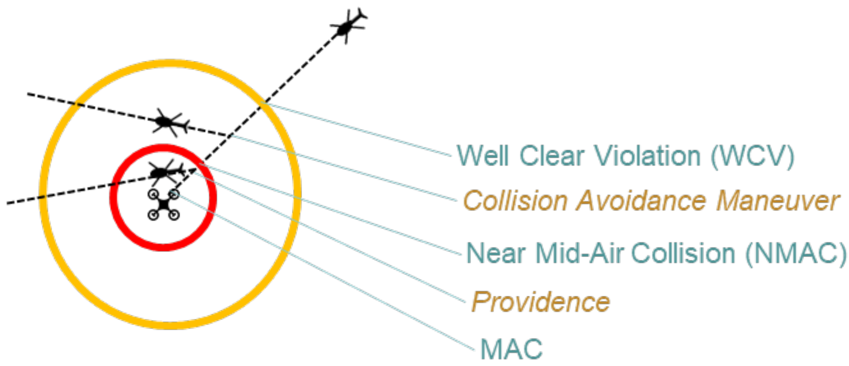

Figure 4 Air Risk Situations

Each air risk situation is caused by the joint occupancy of a cell by the drone and an intruding Aircraft. A well-Clear Violation (WCV) occurs when the drone and the intruder aircraft are closer than a predefined distance. In this situation either a successful collision avoidance maneuver is performed or NMAC occurs. When a NMAC occurs either Providence avoids the collision or MAC occurs.

The probability of MAC situation in a cell can be computed using the following equation [AirRisk12]:

(Equation 1) p(MAC) = p(MAC | NMAC).p(NMAC|WCV).r(WCV)

- p(MAC|NMAC) is the conditional probability of MAC when NMAC occurs, it is the probability of lack of providence and we note it NoProvidence in the following of this document.
- p(NMAC|WCV) is the conditional probability of NMAC when WCV occurs, it is the probability of absence of avoidance maneuver when needed and we note it NoAvoidance in the following of this document.
- r(WCV) is the rate of well-clear violation per hour. It is the product of the drone cell occupancy probability, the aircraft cell occupancy rate and the below factor.
    - Drone cell occupancy probability (noted DroneCellProba) is computed using the drone speed, the cell size and the number of planned drone operations during the observation period.

- The aircraft cell occupancy rate (noted AircraftIntersection_) is derived from the analysis of ADS-B and FLARM traffic data. Each aircraft overflying the cell at an altitude up to 1000 m is counted during the observation period.
- A Below factor is applied in order to compute the probability that the aircraft observed up to 1000m could actually fly at 120 m due to an abnormal situation. This below factor depends on aircraft type. For instance, a helicopter is more likely to fly at 120 m than a general aviation aircraft.

So MAC probability is computed by the formula:

NoProvidence * NoAvoidance * DroneCellProba * AircraftIntersection_h * Below

The MAC probability for a flight plan is the sum of the MAC probabilities over all the cells of the flight plan.

The Flight Plan is acceptable with respect to air risk if its MAC probability is smaller than the target level of safety that is equal to 10^{-7} per hour for the General Aviation category.

3.2.2 Risk levels

The air risk map displays the aircraft cell occupancy rate of each cells. We selected this air risk index because we wanted to use concepts similar to the one used by the ground risk assessment that is usually based on maps showing the density of population of overflown areas. The Aircraft cell occupancy rate can be viewed as an aircraft density over a cell.

We use colours to indicate the level of air risk of cell. We have again tried to use levels of air risk that share some similarity with population density levels used in the ground risk assessment. Ground Risk levels in SORA 2.5 are defined with a factor of ten between the minimal and maximal value in one category of population densities. For instance, the density in a Suburban area ranges from 500+1 to 10*500 people per square kilometre.

Population Densities (people/km^2)	Qualitative Descriptors
< 5	Remote
5 to 50	Rural
51 to 500	Sparsely Populated /Rural Residential
501 to 5,000	Suburban Low Density Urban
5,001 to 50,000	High Density Urban
> 50,000	Assemblies of People

Table 1 SORA 2.5 Population densities classes

A similar table for Aircraft density does not currently exist in the SORA. We propose to define four air risk levels based on the contribution of the cell risk index to the probability of MAC.

We first consider typical values for all the variables contributing to the MAC probability:

- NoProvidence ~ 10^{-2},
- NoAvoidance ~ 10^{-1},
- Drone occupancy ~ 10^{-2}
- Below ~ 10^{-2}.

With these values and considering that Aircraft Flight Plan Occupancy is the sum of AircraftIntersection_h for all the cells of the flight plan:

MAC ~ 10^{-2} * 10^{-1} * Aircraft Flight Plan Occupancy * 10^{-2} * 10^{-2}

MAC ~ 10^{-7} * Aircraft Flight Plan Occupancy.

It is sufficient that Aircraft Flight Plan Occupancy < 1 /h so that MAC < 10^{-7}/h. Consequently, the MAC probability would be acceptable as long as less than 1 aircraft per hour overflows the cells of the intended flight plan. We call this value the Budget allocated to the flight plan. This Budget might need to be adjusted when hypothesis about the typical values of the variables contributing to the MAC probability change. We use the Budget in order to define the 4 risk levels:

- High Risk: The cell risk index is greater than the Budget. The cell is coloured in Red.
- Moderate Risk: The cell risk index is greater than Budget/10 and smaller than the Budget. The cell is coloured in Orange.
- Low Risk: The cell risk index is greater than Budget/100 and smaller than Budget/10. The cell is coloured in Green.

- Unknown Risk: The cell risk index is smaller than Budget/100. We consider such values as suspiciously Low. It is likely that not enough traffic was observed in this cell because the ADS-B and FLARM ground receivers do not cover adequately the cell. The cell is coloured in Light Blue.

A Budget of 1 aircraft/h would be similar to observing 500 aircraft during an observation interval of 500 h. The following table relates the qualitative risk levels with number of aircraft observed in a cell during an observation period of 500 hours.

Aircraft Densities (Aircraft/500 h)	**Qualitative Risk levels**	**Colour**
< 5	Unknown Risk	Blue
5 to 50	Low Risk	Green
51 to 500	Moderate Risk	Orange
> 500	High Risk	Red

Table 2 Air Risk Levels

The following picture shows the air risk map for the Aix-en-Provence and Marseilles area in the South of France. It covers the southern part of the fast railway line that was introduced in the previous section.

