Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels
UNIVERSITAT POLITÈCNICA DE CATALUNYA

# FINAL DEGREE PROJECT

**Title:** Automatic Remain Well Clear Detection and Maneuvering for Drones

**Bachelor's Degree:** Telecommunication Systems Engineering and Aerospace Systems Engineering

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**Director:** Enric Pastor Llorens

**Date:** October 21th, 2021

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**Overview**

In this project, a Well Clear system for drones has been developed by adapting an existing system used for a Remotely Piloted Aircraft System. The Well Clear system proposed in this project can determine the drone's Well Clear status and give the optimal solution to the remote pilot.

The solution that the software provides to the pilot to remain in Well Clear will be a horizontal, a vertical, or a speed maneuver. The software will loop over all possible maneuvers to find the best one from each type and finally, it will select the optimal one among the three maneuvers.

To compare the cost of all maneuvers, the following two variables will be considered: the amount of time that the drone remains in Well Clear Violation, and the impact of the maneuver over the original trajectory.

Also, this project will study the impact of the used technology for telecommunication on the Remain Well Clear system. The selected technology for drone's air traffic communications is the mobile network, which is adapted for terrestrial users instead of aerial ones, leading to interference problems.

Not only interferences will be discussed, but also delay and the handover processes performance will be considered. There is a maximum latency fixed for U-Space communications and it will be proved if the mobile telecommunication network fits with this requirement.

Handover processes will be considered as they could decrease communication performance. Finally, the pilot time response will be studied as it could be a key factor when determining whether the Remain Well Clear system is viable or not.

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**Resumen**

En este proyecto, se ha desarrollado un sistema Well Clear para drones adaptando un sistema existente utilizado para el sistema de aeronave pilotada remotamente. El sistema Well Clear propuesto en este proyecto puede determinar el estado Well Clear del dron y dar la solución óptima al piloto en remoto.

La solución que el software le da al piloto para recuperar el Well Clear podrá ser una maniobra horizontal, vertical o de velocidad. El software hará un bucle recorriendo todas las posibles maniobras para encontrar la mejor de cada tipo y finalmente seleccionará la más óptima de entre las tres maniobras.

Para comparar todas las maniobras, calculará un coste que dependerá de dos variables que son: la cantidad de tiempo que el dron permanece en Well Clear Violation y el impacto de la maniobra sobre la trayectoria original.

Asimismo, en este proyecto se estudiará el impacto de la tecnología utilizada para telecomunicaciones en el sistema de Remain Well Clear. La tecnología seleccionada para las comunicaciones de tráfico aéreo de los drones es la red móvil, que está adaptada para usuarios terrestres en lugar de aéreos, lo que genera problemas de interferencias.

No solo se discutirán las interferencias, sino que también se considerará el delay de la comunicación. Como hay un valor máximo para la latencia en las comunicaciones dentro de U-Space, se comprobará que la red de comunicación móvil cumple con este requerimiento.

Además, se considerarán los procesos de handover ya que podrían disminuir el rendimiento de la comunicación. Y por último se estudiará el tiempo de respuesta del piloto ya que será clave para determinar la viabilidad del sistema.

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## Acronyms and abbreviations

| | |
|---|---|
| ACAS | Airborne Collision Avoidance System |
| AIMP | Aeronautical Information Management Providers |
| ANSP | Air Navigation Service Providers |
| ASM | Airspace Management |
| ATC | Air Traffic Control |
| ATCO | Air Traffic Control Officer |
| ATFCM | Air Traffic Flow and Capacity Management |
| CA | Collision Avoidance |
| CFR | Code of Federal Regulations |
| CIS | Common Information Services |
| ConOps | Concept of Operations |
| CORUS | Concept of Operation for European Unmanned Traffic Management Systems |
| DAA | Detect And Avoid |
| DAIDALUS | Detect and Avoid Alerting Logic for Unmanned Systems |
| DL | Downlink |
| EASA | European Aviation Safety Agency |
| EC | European Commission |
| EU | European Union |
| EUROCAE | European Organization for Civil Aviation Equipment |
| EUROCONTROL | European Organization for the Safety of Air Navigation |
| FAA | Federal Aviation Administration |
| FL | Flight Level |
| HO | Handover |
| HWCV | Horizontal Well Clear Violation |
| ICAO | International Civil Aviation Organization |
| ICAROUS | Integrated Configurable Algorithm for Reliable Operations of Unmanned Systems |
| IFR | Instrumental Flight Rules |
| JARUS | Joint Authorities on Rulemaking for Un-manned Systems |
| KPI | Key Performance Indicator |
| LOS | Line Of Sight |
| LoWC | Loss of Well Clear |
| LTE | Long Term Evolution |
| MOPS | Minimum Operational Performance Standard |
| NASA | National Aeronautics and Space Administration |
| MTCD | Medium-Term Collision Detection |
| MTDCB | Medium-Term Demand and Capacity Balancing |
| OSED | Operational Service and Environment Description |
| RoW | Right of Way |
| RPAS | Remote Pilot Aircraft System |
| RTCA | Radio Technical Commission for Aeronautics |
| RWC | Remain Well Clear |
| SC | Special Committee |
| SDSP | Supplemental Data Services Providers |
| SERA | Standardized European Rules of the Air |

| | |
|---|---|
| SESAR | Single European Sky ATM Research |
| SJU | SESAR Joint Undertaking |
| STCA | Short-Term Confliction Avoidance |
| STDCB | Short-Term Demand and Capacity Balancing |
| TCAS | Traffic alert and Collision Avoidance System |
| TCT | Tactical Controller Tool |
| UAS | Unmanned Aircraft System |
| UE | User Equipment |
| UL | Uplink |
| US | United States |
| USSP | U-Space Services Providers |
| UTM | Unmanned Traffic Management |
| VFR | Visual Flight Rules |
| VLL | Very-Low-Level |
| VWCV | Vertical Well Clear Violation |
| WC | Well Clear |
| WCV | Well Clear Violation |
| WG | Work Group |
| 3GPP | 3$^{rd}$ Generation Partnership Project |

## Symbols

| | |
|---|---|
| $\alpha$ | Turn angle |
| $\omega$ | Turn speed |
| [B, T] | The lookahead time interval, where $0 \leq B \leq T$ |
| c | Speed of light in vacuum |
| $d_{cpa}$ | Distance at Closest Point of Approach |
| DMOD | Modified Distance Threshold |
| DTHR | Distance Threshold |
| HMD | Horizontal Miss Distance |
| r | Turn Radius |
| s | Turn sign |
| **s, v** | Two-dimensional aircraft state, horizontal position, and speed respectively |
| $s_z$, $v_z$ | Vertical aircraft state, vertical position, and speed, respectively |
| $\tau$ | Tau |
| $\tau_{mod}$ | Modified Tau |
| $t_{ep}$ | Time to entry point |
| $t_{coa}$ | Time to Co-Altitude |
| $t_{cpa}$ | Time to Closest Point of Approach |
| TTHR | Time Threshold |
| ZTHR | Vertical Threshold |

### Subscripts

| | |
|---|---|
| a, c, d | Acceleration, constant speed, and deceleration |
| ep | Entry point |
| h, v, s | Horizontal, vertical, and speed maneuver |

| | |
|---|---|
| i, j | Maneuver start and end |
| m | Maneuver |
| max, min | Maximum and minimum maneuver value |
| trans, prop | Transmission, and propagation delay |
| target | Target maneuver or speed |
| o, i | Ownship and Intruder information |
| x, y, z | Northern, Eastern, and altitude components |
| 1, 2 | Entry and Exit Well Clear Violation point |

# CHAPTER 0. INTRODUCTION

In this chapter, the objectives, the approach, and the structure of the project will be introduced.

## 0.1. Objectives

The objective of this project is to study the viability of an automatic Remain Well Clear system for drones. The Remain Well Clear system proposal is not only able to predict if a drone will be in Well Clear violation but also to provide the pilot with the optimal maneuver to remain in a Well Clear status.

Well Clear is a term used to describe the status of an aircraft that is not operating in such proximity to other aircraft as to create a collision hazard. Therefore, if an aircraft is not in Well Clear, it will be in Well Clear violation. The Remain Well Clear system is a system that tries to keep the drone in a Well Clear status.

## 0.2. Approach

To implement the Remain Well Clear system, an existing system used by RPAS, which are unmanned aircraft larger than drones that flight in the same airspace classes as manned aircraft, will be adapted. This Remain Well Clear system will target small drones which fly in Very-Low-Level airspace, so the Remain Well Clear system will be an extra module for the U-Space services.

As there are no large databases with data from drone trajectories, the data used is obtained by simulating random trajectories and then creating encounters by overlapping two trajectories.

The proposed Remain Well Clear system predicts if the drone will enter in Well Clear Violation and gives a maneuver to remain in a Well Clear status. To select the maneuver, the software compares all the possible maneuvers from vertical, horizontal, and speed maneuvers to find the optimal one. Horizontal maneuvers consist of a left or right turn while the vertical drone speed remains constant. Vertical maneuvers consist of an altitude change at a constant horizontal speed and speed maneuvers consist of a horizontal speed change while the vertical speed remains constant.

Each possible maneuver will have an associated cost that will depend on the time that the drone will be in Well Clear Violation and it will also depend on the impact of the maneuver on the current trajectory. As the Well Clear Violation increases, the cost increases, and also as the impact of the maneuver increases, the cost increases too. Therefore, the optimal maneuver will be the maneuver with the lower cost from all the possible maneuvers.

After the drone performs the Remain Well Clear maneuver and it stops predicting a Well Clear Violation, the drone must perform a maneuver to recover its original flight plan. In case that after performing the maneuver, a Well Clear Violation is still predicted, another Remain Well Clear Maneuver will be performed. As the goal of the project is to predict Well Clear Violations and compute the maneuver to avoid them, how to recover the original trajectory will not be discussed.

The proposed Remain Well Clear service, which involves Well Clear Violation prediction and maneuver selection, will be provided by a cloud server. To predict a Well Clear Violation and select the optimal maneuver the drone position and speed will be needed, therefore the drones will send their position and speed data.

Once the Well Clear maneuver has been selected, it is sent to the remote pilot who is responsible for avoiding the Well Clear Violation. Then, the pilot action needs to be sent back to the drone.

To communicate the drone with the Remain Well Clear service provider, the mobile telecommunication network will be used. Even though the mobile telecommunication network fits well with the service needs, it will have also some disadvantages as there are communication delays and interferences with the other network users.

## 0.3. Project structure

The project is divided into two parts. The first one goes from chapters one to seven, and it covers how the Well Clear system works. The second part goes from chapter seventh to the end of the project, and it focuses on the network used to provide the Well Clear systems.

The first chapter introduces the U-Space project, which tries to provide a set of services to drones. One of those services is the Detect and Avoid systems which combine Well Clear and Collision Avoidance Systems. Then, in the second chapter, the Well Clear term is defined. An aircraft is in Well Clear if it is safely separated from other aircraft, and the responsibility of being Well Clear relies on the pilot. As drones do not have a pilot on board Detect and Avoid systems become a key factor in their safety.

The third chapter defined the algorithm used to predict a Well Clear Violation, and it also defines some terms as the Well Clear Violation interval or the Well Clear Violation volume, which are the time interval and the volume in which the drone is in a Well Clear Violation status.

In the fourth chapter, the three different types of maneuvers proposed to remain in a Well Clear status are defined and in the fifth chapter, it is explained how to select the optimal one from all the possible maneuvers. To select the optimal maneuver, each maneuver will have an associated cost, and the maneuver with the lower cost will be the optimal one.

In the sixth chapter, a step-by-step simulation will be explained to have a better understanding of the software. Also, a large set of encounters will be simulated to see the patterns that the software follows when it selects the maneuver.

From the seventh chapter, the project focuses on the communication network. The seventh chapter describes the characteristics that a U-Space network architecture needs, and it also defines the architecture that will be used to compute delays in the following chapters.

The eighth chapter explains all the possible problems related to using mobile telecommunication networks to provide U-Space services. The discussed problems are the interferences, the delay, and the performance of the handover process. The interferences and the handover could lead to an increase of the delay that is a key factor to make the Remain Well Clear services reliable.

In the ninth chapter, some previous experiments of the pilot time response to TCAS II and ACAS are discussed. And in the tenth chapter, it is computed the total delay and how the delay combined with the pilot time response affects the system.

# CHAPTER 1. U-SPACE

In this chapter, the U-Space concept will be explained. And Detect and Avoid systems, which are defined in the third phase of the U-Space, will be introduced.

## 1.1. U-Space concept

Drones are a growing business, which flies over the same airspace as aircraft, other drones, gliders, etc. To integrate them into the airspace, many states have tried with their own regulation. But as in some cases, the regulations from different states became incompatible, regulations at the European level need to be developed.

The European Commission (EC), the European Aviation Safety Agency (EASA), the SESAR Joint Undertaking (SJU) [1], and EUROCONTROL are working together with Joint Authorities on Rulemaking for Un-manned Systems (JARUS) to develop a standard to make operations easier to commercial and recreational pilots in Europe.

The EC has developed a phased plan whose regulations have been proposed by EASA. EUROCONTROL has produced a draft high-level UAS air traffic management (ATM) operational concept that describes the drone's operation in order to co-exist safely with manned aircraft. How this operational concept is enabled is explained in a lower-level document which is the Concepts of Operation (ConOps) [2], which has been sponsored by SESAR Joint Undertaking (SJU).

The Concept of Operation for European Unmanned Traffic Management (UTM) Systems (CORUS) is a project to integrate drones into the very low level (VLL) airspace. Then, CORUS's task is to determine how U-Space will operate to make the use of drones safe and socially accepted. To carry out this task, CORUS is developing U-Space ConOps throughout an iterative process.

But what is U-Space? Is it an area? Even though its name contains the word space, it is not a regulated area as the ones where manned aircraft fly. Instead, U-space refers to the space in which a variety of air traffic services are provided to drones to leverage existing services and technologies as much as possible.

### 1.1.1. U-Space versions

U-Space's goal is to define a flight restriction system across the European Union and for all drone manufacturers. Also, this system must be compatible with other services because in each U-space version new services are added.

U-Space is scheduled to be released in four stages as is shown in Fig. 1 [2]. U1 is available since 2019 while U2 will be available during 2021.

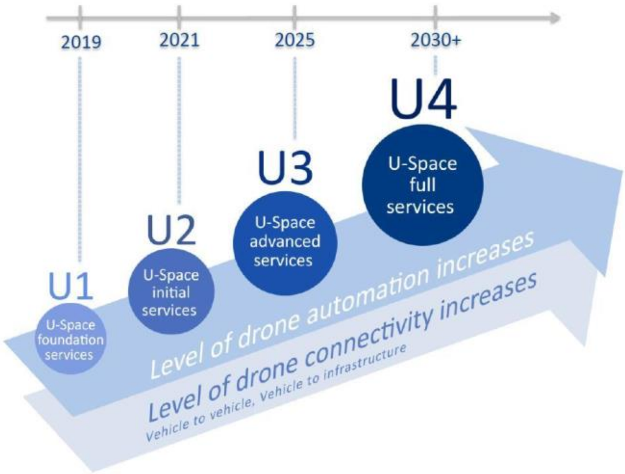


**Figure 1:** U-Space releases scheme.

*U-Space foundation services (U1)*

As said before, the number of drones is increasing due to their cheap cost and different functionalities. Registering all drones is needed due to safety reasons but registering them by regular means would be a tedious task.

Here is when it comes to a kind of e-registration that registers the operator and, in some cases, the UA itself. This electronic registration is digital, interoperable, and accessible in real-time, which makes it usable by other flight systems.

The other service provided by U1 is geofencing. Geofencing refers to virtual boundaries which limit the area in which a drone can fly. The aim is to prevent airspace violation even if the pilot ignores the alerts so the capabilities will be in the drone itself.

*U-Space initial services (U2)*

The goal of U2 services is to provide the drone with updated information. The first services are focused on controlling unmanned air traffic trajectories while the second ones are focused on flight planning, tracking, dynamic airspace information, and interfaces with ATC.

*U-Space advanced services (U3)*

U3 services focus on compensating the fact that the drone does not have any pilot on board by using Detect And Avoid systems. This service combines the ability to detect any unexpected hazard and geofencing to prevent the drone from colliding with it.

*U-Space full Services (U4)*

U4 also called full services, signifies the complete integration with manned air traffic and all services provided in the airspace.

### 1.1.2. U-Space volumes

U-Space is focused on Very Low-Level operations and ConOps divides U-Space's airspaces into three different types, which are shown in Figure 2, depending on the services provided inside them [2].

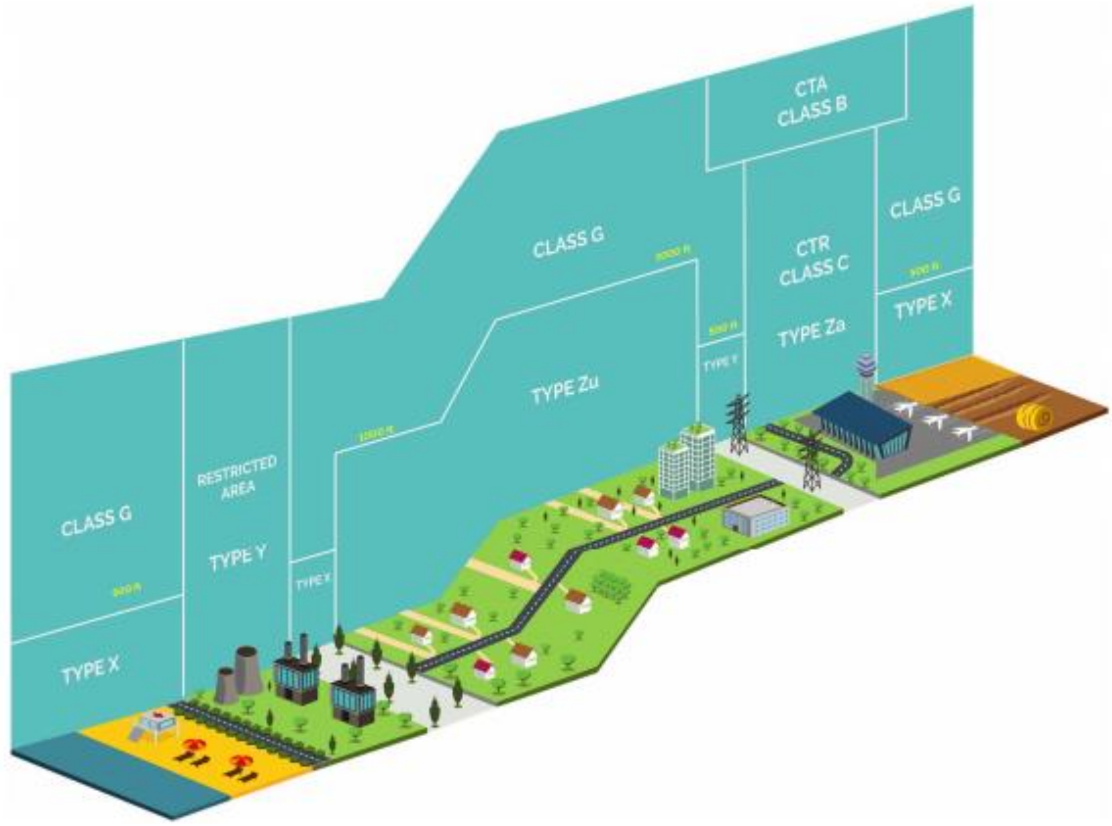


**Figure 2:** U-Space space types.

- X Volume – Conforming UAS Operators: X Volumes are low populated spaces with low U-Space services demand. They do not offer separation services and all the responsibility for safe separation relies on pilots.

- Y Volume – Collaborating UAS Operators: Y Volumes are spaces with significant traffic and with higher risks than X Volumes. Y Volumes offer strategic conflict resolution and traffic information during the flight.

- Z Volume – Coordinating UAS Operators: Z Volumes are the most crowded Volumes of the U-Space division. They provide strategic and tactical conflict resolution.

### 1.1.3. U-Space Detect and Avoid systems

Air Traffic Management (ATM) is made up of three different safety layers which are Airspace Management (ASM), Air Traffic Flow and Capacity Management (ATFCM), and Air Traffic Control (ATC) [31]. These three layers try to avoid and reduce hazards and to reduce the severity of the hazards. Each of the layers has its own purpose, the ASM layer determines the volumes and conditions under which aircraft can operate. ATFCM layer makes compatible the demand of flights with the airspace capacity, while ATC layer looks if aircraft separation is under the separation minima.

Air traffic controllers work together with pilots within the ATC layer, which is also made up of three more layers that are: MTCD, TCD, and DTCA. Beyond the ATC layer, commercial aircraft have TCAS systems, and beyond TCAS, the See and Avoid and the Providence are the very last resource to avoid a possible accident.

In Figure 3, it is shown the different layers involved in the ATM and how they are activated while the aircraft approximates to the Closest Point of Approach (CPA).

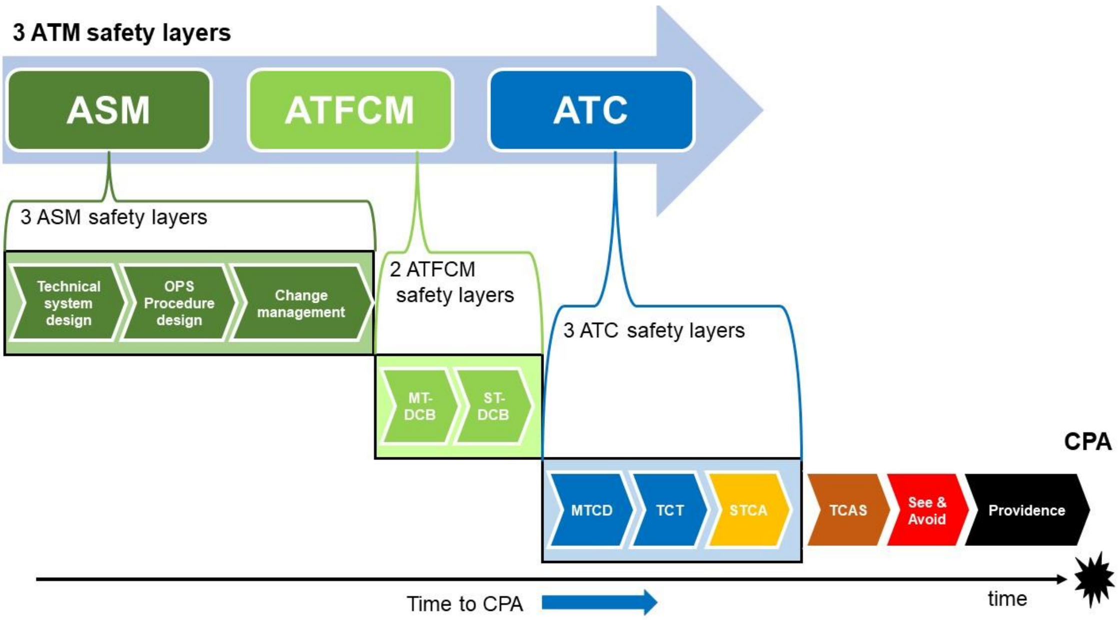


**Figure 3:** ATM safety layers.

With the introduction of RPAS into non-segregated airspaces, the See and Avoid regulation could not be followed by them due to the lack of an onboard pilot. Therefore, Detect and Avoid systems, which are the combination of Remain Well Clear and Collision Avoidance systems, came to substitute the See and Avoid task.

Finally with the introduction of drones into airspace that neither have an onboard pilot or ATC separation services, the See and Avoid responsibility and the separation services provided by ATC will be substituted by the U-Space services, in which Detect and Avoid services are included.

U3 services are focused on DAA, which helps drones to avoid collision between them or with any other hazard. Nevertheless, Collision Avoidance systems are not the only systems that increase drone safety.

Another way to succeed in it is by guaranteeing that drones are not flying too close between them to become a hazard. The systems that take over it are known as Remain Well Clear systems, which are just another U-space system.

The introduction of DAA systems will enable operation in high-density and high-complexity areas. It will also allow drones to fly faster, longer, and higher. This will lead to an increase in the number of drone operations.

Then, DAA will be mandatory to flight in high-complexity heterogeneous areas, which means that Europe should address the following needs in terms of R & D.

- Development of DAA systems.
- Demonstrate that the DAA system works in high-density areas.
- Explore how to detect non-cooperative intruders with current systems.
- Develop a cost-effective, collaborative, and non-collaborative DAA.
- Develop operational procedures for pilots explaining how to react to electronic conspicuity and DAA.

## 1.2. Introduction to the Well Clear concept

The airspace safety layers are made up of different types of layers which go from the airspace class separation to the collision avoidance system that is used as a last resource.

