Statistical Mid-Air Collision Risk Assessment

by

© Sam Sangsueng Lee

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Abstract

This thesis describes current Detect and Avoid (DAA) equipment and communication methods among aircraft, Air Traffic Control (ATC) and Uninhabited Aerial Vehicle (UAV) Ground Control Stations (GCS). The limitations of current DAA systems are explored and analyzed to evaluate the effectiveness of each surveillance equipment combination. Notwithstanding the ongoing COVID-19 pandemic, future air traffic is predicted to increase and the airspace to become very congested due to the popularity of air travel and the increasing usage of UAVs.

Background information is provided for the current recommendations for the definitions of Loss of Separation (LOS) and for determining Well-Clear (WC), Loss-of-Well-Clear (LOWC), unmitigated Near-Miss Air Collision (NMAC) and mitigated NMAC for detecting any intruder aircraft and maintaining separation to avoid any risk of a Mid-Air Collision (MAC).

The primary contributions of this work are the determination of the impact of possible combinations of surveillance equipment that could be installed on current manned and unmanned aircraft, the estimated reduction of risk of violation of WC boundaries and thus the probability for maintenance of safe aircraft separation. The impact on mid-air collision risk is determined by considering the impact of DAA/Surveillance Equipment on the MAC (and NMAC) risk ratio.

The concepts herein focus on existing technologies as used in manned aviation and their possible extension to use in UAS operations. The integration of such technologies into future DAA systems is the major recommendation for future study.

Acknowledgements

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Abbreviation

ACAS Airborne Collision Avoidance System

ADS-B Automatic Dependent Surveillance-Broadcast

AAE Aerodrome Elevation

AGL Above Ground Level

AIM Aeronautical Information Manual

AIRMET AIRman's METeorological Information

AMS Aircraft Management System

ANSP Air Navigation Service Provider

ARNS Aeronautical Radio Navigation Spectrum

ASDE Airport Surface Detection Equipment

ATAR Air-To-Air-Radar

ATC Air Traffic Control

ATCRBS Air Traffic Control Radar Beacon System

BCAS Beacon Collision Avoidance System

CA Collision Avoidance

CAASD Center for Advanced Aviation System Development

CAP Canada Air Pilot

CARs Canadian Aviation Regulations

CAS Collision Avoidance System

CPA Closest Point of Approach

CZ Control Zones

DAA Detect and Avoid

DMOD Distance Modification

DWC DAA Well-Clear

ECAC European Civil Aviation Conference

ES Extended Squitter

FAA Federal Aviation Administration

FIS-B Flight Information Service-Broadcast

FL Flight Level

FMS Flight Management System

FOV Field of View

GNSS Global Navigation Satellite System

HMD Horizontal Missed Distance

IAF Initial Approach Fix

ICAO International Civil Aviation Organization

IFF Identification Friend or Foe

IFRs Instrument Flight Rules

ILS Instrument Landing System

IMC Instrument Meteorological Conditions

LEO Low Earth Orbit

LOWC Loss-of-Well-Clear

MAC Mid-Air Collision

MCTOW Maximum Certificated Take-Off Weight

MFD Multi-Function Display

MLAT Multilateration

MOPS Minimum Operational Performance Standards

MSC Meteorological Service of Canada

NAS National Airspace System

NEXRAD Next Generation Radar

NMAC Near Mid-Air Collision

NOAA National Oceanic and Atmospheric Administration

NOE Nap of the Earth

NOTAMs Notices to Airmen

PAR Precision Approach Radar

PSR Primary Surveillance Radar

RAs Resolution Advisories

RCAP Restricted Canada Air Pilot

RNAV Area Navigation

ROW Right of Way

RR Risk Ratio

RTU Radio Tuning Unit

RVSM Reduced Vertical Separation Minima

SAA See and Avoid

SAR Search and Rescue

SS Self-Separation

SSR Secondary Surveillance Radar

TAs Traffic Advisories

TC Transport Canada

TCAs Terminal Control Areas

TCAS Traffic Collision Avoidance System

TIS-B Traffic Information Service-Broadcast

TSR Terminal Surveillance Radar

VFRs Visual Flight Rules

VHF Very High Frequency

VMC Visual Meteorological Conditions

VOR VHF Omnidirectional Radio Range

WAAS Wide Area Augmentation System

WC Well Clear

WOW Weight On Wheel

WR Weather Radar

UAS Unmanned Aircraft Systems

UAT Universal Access Transceiver

UAVs Unmanned Aerial Vehicles

XPDR Transponder

Chapter 1

Introduction

1.1 Purpose of the Mid-Air Collision Risk Assessment

Flight operators and Air Navigation Service Provider (ANSP)[1] want to minimize any potential Mid-Air Collision (MAC) risk prior to flight as well as in the enroute phase of flight. The goal is to prevent Near Mid-Air Collision (NMAC) incidents, and thus avoid MAC accidents entirely, by ensuring that adequate aircraft separation is maintained at all times. This study describes the principle of current Detect and Avoid (DAA) systems and discusses ways to reduce the risk of losing enroute aircraft

[1] ANSP refers to any organization which is responsible for the provision of air navigation services in domestic or international airspace [1]. Air Traffic Control (ATC) is a service provided to aircraft in controlled airspace [2]. In this thesis, ANSP specifically refers to a Regional Area Control Centre (i.e. Gander(CDQX; Domestic, CZQX; Oceanic), Moncton(CZQM), Edmonton(CZEG)). ATC refers to a Local ATC unit that provides ATC service within controlled airspace (i.e. St. John's(YYT), Deer Lake(YDF))[3].

separation.

1.2 Problem Statement

The future of air-traffic is expected to become busier with more complicated and congested flight-routes in the airspace since air-travel is more common than ever and because of the popularity of Unmanned Aerial Vehicles (UAVs)[2]. The probability of NMAC increases among airspace-classes under two types of weather conditions: Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC). The current DAA systems are limited; all aircraft have various types of anti-collision equipment. The effectiveness of different combinations of existing equipment is not defined to a quantifiable level, as are the effects of environmental conditions and air-traffic density towards minimizing the risk of MAC. Current limitations are: 1) radar coverage of surveillance aircraft, 2) various types of DAA equipment onboard all aircraft, and 3) unknown potential for the presence of UAVs.

1.3 Thesis Outline & Scope

The scope of the research presented in this thesis, in particular the problem statement and need to provide accurate mid-air collision risk assessments, is given in the present Chapter. Chapter 2 provides the background and literature overview of existing

[2]UAV is Uninhabited Aerial Vehicle, and also well known as Unmanned Air Vehicle. This terminology has been replaced by unmanned aircraft (UA) in Federal Aviation Administration (FAA) and International Civil Aviation Organization (ICAO) uses terminology Remotely Piloted Aircraft (RPA), which will replace UAV in the Canadian Aviation Regulations (CARs) [4].

surveillance/DAA methods and systems, including the current state of equipment and the limitation of existing variable surveillance items, an understanding of ATC operations process with traditional aircraft operators, and the principle of aircraft separation in the air. In Chapter 3, a modular simulation concept is presented based on theoretical collision risk calculations. The probability of encountering aircraft is also discussed. Further, the determination of NMAC risk leads to the creation of the probability of a NMAC calculation model. Chapter 4 presents results from this study. It describes the probability of air-to-air encounters, the effectiveness of any DAA/Surveillance Equipment, and determines the impact on the mid-air collision risk (i.e., by determining the risk ratio). The final chapter, Chapter 5 summarizes the research and provides recommendations for future work.

1.4 Out of Scope

Outside the scope of this thesis is researching and developing the equipment needed to collect the raw traffic data with each aircraft's DAA capability in a particular airspace/geographical location. Each surveillance equipment combination is represented as a percentage of efficacy versus a given traffic density rate, using estimates as provided by prior future research. These are used solely to support the methods used by the risk calculation model built in this study. This out of scope portion could be a future research focus to improve the accuracy of the estimate of percentage of efficacy for DAA equipment to verify the risk of mid-air collision among various aircraft, including fixed-wing, rotary-wing manned aircraft and unmanned aircraft; and of various sizes for each category of aircraft.

Chapter 2

Background and Literature Review

2.1 Air Navigation Service Provider (ANSP)

ANSP is defined as an organization which is responsible for the provision of air navigation services in domestic or internal airspace [1]. In the air traffic industry, ANSP utilizes a surveillance system to reduce aircraft separation, and also provides information about weather and traffic navigation assistance. In Canada, ANSP are the responsibility of and operated by Nav Canada. Note these include both Regional Area Control Centre such as Gander (CDQX; Domestic, CZQX; Oceanic), Moncton(CZQM), Edmonton(CZEG) and Local ATC services at airports such as St. John's (YYT) [3]. ANSP currently uses four types of surveillance systems: Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), ADS-B, and MLAT [3].

2.1.1 ANSP Role and Duty

The ANSP primary role is Air Traffic Management and Aeronautical Information Management. ANSP provides the safe separation among aircraft with clearance in Airspace Classes A, B, C, D, and E flying under IFR and Class B and C flying under VFR [5]. Within the Transponder (XPDR) area, ANSP provides essential weather information as well. The XPDR area is a part of the controlled zone that includes Class A, B, C, D, and E airspace under IFR. A detailed discussion on Airspace Classes may be found in Subsection 2.1.3.

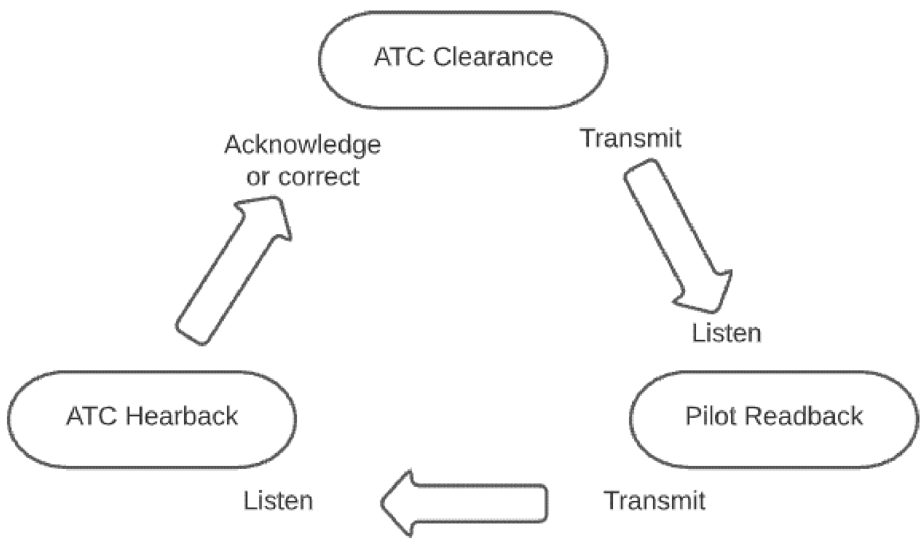

Figure 2.1: General Format of Airband Radio Communication[6]

ANSP uses Very High Frequency (VHF) radio (also called Airband) to communicate with aircraft. Listening is a critical factor for safe operations under their service. ANSP operations are supported by many advanced technologies, but the interactions of pilots/ANSP remains a crucial component of air-traffic control operations. The

ATC clearance is the essential duty of ANSP for both VMC and IMC conditions, and VFR and IFR flying rules. Figure 2.1 shows the general flow and format for Airband communication between ATC and aircraft. The flight operator, pilot, or flight dispatcher sends their flight-plan to ANSP. ANSP supplies the clearance to the pilot for their flight route. The pilot does a read-back to ANSP, confirming the condition of flight and/or any circumstances of their current flight route. After ANSP hears back from the pilot, ANSP acknowledges the situation and corrects the route accordingly as necessary. ANSP then transmits the clearance information to the pilot. These communications are maintained until the pilot lands at the airport or transitions out of the Local ATC control zone. For civilian transport flights over Canada, it is typical for each ATC unit to transfer control of a particular flight to the Regional Area ANSP unit (e.g., for St.John's, this is Gander Zone Control) or to another adjacent ATC control zone. In this way, continuous "flight following" services are maintained for a given aircraft.

2.1.2 Controlled Zones (CZ)

The author researched the actual procedures used by aircraft and local-ATC at St.John's International Airport (YYT) through a series of interviews. The outcome of these are detailed below:

1. Interview with local-ATC (St.John's Centre at YYT):

   The local-ATC at YYT operates under two types of flight-rules: Instrument (IFR) and Visual (VFR) Flight Rules. Most local aircraft operations operate under IFR. IFR-flight follows strict regulations in terms of separation between aircraft. There is generally a set number of miles between aircraft or a separation of altitude to keep them apart from each other. Depending on weather conditions, the aircraft can operate under Visual Flight Rules (VFRs). Smaller separation standards can be followed if the aircraft can be in sight of each other. If the weather condition and VMC are correct and the aircraft requests or agrees with the VFR-flight, then ATC can only operate under the visual separation rule. This rule dictates that the aircraft is responsible for separation after they have been advised of VFR-flight by ATC, and aircraft has a visual sight. Under IFRs, there is a controlled zone (CZ) within a 7 NM radius around YYT, referred to as local-ATC (St. John's Centre). Outside of this 7 NM radius, control is transferred to the ANSP Area-controllers at YQX (Gander Centre) [7].

2. Interview with Lead Search and Rescue (SAR) Pilot (Cougar Helicopters):

    - Out-bound (YYT to Offshore):

      Before taxiing the helicopter, the pilot talks to the local ATC tower (St. John's) and delivers information on altitude and speed for separation of aircraft. Helicopters take off and climb to above 400 feet AGL and then normally switches to Regional Area-ANSP (Gander Centre) from local-ATC (St. John's Tower), even though the flight still remains within local ATC controlled zone (7 NM radius YYT boundary).

    - In-bound (Offshore to YYT):

      The pilot communicates with the Regional Area-ANSP (Gander Centre) when the aircraft enters radar range (60 NM) and sets the landing runway according to the flight rules active at YYT, either IFR or VFR. The pilot contacts the local-ATC tower (St. John's Centre) before entering the controlled zone within 7 NM radius YYT for clearance. Local-ATC authorizes and provides separation-information of altitude and speed for approaching the controlled zone to pilot.

(a) An example of the pilot's experience while flying in-bound to YYT is as follows: The helicopter was flying in-bound to YYT from offshore at 15 NM and 2,500ft in IMC. The Regional Area-ANSP controller (Gander Centre) checked the weather and the weather was in good condition at YYT on their weather radar screen. The ANSP controller asked the pilot whether he would prefer using a VFR or IFR approach to YYT airport. The pilot could not tell what the weather conditions were around St.John's due to the distance (15 NM) and altitude of 2,500 feet, and relying on ANSP controller's opinion about the weather, agreed with using a VFR approach. The ANSP controller instructed the pilot to "fly from present position directly towards the NL beacon (signal-hill), while maintaining 2,400 ft in controlled airspace with Area Navigation (RNAV) 34". Pilot set/loaded these instructions as per the ATC's request. However, as the pilot passed to within 8-9NM outside of YYT airport he encountered low visibility due to the surrounding clouds. Pilot talked to both local-ATC (YYT) and Regional Area-ANSP (YQX) and decided to switch to an IFR approach on short notice. The pilot had to set automation mode (VHF Omnidirectional

Radio Range (VOR)/,Instrument Landing System (ILS)) into Flight Management System (FMS) from Initial Approach Fix (IAF) which is what Regional Area-ANSP controller initially asked for. Pilot said that the Regional Area-ANSP controllers (Gander centre) should have been more assertive and able to refuse the full procedure of clearances from incorrect weather sources alone.

2.1.3 Airspace Class

Canadian airspace is divided into seven different Airspace Classifications (or Classes). Each is designated using the letters A, B, C, D, E, F and G under the Transport Canada (TC) CARs 601 Division I, Airspace Structure and Classification [8]. As mentioned in Subsection 2.1.1, Controlled Zones (CZ) are also designated as class A, B, C, D, and E airspace in Canada. The requirements for flying within each Class of Airspace are summarized in Table 2.1. Class F is a special-use airspace and Class G is uncontrolled airspace [5].

Operating rules	ATC service	Class A	Class B	Class C	Class D	Class E
IFR	Traffic info	N/A	N/A	Yes	Yes	Workload-permitting
	Separation	All aircraft	All aircraft	IFR from IFR	IFR from IFR	IFR from IFR
	Radio	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory
	XPDR	Yes	Yes	Yes	Yes, in designated areas	Yes, in designated areas
	Clearance	ATC	ATC	ATC	ATC	ATC
VFR	Traffic info	No VFR	N/A	Yes	Yes	Workload-permitting
	Separation	No VFR	All aircraft	VFR from IFR	Nil	Nil
	Radio	No VFR	Mandatory	Mandatory	Mandatory	Not required
	XPDR	No VFR	Yes	Yes	Yes, in designated areas	Yes, in designated areas
	Clearance	No VFR	ATC	ATC	Establish radio contact	Not required

Table 2.1: Canadian Controlled Zone Requirements [5]

The Canadian airspace classification structure is usually summarized into a diagram as shown in Figure 2.2 and simplified description of operating rules are presented in Table 2.2.

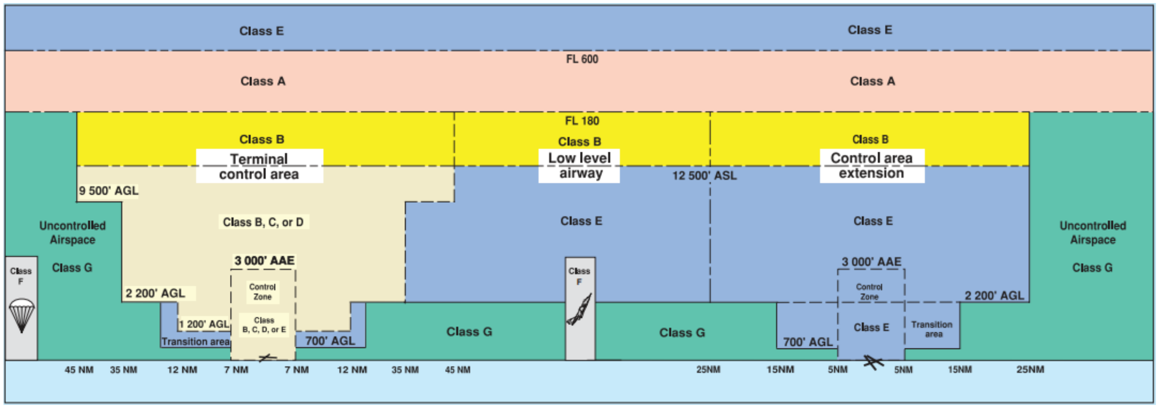

Figure 2.2: Canadian Airspace Class Structure [5]

The airspace area has two main segments, which are controlled airspace and uncontrolled airspace by weather minima. The weather conditions are a critical factor to give the permission to fly depending on various rules. The two different weather conditions are called VMC and IMC [8]. In general, VMC can be flown by either VFRs or Instrument Flight Rules (IFRs), but IMC cannot be flown using VFR, and must only be flown by IFR. While flying under VMC, a pilot must fly according to a VFR-flight plan. However, sometimes weather changes may force a transition to IMC on their flight path, so pilot must fly VFR-over-the-top. The description of airspace under the VFR flying is as shown in Figure 2.3.

In the United States, the FAA regulates and guides the pilot to define the specific ceiling and visibility values of weather flight conditions to determine the flight rules,

Type of airspace class	Description
Class A	Controlled high-level airspace. IFR only
Class B	Controlled low-level airspace (above 12,500 feet ASL, up to 18,000 feet ASL). IFR and CVFR only
Class C	Controlled airspace. IFR and VFR permitted. ATC provides separation for IFR and VFR flights, when necessary
Class D	Controlled airspace. IFR and VFR permitted. ATC provides separation for IFR aircraft only.
Class E	Controlled airspace. IFR and VFR permitted. ATC provides separation for IFR aircraft only.
Class F	Special-use airspace. May be controlled or uncontrolled. May be a restricted or advisory area.
Class G	Uncontrolled airspace

Table 2.2: Airspace Classification

either the VFRs or IFRs. In Canada, the Transport Canada rules have been mostly harmonized and are essentially the same as those in the U.S..

As can be seen in Table 2.3, the ceiling is less than 1,000 feet AGL and/or visibility less than 3 miles. The pilots must fly under the IFRs and only VFRs capable aircraft are not allowed to fly [10].

2.1.4 ANSP Surveillance Systems

There are currently four technologies used as surveillance systems by ATC: PSR, SSR, ADS-B, and Multi-lateration (MLAT) [8].

The current Aeronautical Information Manual (AIM) version [8] shows that the St.John's Airport Area (YYT) has both a PSR (Figure 2.4) and SSR (Figure 2.5). However, the ATC unit at YYT is not currently using PSR as their primary air search service, according to a recent local ATC controller interview.

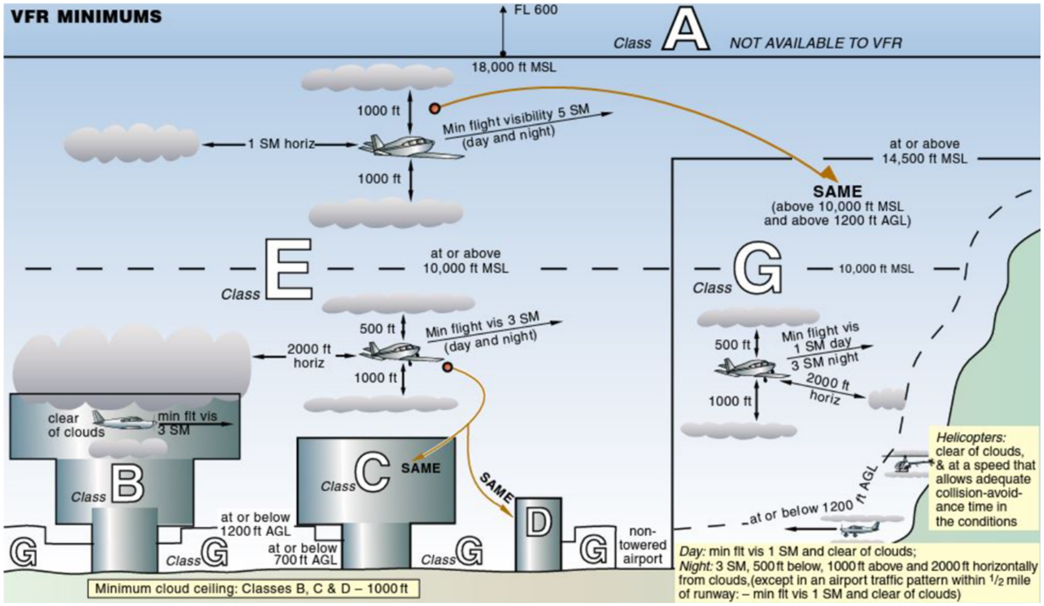

Figure 2.3: Airspace definition under VFRs [9]

Air search radar can use the frequency bands of C, X, or K_u on the Aeronautical Radio Navigation Spectrum (ARNS) [11] for the detection and tracking of both cooperative and non-cooperative traffic [11].

2.1.4.1 PSR (Primary Surveillance Radar)

PSR is a passive surveillance system which computes radio waves' travel times between PSR and target aircraft to determine range. PSR sends out microwave signals towards the target aircraft and looks for the reflected signal from the target aircraft's metallic surfaces [12]. PSR Range is measured as the distance D based on the wave transit time of travel of the signal to and from the target. Target position is determined as angle θ based on the position of a directional antenna in azimuth. Radial target velocity can also be determined by using the Doppler effect [13]. PSR is gener-

Category	Ceiling		Visibility
Visual Flight Rules (VFRs)	Greater than 3,000 feet AGL	and	Greater than 5 miles
Marginal Visual Flight Rules (MVFRs)	1,000 to 3,000 feet AGL	and/or	3 to 5 miles
Instrument Flight Rules (IFRs)	500 to below 1,000 feet AGL	and/or	1 mile to less than 3 miles
Low Instrument Flight Rules (LIFRs)	Below 500 feet AGL	and/or	less than 1 mile

Table 2.3: Weather Flight Conditions Rules [10]

ally used in four applications: 1.) Terminal Surveillance Radar (TSR), 2.) Precision Approach Radar (PAR), 3.) Airport Surface Detection Equipment (ASDE) and 4.) Weather Radar (WR) [8].

- TSR: terminal operations (i.e. near airports) use radar frequencies between 1250 to 1350 MHz for a short-range, 80 NM operations.

- PAR: this application is used as an approach navigational aid, using frequencies between 9000 to 9180 MHz for a shorter range high definition tracking near airports. This provides the Local ATC provider with target altitude, azimuth, and range information of high precision. PAR is typically used by military operations, but some civilian airports also provide the PAR service. The Canada Air Pilot (CAP) and Restricted Canada Air Pilot (RCAP) publish the civil aircraft approach limits.

- ASDE: Local ATC uses the ASDE service for monitoring the ground position of aircraft around the airport, especially runways and taxiways during low visibility conditions. ASDE gives high definition and uses a 16 GHz frequency band.

- WR: Meteorological Service of Canada (MSC) uses this weather radar to provide weather conditions (i.e. cloud and precipitation).

The PSR coverage in Canada may be seen in Figure 2.4 below, "Primary Surveillance Radar Coverage [3]."

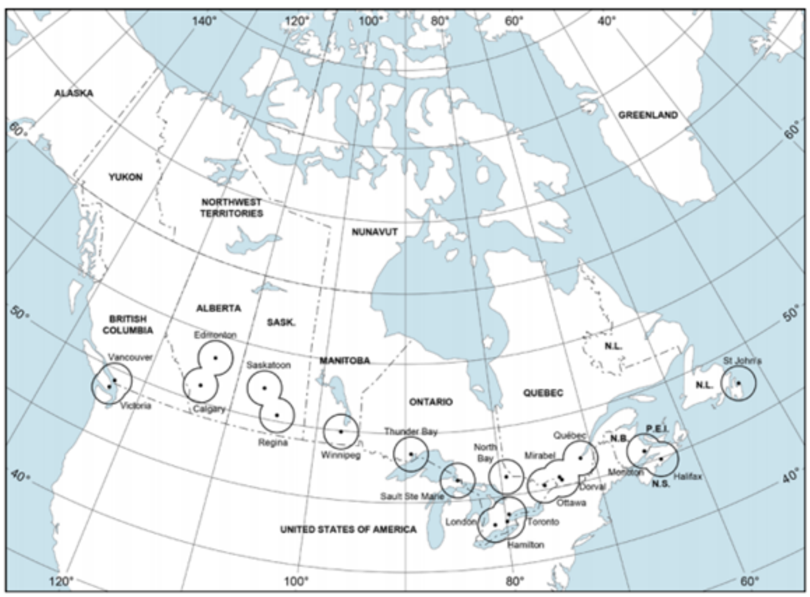

Figure 2.4: Primary Surveillance Radar Coverage [3]

2.1.4.2 SSR (Secondary Surveillance Radar)

SSR is used in two different applications: 1.) En-Route Control, and 2.) Terminal Control. En-route refers to surveillance coverage along airway/RNAV routes, and is main usage of SSR at present. TSR uses both long-range SSR and short-range PSR for controlling the terminal area.

The aircraft XPDR receives interrogation impulses from the ground SSR antenna, using a receiver that amplifies and demodulates the signal. The decoder decodes the interrogation pulse and generates the appropriate response. This response is then transmitted back to the SSR antenna so that ATC or ground station can receive the aircraft data within the SSR coverage area. ATC typically transfers un-cooperative aircraft tracks from PSR to SSR, which gives cooperative and dependent air traffic surveillance system. The current SSR coverage in Canada may be seen in Figure 2.5,

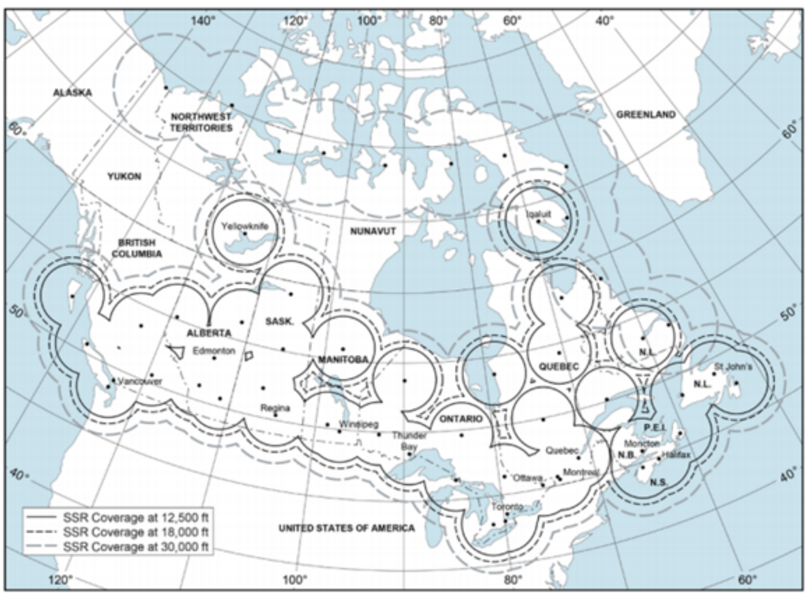

Figure 2.5: Secondary Surveillance Radar Coverage [3]

“Secondary Surveillance Radar Coverage [3].” SSR has ability to cover a range of 200 NM or more [8]. According to ATC procedures, there are three flight altitude limits typically used in Canada: at 12,500 ft, 18,000 ft, and 30,000 ft; as shown in Figure 2.5. Regional Area-ANSP typically keep their SSR range set on 25 NM. In case of an aircraft flying by at FL20[1] using VFR flight, although aircraft would be within radar coverage, Regional Area-ANSP would not necessarily be watching that aircraft on radar. The Regional Area-ANSP (YQX) may see the target aircraft. However, ANSP would not have any information on the aircraft if it is a VFR flight. Both the Regional Area-ANSP (YQX) or Local ATC (YYT) should not be watching full radar coverage other than their set-range of 25 NM radius. Local ATC is responsible within 7NM radius coverage and Regional Area-ANSP is not responsible outside of their 25 NM set-range.