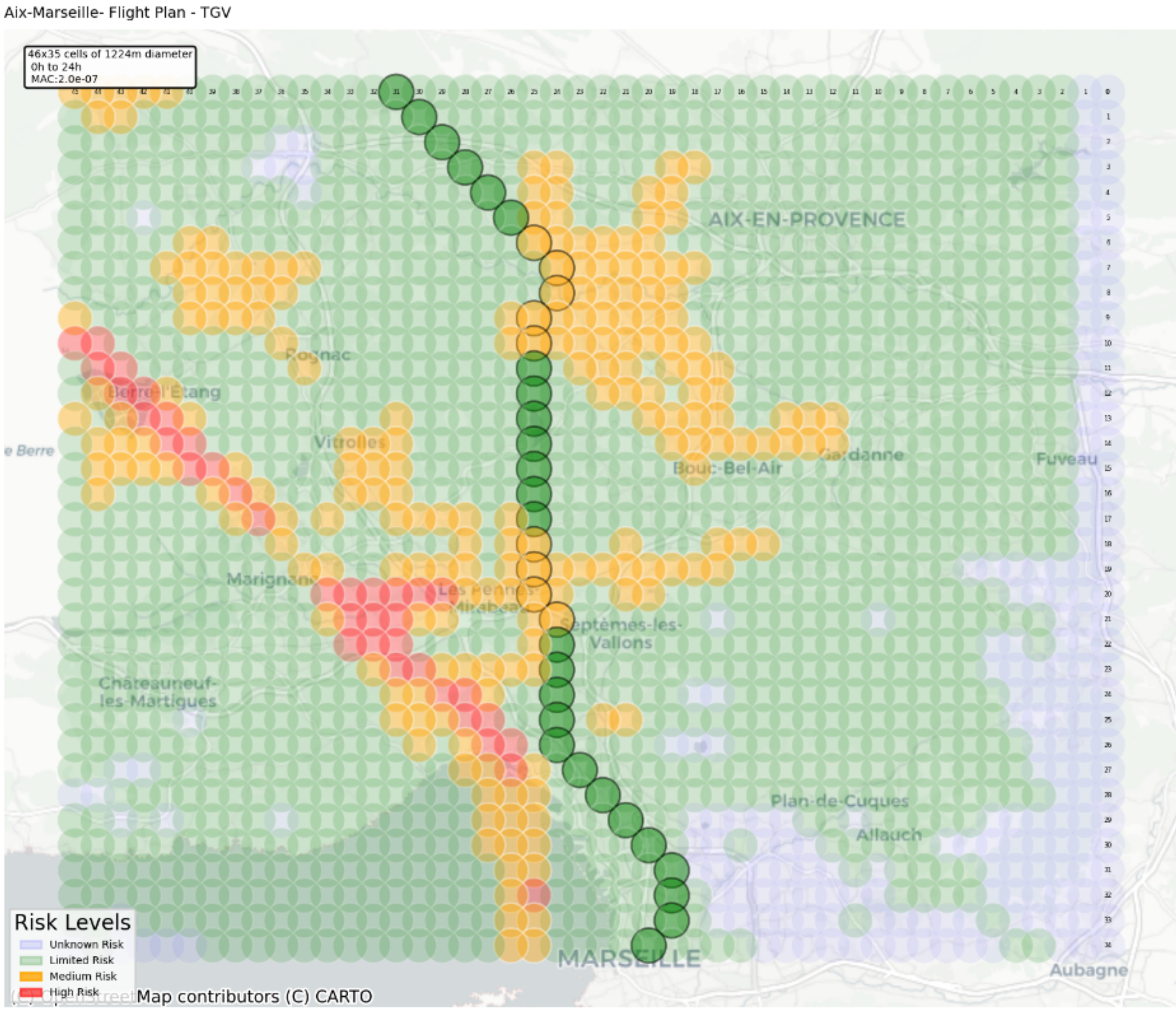

Figure 5 **Air Risk Map for the fast railway line in Marseilles-Aix area**

Red cells in the map show the commercial traffic landing or taking-off from Marseilles-Provence airport. Clusters of orange cells show general aviation traffic around Aix-Les milles, Berre La Fare and Salon aerodromes. Blue cells are mainly located in the south-east of the map, this is likely to indicate a lack of coverage of this area by the ADS-B and FLARM ground receivers. A more detailed analysis of the air traffic in this area is described in [AirRisk5].

The highlighted cells show the intended flight plan overflying the fast railway tracks. The user can quickly assess the air risk by checking the existence of red, orange or blue cells. The intended flight plan mainly intersects with low risk cells coloured in green. The flight plan intersects with a few orange cells (4 cells between Les Pennes-Mirabeau and Septèmes-les-Vallons and again 5 cells east of Aix). These are the 9 cells whose air risk should be precisely estimated. Fortunately, the intended flight plan does not intersect with red or blue cells.

Intersecting with a red cell means that the MAC probability would not be acceptable as more aircraft than the Budget would overfly this cell. The intended flight plan must avoid red cells.

Intersecting with blue cells pose the problem of underestimating the actual MAC probability because the count of observed aircraft over the blue cells could be much smaller than the count of aircraft actually overflying the cell. We suggest to set an acceptability threshold for the maximal number of blue cells in the intended flight plan.

The MAC probability for this intended flight plan is not acceptable because it is equal to 2. 10^{-7} that is twice the acceptable level. The global count of aircraft overflying the cells is 2,8 per hour. Orange cells contribute up to 60% of this count whereas they only account for a third of the cells in the flight plan.

We defined a set of 36 North-South flight plans. Each flight plan is made of 35 cells that cross vertically the Aix-Marseilles area. We use these flight plans to validate the air risk computations and compare the efficiency of risk avoidance strategies

17 North-South flight plans out of 36 have a MAC probability smaller than 10^{-7}/h. But several of these flight plans have a lot of Blue cells so we have to discard them as the computation of the MAC probability is uncertain. If we set the maximal acceptable ratio of Blue cells to 25% then we have to discard 5 flight plans and only 12 flight plans would be acceptable.

We note that most of the acceptable flight plans contain a vast majority of green cells and a small number of blue cells. A few acceptable flight plans contain a mix of green cells together with a very limited number (less than 3) of orange cells. All flight plans containing red cells are unacceptable.

3.3 Risk Avoidance Strategies

When the MAC probability is not acceptable then there are several options that can lead to risk reduction. One option is to add risk mitigation means on board the drone in order to improve the capability to detect intruding aircraft and to perform maneuvers in order to reduce well-clear violations and avoid collisions. This should lead to a reduced MAC probability. The drone community is actively investigating air risk mitigations but, by now, there is no consensus on the best approach for air risk mitigation. Hence current drone regulations do not mandate the drones to be equipped with specific Detect and Avoid equipment.

Another option is to avoid the risk situations. This strategy is currently applied by drone operators when the intended flight plan overflies areas with high population density. They define flight plans that circumvent urban areas. Similarly, the air risk map could be used in order to propose alternate flight plans that avoid flying in cells with high aircraft density.

We must note that there is an important difference between ground and air risk assessment. Ground risk is based on population density maps that are mainly static. It is assumed that the population density does not change a lot over time. Aircraft density could vary more than population density. Commercial aviation that follows the same routes around the same time of the day could be supposed not to vary a lot. But trajectories of other airspace users such as emergency helicopters, aircraft used for aerial work or leisure aircraft can vary a lot. So even if the intended flight plan has an acceptable MAC probability there is a possibility that aircraft are present in some of the cells. Hence, it is very important that air traffic surrounding the drone operations is continuously monitored. A U-space service provider [DroneReg5, DroneReg6] could monitor the traffic in the surrounding area and alert the drone remote pilot in case of an aircraft intrusion into the buffer of the intended flight plan.

3.3.1 Deviate Strategy

This strategy looks for flight plans that deviate slightly from the intended plan in order to avoid High and Moderate Risk cells. The strategy compares high and moderate risk cells with similar cells in the right-hand side and left-hand side flight plans. A deviation to the right or left cell is proposed whenever the aircraft density is lower than in the cell of the intended flight plan.