Depending on the airspace class where the aircraft is flying, separation services are provided or not. There are airspace classes where separation services depend on the flight type, which could be either IFR or VFR, as is shown in Table 1 [20].

**Table 1:** Separation services depending on airspace class.

| Airspace class | Flight type | Separation provided |
|---|---|---|
| A | IFR only | All aircraft |
| B | IFR<br>VFR | All aircraft<br>All aircraft |
| C | IFR<br>VFR | IFR from IFR and VFR<br>VFR from IFR |
| D | IFR<br>VFR | IFR from IFR<br>Not provided |
| E | IFR<br>VFR | IFR from IFR<br>Not provided |
| F | IFR<br>VFR | IFR from IFR as far as practical<br>Not provided |
| G | IFR<br>VFR | Not provided<br>Not provided |

To ensure safe vertical separation between aircraft, flight levels are used. The flight level from an aircraft is its altitude at standard air pressure. The vertical separation required is of 2000 ft until FL270 and of 4000 ft from FL270.

Even though aircraft are separated into different airspace classes and flight at different flight levels, aircraft might be not safely separated. In these cases, the responsibility to maintain the separation between aircraft is led to ATCO and the pilot's interpretation (only in airspace classes where separation services are provided).

Pilots have the responsibility of applying See and Avoid regulations, which obligate them to not fly close enough to another aircraft to cause any possible collision. If an aircraft is flying separated enough from other aircraft, it is considered to be in a Well Clear status.

As a last resource, ACAS systems help to avoid collision when none of the previous systems has been capable of maintaining aircraft safely separated. The system currently used is the TCAS II, which issues a Resolution Advisory to either climb or descend in other to avoid the collision.

Collision avoidance systems alert if an intruder aircraft enters a given volume around the own aircraft. And Well Clear services also alerts if the intruder enters inside a given volume, in which collision avoidance volume is included.

Even though Well Clear (WC) is not defined in the ICAO, this was not a problem as it was led to Air Traffic Control Operators (ATCO) and the pilot's interpretation.

But with the introduction of RPAS into non-segregated airspaces, defining Well Clear became an urgency.

### 1.2.1. From See and Avoid to Detect and Avoid

Separation responsibility between aircraft goes to ATCO while pilots are responsible for the Well Clear. As Well Clear is a term that has not been defined by distance and time thresholds, pilots use See And Avoid to implement Well Clear regulations.

*See and Avoid*

See and Avoid has different definitions for manned/unmanned aviation in the Federal Aviation Administration (FAA) and the Standardized European Rules of the Air (SERA) [3]. But even though there are some differences between the US and Europe, the concept is similar.

See and Avoid is a term included by US FAA in the following parts from the Regulation 14 CFR.

> 91.111 (a) No person may operate an aircraft so close to another aircraft as to create a collision hazard [21].
>
> 91.113 (b) General. When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear [21].

Even though in the SERA See and Avoid does not appear, there is a similar indication for proximity in flights that are shown below:

> Regulation (EU) No 923/2012. An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard [3].

*Detect and Avoid*

The previous definition of See and Avoid cannot be carried out by unmanned systems that do not have a pilot. Therefore, to maintain a certain level of safety, they will do it differently.

Detect and Avoid (DAA) systems are an alternative for drones and RPAS to follow the See and Avoid regulations.

DAA should determine Well-Clear status, provide separation, and operate with existing collision avoidance systems. Then, DAA systems must provide Well Clear and Collision Avoidance services.

### 1.2.2. Well Clear on drones

The previously explained DAA system allows RPAS to follow the See and Avoid regulations. But what is going on with drones?

Drones are smaller unmanned aircraft than RPAS which fly at Very-Low-Level airspace instead of flying in the conventional airspace for manned aircraft as RPAS do.

Unlike drones, RPAS has ATC services, but they still need the Remain Well Clear systems due to the lack of a pilot who implements See And Avoid regulation. And as drones also do not have a pilot on board, to implement a Remain Well Clear system for them, the existing system used for RPAS will be adapted.

# CHAPTER 2. WELL CLEAR DEFINITION

In this chapter, Well Clear will be defined while explaining which regulatory bodies are involved in its definition. Lastly, some Detect and Avoid implementations, which apply the Well Clear definition from RTCA, will be summarized.

## 2.1. Detect and Avoid systems

With the introduction of RPAS into non-segregated airspace, the responsibility of Remaining Well Cleared will not lead to ATCO and pilots, instead, a Detect and Avoid system will be used.

The DAA system must provide both Remain Well Clear and Collision Avoidance services. CA is defined by a Collision Avoidance Volume while for Well Clear there is no defined WC volume, so a Remain Well Clear function cannot be defined either. The difference between CA and RWC is shown in Table 2 [22].

**Table 2:** Difference between CA and RWC functions.

| | **CA** | **RWC** |
|---|---|---|
| Decision factors | Safety | Safety, acceptability, tactic |
| Responsibility | Pilot | Depends on the airspace class |
| ATC contact | If time allows | Yes |
| Start | Collision hazard | Conflict |
| End | NMAC or CoC | Collision hazard or Coc |
| Time horizon | Seconds | Minutes |
| Maneuver | Strong | Smooth |
| Maneuver constraints | None | Right of Way rules, clearance |

### 2.1.1. Remain Well Clear concept

As defined in the regulations from section 1.2, the WC's objective is to avoid possible conflicts between aircraft.

The “conflict” term is defined by ICAO as: “Predicted converging of aircraft in space and time which constitutes a violation of a given set of separation minima” [23].

WC is an aircraft status while RWC is a function with the aim of predicting if the RPAS will be outside the separation minima. RWC function has three tasks which are: to detect, analyze, and maneuver to avoid a possible conflict.

RWC starts when a conflict is predicted what happens when the ownship enters the Remain Well Clear threshold. At first, the ownship is in Well Clear status, and depending on its status after performing the maneuver, RWC has three possible endings which are the following ones (RWC and CA volumes and thresholds refer to Fig. 4).

- The ownship does not enter in the Remain Well Clear Volume after applying the Remain Well Clear maneuver.

- Even though the ownship performs the Remain Well Clear maneuver, it still enters in the Remain Well Clear Volume. After having entered inside the RWC volume the ownship recovers a Well Clear status by applying a regain Well Clear maneuver.

- The ownship does not solve the Well Clear conflict and finally, it enters inside the Collision Avoidance threshold, which means that the conflict will be delegated to Collision Avoidance systems.

This definition relies on separation minima, which are boundaries that enclose a safety volume around an aircraft.

### 2.1.2. Boundaries

When there is a conflict between two aircraft, the Right of Way (RoW) rules must be followed. In each conflict, one aircraft has the right-of-way while the other has not.

If the aircraft has the RoW and there is not a conflict, it can move freely. But, in case there is a conflict it must continue with its heading and speed.

The aircraft that does not have the RoW can move freely when there is not a conflict which leads to a loss of Well Clear. In case that the Well Clear is lost, RoW rules must be followed by the aircraft.

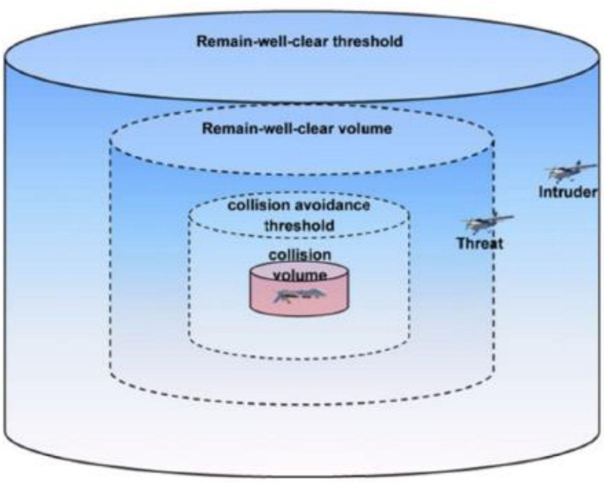


**Figure 4:** RWC and CA thresholds and volumes.

### 2.1.3. Alerts

For the RWC function, four types of alerts are considered, which are: information, advisory, caution, and warning.

The information alerts request awareness and does not require any action by the pilot. The advisory alerts request awareness and possible action by the pilot. The caution alert requests immediate awareness and a possible corrective or compensative action. Finally, the warning alerts request for immediate awareness and a corrective or compensation action.

Alerts should be accompanied with guidance when an action is needed.

### 2.1.4. Guidance

There are four types of guidance depending on its information, which are: informative, suggestive, directive, and automatic.

Informative guidance provides awareness, suggestive guidance limits the possible actions performed by the pilot, directive guidance provides a set of possible actions and automatic guidance provides information to the pilot of its intention of performing a maneuver.

## 2.2. Regulatory bodies

To implement an air traffic Detect and Avoid system, Well Clear must be defined previously. The term of Well Clear is used by ICAO without defining it. Then, the standardization of Well Clear leads on RTCA and EUROCAE.

### 2.2.1. RTCA

Two Special Committees (SCs) from RTCA worked on DAA, which were SC-228 and SC-147 [22].

The SC-228 developed a Minimum Operational Performance Standard (MOPS) for RPAS, including the part of DAA. While the SC-147 identified and updated the work of ACAS performance standards.

The standard from RTCA is defined on the document DOC-365A.

### 2.2.2. EUROCAE

Three Work Groups (WGs) from EUROCAE worked on the DAA standardization [22].

The WG-73 task was to develop a support document for CA in airspace classes from A to C. This WG created a CA function Operational Service and Environment Description (OSED) and then, it was reshaped to create the WG-105. The WG-75 focused on ACAS and ACAS X.

### 2.2.3. ICAO

ICAO's task is to provide a definition with which EUROCAE and RTCA will continue to build their work [22].

## 2.3. DAA implementations

In this section, some implementations of Detect and Avoid systems will be introduced. These implementations will be used as a reference in order to implement the automatic Remain Well Clear system for drones.

### 2.3.1. DAIDALUS

Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) [24] is DAA implementation for Unmanned Aircraft Systems whose main functions are maintaining a well clear separation between aircraft and recovering well clear status in case of well clear violation.

DAIDALUS is under consideration to be included in the DAA reference from the RTCA SC-288 MOPS for unmanned aircraft.

DAIDALUS is a software implementation that attempts to satisfy NASA's DAA concept for UAS by providing an algorithm to compute:

1. Determining actual well clear status.
2. Providing maneuvers guidance to recover a well clear status.
3. Determine alerting type.

To implement DAIDALUS software the architecture from Fig. 5 will be used. In this figure, it is shown what type of data is needed as an input and the different algorithms implemented to output an alert.

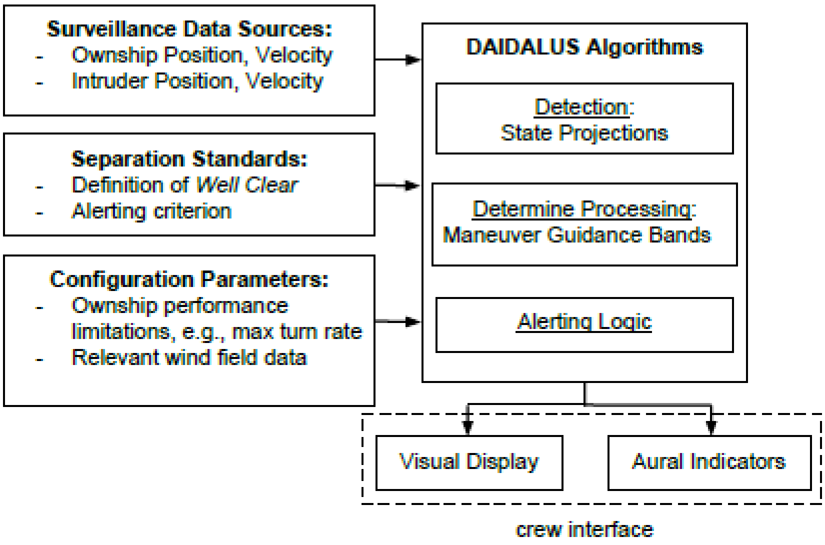


**Figure 5:** DAIDALUS architecture.

DAIDALUS alerts that the aircraft is not in Well Clear status if the vertical and horizontal distance between itself and the intruder is shorter than the predefined thresholds. It also uses a time threshold to alert in case that both aircraft are converging, and they will not be in Well Clear.

Depending on the thresholds, DAIDALUS has different alert types which require a different action. The alert types are the following ones: None, Preventive, Corrective, Recovery, and Full red. The alert types have been ordered from less to more dangerous, and the more dangerous an alert is the lower are its time and distance thresholds.

The outputs obtained from DAIDALUS are the following ones: prediction of loss of Well Clear, checking Well Clear, computing the alert level, and computing conflict and recovery bands. Computing the bands means that DAIDALUS provides the Well Clear status for all the possible maneuvers.

### 2.3.2. ICAROUS

ICAROUS (Integrated Configurable Algorithm for Reliable Operations of Unmanned Systems) [10] is a software that builds safe and autonomous unmanned aircraft operations.

ICAROUS follows a long history of air traffic applications, and DAIDALUS is one of them. DAIDALUS is a self-separation and alerting software that provides guidance to pilots to recover or remain in a Well Clear status.

ICAROUS computes recovery and resolution maneuvers and maneuvers to recover the original route without conflict. To provide these types of maneuvers, ICAROUS has the following functionalities:

- Detect and Avoid (DAA): ICAROUS provides Detect and Avoid by using the DAIDALUS library.

- Geofence Conformance: it refers to an implementation integrated into ICAROUS that monitors the conformance of a stay-in/stay-off geofence boundary.

- Obstacle Avoidance: The current ICAROUS version assumes that the area is cleared of obstacles such as trees or buildings, but in future versions, ICAROUS will have sensors to detect them. Currently, a 2D detection algorithm is under development.

- Stand-off Distance: the stand-off Distance function keeps the aircraft at a predetermined distance from a given target.

- Return to mission: ICAROUS computes routes to return to mission avoiding any conflict.

# CHAPTER 3. WELL CLEAR VIOLATION ALERTING LOGIC

In this chapter, the logic used in the implementation proposed in this project to detect a Well Clear Violation will be explained. Also, some concepts related to the Well Clear Violation as the Well Clear Violation interval and volume will be introduced.

## 3.1. Well Clear Variables

Before explaining the logic used for detecting a Well Clear Violation, we are going to introduce the used variables, which are inherited from TCAS system algorithms.

It is supposed that the surveillance information from both aircraft is available as horizontal and vertical components in 3-D airspace. Also, bold characters represent 2-dimensional vectors, which are used in the horizontal plane.

The variables used are relative, as they are the result of subtracting the ownship and intruder variables. The subindex "o" will be assigned to the ownship parameters while "i" will be assigned to the intruder ones.

The vector operations used during this chapter are addition, subtraction, dot product and norm vector. The dot product is defined as $\mathbf{s} \cdot \mathbf{v} = s_x \cdot v_x + s_y \cdot v_y$, the norm vector as $||\mathbf{s}|| = (s \cdot s)^{1/2}$, the perpendicular vector $\mathbf{v}^{\perp} = (v_y, - v_x)$

$$s_z = s_{zo} - s_{zi} \quad \textbf{(1)}$$

$$v_z = v_{zo} - v_{zi} \quad \textbf{(2)}$$

$$\mathbf{s} = \mathbf{s}_o - \mathbf{s}_i \quad \textbf{(3)}$$

$$\mathbf{v} = \mathbf{v}_o - \mathbf{v}_i \quad \textbf{(4)}$$

To determine if aircraft are in Well Clear Violation, the relative distance (which is represented by S) is used. But time variables are also used to detect a WCV in case that both aircraft are converging quickly. Time variables are only used in the horizontal plane because aircraft speeds are usually higher than in the vertical plane.

### 3.1.1. Vertical time variables

The vertical time variable used in Vertical Well Clear Violation prediction is the time to co-altitude ($t_{coa}$), which is the time that satisfies that the vertical distance ($s_z$) is equal to 0. It is computed with (5) and (6) (Note that if $s \cdot v < 0$ aircraft will be vertically converging, while if $s \cdot v \geq 0$ aircraft will be vertically diverging).

$$t_{coa}(s_z, v_z) = -s_z / v_z \quad \text{if } s \cdot v < 0 \quad \textbf{(5)}$$
$$t_{coa}(s_z, v_z) = -1 \quad \text{if } s \cdot v \geq 0 \quad \textbf{(6)}$$

### 3.1.2. Horizontal time variables

To determine if an aircraft is in Well Clear Violation two variables, which are relative to the Closest Point of Approach, are computed in the horizontal plane.

The time to the closest point of approach ($t_{cpa}$) is defined in (7) and (8).

$$t_{cpa}(\mathbf{s}, \mathbf{v}) = -(\mathbf{s} \cdot \mathbf{v}) / \mathbf{v}^2 \quad \text{when } \mathbf{v} \text{ is not } 0 \quad \textbf{(7)}$$
$$t_{cpa}(\mathbf{s}, \mathbf{v}) = 0 \quad \text{when } \mathbf{v} \text{ is } 0 \quad \textbf{(8)}$$

The distance to the closest point of approach is computed as (9). In case instead of using the time to the closest point of approach an approximation is used, the result of that approximation will be used to compute the distance.

$$d_{cpa}(\mathbf{s}, \mathbf{v}) = ||\mathbf{s} + t_{cpa} \cdot \mathbf{v}|| \quad \textbf{(9)}$$

To compute the time to the closest point of approach, an approximation was used in the earlier version of TCAS, which was the variable tau and is defined in (10) and (11).

$$\tau(\mathbf{s}, \mathbf{v}) = -\mathbf{s}^2 / (\mathbf{s} \cdot \mathbf{v}) \quad \text{if } \mathbf{s} \cdot \mathbf{v} < 0 \quad \textbf{(10)}$$
$$\tau(\mathbf{s}, \mathbf{v}) = -1 \quad \text{if } \mathbf{s} \cdot \mathbf{v} > 0 \quad \textbf{(11)}$$

As tau is not accurate when the distance between aircraft is too low, a better approximation was used instead, which is the modified tau ($\tau_{mod}$) and is defined in (12) and (13).

$$\tau_{mod}(\mathbf{s}, \mathbf{v}) = (DTHR^2 - \mathbf{s}^2) / (\mathbf{s} \cdot \mathbf{v}) \quad \text{if } \mathbf{s} \cdot \mathbf{v} < 0 \quad \textbf{(12)}$$
$$\tau_{mod}(\mathbf{s}, \mathbf{v}) = -1 \quad \text{if } \mathbf{s} \cdot \mathbf{v} > 0 \quad \textbf{(13)}$$

The other time variable used to predict a Horizontal Well Clear Violation is the time to entry point ($t_{ep}$), which predicts the time to loss horizontal separation and is defined in (14) and (15).

$$t_{ep} = \theta(\mathbf{s}, \mathbf{v}, DTHR, -1) \quad \text{if } (\mathbf{s} \cdot \mathbf{v}) < 0 \text{ and } \Delta(\mathbf{s}, \mathbf{v}, DTHR) \geq 0 \quad \textbf{(14)}$$
$$t_{ep} = -1 \quad \text{otherwise} \quad \textbf{(15)}$$

Where θ and Δ are computed with (16) and (17).

$$\theta\,(\mathbf{s}, \mathbf{v}, D, -1) = (-\,\mathbf{s} \cdot \mathbf{v} + \mathrm{sqrt}\,(\Delta(\mathbf{s}, \mathbf{v}, D)))\,/\,\mathbf{v}^2 \quad \textbf{(16)}$$
$$\Delta\,(\mathbf{s}, \mathbf{v}, D) = D^2\mathbf{v}^2 - (\mathbf{s} \cdot \mathbf{v}^{\perp})^2 \quad \textbf{(17)}$$

## 3.2. Well Clear Violation

The Well Clear Violation (WCV) is an aircraft status, which is the opposite status of the Well Clear one.

Aircraft are in a Well Clear Violation status if the distances between them are lower than the predefined thresholds, but time thresholds can be used to increase safety in cases where aircraft are converging fast. As vertical velocities are usually low, vertical time thresholds are not used.

### 3.2.1. Vertical Well Clear Violation

Time thresholds are not used to compute if an aircraft is in Vertical Well Clear Violation. Therefore, the VWCV is computed by comparing the relative vertical distance between itself (the ownship) and the intruder ($s_z$) with a distance threshold (ZTHR).

Then the ownship is in VWCV when $s_z$ is lower than ZTHR as it is shown in Fig. 6.

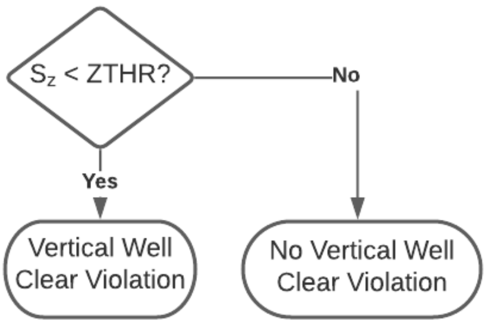


**Figure 6:** Vertical Well Clear Violation detection logic.

### 3.2.2. Horizontal Well Clear Violation

Unlike VWCV, to compute if an aircraft is in Horizontal Well Clear Violation (HWCV), not only distance thresholds are used, but also time thresholds are used.

An aircraft is in HWCV if any of these two conditions is accomplished:

1. The relative horizontal distance between the ownship and the intruder (**s**) is lower than a predefined threshold (DTHR). This condition is useful for encounters in which aircraft are not converging quickly, as their speeds are not considered in WCV detection.

2. In case that both aircraft are converging quickly, the time to reach the point where the horizontal distance is minimum will be considered to detect a Well Clear Violation. If the closest point of approach between the ownship and the intruder ($d_{cpa}$) is lower than the DTHR while the time to the closest point of approach is in between a given time interval that goes from 0 to TTHR a WCV will be detected.

Then if any of these two conditions is accomplished, the aircraft is in HWCV but if neither of these conditions is accomplished, the aircraft is not in HWCV.

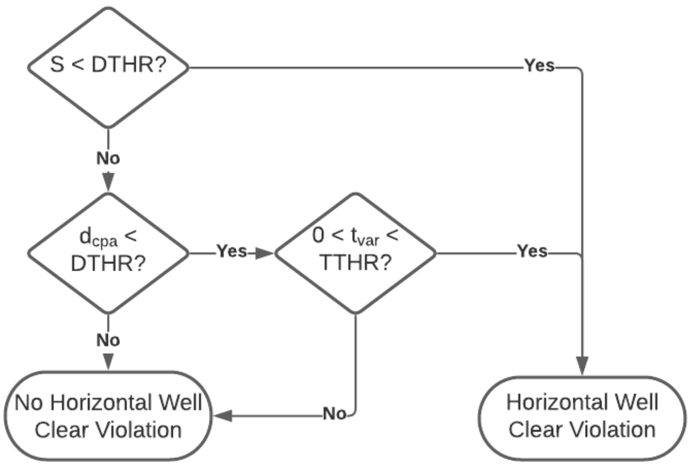


**Figure 7:** Horizontal Well Clear Violation detection logic.

### 3.2.3. Well Clear Violation Logic

An aircraft is in Well Clear Violation (WCV) only if it is in both Horizontal Well Clear Violation and Vertical Well Clear Violation.

In case that the ownship is only in HWCV or VWCV, but not in both, the ownship will be in WC status.

## 3.3. Well Clear Violation Volume

The WCV volume is the volume around an aircraft that involves all the possible positions in which an intruder would make the ownship to be in a WCV status. Then, the Well Clear Violation interval is a time-lapse, where the ownship is in WCV status.

There are different variables involved in the Well Clear Violation detection, which are speed, encounter angle, and distance. The effect of aircraft speed makes that the volume will have a strange shape that will differ from a cylinder or a sphere.

In the paper “Analysis of Well-Clear Boundary Models for the Integration of the UAS in the NAS” [11] some possible WCV areas, as the one from Fig. 8, are shown. This area is the section in the horizontal plane from a WCV volume, and it might help to understand what kind of shape that volume can have.