2.1.4.3 SSR (Secondary Surveillance Radar) Limitations

There are two significant radar limitations which impact SSR in particular: 1) Radar Horizon and 2) Terrain Obstacles such as mountains. The definition of radar horizon is the location when the direct radar rays are tangential to the earth's surface, and is usually the same as the radio horizon. In other words, the radar horizon refers to the line of sight as radar usually travels in a straight line at the frequencies typically used in aviation as shown in Figure 2.7. Therefore, it creates a limited angle of travel by the natural curvature shape of earth as illustrated in Figure 2.6.

Radar Range (to horizon) may be estimated as:

$$R_{\mathrm{NM}} = 1.23\sqrt{\mathrm{h}_{\mathrm{radar}}} \tag{2.1}$$

where: h is height in feet.

Radar Range (beyond horizon/ over earth curvature):

$$R_{\mathrm{NM}} = 1.23(\sqrt{\mathrm{h}_{\mathrm{radar}}} + \sqrt{\mathrm{h}_{\mathrm{target}}}) \tag{2.2}$$

[1] FL refers to Flight Level, FL20 means 2,000 feet

where: h is height in feet.

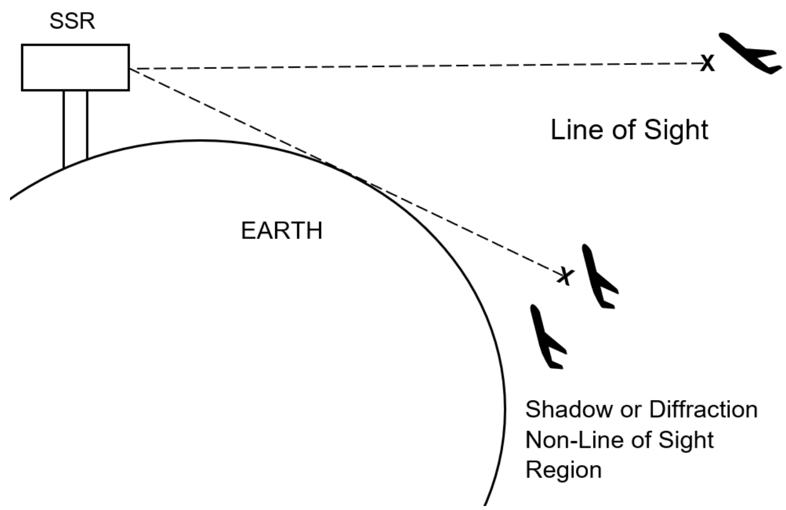

Figure 2.6: SSR Range Limitations

In military aviation, pilots often fly “under the radar”, a technique called ”Nap of the Earth (NOE)”. This is used to avoid detection by enemy radar. It is suspected that the missing Malaysian Airline MH370 Boeing 777 aircraft may have used this tactic to avoid radar detection during an apparent avoidance and escape maneuver over the Malaysian Peninsula[15] [16]. In practical terms, current SSR coverage is typically limited as described above, to a radius of 60 NM. Radar cannot cover beyond this area, and thus ATC cannot monitor aircraft by XPDR if the aircraft is outside of this radar coverage.

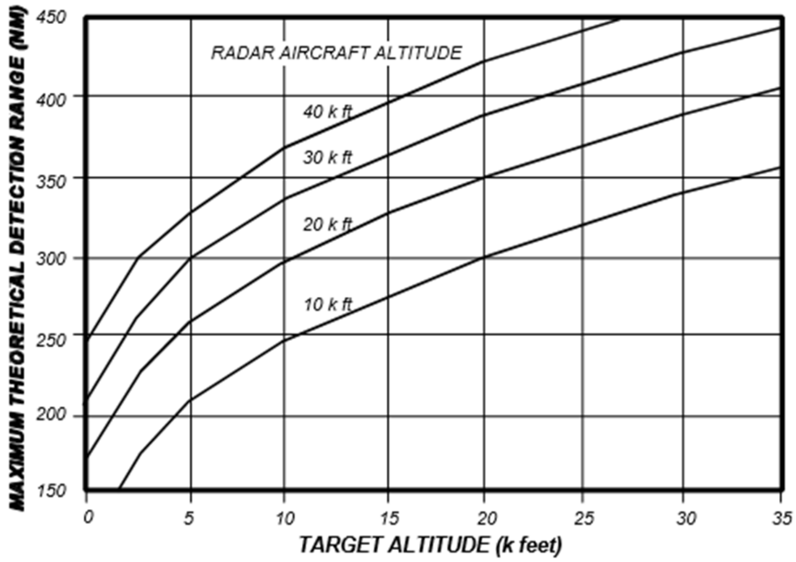

Figure 2.7: Target Maximum Detection Range vs Aircraft Altitude [14]

2.2 Loss of Separation (LOS)

The maintenance of adequate separation between aircraft is a key factor in the avoidance of NMAC/MAC incidents. The detection of a Loss of Separation (LOS) and mitigation of such an event is therefore a critical component of modern aviation safety. This section explores the current standards regarding the loss of separation in aviation.

2.2.1 Separation Standards

Separation standards can be broken down into three separation standards: 1) vertical separation, 2) lateral separation, and 3) longitudinal separation.

2.2.1.1 Vertical Separation

Vertical separation is determined by altimeter pressure setting within designated airspace altitude or Flight Level (FL), ICAO's minimum vertical separation for IFR is 1,000 ft below FL290 and 2,000 ft above FL290 except for when reduced vertical separation minima (RVSM) apply [7].

2.2.1.2 Lateral Separation

The lateral distance is determined based on geographic locations of aircraft's flight paths by reported position. Lateral separation distance is minimum 15 NM by the minimum angle from target facility to aircraft.

2.2.1.3 Longitudinal Separation

Longitudinal separation is determined based on comparing each aircraft's reported time and speed versus established jet-way positions (waypoints), to establish the position difference between Ownship[2] and Intruder[3] aircraft. This is typically used during long-distance international travel along established high-altitude jet-ways involving large East-West movements, hence the source of the longitudinal terminology. A minima of 15 minutes time separation between following aircraft is typically used. The following aircraft ensures that its speed does not exceed the leading aircraft's speed.

[2] Ownship aircraft refers to one's own aircraft, as represented in a traffic collision avoidance system.

[3] Intruder aircraft is a target that has satisfied the traffic detection criteria[17] and refers to encountering aircraft in this thesis.

2.3 DAA (Detect and Avoid)

Pilots primarily rely on their Eyesight, and this is the central assumption built into the See and Avoid (SAA) principle inherent in manned aviation. DAA/Surveillance Equipment (if present) may provide extra help to mitigate the mid-air collision risk by enhancing the pilot's situational awareness. Aircraft always have some potential MAC risk when flying amongst traditional manned aircraft (rotary-wing and fixed-wing) and unmanned aerial vehicles (UAVs) within both regulated and non-regulated airspace. These two categories of airspace have four types: controlled, uncontrolled, special use, and other airspace [18].

There are two types of Intruder aircraft which might approach an aircraft, hereafter referred to as our Ownship: 1) cooperative and 2) non-cooperative. Cooperative Intruder aircraft have some form of electronic means of identification equipment on board. These may be tracked by ATC and other aircraft that have the appropriate DAA/Surveillance Equipment on board [19]. In current aviation practise, Cooperative Intruder aircraft have either Identification Friend or Foe (IFF) XPDR, Mode C/S XPDR, Traffic Collision Avoidance System (TCAS) I/II, or Automatic Dependent Surveillance-Broadcast (ADS-B) In/Out. Non-cooperative Intruder aircraft include those that do not have any electronic means of identification aboard or are not operating such equipment due to a malfunction or deliberate action [20]. Non-cooperative Intruder aircraft may have a Mode A XPDR or Air-To-Air-Radar (ATAR) on board. However, airborne radar sensors can detect non-cooperative Intruder aircraft for registration (IDENT), and a cooperation-enabled Ownship aircraft cannot obtain any cooperation functionality with them. The various types of transponders are explained in the subsequent sections.

2.3.1 Transponder (XPDR)

A XPDR combines two words: transmitter and responder. It is an onboard electronic device that produces a response when it receives a transmitted radio-frequency interrogation. XPDR technology was developed during World War II as part of radar development by the British for detecting enemy aircraft. Initial radar development focused on PSR. It was quickly noticed there was limit on aircraft identification solely by PSR. Following this development, the SSR concept was introduced and developed as an IFF XPDR by Watson-Watt, which gave improved identification detection by an onboard XPDR unit [21]. An IFF XPDR is primarily intended for military authorities to identify the IFF code for detecting friendly aircraft. Today, XPDR helps ANSP in identifying aircraft by SSR with synchronizing targets aircraft detected by PSR. Other aircraft equipped with Collision Avoidance System (CAS) also assists to identify aircraft equipped with an onboard XPDR system [17].

There are three popular types of the XPDR used in the current civilian aviation industry: Mode A, Mode C, and Mode S XPDR [17].

2.3.1.1 Mode A XPDR

The Mode A XPDR receives interrogation pulses on 1030 MHz from a nearby SSR, and replies with the XPDR's squawk code signal on 1090 MHz to SSR continuously with an aircraft identification code. This Mode A XPDR operation does not transmit altitude information. ATC sees Mode A XPDR equipped aircraft on their radar screen in 2D along with identification information only [21][8].

2.3.1.2 Mode C XPDR

The Mode C XPDR operates in a similar mode as Mode A; however, it includes pressure altitude information in its reply messages due to SSR interrogations. A Mode C XPDR interrogation is also called an 'All-Call', and contains a digital code that represents the aircraft altitude information. Mode C XPDR supplies ATC and any nearby TCAS-equipped aircraft with 1) 2D radar location, 2) pressure altitude, and 3) aircraft identification. The enhanced 3D aircraft location information provided by Mode C replies allows ATC to detect and mitigate any potential loss of separation event quickly. This also provides information to nearby TCAS-equipped aircraft in the form of a Traffic Advisories (TA) [8].

2.3.1.3 Mode S XPDR

The Mode S XPDR "S" means Selective in its acronym. Mode S is designed to exchange maneuvering intentions. Mode S XPDR broadcasts, 1) aircraft call sign, 2) ICAO 24-bit address (unique address), 3) location information including altitude and airspeed, and 4) other air traffic communications [20]. The data is transmitted once per second by 1090 MHz Extended Squitter (ES), often notated 1090ES, so ATC can access the real-time aircraft position information [8]. This Mode S data link allows communication with TCAS, and generates automatic Resolution Advisories (RA) with other Mode S XPDR equipped aircraft for avoiding potential conflict situations. The Mode S XPDR provides the ability to interrogate a single aircraft at a time. A Mode S XPDR can transmit through selective interrogation to prevent the synchronous garbling as may happen with the Mode C XPDR. Mode S XPDR has minimized synchronous garble from ground or ocean beneath [22].

2.3.1.4 XPDR Requirements

According to TC, CARs 605.35 [23], aircraft must be equipped with an appropriate XPDR before entering any XPDR-mandatory areas. For example, for in order to operate in Canadian airspace class A, B, C, D, and E (CARs 601.03) [23], an aircraft must be equipped with at least a Mode C XPDR. The detailed information of Terminal Control Areas (TCAs), Control Zones (CZ), and transition areas are described in the TC AIM [8] and designated airspace handbook [24], which show the detailed airspace areas across Canada. In terms of CZ, four classes (Class B, C, D or E) can be a part of the CZ, typically with dimensions of 7 NM radius and 3,000 feet Aerodrome Elevation (AAE) high, centered around an airport [5]. IFRs require XPDR within the controlled area. It is applied as per the circumstance with XPDR functionality and followed by the airspace classes under the CARs 601.03 [23]. XPDR use reduces the communications among ATC and other aircraft for more efficient ATC traffic service, and significantly increases the chances of detection of XPDR equipped aircraft by radar systems, including SSR. Figure 2.8 shows the area of XPDR airspace across Canada [8].

2.3.1.5 XPDR User/Pilot Procedure

Aircraft operators/dispatchers propose the itinerary and request taxi to the active runway for the takeoff to ATC. Local ATC issues a XPDR code to aircraft before taxiing via Airband Radio. The pilots should enter the XPDR code accordingly, and if ANSP has not been issued the XPDR code, pilots should select XPDR code 1000.

Figure 2.8: XPDR Airspace in Canada [8]

Pilots adjust the mode of XPDR to STANDBY during taxiing aircraft before takeoff and switches to ON or NORMAL mode on the runway as close to takeoff as possible. Unless the airport uses Multilateration (MLAT), landing also requires that the XPDR is switched to STANDBY mode or OFF when the aircraft exits the runway [8]. In the event of XPDR fails during flight within Class B airspace, the Pilot has to report the nearest ATC and request the clearance. ANSP can assist with authorizing deviation from XPDR requirement for allowing aircraft enter the controlled airspace area as emergency landing. Pilot should cooperate with ANSP's direction [8].

2.3.2 TCAS (Traffic Alert/ Collision Avoidance System)

TCAS is airborne collision avoidance system for reducing the risk of MAC between aircraft. Another terminology, Airborne Collision Avoidance System (ACAS) is used internationally by the ICAO. The primary goal of TCAS is to prevent MAC that would result in a catastrophic disaster with many fatalities, and provides important advisories to protect people and aircraft.

A historical mid-air collision happened over the Grand Canyon on 30th June, 1956. This accident and several other high-profile mid-air incidents with involving airliners highlighted the need of some form of airborne anti-collision system. The newly-formed FAA was tasked with the important task of supporting the development of some form of airborne CAS.

During the late 1950s and early 1960s, CAS development focused on passive and non-cooperating systems. However, Dr. John S. Morrell of Bendix Avionics introduced a closure rate algorithm concept using a Tau which calculates the slant range between aircraft divided by the closure rate based on time by way of an alternative distance for Closest Point of Approach (CPA). During the late 1960s and early 1970s, a few companies worked on CAS development mostly using transponder interrogation and time-frequency methods. The functionality worked adequately but FAA and airline operators noticed that the system produced a high level of unnecessary alerts within busy traffic areas near airport. In addition, every aircraft required the same equipment on board for targeting aircraft to give a warning. In the mid-1970s, Beacon Collision Avoidance System (BCAS) developed and used existing Air Traffic Control Radar Beacon System (ATCRBS) to determine an Intruder aircraft's range and altitude. ATCRBS transponders were widely equipped with most aircraft and all BCAS equipped aircraft were able to detect and prevent MAC without the need for new equipment installation.

In 1978, a mid-air collision occurred near San Diego between a light GA aircraft and an airliner. This accident served to pressure FAA in its efforts to develop a more effective collision avoidance system [17]. In 1981, FAA decided to use BCAS design of interrogation and tracking for developing and implementing TCAS. Throughout the 1980s, the FAA Technical Center tested and evaluated the development of TCAS. RTCA established the Minimum Operational Performance Standards (MOPS). In the late 1980s, FAA certified TCAS [22]. TCAS is an independent warning system. TCAS integrates XPDR Mode C or S signals from Intruder aircraft as received by the Ownship aircraft. This signal information is analyzed to determine Intruder aircraft flight paths. TCAS I gives warning to the pilot in the form of Traffic Advisories (TAs). TCAS II also computes the safe flight path by the Ownship that will mitigate any detected risk, in the form of Resolution Advisories (RAs). Further details of TAs and RAs are following Subsection 2.3.2.4 and 2.3.2.5. The Mode S XPDR and TCAS were developed simultaneously, and Mode S XPDR supports the TCAS operations. The TCAS computer always monitors all Mode S XPDR 1090 MHz signal (squitters) to detect other Intruder aircraft and examine each squitter to give advisories (TAs or RAs) for preventing mid-air collisions [22] [25].

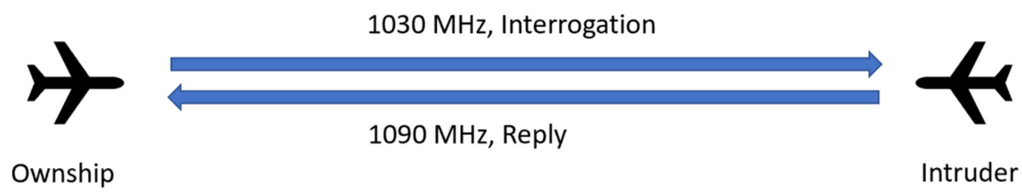

Figure 2.9: TCAS Transmit Signals

The TCAS concept makes use of the same radar beacon XPDRs installed on aircraft to operate with ATC's ground-based radars. TCAS works by sending interrogations to other aircraft's XPDRs. The XPDR replies to the interrogation in a similar way it responds to radar. It calculates the distance between aircraft based on the time differences between the interrogation and the reply. The reply itself also contains the altitude of the other aircraft. TCAS transmits, interrogations and replies in the same frequency bands as ATC surveillance radar: 1030 MHz for interrogations and 1090 MHz for replies (Figure 2.9) [22].

2.3.2.1 TCAS Regulations

TCAS has mainly used two different classes in the industry: TCAS I and TCAS II. TCAS I and TCAS II primarily differ by their alerting capability as described more details below (Subsection 2.3.2.2 and 2.3.2.3). Under the Section 129.18 of FARs (Federal Aviation Regulations), Canadian air operators must be complied with TCAS system to operate in United States airspace. In Table 2.4, CARs regulated

CARs	TCAS I	TCAS II
Subpart 702.46	Not required	Required for turbine-powered aeroplanes of Maximum Certificated Take-Off Weight (MCTOW) exceeding 15,000kg (33,069 lb.)
Subpart 703.70	Minimum required for aeroplanes of MCTOW exceeding 5,700kg (12,566lb.) outside of Reduced Vertical Separation Minima (RVSM) airspace	Not required but acceptable outside of RVSM airspace
Subpart 704.70	Minimum required for aeroplanes of MCTOW exceeding 5,700kg outside of RVSM airspace	Required for turbine-powered aeroplanes of MCTOW exceeding 15,000kg
Subpart 705.83	Minimum required for non-turbine powered outside of RVSM airspace	Required for turbine powered aeroplanes

Table 2.4: TC Air Operator TCAS Requirements

air-operator TCAS requirement [26]. Turbine-powered airplane with more than ten seats but less than 30 passenger seats configuration , excluding any pilot seats, must be equipped with TCAS I. If a turbine-powered airplane has more than 33,000 pounds of MCTOW, it must be equipped with TCAS II [26].

Since 30th December 1993, TCAS I has been mandated in the U.S. for turbine-powered, passenger-carrying aircraft with more than ten and less than thirty-one seats. In Europe there were two steps to mandate ACAS installation for the airspace of the European Civil Aviation Conference (ECAC). The first step was aircraft with more than thirty seats or a certified take-off mass of more than 15,000 kg by 1st January 2000, and the second step was aircraft with more than nineteen seats or a certified take-off mass of more than 5,700 kg by 1st January 2005. After that, EU commission regulation agreed with No. 1332/2011, which means aircraft had to be issued an individual certificate of airworthiness before the 1st March 2012. They had to be equipped with the ACAS II V7.1, collision avoidance logic version 7.1 by December 1, 2015 [27].

2.3.2.2 TCAS I

TCAS I provides Traffic Advisories (TAs) to assist pilots in the visual and aural acquisition of Intruder aircraft [26]. TCAS I interfaces with Aircraft Management System (AMS) via an ARINC 429 data bus to display this traffic information, as shown in Figure 2.10. According to CARs, exceeding MCTOW 5,700 kg (12,566 lbs) capacity of aircraft requires the use of TCAS I (Table 2.4) [26].

2.3.2.3 TCAS II

TCAS II provides Traffic Advisories (TAs) and Resolution Advisories (RAs) in the vertical dimension to either increase or decrease altitude or maintain the existing vertical separation between aircraft [26]. TCAS II is mandated in the U.S. for commercial aircraft, including regional airlines with more than thirty seats per plane or a maximum takeoff weight greater than 33,000lbs. Although not mandated for general aviation use, many turbine-powered general aviation aircraft and some helicopters

Figure 2.10: TCAS Display on MFD

are equipped with TCAS II version 7.1 [17]. TC CARs are described in Table 2.4. TCAS I provides TAs only for target aircraft equipped with any XPDR type in terms of the TCAS safety levels of protection. But TCAS II could protect different levels depending on target aircraft's equipment levels. A Mode A XPDR still only provides TAs with Ownship aircraft equipped with TCAS II system. Mode C, Mode S XPDR or TCAS I with target aircraft would get TAs and vertical RAs as well. TCAS II benefits from fully functioning with TAs and coordinated vertical RAs with Intruder aircraft equipped with the same TCAS II system. TCAS II processes are organized into several elements, as described in the algorithms diagram shown in Figure 2.11.

The surveillance sensors collect state information about the Intruder aircraft and pass the information to a set of algorithms to determine whether a LOS threat exists and analyzes a collision threat exists a NMAC and then MAC. If a threat is identified, the second set of threat resolution algorithms determines an appropriate response. If the Intruder aircraft is equipped with TCAS II, the response is coordinated through a

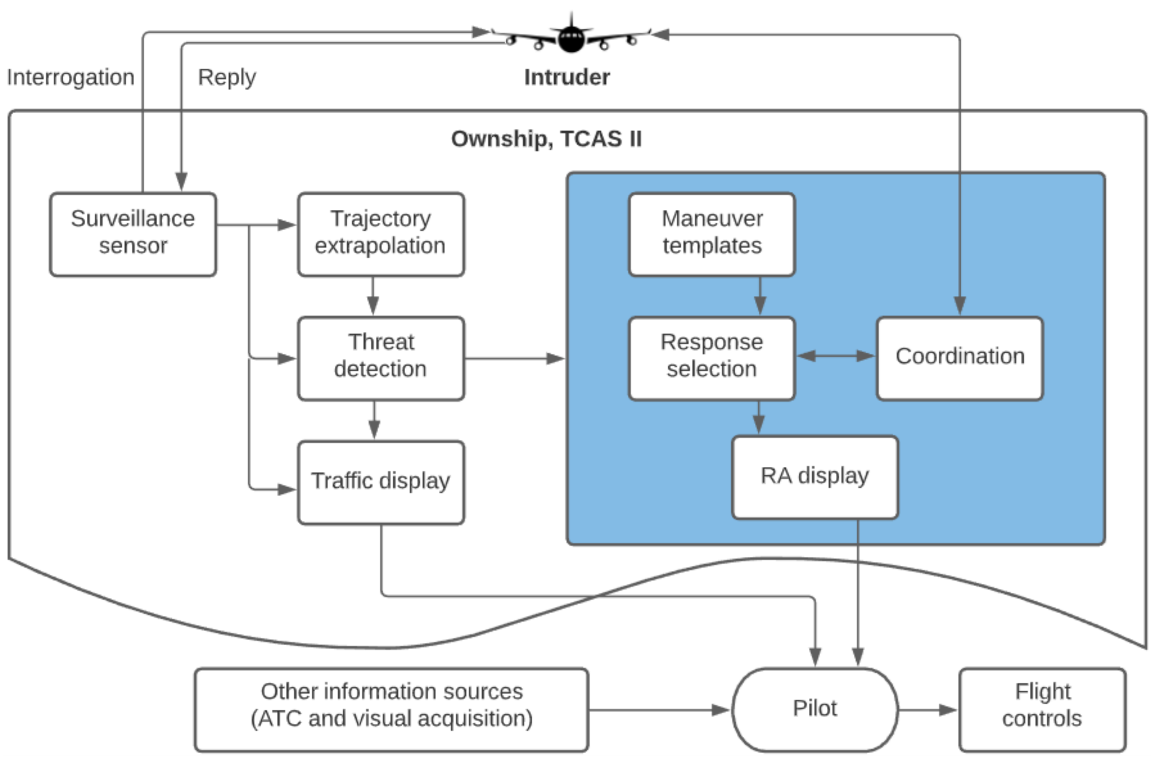

Figure 2.11: TCAS II Processing Algorithms Diagram [28]

data link to ensure that each aircraft maneuvers in an appropriate direction. Collision avoidance maneuvers generated and displayed by TCAS are treated as advisories to flight crews, who then take manual control of the aircraft and maneuver accordingly. Pilots are trained to follow TCAS advisories unless doing so would jeopardize the safety of air-crews, passengers and the aircraft [28].

TCAS-associated components communication relationship summarized in Figure 2.12.

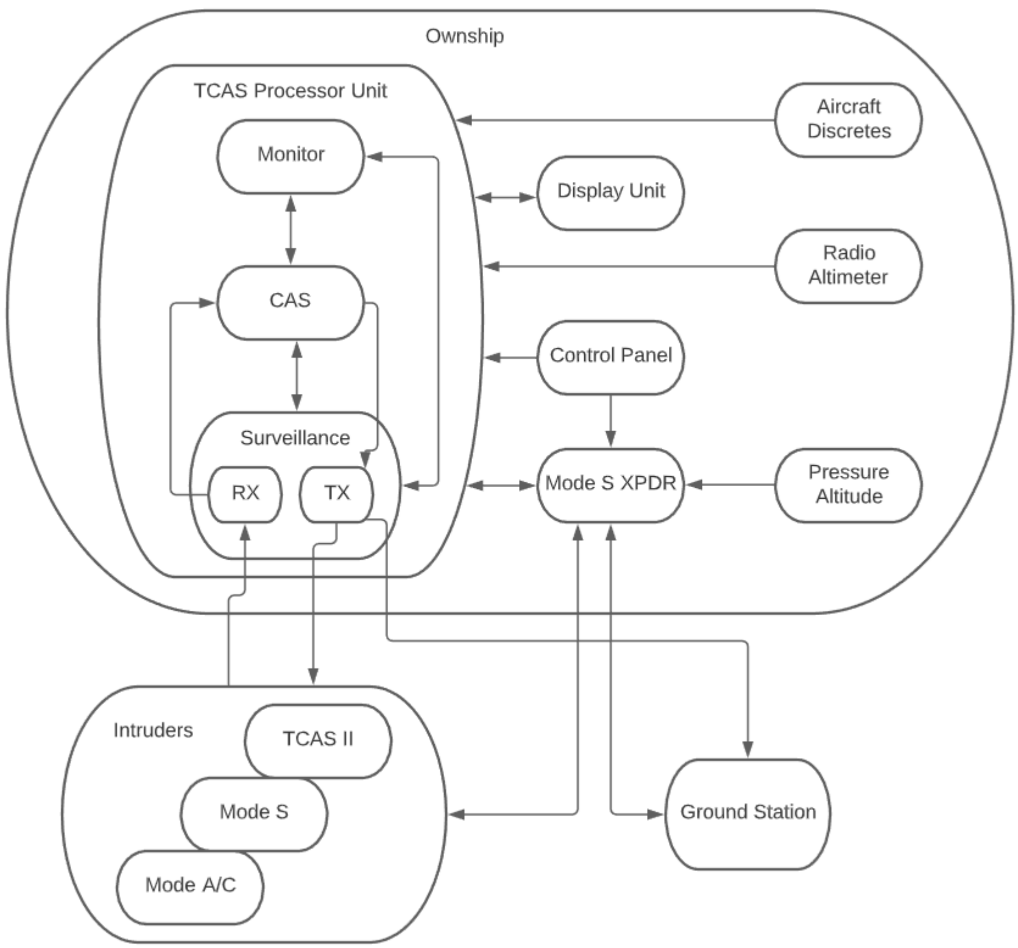

Figure 2.12: TCAS Radio Frequency System Components [29]

2.3.2.4 Traffic Advisories (TAs)

Traffic Advisories TAs give aural and visual warnings to the pilots and help them in the visual acquisition of any Intruder aircraft. The enhanced situational also awareness alerts the pilots in case a Loss of Separation (LOS) or Near Mid-Air Collision (NMAC) situation is developing. A detailed discussion of LOS/NMAC is deferred to Chapter 3.2.3.1.

The threshold of closure in range is called Tau (τ), which is the range divided by the range-rate, as in Equation 2.3:

$$\tau = -\frac{\gamma}{\dot{\gamma}} \; (if \; \dot{\gamma} \neq 0) \tag{2.3}$$

where:

γ is the horizontal range between aircraft.

$\dot{\gamma}$ is the horizontal range rate between aircraft.

TCAS uses an upper limit of 48 sec to determine if there is a risk for LOS/NMAC incident to develop. The CPA time limit for a TA is defined as 25 to 48 seconds, depending on altitude as shown in Table 2.5 [25], [30].

Simple Tau is used to describe the horizontal range rate, ignoring altitude:

$$\tau = \; -\frac{\gamma}{d\gamma/dt} \tag{2.4}$$

Modified Tau that measures the range of Intruder aircraft by using the time to the closest point of approach including a safety factor Distance Modification (DMOD):

$$\tau^*_{mod} = \; -\frac{\gamma - dmod^2/\gamma}{\frac{d\gamma}{dt}} \tag{2.5}$$

Altitude (feet)	Tau (Seconds)
Up to 1,000	20
1,000 - 2,350	25
2,350 - 5,000	30
5,000 - 10,000	40
10,000 - 20,000	45
20,000 - 42,000	48
42,000 and above	48

Table 2.5: TA Threats of Sensitivity Level at Different Altitude [17]

TCAS sensitivity levels are used to control TA/RA determinations based on different altitude dependent values of Tau. Table 2.5 shows that Ownship aircraft detects CPA of Intruder aircraft and calculates Tau depending on the altitude of aircraft for generating TA functions at certain time [30] [25].