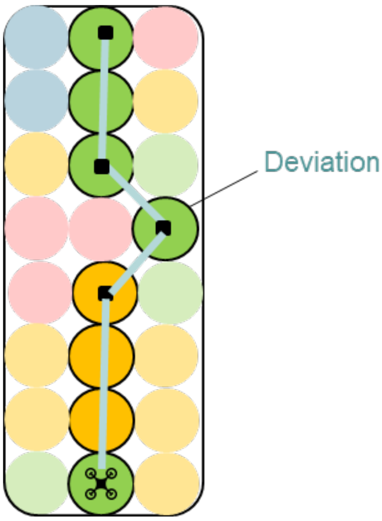

Figure 6 **Illustration of the Deviate strategy**

We have previously seen that the intended flight plan for the monitoring of the fast railway line contains 9 orange cells. The deviate strategy applied to this flight plan is able to propose an alternate flight plan that reduces the number of orange cells (from 9 to 1), the aircraft density from 2,8/H to 1,95/h and the MAC probability from 2. 10^{-7} to 1,5. 10^{-7}, that is still greater than the acceptable level of safety.

The next figure compares the Air Risk maps for the intended and deviated flight plans for a North-South flight plan 23 that crosses vertically the Aix-Marseilles area. On the left-hand side the map shows the intended flight plan that contains 8 orange cells, with a MAC probability of 2,1. 10^{-7}. On the right-hand side the map shows the deviated flight plan with 6 deviations that contains 6 orange cells, with a MAC probability reduced to 1,6 .10^{-7}.

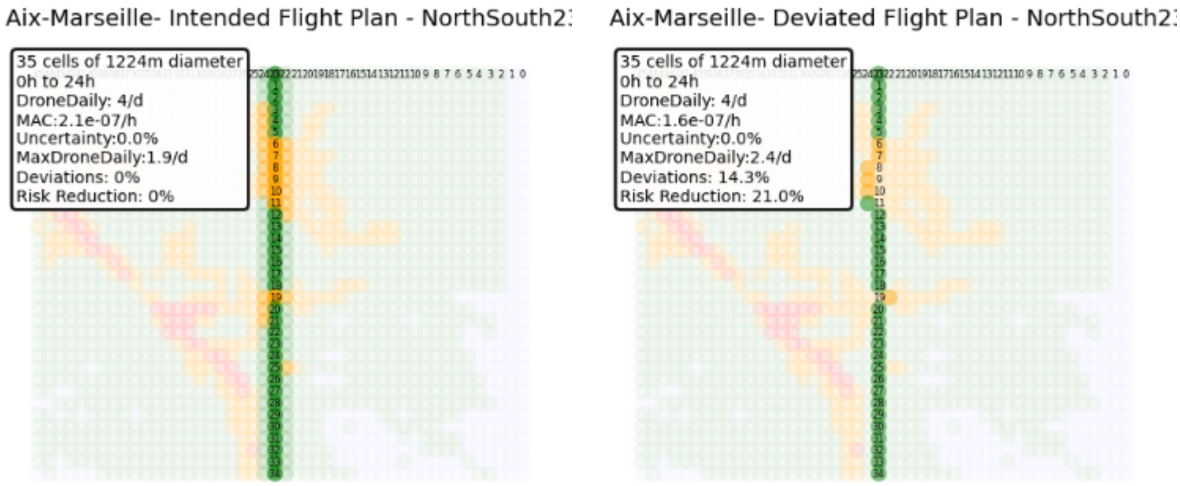

Figure 7 Air Risk for Intended and Deviated Flight Plans

More generally, the deviate strategy helps to decrease the MAC probability for all North-South flight plans. Some deviations greatly reduce the MAC probability (with MAC probability reduction between 50% and 70%), especially when red cells are replaced by orange or green cells. But the deviations are not sufficient to decrease the probability under the target level of safety. Hence other risk avoidance strategies have to be applied.

A drawback of the deviate strategy is that it can have a negative impact on the drone mission. For infrastructure monitoring mission it is important to fly as close as possible to the infastructure in order to capture high quality images of the infrastructure. So adding deviations where you cannot monitor the infrastructure might not be acceptable mission-wise.

3.3.2 Divide Strategy

This strategy divides the cells into cells of smaller radius. We have considered that the initial risk assessment would use large size cells of 612 m (2 000 ft) radius. The joint occupancy of such a cell represents a Well Clear violation situation. These cells can be divided into medium size cells with a 306 m (1 000 ft) radius that would represent a more severe well-clear violation. Medium size cells could be divided into small size cells with a 153 m (500 ft) radius that would represent a NMAC situation.

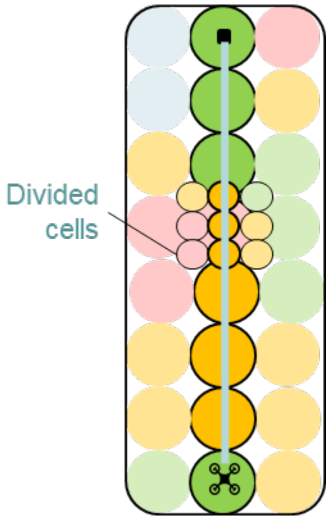

Figure 8 Illustration of the Divide strategy

The divide strategy is effective when a high or medium risk cell is replaced by less risky smaller cells. This occurs when aircraft overflying a large cell are not evenly spread over the cell surface and a smaller cell might have a much smaller aircraft density than the large cell. This is possible when the traffic follows pre-defined routes. The cells that do not intersect with the routes will have a much smaller density. In that case, the MAC probability of the intended flight plan could be reduced. But if the intended flight plan follows the same pre-defined route than the aircraft then the MAC probability would increase. In that case it might be interesting to combine the divide strategy with the deviate strategy in order to find a deviation that avoids high density cells

The Budget has to be adjusted in order to take into account the smaller size of the cells. Dividing by 2 the size of cells decreases the duration of occupancy of a cell by a drone by 2 but on the other hand the flight plan should contain 2 times more cells. Furthermore, values of NoProvidence and Below are considered to be unchanged. The increase of NoAvoidance due to the use of smaller cells leads to decreasing the Budget allocated to Aircraft density per hour.

The following figure shows the Air Risk map for Aix-Marseilles area using medium cells. When compared with the Air Risk map in figure 5, the red cells in this new map improve the visualisation of high-density predefined routes for landing and take offs at Marseille-Provence airport.