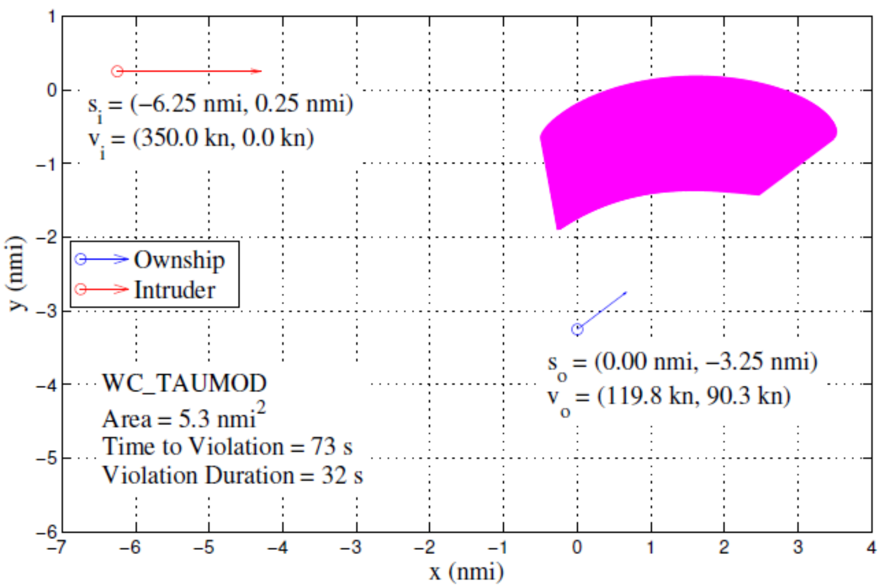


**Figure 8:** Well Clear Violation area.

## 3.4. Well Clear Violation Interval

The Well Clear Violation interval is defined by the time-lapse in which the ownship enters and exits the Well Clear Violation volume of the intruder.

As the information of the interval in which an aircraft is in WCV could have happened in past or in a long time in the future. Then, the WCV interval must be included in a predefined interval lookahead interval B-T, where B used to be 0 as it is the actual time and T is a time variable. Therefore, the Well Clear Violation interval function will return an interval if the WCV happens in between the lookahead interval, and it will return an empty interval if there is not a WCV or if the WCV happens outside the lookahead interval.

Evaluating the Well Clear status during a lookahead time tells us if the ownship will be in Well Clear in the future. And depending on the time to Well Clear Violation the alert level must be different. The Radio Technical Commission for Aeronautics (RTCA) describes different alert levels depending on the time until Loss of Well Clear (LoWC) and on the distances and time thresholds. The alert level from the RTCA standard is defined in Table 3 [9].

All four alert levels are differently defined from each other, as they do have not the same Well Clear parameters and time until LoWC. As the alert level increase, the Well Clear Violation volume resulting from the parameters will decrease. Even though there are some alert levels with the same time until LoWC, they have different Well Clear parameters, which are lower as the alert level increase. Also, there are alert levels with the same Well Clear parameters, but with different times to LoWC. When alert levels have equal Well Clear parameters, the higher the alert level, the lower the time to LoWC.

In the RTCA standard (Table 3) there are four alert levels because they have different purposes. The Warning and Corrective alert have as Well Clear parameters the Well Clear Volume distances but with different times until LoWC. Therefore, depending on the time until the Well Clear Violation happens, the alert will be either Warning or Corrective.

Preventive and Proximate alert levels have larger distance values for HMD and ZTHR while they have almost the same time until LoWC as the Corrective alert. It happens because the purpose of these alert levels is to indicate to the pilot that if he continues to not perform any maneuver it will be in Well Clear, while a change in the aircraft dynamic may lead to a Well Clear Violation.

**Table 3:** RTCA standard alert levels.

| **Alert level** | **Well Clear parameters** | | | **Time until** |
|---|---|---|---|---|
| | **DMOD** | **HMD** | **ZTHR** | **LoWC** |
| Warning | 0.75 nmi | 0.75 nmi | 450 ft | 25 sec |
| Corrective | 0.75 nmi | 0.75 nmi | 450 ft | 75 sec |
| Preventive | 0.75 nmi | 1.0 nmi | 700 ft | 75 sec |
| Proximate | 0.75 nmi | 1.5 nmi | 1200 ft | 85 sec |
| None | N/A | N/A | N/A | N/A |

$\tau_{mod}$ = 35 sec and $t_{coa}$ = 0 sec

Even though there are different alert levels in Table 3, this project will focus on the Warning alert level, which requires an action by the pilot to remain in a Well Clear status. But the threshold values and the time until LoWC will be different because they will be adapted to the drone’s performance.

As there are different definitions for Vertical Well Clear and Horizontal Well Clear, the Vertical and Horizontal Well Clear Violation interval should be computed separately from each other.

#### 3.4.1. Vertical Well Clear Violation interval

To compute the Vertical Well Clear Violation (VWCV) interval consist of computing the interval inside the B-T interval in which the aircraft is in VWCV. It is assumed that during the interval B-T, both aircraft, the ownship and the intruder, fly with a constant speed vector.

The function that computes the VWCV, which is the function VWCV(B, T, sz, vz, rwc_params), interval needs as inputs:

- The lookahead interval [B, T].

- The current position and speed from the ownship and the intruder.

- The RWC parameters.

All the time and distance values used through the function are relative values, where $V_z$ is the relative vertical speed and $S_z$ is the relative vertical speed.

Firstly, the function will look for a vertical speed close to zero. If it is the case, it will look for the vertical distance and if it is lower than the threshold, the Well Clear Violation will remain for the whole time interval, while if the vertical distance is larger than the threshold there will be not a Well Clear Violation and the function will return an empty interval.

In case that the vertical speed is not close to zero, it will compute the entry and exit time from the Well Clear Violation interval, and then it will compare the obtained times with the lookahead interval. If entry time is higher than T or exit time is lower, there will not be any Well Clear Violation during the interval B-T and the returned interval will be empty.

If any of these conditions has been accomplished, the interval will be between the maximum from entry time and B and the minimum from exit time and T.

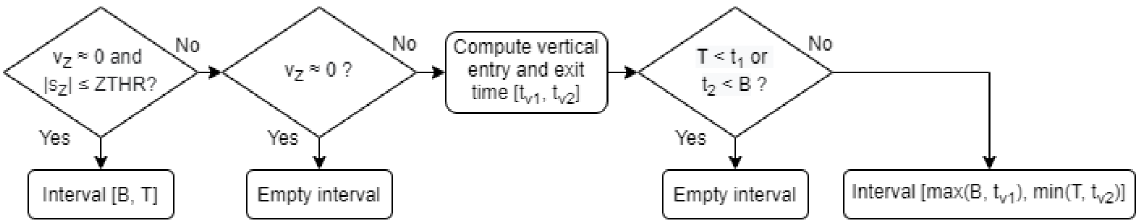


**Figure 9:** VWCV interval function flow diagram.

In Figure 9 it is summarized how the Vertical Well Clear Violation is computed. And in (18) and (19), it will be explained how the entry and exit times ($t_{v1}$ and $t_{v2}$) are obtained.

$$t_{v1} = (\mathrm{sign}(v_z)\ H - s_z) / v_z \quad \textbf{(18)}$$
$$t_{v2} = (\mathrm{sign}(v_z)\ ZTHR - s_z) / v_z \quad \textbf{(19)}$$

Where the variable H used to obtain the entry time is computed in (20). Also, notice that the time of co-altitude will be set to zeros, so the H variable will be equal to the vertical threshold (ZTHR).

$$H = \max(ZTHR,\ t_{coa} \cdot |v_z|) \quad \textbf{(20)}$$

### 3.4.2. Horizontal Well Clear Violation interval

To compute the Horizontal Well Clear Violation (HWCV) interval consists of computing the interval inside the 0-T interval in which the aircraft is in HWCV. It is assumed that during the interval 0-T, aircraft, the ownship, and the intruder, fly with a constant speed vector.

The function that computes the HWCV, which is the function HWCV(T, **s**, **v**, rwc_params), interval has as inputs the horizontal position and speed relative values and T. The T values used in the HWCV will be the subtraction of the exit and entry times of the previously computed VWCV ($T = t_{v2} - t_{v1}$).

Depending on the definition of the time variable ($t_{var}$), which could be $\tau$, $\tau_{mod}$, and $t_{coa}$, the function applied will be different. As the variable used in this system is the modified tau, we will explain this case in the flow diagram from Fig. 10. The variables $\Delta$ and $\theta$, which are used in Fig. 8, are obtained with (16) and (17).

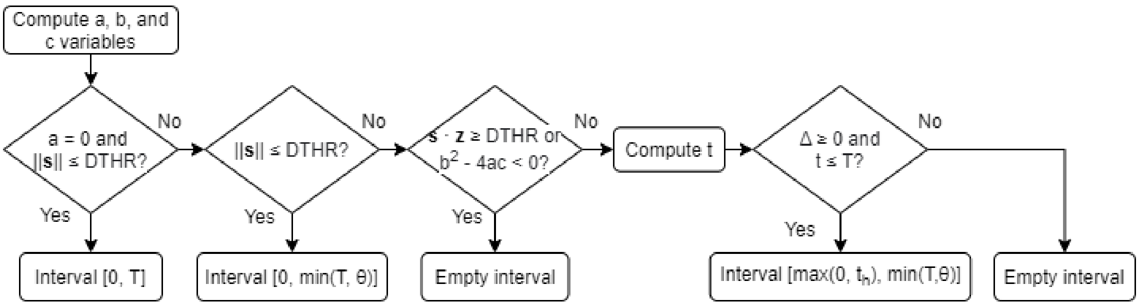


**Figure 10:** HWCV interval function flow diagram.

The variables a, b, and c used to predict an HWCV in the flow diagram from Fig. 8 are obtained in (21), (22), and (23).

$$a = \mathbf{v}^2 \quad \textbf{(21)}$$
$$b = (\mathbf{s} \cdot \mathbf{v}) + TTHR\ \mathbf{v}^2 \quad \textbf{(22)}$$
$$c = s^2 + TTHR\ (\mathbf{s} \cdot \mathbf{v}) - DTHR \quad \textbf{(23)}$$

And the variable $t_h$ is computed in (24).

$$t_h = (-b - \mathrm{sqrt}(b^2 - 4ac)) / 2a \quad \textbf{(24)}$$

### 3.4.3. Well Clear Violation interval

The first step to compute the Well Clear Violation interval will be to compute the Vertical Well Clear Violation interval and if it is empty, the Well Clear Violation interval will be empty too. This happens due to the Well Clear Violation definition, in which the ownship must be in both Vertical and Horizontal Well Clear Violation.

In case that the entry point and exit point from the VWCV interval are the same, the HWCV interval will be computed to see if in that instant there is an HWCV. If an HWCV happens at the same time as the VWCV entry point, the returned interval will be an interval in which both time values are the entry time from the VWCV interval. And in case that the entry point and exit point from the VWCV interval are the same, but there is no HWCV, an empty interval will be returned.

Finally, in case that the VWCV interval is not empty and its entry and exit times have not the same value, the returned interval will be the union from both the VWCV and the HWCV interval.

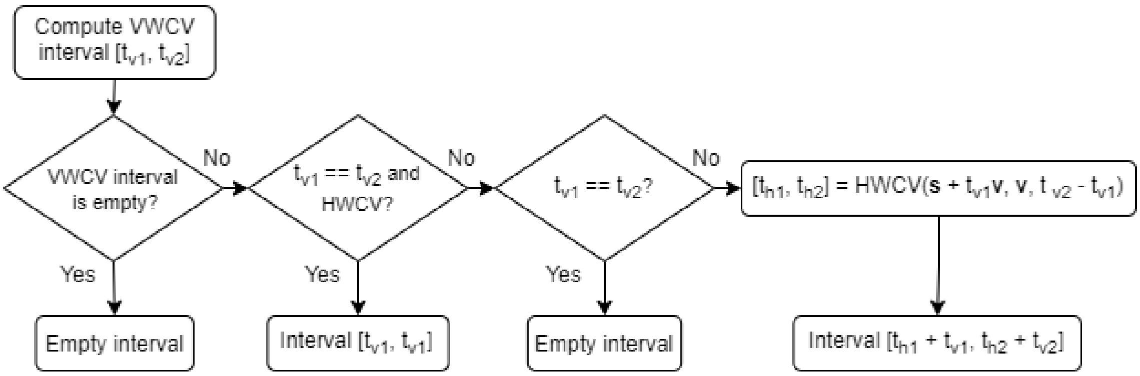


**Figure 11:** Well Clear Violation flow diagram.

# CHAPTER 4. REMAIN WELL CLEAR MANEUVERS

In this chapter how the ownship position and speed are computed during the maneuvers performed to remain in a Well Clear status. It will be explained for all three proposed maneuver types that are: horizontal, vertical, and speed maneuvers.

## 4.1. Maneuver types

To remain in a Well Clear status, three maneuvers are being considered, which are horizontal, vertical, and speed maneuvers. A horizontal maneuver consists of a turn to either left or right. A vertical maneuver consists of an altitude change that can be either a climb or a descend in which the drone ends the maneuver when it reaches the target altitude, and it has a zero vertical speed. Lastly, a speed maneuver consists of a speed change that can be either acceleration or deceleration.

Each of these maneuvers is computed by a function that returns the drone position at a given time by applying the respective maneuver. The maneuver parameters which determine the maneuver are packaged in an object.

For each of the maneuvers, there is a class with its attributes, but there are some attributes present in each of the three maneuvers that are:

- Maneuver type shows whether the maneuver is horizontal, vertical, speed, or a maneuver to recover the original trajectory which will be explained later.

- Maneuver initiation time and end time are the times at which the maneuver starts and ends and will be very helpful while executing the main program.

- Maneuver cost indicates the cost of performing a given maneuver and it is used to compare different maneuvers to choose the optimal one.

The maneuver performed by the drone depends on the drone's performance that is simplified to the parameters defined in Table 4.

**Table 4:** Drone parameters class.

| Attribute | Description |
|---|---|
| Climb rate | The climb rate is the target climb speed |
| Descend rate | The descend rate is the target descend speed |
| Turn rate | The turn rate is the turning speed in rad/s |
| Radius | The radius is the turn radius which depends on the drone speed during the turn |
| Acceleration rate | The acceleration rate is the acceleration used to achieve the target speed |

| | |
|---|---|
| Deceleration rate | The deceleration rate is the deceleration used to achieve the target speed |
| Climb acceleration | It is the acceleration to achieve the climb rate |
| Climb deceleration | It is the deceleration from the climb rate to zero vertical speed |
| Descend acceleration | It is the acceleration to achieve the descend rate |
| Descend deceleration | It is the deceleration from the descend rate to zero vertical speed |

During this chapter, different time variables, which are defined in Table 6., will be used to define the maneuvers. It is also assumed that the surveillance information is available as “x”, “y”, and “z” components in Euclidean 3-D airspace.

The software will compute another maneuver if needed, only when the drone has completed the selected Remain Well Clear maneuver.

**Table 5:** Maneuver time variables.

| Variables | Description |
|---|---|
| $t_i$ | Time at which the maneuver starts |
| $t_j$ | Time at which the maneuver ends |
| $\Delta t$ | Time elapsed from $t_i$ |
| $t_m$ | The required to perform the maneuver |

## 4.2. Horizontal maneuver

A horizontal maneuver consists of changing the current horizontal direction to remain in a Well Clear status. This maneuver should be divided into three parts:

1. The drone accelerates until reaching the turning speed. During this period the turning rate accelerates from zero to the target turning rate.

2. The drone keeps turning at a constant speed without changing its roll angle.

3. The drone decelerates until reaching a turn speed equal to zero. During this period the turning rate decelerates from the value used in part 2 to zero.

Even though this is more accurate, an approximation will be used. As the simulations are performed with small drones which have high accelerations, the time needed to reach the turning rate will be considered negligible. Then, the maneuver is just a circular trajectory with a radius and turn rate determined by the ownship performance.

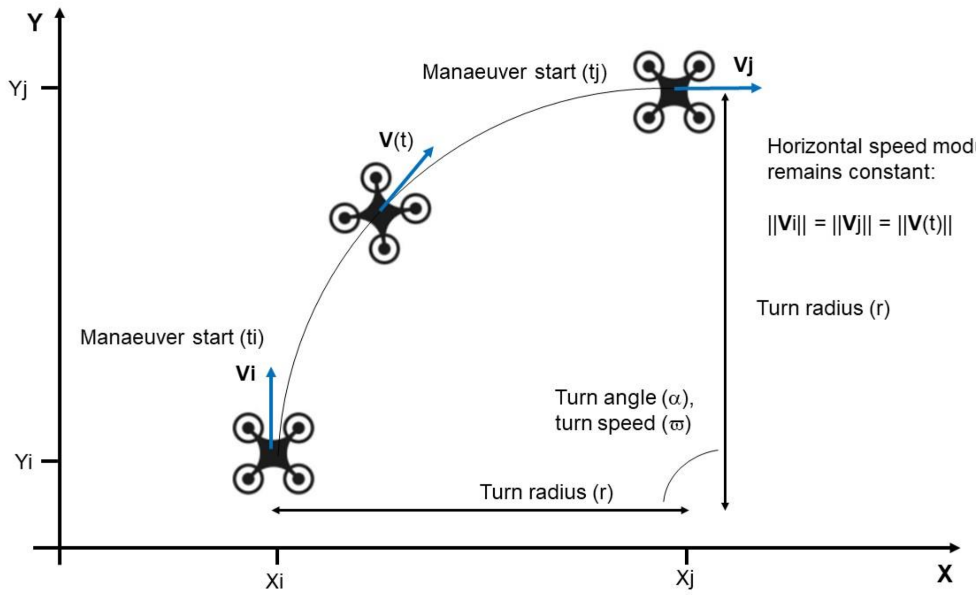


**Figure 12:** Horizontal maneuver.

Figure 12 shows a 90-degree horizontal maneuver. At $t_i$ the maneuver starts and it ends at $t_j$. The speed module remains constant during the whole maneuver, but its components change. At $t_i$, the drone's horizontal speed has only any component, while after the drone has completed the maneuver ($t_j$), the speed has only the x component. After completing the maneuver, the drone continues with a constant speed vector until the drone is not in Well Clear Violation.

During a horizontal maneuver, the horizontal speed module will remain constant, which means that the turn radius is computed in (25).

$$r = ||\mathbf{v}|| / \omega \quad \textbf{(25)}$$

The ownship position will be computed in (26), (27), and (28).

$$x(t) = x_i + r \cdot (sign \cdot (1 - \cos(\omega \cdot \Delta t)) \cdot \sin(h) + \sin(\omega \cdot \Delta t) \cdot \cos(h)) \quad \textbf{(26)}$$
$$y(t) = y_i - r \cdot (sign \cdot (1 - \cos(\omega \cdot \Delta t)) \cdot \cos(h) + \sin(\omega \cdot \Delta t) \cdot \sin(h)) \quad \textbf{(27)}$$
$$z(t) = z_i + v_z \cdot t \quad \textbf{(28)}$$

**Table 6:** Maneuver equation's variables.

| Variables | Description |
|---|---|
| $x_i$, $y_i$, $z_i$ | Position at the maneuver start |
| sign | Turn sign. s = 1 if right turn and s = -1 if left turn |
| r | Turn radius in meters |
| ω | Turn rate in rad/s |
| h | The heading at the maneuver's start, defined as $\arctan(v_y/v_x)$ |

Ownship speed module remains constant during the whole maneuver, but its x and y components change during the turn. Ownship speed during the maneuver is computed in (29), (30), and (31).

$$v_x(t) = v_{xi} \cdot \cos(\omega \cdot \Delta t) + v_{yi} \cdot \sin(\omega \cdot \Delta t) \quad \textbf{(29)}$$
$$v_y(t) = - v_{xi} \cdot \sin(\omega \cdot \Delta t) + v_{yi} \cdot \cos(\omega \cdot \Delta t) \quad \textbf{(30)}$$
$$v_z(t) = v_{zi} \quad \textbf{(31)}$$

Finally, the time taken by the ownship to perform the given maneuver is computed as the division between the turn angle and the turn rate as is shown in (32).

$$t_m = \alpha / \omega = t_j - t_i \qquad \text{Where } \alpha \text{ is the turn angle} \quad \textbf{(32)}$$

All the parameters needed to perform a horizontal maneuver are defined in the HorizontalManeuver class whose attributes are written down in Table 7.

**Table 7:** Attributes from HorizontalManeuver class.

| Attribute | Description |
|---|---|
| Maneuver type | Horizontal Maneuver |
| Initial time | Time at which maneuver starts |
| Ending time | Time at which maneuver ends |
| Maneuver time | Ending time – initial time |
| Maneuver radius | Turn radius |
| Turn rate | Turn rate in º/s |
| Turn | Turn to be performed during the maneuver |
| Cost | Maneuver cost (cannot be lower than 0) |

## 4.3. Vertical Maneuver

A vertical maneuver is performed by climbing or descending until the aircraft reaches the target altitude. Unlike horizontal maneuvers, vertical ones are not coded using the same kind of approximation. Instead of that, vertical maneuvers are divided into three maneuvers as is shown in Fig. 11.

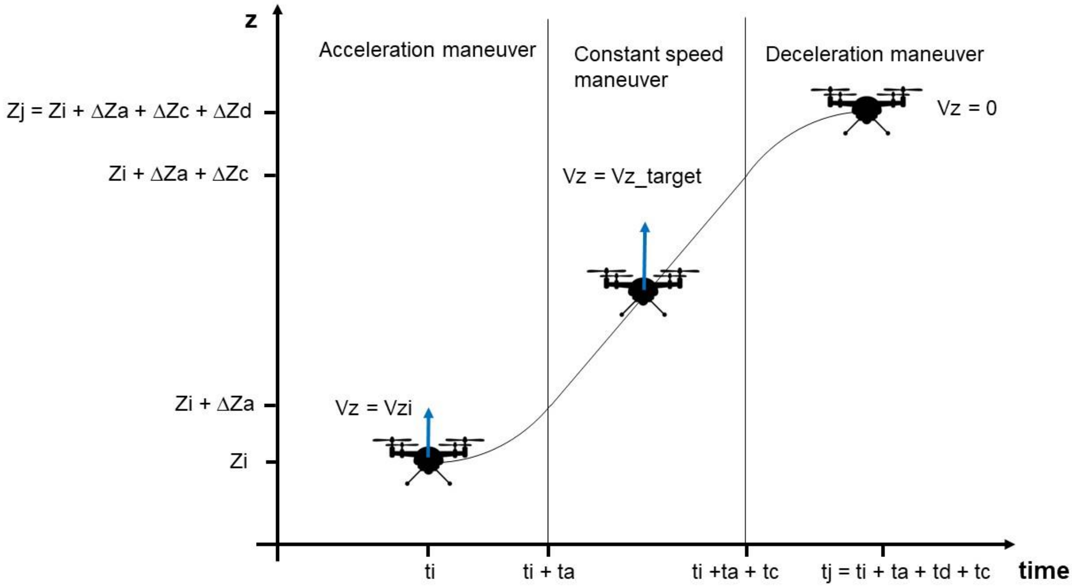


**Figure 13:** Vertical maneuver.

Figure 13 shows a vertical maneuver. In the first part of the trajectory, the drones accelerate until reaching the target vertical speed. At the second part of the trajectory, it continues at constant vertical speed, and at the third part of the trajectory, it decelerates until reaching zero vertical speed at the time it reaches the target altitude ($z_j$).

