

---

# VISUAL CUEING FOR COLLISION AVOIDANCE SYSTEM

---

HUIYING LI  
MSc BY RESEARCH



AUTONOMOUS AND INTELLIGENT SYSTEMS  
DEPARTMENT OF ENGINEERING PHYSICS  
SCHOOL OF ENGINEERING  
CRANFIELD UNIVERSITY, CRANFIELD  
UNITED KINGDOM

2012



---

## Abstract

The modern Traffic Alert and Collision Avoidance System (TCAS) used in airlines today is the TCAS II. It provides pilots with both Traffic Advisory (TA) and Resolution Advisory (RA) which in turn reduces the incidence of mid-air collisions. It was demonstrated that TCAS could provide safety and economy benefits for airlines nowadays. However, as the demand for commercial air travels increases, it exerted a considerable amount of strain on the current ‘traditional’ TCAS system. This is primarily due to the increase in competition for airspace. Trajectory-based TCAS systems have been proposed to overcome the emerging difficulties with collision avoidance. To date, TCAS systems only provide vertical 2D guidance for the aircraft, that is to say, that the pilot only receives a ‘Climb’ or ‘Descend’ indicator with minimalistic visual cues. The following thesis proposes a new visual cueing method which integrates 3D trajectory path planning for TCAS system.

In general, Head-up Display (HUD) instrumentation provides the pilot with primary flight display, navigation and guidance information pertaining to the aircraft’s states. It is especially useful during the critical flight phases, such as approach, landing and manoeuvring. Furthermore, as the HUD is located in the direct front field of view, it allows the pilot to keep his/her head up while performing special tasks. It has been demonstrated that the HUD adds a substantial safety benefit as well as mitigating pilot workload. Thus a conceptual HUD has been proposed and was used in this project, the developed TCAS manoeuvre display and conflict alerts were superimposed on HUD.

A *Boeing 747* aircraft model developed in the MATLAB/Simulink environment has been integrated with a 3D trajectory-based TCAS system. Perspective projection techniques were addressed for TCAS resolution display and were developed in Java. The resolution display utilizes 3D tunnel-in-the-sky concept as an advanced visual cue. TCAS traffic indications and aural announcements were implemented using Java and MATLAB respectively. The HUD concept was designed in the de-cluttered format in accordance with FAR 25.1321/SAE ARP5288 standards, and was also developed in Java language. It maximised compatibility with head down display. Finally, the impact of the developed visual cueing methods were discussed and as-

essed through scenario trials.

This thesis presents an account of the work done within the scope. It underlines the main considerations of the design, how scenarios were implemented and their measurements. The research indicated that tunnel-in-the-sky was an appropriate display solution for trajectory-based collision avoidance. It has the advantage of presenting the predictive flight path in an intuitive and natural way.

---

## Acknowledgements

I wish to express my most sincere gratitude to everyone who has helped me throughout my research life in Cranfield University.

First and foremost I would like to thank my supervisor Dr. Al Savvaris, who has provided me constant motivation and constructive suggestion. I wish to acknowledge my project advisor Marco Melega for helping me to learn MATLAB/Simulink, Java language and encouraging and advising me on all aspects of work. I am also grateful to Mr. M.M.Lone who was my second supervisor for his excellent and untiring support and guidance.

Thanks must go to all members of office *F51*: Ramey Jamil, Henry Andres Porras, Kai Liao, Hyondong Oh, Ken Lai, Hakim Oheda, Hamid Alturbeh, Konstantinos Malandrakis, Leda Mer, Vasilis Rtms, Solange Baena Zambrana, Mark Picciani, Alessandro Gardi, Hernan Amaya, Charles Turquand Dauzay. Particular thanks express to Ramey Jamil for supervising me with flight dynamics principle, patient and critical to review my thesis.

I am very happy to know great friends here who help me to make balance between work and life, many thanks also for them: Chen Wentao, Jia Ninghong, Leonardo Lopez Mejia, Charlotte Ellis, Du Zongqi, Liu Wei, Paul Du, Liu Yijun, Dennis Yau, Jessica Guo, Colina Li, Melody Zhang, Peter Thomas, Nurhana M Rouyan, Tierry Bertrand, Hamberth Ruge, Oshiobugie Dokpesi, Julie Bruzi, Jean Louis, Jason Bl, Luca Gallo, Jesus Martinez, Daniel Grant, Lewis Read, Daniel Watt, Rowena Brown, Saurav Agarwal, James Clark, Alix Iain James Leckie, Claire Leckie, all my house mates in Building 16A and all friends from AVIC.

I would like also to give a special thank to all my COMAC colleagues in Cranfield who helped me during group design: Li Weiping, Guo Jianing, Liu Qingling, Shi Jie, Zeng Chao, Chen Jian, Liao Kai, Yang Yafang, Huang Feng. Thanks also give to Professor Ray Whitford who contributes to my basic flight dynamics knowledge.

I am also sincere indebted to all my leaders and colleagues in COMAC headquarters and SADRI, without their help and supports I cannot make my study in UK come true.

Last but not the least, I would like to thank my parents, my uncle, my younger sister and my elder cousins for their unwavering support and confidence with me.

Alicia Li

---

# Contents

<b>Abstract</b>	<b>iii</b>
<b>Acknowledgements</b>	<b>v</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Introduction . . . . .	1
1.2 Aim and Objectives . . . . .	2
1.3 Scope . . . . .	2
1.4 Thesis Structure . . . . .	3
<b>2 Literature Review</b>	<b>4</b>
2.1 Aircraft Cockpit Interface . . . . .	4
2.1.1 Glass Cockpit Instrumentation . . . . .	4
2.1.2 Display Integration Analysis . . . . .	6
2.2 Review of Head-up Display . . . . .	7
2.2.1 Field of View Definition . . . . .	8
2.2.2 HUD Function Description . . . . .	9
2.2.3 Selected HUD Symbology Discussion . . . . .	10
2.2.4 Development Consideration . . . . .	13
2.3 Review of Traffic Alert and Collision Avoidance System . . . . .	14
2.3.1 Development of TCAS . . . . .	14
2.3.2 Human Machine Interface . . . . .	17
2.3.3 Collision Avoidance Logic . . . . .	19
2.3.4 TCAS III principle . . . . .	23
2.3.5 Future Horizontal Resolution . . . . .	24
2.3.6 TCAS Failure Example . . . . .	26
2.4 Review of Tunnel-in-the-Sky . . . . .	28
2.4.1 Grunwald’s research about Tunnel-in-the-sky . . . . .	29
2.4.2 Tunnel-in-the-sky of Japan Aerospace Exploration Agency . . . . .	29
2.4.3 Effects Analysis . . . . .	30
2.4.4 Conclusion . . . . .	31
<b>3 Visual Cueing Design Methodology</b>	<b>32</b>
3.1 General Introduction . . . . .	32
3.1.1 Definitions . . . . .	32
3.1.2 Coordinates Transformation . . . . .	33

3.2	Perspective Display Design Method . . . . .	37
3.2.1	General Introduction . . . . .	37
3.2.2	Perspective Projection Method . . . . .	38
3.3	TCAS Manoeuvre Display Design Method . . . . .	39
3.3.1	Define Flight Path . . . . .	40
3.3.2	Generate the nominal tunnel . . . . .	40
3.3.3	Accomplish TCAS Interface . . . . .	41
3.4	Flight Path Predictor Design Method . . . . .	42
3.4.1	Design Consideration . . . . .	42
3.4.2	Algorithms Development . . . . .	43
<b>4</b>	<b>Interface Development and Integration</b>	<b>46</b>
4.1	General Consideration . . . . .	46
4.1.1	HUD Design Consideration . . . . .	46
4.1.2	Tunnel Size Definition . . . . .	50
4.2	System Integration . . . . .	53
4.2.1	Introduction . . . . .	53
4.2.2	Aircraft Model . . . . .	54
4.2.3	TCAS system . . . . .	55
4.2.4	FlightGear . . . . .	55
4.2.5	Integration Process . . . . .	56
4.3	Display Symbology . . . . .	58
4.3.1	HUD Symbology . . . . .	58
4.3.2	Avoidance Manoeuvre Symbology . . . . .	61
4.4	Final Display Information Analysis . . . . .	64
4.4.1	Guidance to the Tunnel Consideration . . . . .	64
4.4.2	Traffic Display Consideration . . . . .	65
<b>5</b>	<b>Collision Avoidance Scenario</b>	<b>66</b>
5.1	Mid-air Collision Definition . . . . .	66
5.2	Scenario Description . . . . .	67
5.2.1	Scenario One Description . . . . .	67
5.2.2	Scenario Two Description . . . . .	69
5.2.3	Scenario Three Description . . . . .	71
5.3	Scenario Implementation . . . . .	72
5.3.1	Basic Pull-up Scenario One Implementation . . . . .	73
5.3.2	Turn Right Scenario Two Implementation . . . . .	77
5.3.3	Trajectory-based Manoeuvre Scenario Three Implementation . . . . .	81
5.4	Discussion . . . . .	82
5.4.1	Problem Discussion and solution . . . . .	85



<b>6 Conclusion and Future Work</b>	<b>88</b>
6.1 Summary of the Research . . . . .	88
6.2 Conclusive Remarks . . . . .	88
6.3 Future Work . . . . .	89
<b>Bibliography</b>	<b>90</b>

---

## List of Figures

2.1	The Primary Flight Display . . . . .	5
2.2	The Multi-Function Display . . . . .	5
2.3	Head-up Display in B787. . . . .	7
2.4	HUD fields-of-view defined . . . . .	9
2.5	Vertical Deviation Indicator . . . . .	11
2.6	Glideslope Deviation Indicator . . . . .	12
2.7	Glideslope Deviation Indicator - AIII or IMC Mode . . . . .	12
2.8	Primary Mode Symbolology - In Flight . . . . .	15
2.9	HUD de-clutter Display - HGS AIII Approach and Landing . . . . .	15
2.10	TCAS traffic display on EFIS . . . . .	19
2.11	TCAS traffic display with IVSI . . . . .	19
2.12	TCAS RA Example on EFIS . . . . .	19
2.13	TCAS RA Example on HUD . . . . .	19
2.14	Sensitivity Level Definition and Alarm Thresholds . . . . .	20
2.15	TCAS Protection Volume (horizontal) . . . . .	21
2.16	TCAS Protection Volume (vertical) . . . . .	21
2.17	CAS Logic Functions . . . . .	22
2.18	RA Sense Determination . . . . .	23
2.19	Resolution in the horizontal plane . . . . .	25
2.20	Conflict resolution cone . . . . .	25
2.21	Strategic AOP conflict detection . . . . .	26
2.22	Map of Mid Air Collision in Germany . . . . .	27
2.23	Schematic of Aircraft Manoeuvre for Uberlingen Mid Air Collision . . . . .	27
2.24	Curved Tunnel Display with Control Information . . . . .	29
2.25	Horizontal symbolology of tunnel-in-the-sky . . . . .	30
2.26	Basic Information of tunnel-in-the-sky . . . . .	31
3.1	ECEF Reference Frame. . . . .	33
3.2	Flight–Path Reference Frame Definition . . . . .	33
3.3	WGS 84 . . . . .	34
3.4	ECEF and Reference Ellipsoid . . . . .	34
3.5	The relationship between ECEF reference frame and NED reference frame . . . . .	36
3.6	The 3D projection method . . . . .	38
3.7	Vertices of the tunnel . . . . .	40