2.3.2.5 Resolution Advisories (RAs)

Resolution Advisories (RAs) recommend avoidance maneuvers to the pilots while coordinating with any XPDR-equipped Intruder aircraft (Mode S or Mode C XPDR), RAs currently only provide avoidance maneuvers in the vertical direction, advising either a climb or descent to re-establish proper separation. The descent RAs are inhibited below 1,200 feet Above Ground Level (AGL) while climbing and below 1,000 feet AGL while descending. The increasing descent RAs are inhibited below 1,450 feet AGL. The aural warning is inhibited below 600 feet AGL while climbing and below 400 feet AGL while descending. The TCAS threat analysis algorithms calculate the flight path of Intruder aircraft, and the Tau of RA within 15 to 35 seconds at the specified altitudes, as shown in Table 2.6 [30] [25].

Altitude (feet)	Tau (Seconds)
1,000 - 2,350	15
2,350 - 5,000	20
5,000 - 10,000	25
10,000 - 20,000	30
20,000 - 42,000	35
42,000 and above	35

Table 2.6: RA Threats of Sensitivity Level at Different Altitude [17]

TCAS calculates the risk of collision by solely considering closing speed and vertical rate. It does not calculate clear levels, and the ATC control instructions and ICAO recommendations are different. ATC control instructions require aircraft to maintain the vertical rate at 2,000 feet per minute, and ICAO recommends reducing the vertical rate to 1,500 feet per minute. Recent performance assessment of pilot compliance with TCAS advisories using flight data monitoring (2nd edition) made recommendations that pilots limit vertical rates to 1,500 feet per minute or less when within 1,000 feet of assigned altitudes unless ANSP gave other instruction [31].

2.3.3 ADS-B (Automatic Dependent Surveillance – Broadcast)

ADS-B uses electronic equipment on-board an aircraft to automatically broadcast its precise location via a digital data link. This is the most basic function of ADS-B and is referred to as the ADSB-Out mode. This data can be received and used by other ADSB-In equipped aircraft or ATC in range, to show the aircraft's position and altitude on their display screens without the need for radar systems.

The ADS-B system determines the aircraft location using the Global Navigation Satellite System (GNSS). It uses this information plus aircraft parameter measurements from other on-board sensors to relay aircraft information, including position, altitude, airspeed, and identification, through the aircraft's Mode S XPDR to ATC services [32].

An ADSB-Out system broadcasts information at a high rate, allowing precise tracking of the aircraft. ADS-B data is broadcasted every half-second on a 1090MHz digital data link. This data link may may carry many types of aircraft information including: flight identification (flight number call sign), ICAO 24-bit aircraft address, position (latitude and longitude), position integrity/accuracy (GPS horizontal protection limit), barometric and geometric altitudes, vertical rate (rate of climb and descent), track angle and ground speed (velocity), emergency indication (if an emergency code is selected by the pilot), special position identification (as IDENT selected).

Dedicated ADS-B ground station are used to receive and relay ADS-B transmissions to all authorized airspace users. In the U.S. this includes all ATC units plus an array of ADS-B receive stations distributed across the country. A ground station's ability to receive signal data depends on altitude and distance from transmitting aircraft and obstructing terrain. The maximum range of each ground-station can exceed 250 nautical miles. In airspace immediately surrounding each ground station, surveillance coverage extends to near the surface.

The FAA mandated ADSB-Out technology to be on-board all planes which intended to operate in the U.S National Airspace as defined in 91.225, as of January 1, 2020, and as published in FAA regulation 14 CFR 91.225 and 14 CFR 91.227 in May 2010 [33]. The TC has likewise also considered making ADSB-Out a requirement to fly over Canadian airspace, especially northern portions of Canada and over the North Atlantic Ocean where current radar surveillance cannot cover. However, implementation of this order in Canada has stalled due to push back by small aircraft operators, citing the financial burden of installing ADSB-Out systems [34]. The current ADS-B coverage in Canada is shown in Figure 2.13 below, "Automatic Dependent Surveillance – Broadcast Coverage [3]."

Two ADSB-Out frequencies are using for transmitting data: one is 1090MHz (or also called 1090ES) and the other is 978MHz. 1090MHz is fed through the Mode S XPDR communication link with a 50kHz bandwidth. 978MHz is the Universal Access Transceiver (UAT) with a 1.3 MHz bandwidth which includes transmitting weather data. However, 1090MHz is the only international standard in current ADSB market [35].

Nav Canada started ADS-B service in March 2019 at two Regional Area-ANSP Centres: Edmonton (ZEG) and Gander (ZQX Oceanic/Domestic). These provide limited service within Canadian airspace compared to the US National Airspace

Figure 2.13: ADS-B Coverage [3]

System (NAS). In the U.S., the NAS provides two main services for ADS-B: 1) Flight Information Service-Broadcast (FIS-B) and 2) Traffic Information Service-Broadcast (TIS-B). These two services use the satellite, and broadcast the data among ATCs, ground-based ADS-B stations, flying aircraft pilots, aircraft operators, and unmanned aircraft via ground control stations. Detailed FIS-B and TIS-B information are in Subsection 2.3.3.1 and 2.3.3.2. In Canada, Nav Canada's ADS-B system is part of the Aireon System and operates as space-based ADS-B using 66 Low Earth Orbit (LEO) satellites orbiting the earth, but with only 1090 ES frequency capability [6].

2.3.3.1 FIS-B (Flight Information Service-Broadcast)

FIS-B mainly includes the weather information, Notices to Airmen (NOTAMs), temporary flight restrictions, updates to the flight plans, and other relevant flight information by UAT or 978 MHz datalink. 1090 ES does not broadcast weather data due to bandwidth considerations [36]. This service assists pilots in making strategic decisions while flying, by allowing the avoidance of potentially hazardous weather conditions [33].

2.3.3.2 TIS-B (Traffic Information Service-Broadcast)

TIS-B sends real-time traffic information to aircraft that are equipped with ADSB-In capacity on 978 MHz (UAT) or 1090 MHz (1090ES) [37] at or below 24,000 feet (FL240) within ADS-B coverage. It provides an additional safety net to pilots by enhancing situational awareness. In addition, TIS-B can be beneficial for aircraft that have no collision avoidance system but which are equipped with with ADSB-In/Out equipment. Such aircraft can benefit from TIS-B transmissions which can also include radar target information provided by ADS-B ground stations for traffic information [36].

Chapter 3

Theory - Model Flight CONOPs (Concept of Operations)

The following chapter presents the mathematical and statistical methods used to determine how to reduce the collision rate by using a variation of available DAA/Surveillance Equipment and/or surveillance methods. The goal is to provide a satisfactory level of safety while performing flight operations, using available DAA and/or surveillance equipment on the market. This will also include a discussion of flight operations concepts which might also be employed to prevent NMAC/MAC incidents.

3.1 Background

This chapter describes how to operate the modular flight simulation in order to determine how much to reduce the collision rate by using each device to increase the chance remaining /Well Clear (WC) and thus reducing NMAC/MAC. This leads to creating mid-air collision risk assessment in both qualitative and quantitative terms as presented in Chapter 4.

The original plan was to pursue empirical research to collect the real regional air traffic data and then apply Monte Carlo methods [38] to simulate the result to determine WC and LOWC, and thus create a better mid-air collision risk assessment tool applicable to Canadian airspace. This would have been the translation of the methods employed by Lincoln Labs/MIT as described in ATC-244 [39], but applied to Canadian airspace regions of interest. This would yield an excellent model. However, the level of effort involved (i.e. LL had the assistance of US government resources, including USAF personnel, to do much of the raw radar data collection and initial processing) is far above what was deemed reasonable for this Master's thesis project.

As an alternative, this research was limited to collecting real traffic statistics as compiled by Statistics Canada [40]. This study used this historical air traffic data with possible realistic variable surveillance items instead of collecting real individual aircraft equipment's information and traffic data. The detailed information of possible realistic variable surveillance items is shown in Section 3.4. Moreover, the current COVID-19 pandemic has resulted in a significant reduction of air traffic since March 2020. However, air traffic levels are expected to rebound significantly once this pandemic is over [41]. The use of Canadian historical data over the past decade (2010-2019) was therefore deemed a more reasonable and accurate way to assess future NMAC/MAC rates.

In the following discussions there is an overview of collision risk. This includes the WC equation and calculation of the collision risk ratio which has variables such as MAC, NMAC, traffic density, and risk ratio. The risk assessment framework is presented in Section 3.3. This includes a conceptualized assessment of the impact of currently available DAA and/or existing surveillance equipment options. Section 3.4 addresses the contributions details of this research thesis.

3.2 Collision Risk

A mid-air collision (MAC) is defined as the the aviation accident category when one aircraft contacts another while in flight. TC states that collision means an unplanned impact between two aircraft, i.e. other than any contact associated with normal operating circumstances, between aircraft or between an aircraft and another object or terrain [42]. This therefore excludes such events as normal landings, water-bomber pickup operations along the surface of a lake, or mid-air refueling of military vehicles. TC also states that a "risk of collision" incident means a situation in which an aircraft comes so close to being involved in a collision that a threat to the safety of any person, property or the environment exists [42]. This is also called a near-miss or NMAC.

Aircraft are always exposed to some level of risk of mid-air collision and flight operators want to ensure that this risk is kept as low as possible. ATC can detect the aircraft by SSR in an XPDR-area and can give conflict resolution advice to pilots to prevent MAC accidents or NMAC incidents. The primary objective of ATC is to maintain the orderly and efficient flow of traffic while maintaining minimum separations among aircraft in the controlled zone. This ensures the maintenance of the concept of Well-Clear in DAA terms. The qualitative definition of DAA Well-Clear (DWC) is "a temporal and/or spatial boundary around the aircraft intended to be an electronic means of avoiding conflicting traffic" [11]. However, ATC has no obligation outside of the XPDR-area under the current ATC system. Further information on the concept of Well Clear (WC), including the quantitative definition, is provided in Subsection 3.2.1.

3.2.1 Well-Clear (WC)

Well-Clear (WC) is a separation standard of space between airborne traffic. The FAA-sponsored Sense-and-Avoid (SAA) Workshop [20] defined SAA as the capability of a UAS to remain WC from and to avoid collisions with other airborne traffic [43]. The concept of WC has been proposed as an airborne separation standard to which any DAA system intended for use on UAS must adhere to in order to achieve Self-Separation (SS). This means UAS must remain WC of other aircraft in accordance with the accepted definition of WC. The SS function is intended to give UAS the ability to ensure WC separation standards are adhered to, in a manner the same as the See and Avoid principle has been used in manned aircraft for years.

The basic concept of SS is that the Ownship aircraft independently determines what necessary action is required to maintain an appropriate distance from other encountered "Intruder" aircraft (i.e., without any assumption of coordination or even detection/knowledge by the Intruder). This concept applies to both manned and unmanned aircraft to detect and avoid possible collision among aircraft, though in practice manned aviation follows a more cooperative/coordinated approach such as with TCAS. The SAA workshop focuses on the requirements for UAS to behave in a similar manner to manned aircraft, while being as unobtrusive as possible in existing manned airspace. The SAA workshop defined WC as the state of maintaining a safe distance from other aircraft that would not usually cause the initiation of Collision

Avoidance (CA) manoeuvre(s) by either aircraft [20]. DAA performance evaluations typically use the definition of WC as detailed below [44].

As described Chapter 2, the Equation 2.3 used to calculate τ shows that a higher τ value means lower collision risks, while a lower τ value indicates a higher risk of collisions. A higher τ also gives more time to detect and track intruders, and also to engage in any avoidance maneuvers.

Fang's thesis Section 4.2 describes WC mathematical definitions as shown below [45], An Intruder is considered to have violated the WC boundary around the Ownship when:

$[0 \leq \tau_{mod} \leq \dot{\tau}_{mod}]$ and $[HMD \leq HMD*]$ and [-h*≤d_h≤h*]

with $\dot{\tau}_{mod} = 35\ sec$, $HMD^* = 4000\ ft$, $DMOD = 4000\ ft$,and $h^* = 450\ ft$

Where:

τ_{mod} is Modified Tau,

$\dot{\tau}_{mod}$ is the Modified Tau Threshold,

HMD is Horizontal Missed Distance at CPA,

HMD^* is the Horizontal Missed Distance Threshold,

d_h is the Vertical Separation,

h^* is the Vertical Separation Threshold,

DMOD is the Distance Modification associated with Modified Tau. Modified Tau (τ_{mod}) is defined as:

$$\tau_{mod} = \frac{-\left(r^2 - DMOD^2\right)}{\gamma\dot{\gamma}} = \frac{DMOD^2 - \gamma^2}{d_x v_{\gamma x} + d_y v_{\gamma y}} \tag{3.1}$$

For closing geometries where $\gamma > DMOD$

$\tau_{mod} = 0$ for $\gamma \leq DMOD$

$\tau_{mod} = inf$ for non-closing geometries where $\gamma > DMOD$

Where:

$\gamma = \sqrt{{d_x}^2 + {d_y}^2}$ (the horizontal range between aircraft)

$\dot{\gamma} = \frac{d_x v_{\gamma x} + d_y v_{\gamma y}}{\gamma}$ (the horizontal range rate between aircraft)

$d_x = x_2 - x_1$ (the current horizontal separation in the x dimension)

$d_y = y_2 - y_1$ (the current horizontal separation in the y dimension)

$v_{\gamma x} = \dot{x}_2 - \dot{x}_1$ (the relative horizontal velocity in the x dimension)

$v_{\gamma y} = \dot{y}_2 - \dot{y}_1$ (the relative horizontal velocity in the y dimension)

Note that $\dot{\gamma}$ is negative for closing geometries, while the τ_{mod} is positive. All ranges and range rates are in the horizontal plane and are not slant ranges.

The Modified Tau Threshold (τ^*_{mod}) is the value with which the calculated τ_{mod} is compared against Intruder aircraft.

Horizontal Missed Distance (HMD) at CPA is defined as:

$$HMD = \sqrt[2]{(d_x + v_{rx} t_{CPA})^2 + (d_y + v_{ry} t_{CPA})^2} \tag{3.2}$$

For $t_{CPA} \geq 0$

and,

$$HMD = -\infty \tag{3.3}$$

For $t_{CPA} < 0$ (equivalently, HMD could be simply defined as r)

Where:

$t_{CPA} = -\frac{d_x v_{\gamma x} + d_y v_{\gamma y}}{v_{\gamma x}^2 + v_{\gamma y}^2}$

t_{CPA} represents the time to the closest point of approach and is positive for closing geometries. Horizontal Missed Distance Threshold (HMD^*) is the value with which the calculated HMD is compared against other aircraft.

Vertical Separation (d_h) is defined as:

$$d_h = h_2 - h_1 \tag{3.4}$$

3.2.2 Well−Clear Separation Requirements

In current manned aviation, the ATC separation standard is a cylindrical volume with dimensions of 5 NM horizontally and 1,000 ft vertically, centered on a given aircraft, sometimes also called the "hockey puck". Most of the manned aircraft in en-route and transition airspace fly from origin to destination along fixed airways. However, many unmanned aircraft need to perform "mission-oriented" operations such as flying a loitering pattern, grid pattern, or non-predetermined missions with frequently changing flight plans. This difference in mission profiles may create different conflict situations between unmanned and manned aircraft [43]. Separation should be large enough to avoid an intruder aircraft's corrective maneuvers to minimize traffic alert assurances by ANSP and avoid excessive concern for proximate SAA flights. Deviations should be small enough to avoid disruptions to traffic flow and vary appropriately with encounter geometry and operational areas [20]. The UAS pilot, who is considered as the GCS Operator responsible for a given unmanned aircraft, typically uses UAS DAA/Surveillance Equipment in order to properly maneuver the aircraft in accordance with ATC clearances and instructions. The GCS operator also considers Right of Way (ROW) rules under 14 CFR 91.113, to remain WC and to avoid creating a collision hazard with other aircraft under 14 CFR 91.181 [44]. The maneuvers performed using the DAA/Surveillance Equipment consist of maneuvers performed within a timeframe normally sufficient to safely coordinate with ANSP to remain DWC or return to DWC. If an UAS is equipped with option TCAS II, then Resolution Advisory (RA) maneuvers may be performed to prevent Intruder aircraft from penetrating the WC volume, as the "first line of defence" in avoiding the development of a NMAC or even MAC situation. This situation would then require immediate execution followed by ATC notification. DAA maneuvers may be performed in the vertical or horizontal dimensions. TCAS II RA maneuvers are performed in the vertical dimension (climb and descent). TCAS III is intended to assess horizontal separation, and TCAS IV is projected to utilize GNSS with Wide Area Augmentation System (WAAS) ability which includes the concept of ADS-B system. TCAS II RA maneuvers are expected to be initiated as a last resort before the CPA. TCAS II is intended to engage and separate when Intruder aircraft come close to vertical dimensions. The boundary of a Self-Separation Traffic Advisory Alert Threshold is at a vertical distance (altitude difference) of 700 ft. Furthermore, the preferred formulation consists of a horizontal dimension of a modified Tau value of 35 seconds with a distance threshold (both a minimum distance modification and horizontal miss distance filter) of 4,000 ft, as shown in Figure 3.1 [46].

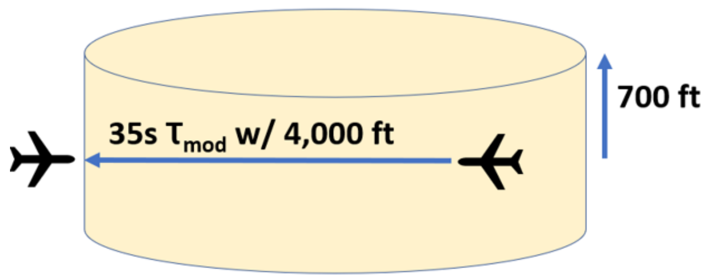

Figure 3.1: UAS Well-Clear Recommendation from SaRP to SC-228 [46]

The FAA Sense and Avoid Workshop concluded in 2013 that "For a technical system to perform the function of a pilot to remain WC, it is necessary to have an unambiguous, implementable definition of the separation minima" to modify the existing vertical definition of WC to 450 ft with no change to the horizontal modified Tau, as shown in Figure 3.2 [20]. Determination of a quantitative definition for UAS WC is significant step forward in requirements for DAA MOPS. It provides clear success criteria for the DAA intended function of "remaining WC" [44].

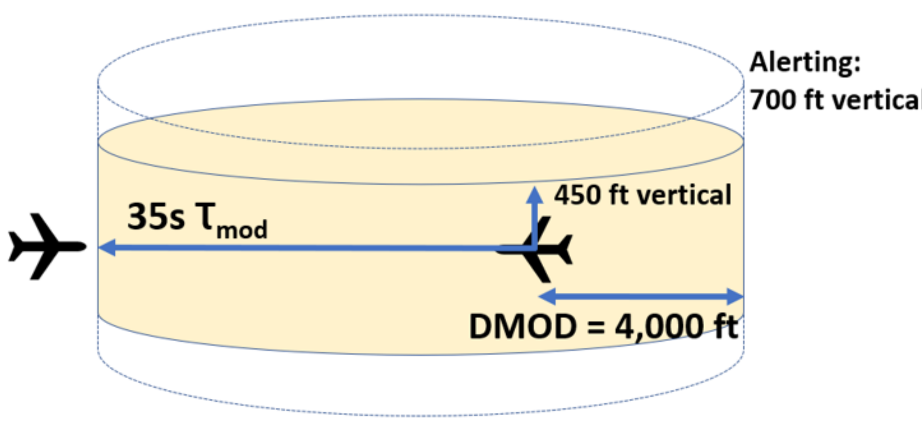

Figure 3.2: Large UAS Well-Clear Separation Definition [20] [47]

The Alerting Threshold function within any DAA System needs to define and understand the separation requirements applicable to host UAS in order to remain WC, and decide at what position to activate the alert. However, the minimum alerting thresholds could differ based on sensor or aircraft performance [44].

3.2.3 Collision Risk Ratio Calculation

A concise formulation for the collision risk ratio [11] is shown below.

$$NMAC_{mit} = NMAC_{unmit} \times RR \tag{3.5}$$

where:

NMAC_{mit} = mitigated NMAC rate per flight hours

NMAC_{unmit} = unmitigated NMAC rate per flight hours

RR = Risk Ratio

NMAC_{mit} is the statistic measuring the rate of NMAC where the Intruder is detected and some form of reaction is taken which effectively avoids, or mitigates the NMAC incident. Conversely, NMAC_{unmit} is the raw chance of a near-miss occurring due to air traffic density and flight patterns, without any mitigation. Assessing mitigation of NMAC is challenging. However, this collision risk ratio calculation helps to give an awareness so that UAS flight operators and pilots can prepare any risk condition of their flight plan.

3.2.3.1 NMAC (Near Mid-Air Collision)

In this study, the NMAC volume around an aircraft is defined as the cylindrical volume, with a radius of horizontal 500 feet and vertical height of +/- 100 feet, centered on each aircraft [11][48]. This NMAC volume is illustrated in in Figure 3.3.

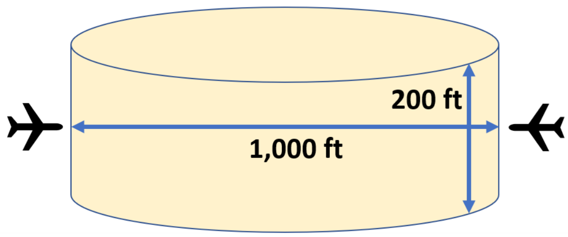

Figure 3.3: NMAC Cylinder[11][48]

As shown in Equation 3.6, mitigated NMAC rate is number of mitigated NMAC events over total flight hours in the region.

$$NMAC_{mit} = \frac{Number\ of\ NMAC\ events}{Flight\ hours\ in\ Canada\ or\ specific\ region\ a\ year} \tag{3.6}$$

where:

$NMAC_{mit}$ is mitigated NMAC rate per flight hours

The unmitigated NMAC rate means that Ownship aircraft has the potential of encountering an Intruder with no chance of avoidance, which could lead to MAC accidents. The mitigated NMAC rate can quantify the collision risk of aircraft with risk ratio by having the plane equipped with Mode A, C, S XPDR, or TCAS (Traffic Collision Avoidance System), or ADS-B (Automatic Dependent Surveillance-Broadcast) systems.

As described in Equation 3.5, in order to calculate the mitigated NMAC rate per flight hours ($NMAC_{mit}$), the unmitigated NMAC rate per flight hours ($NMAC_{unmit}$) and risk ratio must be known to calculate the $NMAC_{mit}$.

3.2.3.2 Risk Ratio (RR)

Risk Ratio (RR) is the primary source of assessing the risk of safety, while taking into account the benefit of equipping DAA surveillance systems. This measurement factor can determine the value of avoiding NMAC if DAA systems introduce. Smaller risk ratios mean less chance of $NMAC$ and bigger numbers are more likely to have a $NMAC$ [11][45].

$$RR = \frac{NMAC_{mit}}{NMAC_{unmit}} = \frac{P(NMAC_{mit})}{P(NMAC_{unmit})} = \frac{N_{NMAC_{mit}}}{N_{NMAC_{unmit}}} \tag{3.7}$$

Where:

P(NMAC$_{unmit}$) $= \frac{N_{unmitNMAC}}{N_{ENCOUNTERS}}$ = Probability of unmitigated NMAC

N$_{ENCOUNTERS}$ = Total number of encountered aircraft

N$_{NMAC_{mit}}$ = Number of encountered aircraft with mitigated NMAC

N$_{NMAC_{unmit}}$ = Number of unmitigated NMAC

P(NMAC$_{mit}$) = Probability of mitigated NMAC

Many research papers make the assumption of collision risk [47][49] where 1 of 10 NMAC leads to real MAC rates as incidents/hour for developing calculation models, which estimates a highly conservative rate. Collision risk ratio is then 0.1 probability under the NMAC cylinder.

$$\frac{MAC}{NMAC} = \frac{1}{10}\ probability \tag{3.8}$$

From the development of the NMAC risk rate (RR_{DAA}) calculator model, Equation 3.17, generates collision risk ratio with variable DAA/Surveillance Equipment on board for both Ownship and Intruder aircraft.

3.2.3.3 Airspace Volume

The airspace volume defines the volume of flight operations for a simple circular cylinder equation, as shown in Equation 3.9.

$$Airspace\ volume\ (V_{airspace}) = \pi r^2 h \tag{3.9}$$

where:

r is radius

h is height

For example, for the CZ airspace mentioned in Section 2.3.1.4, the CZ airspace is 7 NM radius and 3,000 feet AAE surrounding airport, as shown in Figure 3.4. Using the CZ dimensions in Equation 3.9, the CZ airspace volume may be calculated as shown in Equation 3.10.

$$\begin{aligned} CZ\ airspace\ volume &= \pi 7\ NM\ (13\ Km)^2 \times 3,000\ Feet\ (914.4\ m) \\ &= 461,814.1201\ Cubic\ NM\ (485,481.6\ Cubic\ Meter) \end{aligned} \tag{3.10}$$

3.2.3.4 Traffic Density

The key to estimating traffic density is collecting real traffic data and defining the operating airspace volume as shown previously in Subsection 3.2.3.3. The real data of air traffic is limited at this stage of research as mentioned in Subsection 1.4 and actual data to collect and calculate accurate traffic density portion of study is recommended

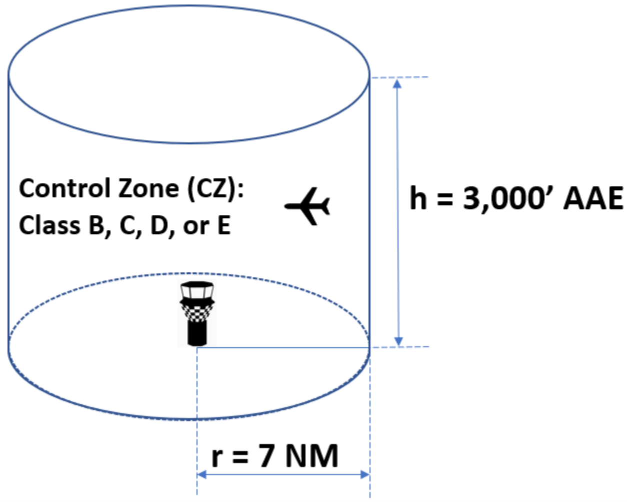

Figure 3.4: Control Zone (CZ) Airspace Dimension [5]

to future work. However, excellent statistics on aircraft movements in and out of most major airports in Canada are collected by Transport Canada monthly, and available for use. These may be used to derive a very good estimate of typical traffic densities around airports, including St.John's (CYYT).

Airspace traffic density is associated with the number of encountering aircraft and the volume of airspace area within the duration of definite time [50], as shown in Equation 3.11.

$$\text{Traffic density} = \frac{N_{ENCOUNTER}}{\text{airspace volume}} \tag{3.11}$$

where:

$\mathrm{N}_{ENCOUNTER}$ = Number of Encounter (Air traffic Intruders) during the sample time.

3.3 Risk Assessment Framework

This section conceptualizes the idea of approaching risk assessment to investigate the modular flight simulations. There are nine different surveillance options for both the Ownship and Intruder aircraft within the controlled zone and outside of the XPDR area, as shown in Table 3.1.

Figure 3.5 shows the limitations and problems of current surveillance systems, using a bow-tie analysis approach to assess the MAC risk. As discussed in Section 1.2 and 2.3 regarding MAC risk, the left side of a bow-tie has three barriers to the prevention of MAC, the potential consequence of risk is in the middle of the bow-tie, and the right side of a bow-tie has three prevention (or mitigation) controls against each barrier.

Figure 3.5: Bow-Tie Analysis

The following sections outlines the various forms of surveillance/DAA/Surveillance Equipment we might consider in the modular flight simulation scenario model. The first and most basic surveillance equipment on manned aircraft is human Eyesight. The pilot would not have the ability to fly their aircraft without good Eyesight. In-

Surveillance options		Intruder								
		Eyesight(1)	Airband Radio(2)	XPDR			TCAS I(6)	TCAS II(7)	ADSB-In(8)	ADSB-Out(9)
				Mode A(3)	Mode C(4)	Mode S(5)				
Ownship	Eyesight(1)	a11	a12	a13	a14	a15	a16	a17	a18	a19
	Airband Radio(2)	a21	a22	a23	a24	a25	a26	a27	a28	a29
	Mode A XPDR (3)	a31	a32	a33	a34	a35	a36	a37	a38	a39
	Mode C XPDR (4)	a41	a42	a43	a44	a45	a46	a47	a48	a49
	Mode S XPDR (5)	a51	a52	a53	a54	a55	a56	a57	a58	a59
	TCAS I(6)	a61	a62	a63	a64	a65	a66	a67	a68	a69
	TCAS II(7)	a71	a72	a73	a74	a75	a76	a77	a78	a79
	ADSB-In(8)	a81	a82	a83	a84	a85	a86	a87	a88	a89
	ADSB-Out(9)	a91	a92	a93	a94	a95	a96	a97	a98	a99

Table 3.1: Surveillance Options Matrix between Ownship and Intruder Aircraft

deed, CARs Part IV standard 424 [51], FAA Part 67 [52], and EASA Annex IV MED.B.070 [7] all regulate pilot license requirements to include the need for a proper medical eye examination. Therefore it is safe to assume all manned aircraft should possess the most basic of surveillance equipment, namely the pilot's Eyesight.