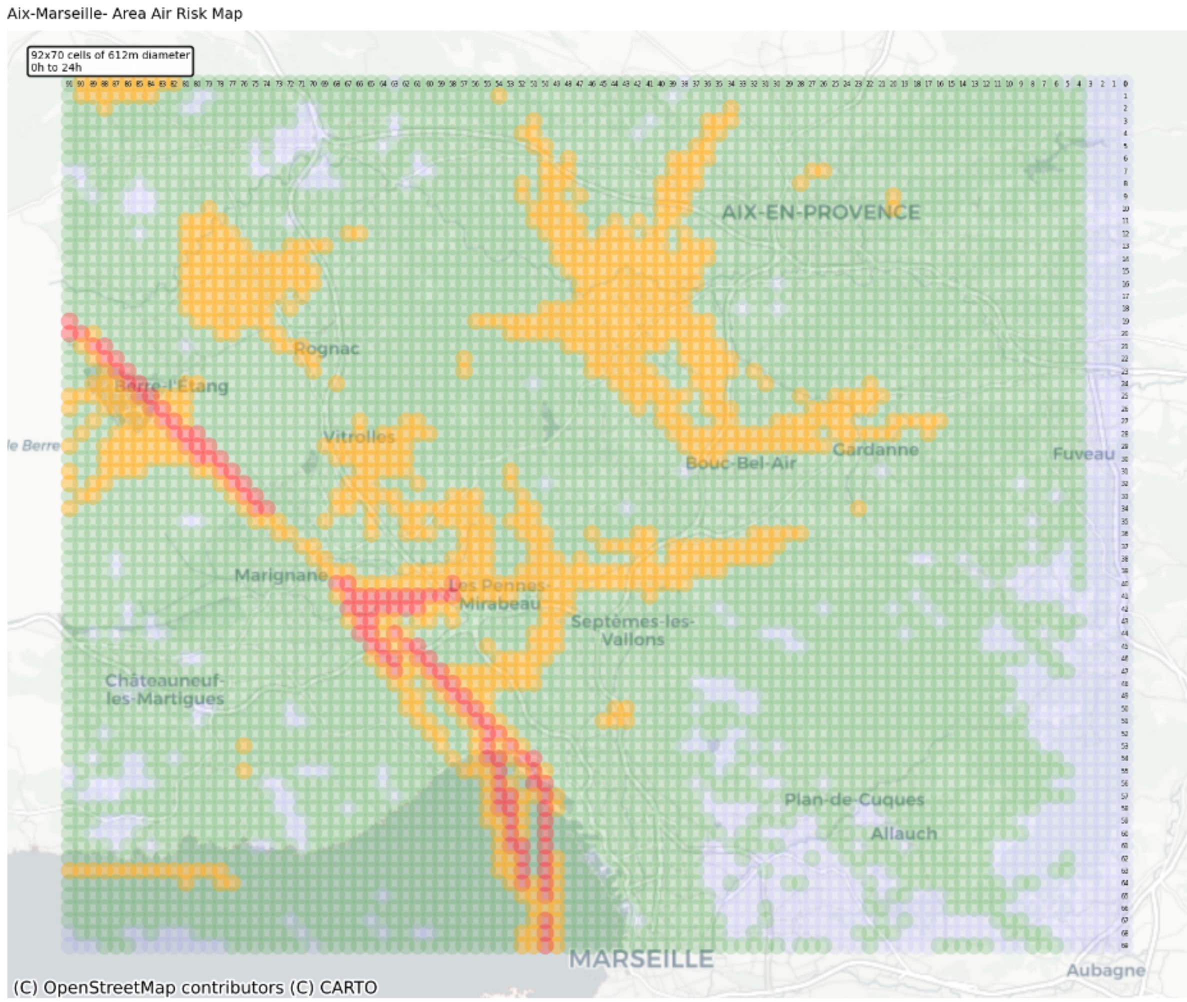

Figure 9 Air Risk Map using Medium cells

The next figure compares the Air Risk maps for the intended and deviated flight plans for a North-South flight plan similar to the one presented in figure 7. The MAC probabilities are unchanged: 2,1. 10^{-7} for the intended flight plan and 1,6 .10^{-7} for the deviated flight plan. The ratio of orange cells is slightly smaller when medium cells are used and the flight plans contain one blue cell. The deviated flight plan achieves the same reduction of MAC probability using a smaller ratio of deviations.

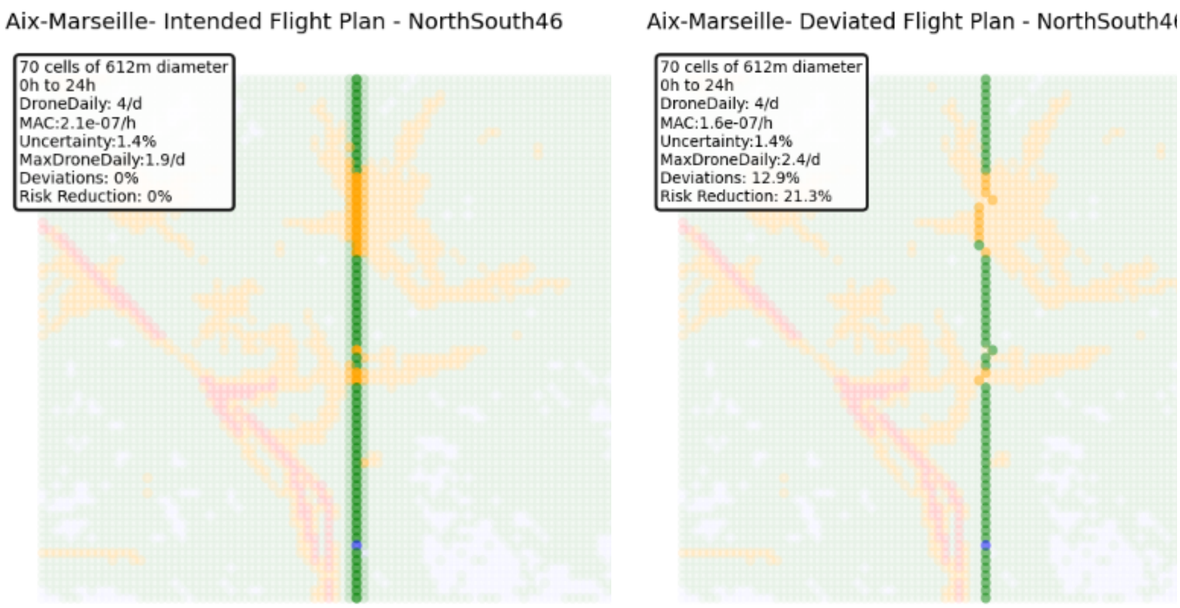

Figure 10 Intended and Deviated Flight Plans with Medium Cells

As there are 90*70 cells in the Air Risk map using medium cells we can define and assess 90 North-South flight plans. The same proportion of flight plans have an acceptable MAC probability than with the air risk map based on large cells. When the deviate strategy is applied with medium cells, there is a general reduction of the MAC probability. For a few (6 out of 70) flight plans the MAC probability can be sufficiently reduced to be acceptable. Interestingly, the MAC probability reductions are generally achieved using a smaller deviation ratio than with large cells.

One drawback of the divide strategy is that as the size of the cells decrease the value of NoAvoidance increases. So even if the aircraft density in these smaller cells decrease, the increase of NoAvoidance might not provide a much smaller MAC probability.

3.3.3 Delay Strategy

The simplest strategy to reduce risk is to decrease the number of daily drone flights. The drone cell occupancy probability depends linearly on the number of drone operations per day. Dividing by a factor the number of drone operations per day, leads to dividing by the same factor the drone cell occupancy probability and the MAC probability. For instance, in the case of the fast train line intended flight plan, dividing by 2 the number of drone operations would lead to an acceptable MAC rate of 10^{-7}. We call Maximal Drone Daily the maximal number of daily operations that could be performed while satisfying the MAC probability target. This number could be much smaller than the intended number of drone daily operation. It might not be acceptable from the economical point of view to decrease too much the number of daily drone operations.