### 4.2.1. Vertical acceleration maneuver

During this maneuver, the ownship accelerates until it reaches the climb or the descending speed. The ownship position during this part of the acceleration part of the vertical maneuver is computed in (33), (34), and (35).

$$x(t) = x_i + v_x \cdot \Delta t \quad \textbf{(33)}$$
$$y(t) = y_i + v_x \cdot \Delta t \quad \textbf{(34)}$$
$$z(t) = z_i + v_{zi} \cdot \Delta t + 0.5 \cdot a_{za} \cdot \Delta t^2 \quad \textbf{(35)}$$

During this maneuver, horizontal speed remains invariable, while vertical speed accelerates until the ownship reaches the target vertical speed. The ownship speed will be computed in (36), (37), and (38).

$$v_x(t) = v_{xi} \quad \textbf{(36)}$$
$$v_y(t) = v_{yi} \quad \textbf{(37)}$$
$$v_z(t) = v_{zi} + a_z \cdot \Delta t \quad \textbf{(38)}$$

The time that the ownship takes to complete the maneuver is computed as (39), and the vertical distance traveled is computed as (40).

$$t_a = [v_{z\_target} - v_{zi}] / a_{za} \quad \textbf{(39)}$$
$$\Delta z_a = v_{zi} \cdot t_a + 0.5 \cdot a_{za} \cdot t_a^2 \quad \textbf{(40)}$$

### 4.2.2. Vertical constant speed maneuver

During this maneuver, the ownship keeps its vertical speed constant. The ownship position during the part of the vertical maneuver, in which the ownship flies at constant vertical speed, is computed in (41), (42), and (43).

$$x(t) = x_i + v_x \cdot \Delta t \quad \textbf{(41)}$$
$$y(t) = y_i + v_y \cdot \Delta t \quad \textbf{(42)}$$
$$z(t) = \Delta z_a + (\Delta t - t_a) \cdot v_{z\_target} \quad \textbf{(43)}$$

During these maneuvers, vertical and horizontal speeds remain also constant. The ownship speed will be computed in (44), (45), and (46).

$$v_x(t) = v_{xi} \quad \textbf{(44)}$$
$$v_y(t) = v_{yi} \quad \textbf{(45)}$$
$$v_z(t) = v_{z\_target} \quad \textbf{(46)}$$

The time-lapse ($t_c$) and the altitude change ($\Delta z_c$) while the drone flies at constant vertical speed will be computed in (47) and (48).

$$\Delta z_c = [z_j - z_i] - [\Delta z_a + \Delta z_d] \quad \textbf{(47)}$$
$$t_c = \Delta z_c / v_{z\_target} \quad \textbf{(48)}$$

### 4.2.3. Vertical deceleration maneuver

During this maneuver, the ownship decelerates until reaching a vertical speed equal to 0, which happens when it has also reached the desired altitude. The ownship position during the deceleration part of the vertical maneuver is computed in (49), (50), and (51).

$$x(t) = x_i + v_x \cdot \Delta t \quad \textbf{(49)}$$
$$y(t) = y_i + v_x \cdot \Delta t \quad \textbf{(50)}$$

$$z(t) = z_i + v_{z\_target} \cdot t_c + 0.5 \cdot \Delta z_c \cdot \Delta t^2 \quad \textbf{(51)}$$

During this maneuver, ownship horizontal speed vector remains constant while vertical speed decelerates until it reaches zero vertical speed. The ownship speed will be computed in (52), (53), and (54).

$$v_x(t) = v_{xi} \quad \textbf{(52)}$$
$$v_y(t) = v_{yi} \quad \textbf{(53)}$$
$$v_z(t) = v_{z\_target} + a_{zd} \cdot [\Delta t - [t_a + t_c]] \quad \textbf{(54)}$$

The time that the ownship takes to decelerate and the vertical distance travelled are computed in (55) and (56),

$$t_d = (0 - v_{z\_target}) / \Delta z_d \quad \textbf{(55)}$$
$$\Delta z_d = v_{z\_target} \cdot t_d + 0.5 \cdot a_{zd} \cdot t_d^2 \quad \textbf{(56)}$$

Finally, the maneuver time ($t_m$) can be computed as the sum of all the three maneuver parts as is shown in (57).

$$t_m = t_a + t_c + t_d \quad \textbf{(57)}$$

All the parameters needed to perform a vertical maneuver are defined in the VerticalManeuver class whose attributes are written down in Table 8.

**Table 8:** Attributes from VerticalManeuver class.

| Attribute | Description |
|---|---|
| Maneuver type | VerticalManeuver |
| Initial time | Time at which maneuver starts |
| Ending time | Time at which maneuver ends |
| Maneuver time | end_time - init_time |
| Time array | An array with a length equal to three with the times at which end each of the three maneuvers performed during the vertical maneuver |
| Rate | Climb/descend rate in meters per second |
| Acceleration | The acceleration needed to achieve the speed rate |
| Deceleration | The acceleration needed to achieve a zero-vertical speed from a vertical speed equal to the rate parameter |
| Altitude change | It is the altitude change during the maneuver |
| Cost | Maneuver cost (cannot be lower than 0) |

### 4.2.4. Particular cases

While performing a vertical maneuver, there are some cases in which performing it with the default value of vertical target speed will be impossible and a different solution will be needed for it.

*The target altitude is too close*

The case where $\Delta z_a + \Delta z_d$ is higher than the altitude difference between actual altitude ($z_i$) and altitude at the end of the maneuver ($z_j$).

In this case, we will only have two parts that are:

- The first part of the maneuver consists of accelerating until reaching a vertical speed ($v_{z\_target\_1}$) which is lower than the maximum vertical target speed ($v_{z\_target}$).

- The second part consists of decelerating from $v_{z\_target\_1}$ until reaching a zero vertical speed.

To obtain the maneuver values we must solve the following five equations system with also knowns ($\Delta z_a$, $\Delta z_d$, $v_{z\_target\_1}$, $t_a$, $t_d$).

The equations (58) and (59) are used to obtain the altitude change during the acceleration part of the maneuver, and the final vertical speed after having accelerated.

$$\Delta z_a = v_{zi} \cdot t_a + 0.5 \cdot a_{za} \cdot t_a^2 \quad \textbf{(58)}$$
$$v_{z\_target\_1} = v_{zi} + a_{za} \cdot t_a \quad \textbf{(59)}$$

The equations (60) and (61) are used to compute the altitude change while the drone is decelerating until it reaches a zero vertical speed

$$\Delta z_d = v_{zi} \cdot t_d + 0.5 \cdot a_{zd} \cdot t_d^2 \quad \textbf{(60)}$$
$$v_{zj} = v_{z\_target\_1} + a_{zd} \cdot t_d = 0 \quad \textbf{(61)}$$

To be able to solve this system we need a fifth equation, which is equation (62). This equation says that the sum of the altitudes needed to accelerate and decelerate will be equal to the maneuver altitude change.

$$\Delta z_a + \Delta z_d = z_j - z_i \quad \textbf{(62)}$$

With these equations, we obtain a second-degree equation that gives us the time required for decelerating ($t_d$). The variables a, b, and c from the equation are the following ones.

$$a = -z_j + z_i + 0.5 \cdot v_{zi}^2 / a_{za} \quad \textbf{(63)}$$
$$b = -2 \cdot a_{zd} \cdot v_{zi} / a_{za} \quad \textbf{(64)}$$
$$c = 0.5 \cdot [a_{zd}^2 / a_{za} - a_{zd}] \quad \textbf{(65)}$$

Once we have obtained $t_d$, we can compute $t_a$ in (66).

$$t_a = -[a_{zd} \cdot t_d + v_{zi}] / a_{za} \quad \textbf{(66)}$$

The new target vertical speed ($v_{z\_target\_1}$) will be computed in (67)

$$v_{z\_target\_1} = -a_{zd} \cdot t_d \quad \textbf{(67)}$$

Finally, we can compute the time required to perform the maneuver ($t_m$), which will be the sum of the time required to accelerate and decelerate.

$$t_m = t_a + t_d \quad \textbf{(68)}$$

*The current vertical speed and the target one are equal*

In this case, it will not be needed an acceleration period to reach the target vertical speed. Therefore, they will be divided into two cases:

- The first one is where the distance until reaching the target altitude is not enough to decelerate from the current speed until zero vertical speed. The altitudes that lead to this problem will not be considered by the software when it looks for the optimal maneuver.

- The second one is where the altitude change allows the drone to decelerate. Therefore, the maneuver could be either a vertical speed deceleration or a constant vertical speed part plus a deceleration one.

## 4.3. Speed Maneuver

A speed change maneuver is performed by applying an acceleration or deceleration until reaching the desired speed. During this maneuver, the heading remains invariable.

The function that computes position and speed during the maneuver computes them by applying the expressions of a uniform accelerated rectilinear movement to the three-axis component since the maneuver start until it ends. Therefore, the position is computed with (69), (70), and (71) (Note that the speed change is only applied to the horizontal plane speed components).

$$x(t) = x_i + v_x \cdot \Delta t + 0.5 \cdot a_x \cdot \Delta t^2 \quad \textbf{(69)}$$
$$y(t) = y_i + v_y \cdot \Delta t + 0.5 \cdot a_y \cdot \Delta t^2 \quad \textbf{(70)}$$
$$z(t) = z_i + v_z \cdot \Delta t \quad \textbf{(71)}$$

And its speed is computed with (71), (72), and (73).

$$v_x(t) = v_{xi} + a_x \cdot t \quad \textbf{(71)}$$
$$v_y(t) = v_{yi} + a_y \cdot t \quad \textbf{(73)}$$
$$v_z(t) = v_{zi} \quad \textbf{(74)}$$

The acceleration used through the maneuver is a drone parameter, and the acceleration shown in the expression above is obtained from the drone parameter assuming that the acceleration points to the same direction as the current speed. Therefore, the accelerations are obtained with (75) and (76).

$$a_x = a \cdot \cos(h) \quad \textbf{(75)}$$
$$a_y = a \cdot \sin(h) \quad \textbf{(76)}$$

Assuming that the heading (h) is computed with (77).

$$h = \mathrm{atan}(v_{yi} / v_{xi}) \qquad \text{if } v_{xi} < 0 \text{ h += } \pi \quad \textbf{(77)}$$

And the time needed to complete the maneuver is equal to the division between the speed change and the acceleration as is shown in (78).

$$t_m = [v_{target} - v_i] / a \quad \textbf{(78)}$$

All the parameters needed to perform a speed change maneuver are defined in the SpeedManeuver class whose attributes are written down in Table 9.

**Table 9:** Attributes from SpeedManeuver class.

| Attribute | Description |
|---|---|
| Maneuver type | SpeedManeuver |
| Initial time | Double that indicates the time at which maneuver starts |
| Ending time | Double that indicates the time at which maneuver ends |
| Maneuver time | end_time - init_time |
| Acceleration | acceleration needed to achieve the target speed in the maneuver_time |
| Cost | Maneuver cost, cannot be lower than 0 |
| Speed change | It is the difference between the current speed and the target one |

# CHAPTER 5. OPTIMAL MANEUVER SELECTION

In this chapter, it will be explained the procedure to choose the optimal maneuver to remain in a Well Clear status. The first step will be to associate each possible maneuver to a cost that depends on the Well Clear Violation interval, and it also depends on how that maneuver affects the current drone trajectory. As the cost of the maneuver increase, it will be less optimal, therefore, the optimal one will be the one with the lower cost from all the maneuvers that could be either a horizontal, a vertical, or a speed maneuver.

## 5.1. Maneuver selection

In order to remain in a Well Clear status after predicting a well clear violation, there are three possible ways to avoid that violation:

- Horizontal maneuver.
- Vertical maneuver.
- Speed change.

Nowadays, aircraft use TCAS II to avoid mid-air collisions whose resolution advisories are in the vertical plane. TCAS II only takes vertical maneuvers due to the higher precision in vertical position than the horizontal one.

As unmanned aircraft in U-Space fly below 150 meters above ground level, the vertical maneuver may not be viable and horizontal, or speed maneuvers must be considered.

To implement a loop that looks for the optimal maneuver, there are some variables needed that are common in all three maneuvers, which are defined in Table 10. The minimum and maximum values are useful to know maneuver possibilities while the step is used to loop through all the maneuvers.

Also, each maneuver has its own cost, which multiplied by the maneuver will result in one of the maneuver cost components. The other cost component is the WCV interval that will have its own cost constant.

**Table 10:** Parameter's class.

| Attribute | Description |
|---|---|
| min | The minimum value for the maneuver used in the loop which finds the optimal maneuver |
| max | The maximum value for the maneuver used in the loop which finds the optimal maneuver |
| c | The step used in the loop which finds the optimal maneuver |
| $k_h$, $k_v$, $k_s$ | Maneuver cost constant. The subindex depends on the maneuver type |
| k | Well Clear Violation interval cost constant |

### 5.1.1. Horizontal maneuver selection

Horizontal Remain Well Clear (HRWC) maneuvers consist of turning left or right. As a difference from vertical maneuvers, horizontal ones are only limited by the aircraft's performance.

Turns are performed by doing a circular trajectory with a given turning rate and circle radius which depends on the drone. The maneuver ends when the drone reaches its desired heading and then it goes on with the previous speed and a constant heading.

To compute the optimal horizontal maneuver, it is needed to implement a loop that goes over all possible horizontal maneuvers. The loop starts at the left turn with the bigger yaw angle, and it ends with a right turn with the bigger yaw angle. Left turns have negative rotation angle values, while right turns have positive ones. Therefore, the minimum yaw angle will correspond to a left turn while the maximum will correspond to a right one.

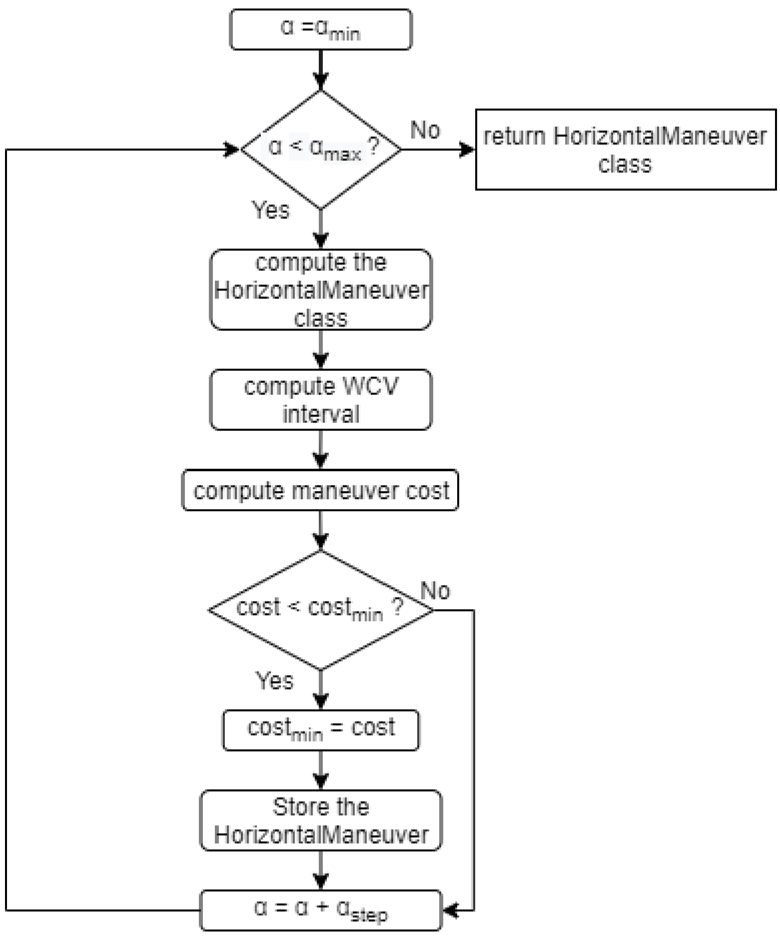


**Figure 14:** Selecting the horizontal optimal maneuver flow diagram.

Along this loop, it is computed the cost for each of the possible maneuvers and the lower cost maneuver is stored and returned by the time the loop ends.

In the flow diagram from Fig. 14, it is explained more in-depth how the compute_horizontal_maneuver function works. This function has as inputs ownship and intruder position classes, time interval B-T, actual time, and a DronePerformanceParameters and a rwc_param class.

### 5.1.2. Vertical maneuver selection

Vertical Remain Well Clear Recovery (VRWC) maneuvers consist of an altitude change by climbing or descending. This altitude change is limited by ground proximity and the zone maximum altitude, which is 150 meters.

Vertical maneuvers consist of implementing a loop with different vertical speeds but for this implementation vertical maneuvers must be defined differently. As said before, aircraft altitude is a crucial parameter so it would be significantly better to provide a new altitude instead of a vertical speed change.

Therefore, the drone will have predetermined climb and descend rates which will be used to achieve the new altitude. The vertical maneuver consists of a climbing/descend period to reach the target altitude, and then the drone continues at a constant altitude. Drone horizontal speed will not be changed at any time of this maneuver.

The VWCR output will be a maneuver object with the parameters from the lower cost vertical maneuver.

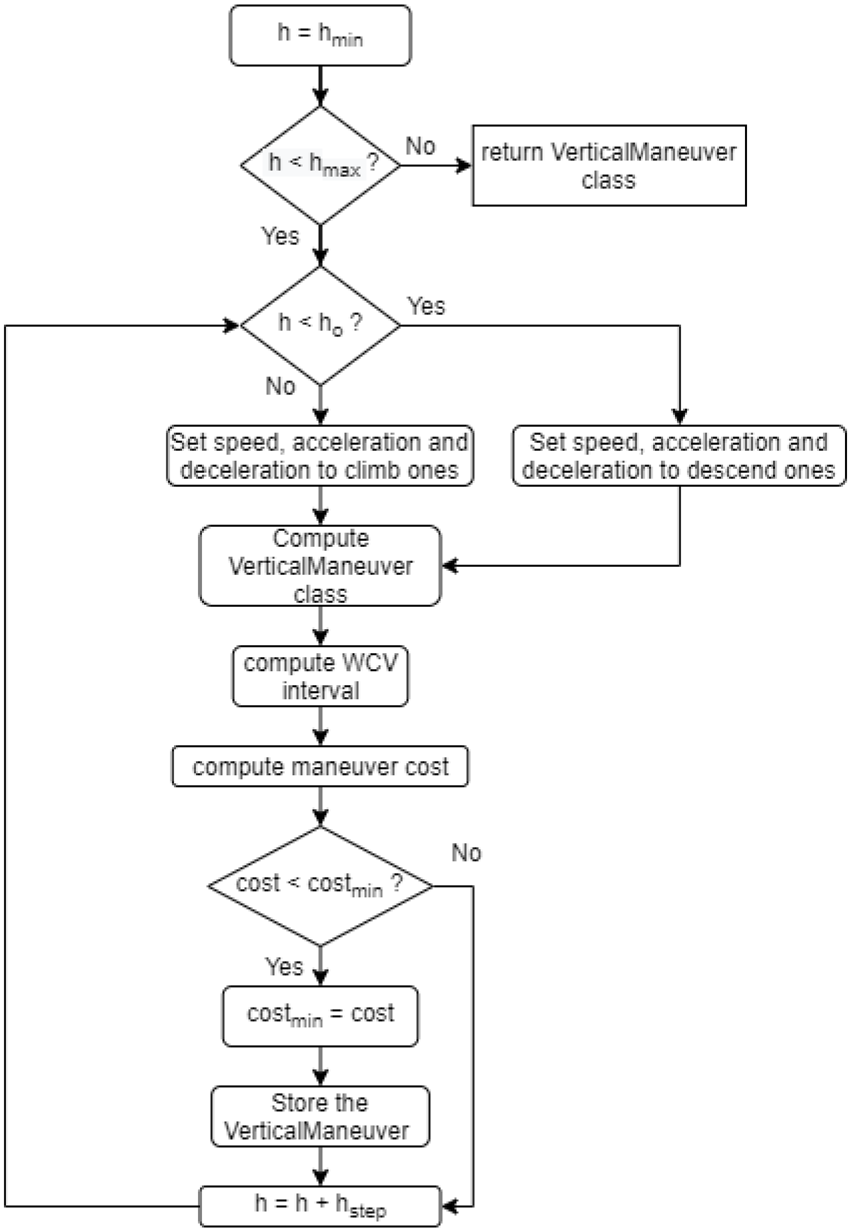


**Figure 15:** Selecting the vertical optimal maneuver flow diagram.

### 5.1.3. Speed maneuver

Speed Remain Well Clear (SRWC) maneuvers might be some of the easiest to perform as they allow the aircraft to continue its track. Its limitations rely on aircraft performance like the maximum and minimum speed and the maximum acceleration.

Even though this type of maneuver does not change the trajectory, they have an impact on trajectory time. Its impact on the current aircraft maneuver will be measured by the difference between actual and new speed.

The minimum speed value considered will be zero, which is to stop moving horizontally. Negative speed values are not considered because they are the same as a 180º horizontal maneuver. The maximum value is the maximum speed value that can be achieved by the drone.

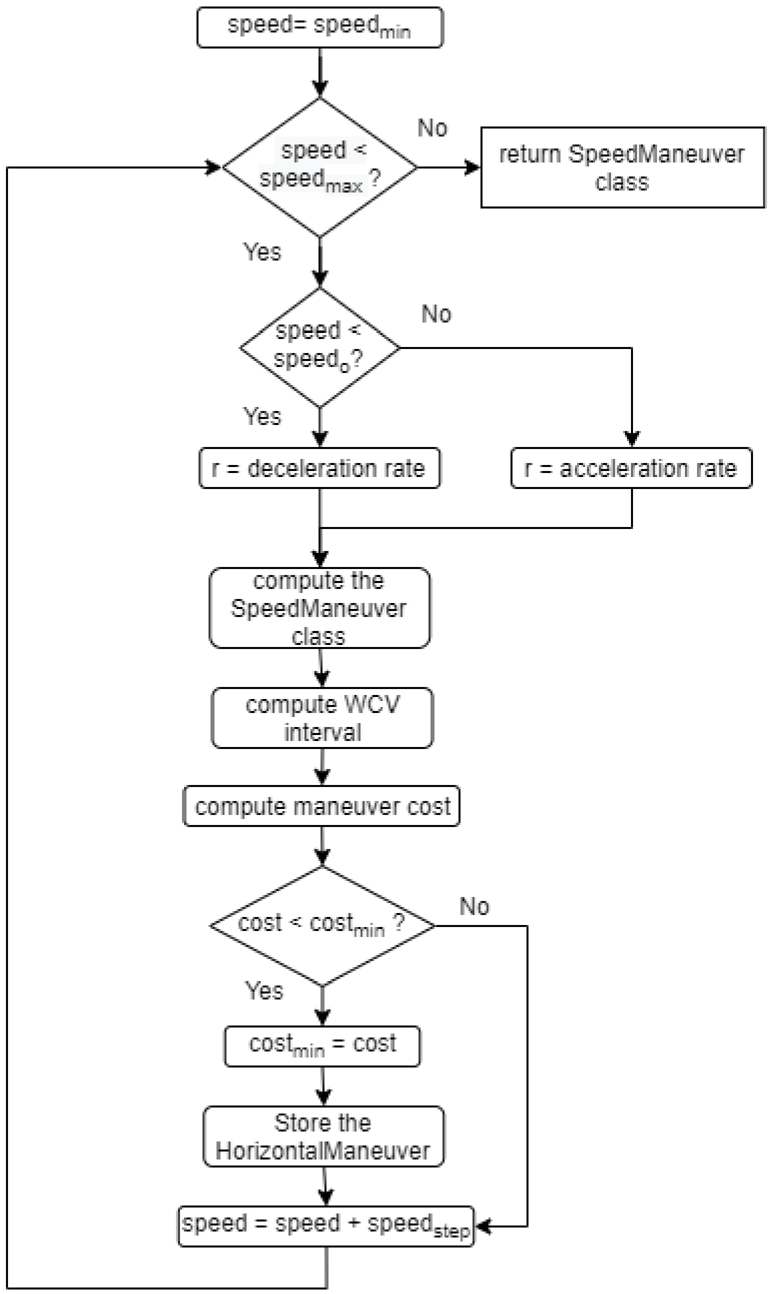


**Figure 16:** Selecting the speed optimal maneuver flow diagram.

### 5.1.4. Maneuver cost constants

In order to determine which maneuver is the optimal one, a cost is assigned to each of them. Each maneuver cost depends on two factors, which are the Well Clear Violation interval and the effect of the maneuver on the original trajectory.

The Well Clear Violation interval indicates the severity of the encounter because if the interval is higher, it means that the ownship will be more time in Well Clear Violation.

The performed maneuver will change the Well Clear interval, but also it affects the current ownship trajectory. This is the reason why the maneuver performed is a variable in the cost function.

To be able to sum the two cost components which have different units and magnitudes, they are divided into their maximum value. The WCV interval will be divided by the lookahead interval, and the performed maneuver will be divided by the maximum value for that maneuver that can perform the drone.

Even though dividing the components by their maximum values results in a non-dimensional component, they could have different magnitudes and it could be needed to give more importance to one component over the others. Therefore, to compare them, to be able to prioritize any maneuver over the others, or to give more importance to the WCV interval, the cost components are multiplied by a set of constants.

The maneuver cost is computed by expressions (79), (80), and (81) depending on the maneuver type (The subindex of the cost refers to the maneuver, where “h” refers to horizontal, “v” to vertical, and “s” to speed maneuver).

$$cost_h = k \cdot (t_2 - t_1) / (T - B) + k_h \cdot | \alpha_j / \alpha_{max} | \quad \textbf{(79)}$$
$$cost_v = k \cdot (t_2 - t_1) / (T - B) + k_v \cdot | (s_{zj} - s_{zi}) / (z_{max} - z_{min})| \quad \textbf{(80)}$$
$$cost_s = k \cdot (t_2 - t_1) / (T - B) + k_s \cdot ||\mathbf{v}_j - \mathbf{v}_i|| / |v_{max}| \quad \textbf{(81)}$$

The constant k indicates the weight of the WCV interval when computing the cost. This constant is multiplied by the WCV interval, which is the subtraction of $t_2$ and $t_1$, and it is divided by the lookahead interval [B, T]. By dividing the WCV interval by the lookahead interval we get the percent of the time that the drone is in WCV.

The maneuver constant ($k_h$, $k_v$, and $k_s$) is multiplied by a ratio obtained by multiplying the selected maneuver by the maneuvering range. The horizontal maneuver constant ($k_h$) is multiplied by the maneuver turn and divided by the maximum turn used to compute the optimal maneuver. The vertical maneuver constant ($k_v$) is multiplied by the altitude change, which is the difference between the altitude when the WCV is predicted and the target altitude, and it is divided by the maximum altitude change. The speed maneuver constant ($k_s$) is multiplied by the speed change and divided by the maximum speed change. As the minimum speed is zero, the maximum speed change will be equal to the maximum speed

The value of all the constants can be determined depending on the maneuvers that you want to prioritize. The only constant that should be higher is the WCV interval constant because it will make the software prioritize safety over the maneuver effect on the current trajectory.