A second very basic piece of equipment is the VHF (Airband) radio. Under the CARs Part VI [53], general operating and flight rules, 602.136, 602.137, and 602.138 regulate that the pilot-in-command shall be sure to remain on the appropriate Airband (VHF) frequency with a continuous listening. This means that Air-band radio communication equipment should be on board, whether IFR or VFR, especially if the the aircraft intends to operate in controlled airspace. These regulations mean that all manned aircraft should have an essential communication tool either two-way FM/VHF radio or handheld radio, which small minimum equipped aircraft can use to handle an emergency (VHF frequency 121.5 MHz) [51].

A third group of equipment is XPDRs, which in current practice could be either Mode A, C, or S types (Figure 3.6). Each XPDR mode can be further broken down

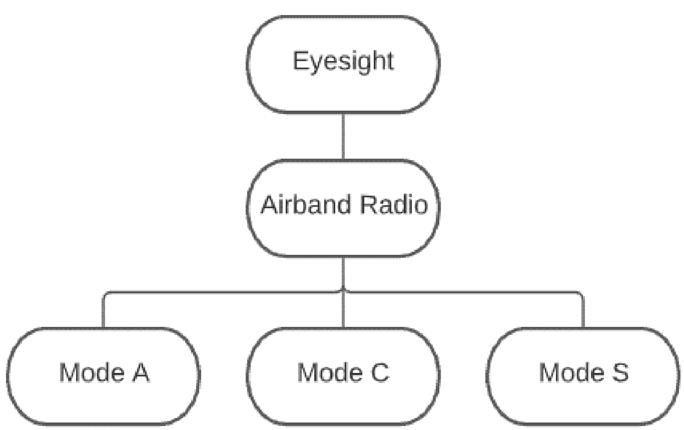

Figure 3.6: Basic Surveillance Equipment Options Tree

by combining other surveillance options such as No TCAS, TCAS I, TCAS II, No ADS-B, ADSB-In, and/or ADSB-Out modes.

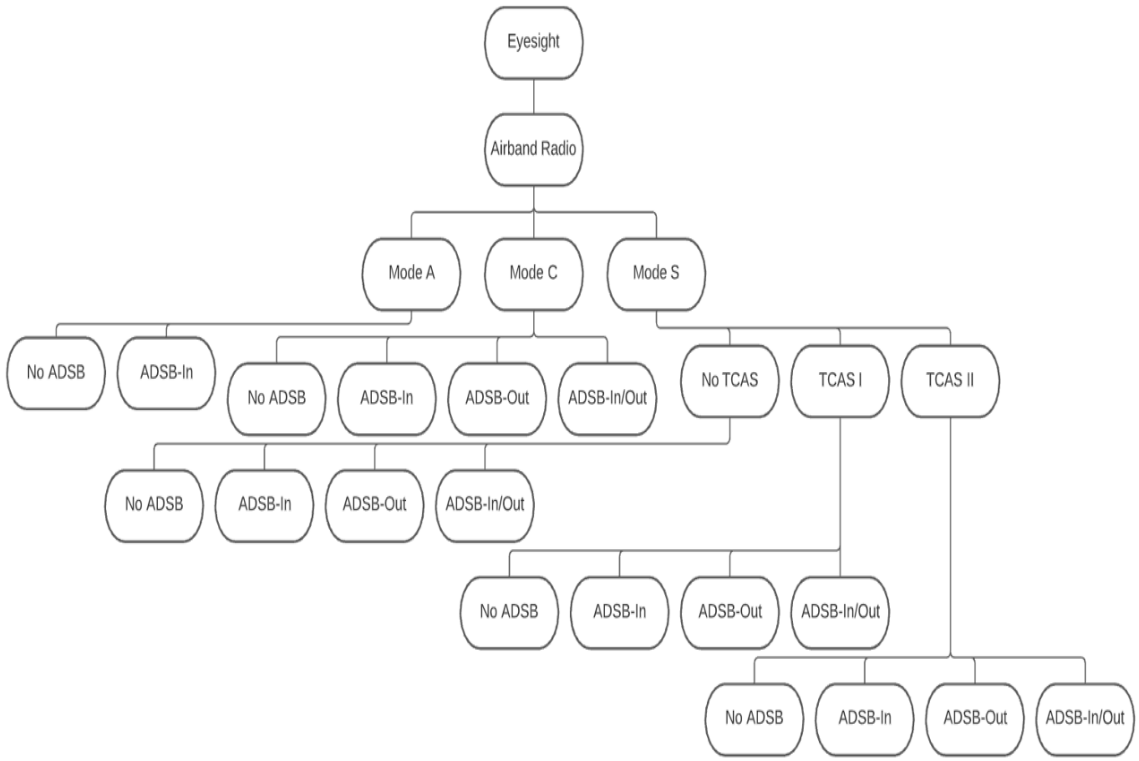

Figure 3.7: Simplified Overall Surveillance Equipment Options Tree

The variable forms of surveillance system could be onboard among aircraft in the current airspace without any consistent surveillance system. This variety of surveillance systems is one of the major limitations of the current aviation surveillance system.

Over the course of this research, it was noted that there is current trend for ATC to rely on SSR, rather than PSR. The main reason is to reduce the operational cost and prepare for the unmanned ground traffic control tower/system. NAV Canada provides their ADS-B service to flight operators at low cost so that flight operators are encouraged to install the ADS-B system. It helps to use an ideal way of traffic control, such as aircraft separation and tracking the aircraft without any conventional radar system.

Figure 3.7 shows the simplified overall surveillance equipment options. These have been broken down into 21 possible scenario surveillance combinations (Table 3.2).

These 21 possible scenarios of surveillance combinations can be applied to both Ownship and Intruder aircraft as potential encounter scenarios. Examples of such combinations and their impact of risk assessment, are given below.

1. Ownship with Eyesight, Airband Radio, and Mode A XPDR

    - 1.1. Intruder with Eyesight, Airband Radio, and Mode A XPDR:

      Both Ownship and Intruder aircraft have the same Eyesight, Air-band radio, and Mode A XPDR. This Mode A XPDR only transmits an identifying code. They cannot enter controlled airspace (class A, B, and C). However, they may enter a Class D control zone by contacting ATC via two-way radio(Airband Radio). Class E zone allows both Ownship and Intruder aircraft to fly with no XPDR requirement. This case only relies on pilots' Eyesight, and the aircraft does not have any ability to detect Intruders.

    - 1.2. Intruder with Eyesight, Airband Radio, and Mode C XPDR

      The Intruder aircraft has Eyesight, Airband Radio, and Mode C XPDR. Mode C equipped aircraft can enter Class A, Class B, and Class C as well. The Ownship cannot enter any controlled zone, and both aircraft only

No	Surveillance options on board	remark
1	Eyesight, Airband Radio, and Mode A XPDR	
2	Eyesight, Airband Radio, and Mode C XPDR	
3	Eyesight, Airband Radio, and Mode S XPDR	
4	Eyesight, Airband Radio, Mode A XPDR, and No ADSB	
5	Eyesight, Airband Radio, Mode A XPDR, and ADSB-In	
6	Eyesight, Airband Radio, Mode C XPDR, and No ADSB	
7	Eyesight, Airband Radio, Mode C XPDR, and ADSB-In	
8	Eyesight, Airband Radio, Mode C XPDR, and ADSB-Out	
9	Eyesight, Airband Radio, Mode C XPDR, ADSB-In/Out	
10	Eyesight, Airband Radio, Mode S XPDR, No TCAS, and No ADSB	
11	Eyesight, Airband Radio, Mode S XPDR, No TCAS, and ADSB-In	
12	Eyesight, Airband Radio, Mode S XPDR, No TCAS, and ADSB-Out	
13	Eyesight, Airband Radio, Mode S XPDR, No TCAS, and ADSB-In/Out	
14	Eyesight, Airband Radio, Mode S XPDR, TCAS I, and No ADSB	
15	Eyesight, Airband Radio, Mode S XPDR, TCAS I, and ADSB-In	
16	Eyesight, Airband Radio, Mode S XPDR, TCAS I, and ADSB-Out	
17	Eyesight, Airband Radio, Mode S XPDR, TCAS I, and ADSB-In/Out	
18	Eyesight, Airband Radio, Mode S XPDR, TCAS II, and No ADSB	
19	Eyesight, Airband Radio, Mode S XPDR, TCAS II, and ADSB-In	
20	Eyesight, Airband Radio, Mode S XPDR, TCAS II, and ADSB-Out	Most Popular Modern aircraft
21	Eyesight, Airband Radio, Mode S XPDR, TCAS II, ADSB-In/Out	

Table 3.2: Possible Scenario Surveillance Combinations

have a chance to encounter each other within an uncontrolled area, so the situation is the same as item 1.1. case, and the risk remains the same as item 1.1. case.

- 1.3. Intruder with Eyesight, Airband Radio, and Mode S XPDR

  An Intruder aircraft has Eyesight, and Mode S XPDR. Mode S equipped aircraft can enter the controlled airspace. However, the Ownship is still not allowed to enter the controlled area. The risk stays the same as 1.1. and 1.2. cases.

2. Ownship with Eyesight, Airband Radio, and Mode C XPDR

- 2.1. Intruder with Eyesight, Airband Radio, and Mode A XPDR

  Ownship aircraft has the pilot's Eyesight, Airband Radio, and Mode C XPDR. The Mode C equipped aircraft can enter the controlled airspace. However, Intruder only has Eyesight and Mode A XPDR. It gives the same risk of 1.1., 1.2., and 1.3. cases.

- 2.2. Intruder with Eyesight, Airband Radio, and Mode C XPDR

  Both Ownship and Intruder aircraft have the same pilots' Eyesight, Airband Radio, and Mode C XPDR. Both Ownship and Intruder aircraft can now operate in controlled airspace. They can communicate with ATC and each aircraft by Airband. ATC and TCAS-enabled aircraft can monitor their Mode C transmitted information, including aircraft altitude (ref. ch.2) or flight level. But both aircraft cannot detect each Intruder. The risk progresses by entering the controlled airspace where there is a higher chance of other aircraft traffic (risk ratio higher than 1.1., 1.2., 1.3., and 2.1. cases)

- 2.3. Intruder with Eyesight, Airband Radio, and Mode S XPDR

  An Intruder aircraft has the pilot's Eyesight, Mode S XPDR. The Mode S XPDR equipped aircraft can enter controlled airspace and transmit information containing 24 bits address (ref. Chapter 2). ATC can receive the Intruder's location, airspeed, altitude, aircraft ID. Also, TCAS equipped aircraft can detect Mode S XPDR equipped Intruder, TCAS I gives TA, and TCAS II provides TA and vertical RA. In this case, the Ownship does not have any TCAS system, and hence no ability to detect Mode S XPDR equipped aircraft. The potential risk would be the same as 2.2. case.

3. Ownship with Eyesight, Airband Radio, and Mode S XPDR

- 3.1. Intruder with Eyesight, Airband Radio, and Mode A XPDR

  Even though the Ownship aircraft can enter the controlled airspace, an Intruder may only fly outside of controlled airspace. The situation is the same with the 1.3. case and the risk is the same as 1.1., 1.2., 1.3., and 2.1. cases.

- 3.2. Intruder with Eyesight, Airband Radio, and Mode C XPDR

  This case is the opposite way of 2.3. case, and the potential risk would be the same as 2.2. and 2.3. cases.

- 3.3. Intruder with Eyesight, Airband Radio, and Mode S XPDR

  Both Ownship and Intruder aircraft have the Mode S XPDR system, and they can enter controlled airspace. ATC can monitor their activity and track their flight. Neither aircraft is detected the other directly, although Airband communications should alert each other to their presence. ATC would manage the separation, and this gives a layer of protection within controlled airspace.

These combination of options breaks down to different circumstances whether the aircraft are operating in a controlled zone or outside in uncontrolled airspace. A controlled zone is under the ATC supervision and is covered by SSR and PSR. This area is affected by selected surveillance system such as Mode C and Mode S XPDRs. The uncontrolled airspace outside any CZs is generally outside ATC coverage in general.

The weather conditions (i.e. whether VMC or IMC weather) must also be considered when assessing the NMAC/MAC risk in the modular flight simulation. The weather conditions determine the aircraft flight rules, whether VFRs or IFRs, plus the surveillance type of aircraft on board. It allows XPDR equipped aircraft to enter the controlled area, Class A, and Class E, the specific near airport area, Class B, and Class C airspace. Another current major limitation of the current aviation surveillance system is the SSR coverage by Line of Sight, as described in Radar limitation Equation 2.1. SSR range is limited to its Radar Horizon Equation 2.1, and is primarilly affected by its installation height as shown in Figure 3.8.

The problem is that the SSR signal only travels straight, and the earth is curved as shown in Figure 2.6. SSR only covers so much of the line of sight region, even though the SSR signal might travel much farther. In the shadow area of SSR, ATC cannot tell how many aircraft fly and which aircraft fly in that diffraction non-line of

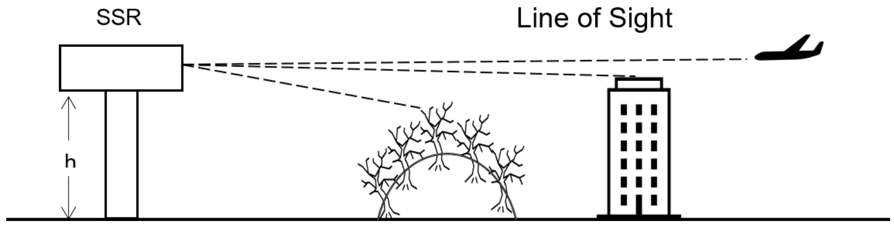

Figure 3.8: SSR's Line of Sight by SSR Height

sight region. In other words, the XPDR area is limited, and ATC therefore can only monitor aircraft within the XPDR area. For this reason, ATC focuses its attention on aircraft in a controlled zone which is typically much smaller than XPDR area, and indeed does not wish to be distracted by the extra workload of adjacent uncontrolled airspace traffic.

In terms of Mid-air collision risk mitigation, the weather could be one of the significant factors to consider whether IFR or VFR will be used when making a flight plan before flying the aircraft by pilots and dispatchers from flight operators with associated ATC direction. The weather forecast can help when planning the flight route and time, but it is often difficult to predict the weather for the whole flight journey, and there are five ways to collect the weather information during En-Route as shown in Table 3.3. The pilot of course can see the real-time weather information in front of their aircraft. However, this has a limited vision angle, and humans can make a mistake in judging conditions, especially at far range. The rest of the weather surveillance options might detect differences among them. There are two significant differences: Active independent reception of the weather information versus passive collection of weather information by pilots.

Airborne Weather radar and the ADSB-In system can automatically get the weather data. This is driven by their independent system and show the current weather information to pilots in real-time. The Airband Radio and SATCOM system can get the weather information too, but pilots must contact this data passively.

	Active Independent Rx	Passive collect WX info by pilots	Remark
Eyesight(1)	-	-	Human vision limitation
Airband Radio (2)	X	X	
WX Radar(3)	X	-	
SATCOM(4)	-	X	
ADSB-In(5)	X	-	

Table 3.3: Weather Surveillance Options On-Board, EnRoute (On Flight)

In general, the pilot makes a pre-flight plan which includes consideration of predicted weather conditions along the route, but gathers the finalized weather information prior to flight from their dispatcher, ATC, or themselves on the ramp. The pilot's visual acquisition in the cockpit includes angle and viewpoints and the pilot needs the right reference of angle. According to Dr. Smith's eye-marker studies [54], the human Eyesight reads and measures the target object by moving the directional Eyesight. Human visual acceptable function needs to have the necessary amount of time to redirect their visual attention [54].

Airband Radio can receive weather information from one of seven VHF frequencies from 162.400 MHz to 162.550 MHz. It gives a warning of local weather advisories by National Oceanic and Atmospheric Administration (NOAA) weather radio in the United States, and the Weatherradio network in Canada by delivering the weather and environmental information service automatically through Airband Radio public service band 24-hours a day, 7 days a week [55][56]. Pilots can also contact local-ATC to collect the area environmental weather information for coordinating their flight path. Aircraft Airborne Weather Radar (WX) offers real-time weather during flight by detecting precipitation and displaying the weather activity on the cockpit display. However, WX has limitations. The airborne weather's reflectivity/detection of precipitation is not accurate depends on the type of particles, as shown in Figure 3.9. The reference gives the example that wet hail, rain and wet snow are much greater reflective signals than dry particles such as dry hail, ice crystals or dry snow. Another major limitation is that airborne weather radar has radar attenuation and create black areas instead of real precipitation conditions. Also, the pilot can control the horizontal sweep and limited vertical angle +/- 15 degrees. Most importantly, the WX radar is directional, and if radar points out to the wrong angle, it cannot display the accurate flight path weather information. Plus, it only covers the range of about 80 miles. Next Generation Radar (NEXRAD)'s range is from 143 and 286 miles depending on the surveillance mode [57].

SATCOM is a communication tool and can switch their Iridium or Inmarsat satellite networks to terrestrial cellular networks on the ground and provide weather information by calculating GPS flight location [59]. The limitation is this is only a passive way to to collect the information, as the pilot must actively contact either ATC or ground service agencies to get this information. The ADSB-In system pro-

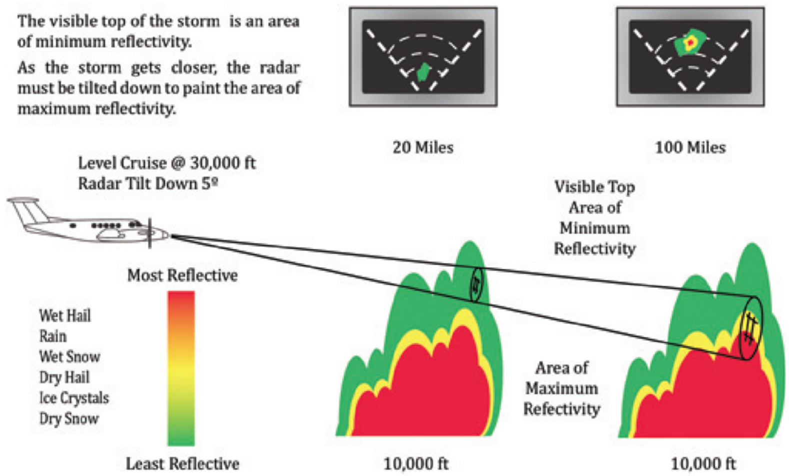

Figure 3.9: Airborne Weather Radar Reflectivity [58]

vides weather, traffic, and other selected data information on a pilot screen or wireless portable tablet using the 978 MHz datalink frequency. The limitation is that the weather data is not instantaneous and it may be delayed [60]. Six types of weather information are provided by FIS-B: 1) Lightning, 2) Turbulence, 3) Icing, 4) Cloud Tops, 5) Graphical AIRman's METeorological Information (AIRMET), and 6) Weather Advisories [33].

Ground weather radar's range: Detection range: 250 km (134.99 NM), Doppler range: 120 km (64.79 NM) [62]. The Canadian Weatheradio coverage is shown in Figure 3.10, and USA weather radio coverage is shown in Figure 3.11.

Another significant factor of Mid-air collision risk mitigation would be the likelihood of detecting other traffic density. A summary of the available traffic surveillance equipment options onboard during flight is shown on Table 3.5. Two main factors are considered in this analysis, 1) Active and 2) Passive ways. Airband Radio and SATCOM are mainly passive ways to collect traffic information by pilots. Mean-

	Eyesight	Airband Radio	Airborne wx radar	SATCOM	ADSB-In
Range(NM)	$0.034 cd/m^2$	32 each weatheradio station [61]	100	anywhere	150 [36]
Comment	Minimum requirement of pilot Eyesight under TC, FAA (20/20 vision) Limited eye ability (Eye movement at a time) Potential human error	The average range, 60 km= 32.387NM The range is varying depends on the terrain 90% of Canada coverage	Narrow band Tilt selection Exist dead zone Directional scanning only only vertical angle +/- 15 degrees	Rely on iridium satellites	Rely on ADS-B satellite and ground station Depends on aircraft's altitude, and line of sight
Coverage	Eyesight	90% Canada	Equipped wx radar range only	Satellite	Iridium Satellite network
Comment	Limited with human Eyesight	24/7 service AM service cover much further	Not 100% accurate wx info by airborne radar, because of directional scanning and radar attenuation	Not 100% entire world, but much further of ground wx radar coverage	Space-based ADS-B with the Iridium Satellite network, LEO satellite network
Accuracy	Human factor	fair accuracy	Trends to be missing overall view	Typically around 0.5 second delay	More accurate than the current available information based on radar systems
Response time	Real time	Real time	12.36 microseconds	0.5 seconds	every second
Comment	Even though human factor, human pilot always there to respond on manned aircraft	Traditional trust communication tool	Two-way process Start of the pulse from antenna to target, and return to antenna	signal sent to satellite and transmits to receiver	real-time information available
GPS ability	-	-	-	X	X
Independent Rx	X	-	X	-	X
Passive Rx	-	X	-	X	-
Installation cost	None	Standard equip, and no extra cost	High	Medium	Low
Operating cost	None	Low	Medium	Medium	Low
Comment	No extra, but only requires to train properly people	Government weather service	Maintenance cost only	Subscription plan	Currently free of charge

Table 3.4: Surveillance Equipment Analysis

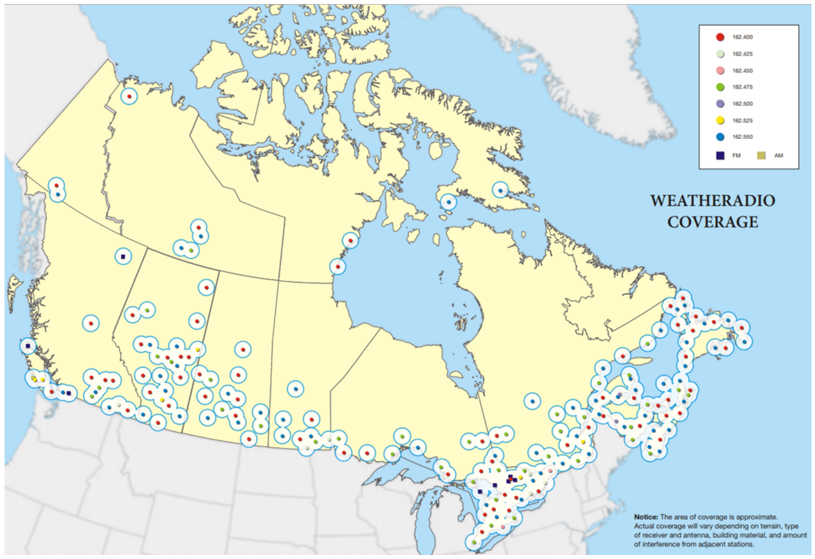

Figure 3.10: Canadian Weatheradio Coverage [62]

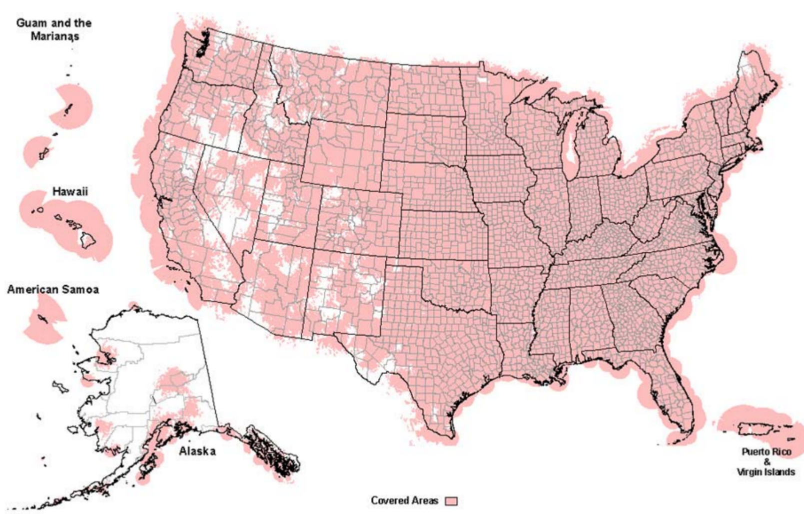

Figure 3.11: USA Weather Radio Coverage [56]

while, TCAS I, TCAS II, and ADSB-In are receive traffic detection information by automatic active independent functions, assuming the cooperative use of XPDRs.

	Active Independent Rx	Passive collect traffic info by pilots	Remark
Eyesight(1)	-	-	Limited human vision and reaction time
Airband Radio (2)	-	X	2-way channel by Ownship and among ATC, Dispatch, other Intruder aircraft
SATCOM(3)	-	X	As long as having a satellite reception
TCAS I(4)	X	-	Only TA
TCAS II(5)	X	-	TA/ RA
ADSB-In(6)	X	-	-
ADSB-Out(7)	-	-	Active Tx

Table 3.5: Traffic Surveillance Equipment Options On Board, EnRoute

Over the course of this research, there are two main factors of avoiding mid-air collision, as mentioned above, weather and traffic density information. Some forms of equipment have common surveillance equipment for collecting both sets of data (weather and traffic). The overlapping equipment list is shown in Figure 3.12.

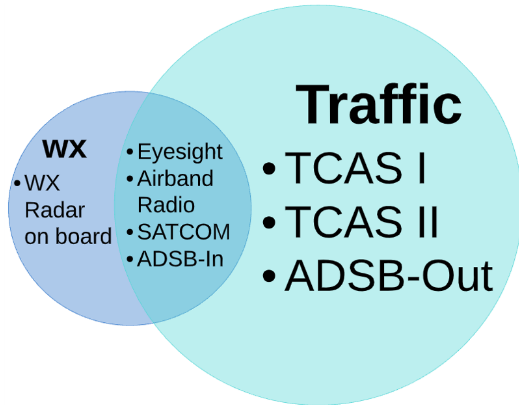

Figure 3.12: Weather and Traffic Surveillance Equipment Onboard Comparison, Enroute

3.4 Statistical Risk Assessment

In this current era, with the popularity of surveillance on-board systems as discussed in Section 3.3, the mid-air collision risk assessment of (model flight) can have six main surveillance variable items: Eyesight (A), Airband Radio (B), XPDR (C), TCAS (D), SATCOM (E), and ADS-B (F) independently. These main variable items might have sub-variable 2, 4, or 3 different surveillance options under them depending on each main surveillance variable item. Model flight only selects one sub-variable item at a time. These concepts apply to both Ownship and Intruder aircraft. The Ownship aircraft hereafter is designated by subscript 'O' and the Intruder aircraft by subscript 'I', and the sub-surveillance variable items are designated as $A_0, A_A, B_0, B_A, C_0, C_A, C_C, C_S, D_0, D_I, D_{II}, E_0, E_S, F_0, F_{IN}, F_{OUT}, and\ F_{IO}$, as shown in Table 3.6 and 3.7.

Each Ownship and Intruder has 384 combination cases, assuming that the probabilities being multiplied with each surveillance variable item are statistically inde-

Model flight AC	Main No.	Main Surveillance variable items	Sub No.	Sub-Surveillance variable items
Ownship(O)	1	Eyesight(A)	1.1.	No Eyesight (A_0)
			1.2.	Eyesight (A_A)
	2	Airband Radio(B)	2.1.	No Airband Radio (B_0)
			2.2.	Airband Radio (B_A)
	3	XPDR(C)	3.1.	None (C_0)
			3.2.	Mode A (C_A)
			3.3.	Mode C (C_C)
			3.4.	Mode S (C_S)
	4	TCAS(D)	4.1.	None (D_0)
			4.2.	TCAS I (D_I)
			4.3.	TCAS II (D_{II})
	5	SATCOM(E)	5.1.	No SATCOM (E_0)
			5.2.	SATCOM (E_S)
	6	ADSB(F)	6.1.	None (F_0)
			6.2.	ADSB-In (F_{IN})
			6.3.	ADSB-Out (F_{OUT})
			6.4.	ADSB-In/Out (F_{IO})

Table 3.6: Surveillance Variable Items for Ownship (O)

Model flight AC	Main No.	Main Surveillance variable items	Sub No.	Sub-Surveillance variable items
Intruder(I)	1	Eyesight(A)	1.1.	No Eyesight (A_0)
			1.2.	Eyesight (A_A)
	2	Airband Radio(B)	2.1.	No Airband Radio (B_0)
			2.2.	Airband Radio (B_A)
	3	XPDR(C)	3.1.	None (C_0)
			3.2.	Mode A (C_A)
			3.3.	Mode C (C_C)
			3.4.	Mode S (C_S)
	4	TCAS(D)	4.1.	None (D_0)
			4.2.	TCAS I (D_I)
			4.3.	TCAS II (D_{II})
	5	SATCOM(E)	5.1.	No SATCOM (E_0)
			5.2.	SATCOM (E_S)
	6	ADSB(F)	6.1.	None (F_0)
			6.2.	ADSB-In (F_{IN})
			6.3.	ADSB-Out (F_{OUT})
			6.4.	ADSB-In/Out (F_{IO})

Table 3.7: Surveillance Variable Items for Intruder (I)

pendent of each other. The combination calculation is presented below:

$A =_2 C_1 = 2, B =_2 C_1 = 2, C =_4 C_1 = 4, D =_3 C_1 = 3, E =_2 C_1 = 2, F =_4 C_1 = 4$

Total combination cases $= A * B * C * D * E * F = 2 * 2 * 4 * 3 * 2 * 4 = 384\ cases$

3.4.1 Probability of Encountering an Intruder Aircraft with DAA Surveillance Equipment

The probability that the Ownship aircraft encounters an Intruder aircraft which is equipped with a specific type of surveillance DAA/Surveillance Equipment can be found using Equation 3.12.

$$P_{ENCTR\ type} = A_{equip} * B_{equip} * C_{equip} * D_{equip} * E_{equip} * F_{equip} \tag{3.12}$$

where:

$P_{ENCTR\ type}$ is the probability of encountering an Intruder aircraft with surveillance equipment on board, A_{equip} – Eyesight, B_{equip} – Airband Radio, C_{equip} – XPDR, D_{equip} – TCAS, E_{equip} – SATCOM, F_{equip} – ADS-B.