If we want to keep the number of daily operations unchanged we could also try to postpone some drone flights to time slots with less aircraft density. We can filter ADS-B or FLARM Air Traffic data to select aircraft flying during a given time slot and compute Aircraft densities during this time slot. Air Risk maps for several time slots such as: Morning (6h-12h), Afternoon (14h-18h), Evening (18h-24h), Night (0h-6h) can be produced. We could also produce air risk maps for time slots with a smaller duration such as 1h or 2h time slots.

The delay strategy is effective when aircraft overflying the buffer are not evenly spread over time. This is often the case because there are only a few general aircraft flying during the evening and the night, and less commercial aircraft are flying by night.

The four maps in the figure below show the Air Risk for various time slots. The traffic to Marseille-Provence airport is almost continuous. So there are red cells along the routes to and from this airport in the four maps. The traffic in Aix-Les Milles, is inactive in the night and it is more active in the morning than in the afternoon. This area is covered by green and blue cells during the night and the evening. The area has more orange cells and red cells during the morning than during the afternoon.

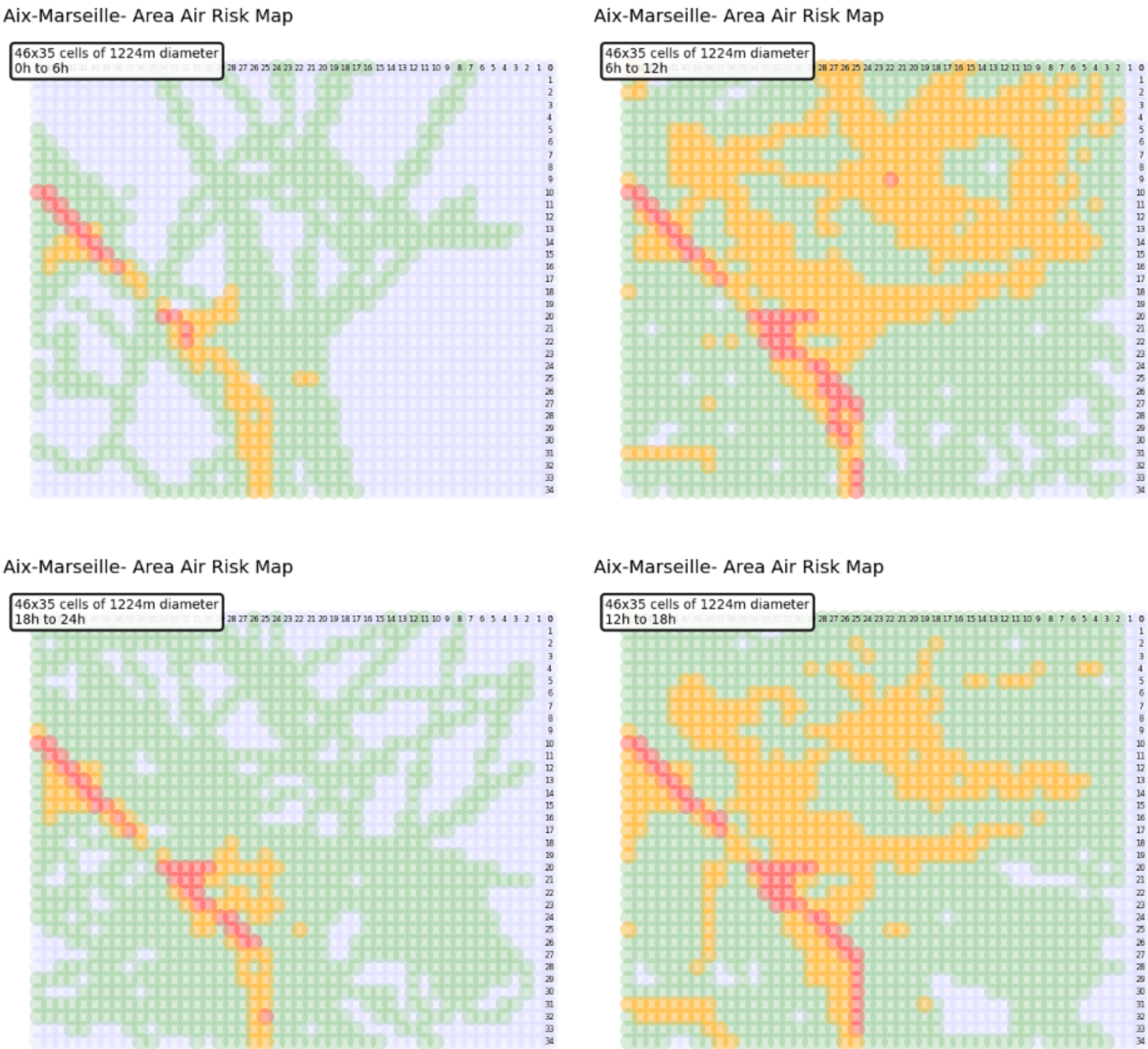

Figure 11. Air Risk maps for time slots (0-6h,6-12h,12-18h and 18-24h)

The Budget has to be adjusted in order to take into account the smaller amount of observation time. We have divided the traffic air data into 4 time slots (0h-6h, 6h-12h, 12h-18h and 18h-24h) consequently we divided the original Budget by 4.

A limitation of this strategy is that air risk maps for night time slots might have very low aircraft density resulting in a high number of Blue cells (Unknown Risk). Consequently, the MAC probability computed for these time slots could be regarded as very uncertain. Another limitation of this strategy is that flying by night might be incompatible with the mission success. For instance, daylight might be needed to correctly monitor an infrastructure, or the drone noise could be unacceptable in suburban areas by night.

3.4 Safety, Uncertainty and Mission performance Metrics.

The Digital Assistant computes several metrics that help to assess and to compare the merits of flight plan alternatives. The metrics are related with Safety, Mission performance and Uncertainty aspects.

MAC probability is the main Safety metric. We associate to this metric the Target Level of Safety (TLOS) that helps to evaluate whether the flight plan is acceptable with respect to safety. In order to assess the efficiency of the risk avoidance strategy, we also compute the Risk Reduction ratio (RR) that is equal to the difference between Intended flight plan MAC probability and Risk Avoidance flight plan MAC probability divided by the Intended flight plan MAC probability. The higher the Risk Reduction is, the more efficient the avoidance strategy is. This metric is used by JARUS experts to compare the efficiency of mitigation means.

We already mentioned that we wanted to measure uncertainty about the safety computations. A basic metric that can be easily measured is the ratio of Blue cells representing cells with very low aircraft density over the total count of cells in the flight plan. We relate this metric with a threshold that defines the maximal percentage of blue cells in a flight plan. Flight plans with a higher percentage of blue cells than this threshold will be considered as unacceptable with respect to uncertainty.

The last category of metrics can be related with mission performance. It helps to evaluate whether the risk avoidance strategy (e.g. deviate, divide or delay) generates flight plans that are acceptable mission-wise. The strategies might introduce deviations (deviate & divide strategy) or delays (delay strategy). The deviation metric is measured by the number of cells in the deviated flight plan that do not belong to the intended flight plan divided by the number of cells in the intended flight plan. The delay metric is the difference between the intended number of drone daily operations and the maximal number of drone daily operations that can be performed while satisfying the safety objectives.