3.8	Method to estimate attitude based on trajectory position . . . . .	42
3.9	Control activities required with predictor symbol . . . . .	43
4.1	The 3D projection method - Top view . . . . .	47
4.2	The 3D projection method - Side view . . . . .	47
4.3	Typical HUD Fields-of-View . . . . .	48
4.4	The proposed HUD layout. . . . .	50
4.5	The proposed tunnel in the real world. . . . .	52
4.6	Integration block . . . . .	54
4.7	Overview TCAS system logic. . . . .	55
4.8	Information from aircraft model. . . . .	57
4.9	Information from TCAS. . . . .	57
4.10	The primary symbols of the developed HUD concept. . . . .	58
4.11	Avoidance manoeuvre symbology with HUD . . . . .	62
4.12	Turn right Advisory display . . . . .	63
5.1	Flight status of two conflict aircraft. . . . .	68
5.2	Conventional RA (pull up or push down). . . . .	69
5.3	Flight status of two conflict aircraft (face to face). . . . .	70
5.4	Horizontal RA (turn left or turn right). . . . .	71
5.5	Trajectory-based RA (climb and turn right). . . . .	72
5.6	Manoeuvre strategy (PULL UP). . . . .	74
5.7	Flight path angle of intruder. . . . .	77
5.8	Intruder's descending trajectory. . . . .	77
5.9	Manoeuvre strategy (TURN RIGHT). . . . .	79
5.10	Heading angle of intruder. . . . .	81
5.11	Intruder's turn right trajectory. . . . .	81
5.12	Intruder's 3D trajectory. . . . .	82
5.13	Vertical collision avoidance manoeuvre (3D, Latitude, Longitude and Altitude status). . . . .	83
5.14	Horizontal collision avoidance manoeuvre (3D, Latitude, Longitude and Altitude status). . . . .	84
5.15	Trajectory-based collision avoidance manoeuvre (3D, Latitude, Longitude and Altitude status). . . . .	85
5.16	Trajectory-based manoeuvre montages. . . . .	86
5.17	New trajectory generation strategy. . . . .	87

---

## List of Tables

4.1	Characteristics of Tunnel-in-the-sky . . . . .	51
4.2	Parameter of Tunnel for TCAS . . . . .	52



---

# Nomenclature

## Algorithm

$\gamma$	Aircraft flight path angle
$\iota$	Geodetic latitude information
$\mu$	Geodetic longitude information
$\omega$	The intruder's bearing rate
$\vec{P}_{Traj}$	Trajectory's position vector
$\phi$	Aircraft roll angle
$\psi$	Aircraft heading angle
$\sigma_\omega$	The intruder's bearing rate error
$\sigma_m$	Horizontal miss-distance error
$\theta$	Aircraft pitch angle
$\vec{v}_R$	The relative velocity between intruder and host aircraft
$C_1, C_2, C_3, C_4$	Vertex of tunnel frame
$d$	The relative range between intruder and host aircraft
$k$	Distance between origin of $V$ and $V_f$ reference frame
$l$	Half length of the tunnel frame
$m$	Horizontal miss-distance
$p$	Angular rate about the $x_b$ axis
$q$	Angular rate about the $y_b$ axis
$r$	Angular rate about the $z_b$ axis
$T_{pred}$	The selected time ahead of flight path vector
$v_n$	The estimated velocity vector in NED reference frame
$w$	Half width of the tunnel frame
R	TCAS horizontal protection zone radius

## Acronyms

AOP	Autonomous Operations Planner
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon Beacon System
BCAS	Beacon Collision Avoidance System
CAS	Collision Avoidance System
cg	Aircraft centre of gravity
COMAC	Commercial Aircraft Corporation of China, Ltd.
CPA	Closest Point of Approach
CRT	Cathode Ray Tubes
DCM	Direction Cosine Matrix
ECEF	Earth–Centred Earth–Fixed

EFIS	Electronic Flight Instrument System
EICAS	Engine Indicating and Crew Alerting System
ENU	Local East, North, Up
FAA	Federal Aviation Administration
FD	Flight Director
FMS	Flight Management System
FOV	Field of View
GPS	Global Positioning System
HDD	Head-Down Display
HMI	Human Machine Interface
HUD	Head-up Display
ICAO	International Civil Aviation Organization
IMC	Instrument Meteorological Conditions
IVSI	Instantaneous Vertical Speed Indicator
JAXA	Japan Aerospace Exploration Agency
LCD	Liquid Crystal Display
LLA	Latitude, Longitude, Altitude
MFD	Multi-Function Display
MFP	Manoeuvre Display
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NED	Local North, East, Down
NMAC	Near Mid-air Collision
NTSB	National Transportation Safety Board
PFD	Primary Flight Display
RA	Resolution Advisory
RF	Radio Frequency
SL	Sensitivity Level
SSR	Secondary Surveillance Radar
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
WGS	World Geodetic System

---

## Introduction

### 1.1 Introduction

With the fast growing air traffic, the Free Flight regulation is becoming evermore popular. Free Flight provides economical advantage, while increasing capacity and improving safety, and as such, it is considered to be promising concept for future aeronautical research [1]. To support this mode of operation, a considerable amount of research in conflict detection and resolution which is used to remind pilots about the immediate loss of separation, must first be established [2]. The current widespread TCAS system is one available approach for traffic resolution, however it only possesses the capability of issuing the vertical resolution advisory without the horizontal, thus pilots regard it as an interim development and desire a new TCAS system with greater functionality [3].

A significant amount of research has been conducted in to the latest generation of trajectory-based TCAS systems [2, 3, 4, 5, 6, 7, 8]. These systems can issue horizontal or random *3D* RAs as a supplement of the vertical RAs when appropriate and necessary with the help of more accurate location and heading information. It is expected to be more flexible, effective and safe compared with the conventional commercial TCAS system. Apart from the Collision Avoidance System (CAS) logic, the Human Machine Interface (HMI) for TCAS system is also crucial, as it is the primary and elemental way for pilots to communicate with TCAS system. The conventional flight displays can only provide the vertical *2D* plane guidance for TCAS system, it cannot present a nature and intuitive display for the trajectory-based TCAS system, thus a new visual cueing method needs to be developed.

‘Tunnel-in-the-sky’ concept is a *3D* display with the feature of presenting the recommended flight path by a series of different size tunnel frames. It illustrates the scenes outside of cockpit through perspective projection method. It was particularly investigated for normal or low visibility approaching, landing flight phase, and airborne remote sensing. Researchers founds it had the advantage to predict the flight path, enhance pilot’s situational awareness, improve flight accuracy and reduce training cost [9, 10, 11, 12, 13]. However integrating tunnel concept with TCAS HMI for mid-air collision has not yet to be performed. Hence this project presents a novel tunnel-in-



the-sky concept to trajectory-based TCAS system as part of its manoeuvre display.

## 1.2 Aim and Objectives

The aim of this project is to develop visual cueing techniques for future trajectory-based collision avoidance system, and explain its effectiveness and benefits through scenarios implementation and discussion.

In order to achieve the aim, so that it is comparable with industry requirements, the following objectives need to be conducted:

1. Review and discuss about current display technologies, TCAS system and tunnel-in-the-sky display, including background, history, relative standards, function discussion, advanced research and benefits.
2. Develop prototype HUD that is comparable with current symbology approach and industry regulations.
3. Apply tunnel-in-the-sky concept and develop visual cueing methods and conflict alert announcement for TCAS system.
4. Discuss and assess the developed visual cueing method through scenarios definition and implementation.

## 1.3 Scope

This project mainly dealt with avoidance manoeuvre display and HUD concept development. Due to the trival nature of the traffic display and oral prompt systems, these have simply been implemented, disregarding further discussion and investigation. The visual cueing utilises perspective projection method for tunnel-in-the-sky, and is applied to the trajectory-based TCAS system.

To evaluate and demonstrate the novel visual cueing method, a *Boeing 747* aircraft model developed by Dynamics, Simulation & Control Group of Cranfield University was chosen as the host aircraft. To maintain a measure of simplicity, the intruder is denoted as a set of known Longitude, Latitude, Altitude positions. The host aircraft was controlled by pilots through joystick with pitch and roll commands.

## 1.4 Thesis Structure

**Chapter 2** presents the literature review of the aircraft cockpit interface, HUD, TCAS system and tunnel-in-the-sky display. Their relative background, specific system function, selected symbology and integration analysis have been given.

**Chapter 3** explains the methodology utilised in this thesis. The perspective projection method is used to generate the tunnel-in-the-sky symbology from the virtual tunnel frame in the real world. An appropriate TCAS manoeuvre algorithm was implemented using aircraft position and velocity vector to generate the nominal trajectory for TCAS manoeuvre display. A second order function was adopted for longitudinal and lateral flight path predictor design. The predictor's development for perspective flight path display was mainly based on the navigation and control requirement.

**Chapter 4** describes and explains the process of system integration. Every block function of the model was presented separately. It also presents the novel HUD concept and avoidance manoeuvre display symbology, discusses the design consideration and corresponding solution for visual cueing method.

**Chapter 5** describes the scenario studies of the final display solution. Three collision avoidance scenarios are defined and implemented, involving the basic pull-up advisory, turn right advisory and trajectory-based resolution advisory scenarios. The two conflicted aircraft's position information are recorded and discussed after the scenario trials.

**Chapter 6** draws some final conclusion of this project, also presents a direction of further research in this field.

---

## Literature Review

This chapter provides the essential knowledge for aircraft cockpit displays, TCAS system and tunnel-in-the-sky display. It establishes the significant aspects related with the HMI which contributes to the design of visual cueing for collision avoidance system.

### 2.1 Aircraft Cockpit Interface

The cockpit is regarded as aircraft's eye, it provides pilots with the fundamental information for safe flight, the Flight deck system is the control and monitor centre offering pilots the main HMI to perform flight task. Some of the first examples of the flight deck systems utilised switches and electromechanical instrumentation. The development of the Cathode Ray Tubes (CRT) brought on a new era of systification to the flight deck system, this was soon follow by the Liquid Crystal Display (LCD) system which are in use today.