The assumption for Equation 3.12 is that every manned aircraft flying in Canada should include a pilot (with good Eyesight) and Airband Radio and these equipment are expressed as A_{equip}=1 (100%) and B_{equip}=1 (100%). If human error is considered as part of the human factors on manned aircraft, human error will be 1% and the probability that Intruder aircraft has A_{equip} will be 99%.

$$A_{equip} = 1\ (100\%) - 0.01\ (1\%; human\ error) = 0.99\ (99\%) \tag{3.13}$$

If 2% of aircraft have no Airband Radio, B_{equip} will be 98% which described in following Equation 3.14.

$$B_{equip} = 1\ (100\%) - 0.02\ (2\%; not\ equipped\ with\ airband\ radio) = 0.98\ (98\%) \quad (3.14)$$

These cases' notation are,

A_{none} – No Eyesight (Human factor), A_{equip} – Eyesight on board, B_{none} – No Airband Radio, B_{equip} – Airband Radio on board.

Type C (XPDR) has four sub-cases: No XPDR, Mode A, C, and S XPDR. This study assumes each aircraft has only one XPDR of 4 sub-cases.

So,

$$C_{equip} = C_{none} + C_{equip\ A} + C_{equip\ C} + C_{equip\ S} = 1\ (or\ 100\%)$$

where:

C_{equip} is XPDR category, C_{none} – No XPDR on board, C_{equipA} – Mode A, C_{equipC} – Mode C, C_{equipS} – Mode S.

Type D_{equip} (TCAS) has three sub-cases: No TCAS, TCAS I, and TCAS II.

So,

$$D_{equip} = D_{none} + D_{equip\ I} + D_{equip\ II} = 1 (or\ 100\%)$$

where:

D_{equip} is TCAS system category, D_{none} – No TCAS system on board, $D_{equip\ I}$ – TCAS I, $D_{equip\ II}$ – TCAS II.

Type E_{equip} (SATCOM) has two sub-cases: SATCOM Off and SATCOM On.

So,

$$E_{equip} = E_{none} + E_{equip\ S} = 1 (or\ 100\%)$$

where:

E_{equip} is SATCOM category, E_{none} – SATCOM Off, $E_{equip\ S}$ – SATCOM On and SATCOM system on board.

Type F_{equip} (ADS-B) had four sub-cases: No ADS-B, ADSB-Out, ADSB-In, and ADSB-In/Out.

So,

$$F_{equip} = F_{none} + F_{equip\ OUT} + F_{equip\ IN} + F_{equip\ IO} = 1(or\ 100\%)$$

where:

F_{equip} is ADS-B category, F_{none} – No ADS-B system, $F_{equip\ OUT}$ – ADSB-Out, $F_{equip\ IN}$ – ADSB-In, $F_{equip\ IO}$ – ADSB-In/Out.

3.4.1.1 DAA-Equipment Probability Calculation Model

In this subsection adapted the model of probability of encountering aircraft with variable type of onboard DAA/Surveillance Equipment ($P_{ENCTR\ type}$) in Subsection 3.4.1.

The $P_{ENCTR\ type}$ model calculates the probability of encountering Intruder aircraft with different combinations of DAA system onboard each aircraft versus the Ownship aircraft. Figure 3.13 shows an example of the calculator output for a given set of DAA/Surveillance Equipment on the Intruder aircraft.

This calculation model is associated with the probability of DAA/Surveillance Equipment on board an Intruder aircraft in the Table 3.8. The response to each question gives a probability of equipment ability based on statistical results of current aviation operations. However, this study did not collect the real data at this point

DAA/Surveillance Equipment		Probability (%)	
A_{equip}	A_{none}	The probability that aircraft have no Eyesight?	1.00%
	$A_{equip\ A}$	The probability that aircraft have Eyesight	99.00%
B_{equip}	B_{none}	The probability that aircraft have no Airband Radio	5.00%
	$B_{equip\ A}$	The probability that aircraft have Airband Radio	95.00%
C_{equip}	C_{none}	The probability that aircraft have no XPDR	20.00%
	$C_{equip\ A}$	The probability that aircraft have Mode A XPDR	10.00%
	$C_{equip\ C}$	The probability that aircraft have Mode C XPDR	30.00%
	$C_{equip\ S}$	The probability that aircraft have Mode S XPDR	40.00%
D_{equip}	D_{none}	The probability that aircraft have no TCAS	20.00%
	$D_{equip\ I}$	The probability that aircraft have TCAS I	50.00%
	$D_{equip\ II}$	The probability that aircraft have TCAS II	30.00%
E_{equip}	E_{none}	The probability that aircraft have no SATCOM	40.00%
	$E_{equip\ S}$	The probability that aircraft have SATCOM	60.00%
F_{equip}	F_{none}	The probability that aircraft have no ADSB	30.00%
	$F_{equip\ IN}$	The probability that aircraft have ADSB In	20.00%
	$F_{equip\ OUT}$	The probability that aircraft have ADSB Out	35.00%
	$F_{equip\ IO}$	The probability that aircraft have ADSB In/Out	15.00%

Table 3.8: Probability of Onboard DAA/Surveillance Equipment in Intruder Aircraft

Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
Transponder (C)	Mode S
TCAS (D)	TCAS I
SATCOM (E)	No
ADSB (F)	None
$P_{ENCTR\ type}$ =	2.26E-02

Figure 3.13: $P_{ENCTR\ type}$ Calculator Model

as mentioned in Section 1.4. Consideration of each element of surveillance equipment generates relevant questions to determine what percentage of aircraft is equipped with specific types of onboard surveillance equipment. Due to the unavailable real data, the probability of each case of onboard DAA/Surveillance Equipment in Table 4.1 is currently a nominal number. The probability gives an idea of how to demonstrate and determine the acceptable level of detection with currently available surveillance equipment.

The Encounter DAA Type Calculator, Figure 3.13, is based on the assumption in Subsection 3.4.1 and Table 3.8; Figure 3.14 shows how to select types of DAA/Surveillance Equipment. For example, an aircraft with a human pilot, Airband Radio, Mode S XPDR, TCAS I, no SATCOM, and no ADS-B system on board can be selected to find the probability of encounter an Intruder aircraft with this set of DAA/Surveillance Equipment. This calculator model also can be expressed with Equation 3.15.

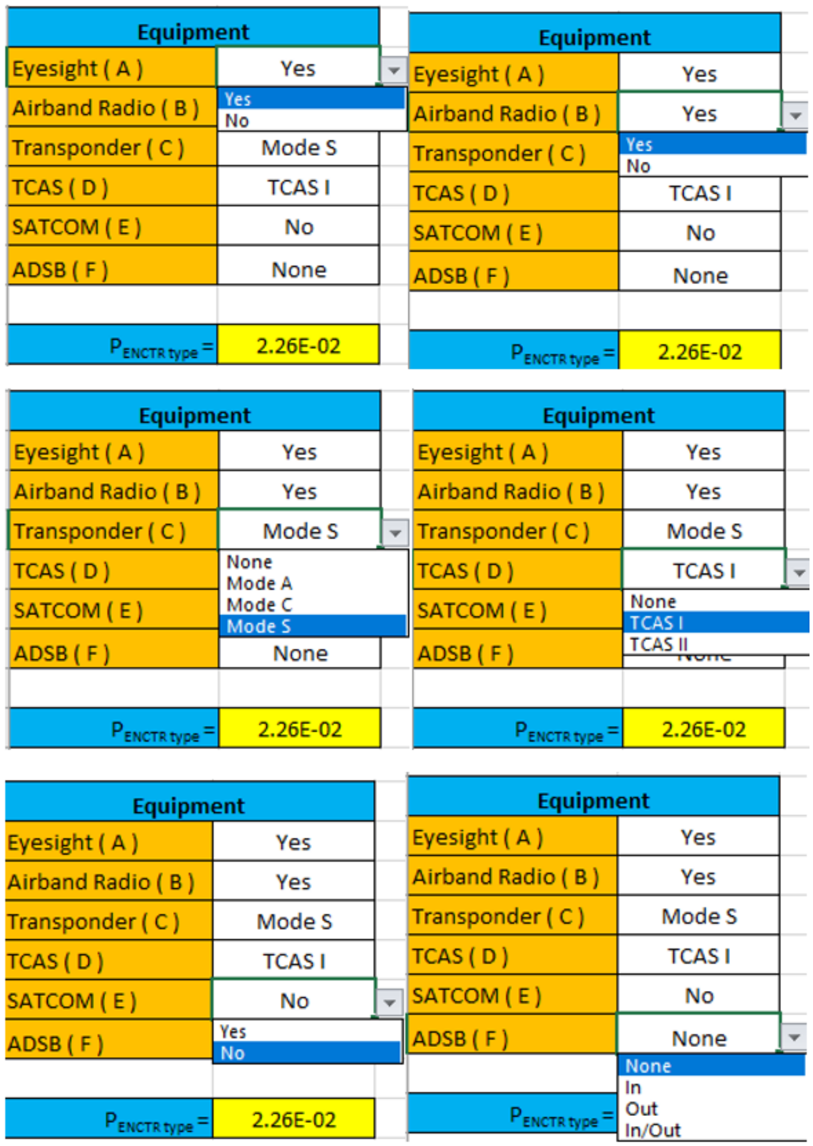

Figure 3.14: Probability of Encounter DAA Type Calculator with Drop-down Menu

$$P_{ENCTR\ type} = A_{equip\ A} * B_{equip\ A} * C_{equip\ S} * D_{equip\ I} * E_{none} * F_{none} \tag{3.15}$$

The probability of an encounter with an Intruder aircraft with 99% of pilot without human error, 95% of Airband Radio, 40% of Mode S XPDR, 50% of TCAS I, 40% of no SATCOM, and 30% of no ADSB system on board from Table 3.8 when each probability is applied to Equation 3.15, may be estimated as:

$$\begin{aligned} P_{ENCTR\ type} &= 0.99 * 0.95 * 0.4 * 0.5 * 0.4 * 0.3 \\ &= 2.26E - 02 \end{aligned} \tag{3.16}$$

We have therefore estimated that the Ownship aircraft has 2.3% chance of encountering an Intruder aircraft that is equipped with a pilot with 99% effective vision, Airband Radio, Mode S XPDR, TCAS I, no SATCOM, and no ADS-B system.

3.4.2 Mid-Air Collision Risk Determination

The following probabilistic process is used to determine the mid-air collision risk. The results from three steps are combined to determine the collision risk ratio by using each variable DAA surveillance item. The first step determines the risk ratio of variable DAA/Surveillance Equipment between Ownship and Intruder aircraft cases. The second step calculates the probability of unmitigated NMAC rate. The third step moves onto using the first and second steps' results to determine the probability of mitigated NMAC rate for the mid-air collision risk determination.

3.4.2.1 Risk Ratio of Variable DAA/Surveillance Equipment (RR$_{DAA}$) Calculator Model

The RR$_{DAA}$ calculator model determines the probability of risk ratio when an Ownship aircraft equipped with known DAA/Surveillance Equipment and encounters an Intruder aircraft equipped with variable types of DAA/Surveillance Equipment. The effectiveness of each type of DAA/surveillance equipment is expressed between 0 and 1 (0 to 100%) as the inverse likelihood to prevent an NMAC; a probability of 0 indicates the equipment will achieve well-clear (WC) 100% of the time and 1 represents it will not prevent a NMAC. In Equation 3.17, acronym letters are used to represented each variable DAA/Surveillance Equipment on board for both Ownship and Intruder aircraft as shown in Table 3.6 and 3.7.

$$\begin{aligned} RR_{DAA} &= Ownship\ Equipment\ *\ Intruder\ Equipment \\ &= (A * B * C * D * E * F) * (A * B * C * D * E * F) \end{aligned} \tag{3.17}$$

The probability of NMAC scenarios is affected by each piece of onboard DAA/Surveillance Equipment and the probability represents 0 to well-clear as safe and 1 to NMAC. Each probability in Table 3.9 shows the nominal numbers that have been used in the RR$_{DAA}$ calculator model sample (Figure 3.15).

The assumption of probability in this study is that all manned-aircraft have a pilot with good Eyesight. Risk ratio of NMAC while relying solely on the pilot's vision (A$_A$) is estimated to be 0.45 (45%) as shown in Equation 3.20 because the pilot's front visibility is 220 degrees and obscured view is 140 degrees (Equation 3.18). Obscured view rate is 0.39 (39%) as described in Equation 3.19. The human Eyesight risk ratio is also affected by human factors such as pilot error and distraction and the

DAA Type		Probability (%)	
A	A_0	The probability that no Eyesight occurs NMAC	100.00%
	A_A	The probability that Eyesight occurs NMAC	45.00%
B	B_0	The probability that no Airband Radio occurs NMAC	100.00%
	B_A	The probability that Airband Radio occurs NMAC	50.00%
C	C_0	The probability that no XPDR occurs NMAC	100.00%
	C_A	The probability that mode A XPDR occurs NMAC	80.00%
	C_C	The probability that mode C XPDR occurs NMAC	60.00%
	C_S	The probability that mode S XPDR occurs NMAC	40.00%
D	D_0	The probability that No TCAS occurs NMAC	100.00%
	D_I	The probability that TCAS I occurs NMAC	30.00%
	D_{II}	The probability that TCAS II occurs NMAC	20.00%
E	E_0	The probability that no SATCOM occurs NMAC	100.00%
	E_S	The probability that SATCOM occurs NMAC	50.00%
F	F_0	The probability that no ADSB occurs NMAC	100.00%
	F_{IN}	The probability that ADSB In occurs NMAC	50.00%
	F_{OUT}	The probability that ADSB Out occurs NMAC	35.00%
	F_{IO}	The probability that ADSB In/Out occurs NMAC	5.00%

Table 3.9: Probability of NMAC with DAA/Surveillance Equipment

probability of these factors is 0.06 (6%). Another perspective view of A_A is what Eyesight remains WC (Equation 3.21). The remaining WC Eyesight rate is 0.55 (55%) and pilot has 55% of front visibility (Equation 3.22), which means Eyesight cannot detect 45% of other Intruder aircraft.

Field of View (FOV) = 220 degree:

$$Obscured\ view = 360^\circ - 220^\circ = 140^\circ \tag{3.18}$$

140 degree of 360 degree:

$$Obscured\ view\ rate = \frac{140^\circ}{360^\circ} = \frac{14}{36} = 0.39 = 39\% \tag{3.19}$$

The probability that Eyesight occurs NMAC:

$$\begin{aligned} A_A\ (Eyesight\ Risk\ Rate) &= Equation\ 3.19 + human\ factor \\ &= 0.39 + 0.06 = 0.45 = 45\% \end{aligned} \tag{3.20}$$

What does Eyesight do to remaining WC?:

$$Remain\ WC\ Eyesight\ rate = 1 - A_A\ (Eyesight\ Risk\ Rate\ of\ NMAC) \tag{3.21}$$

$$Remain\ WC\ Eyesight\ rate = 1 - 0.45 = 0.55 = 55\% \tag{3.22}$$

The same method applies to other surveillance equipment items as shown in Table 3.9. The limitation of this study, wherein the collection of real data did not take place, means much of the estimates presented here are based on experience. It is strongly recommended that real data be used, both for the effects of current equipped DAA surveillance items on board real aircraft, and for calculating real-world traffic densities using regional air traffic data similar to the methods used at Lincoln Labs/MIT [38].

The finalized probability of NMAC risk ratio calculator model considers both Ownship and Intruder aircraft's equipment availability to show the RR_{DAA} as describe the concept of calculation in Chapter 3. This study generates the simple calculation method model shown in Figure 3.15.

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	Out		ADSB (F)	In/Out
$\mathrm{RR}_{\mathrm{DAA}}$ =	8.8594E-04			
	0.0008859375			
Eyesight (A)	0.45		Eyesight (A)	0.45
Airband Radio (B)	0.5		Airband Radio (B)	0.5
ADSB (F)	0.35		ADSB (F)	0.05

Figure 3.15: Probability of RR_{DAA} Calculator Model

One of scenarios applies to Equation 3.17 with an Ownship aircraft equipped with $A_A B_A F_{OUT}$ and an Intruder aircraft with $A_A B_A F_0$. Based on Table 3.9, the probability assumption made to both Ownship and Intruder aircraft is as follows. The probability of human vision being on both aircraft (A_A), its probability is 0.45 (45%). Both aircraft have Airband Radio (B_A) and the probability of B_A is 50%. Ownship aircraft has ADSB-Out, F_{OUT} and Intruder aircraft have ADSB-In/Out system on board, F_{IO}. F_{OUT} is 0.35 (35%), and F_{IO} is 0.05 (5%).

So,

$$\begin{aligned} RR_{DAA} &= (A_A * B_A * F_{OUT}) * (A_A * B_A * F_{IO}) \\ &= (0.45 * 0.5 * 0.35) * (0.45 * 0.5 * 0.05) \\ &= 8.86E - 04 \end{aligned} \tag{3.23}$$

Equation 3.23 means that the given DAA/Surveillance Equipment between an Ownship aircraft case ($A_A B_A F_{OUT}$) and an Intruder aircraft case ($A_A B_A F_{IO}$) has 0.089% probability of NMAC risk ratio (RR$_{DAA}$).

3.4.2.2 Determine the Probability of Mitigated NMAC Rate

This determining process adapts a statistical approach to calculate mitigated NMAC rates from Stevenson's research [63]. The statistical approach is applied to Equation 3.6 as shown in below Equation 3.24.

$$\begin{aligned} NMAC_{mit}\ rate\ per\ flight\ hours &= \frac{x}{y} \\ &= \frac{Number\ of\ reported\ NMAC_{mit}\ events}{Total\ Canadian\ registered\ aircraft\ flight\ hours} \end{aligned} \tag{3.24}$$

This study defines risk collision/loss separation events as mitigated NMAC events and collision events as MAC events; TSB statistical information does not specify the rate of NMAC or MAC event only the situation. As mentioned in Subsection 3.4.2.2, mitigated NMAC rate calculation adapted from Dr. Jonathan Stevenson's research which was based on statistical approach method [63]. Table 3.10 includes the calculations of the mitigated NMAC and mitigated MAC rates per flight hours in Canada based on the reported-incidents information from Transportation Safety Board (TSB) of Canada[42].

Year	Total Incidents	Risk Collision/Loss Sep	Collision	NMAC%	MAC%	Flight HRS (thousands)	NMAC rate per Flight HRS	MAC rate per Flight HRS	MAC/NMAC ratio
2005	796	174	12	22%	2%	3755	4.63E-05	3.20E-06	0.069
2006	807	168	21	21%	3%	3919	4.29E-05	5.36E-06	0.125
2007	874	168	13	19%	1%	4201	4.00E-05	3.09-06	0.077
2008	898	176	8	20%	1%	4243	4.15E-05	1.89E-06	0.045
2009	789	153	10	19%	1%	3871	3.95E-05	2.58E-06	0.065
2010	814	206	5	25%	1%	3992	5.16E-05	1.25E-06	0.024
2011	673	120	7	18%	1%	4284	2.80E-05	1.63E-06	0.058
2012	645	102	5	16%	1%	4393	2.32E-05	1.14E-06	0.049
2013	689	115	15	17%	2%	4294	2.68E-05	3.49E-06	0.130
2014	741	94	16	13%	2%	4271	2.20E-05	3.75E-06	0.170
2015	789	111	8	14%	1%	4334	2.56E-05	1.85E-06	0.072
2016	833	139	18	17%	2%	4473	3.11E-05	4.02E-06	0.129
2017	939	172	24	18%	3%	4721	3.64E-05	5.08E-06	0.140
2018	860	141	26	16%	3%	5050	2.79E-05	5.15E-06	0.184
2019	911	135	31	15%	3%	5201	2.60E-05	5.96E-06	0.230

Table 3.10: $NMAC_{mit}$ and MAC_{mit} Rates Statistics (2005-2019) [42]

Table 3.10 indicates 911 events of total incidents and 135 events of the risk of collision/loss separation reported in 2019. Also, the portion of mitigated NMAC rate in total number of reported incident events is 15%; this can be used to calculate the number of reported NMAC events and the total number of reported incidents events. That is,

$$\begin{aligned} NMAC_{mit}\% &= \frac{Number\ of\ reported\ NMAC_{mit}\ events}{Total\ number\ of\ reported\ incidents\ events} \\ &= \frac{135\ events}{911\ events} = 0.148 = 15\% \end{aligned} \tag{3.25}$$

The mitigated NMAC rate per flight hours calculates by Equation 3.6 and Equation 3.24.

$$NMAC_{mit}\ rate\ per\ flight\ hours = \frac{Number\ of\ reported\ NMAC_{mit}\ events}{Total\ Canadian\ registered\ aircraft\ flight\ hours}$$
$$= \frac{135\ events}{5,201,000\ flighthours} = 2.60E - 05 \tag{3.26}$$

Figure 3.16 shows the last fifteen years of mitigated NMAC rates per flight hours in Canada.

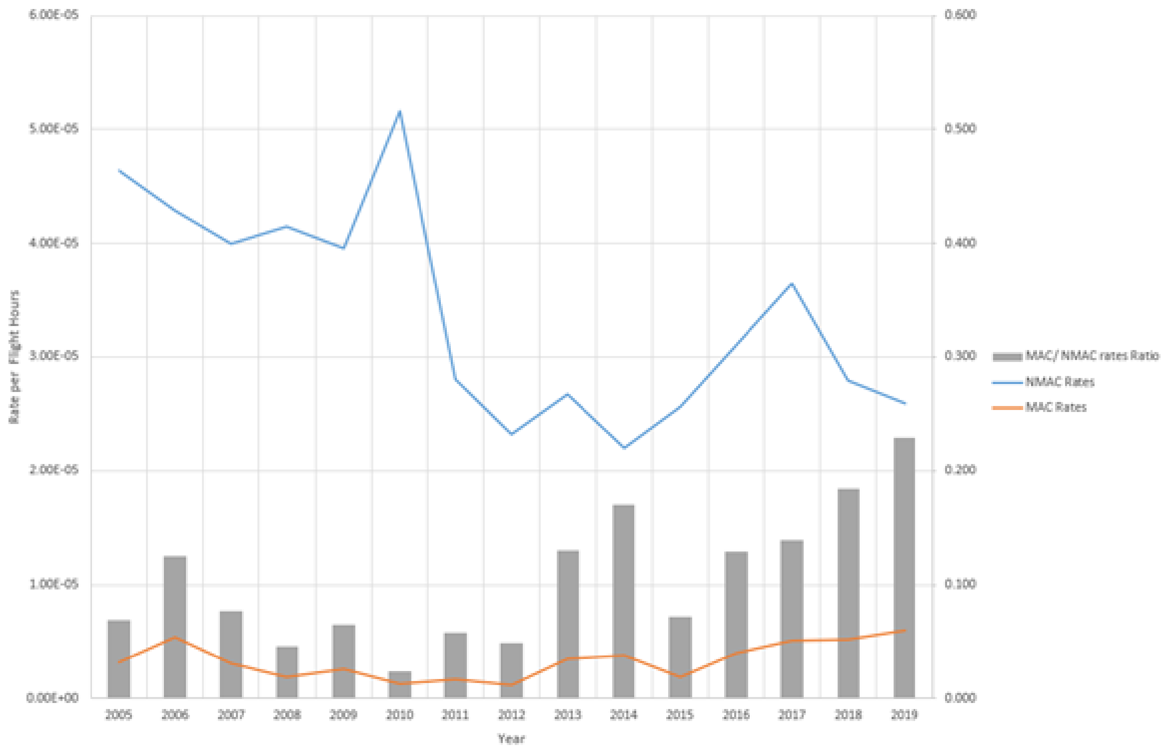

Figure 3.16: NMAC and MAC Rates per Flight Hours (2005-2019)

3.4.2.3 Determine the Probability of Mitigated NMAC Rate

The probability of mitigated NMAC rate determines when encountering an Intruder from Ownship aircraft. Mitigated NMAC rate depends on risk ratio of DAA/Surveillance Equipment onboard as shown in 3.27

$$NMAC_{mit} = NMAC_{unmit} * RR_{DAA} \tag{3.27}$$

where:

$NMAC_{mit}$ is mitigated NMAC rate per flight hours.

$NMAC_{unmit}$ is unmitigated NMAC rate per flight hours; Section 3.4.2.2.

RR_{DAA} is risk ratio of variable DAA/Surveillance Equipment; Equation 3.17.

This research simulates the relationship with variable DAA/Surveillance Equipment risk ratio (RR$_{DAA}$) to calculate the mitigated NMAC rate per flight hours. The calculation of NMAC$_{mit}$ rate per flight hours is accomplished by multiplying RR$_{DAA}$ (Subsection 3.4.2.1) by the NMAC$_{unmit}$ per flight hours (Subsection 3.4.2.2).

Chapter 4

Risk Probability Calculation Model Results

This chapter discusses the mid-air collision risk assessment for the Ownship, for the case of both manned aircraft and unmanned aircraft, utilizing the risk probability calculation model tool as presented in Section 3.4. The calculator model may be used to calculate the NMAC risk ratio (RR) and assess the NMAC risk before a planned flight operation. The collision risk calculator is based on Equation 3.5. At this point, the risk ratios are based on assumed values, due to the difficulty of assessing the effect of DAA/surveillance equipment on LOS/NMAC/MAC at this point in the research. More details on these limitations are in Section 1.4. The risk probability calculation model has options to choose different combinations of DAA/Surveillance Equipment on board each aircraft to estimate the NMAC risk. The Calculation Model was built in the Microsoft excel system. It can easily be transferred to other platforms if required. The critical measure of risk is the risk ratio value which varies from 0 to

1. A risk ratio 0 would mean that the DAA surveillance methods are 100% effective in avoiding NMAC incidents. A risk ratio of 1 means that the risk is high, and the onboard technology is not implemented to prevent any Intruders from initiating the NMAC. The calculations use 2019 data from the Transportation Safety Board of Canada [42].

4.1 Manned Aircraft Application

The discussion of idealized traffic population with onboard DAA/Surveillance Equipment types was first described in Section 4.1.1. From the available 2019 accident/ incident statistics, the average Canadian aircraft NMAC rate may be estimated. This may be used as the baseline NMAC used in the following NMAC risk assessments. The chance of encountering an aircraft with a particular combination of DAA/Surveillance Equipment may then be calculated using the methods outline in Section 4.1.3. Section 4.1.4 calculates Mid-Air collision risk by considering three factors: the variable DAA onboard equipment NMAC risk ratio (RR_{DAA}), unmitigated NMAC rate per flight hours, and mitigated NMAC rate per flight hours. The loss of Eyesight or sensor failure example also explores the case for both Ownship and Intruder aircraft suffering equipment failures in Section 4.1.5. These calculations will now be detailed.

4.1.1 Assumptions of Traffic Population

Total idealized traffic population assumes that all aircraft are equipped with or without ADSB-Out systems (20% with ADSB-Out and 10% within the 20% of ADSB-Out have also ADSB-In) as shown in Figure 4.1 and Table 4.1. We also assume that all aircraft already have Pilots' Eyesight and Airband Radio.

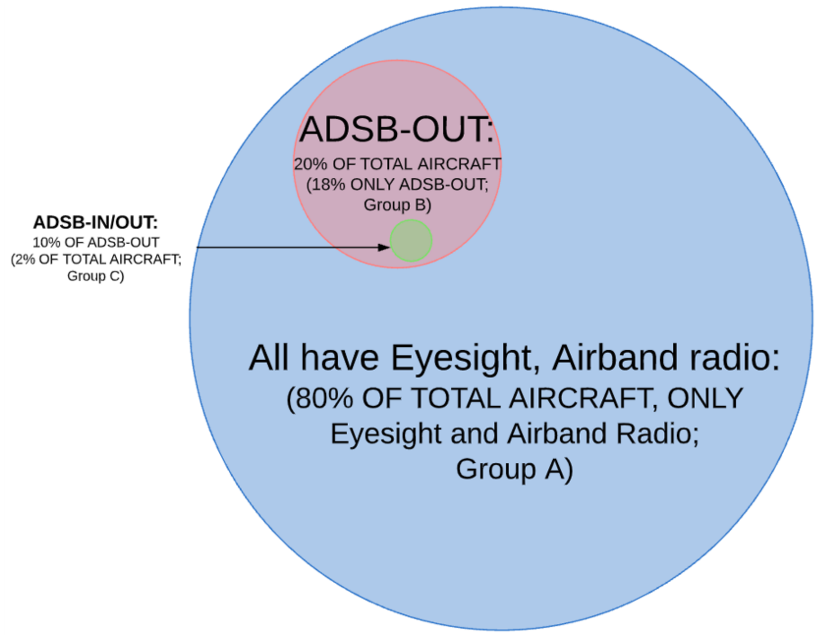

Figure 4.1: Traffic Population Assumptions

No.	Group	DAA/Surveillance Equipment on board	Traffic Population	Remark
1	Group A	Only Eyesight and Airband Radio	80%	
2	Group B	Only ADSB-Out	18%	
3	Group C	Only ADSB-In/Out	2%	
Total:			100%	

Table 4.1: Assumption Traffic Table

4.1.2 NMAC Rate Baseline

Total 2019 Canadian aircraft NMAC rate considers total reported events over the total aircraft flight hours [42]. This result is the reference point for the mitigated risk estimates.

$$\begin{aligned} &\text{All registered Canadian aircraft's NMAC}_{mit}\text{ rate per flight hours} \\ &= \frac{\text{Number of reported NMAC}_{mit}\text{ events in 2019}}{\text{Total Canadian registered aircraft flight hours in 2019}} \\ &= \frac{135\text{ events}}{5,201,000\text{ flight hours}} \\ &= 2.60E-05\text{per flight hours} \end{aligned} \tag{4.1}$$

4.1.3 Determine the P$_{ENCTR\ type}$; Probability of Encountering Aircraft with a certain DAA/Surveillance Equipment Configuration

The assumption-based traffic populations are made in the table below. Using the P$_{ENCTR\ type}$ calculator, the DAA/Surveillance Equipment configuration is selected, and the probability of encountering this type of aircraft may be calculated, as shown below.