The comparison criteria between a flight plan adding deviations and another one adding delays might mission dependent. On one hand, for infrastructure (railway tracks, electricity distribution lines, roads, …) monitoring missions, adding too many deviations is not acceptable as it is not possible to properly monitor the infrastructure but adding delay to the mission might be acceptable. On the other hand, for logistics (medical samples and goods transport, commercial good delivery, …) missions, adding delay is not acceptable but adding deviations might be acceptable.

4 System Implementation

4.1 System Architecture

The general architecture of the Digital Assistant is a pipeline starting from data sources, going through data intensive computation and finally generating Air Risk maps. In the following we provide information about the three steps in this pipeline.

4.1.1 Data sources

ADS-B (Automatic Dependent Surveillance—Broadcast) is a technology based on transceivers, electronic on-board devices which help to identify aircraft on air traffic control (ATC) radars. Unlike transponders, transceivers emit signals on the 1090 MHz frequency but do not require interrogations. The FAA and the European Commission issued regulations to mandate aircraft to be ADS-B compliant [AirData8, AirData9], but these mostly apply to large and fast aircraft flying in designated airspaces. Low altitude ADS-B coverage is affected by the very low equipage rate for General Aviation aircraft, as documented in [AirData4]: as a result, even a ground receiver with a good low altitude coverage will not provide any trajectory information for a significant portion of General Aviation aircraft.

FLARM is, with TCAS [AirData5], one of the most widespread technologies for traffic awareness and collision avoidance, initially designed for gliders, light aircraft, rotorcraft, and drones. FLARM obtains its position and altitude readings from a GPS antenna and an internal barometric sensor, then broadcasts these together with forecast data about the future 3D flight track. At the same time, its receiver listens for other FLARM devices within range and processes the information received. Although the FLARM radio protocol features message encryption in order to ensure integrity and confidentiality, implementation and encryption keys are available. The Open Glider Network (OGN) maintains a tracking platform with the help of many receivers, mostly collocated with flying clubs operating light aircraft at local airfields. The OpenSky Network [AirData3] also collects FLARM raw messages, with data accessible to institutional researchers.

The transponders equipping most General Aviation aircraft are Mode A/C transponders only: they reply to Secondary Surveillance Radars (SSR) with squawk (Mode 3/A) and altitude information (Mode 3/C), by increments of 100 ft. Mode S is a further extension of Mode A/C where queries are addressed to specific aircraft (S stands for selective). We documented in [AirRisk5] how to combine trajectory information from those sources (ADS-B, FLARM and Mode S) to create density maps at various altitude levels, and use such distributions to compute a mid-air collision risk.

We used for the SafeTeam project two datasets. First, ADS-B and FLARM data collected below 3,000 ft (about 914 m) between 15 and 30 June 2022 in the vicinity of Salon-de-Provence air base (LFMY) in Southern France. This data sources covers the air traffic overflying the fast train line connecting Marseilles with Avignon. The area is approximately 5000 square kilometres.

The ADSB dataset includes 5766 flights performed by 1111 aircraft. With 4546 commercial flights mostly operating to/from Marseille Provence Airport. There are also 161 flights performed by military aircraft, 106 rotorcraft test flights by Airbus and Guimbal helicopters, 134 flights by firefighter aircraft and 72 Life & Rescue helicopter flights and 895 General Aviation flights. The FLARM dataset includes 650 flights performed by128 aircraft: 99 General aviation flights, 418 Glider flights, 76 glider tow-plane flights and 48 Parachute Drop-Plane flights.

The second dataset that we used collected ADS-B data from emergency helicopters in the Toulouse urban and suburban area during the whole 2022 year. The area is approximately 500 square kilometres. The dataset includes 1859 flights.

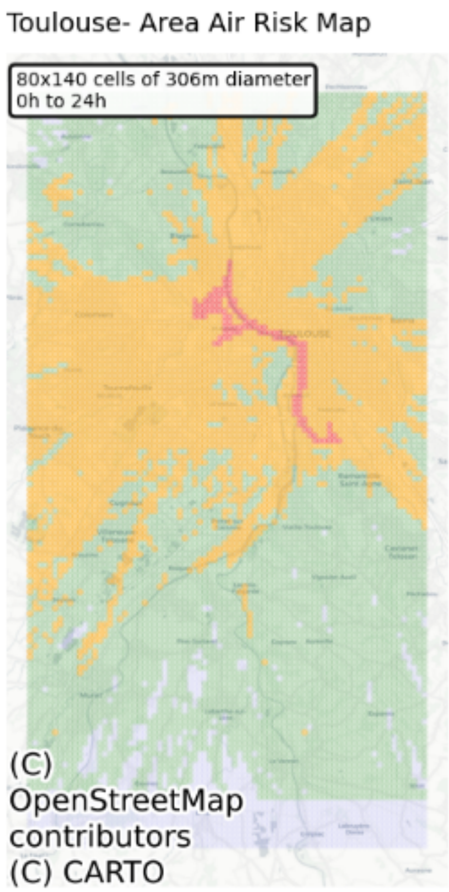

Figure 12 Emergency helicopter Air Risk map in Toulouse

4.1.2 Data intensive algorithms

Data intensive computations rely on various Python libraries. The Traffic library [AirData6] was very useful. This library connects to Opensky and retrieves air traffic data for a given period and geographical area. The main data structure used is a table of data combined with geometrical data.

An example of two lines in the flight data table built by Traffic with ADS-B information is given in the following table. It shows two aircraft positions separated by one second for emergency helicopter flight SAMU63_000.

callsign	geoaltitude	groundspeed	latitude	longitude	onground	timestamp	track	flight_id
SAMU63	1525	125	43.786895	1.500746	False	2022-10-05 09:24:07+00:00	216.869898	SAMU63_000
SAMU63	1500	126	43.78643	1.500288	False	2022-10-05 09:24:08+00:00	215.960517	SAMU63_000

The structure of the FLARM flight data table is very similar to ADS-B. One difference is that the table directly includes information about the aircraft type.

Once Traffic has built the flight data tables, it is easy to filter the ADS-B or FLARM messages based on the values of their attributes (column names). For instance, we used latitude and longitude attributes to select flights overflying the intended flight plan buffer. We also used the geoaltitude attribute to select flights flying under 1000 m. We used the timestamp attribute to select flights that are active during a given time slot.

The Traffic library enables the visualisation of a flight trajectory. The next figure shows the trajectory of a Cessna 182T Skylane general aviation aircraft that flew during 1h and 45 minutes. Traffic collected 6330 ADS-B messages, grouped them into a geometrical object defining the complex trajectory shown below.

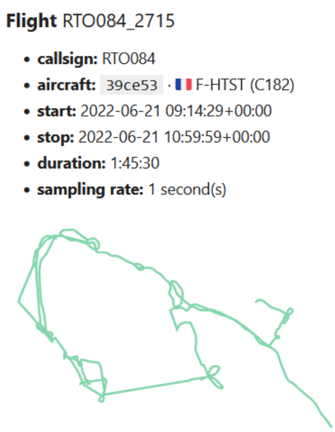

Figure 13 Visualisation of the trajectory of flight RTO084_2715

Once the trajectory geometry is produced by Traffic, it is easy to compute whether a trajectory intersects with a cell and to compute the duration of a flight over this cell. This is used to compute the aircraft density over a cell.