#### 2.1.1 Glass Cockpit Instrumentation

Glass cockpit is evermore popular and has now become the standardised equipment for modern airliners today. Electronic Flight Instrument System (EFIS) is its patent representation, normally including Primary Flight Display (PFD), Multi-Function Display (MFD) and Engine Indicating and Crew Alerting System (EICAS) display. They provide aircraft operation and navigational information at the pilot's command.

##### Primary Flight Display

PFD provides the most critical flight information to pilots and flight crews. As Figure 2.1 shown, it involves Airspeed Indicator, Altitude Indicator, Attitude Indicator, Flight Director and Flight Mode Indicator. The arrangement of PFD satisfies FAR 25.1321 item requirement, such that the attitude indicator is on the top centre location of the display panel, airspeed indicator is located on the left hand side while altitude is mirrored to the airspeed on the right hand[14]. The PFD integrates information on one display in order to increase pilots' situational awareness, improve reliability and reduce their workload.

### Multi-Function Display

The MFD also is called Navigation Display (ND), commonly, it provides pilots navigation and weather information. The buttons around the instrument margin allow the pilots to change different display areas. Figure 2.2 is MFD with Map Mode, it consists of compass rose, heading information and waypoint information. The white connection line of the several waypoints builds the planned trajectory. The Map Mode function is used to describe the aircraft position related to the fixed routes and airports.



Figure 2.1: The Primary Flight Display[15].



Figure 2.2: The Multi-Function Display[16].

### 2.1.2 Display Integration Analysis

From the development of EFIS display, it is not difficult to call information which allows pilots to perform flight task precisely and effectively. It is integrated properly and naturally allowing pilots to perceive information without increasing workload. A good example of integrating more flight information into one display is artificial horizon. Not only presenting aircraft's pitch attitude, but it also provides aircraft's roll attitude information which is compatible with the real horizon outside of cockpit. It helps pilots to perceive aircraft flight dynamics immediately and directly. Information integration does not mean collecting a bundle of information together and showing it completely on one display, the basic principle is to depict the information with their relationships which is simple to interpret and execute[17].

MFD Map Mode is the typical intuitive symbology which is extensively used today. Pilots can get aircraft situation awareness easily through the horizontal navigation information, it is the classic example that illustrates the benefit of information integration. However, the pilots still cannot forecast the detailed flight path via this kind of display. In this instance the pilot can only follow the Flight Director (FD) in PFD[18]. FD works together with attitude indicator to display the required pitch angles and roll angles in order to follow the planed trajectory. The pilots only perceive the horizontal and vertical angle error from FD, and try to minimise the error, they have no idea about the aircraft motion against the desired trajectory. EFIS works well during the normal flight phases, such as normal take off, climbing, cruising, and even approach and landing. Whereas during some crucial flight status, for instance in the event that a coupled sharp roll and pitch is required - it is hence difficult for pilots to follow. If a type of display could provide pilots with the predictive flight path, pilots could discover the severe condition ahead and adjust their control according to the mission. Therefore, the advantage of predictive display is obvious. It not only provides more time for pilots to be aware the flight situation, but also releases them from passively chasing the FD.

As discussed previously, the latest EFIS display served in airlines will not satisfy the growing aviation, specially when performing particular flight task, such as complex trajectory following or low visibility take off and landing. Researchers found the display with integrated components could reduce pilots scanning and workload[17]. Thus a new format of display, more integrated with 3D/4D flight information, is necessary for the future cockpit instrumentation. The advantage of this display system is presenting pilots with the defined time-domain or distance-domain planned trajectory. Hence the pilots can perceive aircraft situation, motion and the required control in advance. It could further reduce pilot workload as it will significantly

increase the reaction time. The detailed information related with 3D/4D flight display is described in section 2.4.

## 2.2 Review of Head-up Display

A HUD is a transparent glass ‘combiner’ screen located in the pilot’s forward field of view[19]. Compared with the conventional cockpit display system, Head-Down Display (HDD), the HUD allows the pilot to maintain his usual viewpoint without changing between head-up and head-down position. Initially it was used by the military for their gunsight[20]. Gradually, HUD was found could provide additional accuracy compared with conventional flight display. The discovery induced the the first commercial aircraft HUD system development which was dedicated for landing. Firstly it was practised for Mercure aircraft in 1970s. Later, Alaska Airline adopted a holographic optical system-contributed to HUD guidance system, to conduct manually CAT IIIa landing. This was the beginning of an airline utilising a HUD system. After, HUD system was demonstrated specially useful for low visibility operations, thus it was selected by regional airlines to support their routine operations during the bad weather days. Gradually, HUD system became popular in commercial aircraft aviation and installed in several worlds airline flets, such as: *Boeing 737*, *Boeing 747*, *Airbus 318*, business jets and etc. Today, HUD presents the standard flight instrumentation as addition to PFDs, while it offers enhanced performance, such as low-visibility take-off and AIII approach mode. Figure 2.3 presents a HUD and two PFDs. Pilots have indicated that the HUD system can improve flight performance and increase situational awareness in critical phases of flight.



Figure 2.3: Head-up Display in B787.

### 2.2.1 Field of View Definition

A HUD is located between the pilot's position and aircraft's windshield. According to its size and specific position, the features of pilot's visual range are described as follows. It is based on several parameters which are defined in the SAE AS8055 'Minimum Performance Standard for Airborne Head Up Display (HUD)' standard.

A field of view is a visual solid angle with boundaries[21]. The boundaries are the substantial facts that decide how much fundamental flight parameters and guidance information are superimposed on a HUD. Four different kinds of Field of View (FOV) characteristics[22] are described below, Figure 2.4 illustrates the image range of the pilot.

***Total FOV (TFOV)** – The total FOV is the union of the solid angles subtended at each eye by the clear aperture of the HUD optics from positions within the Eyebox. Thus, the total FOV defines the maximum angular extent of the display than can be seen with either eye allowing head motion within the Eyebox. It is generally specified in degrees vertical and degrees horizontal.*

***Instantaneous FOV (IFOV)** – The instantaneous FOV is the union of the two solid angles subtended at each eye by the clear aperture of the HUD optics from a fixed head position within the HUD Eyebox. Thus, the instantaneous FOV is comprised of what the left eye sees plus what the right eye sees from a fixed head position within the HUD Eyebox. The instantaneous FOV is illustrated in Figure 2.4 as the sum of the left eye and right eye monocular FOV.*

***Binocular overlapping FOV** – The binocular overlapping FOV is the intersection of the two solid angles subtended at each eye by the clear aperture of the HUD optics from a fixed head position within the HUD Eyebox. This defines the maximum angular extent of the HUD display which is visible to both eyes simultaneously. Thus, the binocular overlapping FOV is comprised of what the left eye sees which is common to what the right eye sees from a fixed head position within the HUD Eyebox.*

***Monocular FOV** – The monocular FOV is the solid angle subtended at the eye by the clear aperture of the HUD optics from a fixed eye position. This defines the angular extent of the HUD display as seen by a single eye as shown in Figure 2.4. The size and shape of the monocular FOV is dependent on the eye position within the HUD Eyebox.”*



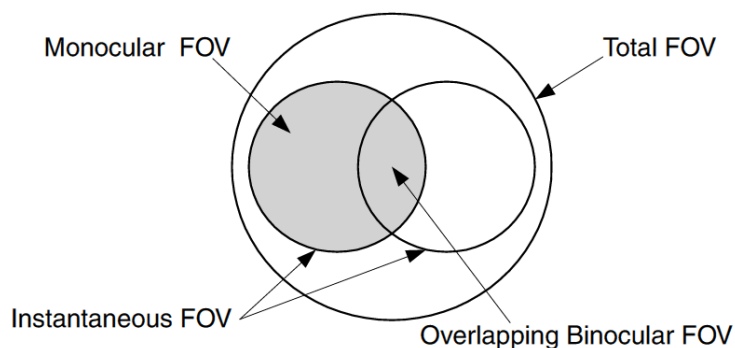


Figure 2.4: HUD fields-of-view defined[23].

The fixed horizontal field-of-view is about  $28deg$  which eliminates the symbology out of this range. For instance, one aircraft is flying on the right hand side of host aircraft and becoming a intruder. Assuming TCAS system does not provide TA and RA for flight crews of both aircraft and each aircraft is outside of 28 degrees of HUD, which implies the conflicts cannot be discovered by each. The consequence is that the two aircraft will collide. Thus the limitation of the HUD's field-of-view leads to the pilot's attention narrowed. The HUD with 20 degrees FOV can present symbology in a conformal way, there is another HUD with 40 degrees FOV which named compressed HUD and can provide pilot with extensive range of view but the symbology is un-conformal. Studies indicated pilots preferred the bigger FOV during the curved trajectory and the conformal HUD during cruising phase with straight flight line[24].

### 2.2.2 HUD Function Description

The HUD aims to provide the pilot with the most adequate information during a particular flight task or operation. It allows pilot to acquire aircraft attitude, airspeed, altitude information and aircraft position rapidly and easily. It was found to reduce pilot's workload and increase safety, especially when aircraft encounter severe weather or specific mission. The HUD's display mode depends on different phases of flight. Typically, it involves supplemental use, alternate use and additional credit use[25].

Depending on the different types of HUD applications and their intended function, the corresponding sets of information displayed on a HUD is different. For instance, if pilots are required to operate aircraft manoeuvres (avoid mid-air collision) during cruising flight phase, the items below may include:

- Aircraft flight conditions, such as: attitude, altitude and airspeed.



- Flight path indication and Flight Director.
- The target airspeed and the speed limit indications.
- The target aircraft altitude.

### 2.2.3 Selected HUD Symbology Discussion

In order to provide the elementary and comparable information for visual cueing methods, the selected HUD symbology is introduced and discussed herein based on the head-up guidance system model 4000 from Rockwell Collins.

#### Aircraft Reference Symbol and Horizon Line

Aircraft Reference Symbol and Horizon Line are the most elementary symbols on a HUD. Regardless of the flight mode, these two symbols will be displayed on the HUD when the system is powered and operating regularly. As shown in Figure 2.8, the aircraft reference symbol is always fixed on the HUD. It is located above the vertical centre of the display, the detailed position is defined by the flight path angle of the aircraft during level flight.

The horizon line is one of the conformal symbols of the HUD, it coincides with the real world horizon. It works with aircraft reference symbol, the vertical distance between boresight of aircraft reference symbol and the horizontal line indicates the aircraft pitch angle. The angle between aircraft reference symbol and horizon line symbol is aircraft roll attitude.