Group A (Figure 4.3),

$$P_{ENCTR\ tpe} = A_{equip\ A} * B_{equip\ A} * F_{none} = 1 * 1 * 0.8 = 8E-01$$

Group B (Figure 4.4),

$$P_{ENCTR\ tpe} = A_{equip\ A} * B_{equip\ A} * F_{equip\ OUT} = 1 * 1 * 0.18 = 1.8E-01$$

Group C (Figure 4.5),

$$P_{ENCTR\ tpe} = A_{equip\ A} * B_{equip\ A} * F_{equip\ IO} = 1 * 1 * 0.02 = 2E-02$$

		Percentages	
A_{equip}	A_{none}	What percentage of aircraft have no eyesight?	0%
	$A_{equip\ A}$	What percentage of aircraft have eyesight?	100.00%
B_{equip}	B_{none}	What percentage of aircraft have no Airband Radio?	0.00%
	$B_{equip\ A}$	What percentage of aircraft have Airband Radio?	100.00%
F_{equip}	F_{none}	What percentage of aircraft have no ADSB?	80.00%
	$F_{equip\ IN}$	What percentage of aircraft have ADSB In?	0.00%
	$F_{equip\ OUT}$	What percentage of aircraft have ADSB Out?	18.00%
	$F_{equip\ IO}$	What percentage of aircraft have ADSB In/Out?	2.00%

Figure 4.2: P$_{ENCTR\ type}$ Table Based-on Assumption

Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	None
$P_{ENCTR\ type}$ =	8.00E-01

Figure 4.3: Group A's P$_{ENCTR\ type}$

Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	Out
$P_{ENCTR\ type}$ =	1.80E-01

Figure 4.4: Group B's $P_{ENCTR\ type}$

Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out
$P_{ENCTR\ type}$ =	2.00E-02

Figure 4.5: Group C's $P_{ENCTR\ type}$

4.1.3.1 Determine $P_{ENCTR\ type}$ of Combinations Cases

There are 9 possible combinations of group A, B, and C types under the current assumptions (Section 4.1.1). The encountering aircraft's $P_{ENCTR\ type}$ multiplies each Ownship and Intruder aircraft $P_{ENCTR\ type}$, as shown in Table 4.2. The total Ownship and Intruder aircraft $P_{ENCTR\ type}$ should be 1 (100%).

No.	Ownship	Ownship $P_{ENCTR\ type}$	Intruder	Intruder $P_{ENCTR\ type}$	Ownship/Intruder $P_{ENCTR\ type}$	Remark
1	Type Group A	8E-01	Type Group A	8E-01	6.4E-01	
2	Type Group A	8E-01	Type Group B	1.8E-01	1.44E-01	
3	Type Group A	8E-01	Type Group C	2E-02	1.6E-02	
4	Type Group B	1.8E-01	Type Group A	8E-01	1.44E-01	
5	Type Group B	1.8E-01	Type Group B	1.8E-01	3.24E-02	
6	Type Group B	1.8E-01	Type Group C	2E-02	3.6E-03	
7	Type Group C	2E-02	Type Group A	8E-01	1.6E-02	
8	Type Group C	2E-02	Type Group B	1.8E-01	3.6E-03	
9	Type Group C	2E-02	Type Group C	2E-02	4E-04	
Total:					1	100%

Table 4.2: Ownship and Intruder Aircraft's $P_{ENCTR\ type}$ Table

- Ownship Type Group A,

Encounter Intruder aircraft with Type Group A:

$$Type\ Group\ A's\ P_{ENCTR\ type}\ *\ Type\ Group\ A's\ P_{ENCTR\ type}$$

$$= 8E-01\ *\ 8E-01 = 6.4E-01$$

Encounter Intruder aircraft with Type Group B:

$$Type\ Group\ A's\ P_{ENCTR\ type}\ *\ Type\ Group\ B's\ P_{ENCTR\ type}$$

$$= 8E-01\ *\ 1.8E-01 = 1.44E-01$$

Encounter Intruder aircraft with Type Group C:

$$Type\ Group\ A's\ P_{ENCTR\ type}\ *\ Type\ Group\ C's\ P_{ENCTR\ type}$$

$$= 8E-01\ *\ 2E-02 = 1.6E-02$$

- Ownship Type Group B,

Encounter Intruder aircraft with Type Group A:

$$Type\ Group\ B's\ P_{ENCTR\ type}\ *\ Type\ Group\ A's\ P_{ENCTR\ type}$$
$$= 1.8E-01\ *\ 8E-01 = 1.44E-01$$

Encounter Intruder aircraft with Type Group B:

$$Type\ Group\ B's\ P_{ENCTR\ type}\ *\ Type\ Group\ B's\ P_{ENCTR\ type}$$
$$= 1.8E-01\ *\ 1.8E-01 = 3.24E-02$$

Encounter Intruder aircraft with Type Group C:

$$Type\ Group\ B's\ P_{ENCTR\ type}\ *\ Type\ Group\ C's\ P_{ENCTR\ type}$$
$$= 1.8E-01\ *\ 2E-02 = 3.6E-03$$

- Ownship Type Group C,

Encounter Intruder aircraft with Type Group A:

$$Type\ Group\ C's\ P_{ENCTR\ type}\ *\ Type\ Group\ A's\ P_{ENCTR\ type}$$
$$= 2E-02\ *\ 8E-01 = 1.6E-02$$

Encounter Intruder aircraft with Type Group B:

$$Type\ Group\ C's\ P_{ENCTR\ type}\ *\ Type\ Group\ B's\ P_{ENCTR\ type}$$
$$= 2E-02\ *\ 1.8E-01 = 3.6E-03$$

Encounter Intruder aircraft with Type Group C:

$$Type\ Group\ C's\ P_{ENCTR\ type}\ *\ Type\ Group\ C's\ P_{ENCTR\ type}$$
$$= 2E-02\ *\ 2E-02 = 4E-04$$

4.1.3.2 Determine the Mitigated NMAC Events by $P_{ENCTR\ type}$

From Subsection 4.1.3.1, the Ownship and Intruder aircraft $P_{ENCTR\ type}$ applies to the total reported mitigated NMAC events for each combination case's mitigated NMAC events, as shown in Table 4.3.

No.	Case	Ownship/Intruder $P_{ENCTR\ type}$	$NMAC_{mit}$	Remark
1	Type Group A & Type Group A	6.4E-01	86.4	
2	Type Group A & Type Group B	1.44E-01	19.44	
3	Type Group A & Type Group C	1.6E-02	2.16	
4	Type Group B & Type Group A	1.44E-01	19.44	
5	Type Group B & Type Group B	3.24E-02	4.374	
6	Type Group B & Type Group C	3.6E-03	0.486	
7	Type Group C & Type Group A	1.6E-02	2.16	
8	Type Group C & Type Group B	3.6E-03	0.486	
9	Type Group C & Type Group C	4E-04	0.054	
Total $NMAC_{mit}$ events in 2019:			135 events	Same as reported $NMAC_{mit}$ events in 2019

Table 4.3: Mitigated NMAC Events Table by $P_{ENCTR\ type}$

- Ownship Type Group A,

Encounter Intruder aircraft with Type Group A:

$$Type\ Group\ A\ \&Type\ Group\ A\ case's\ NMAC_{mit}\ events$$
$$= Type\,Group\,A\,\&Type\,Group\,A\,case's\,P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\,2019$$
$$= 6.4E - 01 * 135\ events = 86.4\ events$$

Encounter Intruder aircraft with Type Group B:

$$\begin{aligned}&Type\ Group\ A\ \&Type\ Group\ B\ case's\ NMAC_{mit}\ events\\ &= Type\,Group\,A\,\&Type\,Group\,B\,case's\,P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\,2019\\ &= 1.44E-01*135\ events = 19.44\ events\end{aligned}$$

Encounter Intruder aircraft with Type Group C:

$$\begin{aligned}&Type\ Group\ A\ \&Type\ Group\ C\ case's\ NMAC_{mit}\ events\\ &= Type\,Group\,A\,\&Type\,Group\,C\,case's\,P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\,2019\\ &= 1.6E-02*135\ events = 2.16\ events\end{aligned}$$

- Ownship Type Group B,

Encounter Intruder aircraft with Type Group A:

$$\begin{aligned}&Type\ Group\ B\ \&Type\ Group\ A\ case's\ NMAC_{mit}\ events\\ &= Type\,Group\,B\,\&Type\,Group\,A\,case's\,P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\,2019\\ &= 1.44E-01*135\ events = 19.44\ events\end{aligned}$$

Encounter Intruder aircraft with Type Group B:

$$\begin{aligned}&Type\ Group\ B\ \&Type\ Group\ B\ case's\ NMAC_{mit}\ events\\ &= Type\,Group\,B\,\&Type\,Group\,B\,case's\,P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\,2019\\ &= 3.24E-02*135\ events = 4.374\ events\end{aligned}$$

Encounter Intruder aircraft with Type Group C:

$$Type\ Group\ B\ \&Type\ Group\ C\ case's\ NMAC_{mit}\ events$$
$$= Type\,Group\,B\,\&Type\,Group\,C\,case's\ P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\ 2019$$
$$= 3.6E - 03 * 135\ events = 0.486\ events$$

- Ownship Type Group C,

Encounter Intruder aircraft with Type Group A:

$$Type\ Group\ C\ \&Type\ Group\ A\ case's\ NMAC_{mit}\ events$$
$$= Type\,Group\,C\,\&Type\,Group\,A\,case's\ P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\ 2019$$
$$= 1.6E - 02 * 135\ events = 2.16\ events$$

Encounter Intruder aircraft with Type Group B:

$$Type\ Group\ C\ \&Type\ Group\ B\ case's\ NMAC_{mit}\ events$$
$$= Type\,Group\,C\,\&Type\,Group\,B\,case's\ P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\ 2019$$
$$= 3.6E - 03 * 135\ events = 0.486\ events$$

Encounter Intruder aircraft with Type Group C:

$$Type\ Group\ C\ \&Type\ Group\ C\ case's\ NMAC_{mit}\ events$$
$$= Type\,Group\,C\,\&Type\,Group\,C\,case's\ P_{ENCTR\ type} * Total\ NMAC_{mit}\,events\,in\ 2019$$
$$= 4E - 04 * 135\ events = 0.054\ events$$

4.1.4 Determination of Mid-Air Collision Risk

4.1.4.1 Determine the Variable DAA/Surveillance Equipment Risk Ratio (RR_{DAA})

Variable onboard DAA/Surveillance Equipment risk ratio (RR_{DAA}) is based on the assumption of the possibility of NMAC with DAA/Surveillance Equipment and determines the mid-air collision risk as shown in Figure 4.6.

		0 - 1 [0 - 100%]: 0 means well-clear, 1 means loss-of-well-clear	
		Percentages	
A	A_0	The probability that no Eyesight occurs NMAC	100.00%
	A_A	The probability that Eyesight occurs NMAC	45.00%
B	B_0	The probability that no Airband Radio occurs NMAC	100.00%
	B_A	The probability that Airband Radio occurs NMAC	50.00%
F	F_0	The probability that no ADSB occurs NMAC	100.00%
	F_{IN}	The probability that ADSB-In occurs NMAC	50.00%
	F_{OUT}	The probability that ADSB-Out occurs NMAC	35.00%
	F_{IO}	The probability that ADSB-In/Out occurs NMAC	5.00%

Figure 4.6: Variable onboard DAA/Surveillance Equipment RR_{DAA} Assumption

The variable onboard DAA/Surveillance Equipment's risk ratio (RR_{DAA}) calculator was built in the Microsoft excel software. The assumption made in the table 4.4 and used in the calculations in this Subsection 4.1.4.1's equations. The RR_{DAA} calculator logic is simple with respect to the DAA/Surveillance Equipment technical operation between aircraft. For example, if only one Aircraft is equipped with an Airband Radio, the assumption is made that the aircraft cannot communicate and

No.	Ownship	Intruder	RR$_{DAA}$	Remark
1	Type Group A	Type Group A	5.063E-02	Higher risk
2	Type Group A	Type Group B	5.063E-02	Higher risk
3	Type Group A	Type Group C	5.063E-02	Higher risk
4	Type Group B	Type Group A	5.063E-02	Higher risk
5	Type Group B	Type Group B	6.202E-03	
6	Type Group B	Type Group C	8.86E-04	
7	Type Group C	Type Group A	5.063E-02	Higher risk
8	Type Group C	Type Group B	8.86E-04	
9	Type Group C	Type Group C	1.266E-04	Least risk

Table 4.4: Results of Variable onboard DAA/Surveillance Equipment Risk Ratio (RR$_{DAA}$)

the effect of Airband Radio would be nil, which is expressed as "1". The same idea applies to other DAA/Surveillance Equipment such as the ADS-B system. This logic is used to compute the risk ratio results for 5 cases in this scenario. Type Group C and Type Group C case has least risk ratio as 1.266E-04. The results are shown in Table 4.4.

1) Type Group A & Type Group A (Figure 4.7),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ A) * Intruder\ Aircraft\ (Type\ Group\ A)$$
$$= (A_A * B_A * F_0) * (A_A * B_A * F_0) = (0.45 * 0.5 * 1) * (0.45 * 0.5 * 1)$$
$$= 5.063E - 02$$

2) Type Group A & Type Group B (Figure 4.8),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ A) * Intruder\ Aircraft\ (Type\ Group\ B)$$
$$= (A_A * B_A * F_0) * (A_A * B_A * F_{OUT}) = (0.45 * 0.5 * 1) * (0.45 * 0.5 * 1)$$
$$= 5.063E - 02$$

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	None		ADSB (F)	None
RR_{DAA} =	5.0625E-02			

Figure 4.7: Type Group A & Type Group A Case's RR$_{DAA}$

In this case, the Intruder aircraft's ADSB-Out does not help it to be detected by the Ownship aircraft (without it also having ADBS-in), and it has to cancel and the RR$_{DAA}$ is the same as Type Group A & Type Group A case.

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	None		ADSB (F)	Out
RR_{DAA} =	5.0625E-02			

Figure 4.8: Type Group A & Type Group B Case's RR$_{DAA}$

3) Type Group A & Type Group C (Figure 4.9),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ A) * Intruder\ Aircraft\ (Type\ Group\ C)$$

$$= (A_A * B_A * F_0) * (A_A * B_A * F_{IO}) = (0.45 * 0.5 * 1) * (0.45 * 0.5 * 1)$$

$$= 5.063E - 02$$

For the same reason as Type Group A & Type Group B case, the Intruder's ADSB-In/Out does not affect detection ability by the Ownship aircraft since the Ownship aircraft does not have ADSB-In. The RR$_{DAA}$ result is the same as Type Group A & Type Group A case.

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	None		ADSB (F)	In/Out
RR_{DAA} =	5.0625E-02			

Figure 4.9: Type Group A & Type Group C Case's RR_{DAA}

4) Type Group B & Type Group A (Figure 4.10),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ B) * Intruder\ Aircraft\ (Type\ Group\ A)$$

$$= (A_A * B_A * F_{OUT}) * (A_A * B_A * F_0) = (0.45 * 0.5 * 1) * (0.45 * 0.5 * 1)$$

$$= 5.063E - 02$$

The same as above case, and the result of RR_{DAA} is the same as Type Group A & Type Group A case.

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	Out		ADSB (F)	None
RR_{DAA} =	5.0625E-02			

Figure 4.10: Type Group B & Type Group A Case's RR_{DAA}

5) Type Group B & Type Group B (Figure 4.11),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ B) * Intruder\ Aircraft\ (Type\ Group\ B)$$

$$= (A_A * B_A * F_{OUT}) * (A_A * B_A * F_{OUT}) = (0.45 * 0.5 * 0.35) * (0.45 * 0.5 * 0.35)$$

$$= 6.202E - 03$$

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	Out		ADSB (F)	Out
RR_{DAA} =	5.0625E-02			

Figure 4.11: Type Group B & Type Group B Case's RR_{DAA}

6) Type Group B & Type Group C (Figure 4.12),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ B) * Intruder\ Aircraft\ (Type\ Group\ C)$$

$$= (A_A * B_A * F_{OUT}) * (A_A * B_A * F_{IO}) = (0.45 * 0.5 * 0.35) * (0.45 * 0.5 * 0.05)$$

$$= 8.86E - 04$$

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	Out		ADSB (F)	In/Out
RR_{DAA} =	8.8594E-04			

Figure 4.12: Type Group B & Type Group C Case's RR_{DAA}

7) Type Group C & Type Group A (Figure 4.13),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ C) * Intruder\ Aircraft\ (Type\ Group\ A)$$

$$= (A_A * B_A * F_{IO}) * (A_A * B_A * F_0) = (0.45 * 0.5 * 1) * (0.45 * 0.5 * 1)$$

$$= 5.063E - 02$$

For the same reason as the above 3 cases, the RR_{DAA} is the same as Type Group A & Type Group A case.

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	In/Out		ADSB (F)	None
RR_{DAA} =	5.0625E-02			

Figure 4.13: Type Group C & Type Group A Case's RR_{DAA}

8) Type Group C & Type Group B (Figure 4.14),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ C) * Intruder\ Aircraft\ (Type\ Group\ B)$$

$$= (A_A * B_A * F_{IO}) * (A_A * B_A * F_{OUT}) = (0.45 * 0.5 * 1) * (0.45 * 0.5 * 0.35)$$

$$= 8.86E - 04$$

Ownship Equipment			Intruder Equipment	
Eyesight (A)	Yes		Eyesight (A)	Yes
Airband Radio (B)	Yes		Airband Radio (B)	Yes
ADSB (F)	In/Out		ADSB (F)	Out
RR_{DAA} =	8.8594E-04			

Figure 4.14: Type Group C & Type Group B Case's RR_{DAA}

9) Type Group C & Type Group C (Figure 4.15),

$$RR_{DAA} = Ownship\ Aircraft\ (Type\ Group\ C) * Intruder\ Aircraft\ (Type\ Group\ C)$$

$$= (A_A * B_A * F_{IO}) * (A_A * B_A * F_{OUT}) = (0.45 * 0.5 * 1) * (0.45 * 0.5 * 0.05)$$

$$= 1.266E - 04$$

Ownship Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out
RR_{DAA} =	1.2656E-04

Intruder Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out

Figure 4.15: Type Group C & Type Group C Case's RR_{DAA}

4.1.4.2 Determine Idealized Unmitigated NMAC Rate

No.	Case	$NMAC_{unmit}$ per flight hours
1	Type Group A & Type Group A	3.287E-04
2	Type Group A & Type Group B	7.395E-05
3	Type Group A & Type Group C	8.216E-06
4	Type Group B & Type Group A	7.395E-05
5	Type Group B & Type Group B	1.358E-04
6	Type Group B & Type Group C	1.056E-04
7	Type Group C & Type Group A	8.216E-06
8	Type Group C & Type Group B	1.056E-04
9	Type Group C & Type Group C	8.215E-05
Total $NMAC_{unmit}$ rate per flight hours in 2019:		9.22E-04

Table 4.5: Unmitigated NMAC Rate per flight hours in 2019

Total traffic population is contingent on the idealized unmitigated NMAC rate.

Earlier Section 4.1.2 (total Canadian aircraft mitigated NMAC rate), Section 4.1.3.1 (combination case's $\mathrm{P}_{ENCTR\ type}$), and Section 4.1.4.1 (combination case's RR_{DAA}) results come together to compute each Ownship and Intruder aircraft case's unmitigated NMAC rate per flight hours. The total unmitigated NMAC rate is 35.462 times more risk than mitigated NMAC rate from Section 4.1.2. Because of assumption type Group cases (Section 4.1.1), the unmitigated NMAC rate is calculated based on the assumption population with their equipment levels. The Section 4.1.2's mitigated NMAC rate came out from real world statistic results of reported mitigated NMAC events and total Canadian aircraft flight hours.

1) Type Group A & Type Group A case,

$$Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$
$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$
$$*\,Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ P_{ENCTR\ type})$$
$$/\ Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ RR_{DAA}$$
$$= (2.60E{-}05\,per\ flight\ hours * 6.4E{-}01)/5.063E{-}02 = 3.287E{-}04\,per\ flight\ hours$$

2) Type Group A & Type Group B case,

$$Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$
$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$
$$*\,Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ P_{ENCTR\ type})$$
$$/\ Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ RR_{DAA}$$
$$= (2.60E{-}05\,per\ flight\ hours * 1.44E{-}01)/5.063E{-}02 = 7.395E{-}05\,per\ flight\ hours$$

3) Type Group A & Type Group C case,

$$Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\,Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ P_{ENCTR\ type})$$

$$/\ Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ RR_{DAA}$$

$$= (2.60E{-}05\,per\ flight\ hours * 1.6E{-}02)/5.063E{-}02 = 8.216E{-}06\,per\ flight\ hours$$

4) Type Group B & Type Group A case,

$$Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\,Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ P_{ENCTR\ type})$$

$$/\ Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ RR_{DAA}$$

$$= (2.60E{-}05\,per\ flight\ hours * 1.44E{-}01)/5.063E{-}02 = 7.395E{-}05\,per\ flight\ hours$$

5) Type Group B & Type Group B case,

$$Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\,Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ P_{ENCTR\ type})$$

$$/\ Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ RR_{DAA}$$

$$= (2.60E{-}05\,per\ flight\ hours * 3.24E{-}02)/6.202E{-}03 = 1.358E{-}04\,per\ flight\ hours$$

6) Type Group B & Type Group C case,

$$Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\, Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ P_{ENCTR\ type})$$

$$/\ Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ RR_{DAA}$$

$$= (2.60E{-}05\, per\ flight\ hours * 3.6E{-}03)/8.86E{-}04 = 1.056E{-}04\, per\ flight\ hours$$

7) Type Group C & Type Group A case,

$$Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\, Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ P_{ENCTR\ type})$$

$$/\ Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ RR_{DAA}$$

$$= (2.60E{-}05\, per\ flight\ hours * 1.6E{-}02)/5.063E{-}02 = 8.216E{-}06\, per\ flight\ hours$$

8) Type Group C & Type Group B case,

$$Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\, Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ P_{ENCTR\ type})$$

$$/\ Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ RR_{DAA}$$

$$= (2.60E{-}05\, per\ flight\ hours * 3.6E{-}03)/8.86E{-}04 = 1.056E{-}04\, per\ flight\ hours$$

9) Type Group C & Type Group C case,

$$Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$= (All\ registered\ Canadian\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\,Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ P_{ENCTR\ type})$$

$$/\ Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ RR_{DAA}$$

$$= (2.60E{-}05\,per\ flight\ hours *4E{-}04)/1.266E{-}04 = 8.215E{-}05\,per\ flight\ hours$$

4.1.4.3 Determining Unmitigated NMAC Events

No.	Case	Ownship/Intruder NMAC_{unmit} rate per flight hours	NMAC_{unmit} events
1	Type Group A & Type Group A	3.287E-04	1,709.569
2	Type Group A & Type Group B	7.395E-05	384.874
3	Type Group A & Type Group C	8.216E-06	42.752
4	Type Group B & Type Group A	7.395E-05	384.614
5	Type Group B & Type Group B	1.358E-04	706.296
6	Type Group B & Type Group C	1.056E-04	549.226
7	Type Group C & Type Group A	8.216E-06	42.731
8	Type Group C & Type Group B	1.056E-04	549.226
9	Type Group C & Type Group C	8.215E-05	427.262
Total NMAC_{unmit} events in 2019:			4,796.55 events

Table 4.6: Unmitigated NMAC Events in 2019

After Subsection 4.1.4.2, the calculated combination case's unmitigated NMAC rate per flight hours is put in the equation below. The total Canadian aircraft flight hours from transport Canada 2019 stats data multiplied by Subsection 4.1.4.2 result for combination case's unmitigated NMAC events. Total unmitigated NMAC events are 4,796.55 events in 2019 followed by each combination's case.

1) Type Group A & Type Group A case,

$$\begin{aligned}
&Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ event\\
&\quad = Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\\
&\qquad\qquad * \ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019\\
&\qquad\qquad = 3.287E-04\ per\ flight\ hours * 5,201,000\ flight\ hours\\
&\qquad\qquad\qquad\qquad = 1,709.569\ events
\end{aligned}$$

Thus, 1,709.569 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group A) meet Intruder aircraft (equipped with Type Group A).

2) Type Group A & Type Group B case,

$$\begin{aligned}
&Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ event\\
&\quad = Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\\
&\qquad\qquad * \ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019\\
&\qquad\qquad = 7.4E-05\ per\ flight\ hours * 5,201,000\ flight\ hours\\
&\qquad\qquad\qquad\qquad = 384.874\ events
\end{aligned}$$

Thus, 384.874 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group A) meet Intruder aircraft (equipped with Type Group B).

3) Type Group A & Type Group C case,

$$
\begin{aligned}
&Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ event \\
&= Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
&\quad * \ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019 \\
&= 8.22E-06\ per\ flight\ hours * 5,201,000\ flight\ hours \\
&= 42.752\ events
\end{aligned}
$$

Thus, 42.752 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group A) meet Intruder aircraft (equipped with Type Group C).

4) Type Group B& Type Group A case,

$$
\begin{aligned}
&Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ event \\
&= Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
&\quad * \ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019 \\
&= 7.395E-05\ per\ flight\ hours * 5,201,000\ flight\ hours \\
&= 384.614\ events
\end{aligned}
$$

Thus, 384.614 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group B) meet Intruder aircraft (equipped with Type Group A).

5) Type Group B & Type Group B case,

$$
\begin{aligned}
&Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ event \\
&\quad = Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
&\qquad * \ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019 \\
&\qquad = 1.358E-04\ per\ flight\ hours * 5,201,000\ flight\ hours \\
&\qquad\qquad = 706.296\ events
\end{aligned}
$$

Thus, 706.296 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group B) meet Intruder aircraft (equipped with Type Group B).

6) Type Group B & Type Group C case,

$$
\begin{aligned}
&Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ event \\
&\quad = Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
&\qquad * \ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019 \\
&\qquad = 1.056E-04\ per\ flight\ hours * 5,201,000\ flight\ hours \\
&\qquad\qquad = 549.226\ events
\end{aligned}
$$

Thus, 549.226 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group B) meet Intruder aircraft (equipped with Type Group C).

7) Type Group C & Type Group A case,

$$\begin{aligned}
&Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ event\\
&= Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\\
&\quad *\ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019\\
&= 8.216E-06\ per\ flight\ hours * 5,201,000\ flight\ hours\\
&= 42.731\ events
\end{aligned}$$

Thus, 42.731 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group C) meet Intruder aircraft (equipped with Type Group A).

8) Type Group C & Type Group B case,

$$\begin{aligned}
&Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ event\\
&= Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\\
&\quad *\ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019\\
&= 1.056E-04\ per\ flight\ hours * 5,201,000\ flight\ hours\\
&= 549.226\ events
\end{aligned}$$

Thus, 549.226 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group C) meet Intruder aircraft (equipped with Type Group B).

9) Type Group C & Type Group C case,

$$Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ event$$
$$= Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$
$$*\ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 8.215E-05\ per\ flight\ hours * 5,201,000\ flight\ hours$$
$$= 427.262\ events$$

Thus, 427.262 unmitigated NMAC events will occur when Ownship aircraft (equipped with Type Group C) meet Intruder aircraft (equipped with Type Group C).

Total unmitigated NMAC events are 4,796.55 events in 2019 based on given assumptions in Section 4.1.1.

4.1.4.4 Determine Total Unmitigated NMAC Rate

The present subsection determines the total unmitigated NMAC rate per flight hours in 2019 based on the given assumption in Section 4.1.1. This total unmitigated NMAC rate may be back-calculated to validate the results from Section 4.1.4.2. The same result of 9.22E-04 per flight hours for the total $NMAC_{unmit}$ rate is obtained.

$$Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019$$
$$= NMAC_{unmit}\ events\ in\ 2019\ /total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 4,796.55\ events\ /5,201,000\ flight\ hours$$
$$= 9.222E-04\ per\ flight\ hours$$

This equation also cross-checks the result of Section 4.1.4.3, and the total unmitigated NMAC events are the same as Subsection 4.1.4.3.

$$Total\ NMAC_{unmit}\ events\ in\ 2019\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight$$
$$hours\ in\ 2019\ *\ total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 9.222E-04\ per\ flight\ hours\ * 5,201,000\ flighthours$$
$$= 4.796E+03\ events$$

4.1.4.5 Determine Idealized Mitigated NMAC Rate

No.	Case	NMAC$_{mit}$ rate per flight hours	Remark
1	Type Group A & Type Group A	1.664E-05	Least safe case
2	Type Group A & Type Group B	3.744E-06	
3	Type Group A & Type Group C	4.161E-07	
4	Type Group B & Type Group A	3.744E-06	
5	Type Group B & Type Group B	8.422E-07	
6	Type Group B & Type Group C	9.356E-08	
7	Type Group C & Type Group A	4.161E-07	
8	Type Group C & Type Group B	9.356E-08	
9	Type Group C & Type Group C	1.04E-08	Safest case
Total:		2.60E-05	

Table 4.7: Mitigated NMAC Rates in 2019

Following the calculation steps, the assessed combination case's unmitigated NMAC rate per flight hours (Section 4.1.4.2) and the combined type group case's RR$_{DAA}$ (Section 4.1.4.1) are applied to this section's equation over the 9 cases.