In case that the ownship is performing a hover maneuver while the WCV is detected, only vertical maneuvers will be considered, which means that the cost of performing a horizontal or a speed maneuver will be infinite.

### 5.1.5. Remain Well Clear maneuver alert

The software is intended to predict Well Clear Violation during any part of the drone flight and then alert the pilot. But it is not feasible that once the software predicts a WCV it keeps sending maneuvers to the pilot until it stops predicting any WCV.

After the software predicts a WCV and computes the optimal maneuver it must send only maneuver in the alert and not changing it until it has passed a certain time. For this software, it is proposed that the time lapse between a change in the optimal maneuver selected must be at least the time needed to perform it. Therefore, the software will reevaluate the situation after the time that the maneuver should be performed and if it is still predicting a Well Clear Violation it will issue another maneuver.

Other possible solutions could be either to wait a fixed amount of time or change the maneuver in case that the situation is going worse while the drone is performing the maneuver. The situation could be considered that is going worse if the WCV interval increases instead of decreasing.

## 5.2. Well Clear Violation interval

To choose the optimal maneuver among all possibilities, the software looks for the maneuver with the lowest cost, which depends on the WCV interval and how the maneuver affects the trajectory.

Then, it is needed the WCV interval during a period where the ownship is performing a maneuver that differs from the WCV interval explained in Chapter 3.3.

To compute the WCV interval when the ownship is performing a maneuver, the interval B-T will be divided into two parts. The first one goes from the maneuver’s start to its ends while the second one goes from the maneuver ends to T.

In the second part, in which the ownship is not performing a maneuver, it will be assumed that it flies at a constant speed, so the functions from Chapter 3.3 will be used.

### 5.2.1. Vertical Well Clear Violation interval

Vertical Well Clear Violation interval is computed by dividing the B-T interval into two parts. The first one corresponds to the time in which the drone is still performing the chosen maneuver and the second one starts when the maneuver ends and lasts until the time is equal to T.

As the first part is when the drone performs the maneuver, it will be computed in a different way depending on the chosen maneuver.

For horizontal and speed maneuvers, VWCV is computed as if the ownship and intruder fly at a constant vertical speed during the interval B-T. This happens because neither of these maneuvers changes the ownship vertical speed. Therefore, the VWCV will be obtained by using the function VWCV(B, T, $s_z$, $v_z$, rwc_params).

For vertical maneuvers, VWCV is computed by dividing the maneuver into two maneuvers. The first one consists of a climb/descend maneuver with a rate of climb/descend that is a performance parameter of the ownship. When the target altitude is reached, the ownship continues flying at a constant altitude. During the second part, in which the ownship flies at constant vertical speed, the function VWCV(B, T - $t_m$, $s_z(t_m)$, $v_z(t_m)$, rwc_params) will be used to compute the interval.

The flow diagram from Fig. 17 shows how the Vertical Well Clear Violation interval is computed by applying the logic explained before.

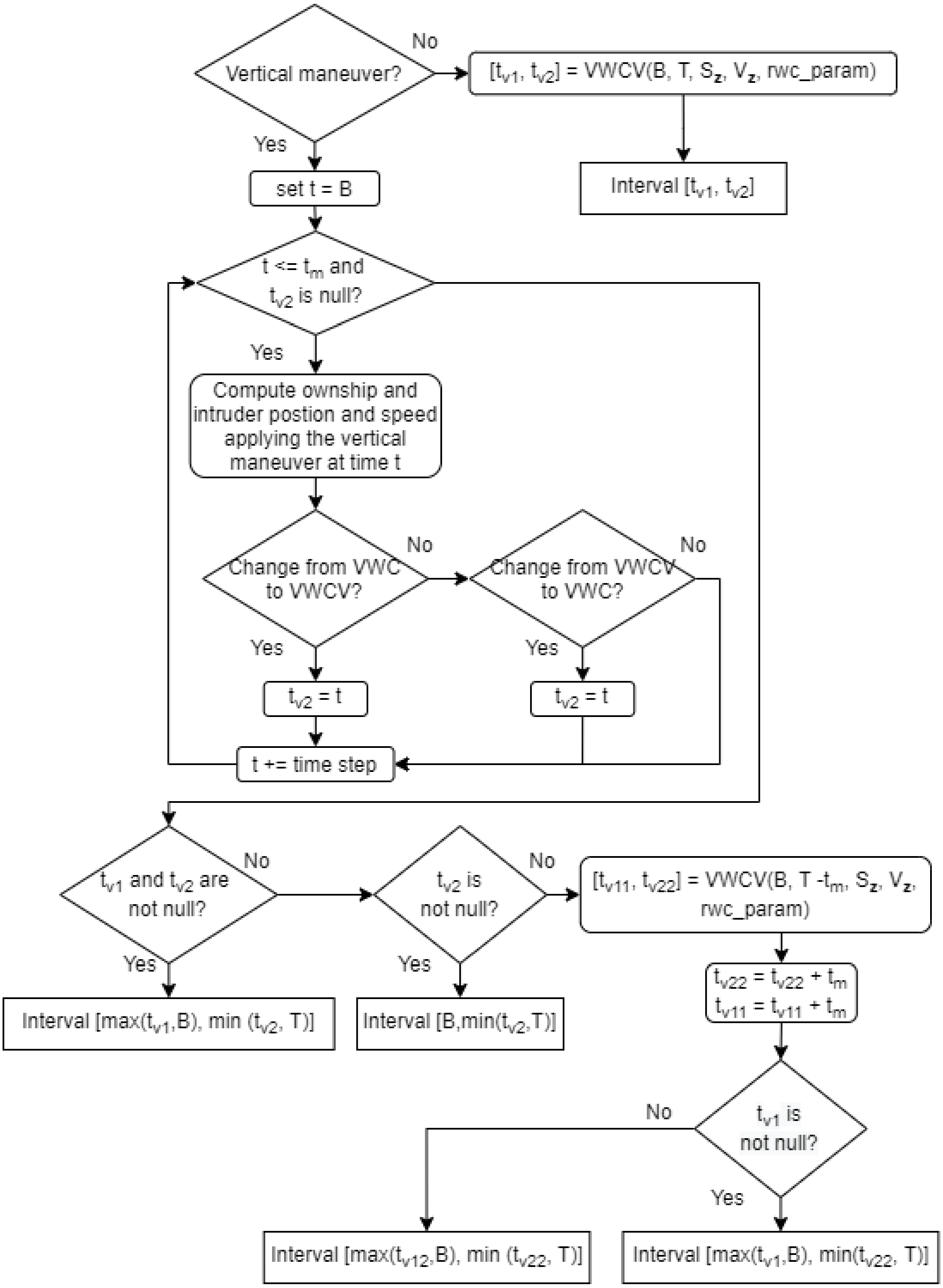


**Figure 17:** VWCV interval function flow diagram.

### 5.2.2. Horizontal Well Clear Violation interval

Horizontal Well Clear Violation interval is computed by dividing the 0-T interval into two parts as in the VWCV interval. The first one corresponds to the time in which the drone is still performing the chosen maneuver and the second one starts when the maneuver ends and lasts until the time is equal to T.

As the first part is when the drone performs the maneuver, it will be computed in a different way depending on the chosen maneuver.

For vertical maneuvers, HWCV is computed as if the ownship and intruder fly at a constant speed vector during the interval 0-T. This happens because vertical maneuvers do not change the ownship horizontal speed. Therefore, the HWCV will be obtained by using the function HWCV(T, s, v, rwc_params).

For horizontal and speed maneuvers, HWCV is computed by dividing the maneuver into two parts. The first one consists of applying the horizontal or the speed maneuver, while the second one, which starts when the maneuver is ended, the ownship continues flying at a constant speed vector. During the second part, in which the ownship flies with a constant horizontal speed vector, the function HWCV($T - t_m$, $\mathbf{s}(t_m)$, $\mathbf{v}(t_m)$, rwc_params) will be used to compute the interval.

The flow diagram from Fig. 18 shows how the Horizontal Well Clear Violation interval is computed by applying the logic explained before.

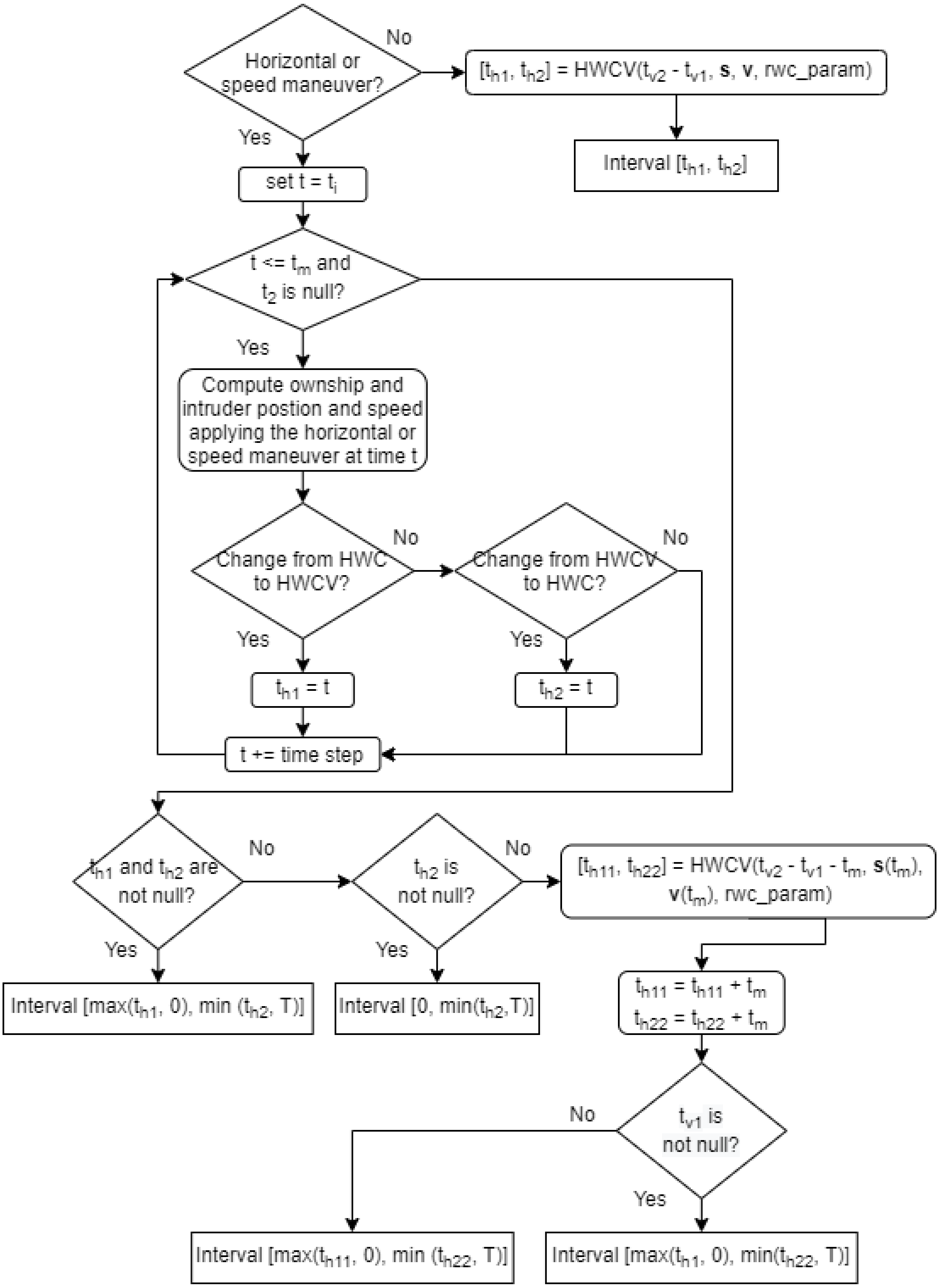


**Figure 18:** HWCV interval function flow diagram.

# CHAPTER 6. SIMULATIONS RESULTS

To understand how the software works, in this chapter one encounter simulation example will be explained step by step and it will be discussed how optimal the maneuvers chosen by the software are.

## 6.1. Step by step simulation

In this section, an encounter will be simulated to observe all the processes carried out by the software in order to predict the Well Clear Violation and to select the Remain Well Clear maneuver.

### 6.1.1. Before starting with the simulation

Before starting with the simulations there are some parameters related to the drone and the maneuver that must be defined.

*Parameters*

All the simulation parameters, which are defined in *Annex A*, belong to classes that have been defined through the project. For a better understanding of the simulation, the most relevant parameters are listed in Table 11.

**Table 11:** Well Clear parameters used in the simulation.

| Parameter | Value |
|---|---|
| DMOD | 15 m |
| $\tau_{mod}$ | 5 s |
| HMD | 15 m |
| ZTHR | 15 m |
| B | 0 s |
| T | 20 s |

*Encounter*

The simulation consists of applying a Well Clear System to a given encounter that has been previously generated by generating two drone trajectories and then overlapping them. All the information on the encounter used for this simulation can be defined in *Annex B*.

In Fig. 19 and Fig. 20 it is shown the encounter that will be used as an example. It is a 120-second simulation of the position and speed of two drones that fly at Very-Low-Level. Note that in Fig. 19, the position of the ownship at the start of the encounter is at x = 23 m and y = - 155 m, while the intruder position is x = 230 m and y = 8 m.

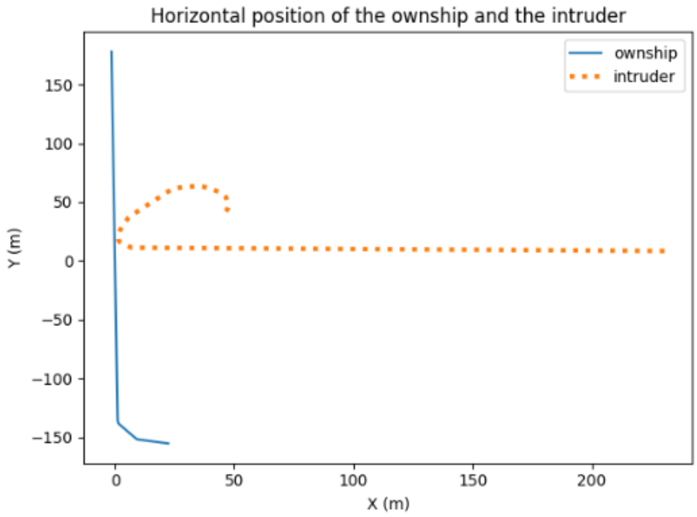


**Figure 19:** Ownship and intruder horizontal position.

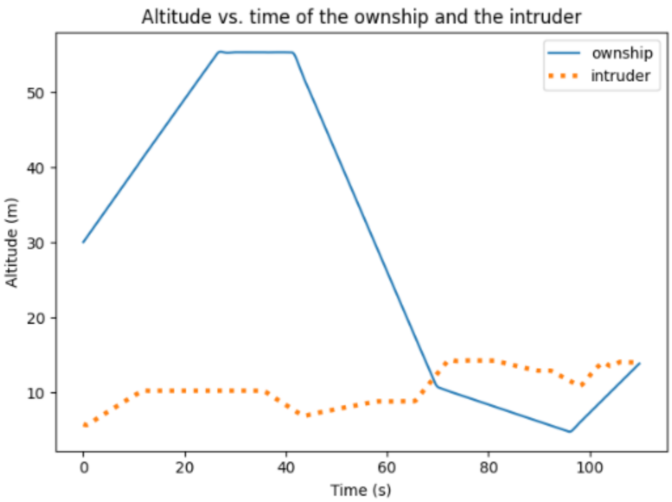


**Figure 20:** Ownship and intruder altitude vs. time.

### 6.1.2. Simulation example

The simulation studies the position and speed from the ownship and the intruder every 0.02 seconds. If there is not any Well Clear Violation, the ownship will continue with its trajectory, but in case that a Well Clear Violation is predicted, the ownship will perform a maneuver to recover a Well Clear status.

*Well Clear Violation prediction*

The Well Clear Violation detection is performed using the algorithm explained in Chapter 3.3. If a Well Clear Violation is predicted, the software will compute a maneuver to remain in a Well Clear status.

During the time that the drone is performing the maneuver, the software will not provide a new maneuver. Changing the maneuver could lead to a pilot distraction. Once the maneuver has ended, the software continues predicting Well Clear Violations and it will provide another maneuver if it is needed.

In Fig. 21 and Fig. 22 it is shown the ownship and intruder position at the time that the WCV is predicted. It is also shown the interval in which is predicted that the ownship will enter in WCV.

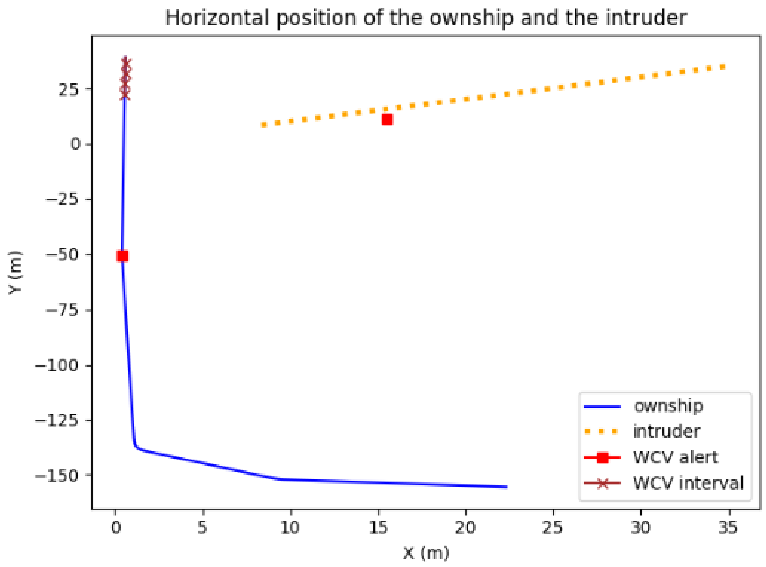


**Figure 21:** Horizontal encounter position with WCV markers.

Note that the software supposes that drones fly at a constant speed while predicting the WCV, therefore the trajectory plotted in Fig. 21 and Fig. 22 will be different from the original one, which is plotted in Fig. 19 and Fig. 20.

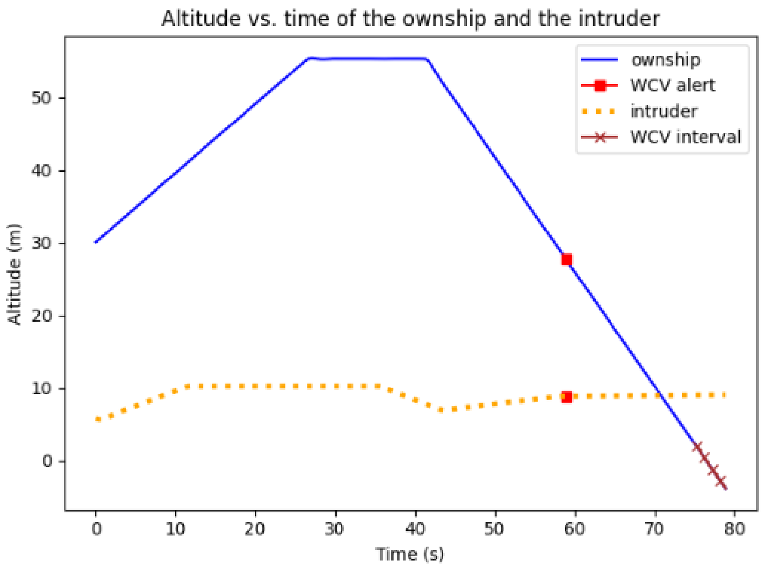


**Figure 22:** Vertical encounter position vs. time with WCV markers.

Table 12 is shown the relative position and speed values at the time that the Well Clear Violation is predicted. These values are the key for selecting the optimal maneuver, which should be a vertical one because the vertical distance and the vertical threshold are close.

**Table 12:** Relative position and speed of the encounter.

| Variable | Value |
|---|---|
| x | -15.09 m |
| y | -61.76 m |
| z | 18.95 m |
| $v_x$ | 0.01 m/s |
| $v_y$ | 3.29 m/s |
| $v_z$ | -1.58 m/s |

In Figures 21 and 22, it is shown the Well Clear Violation interval that corresponds to the last 3 seconds of the lookahead interval. Understanding why the drones are only in WCV during that period is not trivial, in Figures 23 and 24 it is plotted the vertical and horizontal distance during the lookahead interval.

To be in WCV the drone must be in both VWCV and HWCV what means that the distance between drones must be lower than the thresholds. In the vertical plane, the distance is lower than the threshold (ZTHR) during almost all the lookahead interval, while the horizontal distance is only lower than the horizontal threshold for the last 3 seconds of the lookahead interval.

In Figure 23, it is shown the horizontal distance and the distance to the Closest Point of Approach that has been computed with the time to CPA. The distance to CPA is zero at the first part of the lookahead interval because the time to

CPA is also zero. This happens because the time to CPA is zero if it is higher than the modified tau. From the point in which the time to CPA is lower than the modified tau and the distance to CPA is almost equal as the horizontal distance.

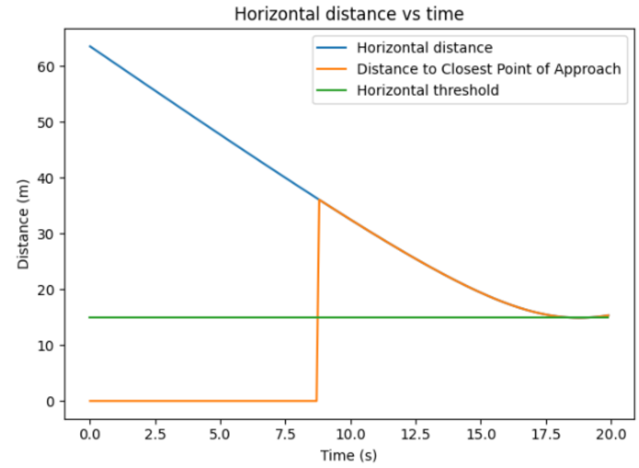


**Figure 23:** Horizontal distance between drones during the lookahead interval.

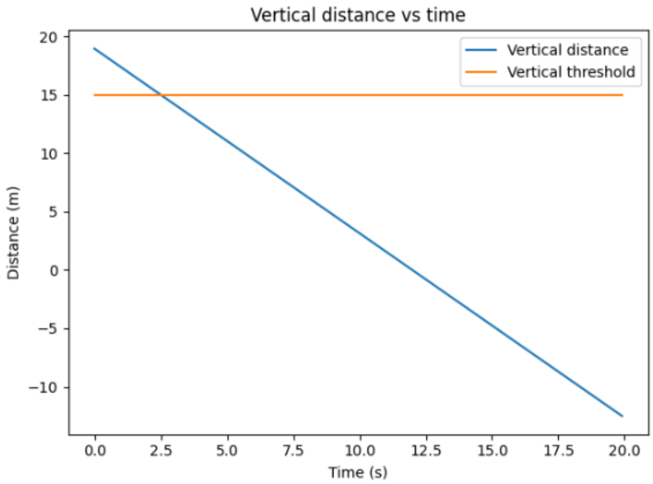


**Figure 24:** Vertical distance between drones during the lookahead interval.

*Remain Well Clear maneuver selection*

After detecting a Well Clear Violation, the Well Clear Recovery maneuver will be computed. To choose from all possible maneuvers, which depend on drone performance, the algorithms from Chapter 5 are used.

The chosen maneuver is either a horizontal, a vertical, or a speed one. And it is the maneuver with the lower cost from all the possible solutions. In Table 13 it is shown the cost of the optimal maneuver of each type, and the values used to compute their cost.

**Table 13:** Optimal horizontal, vertical, and speed maneuvers.

| Maneuver type | WCV interval | WCV interval cost constant | Maneuver | Maneuver cost constant | Total cost |
|---|---|---|---|---|---|
| Horizontal | 0.28 s | 3 | - 20º turn | 0.5 | 0.1 |
| Vertical | 0 s | 3 | Climb 1.25 m | 1 | 0.07 |
| Speed | 0 s | 3 | Accelerate 7.3 m/s | 0.2 | 0.1 |

Therefore, the maneuver performed by the drone will be the vertical one, as it is the one with the lowest cost. The ownship will climb to 29 meters altitude instead of continuing descending.

*Performing the selected maneuver*

During the interval that goes from the starting to the ending maneuver time, the maneuver must be performed, and once the maneuver is performed the Well Clear Violation prediction will be reevaluated.