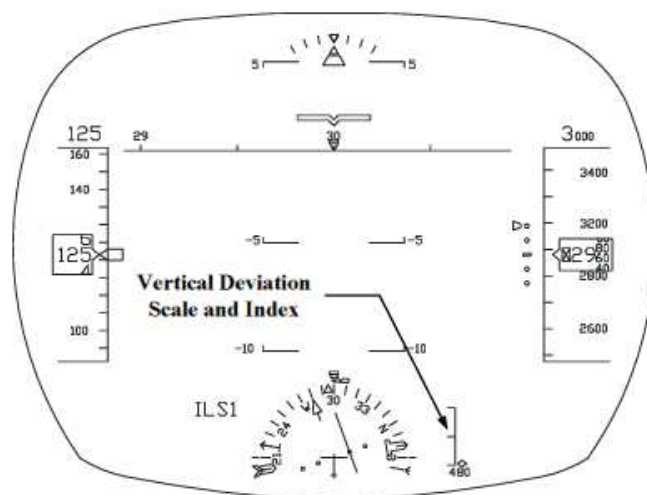
#### Flight-Path Symbol and Flight Director Guidance Cue Symbol

The Flight-path symbol provides pilot with aircraft actual flight path vector to allow for guidance and control tasks (Figure 2.8). It tells the pilots where the aircraft will fly to shortly. The flight-path symbol is relative to pitch scale. The centre of the circle on pitch scale decides the inertial flight path angle and aircraft drift angle. During flight, pilots assess the performance of the aircraft according to flight path angle. If the flight-path symbol resides above the horizon line, it implies the aircraft is climbing.

The flight director guidance cue symbol (Figure 2.8) indicates the pitch and roll steering commands. The pilot needs to react to these commands, by maintaining the flight path symbol over the guidance cue, or in other words, ensuring that both symbols overlap at all time.

### Vertical and Glideslope Deviation

The vertical deviation indicator is consisted of a scale and an index as presented in Figure 2.5, it used to indicate the aircraft's vertical deviation compared with the data from Flight Management System (FMS). The deviation scale is the solid line with three different marks on it and is fixed on the lower right hand corner of the display. If the marker resides in the centre, then this implies that there is no vertical deviation. The maximal scale of the scale is  $\pm 400$  feet. The hollow diamond shaped deviation index located on the right side of the scale is used to illustrate the current vertical deviation of the aircraft.



**Figure 2.5:** Vertical Deviation Indicator [26].

The glideslope deviation indicator also provides the pilots the aircraft vertical deviation indication from the glideslope reference line but only during Instrument Landing System working phase. Figure 2.6 is the symbology for the glideslope deviation primary mode. Glideslope deviation indicator is also consisted of the deviation scale and the index. This is different from the vertical deviation indicator. The glideslope adopts hollow dots and a rectangular as the scale, the rectangular implies no deviation from the glideslope reference line. The hollow trapezoid is the index pointer. Figure 2.7 illustrates the symbology of AIII or Instrument Meteorological Conditions (IMC) mode. As opposed to the primary mode, two horizontal bars are used in the AIII or IMC mode. These bars refer to the glideslope reference line to display the deviation. The reason to change the glideslope deviation indicator is to allow for greater sensing in aircraft control.

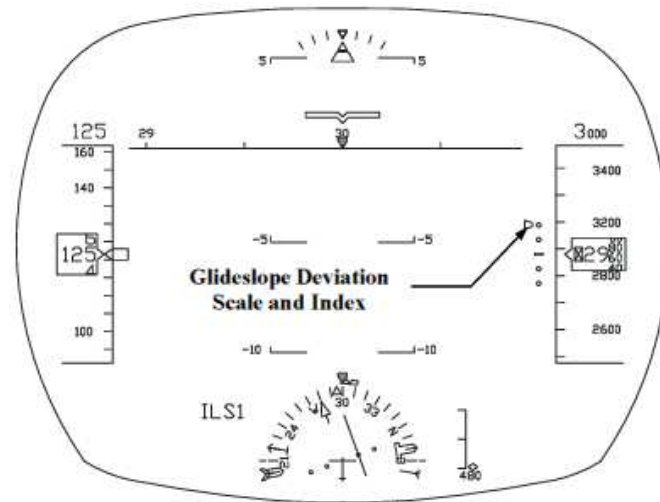


Figure 2.6: Glideslope Deviation Indicator - Primary Mode [26].

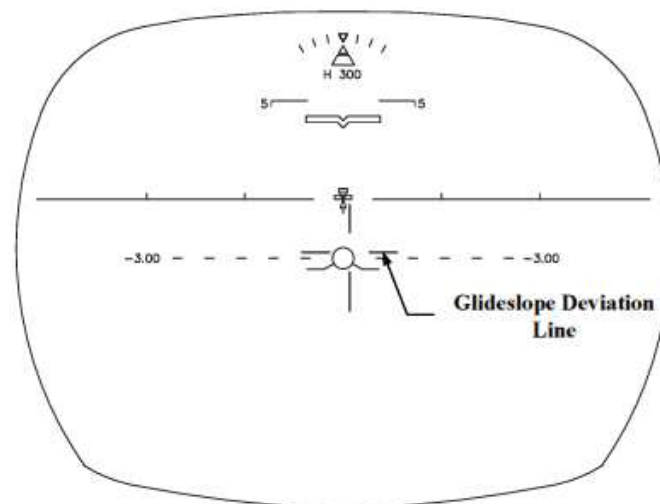


Figure 2.7: Glideslope Deviation Indicator - AIII or IMC Mode [26].

### Digital Indication

One of the significant differences between a HUD and a PFD is that the HUD has its unique display mode, denoted as 'decluttered mode'. This eliminates specific symbology such as airspeed tape and altitude tape but instead displays a digital output. The decluttered mode HUD provides pilot with the critical information according to flight task denoting 'clearer' interface. Herein only the interested digital values are described as follows:

### Digital Current Airspeed

Its position is relative to the flight path symbol or aircraft reference symbol which is located below and on the left of Flight path symbol or aircraft reference symbol with one-knot increment.

### Digital Current Altitude

It is the digital readout of the barometric altitude with 10-foot increments as opposite to the altitude tapes in full mode. Similar to the digital current airspeed, its position is also relative to the flight path symbol or aircraft reference symbol.

### Vertical Speed Indicator

It is used to indicate the inertial vertical speed of the aircraft. The position of the vertical speed indicator is different depending on the phase of flight. In AIII mode, it is located just below and to the right of the flight path symbol. Beside of the digital date, there is a 'VS' symbol showing its special use.

## 2.2.4 Development Consideration

Since the first commercial aircraft HUD was developed in the early 1970s, its occupancy on aircraft spread fast. Rockwell Collins reported in 2000 that, a HUD has the benefit of increasing aircraft safety and reducing airline operation fees[27].

### Layout

In order to reduce pilots' training with HUD and increasing flight safety, the developer should consider how to maximise symbology compatibility between HUD and HDD. Most symbology and their arrangement of these two displays are shared, furthermore, FAR 25.1321 is also applicable for HUD design. However, HUD interface development should not simply copy the HDD's symbology and layout - specific HUD symbology is required depending on aircraft flight mode.

### Conformal Symbology

This is the definition for a *conformal display* according to Newman[20] is as follows:

*“in which the symbols appear to overlie the objects they represent”*

The symbology on a conformal display is aligned as close as possible with the real world. An abundance of Researches demonstrate that the conformal display has the advantage of reducing scan time[28, 29]. For example, during the landing phase, the runway symbols overlying on the real runway outside

of the cockpit, it only moves concord with the relative position of aircraft and the real runway. Another example is the horizon line that conforms with the real world horizon. These kinds of symbology are defined as comfortable symbology, it is one of the unique characteristics of the HUD. Furthermore, *virtually conformal* symbology is one more kind of conformal symbology, which is conformal with the far domain environment. For instant, the flight path and tunnel-in-the-sky symbology is conformal with the commanded trajectory in the real world. While there is no flight path and tunnel can be seen outside of the cockpit, they are the image with predictive information only can depicted on a display. Investigations indicate the conformal flight path symbology improving tracking accuracy and the conformal tunnel could ease the cognitive effects[30].

### **Clutter and De-clutter**

Another unique characteristics of a HUD is called ‘de-clutter’ format due to its smaller size, the de-clutter format presents pilot with a concise display interface in order not contribute to misleading. Figure 2.8 and Figure 2.9 are two different formats of HUD depending on aircraft flight phase. Figure 2.8 presents the typical HUD symbology called the primary mode display, Figure 2.9 shows HUD de-clutter display based on AIII approach and landing. From the figures, it is easy to find the most different between them is Airspeed tape and Altitude tape are eliminated, replacing with digital airspeed and altitude. The basic full format HUD symbology maybe include: Pitch, Roll, Slip/Skid Indicators, Heading, Airspeed, Altitude, Attitude, Flight Director, Flight Path symbol, Vertical Speed, Deviation Indicator and so on[27].

## **2.3 Review of Traffic Alert and Collision Avoidance System**

TCAS is the implementation of collision avoidance system developed by Federal Aviation Administration (FAA) to provide pilots situational awareness. Two levels of TCAS system are used in recent aviation, both of them operated independently from aircraft navigation system and Air Traffic Control (ATC) system [31]. TCAS system is regarded as the ‘last ditch’ of preventing mid-air collision between aircraft and used mandatory and worldly in many airlines[32].

### **2.3.1 Development of TCAS**

The original guarantee for aircraft collision is based on ‘see and avoid’ principal, also related to separation coordinated by ATC system[31, 33]. While with the increasing growth of air traffic, the risk probability of collision

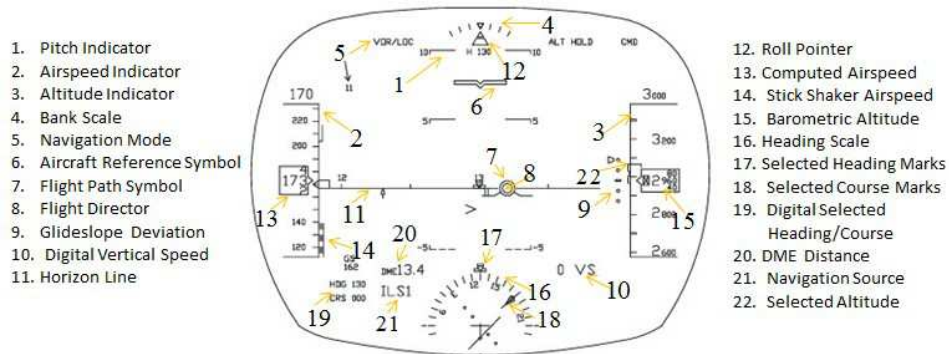


Figure 2.8: Primary Mode Symbology - In Flight [26].