4.1.3 Map Generation

The matplotlib library is used for map generation. The map shows coloured cells over a geographical background. The geographical background is implemented with the contextily library that offers various types of background: with or without city labels, with or without infrastructures.

The title of the map contains the name of the operation that includes the name of the area (Aix-Marseille, Toulouse, Salon, …) and a Flight Path Name (TGV, North-South 23, …). The title also tells whether it is the map for the Intended, Deviated or Divided flight plan. When the map is not focused on a specific flight plan, the title is "Area Air Risk map".

The colours used to indicate the risk level are explained in a legend usually placed in South-West corner of the map. Another part of the map usually placed in the North-West provides more explanations about the map. It contains the number of cells and the cell size. It also recalls what time slot is depicted in the map.

Flight plan risk maps also indicate:

- DailyDrone: the number of intended drone daily operations,
- MAC: the MAC probability for the flight plan,
- Uncertainty: the ratio of Blue cells in the flight plan,
- MaxDroneDaily: the maximal number of drone daily operations that could be performed while satisfying the target level of safety,
- Deviations: the ratio of deviations in the flight plan,
- Risk Reduction: MAC probability for the intended flight Plan – MAC probability for the Risk Avoidance Flight Plan / MAC probability for Intended Flight Plan

In verbose mode other metrics can be displayed: WCV rate, AircraftDensity, Aircraft count, DroneCellProba, Red, Orange and Green cell ratio.

5 Conclusion

5.1 Summary of achievements

We have defined and implemented a Digital Assistant that supports the quantitative air risk assessment in the context of SORA drone operation risk assessment. The Digital Assistant produces Air Risk maps for a geographical area showing the density of aircraft overflying cells. The map provides a means to identify the high-risk cells in the area that a flight plan should avoid. Aircraft densities are computed using captured traffic data in the area.

The Digital Assistant assesses an intended flight plan by computing safety, uncertainty and mission performance metrics. The MAC probability is used to decide whether the intended flight plan is acceptable with respect to safety.

When the intended flight plan is not acceptable then the Digital Assistant explores risk avoidance strategies to propose alternate flight plans. In particular, it looks at potential flight plan deviations that could avoid cells with high or medium aircraft densities. It also explores the possibility to postpone drone flights to time slots with a low aircraft density. The Digital Assistant computes metrics that can be used to compare the efficiency of the risk avoidance strategies.

A preliminary validation of the Digital Assistant results was performed using two medium size datasets in Marseilles-Aix and Toulouse areas.

5.2 Further Work

The first follow-up activity planned within Safeteam is to perform experiments with users of the Digital Assistant in order to assess Human Factor metrics. These metrics should help to assess the quality of the Digital Assistant explanations and the level of trust that users could place into the Digital Assistant.

The second follow-up activity that started during SafeTeam is the validation of the air risk assessment approach by discussing it with the drone rule making community. There is a need to investigate the justification of quality of ADS-B and FLARM traffic data, validity of hypothesis for establishing the values for NoProvidence, NoAvoidance and Below variables, the correctness of MAC probability computation rules.

Other activities that could be performed after Safeteam include extending the Digital Assistant in order to assist the definition of safety objectives for tactical air risk mitigation means and using the air risk map to support air risk monitoring by the remote pilot during the drone flight.

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Appendix A Air Risk Computation Appendix

In this appendix we provide some details about the computation of Air Risk index used in the the Air Risk maps.

A.1 Cells

To produce an Air Risk map we have to compute the air risk index for each of the cells in the buffer of the flight plan. Various volumes are used to define air risk. The following picture illustrates three concentric cells related with an increased air risk: Encounter, Well-Clear Violation, Near Mid-Air collision (NMAC) and Mid-Air collision.

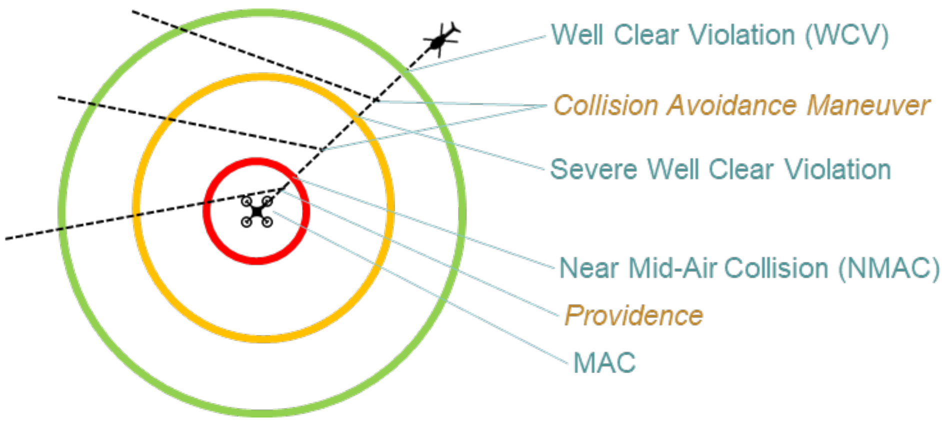

Figure 14 Horizontal View of Air Risk Situations

Each of these air risk situations are caused by the joint occupancy of a cell by the drone and an intruding Aircraft. An encounter occurs when the distance between the drone and the aircraft is close to a predefined separation distance. In this situation either a successful self separation maneuver is performed or a well-Clear Violation (WCV) occurs. In this situation either a successful collision avoidance maneuver is performed or a NMAC occurs. In this situation either Providence avoids the collision or a MAC occurs. In this document we do not make a difference between the MAC and unmitigated MAC situations because we do not consider that Aircraft and drones are necessarily equipped with air risk mitigation solutions such as Detection and Avoid systems [AirRisk11].

Experts are still debating the definitions of some of these air risk situations [AirRisk1]. Various distances defining the cells are proposed in the technical literature. We have mainly considered cells of 612 m (2 000 ft) radius following [AirRisk4]. The joint occupancy of such a cell represents a Well Clear violation situation. We also considered two smaller sizes of cells: cells with a 306 m (1 000 ft) radius that could be used to represent a more severe well-clear violation and cells with a 153 m (500 ft) radius that could be used to represent a NMAC situation.

In this document we focus on a Horizontal view of the Air Risk situations using cells in the horizontal plane. But air risk situations are defined using volumes using also vertical dimensions. For instance, the well clear volume is usually defined using a cell of 612 m radius and a height of 76 m (250 ft).

A.2 Air Risk Computations

A.2.1 Mid-Air Collision probability

The literature [AirRisk12] provides a well-established equation that computes the probability of MAC situation in a cell:

(Equation 1) p(MAC) = p(MAC | NMAC).p(NMAC|WCV).r(WCV)

where p(MAC|NMAC) is the conditional probability of MAC when NMAC occurs, p(NMAC|WCV) is the conditional probability of NMAC when WCV occurs and r(WCV) is the rate of well-clear violation per hour.

The MAC probability for a flight plan is the sum of the MAC probabilities over all the cells of the flight plan.

p(MAC|NMAC) is the probability of lack of providence. We consider that it is equal to 10^{-2}. We consider as it was established in [AirRisk4] that the value p(NMAC|WCV) is 10^{-1} when large cells (612 m radius) are used to model well-clear violation. If medium cells (306 m radius) are used to model severe well clear violation then a higher value should be used for p(NMAC|WCV), we propose to use 2,5 . 10^{-1}. For large and medium cells, the joint cell occupancy rate measures the rate of WCV.