In Figure 25, it is shown the altitude vs. time for the ownship and intruder. The green line represents the climb made to remain in Well Clear, while the blue one is the original trajectory performed by the ownship.

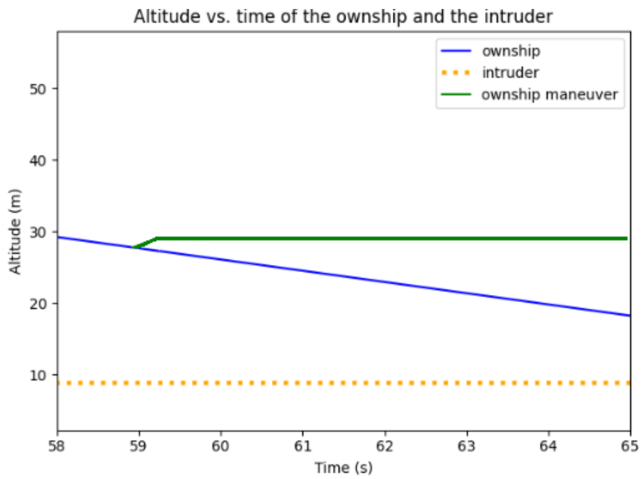


**Figure 25:** Ownship and intruder altitude over time.

Once the ownship reaches the target altitude it keeps flying without changing it. In case the drone is still predicting a WCV after performing the maneuver, instead of continuing flying at a constant altitude, the drone will perform a new maneuver provided by the software.

## 6.2. Results

To ensure that the maneuvers provided by the software are optimal, a 2000-encounter file has been simulated and the result of the software maneuver decision patterns has been analyzed.

The encounter information consists of the position and speed data of the ownship and the intruder, which are two drones that fly close to each other. The drones usually fly at speeds lower than 10 meters per second and at low altitudes, which are lower than 150 meters. These encounters have been provided and their generation is not inside this project scope.

To improve the maneuver selection, a Well Clear Violation threshold of 2 seconds will be introduced, and it will be also compared the difference between applying that threshold or not.

### 6.2.1. Benefits from performing the maneuver

The expected Well Clear interval has been compared between applying the maneuver and without applying it. And the result obtained is that the software has reduced the interval especially to the encounter with large Well Clear intervals.

In the plots of the WCV interval before applying the maneuver a major part of the intervals is almost null. This makes that when the software computes the optimal maneuver the interval has almost no weight in the cost function, resulting in that the optimal maneuver is just continuing with the current trajectory.

The software is predicting the WCV too early to know which must be the maneuver to perform. To solve the problem of having too low WCV intervals, it is proposed to have a WCV interval threshold. Therefore, the software will only alert of the predicted Well Clear Violation and issue a maneuver in case that the predicted WCV interval is higher than the threshold.

During this section, it will be shown the difference in the WCV intervals before and after applying the maneuver for the case in which it is applied a WCV interval (Figure 27) and also when it is not applied (Figure 26).

Before applying the maneuver, the Well Clear Violation interval is reduced to almost 0 seconds for all the encounters independently of the Well Clear Violation threshold.

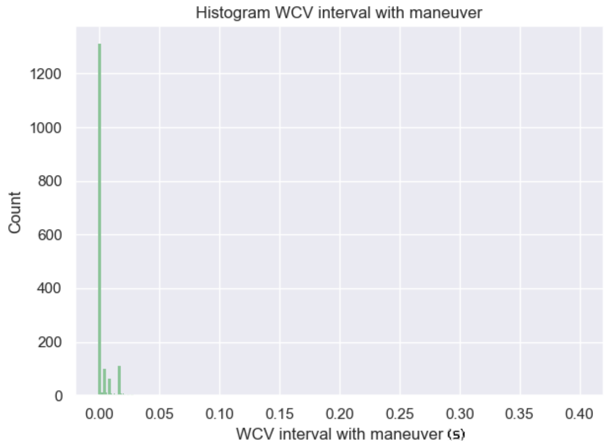


**Figure 26:** Well Clear Violation interval before the maneuver without threshold.

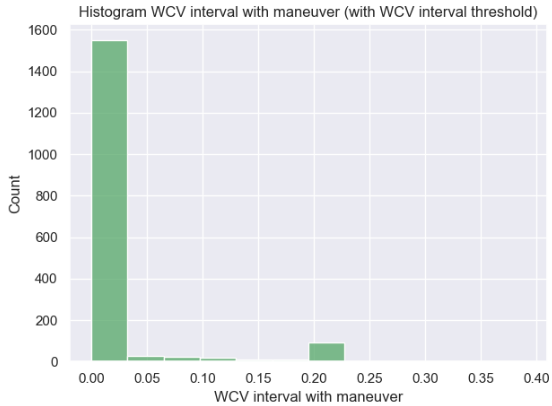


**Figure 27:** Histogram of WCV interval before the maneuver with the threshold.

Before applying the optimal maneuver, the WCV interval reached values of 7 seconds for the encounters in which there is no WCV interval threshold as is shown in Fig. 28.

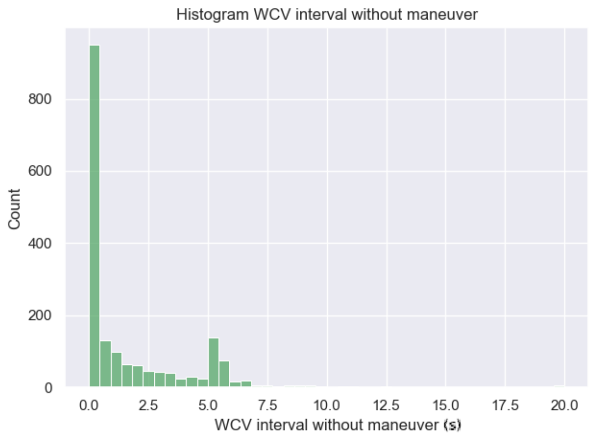


**Figure 28:** Histogram of WCV after maneuvering without the threshold.

After applying the threshold, the predicted Well Clear Violation interval increases. As it is shown in Fig. 29, the predicted interval goes from 2 seconds, which is equal to the threshold, to 12 seconds.

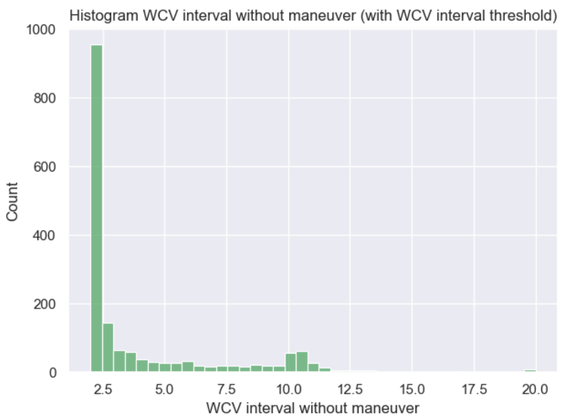


**Figure 29:** Histogram of WCV interval after maneuvering with the threshold.

### 6.2.2. Maneuvers chosen

In this section, it will be shown the histogram from the three maneuvers types that the software selects. From these histograms, it will be noticed that the maneuvers chosen have a lower effect over the original trajectory. It will be also compared the difference in the maneuver selection depending on if there is a minimum Well Clear Violation interval threshold or it is not.

In Figures 30 and 31, it can be seen that when there is no WCV interval threshold the preferred maneuver is to continue straight while if the interval is applied the maneuvers consist of low turn-angles. Even though when the maneuvers were defined the turn sign determined if it was either a left or a right turn, in this plot the values shown are the absolute value of the turn in degrees. The value plotted is the absolute one because the drone has the same performance in right turns and as in left turns.

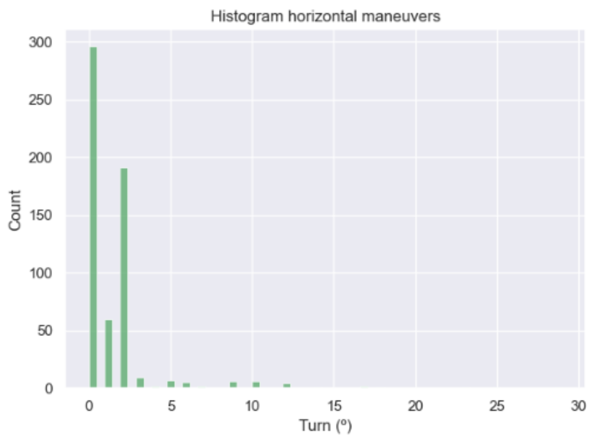


**Figure 30:** Horizontal maneuver’s histogram.

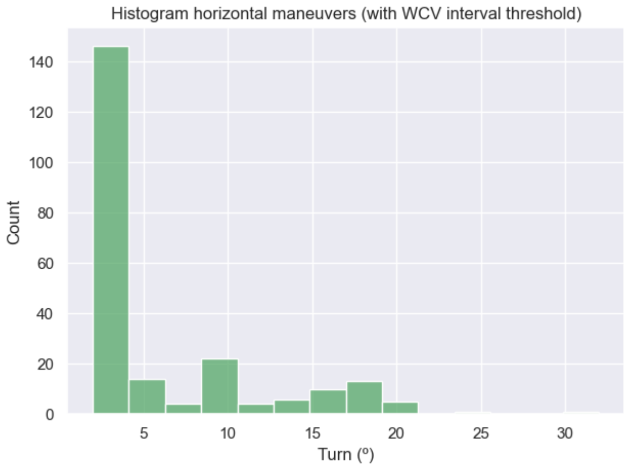


**Figure 31:** Horizontal maneuver's histogram with the threshold.

Most of all vertical maneuvers consist of climbing or descending less than 3 meters. This makes sense because vertical maneuvers are chosen when the vertical separation is close to the vertical threshold, so the altitude change needed to remain in Well Clear status is minimum. It is also noticed that when the WCV interval threshold is not applied (Figure 32), there are a lot of maneuvers that consist of keeping at the same altitude.

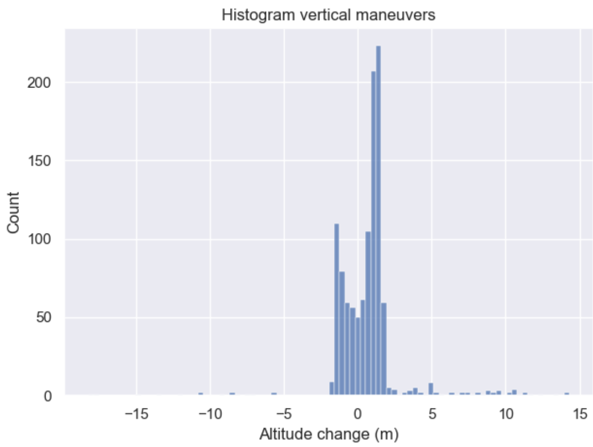


**Figure 32:** Vertical maneuver's histogram.

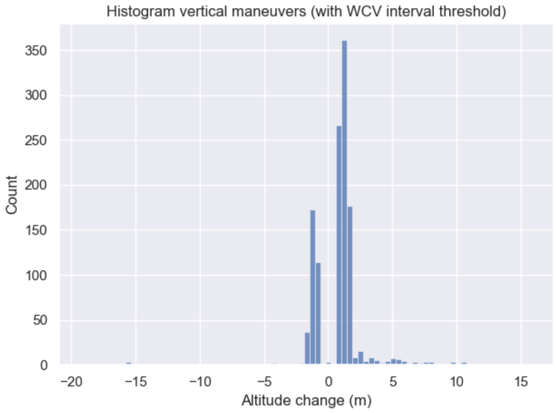


**Figure 33:** Vertical maneuver’s histogram with the threshold.

The speed maneuver consists of speed changes that go from decelerating 4 meters per second to accelerating around 4.5 meters per second for the case that the WCV interval threshold is not applied. For the case in which the threshold is applied (Figure 35), the maneuvers go from decelerating 4 meters per second to accelerating 8 meters per second.

The difference is that when there is no threshold (Figure 34), the maneuvers are close to a zero-speed change while when the threshold is applied the speed changed are higher.

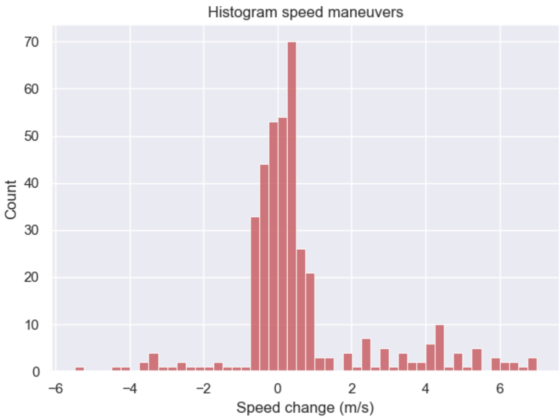


**Figure 34:** Speed maneuver's histogram.

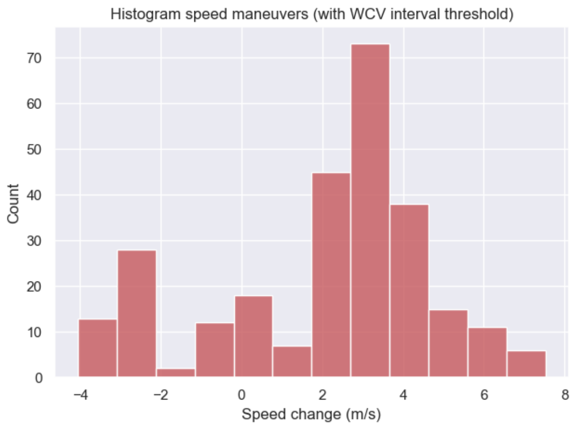


**Figure 35:** Speed maneuver's histogram with the threshold.

#### 6.2.3. Maneuver type chosen

The software must choose between the three possible maneuvers, which are horizontal, vertical, and speed maneuvers. From all the studied encounters, around 70% perform a vertical maneuver while 30% is divided between horizontal maneuvers and speed maneuvers. This is because moving vertically is the fastest way to recover a Well Clear status.

To study how the parameters used to detect a Well Clear Violation affect the chosen maneuvers, the maneuver type will be plotted depending on the variables from Table 14. Also, the scalar product of the position and the speed will be used to know whether if drones are converging or diverging.

**Table 14:** Variables used for plot's axis.

| Symbol | Variable |
|---|---|
| s | Horizontal relative position (2D vector) |
| v | Horizontal relative speed (2D vector) |
| sz | Vertical relative position |
| vz | Vertical relative speed |

Figure 36 shows the maneuver chosen depending on how the drones converge or diverge vertically and their vertical distance. If $sz \cdot vz < 0$ drones are converging while if $sz \cdot vz > 0$ they are diverging.

In Figure 36, we can see how the software chooses a vertical maneuver when the vertical distance is higher than the vertical threshold (ZTHR). It happens because if the distance is higher than the vertical threshold, it will need a low altitude change to remain in Well Clear, which will result in a lower cost maneuver compared with applying a vertical or a horizontal one. Horizontal and speed maneuvers are rarely chosen for an encounter with a vertical distance higher than the threshold.

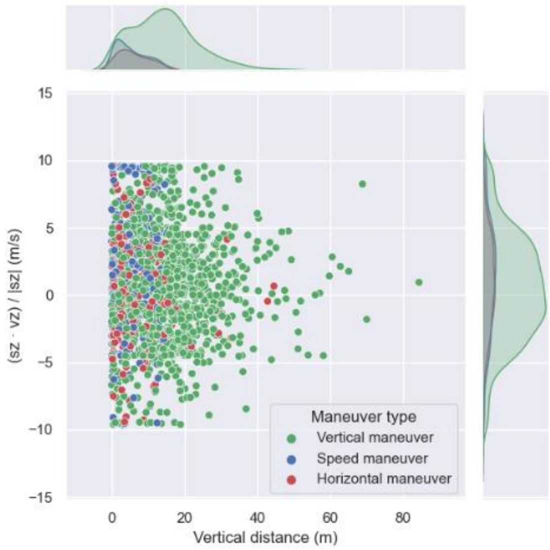


**Figure 36:** Maneuver type depending on vertical speed and distance.

In Fig. 36, the software chooses vertical maneuvers when drones are vertically converging and horizontal maneuvers when drones are vertically diverging. The selection of speed maneuvers seems to be non-related with the vertical speed.

Figure 37 shows the maneuver chosen depending on how the drones converge or diverge horizontally and their horizontal distance. If $s \cdot v < 0$ drones are converging while if $s \cdot v > 0$ they are diverging.

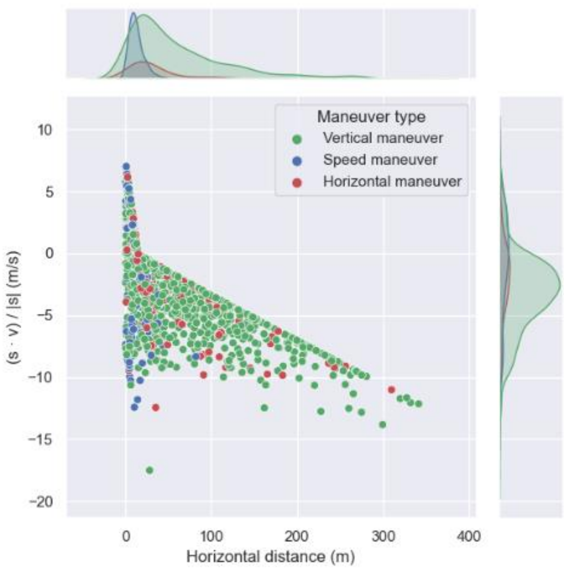


**Figure 37:** Maneuver type depending on horizontal speed and distance.

If comparing Fig. 36 with Fig. 37, it can be seen the effect of having a time variable in the Well Clear Violation detection. The horizontal distance from some encounters is a lot higher than from their vertical distance, while their horizontal distance is related to the speed at which they are horizontally converging.

The software chooses horizontal maneuvers for encounters with a horizontal distance close to the horizontal threshold which is diverging. It happens because if they are diverging and they have a distance close to the threshold, a small direction change could make them remain Well Clear with a low impact on the trajectory.

For an encounter with a larger horizontal distance than the threshold in which both drones are converging, the software prefers speed and vertical maneuvers. In case that there is predicted a Well Clear Violation and the distance is larger than the threshold, the drones must be converging fast, so reducing the speed could be a good solution to remain in Well Clear.

Vertical maneuvers are preferred for an encounter with a lower horizontal distance than the threshold and encounters in which the distance is higher than the threshold but drones are horizontally converging.

In Figure 38 it is shown how affects the encounter angle to the selected maneuver, and we can see how speed maneuvers are rarely chosen in frontal encounters, while they are chosen in perpendicular ones.

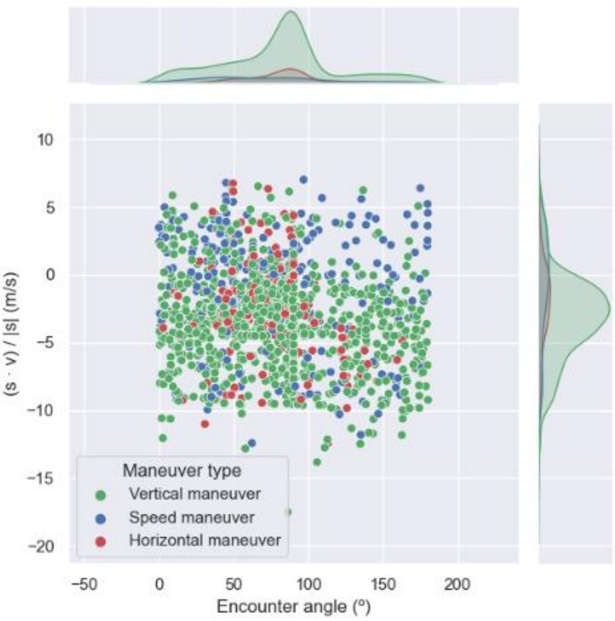


**Figure 38:** Maneuver type depending on horizontal speed and encounter angle.

# CHAPTER 7. U-SPACE NETWORK

In this chapter, the characteristics of the U-Space architecture will be explained, and some architecture examples will be introduced. Also, the application of mobile networks for U-Space and its interference problems will be discussed.

## 7.1. U-Space architecture

There are different possibilities in which architecture to use in order to implement the U-Space systems. But all the proposed architectures must have the same elements and principles that are listed by SESAR JU [25].

### 7.1.1. Core elements

U-Space is a set of services that belong to a framework that aims to support drone operations in any airspace class.

*Scope*

The U-Space involves different challenges that are carried out by different stakeholders. Then, it is essential to share a common architecture between all the stakeholders.

The architecture aim is to support the decision needed to implement new concepts or technologies into the U-Space. All the stakeholders should agree on the architecture, which should not prescribe any implementation model.

*Actors*

Actors are a preliminary list of all the stakeholders involved in the ConOps development, and can be classified as:

- Authorities: authorities can be divided into Civil Aviation Authorities, Military Authorities, Local Authorities, and Other Authorities like registrar, airworthiness authorities, etc.

- Service Providers: depending on the type of service, Service Providers can be divided into Air Navigation Service Providers (ANSP), Aeronautical Information Management Providers (AIMP), Common Information Services (CIS) providers, U-Space Services Providers (USSP), and Supplemental Data Services Providers (SDSP).

- Drone Operators: depending on whether the drone is operated by a pilot or not, they are divided into the remote pilot (role) or Automatic onboard pilot (system).

- Aviation users: the pilot and the crew of an aircraft, gliders, etc.

- Privileged users, law enforcement, military: they are users with special access to U-Space information.

*Services*

A service is a contractual provision of a non-physical object from the service provider to the user or group of users. ConOps and U-Space Blueprint divide U-Space's services into three different groups which are:

- Service to service providers: they are services provided by an authority to a U-Space service provider or services provided between U-Space services providers.

- Supplemental data services: they are services that provide additional data to other services. The data could be terrain, weather, or another type of information.

- Services to drones operators: they are services provided by services providers to drone operators, which could be either remote pilots or any Automatic onboard pilot system.

### 7.1.2. U-Space architecture's principles

The U-Space architecture must implement the principles from the U-space blueprint [6]. The architecture relies on automation, connectivity, and digitalization for the drone and the U-Space systems. Then, the architecture is defined as:

- Service-oriented: it is needed to ensure that the architecture is based on the service's characteristics.

- Modular: the architecture is built by functional blocks that contain a set of functionalities. Blocks can be added to implement new functionalities to provide a scalable and flexible system.

- Safe: the architecture must be safety focused on all the people and stakeholders involved and affected by the U-Space.

- Open: the architecture is composed of published or standardized components, which makes it easier to change its components.

- Standard-based: the architecture interfaces must be defined by the standards.

- Interoperable: the architecture must provide homogeneous services to different operations.

- Technology agnostic: the architecture definition must be independent of its implementation.

- Incremental approach: the definition of architecture is an evolutive and iterative process.

- Automated and digitalized: the architecture must reduce the manual operations by automatizing them as much as possible while keeping secure and safe U-Space services.

- Allowing variants: the architecture should allow alternative solutions while ensuring interoperability between them.

- Deployment agnostic: the architecture must support the business and regulatory frameworks established.

- Securely designed: the architecture must be secure against cyber-attacks.

### 7.1.3. Possible U-Space architectures

Any architecture which accomplishes the principles listed above could be a possible solution for U-Space. In this section, different architecture will be discussed, which are: GOF USPACE, Swiss U-Space, DOMUS, and SAFIR.

*GOF USPACE*

The GOF USPACE (Gulf of Finland) is a SESARJU project that allowed the integration of the solutions from different services providers in all phases from drone operations [25].

The GOF USPACE architecture provides a framework based on SWIM principles, which makes it easier to add, upgrade, or swap the system's components.

"SWIM consists of standards, infrastructure, and governance enabling the management of ATM information and its exchange between qualified parties via interoperable services." [26]

In this architecture, exchange information services use formal templates that separate the data into different documents depending on whether it is logical, technical or runtime concerns.

*Swiss U-Space*

The Swiss U-Space Implementation (SUSI) program is a partnership between the Swiss Federal Office of Civil Aviation, the Swiss ANSP skyguide, and thirty-one UTM/U-Space companies [25].

SUSI implementation architecture is a set of decentralized services and functions that support multiple drone operations. The services are complementary to the traditional ATM. And even though they are provided by different service providers, all services must provide a similar experience.

The Flight Information Management System (FIMS) provides situational awareness to all U-Space participants. The InterUSP platform shares information across the network to ensure situational awareness.

*DOMUS*

The Demonstration of Multiple U-Space Suppliers (DOMUS) is a SESARJU project with the aim to ensure that drones operate safely along with other U-Space users. The demonstration involved three different service providers with one ecosystem manager and different drone operators [25].

DOMUS is a modular architecture with an unlimited number of service providers, which can operate over the same geographical area under the interconnection of an Ecosystem Manager.