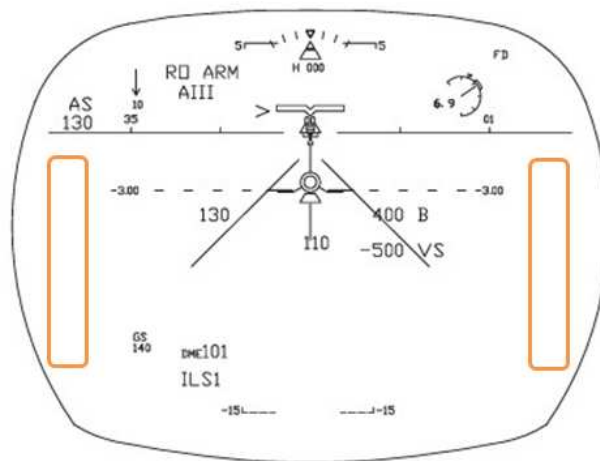


Figure 2.9: HUD de-clutter Display - HGS AIII Approach and Landing [26].

is rising. After the catastrophic mid-air collision between two aircraft in Grand Canyon in 1965, collision avoidance system was considered seriously to move forward. Following, variant TCAS and the related similar devices are developed by FAA Technical Centre, and the International Civil Aviation Organization (ICAO) is responsibility for the standardization activities[31].

Since the mid of 1970s, the innovation of TCAS is described as follows:

### **Beacon Collision Avoidance System**

Beacon Collision Avoidance System (BCAS) is the early form of TCAS system. It gets intruders range and altitude through interrogating the Air Traffic Control Radar Beacon System (ATCRBS) transponders[31, 33]. At the earlier stage, this system worked well and brought safety benefit significantly. However, later the Radio Frequency (RF) efficiency became the problem when the quantity of the aircraft was huge[32].

### **TCAS I**

TCAS I can be looked as the enhanced BCAS system. It is an active interrogation system and provides pilots TA without manoeuver guidance. The avoidance path is decided by the pilots, maybe with the cooperation of ATC. TCAS I has been mandated in U.S. for turbine powered aircraft with seats between 10 and 30 since 1995[32].

### **TCAS II**

TCAS II, the latest version is TCAS II Version 7.1, is known and used world widely by airspace users nowadays. It includes all functions of TCAS I, simultaneously, it could offer pilots vertical manoeuvre recommendation, known as vertical RA. Comparing to the older version of TCAS system, the latest one has the advantages of reducing the nuisance alerts, conformity with ATC system, horizontal and vertical separation distance requirement, more complicated multi-threat logic, providing reversal RAs when future collision detected based on the current RA. Turbine aircraft with passengers more than 19 or aircraft which maximum take-off weight greater than 7500kg are mandated by ICAO to use TCAS in January 2005[34]. Due to a mid-air collision occurred at Ueberlingen in July 2002, TCAS II Version 7.1 was designed. It allowed additional sense reversal RA in coordinated encounters. Simultaneously, the announcement ‘Adjust Vertical Speed, Adjust’ was replaced by ‘Level Off, Level Off’[31, 33].

### **TCAS III and TCAS IV**

TCAS III is the next generation of TCAS II. Compare with TCAS II, it can provide pilots with horizontal manoeuvre. It is flexible when vertical height is not enough or the aircraft is near terrain. While later the M.I.T. Lincoln Laboratory pronounced the bearing information from TCAS III is not accurate enough to support horizontal RA and miss distance filtering effectively. Due to the results, TCAS III was cancelled by FAA and instead by TCAS IV.

TCAS IV will be an integrated system with Global Positioning System (GPS). Its position information will be determined by GPS signals, then broadcast it periodically to enable all imminent aircraft to get the others' location. What is more, the future TCAS IV is also expected to provide intention information. This function will improve the performance of TCAS and deduce the threat from the intruder aircraft. Just like TCAS II, TCAS IV will display traffic location and advisories to flight crew. RAs are expected to involve both the horizontal and vertical manoeuvre advisory[31].

### **2.3.2 Human Machine Interface**

HMI of TCAS II, Version 7.1 is described in this section. It referred to FAA and EUROCONTROL collision avoidance system booklet. There are three kinds of HMI for TCAS system, presented respectively as follows:

#### **Traffic Position display**

Traffic display presents pilots the adjacent aircraft or intruders' position information with respect to the host aircraft. It displays TA, RA and Proximate status, aims to provide flight crews situational awareness in order to assist pilots catch the threat aircraft quickly. Figure 2.10 shows the common traffic information symbology on EFIS and Figure 2.11 depicts another choice of traffic display with Instantaneous Vertical Speed Indicator (IVSI). Three different colors are used to indicate different traffic status. The white and cyan colors mean it is a proximate aircraft, have not bring treat to own aircraft, this kind of traffic is monitored by TCAS system. The solid yellow round shape imply intruders, it triggers a TCAS TA. The solid red square indicates a threaten aircraft and initiates a TCAS RA, it used to assist pilot to perform manoeuvre with visual acquisition. The traffic display also involves the monitored aircraft altitude and motion tendency (climb or descent) information relative to its own aircraft.

#### **Aural Annunciation**

TCAS Aural Annunciation is generated together with traffic position information, aims to get pilots' awareness through aural alert. Depending on



different TCAS TA and RA, the aural prompt is different.

#### **Traffic Advisory**

Only one aural prompt is provided for TA, it is pronounced ‘*Traffic, Traffic*’.

#### **Resolution Advisory**

Distinctive aural prompts are announced according to the issued TCAS RAs, including: ‘*Climb, Climb*’, or ‘*Maintain vertical speed, maintain*’, or ‘*Increase climb, increase climb*’, or ‘*Descend, descend*’, or ‘*Increase descend, increase descend*’, and etc..

#### **Avoidance Manoeuvre Display**

Avoidance manoeuvre display is used to illustrate the issued RAs. It provides pilots visual cueing directly and requires pilots to react immediately.

Figure 2.12 describes an ‘Increase Climb’ RA example on PFD. The red isosceles trapezoid consists a forbidden area for aircraft pitch angle, it requires pilots to pull up or push nose down according to the position of the aircraft symbol is within or out of this forbidden area. Simultaneously, the required vertical airspeed is showed on vertical speed indicator. The green color area represents the allowed vertical airspeed, and the red color area implies need to avoid. The avoidance manoeuvre display on PFD provides pilot a simply and natural way to manual control the aircraft.

Figure 2.13 shows a ‘Climb Corrective’ RA on HUD. Typically, the corrective advisory symbology consists of a double lined box, called ‘Fly to’ symbol, that used to indicate the safe area where Flight Path symbol should be located. The position of the box related to HUD artificial horizon determine the required vertical airspeed. It also involves two angled lines indicated the unsafe area. Comparing TCAS RA on the PFD and HUD, we can find, HUD has the unique TCAS RA symbols - the double lined ‘Fly to’ box. This requirement is coming from HUD transparent display. In order to make sure HUD can provide the distinct guidance information, the doubled line was applied to increase the identification accuracy. It is also easy to understand that benefit of with or without the box, the box can provide more explicit requirement for the pilot to avoid the over vertical separation between two conflicts. It also provides advantage for the future free sky concept requirement, avoids to trigger another collision with the third or more aircraft and provides more safety benefit. The height of the box indicates a 500 *fpm* safe area while flying outside of the box on the safe side is also acceptable[26].



Figure 2.10: TCAS traffic display on EFIS[33].



Figure 2.11: TCAS traffic display with IVSI[33].

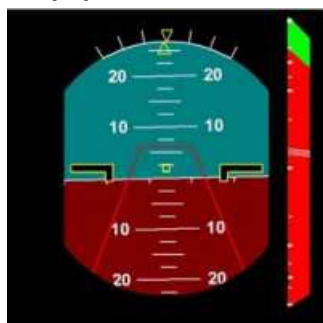


Figure 2.12: TCAS RA Example on EFIS[33].

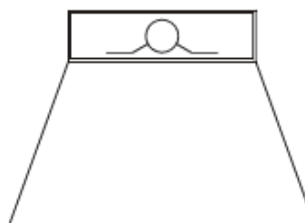


Figure 2.13: TCAS RA Example on HUD[26].

### 2.3.3 Collision Avoidance Logic

Collision avoidance logic is the critical part of TCAS system, the aircraft surveillance data is passed to collision avoidance logic to determine which type of advisory should be initiated. This sub-chapter aims to provide the basic knowledge of CAS logic and describes the logic function of TCAS II, Version 7.1. TCAS II, Version 7.1 is the latest TCAS system implemented world widely and mandatory by the authority. It improves aural prompt and add improved reversal logic compared with version 7.0.

#### Basic Concepts Introduction

- Traffic Advisory:  
A TA is the particular indication (Aural prompt and visual caution on traffic display ) issued by TCAS system to inform pilots or flight crews that the nearby traffic has entered or projected to the protected volume of own aircraft, threat maybe happen if the situation continues to deteriorate. It reminds the pilots and crews to raise the attention.
- Resolution Advisory:

A RA issued by TCAS system that providing advices to pilots and flight crews and requiring them to react immediately (climb or descend, etc.) in order to maintain the safe separation from the intruders.

- Closest Point Approach (CPA):  
CPA locates at the centre of aircraft protective volume that is referred to decide the threat level.
- Sensitivity Level (SL):  
Define CAS protection level based on its own aircraft altitude. It has 7levels utterly, from level 1 to level 7, the high SL suggests high degree protection is served. The definition of SL and the alarm thresholds accompany with it are shown in Figure 2.14. SL is used to determine the category of ‘protected volume’. Figure 2.15 and Figure 2.16 present TCAS horizontal and vertical dimension protection volume. It was defined safety area around own aircraft according to time.
- Warning Time - *Tau*:  
*Tau* is the estimated time (second) to CPA calculated by aircraft speed and attitude. It is the principle term to issue TCAS RA and TA and works together with SL.