Type Group A (Ownship aircraft) and Type Group A (Intruder aircraft) case is the least performing the DAA/Surveillance Equipment and the relatively safest functioning onboard DAA/Surveillance Equipment is between Type Group C (Ownship aircraft) and Type Group C (Intruder aircraft) case based on the assumption of Type Group cases in Table 4.1.

1) Type Group A & Type Group A case,

$$
\begin{aligned}
& Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours \\
& = Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
& \quad * Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ RR_{DAA} \\
& = 3.287E-04\ per\ flight\ hours\ *\ 5.063E-02 \\
& = 1.664E-05\ per\ flight\ hours
\end{aligned}
$$

2) Type Group A & Type Group B case,

$$
\begin{aligned}
& Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours \\
& = Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
& \quad * Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ RR_{DAA} \\
& = 7.395E-05\ per\ flight\ hours\ *\ 5.063E-02 \\
& = 3.744E-06\ per\ flight\ hours
\end{aligned}
$$

3) Type Group A & Type Group C case,

$$
\begin{aligned}
& Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours \\
& = Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
& \quad * Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ RR_{DAA} \\
& = 8.216E-06\ per\ flight\ hours\ *\ 5.063E-02 \\
& = 4.161E-07\ per\ flight\ hours
\end{aligned}
$$

4) Type Group B & Type Group A case,

$$Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$

$$= Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$* Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ RR_{DAA}$$

$$= 7.395E-05\ per\ flight\ hours\ *\ 5.063E-02$$

$$= 3.744E-06\ per\ flight\ hours$$

5) Type Group B & Type Group B case,

$$Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$

$$= Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$* Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ RR_{DAA}$$

$$= 1.358E-04\ per\ flight\ hours\ *\ 6.202E-03$$

$$= 8.422E-07\ per\ flight\ hours$$

6) Type Group B & Type Group C case,

$$Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$

$$= Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$* Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ RR_{DAA}$$

$$= 1.056E-04\ per\ flight\ hours\ *\ 8.86E-04$$

$$= 9.356E-08\ per\ flight\ hours$$

7) Type Group C & Type Group A case,

$$Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$

$$= Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$* Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ RR_{DAA}$$

$$= 8.216E-06\ per\ flight\ hours\ *\ 5.063E-02$$

$$= 4.161E-07\ per\ flight\ hours$$

8) Type Group C & Type Group B case,

$$Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$

$$= Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$* Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ RR_{DAA}$$

$$= 1.056E-04\ per\ flight\ hours\ *\ 8.86E-04$$

$$= 9.356E-08\ per\ flight\ hours$$

9) Type Group C & Type Group C case,

$$Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$

$$= Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$* Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ RR_{DAA}$$

$$= 8.215E-05\ per\ flight\ hours\ *\ 1.266E-04$$

$$= 1.04E-08\ per\ flight\ hours$$

4.1.4.6 Determine $NMAC_{mit}$ Events by Calculated Idealized $NMAC_{mit}$ Rate

As Section 4.1.2 mentioned, the total NMAC events are reported and documented on Transport Canada's statistical summary air transportation occurrences report. However, this section computes from the calculated result of the combination case's mitigated NMAC rate (Section 4.1.4.5) and known total Canadian aircraft flight hours. The computed total mitigated NMAC events are 133,227 events, and the difference has 1.313% from reported events in 2019 due to rounding error of accumulating fraction numbers.

No.	Case	Ownship & Intruder $NMAC_{mit}$ rate per flight hours	$NMAC_{mit}$ events	Remark
1	Type Group A & Type Group A	1.664E-05	84.545	
2	Type Group A & Type Group B	3.744E-06	19.473	
3	Type Group A & Type Group C	4.161E-07	2.164	
4	Type Group B & Type Group A	3.744E-06	19.473	
5	Type Group B & Type Group B	8.422E-07	4.38	
6	Type Group B & Type Group C	9.356E-08	0.487	
7	Type Group C & Type Group A	4.161E-07	2.164	
8	Type Group C & Type Group B	9.356E-08	0.487	
9	Type Group C & Type Group C	1.04E-08	0.0541	
Total $NMAC_{mit}$ events in 2019:			133.227 events	135 events in actual 2019 reported $NMAC_{mit}$ events

Table 4.8: Mitigated NMAC Events by Calculated Idealized $NMAC_{mit}$ Rate in 2019

1) Type Group A & Type Group A case,

$$Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ A\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$* total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 1.664E - 05\ per\ flight\ hours\ * 5,201,000\ flight\ hours$$
$$= 84.545\ events$$

2) Type Group A & Type Group B case,

$$Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ A\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$* total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 3.744E - 06\ per\ flight\ hours\ * 5,201,000\ flight\ hours$$
$$= 19.473\ events$$

3) Type Group A & Type Group C case,

$$Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ A\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$* total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 4.161E - 07\ per\ flight\ hours\ * 5,201,000\ flight\ hours$$
$$= 2.164\ events$$

4) Type Group B & Type Group A case,

$$Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ B\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$*\,total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 3.744E-06\ per\ flight\ hours\ *5,201,000\ flight\ hours$$
$$= 19.473\ events$$

5) Type Group B & Type Group B case,

$$Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ B\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$*\,total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 8.422E-07\ per\ flight\ hours\ *5,201,000\ flight\ hours$$
$$= 4.38\ events$$

6) Type Group B & Type Group C case,

$$Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ B\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$*\,total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 9.356E-08\ per\ flight\ hours\ *5,201,000\ flight\ hours$$
$$= 0.487\ events$$

7) Type Group C & Type Group A case,

$$Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ C\ \&\ Type\ Group\ A\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$*\, total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 4.161E-07\ per\ flight\ hours\ * 5,201,000\ flight\ hours$$
$$= 2.164\ events$$

8) Type Group C & Type Group B case,

$$Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ C\ \&\ Type\ Group\ B\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$*\, total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 9.356E-08\ per\ flight\ hours\ * 5,201,000\ flight\ hours$$
$$= 0.487\ events$$

9) Type Group C & Type Group C case,

$$Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ events$$
$$= Type\ Group\ C\ \&\ Type\ Group\ C\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours$$
$$*\, total\ Canadian\ registered\ aircraft\ flight\ hours\ in\ 2019$$
$$= 1.04E-08\ per\ flight\ hours\ * 5,201,000\ flight\ hours$$
$$= 0.0541\ events$$

4.1.5 "No-DAA" Aircraft (No Vision) and & Malfunctional DAA Equipment

This is a theoretical case, based on the assumption that no aircraft had DAA/Surveillance Equipment in 2019.

No.	Ownship aircraft	Intruder aircraft	RR_{DAA}	$NMAC_{unmit}$ rate per flight hours	$NMAC_{mit}$ rate per flight hours	Remark
1	"No-DAA" Equips	"No-DAA" Equips	1.000E+00	9.22E-04	9.22E-04	Baseline

Table 4.9: Both "No-DAA" Aircraft Case

Both "No-DAA" aircraft cannot see each other and the risk ratio calculated 1.000E+00 (100%) of mid-air collision risk.

- Both "No-DAA" Aircraft Case's RR_{DAA}

$$RR_{DAA} = Ownship\ Aircraft\ (\text{``}No - DAA\text{''}) * Intruder\ Aircraft\ (\text{``}No - DAA\text{''})$$

$$= (A_0 * B_0 * F_0) * (A_0 * B_0 * F_0) = (1 * 1 * 1) * (1 * 1 * 1)$$

$$= 1.000E + 00$$

- Both "No-DAA" Aircraft Case's Unmitigated NMAC Rate

$$Both\ \text{``}No - DAA\text{''}\ aircraft's\ NMAC_{unmit}\ per\ flight\ hours$$

$$= Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019 * Both\ \text{``}No{-}DAA\text{''}\ aircrat's\ RR_{DAA}$$

$$= 9.22E - 04\ per\ flight\ hours\ *\ 1.000E + 00$$

$$= 9.22E - 04\ per\ flight\ hours$$

- Both "No-DAA" Aircraft Case's Mitigated NMAC Rate

$$
\begin{aligned}
&Both\ \text{“}No-DAA\text{”}\ aircraft's\ NMAC_{mit}\ rate\ per\ flight\ hours \\
&\quad = Both\ \text{“}No-DAA\text{”}\ aircraft's\ NMAC_{unmit}\ rate\ per\ flight\ hours \\
&\quad\quad * \ Both\ \text{“}No-DAA\text{”}\ aircraft's\ RR_{DAA} \\
&\quad = 9.22E-04\ per\ flight\ hours\ *\ 1.000E+00 \\
&\quad = 9.22E-04\ per\ flight\ hours
\end{aligned}
$$

4.1.6 "No-DAA" Ownship Aircraft with Other Type of Intruder Aircraft

No.	Ownship aircraft	Intruder aircraft	RR_{DAA}	$NMAC_{unmit}$ rate per flight hours	$NMAC_{mit}$ rate per flight hours	Remark
1	"No-DAA" Equips	Group A type	4.5E-01	4.149E-04	1.867E-04	Same risk
2	"No-DAA" Equips	Group B type	4.5E-01	4.149E-04	1.867E-04	Same risk
3	"No-DAA" Equips	Group C type	4.5E-01	4.149E-04	1.867E-04	Same risk
Total:				1.24E-03	5.6E-04	

Table 4.10: Both "No-DAA" Aircraft with Other Type Intruder Aircraft Case

All cases with "No-DAA" Ownship aircraft have the same risk ratio and the functionalities are the same conditions. This factor brings the same NMAC rates. Three total combination cases are presented in this section and the risk ratio (RR_{DAA}) is calculated considering both aircraft's onboard DAA/Surveillance Equipment (Section 4.1.6.1.1, 4.1.6.2.1, 4.1.6.3.1). Follow the calculated RR_{DAA} result multiply by the 2019 total unmitigated NMAC rate per flight hours would be the case of combination's unmitigated NMAC rate per flight hours (Section 4.1.6.1.2, 4.1.6.2.2, 4.1.6.3.2). The final calculation of mitigated NMAC rate per flight hours can simply multiply both calculated RR_{DAA} and case's calculated unmitigated NMAC rate per flight hours (Section 4.1.6.1.3, 4.1.6.2.3, 4.1.6.3.3).

4.1.6.1 "No-DAA" Ownship Aircraft with Group A Type Intruder Aircraft

4.1.6.1.1 "No-DAA" Ownship Aircraft & Group A Type Intruder Aircraft Case's RR_{DAA},

$$RR_{DAA} = Ownship\ Aircraft\ (\text{“}No - DAA\text{”})\ *\ Intruder\ Aircraft\ (Group\ A\ type)$$
$$= (A_0 * B_0 * F_0) * (A_A * B_A * F_0) = (1 * 1 * 1) * (0.45 * 1 * 1) = 4.5E - 01 \tag{4.2}$$

The Intruder aircraft has an Airband Radio but the Ownship does not equip any communication equipment. The Intruder aircraft Airband Radio does not make any difference and hence the Intruder/Ownship Airband Radio factors cancel such that the Airband Radio factor is "1" in this Equation 4.2.

Ownship Equipment			Intruder Equipment	
Eyesight (A)	No		Eyesight (A)	Yes
Airband Radio (B)	No		Airband Radio (B)	Yes
ADSB (F)	None		ADSB (F)	None
RR_{DAA} =	4.5000E-01			

Figure 4.16: "No-DAA" Ownship & Type Group A Case's RR_{DAA}

4.1.6.1.2 "No-DAA" Ownship aircraft & Group A type Intruder Aircraft Unmitigated NMAC rate per flight hours,

$$\text{“}No - DAA\text{”}\ Ownship\ aircraft\ \&\ Group\ A\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019$$
$$*\ \text{“}No - DAA\text{”}\ Ownship\ aircraft\ Group\ A\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$
$$= 9.22E - 04\ per\ flight\ hours\ * 4.5E - 01\ = 4.149E - 04\ per\ flight\ hours$$

4.1.6.1.3 "No-DAA" Ownship Aircraft & Group A Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$\text{“}No{-}DAA\text{”}\ Ownship\ aircraft\ Group\ A\ type\ Intruder\ aircraft\ case's\ NMAC_{mit}$$
$$rate\ per\ flight\ hours\ =\ \text{“}No{-}DAA\text{”}\ Ownship\ aircraft\ \&Group\ A\ type\ Intruder$$
$$aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours * \text{“}No{-}DAA\text{”}\ Ownship\ aircraft$$
$$\&Group\ A\ type\ Intruder\ aircraft's\ RR_{DAA}\ = 4.149E{-}04\ per\ flight\ hours * 4.5E{-}01$$
$$=\ 1.867E - 04\ per\ flight\ hours$$

4.1.6.2 "No-DAA" Ownship Aircraft with Group B Type Intruder Aircraft

4.1.6.2.1 "No-DAA" Ownship Aircraft & Group B Type Intruder Aircraft Case's RR_{DAA},

$$RR_{DAA} = Ownship\ Aircraft\ (\text{“}No - DAA\text{”})\ *\ Intruder\ Aircraft\ (Group\ A\ type)$$
$$= (A_0 * B_0 * F_0) * (A_A * B_A * F_{OUT}) = (1 * 1 * 1) * (0.45 * 1 * 1) = 4.5E - 01 \tag{4.3}$$

Following the same method as Subsection 4.1.6.1.1, Intruder aircraft's ADSB-Out system does not make any difference because of Ownship aircraft's none of equipment or malfunction of system with "No-DAA" Eyesight.

Ownship Equipment			Intruder Equipment	
Eyesight (A)	No		Eyesight (A)	Yes
Airband Radio (B)	No		Airband Radio (B)	Yes
ADSB (F)	None		ADSB (F)	Out
RR_{DAA} =	4.5000E-01			

Figure 4.17: "No-DAA" Ownship & Type Group B Case's RR_{DAA}

4.1.6.2.2 "No-DAA" Ownship Aircraft & Group B Type Intruder Unmitigated NMAC rate per flight hours,

$$\text{“}No - DAA\text{”}\ Ownship\ aircraft\ \&\ Group\ B\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019$$
$$*\ \text{“}No - DAA\text{”}\ Ownship\ aircraft\ Group\ B\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$
$$= 9.22E - 04\ per\ flight\ hours\ * 4.5E - 01\ = 4.149E - 04\ per\ flight\ hours$$

4.1.6.2.3 "No-DAA" Ownship Aircraft & Group B Type Intruder Aircraft Mitigated NMAC rate per flight hours,

$$\text{“}No\!-\!DAA\text{”}\ Ownship\ aircraft\ Group\ B\ type\ Intruder\ aircraft\ case's\ NMAC_{mit}$$
$$rate\ per\ flight\ hours\ =\ \text{“}No-DAA\text{”}\ Ownship\ aircraft\ \&Group\ B\ type\ Intruder$$
$$aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours * \text{“}No\!-\!DAA\text{”}\ Ownship\ aircraft$$
$$\&Group\ B\ type\ Intruder\ aircraft's\ RR_{DAA}\ = 4.149E\!-\!04\ per\ flight\ hours *4.5E\!-\!01$$
$$=\ 1.867E-04\ per\ flight\ hours$$

4.1.6.3 "No-DAA" Ownship Aircraft with Group C Type Intruder Aircraft

4.1.6.3.1 "No-DAA" Ownship Aircraft & Group C Type Intruder Aircraft Case's RR_{DAA},

$$RR_{DAA} = Ownship\ Aircraft\ (\text{“}No-DAA\text{”})\ *\ Intruder\ Aircraft\ (Group\ A\ type)$$
$$= (A_0 * B_0 * F_0) * (A_A * B_A * F_{IO}) = (1*1*1)*(0.45*1*1) = 4.5E-01 \tag{4.4}$$

The same as in 4.1.6.1.1 and 4.1.6.2.1, the Intruder aircraft's ADSB-In/Out system does not have any effect in this "No-DAA" Ownship case.

4.1.6.3.2 "No-DAA" Ownship Aircraft & Group C type Intruder Unmitigated

Ownship Equipment			Intruder Equipment	
Eyesight (A)	No		Eyesight (A)	Yes
Airband Radio (B)	No		Airband Radio (B)	Yes
ADSB (F)	None		ADSB (F)	In/Out
RR_{DAA} =	4.5000E-01			

Figure 4.18: "No-DAA" Ownship & Type Group C Case's RR$_{DAA}$

NMAC rate per flight hours,

$$\text{“}No - DAA\text{”}\ Ownship\ aircraft\ \&\ Group\ C\ type\ Intruder\ aircraft\ case's$$

$$NMAC_{unmit}\, rate\, per\ flight\ hours\ =\ Total\ NMAC_{unmit}\, rate\, per\ flight\ hours\ in\ 2019$$

$$*\ \text{“}No - DAA\text{”}\ Ownship\ aircraft\ Group\ C\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$

$$= 9.22E - 04\ per\ flight\ hours\ * 4.5E - 01\ = 4.149E - 04\ per\ flight\ hours$$

4.1.6.3.3 "No-DAA" Ownship Aircraft & Group C Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$\text{“}No-DAA\text{”}\ Ownship\ aircraft\ Group\ C\ type\ Intruder\ aircraft\ case's\ NMAC_{mit}$$

$$rate\ per\ flight\ hours\ =\ \text{“}No-DAA\text{”}\ Ownship\ aircraft\ \&Group\ C\ type\ Intruder$$

$$aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\ *\ \text{“}No-DAA\text{”}\ Ownship\ aircraft$$

$$\&Group\ C\ type\ Intruder\ aircraft's\ RR_{DAA}\ = 4.149E-04\ per\ flight\ hours\ *4.5E-01$$

$$=\ 1.867E - 04\ per\ flight\ hours$$

4.2 Unmanned Ownship Aircraft Application

4.2.1 New Ownship Aircraft as the Unmanned Aerial Vehicle (UAV) and Only Equipped with ADSB-Out

No.	Ownship aircraft	Intruder aircraft	RR_{DAA}	$NMAC_{unmit}$ rate per flight hours	$NMAC_{mit}$ rate per flight hours	Remark
1	UAV with only ADSB-Out	Group A type	4.5E-01	4.149E-04	1.867E-04	Highest risk(Same risk)
2	UAV with only ADSB-Out	Group B type	4.5E-01	4.149E-04	1.867E-04	
3	UAV with only ADSB-Out	Group C type	7.875E-03	7.261E-06	5.718E-08	Lowest risk
Total:				8.37E-04	3.73E-04	

Table 4.11: UAV Ownship Aircraft Equipped with ADSB-Out Only Case

This section shows that an UAV equipped with ADSB-Out helps to reduce the risk of mid-air collision and performs better than if Ownship is only equipped with type Group A, type Group B, and type Group C cases in Section 4.1.4.2 and 4.1.4.3. Also, the efficacy of ADSB-Out system with Ownship aircraft expresses the opposition of aircraft equipped with ADSB-In system. Both ADSB-Out system-equipped aircraft could run into each other, as they cannot detect each other without ADSB-In capability. In this particular case, the ADSB-Out equipped aircraft is not effective. Even though Every ADSB-Out system installed aircraft give a benefit to ATC Ground Station and ADSB-In equipped aircraft.

Three total combination cases are presented in this section. The risk ratio (RR_{DAA})

is calculated by considering both aircraft's onboard DAA/Surveillance Equipment (Section 4.2.1.1.1, 4.2.1.2.1, 4.2.1.3.1). The calculated RR_{DAA} results are then multiplied by the 2019 total unmitigated NMAC rate per flight hours, resulting in the DAA combination's unmitigated NMAC rate per flight hours (Section 4.2.1.1.2, 4.2.1.2.2, 4.2.1.3.2).

The final calculation of mitigated NMAC rate per flight hours is done by multiplying the calculated RR_{DAA} by the case's unmitigated NMAC rate per flight hours (Section 4.2.1.1.3, 4.2.1.2.3, 4.2.1.3.3).

4.2.1.1 Ownship UAV with ADSB-Out & Intruder Group A Type Aircraft

4.2.1.1.1 Ownship UAV with ADSB-Out & Group A Type Intruder Aircraft Case's RR_{DAA},

$$\begin{aligned} RR_{DAA} &= Ownship\ UAV\ (Only\ ADSB-Out)\ *\ Intruder\ Aircraft\ (Group\ A\ type) \\ &= (A_0 * B_0 * F_{OUT}) * (A_A * B_A * F_0) = (1*1*1)*(0.45*1*1) = 4.5E-01 \end{aligned} \tag{4.5}$$

Here we assume the Ownship UAV has ADSB-Out system, but the Intruder aircraft does not have ADSB-In or ADSB-In/Out. The Ownship ADSB-Out signal cannot reach the Intruder aircraft in this case and the function of F_{OUT} cancel as "1". Although the Intruder aircraft is equipped with Eyesight (pilot) and an Airband Radio, the Ownship only has ADSB-Out. The Intruder's Airband Radio does not work with Ownship UAV, as it has no Airband Radio. In this scenario, the only effective DAA function is the Intruder aircraft Pilot's Eyesight (A_A).

Ownship Equipment			Intruder Equipment	
Eyesight (A)	No		Eyesight (A)	Yes
Airband Radio (B)	No		Airband Radio (B)	Yes
ADSB (F)	Out		ADSB (F)	None
RR_{DAA} =	4.5000E-01			

Figure 4.19: UAV (Only ADSB-Out) & Type Group A Case's RR_{DAA}

4.2.1.1.2 Ownship UAV with ADSB-Out & Group A Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB-Out)\&\ Group\ A\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019$$
$$*\ Ownship\ UAV(Only\ ADSB-Out)\&\ Group\ A\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$
$$= 9.22E-04\ per\ flight\ hours\ *4.5E-01\ = 4.149E-04\ per\ flight\ hours$$

4.2.1.1.3 Ownship UAV with ADSB-Out & Group A Type Intruder Aircraft Case's mitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB-Out)\ \&\ Group\ A\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\ UAV\ (Only\ ADSB-Out)$$
$$\&\ Group\ A\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$
$$*\ Ownship\ UAV\ (Only\ ADSB-Out)\ \&\ Group\ A\ type\ Intruder\ aircraft's\ RR_{DAA}$$
$$= 4.149E-04\ per\ flight\ hours\ *\ 4.5E-01\ =\ 1.867E-04\ per\ flight\ hours$$

4.2.1.2 Ownship UAV with ADSB-Out & Intruder Group B Type Aircraft

4.2.1.2.1 Ownship UAV with ADSB-Out & Group B Type Intruder Aircraft Case's RR_{DAA},

$$
\begin{aligned}
RR_{DAA} &= Ownship\ UAV\ (Only\ ADSB-Out)\ *\ Intruder\ Aircraft\ (Group\ B\ type) \\
&= (A_0 * B_0 * F_{OUT}) * (A_A * B_A * F_{OUT}) = (1 * 1 * 1) * (0.45 * 1 * 1) \\
&= 4.5E-01
\end{aligned}
\tag{4.6}
$$

Both the Ownship and Intruder aircraft have ADSB-Out systems, but in order to receive ADSB-Out information ADSB-In equipment has to also be equipped on the aircraft. In the case, detection using ADS-B is not possible and thus both ADSB-Out functions have a risk factor of "1".

Ownship Equipment			Intruder Equipment	
Eyesight (A)	No		Eyesight (A)	Yes
Airband Radio (B)	No		Airband Radio (B)	Yes
ADSB (F)	Out		ADSB (F)	Out
RR_{DAA} =	4.5000E-01			

Figure 4.20: UAV (Only ADSB-Out) & Type Group B Case's RR_{DAA}

4.2.1.2.2 Ownship UAV with ADSB-Out & Group B Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\dot{A}DSB - Out)\&\ Group\ B\ type\ Intruder\ aircraft\ case's$$

$$NMAC_{unmit}\, rate\, per\, flight\, hours\ =\ Total\ NMAC_{unmit}\, rate\, per\, flight\, hours\, in\ 2019$$

$$*\ Ownship\, UAV(Only\ ADSB{-}Out)\&\ Group\, B\, type\, Intruder\ aircraft\ case's\ RR_{DAA}$$

$$= 9.22E - 04\ per\ flight\ hours\ * 4.5E - 01\ = 4.149E - 04\ per\ flight\ hours$$

4.2.1.2.3 Ownship UAV with ADSB-Out & Group B Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB - Out)\ \&\ Group\ B\ type\ Intruder\ aircraft\ case's$$

$$NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\, UAV\ (Only\ ADSB - Out)$$

$$\&\ Group\ B\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$*\ Ownship\, UAV\ (Only\ ADSB{-}Out)\ \&\ Group\ B\ type\ Intruder\ aircraft's\ RR_{DAA}$$

$$= 4.149E - 04\ per\ flight\ hours\ *\ 4.5E - 01\ =\ 1.867E - 04\ per\ flight\ hours$$

4.2.1.3 Ownship UAV with ADSB-Out & Intruder Group C Type Aircraft

4.2.1.3.1 Ownship UAV with ADSB-Out & Group C Type Intruder Aircraft Case's RR_{DAA},

$$\begin{aligned} RR_{DAA} &= Ownship\, UAV\ (Only\ ADSB - Out)\ *\ Intruder\ Aircraft\ (Group\ C\ type) \\ &= (A_0 * B_0 * F_{OUT}) * (A_A * B_A * F_{IO}) = (1 * 1 * 0.35) * (0.45 * 1 * 0.05) \\ &= 7.875E - 03 \end{aligned} \tag{4.7}$$

Ownship Equipment			Intruder Equipment	
Eyesight (A)	No		Eyesight (A)	Yes
Airband Radio (B)	No		Airband Radio (B)	Yes
ADSB (F)	Out		ADSB (F)	In/Out
RR_{DAA} =	7.8750E-03			

Figure 4.21: UAV (Only ADSB-Out) & Type Group C Case's RR_{DAA}

4.2.1.3.2 Ownship UAV with ADSB-Out & Group C Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB-Out)\&\ Group\ C\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019$$
$$*\ Ownship\ UAV(OnlyADSB-Out)\&\ Group\ C\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$
$$=9.22E-04\ per\ flight\ hours\ *7.875E-03\ =7.261E-06\ per\ flight\ hours$$

4.2.1.3.3 Ownship UAV with ADSB-Out & Group C Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB-Out)\ \&\ Group\ C\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\ UAV\ (Only\ ADSB-Out)$$
$$\&\ Group\ C\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$
$$*\ Ownship\ UAV\ (Only\ ADSB-Out)\ \&\ Group\ C\ type\ Intruder\ aircraft's\ RR_{DAA}$$
$$=7.261E-06\ per\ flight\ hours\ *\ 7.875E-03\ =\ 5.718E-08\ per\ flight\ hours$$

4.2.2 Ownship UAV Equipped with ADSB-In/Out

In this section we consider the case of the Ownship being an Unmanned Aerial Vehicle (UAV) equipped with ADSB-In/Out, encountering other DAA-equipped Intruder manned aircraft.

No.	Ownship aircraft	Intruder aircraft	RR_{DAA}	$NMAC_{unmit}$ rate per flight hours	$NMAC_{mit}$ rate per flight hours	Remark
1	UAV with only ADSB-In/Out	Group A type	4.5E-01	4.149E-04	1.867E-04	Highest risk
2	UAV with only ADSB-In/Out	Group B type	7.875E-03	7.261E-06	5.718E-08	
3	UAV with only ADSB-In/Out	Group C type	1.125E-03	1.037E-06	1.167E-09	Lowest risk
Total:				4.23E-04	1.87E-04	

Table 4.12: UAV Ownship Aircraft Equipped with ADSB-In/Out Only Case

This analysis shows that UAV aircraft equipped with ADSB-In/Out helps to reduce the risk of mid-air collision and performs better than if the Ownship is only equipped with type Group A, type Group B, and type Group C cases in Section 4.1.4.2 and 4.1.4.3 and with only ADSB-Out in Section 4.2.1. The positive effect of installing ADSB-In/Out in both unmanned aircraft and manned aircraft (Group C type) may be seen in Case 3 of this section. Three total combination cases are presented in this section. The risk ratio (RR_{DAA}) may be calculated considering both aircraft's onboard DAA/Surveillance Equipment (Subsection 4.2.2.1.1, 4.2.2.2.1, 4.2.2.3.1). Following this step, the calculated RR_{DAA} is multiplied by the 2019 total unmitigated NMAC rate per flight hours, yielding the DAA/Surveillance Equipment combination's unmitigated NMAC rate per flight hours (Subsection 4.2.2.1.2., 4.2.2.2.2, 4.2.2.3.2).

The mitigated NMAC rate per flight hours can now be calculated by multiplying the calculated RR_{DAA} by the DAA/Surveillance Equipment case's calculated unmitigated NMAC rate per flight hours (Subsection 4.2.2.1.3, 4.2.2.2.3, 4.2.2.3.3). The total mitigated NMAC rate in this UAV Ownship aircraft case with ADSB-In/Out is bigger than the reference point of 2019 total mitigated NMAC rate (Section 4.1.2). The reason is that in the No. 1 case of this section (UAV with only ADSB-In/Out & Group A type), this case the UAV is blinded even though it has ADSB-In/Out, since Intruder Group A type aircraft does not have ADSB-In/out. The UAV Ownship aircraft's ADSB-In/Out cannot detect the Intruder Group A type aircraft. Also, Intruder aircraft's Airband Radio cannot communicate with UAV Ownship aircraft. However, the Group B type and Group C type Intruder cases shows the benefit of equipping ADSB-In/Out system in the UAV Ownship aircraft.