The Ecosystem Manager acts as a proxy for the ATM system and all the network’s users, and it also acts as a firewall between the ATM system and USP’s network and maintains a central database of airspace, mission plans, e-registry, and tracking.

*SAFIR*

The SAFIR team joined the U-Space VUTURA project, which lead to the foundation of SAFIR-MED. SAFIR-MED focuses on demonstrating medical uses cases of the U-Space services [25].

The SAFIR architecture is designed to minimize the risk of providing situational awareness and redundancy. In SAFIR architecture, all the service providers collaborate to provide the necessary services to drone operators.

USSPs are the actors in SAFIR architecture. And the State Authority DTM system, which is a USSP and an actor from SAFIR architecture, acts as an information exchange gateway for the interactions in centralized service.

Other stakeholders are SDSP, Civil Aviation Authority, aviation users, ANSP, and local authorities.

## 7.2. Proposed architecture for Well Clear services

To provide the Well Clear services proposed along with this project it will be needed an architecture and a telecommunication network to exchange information. In order to analyze the performance of the network, firstly the needed architecture will be introduced in this section.

Well Clear services are provided on the ground, but they need drone position and speed information. Therefore, the drone will send its position and speed data through the mobile telecommunication network, the information will arrive at a Base Station (BS) that will send back the information to the Well Clear service provider. Between Base Station and service provider the communication will be sent through optimal communications instead of using the mobile telecommunication network.

When the drone information reaches the Well Clear service provider, it will predict the drone's Well Clear status and in case that it is in Well Clear Violation it will send back to the pilot in remote the Well Clear Violation alert and its corresponding Remain Well Clear maneuver.

After the pilot receives a Well Clear Violation alert and its maneuver, he will decide whether to perform the maneuver or not. Once the pilot decides the maneuver, he sends back the information to the drone so it can perform the maneuver.

In Fig. 39 it is shown a simplification of the architecture needed to provide the Well Clear services. In Fig. 39 it is also shown the path that the signal follows, the red lines represent the data transmitted by the drone that goes to the server, which predicts the WCV and computes the maneuver, and also the alert and the maneuver issued by the server that reaches the pilot in remote. The blue lines correspond to the signal from the pilot orders to the drone after receiving the alert and the maneuver.

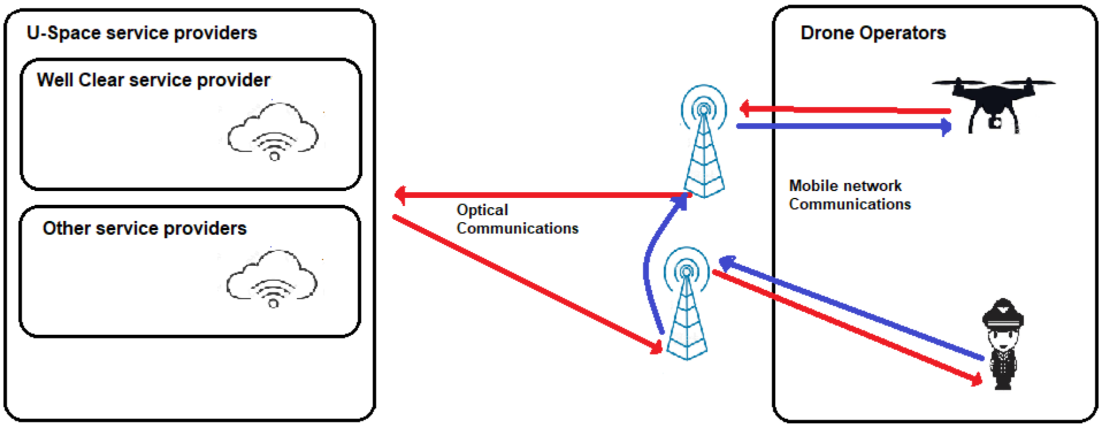


**Figure 39:** Proposed U-Space architecture.

# CHAPTER 8. MOBILE TELECOMUNICATIONS FOR U-SPACE

In this chapter, it will be discussed the implementation of a mobile telecommunication network for the U-Space. During this chapter, it will be explained the different problem that will face a U-Space service when it uses the mobile network which are the interferences, the delay, and the performance during the handover. Handover performance and the communication delay will be studied for each mobile network technology from 2G to 5G.

## 8.1. Mobile telecommunications problems

The main focus of the chapter will be to study the effects of the delay, because if the delay is high enough it will make the U-Space services unavailable. Even though the signal quality could be also a factor, in case that the quality signal is low, the communication speed will be lowered to compensate for it, which will lead to a delay problem.

Another problem that will not be studied is the retransmission of packets with errors. As the information needed to provide the Well Clear service needs to be as fresher as possible, retransmitting packets makes no sense as it will increase the communication delay.

## 8.2. Interference due to using mobile networks for drones

Mobile telecommunication infrastructure is probably the most suitable for providing U-Space services. It will enable flexibility in the implementation and design of U-Space services.

The problem is that current telecommunication services are optimized to ground users instead of air ones, which could lead to interferences and coverage losses. To solve this problem, the cooperation between telecommunication industry and U-Space service providers will be needed to adapt the infrastructure to U-Space’s requirements. Also, U-Space must be able to adapt to the new communication technologies such as the 5G mobile telecommunication infrastructure.

Although mobile telecommunication networks will be used to provide U-Space services, there are some situations where they will not be an optimal solution such as remote locations or the fact that drones are at a higher altitude than the terrestrial users.

### 8.2.1. Mobile networks interference problems

The problems of using the mobile network for U-Space are defined in “Study on Enhanced for LTE Support for Aerial Users”, which is a study performed by the 3GPP in 2017 [17].

The main problems that have drones, which will be known from now on as aerial User Equipment (UE), due to their altitude during flights are interferences that can be divided into uplink (UL) and downlink (DL).

There are also other problems like the lower performance during the Handover process, which will be discussed in Chapter 10, or the fact that the drones are served by the side lobes because the antennas are usually down tilted. In the sidelobes are null which cloud led to a loss of communication.

*Downlink interferences on aerial UEs*

In the downlink, the aerial UE could be interfered with by a higher number of antennas than a terrestrial one since aerial UEs have a Line of Sight (LOS) with more antennas than the terrestrial UEs.

The interference from multiple cells that receive aerial UEs makes that more resources will need to deliver the same amount of data. This leads to lower throughputs, especially at high offered traffic loads. Also, the throughput degradation is higher in aerial UEs than in terrestrial ones.

*Uplink interferences caused by aerial UEs*

Due to the number of antennas that are in LOS with aerial UEs, they cause interferences to terrestrial UEs. This interference caused by aerial UEs to terrestrial ones increases the resources need to transmit the same quantity of data resulting in a throughput degradation for both terrestrial and aerial UEs.

### 8.2.2. Possible solutions for Mobile networks interference problems

To solve the problems caused by interference in DL and UL communications, different possible solutions were proposed in the 3GPP study [17], which can be divided into UL solutions and DL solutions.

*Downlink solutions*

The proposed solutions by 3GPP to reduce the DL interference from the base stations to the aerial UEs are the following ones:

- Using FD-MIMO: Full Dimension Multiple Input Multiple Output (FD-MIMO) consists of using multiple antennas in the transmitter to reduce the interferences in the aerial UEs.

- Using directional antennas at aerial UEs: Consists of equipping aerial UEs with directional antennas to reduce the power of the interference downlink signal. The result of this implementation depends on how well the UEs track the direction of the LOS.

- Beamforming at aerial UEs: Consist of equipping aerial UEs with beamforming receive antennas. The idea behind this technology is to process the received signal with different antennas and combine them optimally by adjusting their phases and amplitudes.

- Employing intra-site coherent Coordinated Multi-Point with Joint Transmission (JT CoMP): JT CoMP is a technique with the aim of reducing the interference in the edge-cell users, which are an increasing problem due to the trend toward smaller cells. JT COMP allows multiple base stations to jointly transmit information to a single user.

- Applying coverage extension techniques: extension techniques are used to enhance synchronization and initial access to aerial UEs.

- Using coordinated data and control transmission schemes: it consists of jointly transmit data from different cells to aerial users, grouping different cells for aerial UEs while for terrestrial UEs they transmit independently from each other.

*Uplink solutions*

To mitigate the UL interferences caused by aerial UEs to terrestrial UEs, 3GPP proposed the following solutions:

- Using power control mechanisms: it consists of controlling the power needed to have a communication and then avoiding emitting a higher power that might lead to interference.

- Using directional antennas: directional antennas allow to reduce the emitted power in a wide range of angles where the signal emission is not needed.

- Using FD-MIMO: it consists of putting multiple antennas in the receiver from the uplink communication to reduce the interferences.

## 8.3. Network delay

To reduce avionics systems in unmanned aircraft, Well Clear systems are executed on the cloud which results in a time delay that could make the system useless.

As this delay between the time at which information is issued by the drone and the maneuver order is returned to it could be a problem, during this section the delay will be divided into different types of delay to see how they affect the total communication delay.

### 8.3.1. Types of delay

The network time delay can be computed as the sum from different types of delay which are the transmission time, the propagation time, and the processing time.

*Processing delay*

Processing delay is the time needed by any of the network components to process the data. The processing delay from the network will be the sum of the processing delays of all the components through which the data passes.

The time needed to process the information by any of the components from the network usually is in the range of 1 to 3 milliseconds. Therefore, it will not be surprising if the processing delay is not the key factor when computing the total communication delay.

*Transmission delay*

Transmission delay is the time needed to push all packet's bits into the channel and it is computed as we can see below where "N" is the number of bits and "R" the transmission rate.

$$t_{Trans} = N/R \quad \textbf{(82)}$$

To compute the transmission time, it is needed the transmission speed of the technology used. Even though each technology has a nominal transmission speed value, the transmission speed is always lower, especially when the mobile is in movement.

The technologies available for our system go from 2G to the latest one which is 5G, the maximum bitrates and their corresponding transmission time delay can be defined in Annex C. For the links in the network which are not using the mobile communication network, it will be assumed that they are using optical communication, which has higher transmission speeds.

The total transmission delay of the communication will be the sum of the transmission delay of each link, and each of the time delays will depend on the technology used. For the parts in the network in which the mobile telecommunication system will not be used, the transmission delay will be way lower because optical fiber has a higher transmission speed.

*Propagation delay*

Propagation delay is the time needed by the signal to reach its destination. It depends on the propagation speed from the channel which should be close to the light's speed ("c" is the light speed and "n" is the channel refraction coefficient) and it also depends on the distance (d) traveled by the signal.

$$t_{Prop} = d \cdot n / c \qquad \textbf{(83)}$$

The total propagation delay will be the sum of the propagation delay between all the steps in the communication.

## 8.4. Handover

Mobile networks provide freedom to end-users in terms of mobility. The end user's mobility could end in link quality variations. Therefore, users may need to change the base station which is known as a handover.

As the drones will be in movement permanently, handover processes need to be considered in the communication study. But there are several types of handovers depending on the technologies used, so handovers will be studied for different technologies from 2G to the newest ones.

### 8.4.1. Handover types depending on the mobile network technology

The type of handover depends on the technologies from both cells involved. Hard Handover is performed by technologies that use FDMA or TDMA while Soft Handovers is available in technologies that use CDMA or WCDMA. And Softer Handover is performed between sectors from a single base station.

*Second-generation mobile systems (2G)*

At the end of the 1980s, second-generation mobile systems were introduced. Unlike first-generation systems, 2G was based on digital transmissions which allowed them to provide better services.

There are different 2G systems standards deployed depending on the region. Even though in this project only GSM will be considered, all four standards are briefly explained below.

- Global System for Mobile Communications (GSM): GSM was the standard deployed in Europe. It operates in the 900 MHz bands with a total bandwidth of 50 MHz. GSM uses TDMA which results in hard handover.

- IS-136: IS.136 was the following version of IS-54 which was deployed in the US. It uses TDMA and hard handover as the GSM standard.

- IS-95: IS-95 was also a 2G standard deployed in the US. But unlike IS-136, IS-95 used CDMA which allowed it to use soft handovers.

- Personal Digital Cellular (PDC): PDC was the standard deployed in Japan which used TDMA and hard handovers like GSM and IS-136 standards.

*Third-generation mobile systems (3G)*

With the increase in 2G network traffic, higher bit rates were needed. 3G systems are designed for multimedia communication and provide larger bit rates than 2G systems.

ITU (International Telecommunication Union) within UMTS (Universal Mobile Telecommunications Services) developed the 3G network IMT-2000. 3G standards can be divided into two types depending on the multiple access technology used, which are UTRA FDD (WCDMA) and UTRA TDD.

Each of the 3G standards will have its handover types, and WCDMA has the following ones:

- Intra-system Handovers: Intra-system Handovers are handovers within one system and are divided into two groups are Inter-frequency and Intra-frequency Handovers. inter-frequency handovers occur between cells with the same WCDMA carrier while intra-frequency handovers occur between different ones.

- Inter-system Handovers: Inter-system Handovers are handovers between cells with different Radio Access Technologies or Radio Access Modes.

- Hard Handover: Hard Handover is a type of handover in which the connection with the old base station is released before connecting with the new one.

- Soft and Softer Handover: unlike Hard Handover, in Soft Handover the Mobile Terminal simultaneously communicates with different base stations. In the downlink, the mobile terminal receives the signal from both base stations and selects the one with the higher power while in the uplink, the signal from the mobile is routed by both base stations for selection combining.

  Unlike WCDMA, UTRA TDD systems do not provide soft handover because it uses time multiple access technologies instead of code multiple access ones.

*Fourth-generation mobile systems (4G)*

4G networks are not cellular networks, instead, they are the result of combining different networks technologies to provide a better service. As each type of network performs well in different situations, 4G networks combine them to provide better services than the previous generation systems.

In 4G systems handovers can be divided into two main types that are vertical handover and horizontal handover.

- Horizontal Handover: A horizontal Handover is a handover between cells with the same technology. It is not always possible to perform a soft handover.

- Vertical Handover: Vertical Handover is handover between different technology cells and is divided into Upward and Downward Vertical Handover. An Upward Vertical Handover happens when the mobile passes to a bigger cell with lower bandwidth to area rate, while a Downward Vertical Handover happens when the mobile passes to a smaller cell with higher bandwidth to area rate (Figure 40).

  As in Vertical Handover, both cells cover the same area, the mobile terminal can be connected to both base stations during the handover.

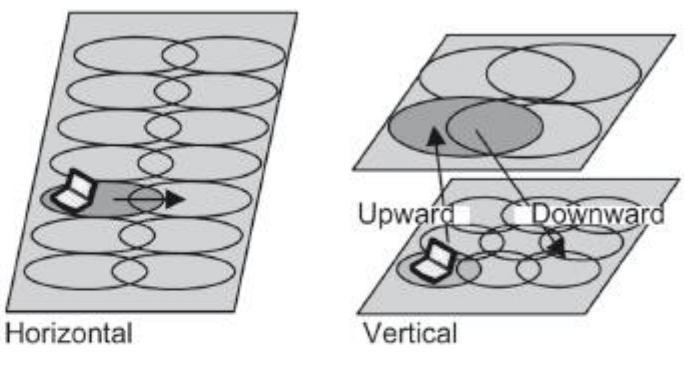


**Figure 40:** Horizontal and Vertical Handover.

- Intra-cell Handover and Inter-cell Handover: Intra-cells handovers are handovers inside a given cell, while inter-cell handovers are handovers between different cells.

#### *8.4.1.1. Fifth-generation mobile systems (5G)*

The introduction of 5G networks will be more heterogeneous and denser, which will increase the number of handovers. Even though the types of handovers are like the ones from the previous technologies, the users will need to be able to perform quicker and more efficiently the handovers to adapt to the network architecture.

### 8.4.2. Handover Performance on enhanced LTE network

To evaluate the handover performance of the 4G network for unmanned vehicles, I am going to expose the results obtained by a study performed by 3GPP [17], in which the following Key Performance Indicators (KPI) were evaluated for different scenarios, altitudes, and speeds.

**Table 15:** Handover's KPIs.

| KPI | Description |
|---|---|
| Handover rate | Number of HO over time including HOF |
| Handover Failure (HOF) rate | Rate between HO failures and Total HO attempts (including HOF) |
| Radio Link Failure (RLF) rate | Number of RLFs over time |
| Time in handoff | Fraction of time a UE is in HO procedure including time for successful HO |
| Time in Qout | Fraction of time a UE is in Qout state |
| Ping Pong rate | Rate between ping-pongs and Total successful HO |

The conclusions the 3GPP study [17] obtained for each of the KPIs will be explained in the following sections.

*Handover rate*

The handover rate is the amount of handover per time unit. The altitude is not correlated with the Handover rate, because in some scenarios the HO rate increased with altitude while in other ones it decreased.

*Handover Failure rate*

The Handover Failure rate is the dividing the number of handovers in which the terminal does not connect to the new base station by the total number of them.

In most of the studied scenarios, it was observed that aerial tested User Equipment (UE) had a higher Handover Failure Rate than terrestrial UEs. In those studies, the HOF rate also increased as the speed increased for aerial UEs.

*Radiolink Failure rate*

The Radiolink Failure is the communication failure due to having a signal strength too weak to continue with the application.

The result obtained from studying the Radiolink Failure rate was the same as the obtained with the Handover Failure Rate. The RLF rate was higher for aerial UEs than for terrestrial ones. When the speed of aerial UEs increases, the RLF rate also increases.

*Time in Hand off*

The time in Hand off refers to the time required for the handover process.

The result obtained is that Time in Hand off is higher for aerial UEs than for terrestrial ones only at high speeds. At low speeds seems that there is no correlation between altitude and Time in Hand off.

*Time in Qout*

The time in Qout is used to study the radio link quality by comparing the power received to the threshold Qout, which is defined as the level at which the DL radio link cannot be reliably received.

The Time in Qout obtained was higher for all the aerial UEs than for the terrestrials' ones, independently of the UE's speed.

*Ping pong rate*

Ping pong is the effect of jumping between cells when the terminal is close to the cell boundary.

The ping pong rate obtained was lower for all aerial UEs than for the terrestrial ones, independently of the UE's speed.

### 8.4.3. Communication latency during the Handover process

When the mobile terminal performs a handover operation, the latency of its communication drops. But the impact from the handover over the communication delays varies with the handover type. As during a hard handover the mobile stays disconnected from both base stations, the latency will be higher than in the soft handover.

There are several examples with a comparison between soft and hard handover, and in Fig. 41 are shown the results from one paper that compares them in an LTE-5G communication [18].

As it is shown in Fig. 41 [18], the difference between latency is noticeable. The latency for soft handover is between 20 and 80 milliseconds, while for hard handover it reaches values of 300 milliseconds. Therefore, the hard handover latency in this study is about ten times the soft handover one.

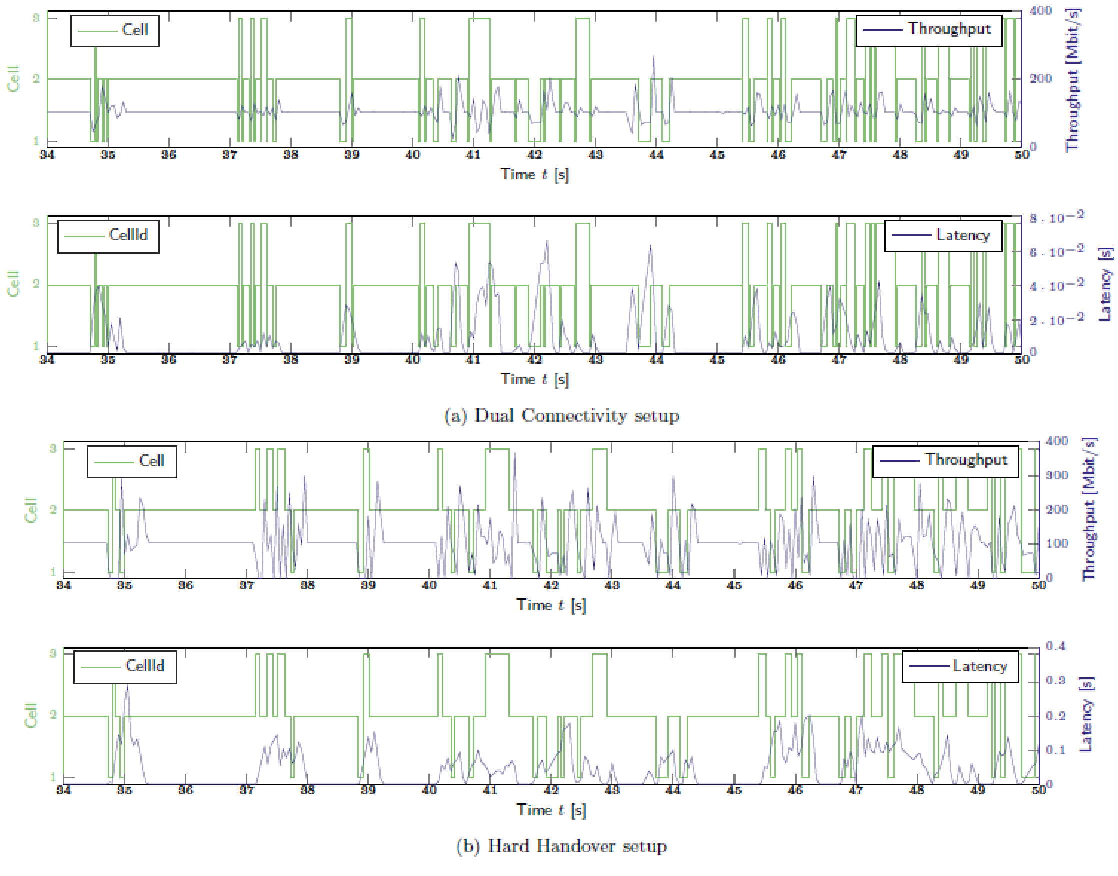


**Figure 41:** Delay comparison between hard and soft handover.

# CHAPTER 9. PILOT REACTION TIME

In this chapter, it will be discussed the amount of time needed by the pilot after he will receive the Well Clear Violation prediction alert and its corresponding maneuver. To quantify this amount of time, the result from some previous studies, which measured the reaction time in TCAS II and ACAS X, will be used

## 9.1. Pilot response time effect on U-Space services

The network delay is not only the time lapse between the instant in which the position and speed information is issued by the drone and the Remain Well Clear maneuver starts.

The time needed by the pilot must be considered, as he must choose whether to perform the maneuver or not. As there are no studies that measure the time needed by the pilots to respond to the given advisory, some previous studies about pilot time response with TCAS II and ACAS X will be considered.

With the studies mentioned in the following sections, it is noticed that the time taken by a pilot to make a decision can be even higher than the delay.

## 9.2. Pilot performance research for TCAS

In “Pilot performance research for TCAS” [14] three different studies were performed to evaluate the pilot performance in responding to advisories given by TCAS II systems.

### 9.2.1. First study

In the first case, 63 people from the airline flight crew were evaluated in simulated air carrier operations, in which they were flying a Boeing 727. Each crew in this study flew eight times with and without the TCAS II systems to evaluate their performance.

When the TCAS was activated, the aircraft never flew below the distance thresholds, which were 200 fts vertically and 1000 fts horizontally. In the 32 flight segments while flying without TCAS systems only in four instances the distance was below the thresholds.

The result obtained was a mean response time of 1.9 seconds and a standard deviation of 1.43 seconds. There was only one instance from the 58 resolution advisories in the study in which the pilot response was higher than 5 seconds.

### 9.2.2. Second study

The second case tested pilots' response to proposed changes in avoidance advisory. The change in the resolution avoidance can be either a change in the climbing or descending rate or a reversal from a descend to climb or vice versa.

The pilot response time to the change in the resolution advisory was under two seconds that is the target of the TCAS logic. On the other hand, the acceleration was lower than assumed by the TCAS logic, which assumes an acceleration of 0.5g.

The increase in the climb or descending rate was performed successfully around 85 % of the time, while a reversal maneuver, which consist of changing from climb to descend or vice versa, was only performed successfully around 15 % of the time.

The result obtained was that each subsequent advisory required a larger response time than the previous one as we can see below. Note that, unlike the first study, in the second study from the paper pilots were not performing any other flight task what resulted in lower responses time.

- 1st RA average time 0.49-sec standard deviation 0.56 sec.

- 2nd RA average time 0.75-sec standard deviation 0.69 sec.

- 3rd RA average time 1.94-sec standard deviation 1.37 sec.

### 9.2.3. Third study

The third case studied the response time depending on the display of the TCAS II resolution advisories. Three different types of the display were tested, which were:

- Red display: it indicates with red lights the vertical speed that the pilot must avoid. For this display type, the pilot response had a mean response time of 1.19 seconds and a standard deviation of 0.59 seconds.