Own Altitude	SL	tau values (sec)		TVTHR (sec)	DMOD values (NM)		ZTHR (feet) Alt. Threshold		ALIM (feet)
		TA	RA	RA	TA	RA	TA	RA	RA
0 – 1000 ft AGL	2	20	no RA	no RA	0.30	no RA	850	no RA	no RA
1000 – 2350 ft AGL	3	25	15	15	0.33	0.20	850	600	300
2350 ft AGL – FL50	4	30	20	18	0.48	0.35	850	600	300
FL50 – FL100	5	40	25	20	0.75	0.55	850	600	350
FL100 – FL200	6	45	30	22	1.00	0.80	850	600	400
FL200 – FL420	7	48	35	25	1.30	1.10	850	700	600
Above FL420	7	48	35	25	1.30	1.10	1200	800	700

Figure 2.14: Sensitivity Level Definition and Alarm Thresholds[33]

### Collision Avoidance System Function for TCAS II

CAS logic function can be presented as Figure 2.17, the operation of TCAS II is summarized as below:

- Surveillance
- Nearby traffic tracking

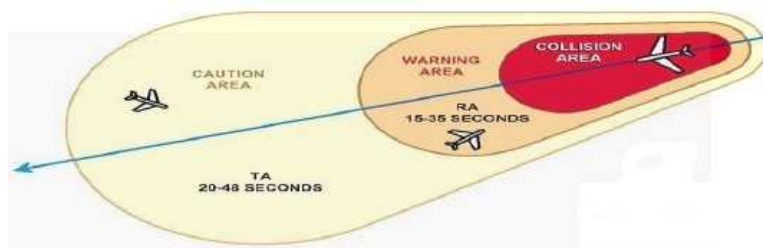


Figure 2.15: TCAS Protection Volume (horizontal)[35]

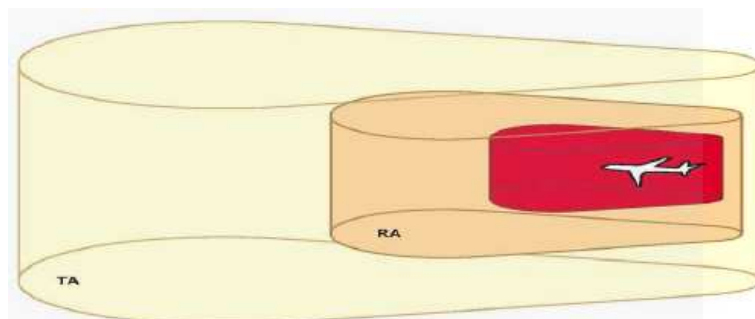


Figure 2.16: TCAS Protection Volume (vertical)[35]

- Threat detection
- Resolution Determination and Coordination

The following paragraphs will discuss these operations separately.

**Surveillance** TCAS can be looked as a mini Secondary Surveillance Radar (SSR) on aircraft, surveillance is its fundamental function that responsible to provide information of the proximate aircraft with slant range, altitude and bearing got by transponder interrogating. Typically, the required reliable surveillance range is  $14nmi$ . Actually, the maximal range that TCAS could cover is up to about  $30nmi$  and could track up to 30 nearby traffic simultaneously.

**Nearby Traffic Tracking** Once the other traffic is determined to be the target aircraft, TCAS system will monitor (tracking function) it until outside of the surveillance range. The tracking function gets partial inputs from surveillance function and cooperate with CAS logic to assess the invasion geometry, including time to CPA and the horizontal distance at CPA. While the altitude, relative altitude and vertical speed are calculated by CAS logic for both target aircraft and own aircraft. The nearby traffic tracking function keep all the target aircraft under watch to locate and track them.

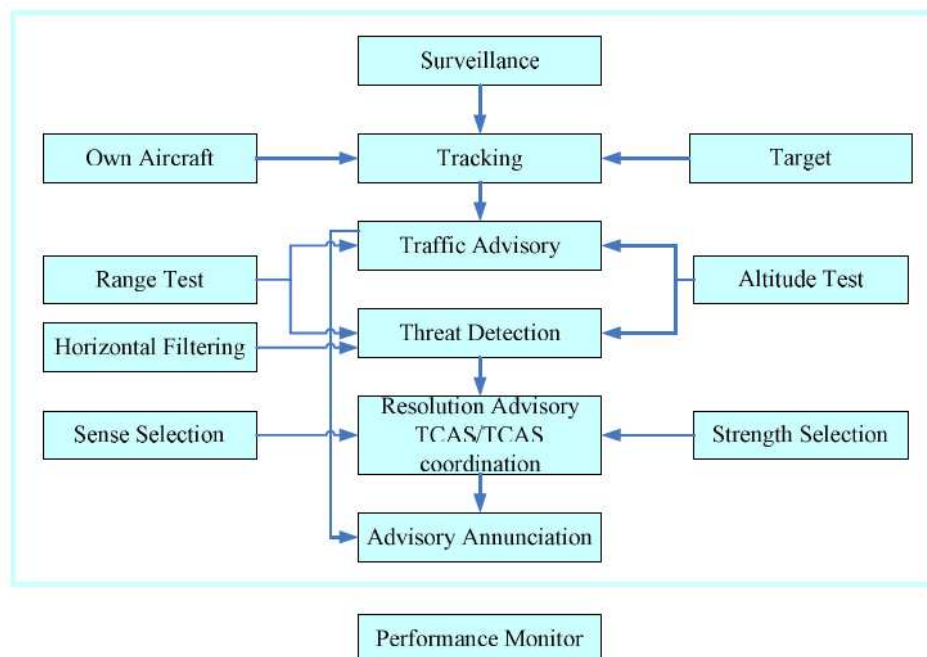


Figure 2.17: CAS Logic Functions[35]

**Threat Detection** Threat detection is responsible to determine whether a TCAS TA or RA need be issued or not. Time to CPA received from nearby traffic tracking function is compared with  $\tau$  to decide the alter. As Figure 2.14 presented,  $\tau$  values change along with SL - aircraft altitude, the higher aircraft altitude with the bigger  $\tau$  value. Miss distance is another threshold of TCAS used to declare a threat. At some particular condition, such as one aircraft is level off, the other aircraft is descending with a slow vertical speed, while these two aircraft are in the collision scenario. In order to avoid the  $\tau$  value never meet, the miss distance is applied. Thus how to decide what kind of threshold is used depends on which of them is meet firstly. TCAS continuously calculate the relative range and altitude between the target aircraft and own aircraft, the alert only will be issued when horizontal and vertical threat are both satisfied.

**Resolution Determination and Coordination** If TCAS TA is trigger, the traffic information on traffic display will change to yellow and aural prompt will provide to flight crew to get awareness. If a threat is affirmed, a TCAS RA will be selected. Correspondingly, the RA will be annunciated to the pilots and the required reaction will be presented on traffic display. TCAS only can perform its function with the aircraft install TCAS system.

In order to select an appropriate RA, two steps are considered. Firstly,

deciding the RA sense, such as upward or downward. Then, choosing the strength for the advisory. As Figure 2.18 shown, suppose CPA is calculated, the vertical separation between two conflict aircraft is the marked as ‘A’ and ‘B’. The downward sense logic can provide greater vertical separation compare to the upward one, therefore the descending RA is selected to own aircraft.

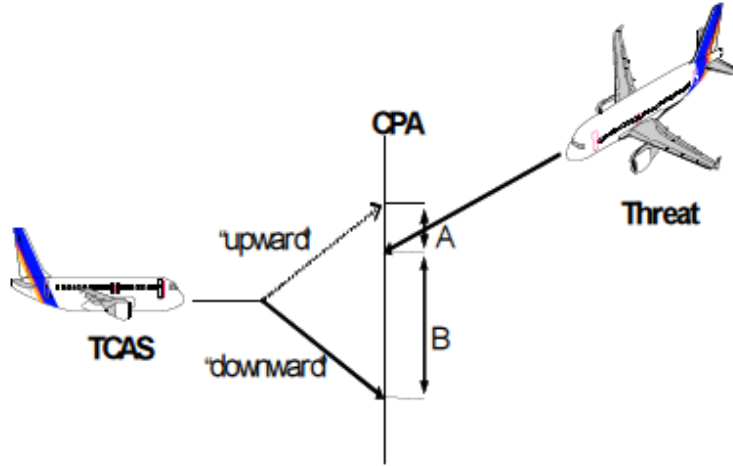


Figure 2.18: RA Sense Determination[35]

### 2.3.4 TCAS III principle

TCAS III is the next generation of TCASS II, it has the ability to provide both horizontal and vertical resolution. The miss-distance estimate is the core parameter to assess and determine threatening. The accurate of miss-distance determines the reliability and dependability of TCAS horizontal RAs.

Refer to Burgess[3], five parameters are needed for TCAS III method, they are range, range rate, bearing, bearing rate and speed of intruder and host aircraft. The miss-distance  $m$  and miss-distance error  $\sigma_m$  can be estimated by:

$$m = \frac{d^2 \omega}{\vec{v}_R} \quad (2.1)$$

where  $d$  is the relative range between intruder and host aircraft,  $\omega$  is the intruder's bearing rate and  $\vec{v}_R$  is the relative velocity of the two aircraft.

$$\sigma_m = \frac{d^2 \sigma_\omega}{\vec{v}_R} \quad (2.2)$$

where  $\sigma_m$  indicates the miss-distance error and  $\sigma_\omega$  stands for bearing rate error.

From these equations, it is easy to find bearing rate error highly decides the characteristics of horizontal RAs. For TCAS III,  $\sigma_\omega$  is not measured directly while is estimated from intruder's bearing information. Burgess and other researchers demonstrated the method used to derive  $\sigma_\omega$  was not effective and accurate enough to support horizontal functions. Due to this discovery, FAA declared to cancel the support for TCAS III development, instead TCAS IV concept was officially proposed[3].

The RAs of TCAS III is selected by the CAS logic. When an RA is needed, CAS logic will select an appropriate avoidance manoeuvre depended on the predicted aircraft relative separation that estimated from every supposed RA, including: climb, descend, turn left or turn right. The CAS logic will select the RA with greatest separation.

### 2.3.5 Future Horizontal Resolution

Future horizontal resolutions described herein are referred from several papers.

As Figure 2.19 shown, Chamlous[7] introduced horizontal detection and manoeuvre solutions for conflict resolution. In his theory, the intruder was considered to be a stationary with specified protected zone, and the host aircraft was flying with a constant relative velocity  $\vec{v}_R(t)$  ( $\vec{v}_R(t) = \vec{v}_O(t) - \vec{v}_I(t)$ ) in North East Down (NED) reference frame. The anticipated threaten was declared if host aircraft was expected to be within the protected zone. For the manoeuvre strategy, Chamlous adopted changing aircraft heading angle to achieve turn right or turn left manoeuvre. Refer to the figure, the dotted rays from the ownship defined the necessary bearing for horizontal manoeuvre, they were derived from the intruders protective zone and tangent to it. The miss-distance of turn left to CPA was smaller then the turn right one, thus a turn right RA was issued.

Figure 2.20 illustrated Carbone and Goss's[4, 5] methods to explore conflict detection and resolution in 3D space.  $\vec{R}_{LOS}$  was aircraft constant relative vector defined the same as  $\vec{v}_R(t)$  while in Earth-Centered Earth-Fixed (ECEF) coordinate. The sphere indicated the intruder protected zone.  $\vec{V}_{rel}$  was the needed relative vector which was outside of the protected area to avoid the adjacent collision. All the vector  $\vec{V}_{rel}$  outside of cone could provide protection, while the tangential solution was decided to the optimal option. Considering the horizontal manoeuvre, the new vector  $\vec{V}_{rel}$  can be achieved by changing host aircraft heading angle.