4.2.2.1 Ownship UAV with ADSB-In/Out & Intruder Group A Type Aircraft

4.2.2.1.1 Ownship UAV with ADSB-In/Out & Group A Type Intruder Aircraft Case's RR_{DAA},

$$\begin{aligned} RR_{DAA} &= Ownship\ UAV\ (OnlyADSB - In/Out) \\ &\quad * Intruder\ Aircraft\ (Group\ A\ type) \\ &= (A_0 * B_0 * F_{IO}) * (A_A * B_A * F_0) = (1 * 1 * 1) * (0.45 * 1 * 1) \\ &= 4.5E - 01 \end{aligned} \tag{4.8}$$

Ownship Equipment	
Eyesight (A)	No
Airband Radio (B)	No
ADSB (F)	In/Out
RR_{DAA} =	4.5000E-01

Intruder Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	None

Figure 4.22: UAV (Only ADSB-In/Out) & Type Group A Case's RR_{DAA}

4.2.2.1.2 Ownship UAV with ADSB-In/Out & Group A Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (OnlyADSB-In/Out)\&\ Group\ A\ type\ Intruder\ aircraft\ case's$$

$$NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\ Ownship\ UAV (OnlyADSB-In/Out)\&\ Group\ A\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$

$$= 9.22E-04\ per\ flight\ hours\ *4.5E-01\ = 4.149E-04\ per\ flight\ hours$$

4.2.2.1.3 Ownship UAV with ADSB-In/Out & Group A type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB-In/Out)\ \&\ Group\ A\ type\ Intruder\ aircraft\ case's$$

$$NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\ UAV\ (Only\ ADSB-In/Out)$$

$$\&\ Group\ A\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$*\ Ownship\ UAV\ (Only\ ADSB-In/Out)\ \&\ Group\ A\ type\ Intruder\ aircraft's\ RR_{DAA}$$

$$= 4.149E-04\ per\ flight\ hours\ *\ 4.5E-01\ =\ 1.867E-04\ per\ flight\ hours$$

4.2.2.2 Ownship UAV with ADSB-In/Out & Intruder Group B Type Aircraft

4.2.2.2.1 Ownship UAV with ADSB-In/Out & Group B Type Intruder Aircraft Case's RR_{DAA},

$$\begin{aligned} RR_{DAA} &= Ownship\ UAV\ (OnlyADSB - In/Out) \\ &* Intruder\ Aircraft\ (Group\ B\ type) \\ = (A_0 * B_0 * F_{IO}) * (A_A * B_A * F_{OUT}) &= (1 * 1 * 0.05) * (0.45 * 1 * 0.35) \\ &= 7.875E - 03 \end{aligned} \tag{4.9}$$

Ownship Equipment	
Eyesight (A)	No
Airband Radio (B)	No
ADSB (F)	In/Out
RR_{DAA} =	7.8750E-03

Intruder Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	Out

Figure 4.23: UAV (Only ADSB-In/Out) & Type Group B Case's RR_{DAA}

4.2.2.2.2 Ownship UAV with ADSB-In/Out & Group B Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB - In/Out) \&\ Group\ B\ type\ Intruder\ aircraft\ case's$$

$$NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019$$

$$*\ Ownship\ UAV (OnlyADSB - In/Out) \&\ Group\ B\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$

$$= 9.22E - 04\ per\ flight\ hours\ *\ 7.875E - 03\ =\ 7.261E - 06\ per\ flight\ hours$$

4.2.2.2.3 Ownship UAV with ADSB-Out & Group B type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (Only\ ADSB-Out)\ \&\ Group\ B\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\,UAV\ (Only\ ADSB-Out)$$
$$\&\ Group\ B\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$
$$*\ Ownship\,UAV\ (Only\ ADSB-Out)\ \&\ Group\ B\ type\ Intruder\ aircraft's\ RR_{DAA}$$
$$=7.261E-06\ per\ flight\ hours\ *\ 7.875E-03\ =\ 5.718E-08\ per\ flight\ hours$$

4.2.2.3 Ownship UAV with ADSB-In/Out & Intruder Group C Type Aircraft

4.2.2.3.1 Ownship UAV with ADSB-In/Out & Group C Type Intruder aircraft case's RR_{DAA},

$$\begin{aligned} RR_{DAA} &= Ownship\,UAV\ (Only\ ADSB-In/Out) \\ &\quad *\ Intruder\ Aircraft\ (Group\ C\ type) \\ &= (A_0 * B_0 * F_{IO}) * (A_A * B_A * F_{IO}) = (1*1*0.05)*(0.45*1*0.05) \\ &= 1.125E-03 \end{aligned} \tag{4.10}$$

4.2.2.3.2 Ownship UAV with ADSB-In/Out & Group C Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (OnlyADSB-In/Out)\&\ Group\ C\ type\ Intruder\ aircraft\ case's$$
$$NMAC_{unmit}\,rate\,per\,flight\,hours\ =\ Total\ NMAC_{unmit}\,rate\,per\,flight\,hours\,in\ 2019$$
$$*\,Ownship\,UAV(Only\ ADSB-In/Out)\&\ Group\,C\,type\,Intruder\,aircraft\,case's\,RR_{DAA}$$
$$=9.22E-04\ per\ flight\ hours\ *\ 1.125E-03\ =\ 1.037E-06\ per\ flight\ hours$$

Ownship Equipment	
Eyesight (A)	No
Airband Radio (B)	No
ADSB (F)	In/Out
RR_{DAA} =	1.1250E-03

Intruder Equipment	
Eyesight (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out

Figure 4.24: UAV (Only ADSB-In/Out) & Type Group C Case's RR_{DAA}

4.2.2.3.3 Ownship UAV with ADSB-In/Out & Group C Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (Only\ ADSB{-}In/Out)\ \&\ Group\ C\ type\ Intruder\ aircraft\ case's$$

$$NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\,UAV\ (Only\ ADSB-In/Out)$$

$$\&\ Group\ C\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours$$

$$*\ Ownship\,UAV\ (Only\ ADSB{-}In/Out)\ \&\ Group\,C\ type\ Intruder\ aircraft's\ RR_{DAA}$$

$$= 1.037E-06\ per\ flight\ hours\ *\ 1.125E-03\ =\ 1.167E-09\ per\ flight\ hours$$

4.2.3 UAV Ownship Aircraft Equipped with ADSB-In/Out, Airband Radio, and Camera

Section 4.2.3 introduced another UAV aircraft case with ADSB-In/Out, Airband Radio, and Camera function. The significant difference was the presence of an Airband Radio on the UAV. The idea is that the UAV human operator at the GCS could monitor and communicate through the Airband Radio system on UAV, in the same manner as a human pilot using their Airband Radio system in the cockpit. In addition, we consider this modern UAV as having some form of optical sensing ability,

No.	Ownship aircraft	Intruder aircraft	RR_{DAA}	$NMAC_{unmit}$ rate per flight hours	$NMAC_{mit}$ rate per flight hours	Remark
1	UAV with ADSB-In/Out, Airband Radio, Camera	Group A type	1.563E-02	1.441E-05	2.252E-07	Highest risk
2	UAV with ADSB-In/Out, Airband Radio, Camera	Group B type	2.734E-04	2.521E-07	6.892E-11	
3	UAV with ADSB-In/Out, Airband Radio, Camera	Group C type	3.91E-05	3.61E-08	1.42E-12	Lowest risk
Total:				1.47E-05	2.25E-07	

Table 4.13: UAV Ownship Equipped with ADSB-In/Out, Airband Radio,& Camera

similar to a bird-eye. The assumptions for these new forms of DAA/Surveillance Equipment need to be carefully chosen, such as the risk ratio effect from each system. For the Airband Radio, we will treat the unmanned Airband Radio effect similar to how the manned risk ratio was defined, giving it a RR_{DAA} of 0.5. For the bird-eye camera system, we make the assumption it is as good as human Eyesight and also has an object detection ability. This bird-eye camera can give a better angle and view without human distraction, so we will assume the RR_{DAA} is 0.25 which is 0.2 better than human Eyesight's risk ratio.

Three total combination cases are presented this section and the risk ratio (RR_{DAA}) is calculated considering both aircraft's onboard DAA/Surveillance Equipment (Section 4.2.3.1.1, 4.2.3.2.1, 4.2.3.3.1). Following this step, the calculated RR_{DAA} for each DAA/Surveillance Equipment combination case is then multiplied by the 2019 total unmitigated NMAC rate per flight hours, which yields the DAA/Surveillance Equipment combination case unmitigated NMAC rate per flight hours (Section 4.2.3.1.2, 4.2.3.2.2, 4.2.3.3.2).

The final calculation of mitigated NMAC rate per flight hours can now be done, by multiplying the calculated RR$_{DAA}$ and the DAA/Surveillance Equipment combination case unmitigated NMAC rate per flight hours (Section 4.2.2.1.3, 4.2.2.2.3, 4.2.2.3.3). The total mitigated NMAC rate per flight hours in this UAV Ownship aircraft case with ADSB-In/Out, Airband Radio and Camera is smaller than the reference point of 2019 total mitigated NMAC rate (Section 4.1.2). This result shows the positive DAA safety effectiveness for an UAS with this set of DAA/Surveillance Equipment. The Airband Radio and camera assisted UAV and lowered the mid-air collision risk, are shown in Table 4.13.

4.2.3.1 Ownship UAV with ADSB-In/Out, Airband Radio and Camera & Intruder Group A type aircraft

4.2.3.1.1 Ownship UAV with ADSB-In/Out, Airband Radio and Camera & Group A Type Intruder Aircraft Case's RR$_{DAA}$,

$$\begin{aligned} RR_{DAA} &= Ownship\ UAV\ (ADSB - In/Out,\ Airband\ Radio,\ and\ Camera) \\ * \ Intruder\ Aircraft\ (Group\ A\ type) &= (A_{Camera} * B_A * F_{IO}) * (A_A * B_A * F_0) \\ &= (0.25 * 0.5 * 1) * (0.45 * 0.5 * 1) = 1.563E - 02 \end{aligned} \tag{4.11}$$

4.2.3.1.2 Ownship UAV with ADSB-In/Out, Airband Radio and Camera & Group

Ownship Equipment	
Camera (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out
RR_{DAA} =	1.5625E-02

Intruder Equipment	
Eyeball (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	None

Figure 4.25: UAV (ADSB-In/Out, Airband Radio, Camera) & Type Group A Case

A Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\,Camera)\ \&\ Group\ A$$
$$type\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total$$
$$NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019 * Ownship\,UAV (Only\ ADSB-In/Out,$$
$$Airband\ Radio,\ and\ Camera)\ \&\ Group\ A\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$
$$= 9.22E-04\ per\ flight\ hours\ *\ 1.563E-02\ =\ 1.441E-05\ per\ flight\ hours$$

4.2.2.1.3 Ownship UAV with ADSB-In/Out, Airband Radio, and Camera & Group A Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\,Camera)\ \&\ Group\ A$$
$$type\ Intruder\ aircraft\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\,UAV$$
$$(Only\ ADSB-In/Out,\ Airband\ Radio,\ and\,Camera)\ \&\ Group\ A\ Intruder\ aircraft$$
$$case's\ NMAC_{unmit}\ rate\ per\ flight\ hours * Ownship\,UAV\ (Only\ ADSB-In/Out,$$
$$Airband\ Radio,\ and\ Camera)\ \&\ Group\ A\ type\ Intruder\ aircraft's\ RR_{DAA}$$
$$= 1.441E-05\ per\ flight\ hours\ *\ 1.563E-02\ =\ 2.252E-07\ per\ flight\ hours$$

4.2.3.2 Ownship UAV with ADSB-In/Out, Airband Radio and Camera & Intruder Group B Type Aircraft

4.2.3.2.1 Ownship UAV with only ADSB-In/Out, Airband Radio and Camera & Group B type Intruder Aircraft Case's RR_{DAA},

$$RR_{DAA} = Ownship\ UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera)$$
$$*\ Intruder\ Aircraft\ (Group\ B\ type)\ =\ (A_{Camera} * B_A * F_{IO}) * (A_A * B_A * F_{OUT})$$
$$= (0.25 * 0.5 * 0.05) * (0.45 * 0.5 * 0.35) = 2.734E-04 \tag{4.12}$$

Ownship Equipment	
Camera (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out
RR_{DAA} =	2.7344E-04

Intruder Equipment	
Eyeball (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	Out

Figure 4.26: UAV (ADSB-In/Out, Airband Radio, Camera) & Type Group B Case

4.2.3.2.2 Ownship UAV with only ADSB-In/Out, Airband Radio and Camera & Group B Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\ UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera)\&\ Group\ B$$
$$type\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total$$
$$NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019 * Ownship\ UAV(Only\ ADSB-In/Out,$$
$$Airband\ Radio,\ and\ Camera)\&\ Group\ B\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$
$$= 9.22E-04\ per\ flight\ hours\ *\ 2.734E-04\ =\ 2.521E-07\ per\ flight\ hours$$

4.2.3.2.3 Ownship UAV with only ADSB-In/Out, Airband Radio and Camera & Group B Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (Only\ ADSB\!-\!In/Out,\ Airband\ Radio,\ and\,Camera)\ \&\ Group\ B\ type\ Intruder\ aircraft\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\,UAV\ (Only\ ADSB\!-\!In/Out,\ Airband\ Radio,\ and\,Camera)\ \&\ Group\ B\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\ *\ Ownship\,UAV\ (Only\ ADSB\!-\!In/Out,\ Airband\ Radio,\ and\ Camera)\ \&\ Group\ B\ type\ Intruder\ aircraft's\ RR_{DAA}$$

$$= 2.521E-07\ per\ flight\ hours\ *\ 2.734E-04\ =\ 6.892E-11\ per\ flight\ hours$$

4.2.3.3 Ownship UAV with ADSB-In/Out, Airband Radio and Camera & Intruder Group C Type Aircraft

4.2.3.3.1 Ownship UAV with only ADSB-In/Out, Airband Radio and Camera & Group C Type Intruder Aircraft Case's RR_{DAA},

$$\begin{aligned} RR_{DAA} &= Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera) \\ &* Intruder\ Aircraft\ (Group\ C\ type)\ = (A_{Camera} * B_A * F_{IO}) * (A_A * B_A * F_{IO}) \\ &= (0.25 * 0.5 * 0.05) * (0.45 * 0.5 * 0.05) = 3.91E-05 \end{aligned} \tag{4.13}$$

Ownship Equipment	
Camera (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out
RR_{DAA} =	3.9063E-05

Intruder Equipment	
Eyeball (A)	Yes
Airband Radio (B)	Yes
ADSB (F)	In/Out

Figure 4.27: UAV (ADSB-In/Out, Airband Radio, Camera) & Type Group C Case

4.2.3.3.2 Ownship UAV with only ADSB-In/Out, Airband Radio and Camera & Group C Type Intruder Aircraft Case's Unmitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera)\ \&\ Group\ C\ type\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours\ =\ Total\ NMAC_{unmit}\ rate\ per\ flight\ hours\ in\ 2019 * Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera)\ \&\ Group\ C\ type\ Intruder\ aircraft\ case's\ RR_{DAA}$$

$$= 9.22E-04\ per\ flight\ hours\ *\ 3.91E-05\ =\ 3.61E-08\ per\ flight\ hours$$

4.2.3.3.3 Ownship UAV with only ADSB-In/Out, Airband Radio and Camera & Group C Type Intruder Aircraft Case's Mitigated NMAC rate per flight hours,

$$Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera)\ \&\ Group\ C\ type\ Intruder\ aircraft\ case's\ NMAC_{mit}\ rate\ per\ flight\ hours\ =\ Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera)\ \&\ Group\ C\ Intruder\ aircraft\ case's\ NMAC_{unmit}\ rate\ per\ flight\ hours * Ownship\,UAV\ (Only\ ADSB-In/Out,\ Airband\ Radio,\ and\ Camera)\ \&\ Group\ C\ type\ Intruder\ aircraft's\ RR_{DAA}$$

$$= 3.61E-08\ per\ flight\ hours\ *\ 3.91E-05\ =\ 1.42E-12\ per\ flight\ hours$$

Chapter 5

Conclusions

5.1 Summary

The Section provides a summary of results of the mid-air collision risk calculations and assessments as detailed in Chapter 4. From these, the following conclusions may be made.

The Mid-air collision risk assessment requires determining the risk ratio and unmitigated NMAC rate per flight hours. Higher air-traffic density creates a higher traffic ratio and thus a higher potential risk of MAC between these aircraft. This study approached the risk assessment of MAC by analyzing different onboard DAA Surveillance Equipment combinations between Ownship and Intruder aircraft. There are many surveillance equipment options in the market and the effectiveness of DAA Surveillance Equipment combinations is unquantified. This remains an active area of research. This thesis instead attempts to use reasonable estimates of the effectiveness of various combinations of DAA/Surveillance Equipment based on experience. Note that Ownship aircraft cannot control nor predict what DAA/Surveillance Equipment will be present on encountered Intruder aircraft. Instead, this study explores the probability of encountering aircraft with various combinations of onboard DAA/Surveillance Equipment and evaluates the mid-air collision risk by a variable combination of onboard DAA/Surveillance Equipment between Ownship and Intruder aircraft.

The Canadian statistical summary air transportation occurrences as of 2019 were utilized to calculate the total mitigated NMAC rate per flight hours. Assumptions are made to characterize the air traffic population into three groups for the mid-air risk assessment. In Section 4.1.3.1, the three groups are broken down into all possible encountering cases considered. The calculated $P_{ENCTRtype}$ can be used to back-calculate the mitigated NMAC events in 2019 and compare the total reported mitigated NMAC events which were 135 events in 2019, thus providing a proof of the $P_{ENCTRtype}$ calculation model.

From the assumptions in Section 4.1.1, the three groups of air traffic result in 9 combinations of Ownship and Intruder aircraft encounter cases and each case was analyzed using the risk ratio calculator (RR_{DAA}). The least mid-air collision risk was found to be between Type Group C (Ownship aircraft) and Type Group C (Intruder aircraft) from the given Group assumption combination cases, as shown in Section 4.1.4.5. The results of Section 4.1.4.1, 4.1.4.5, 4.1.6, and 4.2 also predict the effectiveness of the various combinations of DAA/Surveillance Equipment between Ownship and Intruder aircraft.

It should be noted that in the case of ADS-B, if only one of the aircraft is equipped with an ADSB-In/Out system, the other aircraft must also have at least ADSB-Out for the first aircraft to be able to detect it. This is investigated further for the case of when the Ownship aircraft is an UAV ("Blind", only ADSB-Out, or only ADSB-In/Out equipped) by evaluating the risk ratio and the NMAC rates in this case. In Section 4.2.1, in the case of the Ownship UAV with only ADSB-Out, it is noted that unmanned aircraft have limited communication tools and are absent of traditional surveillance equipment such as Airband Radio or TCAS. Group A and Group B cases of Intruder manned aircraft have Airband Radio, but UAV cannot use Airband Radio in the current aviation market. The FAA mandated ADSB-Out in their NAS airspace, and this has been a major incentive to install at least the ADSB-Out system on commercial manned aircraft. However, we have already shown that in the case of encounters when both aircraft have only ADBS-out, neither gets any benefit in terms of detection of the other, unless at least one also has ADSB-in. Section 4.2.2 shows the benefit when ADSB-In/Out capability is provided to both manned- and unmanned- aircraft.

Section 4.2.3 evaluates another possible future UAV configuration, where it is equipped with ADSB-In/Out, Airband Radio and also an effective machine-vision camera system. With this level of DAA/Surveillance Equipment for the UAV, the results of Section 4.2.3 indicate that this is potentially the safest configuration of DAA system for the UAV, plus also a safety benefit to unmanned aircraft.

This method of mid-air collision risk assessment can simulate the effectiveness of variable onboard DAA/Surveillance Equipment, and indicate the safest case of onboard DAA/Surveillance Equipment for lowering the mid-air collision risk.

The probability of mid-air collision risk depends on the factors discussed in Chapter 3.4.2. These factors include the communication interrelations involved with onboard DAA/Surveillance Equipment among aircraft, ATC, ground operators for manned aircraft and potentially also unmanned aircraft. Figure 5.1 shows the relationship of communication with DAA among manned aircraft, ATC, and Ownship aircraft operators/dispatcher group.

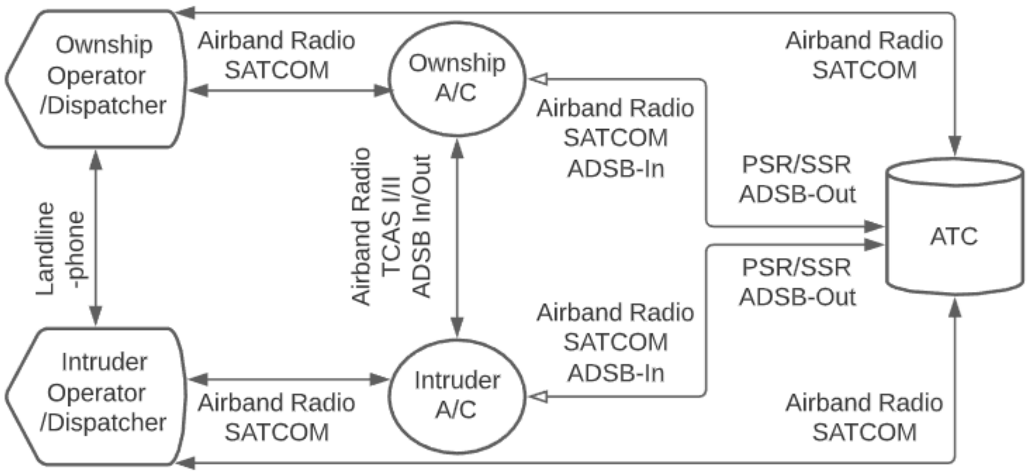

Figure 5.1: Communication Relation with DAA among Manned Aircraft, ATC, and Ground Operators

Ownship aircraft can communicate with Intruder aircraft by Airband Radio and/or cooperative method of communication if Ownship aircraft and/or Intruder aircraft are equipped with surveillance instruments such as TCAS I, TCAS II, or ADS-B In/Out. Ownship aircraft and ATC also can communicate through the traditional way of Airband Radio. ATC can detect aircraft by SSR or PSR within there radar coverage area, including reflected radar signals (if the range and size of aircraft permits), or active XPDR replies from cooperative aircraft with properly functioning XPDRs in the area. Additionally, ATC expands their ADS-B capacity of coverage and can detect aircraft if any aircraft is equipped with a functioning ADSB-Out system.

For example, a local (St. John's, YYT) helicopter company does not have mitigating aircraft procedures other than to set the frequency of ATC on Radio Tuning Unit (RTU) and turn on their TCAS system assuming one is equipped. However, pilots typically follow the AIM which issued by TC. This AIM covers all sources of rules of the air and air traffic services included airspace, VFRs, IFRs with departure-, EnRoute-, arrival- procedures and ATC special procedures as well [8].

In the case of IFR-flight aircraft between YQX and YYT, the general ATC standard would be 5 NM on radar or 1,000 ft vertically. For VFR-flight, once they are 7 NM from the airport they are responsible to see and avoid other VFR-flight aircraft. The general air traffic rules within Canada are covered by TC's CARs Part VI [53], General Operating and Flight Rules and Subpart 2, Operating and flight rules for both VFR under Division VI and IFR under Division VII. The Annex 2, "Rules of the Air" and Annex 11, "Air Traffic Services (ATS)" have been defined and evolved over many years, and are in compliance with International Civil Aviation standards such as the International Civil Aviation Organization's (ICAO) Procedures for Air Navigation Services – Air Traffic Management [7] and Air Traffic Services Planning Manual [64].

Manned aircraft use onboard surveillance equipment and good pilot airmanship to maintain WC and safety in the proximity of other Intruder aircraft. Likewise, UAS aircraft rely on the operators at the GCS and onboard DAA sensors to establish minimum separation to operate safely in the airspace[43]. It should be noted however, that air safety and separation standard specific for UAVs are still under discussion in most jurisdictions around the world.

As mentioned in Chapter 2.3.2, TCAS II equipped Ownship aircraft can coordinate with other TCAS II equipped Intruder aircraft. The TA and RA functions of TCAS enable both the prompt detection of all Mode-S XPDR equipped aircraft in range, the determination of any LOWC conflicts, and also provides coordinated collision avoidance between the aircraft. The RA function and uses CAS logic data to alert pilots in response to climbing or descending of both aircraft's flight controls [11]. The diagram shown in Figure 2.12 is a simple illustration of the TCAS radio frequency system [29]. Following the FAA guideline [65], the priority of response to any LOWC situation is for the pilot to follow the RA determined by the TCAS system. Also, the pilot must communicate with ATC and get advice as an additional measure if the pilot experiences any confusion or workload issues.

Since there are many surveillance equipment options in the market and unknown DAA/Surveillance Equipment combination effectiveness, the Ownship aircraft cannot dictate nor predict what DAA/Surveillance Equipment might be installed on Intruder aircraft they might encounter. This idea applies to the DAA/Surveillance Equipment probability calculator model in Subsection 3.4.2.1. This study narrows down these DAA/Surveillance Equipment options as 6 variable items identified as A, B, C, D, E, and F and builds the calculator model to find the probability of encountering each aircraft configuration type as shown in Subsection 3.4.1.1. Hence we find there are 384 possible DAA/Surveillance Equipment combinations cases of both Ownship and Intruder aircraft. For each risk assessment using the calculator, the Ownship aircraft DAA/Surveillance Equipment configuration is known and defined, whereas the Intruder configuration is allowed to be variable. The risk calculator therefore forecasts the mid-air collision risk for all 384 cases of DAA/Surveillance Equipment onboard Intruder aircraft based on statistical database of the equipped DAA items' rate.

In modern ATC technology, the ADS-B system is mandated in the US NAS airspace and is recommended for installation in Canadian airspace. The use of ADS-B in Canada would maintain equivalent current service with extended coverage at a lower cost.

5.1.1 Summary of Contributions

- Break down combination cases of Onboard DAA Surveillance variable Equipment on both Ownship and Intruder aircraft.
- Create DAA Equipment Probability Calculation Model ($P_{ENCTR\ type}$).
- Create Risk Ratio of Variable DAA/Surveillance Equipment (RR_{DAA}) Calculator Model for proceeding Mid-Air Collision Risk determination.
- Determine the Probability of Mitigated NMAC rate.
- Risk probability calculation model applies to both manned and unmanned aircraft.

5.2 Future Work

The study of DAA/Surveillance Equipment highlights that the ADS-B system is ideal for ensuring detection and maintenance of safe separation among aircraft using current technology available. This is especially true within high traffic density areas and outside of controlled airspace where currently ATC is not able to see them from their SSR system. Although the ADS-B system can help in these DAA tasks, it is noted all aircraft must be equipped with at least an ADSB-Out system to allow ATC to monitor and manage air traffic within their control zones. Even though the FAA mandated the ADSB-Out system, Canada still has challenges to make an ADSB-Out mandate due to the cost of installing the equipment mainly by flight operators.

On April 1st, 2019, the Aireon ADS-B system was introduced to Canada and will help ANSP monitor any conflicts of aircraft in real-time. However, until all aircraft are eventually equipped with ADSB-Out system, air traffic separation management based on ADS-B cannot fully function. During the transition, ANSPs in Canada will continue to use existing technologies, in particular PSR, SSR and XPDRs, to detect aircraft and manage air traffic.

In the meantime, the mid-air collision risk ratio may be used to assess the impact of currently available DAA/Surveillance Equipment, as shown in Section 4.1.4. With the limited work scope, this research uses the nominal number of DAA/Surveillance Equipment percentages and the DAA/Surveillance Equipment's NMAC probabilities.

Future work is proposed to collect the real data of traffic information with DAA Surveillance Equipment onboard each aircraft to calculate the traffic density using Equation 3.11 and a specific percentage of onboard DAA/Surveillance Equipment and NMAC by each DAA option, in Table 3.8 and 3.9. The application of the Monte Carlo method would suggest pursuing a future project and it would be helpful to calculate the real sensitivity of the detecting level of each DAA surveillance technology.

This study also noticed that ATC and manned aircraft want to stay with their traditional communication tools such as basic Airband Radio and (for the time being) the use of standard XPDRs. It would be wise for UAS operators to develop these same capabilities and install them on current unmanned aircraft. Figure 5.2 provides a diagram showing the Ownship UAV aircraft communication relations.

For future applications, the combined SATCOM and ADSB system could be used to link the traditional Airband Radio signal to carry over ANSP or manned aircraft communications to/from the GCS operator/pilot via the UAV. Changes in some of the Airband/Aviation regulations would be required to include this futuristic DAA functionality for UAV operations.

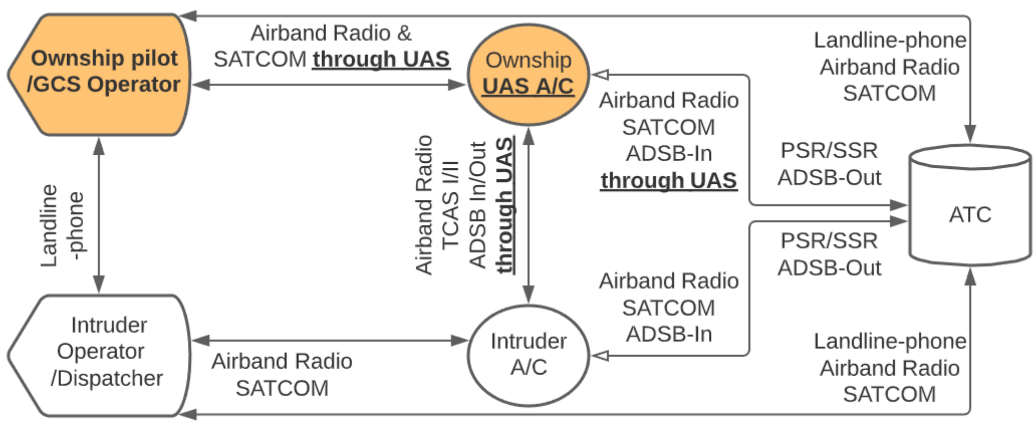

Figure 5.2: Communication Relation with DAA among UAS, Intruder Aircraft, ATC, and GCS

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