- Red and green display: it indicates with red lights the vertical speed that must be avoided, and it also indicates the target vertical speed with green light.

  For this display type, the pilot response had a mean response time of 1 second and a standard deviation of 0.6 seconds.

- Green display: it indicates with green lights the vertical target speed.

  For this display type, the pilot response had a mean response time of 95 seconds and a standard deviation of 0.54 seconds.

The result obtained was that pilots needed less time to react to an advisory issued in a green light than in a red one.

## 9.3. A Human-in-the-loop evaluation of ACAS Xu

The “A Human-in-the-loop evaluation of ACAS Xu” [27] paper studies the performance of ACAS Xu, which is a version of the ACAS X.

ACAS X is the next-generation replacement of TCAS II that provides DAA and Collision Avoidance guidance. The difference is that it does not include DAA warning and guidance warning-level, and also it issues vertical and horizontal RAs instead of issuing only vertical ones as TCAS II.

In the following image, it is shown that the average time needed to recover a Well Clear status is similar for a Standalone configuration and Integrated configuration. In both cases, the time needed is around 17 seconds.

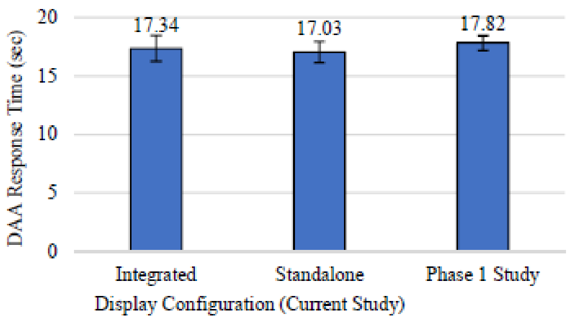


**Figure 42:** DAA Time Response depending on the display configuration.

The time needed by pilots to respond to a Resolution Advisory depends on if it is the first RA or a subsequent one. And the obtained values are shown below that are also reflected in the image with the RA Response time.

- Initial RA needs an average response time of 2.89 seconds and 97 % of them need less than 5 seconds.

- Subsequent RA needs an average response time of 2.68 seconds and 70 % of them need less than 2.5 seconds.

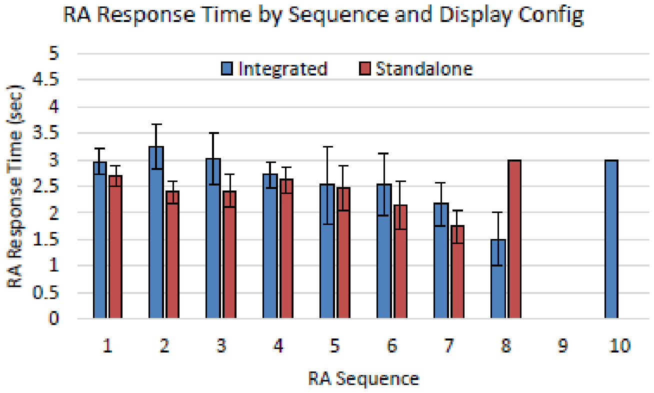


**Figure 43:** Plot with the RA response time from the first 10 RA.

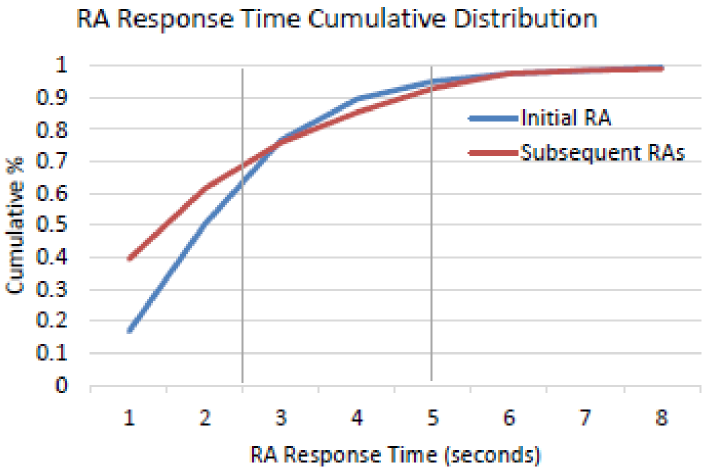


**Figure 44:** Plot with the cumulative % vs time.

# CHAPTER 10. SIMULATION OF DELAY AND TIME RESPONSE

In this chapter, it will be quantified the network delay to see if it fits with the U-Space requirements or not. Will be also computed the overall time lapse between the drone issues its position and speed information and the time that the Remain Well Clear maneuver is started by the drone.

## 10.1. Simulated network delay

In order to introduce a simulated delay in the program to compute the recovery maneuver and to study the delay influence in the maneuver chosen, firstly the delay must be computed. As explained in the previous chapter, the communication delay is computed as the sum of the processing delay, the propagation delay, and the transmission delay.

### 10.1.1. Processing delay

The processing delay ($t_p$) depends on the devices used and the operations needed to compute the maneuvers. Moreover, the time needed to process a packet with a length of 1518 bytes varies from 0.8 to 2 milliseconds [19] depending on the device. Therefore, the total processing delay will be the sum of the processing delays of each of the devices used in the communication.

$$t_p = t_{p1} + t_{p2} + \ldots t_{pn} \quad \textbf{(84)}$$

Then, if the network is like the one from Pic. 32 and each component process the packet once when receiving it and another time when sending it, the number of processing delays will be at least 15. So, to simulate the total processing delay will be created an array with a random length, which must be higher than 15, and with random values that must go from 0.0008 to 0.002 seconds.

### 10.1.2. Transmission delay

The total transmission delay of the communication is computed as the sum of the transmission delay of each of the transmissions involved in it. It is assumed that the drone and the pilot are using the mobile network while the rest of the network is using optical fiber communications.

The mobile network telecommunication can be either 2G, 3G, 4G, or 5G, and the technology will determine the transmission of speed. To be able to compute the transmission delay it will be assumed that all information is packaged in a single packet that has a length (N) of 1518 bytes, like the Ethernet packets.

If the transmission speed from the optical fiber is around 100 Mbps, the delay during its transmission will be of 0.12 milliseconds. Therefore, the mobile telecommunication transmission delay will determine the total transmission delay because is way higher than the optical network transmission delay. The values used for the mobile transmission speed are defined in Annex C.

### 10.1.3. Propagation delay

The propagation delay ($t_{prop}$) is the time required by the signal to travel from the drone to the pilot and then return the maneuver chosen by the pilot to the drone. Therefore, the propagation delay depends on the distance between the drone, pilot, and the service provider's servers.

Pilot and server position can be considered constant throughout the whole flight, while drone position is updated during the flight. The propagation delay depends not only on the distance but also on the light speed which depends on the channel. The propagation speed is computed by dividing the light speed in the vacuum by the refraction coefficient. The refraction coefficients used are approximations that are defined in Table 16.

**Table 16:** Refraction coefficient values.

| Channel | Refraction coefficient |
|---|---|
| Air | 1 |
| Optical fiber | 1.5 |

Then the total propagation delay will be computed with the expression (87), where $d_{AIR}$ is the distance traveled by the signal through the air while $d_{OF}$ is the distance traveled through the optical fiber.

The distance will be created by a random function that returns a distance value lower than the theoretical maximum. For GSM, 3G, 4G, and 5G, the maximum range can be between 50 and 150 km (these values correspond to LOS ranges). Then, $d_{AIR}$ will be the sum of two randomly generated values that correspond to the distance between drone and base station and between the pilot in remote and base station (Note that those base stations can be different ones). The distance between the base station and service provider server has been set as a default of 500 km, which is larger than the maximum ranges from the base stations.

$$t_{prop} = d_{AIR} \cdot n_{AIR} / c + d_{OF} \cdot n_{OF} / c \quad \textbf{(87)}$$

## 10.2. Pilot reaction time

The chosen values to simulate the pilot's reaction time will be similar to the reported response time to Resolution Advisories in the "A Human-in-the-loop evaluation of ACAS Xu" paper. The response time from this paper has been chosen instead of the ones from the "Pilot performance research for the TCAS" paper because they are fresher.

Then, the response time used will consist of randomly generated values with an average value of 2.89, and with 97% of the response time being lower than 5.

Subsequent response time value is not considered as there will be enough time to perform the maneuver between Resolution Advisories.

To create random values with the characteristics from the paper results, a log-normal function from the NumPy library has been used. The histogram and the weight function are the ones shown in Fig. 36, which is created with variables from Table 17.

**Table 17:** Pilot response time variables.

| Variable | Value |
|---|---|
| Mean value | 2.89 |
| Standard deviation | 0.3 |
| Number of samples | 1000 |

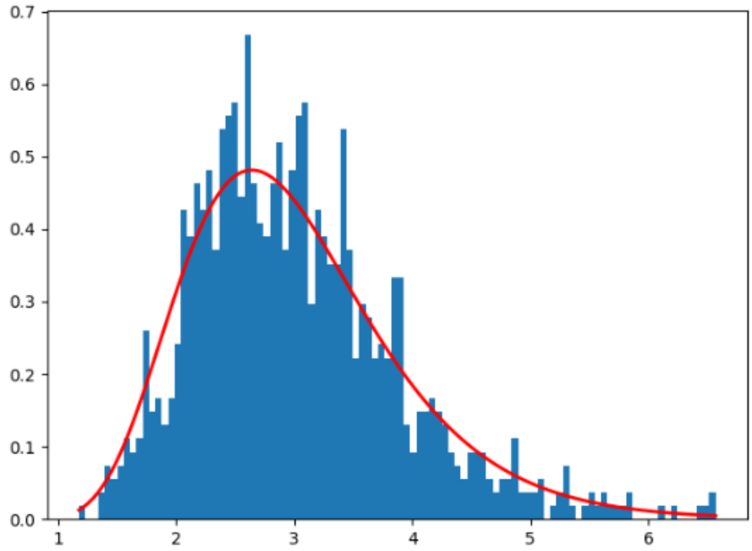


**Figure 45:** Histogram and weight function used for pilot's time response.

## 10.3. Simulated delay and time response results

To compute the total delay, the maximum bitrate of each technology has been used, and the bitrate of a movement terminal from some previous experiments has been considered.

### 10.3.1. Total delay using maximum bitrates

The total simulated delays will be the sum from all the delays, and the obtained result is that:

- The total delay plus the pilot response time is under 5 seconds around 97 % of the time, which is almost the same as without the communication delay for 3G, 4G, and 5G.

  While for 2G networks, it is under 5 seconds around 73 % of the time.

- The communication delay is under 1 second for 3G, 4G, and 5G, which is aligned with the requirement from the U-Space that says that the latency must be lower than 1 second [1].

  But for 2G the delay is usually over 1 second. Therefore, it does not meet the U-Space requirements for this technology.

### 10.3.2. Total delay using bitrates for terminals in movement

The communications delay of mobile networks for aerial users, it’s a bit higher due to the fact that the transmission rate obtained is not the maximum value for each technology. It happens because not all the transmitted symbols are useful bits of data, some of them are redundant symbols to reduce errors. And as the signal quality decreases the rate of redundancy needed increases, which reduces the amount of data bits sent. Also, if the signal quality decreases, the constellation used might change what would lead to a decrease in the transmission speed.

In the previous experiments from the paper “GSM Technology as a Communication Media for an Autonomous Unmanned Aerial Vehicle” [28], the average latency for 2G varies from values between 1 and 4 seconds.

While for newer technologies the latency is lower and meets the U-Space requirement of being under 1 second as it is shown in the studies from “An Experimental Evaluation of LTE-A Throughput for Drones” [29].

# CONCLUSIONS

In this project, it has been presented an automatic Remain Well Clear system that provides maneuvers to drones to keep them safely separated. With the increasing number of drones in the airspace, providing them with safety services became necessary.

To simulate drone encounters over which to apply the Remain Well Clear system, a python program that evaluates the Well Clear status of the drones has been coded and, in case a Well Clear Violation is predicted, it provides a maneuver to remain in a Well Clear status.

The maneuvers to remain in Well Clear used in this software are either a turn, an altitude change, or a speed change. And to choose the optimal one, the software evaluates all the possibilities depending on the drone performance and selects the one with the lower cost, which depends on the effect of the maneuver on the current trajectory and the time that the drone will be in Well Clear violation.

To see if the maneuvers chosen by the software were aligned with the encounter type, the type of encounter depending on the encounter conditions have been plotted and the obtained result is that:

- Horizontal maneuvers are chosen when both drones are converging horizontally with a horizontal distance not a lot higher than the threshold, and the encounter angle is between 0 and 90 degrees. This happens because if drones are horizontally diverging, performing a horizontal maneuver is not necessary to avoid the Well Clear Violation.

- Vertical maneuvers are chosen when the vertical distance is higher than the vertical threshold. It happens because if the distance is close to the threshold or higher than it, increasing vertical separation will have a low effect on the current trajectory.

- Speed maneuvers are chosen when both drones are horizontally converging, and the encounter angle is between 30 and 90 degrees. This makes sense because changing the speed in a frontal encounter will not be the optimal solution to avoid the Well Clear Violation.

In the histogram plots of the chosen maneuvers, it is also noticeable that a minimum Well Clear Violation interval is needed to compute the maneuver because if the interval is infinitesimal, it will have no weight in the cost function, which results in maneuvers that consist of continuing straight. To avoid it, a Well Clear Violation threshold has been proposed.

In future work, neuronal networks could be used either to optimize the constants from the cost function or to choose the maneuver comparing the relative position and speed without evaluating all the possible solutions.

To implement the Remain Well Clear system in the real world, a communication network to exchange information between the drone, the remote pilot, and the Remain Well Clear service provider will be needed. The most suitable one is the mobile telecommunication network, but as it is not optimized for aerial users it will have some drawbacks like:

- The mobile telecommunication antennas are down tilted because their users are terrestrials. This makes that drones will be in Line of Sight with more antennas, which will lead to receiving interferences from antennas whose signal should not arrive at the drone. Also, drones will be in LOS with several terrestrial users, causing interferences to them. To solve this problem 3GPP has proposed several possible solutions in their study of LTE communications for aerial vehicles.

- The communication delay could be also a problem, but as it is shown in the simulations, it is only over 1 second with 2G technologies. Nevertheless, 3G, 4G, and 5G technologies fit the U-Space requirements of having a latency under 1 second.

- The handover process could also present a problem to U-Space communications because during the handover process the latency increases and there is also a possibility of failure. These topics are studied deeply by 3GPP [17].

- Lastly, there is also a problem with the position and speed data which can be solved by applying uncertainty thresholds, which rely on the probability distributions from the position and speed variables. Uncertainty thresholds for sensor uncertainty were introduced in a DAIDALUS update [32].

After studying the viability of using the mobile network for aerial users, I can conclude by saying that the communication delay is not the main problem, unlike interferences or connection losses since the network is optimized for terrestrial users. Therefore, future work must focus on adapting the current mobile network to aerial users and minimizing the handover effects on telecommunications.

# ANNEX A

**Table 18:** Drone performance parameters.

| Parameter | Value |
|---|---|
| Climb rate | 4 m/s |
| Descend rate | -4 m/s |
| Turn rate | 10 rad/s |
| Acceleration rate | 1 $m/s^2$ |
| Deceleration rate | -1 $m/s^2$ |
| Climb acceleration | 15 $m/s^2$ |
| Climb deceleration | -15 $m/s^2$ |
| Descend acceleration | -15 $m/s^2$ |
| Descend deceleration | 15 $m/s^2$ |

**Table 19:** Remain Well Clear parameters.

| Parameter | Value |
|---|---|
| DMOD | 15 m |
| $\tau_{mod}$ | 5 s |
| HMD | 15 m |
| ZTHR | 15 m |

**Table 20:** Horizontal maneuver parameters.

| Parameter | Value |
|---|---|
| Maximum value | 180º |
| Minimum value | -180º |
| Step | 1º |
| Cost | 0.5 |

**Table 21:** Vertical maneuver parameters.

| Parameter | Value |
|---|---|
| Maximum value | 150 m |
| Minimum value | 0 m |
| Step | 1 m |
| Cost | 1 |

**Table 22:** Speed maneuver parameters.

| Parameter | Value |
|---|---|
| Maximum value | 0 m/s |
| Minimum value | 50 m/s |
| Step | 1 m/s |
| Cost | 0.2 |

**Table 23:** Time parameters.

| **Parameter** | **Value** |
|---|---|
| B | 0 s |
| T | 20 s |
| Cost (time in WCV) | 3 |

# ANNEX B

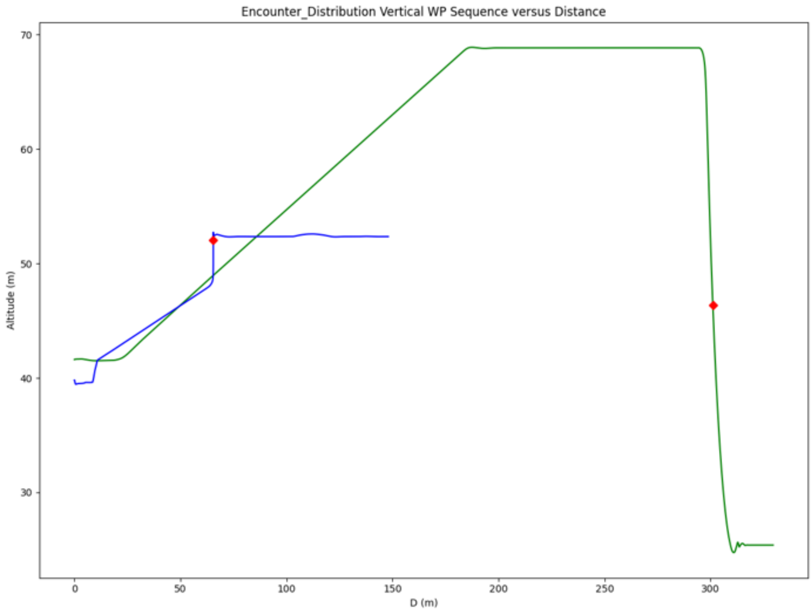


**Figure 46:** Altitude vs. horizontal distance.

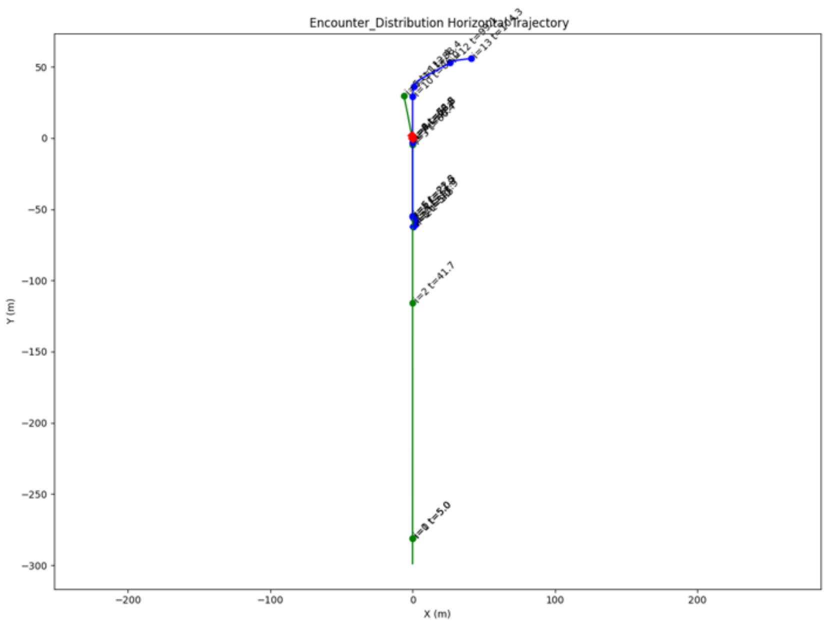


**Figure 47:** Horizontal trajectory.

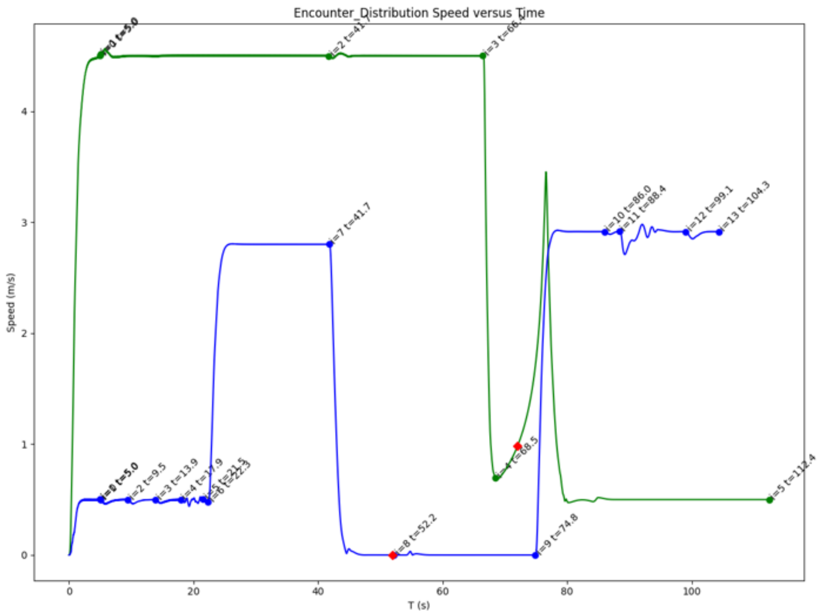


**Figure 48:** Speed vs time.

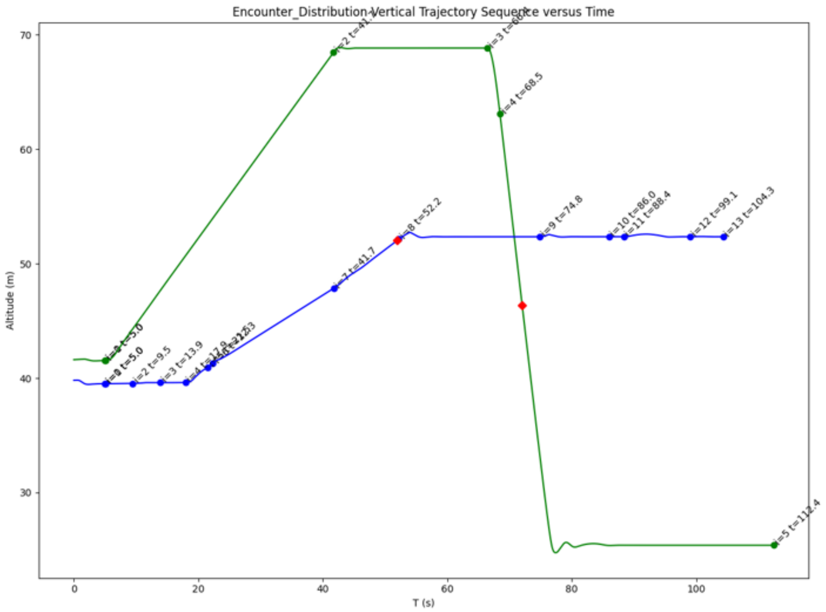


**Figure 49:** Altitude vs time.

# ANNEX C

**Table 24:** Second-generation mobile systems (2G) [28].

| 2G GSM standards | Number of slots | | Bitrate (kbps) | | Time (s) | |
|---|---|---|---|---|---|---|
| | Uplink | Downlink | Uplink | Uplink | Uplink | Downlink |
| CDS | 1 | 1 | 9.6 | 9.6 | 1.265 | 1.265 |
| HSDCS | 2 | 2 | 28.2 | 28.2 | 0.43 | 0.43 |
| | 1 | 3 | 14.4 | 43.2 | 0.843 | 0.28 |
| GPRS CS1 | 2 | 3 | 18.1 | 27.15 | 0.67 | 0.45 |
| | 1 | 4 | 9.05 | 36.2 | 1.34 | 0.34 |
| GPRS CS2 | 2 | 3 | 26.8 | 40.2 | 0.45 | 0.3 |
| | 1 | 4 | 13.4 | 53.6 | 0.91 | 0.23 |
| EDGE | 3 | 4 | 120 | 160 | 0.1 | 0.08 |

**Table 25:** Third-generation mobile systems (3G) (www.3gpp.org).

| 3G GSM standards | Bitrate (Mbps) | | Time (ms) | |
|---|---|---|---|---|
| | Uplink | Downlink | Uplink | Downlink |
| HSPA | 5.8 | 14.4 | 2.1 | 0.84 |
| HSPA+ | 11 | 21 | 1.1 | 0.58 |

**Table 26:** Fourth-generation mobile systems (4G) (www.3gpp.org).

| 4G GSM standards | Bitrate (Mbps) | | Time (ms) | |
|---|---|---|---|---|
| | Uplink | Downlink | Uplink | Downlink |
| LTE | 75 | 75 | 0.16 | 0.16 |

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