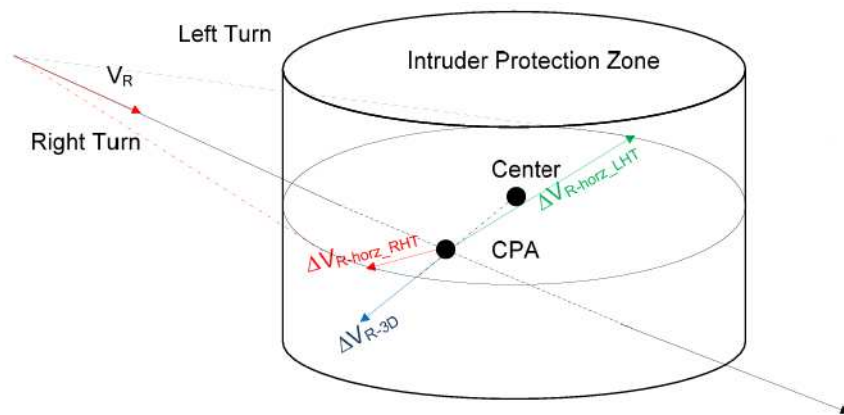


Figure 2.19: Resolution in the horizontal plane[7]

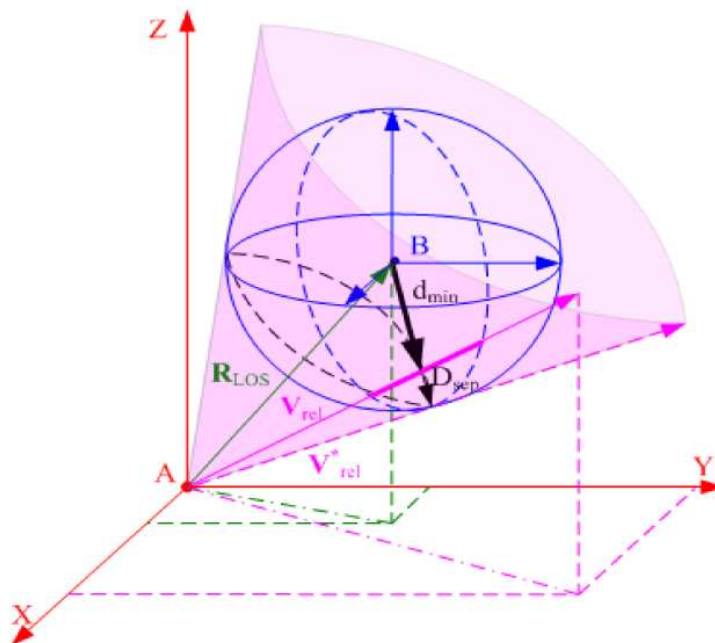


Figure 2.20: Conflict resolution cone[5]

Autonomous Operations Planner (AOP) was invented by National Aeronautics and Space Administration (NASA) Langley used to research self separation. Dowek[2] applied discrete trajectory method to perform AOP conflict detection. The idea is describing host aircraft position and the intruder position as a series of points, named *nodal points* and sending them into the strategic AOP tool. AOP conflict detection compares and analysis



the distance between the two aircraft step by step during the simulation until the moment two points located within the protected area, presented in Figure 2.21. The compared aircraft position is the predicted position with specific time ahead of the real aircraft position. The loss of separation implies the conflict and threaten ahead. While Dowek also found, the discretization made the formal verification complex and also may lead to error accumulation, the continuous trajectory models were the better choice.

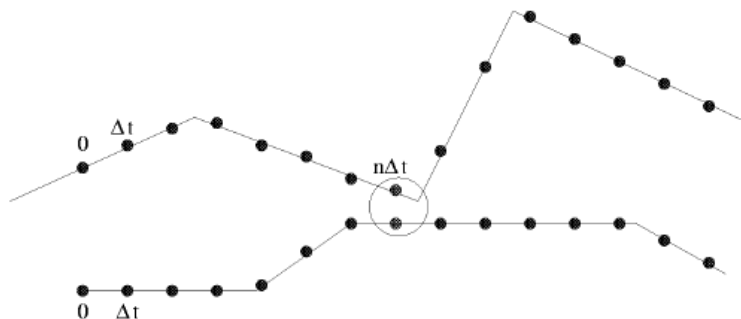


Figure 2.21: Strategic AOP conflict detection[2]

As described, for now we can find, the researchers implemented the horizontal resolution function by aircraft position and velocity vector. Different researches chose different reference frames and methods. For a 3D environment, the trajectory which is tangent to the protected area was the efficient planned way to avoid the conflict, it was implemented and discussed by the plenty of researchers.

### 2.3.6 TCAS Failure Example

#### Event Introduction

On July 1, 2002, a BAL *Tu – 154* commercial aircraft and a DHL *Boeing 757 – 200* collided in mid air over Uberlingen, Germany with all 71 crew members and passengers dead[36]. As Figure 2.22 shown, approximately 60 seconds before the collision, both aircraft were level at *FL360*, the Russian aircraft was flying almost from East to West and the *Boeing 757 – 200* was towards North, they supposed to collided over Germany. Firstly, TCAS systems issued TA to catch the crews' attention on both aircraft. Seven seconds later, the *Tu – 154* received the instruction from Zurich ATC to descend to *FL350*, while another seven seconds later, TCAS generated RA and suggested *Tu – 154* to climb, meanwhile *Boeing 757* got the TCAS RA to descend. Figure 2.23 is the schematic of the event. The Russian *Tu – 154* followed the controller's order to descend while ignore TCAS RA, the *Boeing*

757 pilot took the TCAS mandate also descending. Finally, 50 seconds after the TCAS TA, the two aircraft collided with each at 34890 feet.



Figure 2.22: Map of Mid Air Collision in Germany[32]

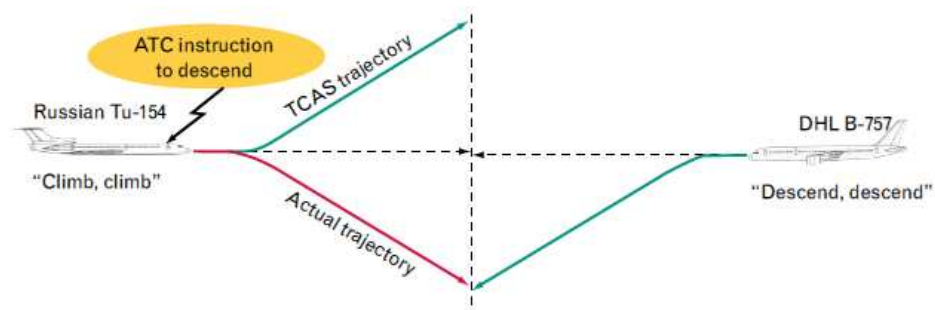


Figure 2.23: Schematic of Aircraft Manoeuvre for Uberlingen Mid Air Collision[34]

### Analysis of the Disaster

Although both aircraft has TCAS installed, the disaster still happened due to human factors issues[34]. The Russian flight crews chose to obey the controller's instruction to do the manoeuvre while ignored the TCAS RA

command. Suppose the two aircraft following TCAS RA instruction, the disaster maybe would not happen. The investigation report identified two main reasons for this mid-air collision casualty: one is the pilots of *Tu - 154* unaware that TCAS RA had the precedence compared with ATC instruction, they continue to perform descending even TCAS advised them to climb. The other cause is the conflicts between TCAS RA and ATC controller, which was not integrated completely. ATC controller did not discover the separation contravention in due time[37]. The other hand, if the TCAS system could issue a 'reversal' of the original warning to *Boeing 757* aircraft, the catastrophe probably be stop. It does not mean a reversal is the final solution, the deeper examination found reversal is inadequate in some encounters[34].

Enhanced situational awareness is another practical way to prevent the collision. Suppose if the flight crews were provide the clear manoeuvre trajectory with indication of the intruder position superpose on it, it would be easier and confidence for pilots to make the right decision. Another solution maybe consider to apply the next generation TCAS system that can perform horizontal manoeuvre, the horizontal RA provided pilots more option could comfortable for pilots to follow during this situation.

## 2.4 Review of Tunnel-in-the-Sky

'Tunnel-in-the-Sky' is the concept came out since 1950 for the purpose of providing pilots the predicted flight path to increase 'situational awareness'. While due to the limitation of technology at that time, Tunnel-in-the-sky concept developed slowly. With the advantage of fast computer applied science spreading, the research enthusiasm to perspective flight-path display boost extensively. The pictorial displays became the main stream, developed and evaluated through different variety methods, including straight or curved approach landing scenario, using channel to present the required flight path, using pathway to indicate the proposed trajectory, or using rectangular/square to present the commanded flight path. The series of symbology superimposed on displays that in pilot front of view is used to present the required flight path and moving along the aircraft flight direction[38]. It presents the pilots how to control the aircraft, which way to fly and originally was designed for general aviation[12, 13]. The investigations indicated that Tunnel-in-the-sky could provide much more precise aircraft tracking capability and enhance situational awareness compare to the conventional displays.

### 2.4.1 Grunwald's research about Tunnel-in-the-sky

Grunwald contributed to the perspective cured tunnel display. Figure 2.24 depicts the format of cured tunnel with control related information[39]. The whole image is perspective projected on a 2D display from the curved 3D trajectory in the real world. The squares also called reference frame, define the required position of flight path symbol, all squares consist the commanded trajectory and present on display to provide pilot the predicted flight path. Point  $C$  is the centre of the image and presents the vehicle axis. The cross is the stand for the flight path predictor symbol, it is displayed  $D$  distance ahead of the aircraft, used to predict the required aircraft position constant time later. the distance  $\epsilon_l$  and  $\epsilon_v$  are illustrate the lateral and vertical deviations, the responsibility of the pilot need to minimize the error. Line A-A is the horizontal line, the inclination angle estimate from the horizon and reference frame  $C_z C_y$  indicates the roll angle  $\phi$ . The position of tunnel related with horizon define the pith angle  $\theta$ [39].