When small cells are used, a simplified equation can be used to compute MAC because the joint cell occupancy rate measures directly the rate of NMAC.

(Equation 2) p(MAC) = p(MAC | NMAC).r(NMAC)

The joint cell occupancy rate has to be measured in order to compute MAC probability using equations 1 or 2. The joint cell occupancy rate can be computed as the product of the aircraft cell occupancy rate and the drone cell occupancy probability.

A.2.2 Aircraft Cell Occupancy rate

For each cell, an Aircraft Horizontal Cell occupancy count is derived from the analysis of ADS-B and FLARM traffic data. Each aircraft overflying the cell at an altitude below 120 m is counted and the occupancy duration of this cell by the aircraft is measured.

The occupancy counts are cumulated for all the aircraft intersecting the cell during the observation period. The cumulated occupation count is divided by the Total Observation Duration (in hours) to obtain the Aircraft cell occupancy rate. We used 120 m because it represents the maximum altitude at which the drone should operate according to the EU regulation [DroneReg1].

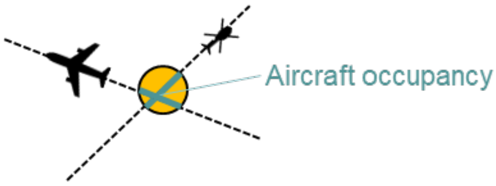

Figure 15 Cell Occupancy

As stated in [AirRisk4, AirRisk5], even if more than 6000 flights were observed by ADS-B and FLARM in the observation period of 16 days no aircraft was observed flying directly over the drone intended flight plan under 120 m. Hence using this direct observation method might lead to the inability to compute WCV rate and MAC probability for numerous cells.

We follow the idea of computing an indirect cell occupancy rate by counting aircraft overflying the cell at an altitude up to 1000 m and multiplying this count by the below factor introduced in [AirRisk3] and used in [AirRisk4]. The below factor can be seen as a conditional probability that an aircraft observed flying under 1000 m could be flying below 120 m.

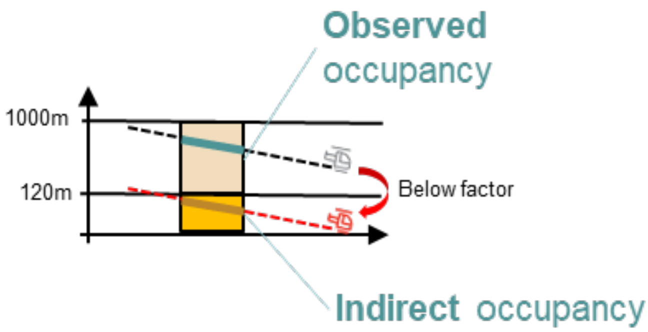

Figure 16 Indirect Cell Occupancy

We assume that in most cases the aircrat would fly below 120 m due to an abnormal operational situation such as an emergency landing. Knowing approximately how often such abnormal operations occur allows for an estimate of how often the aircraft is indeed below 120 m.

The below factor depends on the category of aircraft (Fixed wing General Aviation, Rotorcaft, glider, balloon, ...). A table defining the below factor for various types of aircraft was given in [AirRisk3]. It was computed using data provided by Denmark Aviation Authority.

Type	Below factor	Rationale for flying below 120 m
Rotorcraft	5%	*Emergency, special permit, temporary airstrip, tours, illegal low flight*
Fixed wing	0,1%	*Emergency landing, special permit, landing on temporary airstrip, illegal low flights*
Glider	1%	*Landing outside airport*

A.2.3 Drone cell occupancy probability

The drone cell occupancy probability is computed using simple rules. We assume that the drone is flying at a constant speed (DroneSpeed) and that it intesects a cell of size (CellSize) going through the center of the cell. So the duration of occupancy of a cell by one drone is equal to 2*CellSize/DroneSpeed. The probability of cell occupancy by one drone is equal to the occupancy duration divided by the Total Observation Duration.

Furthermore, we assume that mission planners might want to plan several drone operations per day using one or several drones on the same flight plan. To take this into account, the probability of cell occupancy by one drone is multiplied by the number of planned drone operations during the observation period.

A.2.4 Summary of Inputs, hypothesis and computations

Variables	Explanations	Computation
CellSize (m)	radius of the Air Risk Cell in m	Input
CellNumber	Total number of Air Risk Cells covering the intended flight plan	Input
TotalDay (d)	Total duration of flight data observation in days	Input
DroneSpeed (m/s)	Average Speed of drone in m/s	Input
DroneDaily (/d)	Number of intended drone operations per day. The operation could be performed using several drones.	Input
NoProvidence	Conditional probability that a NMAC (Near Mid Air Collision) situation becomes a MAC (Mid-Air Collision)	Hypothesis
NoAvoidance	Conditional probability that a WCV (Well Clear Violation) situation becomes a NMAC	Hypothesis

Below	Conditional probability that an observed flight flies at Very Low Level (below 120 m above ground level)	Hypothesis
DroneCellDuration (s)	Cell Occupancy duration by one drone in s	2*CellSize/DroneSpeed
DroneCellProba	Probability of cell occupancy by drone(s)	DroneDaily* DroneCellDuration / (TotalDay*24*60*60).
AircraftIntersection	Number of Aircraft intersecting the cells of the intended flight plan	Measured from ADS-B and FLARM traffic data
JointCellOccupancy(/h)	Joint Cell occupancy rate for complete flight plan per hour	(AircraftIntersection/(TotalDay * 24)) * Below * DroneCellProba
MAC (/h)	MAC probability for flight plan per hour	NoProvidence * NoAvoidance * JointCellOccupancy

A.2.5 Typical Values

The following table provides typical values computed using the rules introduced in this section. We compute the maximal number of aircraft crossing the cells of the intended flight plan. We consider three cells sizes and three related values for NoAvoidance. The value of DroneCellProba depends linearly on the value of CellSize. Consequently, this probability is divided by 2 when we go from large to medium cells. This does not lead to dividing by two the MAC probability because of the strong increase of the value of NoAvoidance.

A maximum of 540 aircraft crossing the flight plan cells during the 16 days of observation would be allowed when using large cells. This would lead to a well clear violation rate of 10^{-4}. When medium size cells are used, the maximum number of aircraft crossing drops to 440. And when small size cells are used the maximum number of aircraft crossing drops again to 215.

Variables	Large cell	Medium cell	Small cell
CellSize (m)	**612**	**306**	**153**
TotalDay (d)	**16**	16	16
DroneSpeed (m/s)	**10**	10	10
DroneDaily (/d)	**4**	4	4
NoProvidence	**0,01**	0,01	0,01
NoAvoidance	**0,1**	**0,25**	**1**
Below	**0,0125**	0,0125	0,0125

DroneCellProba	**5,7E-03**	**2,8E-03**	**1,4E-03**
AircraftIntersection	**540**	**440**	**215**
JointCellOccupancy(/h)	**1,0E-04**	**4,0E-05**	**1,0E-05**
MAC (/h)	**1,0E-07**	1,0E-07	1,0E-07