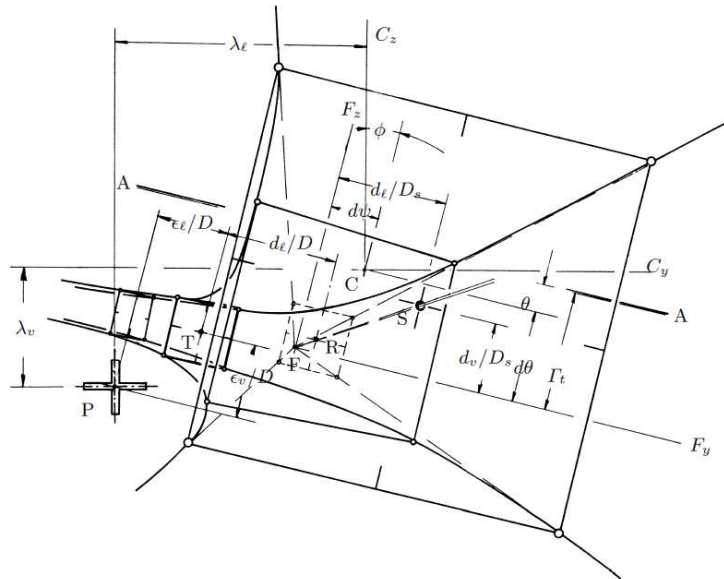


Figure 2.24: Curved Tunnel Display with Control Information[39]

### 2.4.2 Tunnel-in-the-sky of Japan Aerospace Exploration Agency

Japan Aerospace Exploration Agency (JAXA) investigate tunnel-in-the-sky for navigation and guidance purpose. Their main purpose was to improve the tunnel display format since 1997[10]. The display with Tunnel-in-the-sky symbols can provide the pilots predicted flight path with perspective image of the tunnel. The main symbols involved in research are described as follows, refer to Figure 2.25 and Figure 2.26:

1. Flight Path Predictor Symbol  
Flight path predictor defined by JAXA has the same function as Grunwald used. It presents the aircraft attitude ahead and should be coincident with the required flight path.
2. GHOST: the target position  
GHOST is the commanded future aircraft position some seconds later related with aircraft position now. The different between flight path predictor symbol and GHOST is the work of pilots.
3. Tunnel  
Tunnel is the main component of Tunnel-in-the-sky and comprised by a series of gates. The green box is stand of the required flight path, its width is 100 metres and the interval between each is 500 metres in the real 3D world[10].
4. Speed Flag  
Speed flag, the yellow box is the new symbol compared with Grunwald, it used to indicate the speed error related to the reference one[10]. It used to help pilots to control the aircraft status.

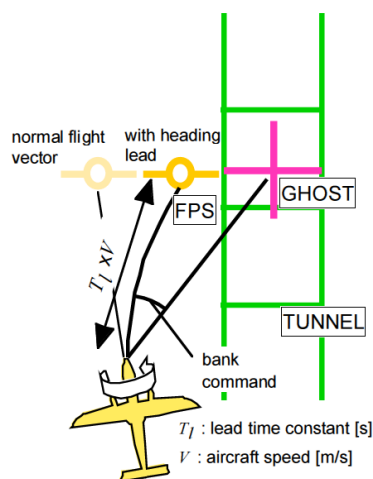


Figure 2.25: Horizontal symbology of tunnel-in-the-sky[10]

### 2.4.3 Effects Analysis

Barrows demonstrated the advantages of tunnel display through flight test. He originally tested the tunnel concepts developed by Stanford University with Piper Dakota aircraft in 1995 and 1996[9]. The straight approaching and missed approaching tests were conducted. Then, tests related to curved



Figure 2.26: Basic Information of tunnel-in-the-sky[10]

approaches and complex paths[13] with tunnel display were also performed. During these tests, tunnel display was the only instrument that pilots relying on to complete the tasks. All these tests demonstrated tunnel-in-the-sky display could improve the tracking accuracy performance and enhance situational awareness for light aircraft. Later, in 1999, Barrows discovered tunnel display could help pilots reduce overlap flying probability and decrease the missing spots when executing remote sensing flight tasks. He also stated the tunnel display was helpful for situational awareness even when aircraft was manoeuvring, easy to understand and operate compared with conventional systems.

#### 2.4.4 Conclusion

Tunnel-in-the-sky technology is demonstrated particularly benefit for curved trajectory tracking performance, it also can decrease pilots workload and enhance situation awareness. Based on these advantages, it gives researchers ideas to investigate tunnelling concept visual cueing technology for trajectory-based TCAS system.

---

## Visual Cueing Design Methodology

Before starting developing visual cueing method for trajectory based collision avoidance system, basic flight dynamics principles was presented firstly, which comprised elementary knowledge of reference frames and coordinates transformation. Then the ecological approach was exposed for visual perception which is the theoretic basis of tunnel-in-the-sky concept. Finally, the perspective display design method is provided used to develop the interface for curvi-linear motion trajectory.

### 3.1 General Introduction

#### 3.1.1 Definitions

The reference frames depicted herein are the coordinates applied in this thesis.

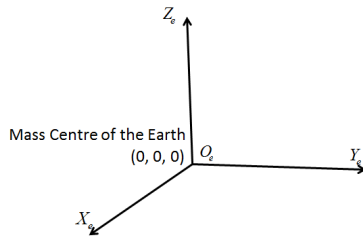
- *The ECEF reference frame*  
As its name, the ECEF reference frame ( $F^e$ ) has its origin at the centre of the earth and fixed on it. It uses three-dimensional  $XYZ$  coordinates (in metres) to describe the location of objects. The  $X_e$  axis is pointed to 0 latitude and prime meridian; the  $Z_e$  axis directs to the north pole, but not exactly pass through it. The  $Y_e$  axis is defined by the right hand screw rule, refer to Figure 3.1. The ECEF reference frame rotates following the earth rotation.
- *The aircraft body reference frame*  
The aircraft body reference frame ( $F^b$ ) is a right handed orthogonal axis system that defined relative to aircraft geometry. Its origin locates at aircraft centre of gravity ( $cg$ ), the longitudinal axis  $ox_b$  is along aircraft symmetric geometrical fuselage centreline and pointing forward to the aircraft nose; the lateral axis  $oy_b$  is towards to aircraft right wing; the axis  $oz_b$  is pointed downwards, perpendicular to the horizontal fuselage,  $ox_b - oy_b - oz_b$  axis follows right-hand screw rule.
- *The local NED reference frame*  
The NED reference frame heritages the definition of local East, North, Up (ENU) system but with  $Z_n$  axis towards down, perpendicular to the earth local tangent plane. Normally, the origin of NED reference frame



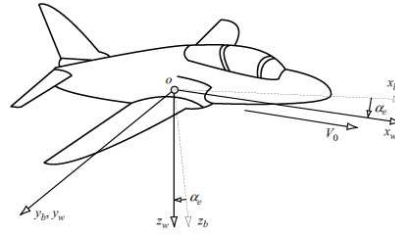
is positioned at aircraft centre of gravity, the  $X_n$  axis points to North, the  $Z_n$  axis points to East, and  $X_n - Y_n - Z_n$  satisfies right-hand screw rule. NED reference frame can be derived from transforming ECEF frame to the aircraft  $cg$ .

- *The flight-path reference frame*

The flight-path reference frame ( $F^w$ ) is also called wind reference frame. As shown in Figure 3.2, its origin is fixed at  $cg$  of the aircraft. The  $ox_w$  axis is aligned with the velocity vector  $V_0$ , the lateral axis  $oy_w$  is pointed to the right of aircraft and perpendicular to the plane  $ox_w - oy_w - oz_w$ , the  $oz_w$  axis is positive down.



**Figure 3.1:** ECEF Reference Frame.



**Figure 3.2:** Flight-Path Reference Frame Definition[40].

### 3.1.2 Coordinates Transformation

Three categories of coordinates transformation are introduced. Respectively, they are from Latitude, Longitude, Altitude (LLA) to ECEF, from ECEF to NED, from ECEF to LLA. LLA reference frame is used to indicate aircraft position in the real world, it is also applied for flightgear platform. NED coordinate can express the relationship between different aircraft. ECEF reference system is the intermediary coordinate demanded from LLA to NED coordinate.

#### LLA to ECEF

Since the earth is not a perfect round shape, a reference ellipsoid is used to convert the coordinate that more common for GPS system. It uses geodetic-mapping coordinates of Latitude, Longitude and Altitude, herein we called it LLA for short. The World Geodetic System (WGS) is a standard usage for the Earth, the latest revision is WGS 84. It can be described by a series of parameters defining the specific ellipsoid shape as shown in Figure 3.3. It includes a semi-major axis ( $a$ ), a semi-minor axis ( $b$ ) and its first eccentricity ( $e$ ) and its second eccentricity ( $e'$ ). Depending on the formulation used, ellipsoid flattening ( $f$ ) may be required. While in this project, the selected simulink block does not require the flattening.



The detailed WGS 84 parameters is expounded as follows:

- $a = 6378137$
- $b = a(1 - f) = 6356752.31424518$
- $e = \sqrt{\frac{a^2 - b^2}{a^2}}$
- $e' = \sqrt{\frac{a^2 - b^2}{b^2}}$

Figure 3.4 explains the transformation relationship between LLA position and ECEF location, therinto  $\varphi$  stands for Latitude,  $\lambda$  indicates Longitude,  $h$  is the height above ellipsoid (meters) and  $N$  expresses radius of curvature (meters) which defined as:

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}} \quad (3.1)$$

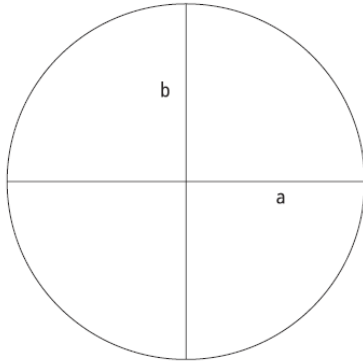


Figure 3.3: WGS 84[41].

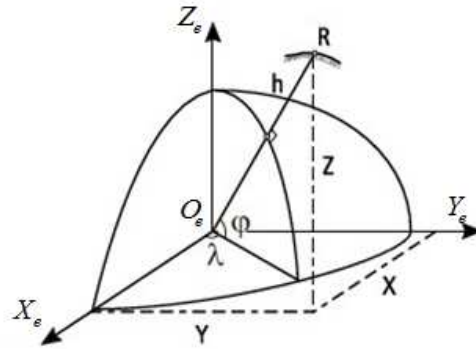


Figure 3.4: ECEF and Reference Ellipsoid[41].

Converting a position from LLA reference frame to ECEF coordinates can be accomplished by following formulas.

$$X = (N + h) \cos \varphi \cos \lambda \quad (3.2)$$

$$Y = (N + h) \cos \varphi \sin \lambda \quad (3.3)$$

$$Z = \left(\frac{b^2}{a^2}N + h\right) \sin \varphi \quad (3.4)$$

**ECEF to LLA**

The conversion from ECEF to LLA is slight complex that can be achieved by one of the following methods:

When  $h \ll N$ ,  $h_0 = 0$ ,

$$\lambda = \arctan \frac{Y}{X} \quad (3.5)$$

Start with  $h_0 = 0$

$$\lambda_0 = \arctan \frac{Z}{p(1 - e^2)} \quad (3.6)$$

Iterate  $\varphi$  and  $h$

$$N_i = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi_i}} \quad (3.7)$$

$$h_{i+1} = \frac{p}{\cos \varphi_i} - N_i \quad (3.8)$$

$$\varphi_{i+1} = \arctan \frac{Z}{p(1 - e^2 \frac{N_i}{N_i + h_{i+1}})} \quad (3.9)$$

or by closed formula set.

$$\lambda = \arctan \frac{Y}{X} \quad (3.10)$$

$$\varphi = \arctan \frac{Z + e'^2 b \sin^3 \theta}{p - e^2 a \cos^3 \theta} \quad (3.11)$$

$$h = \frac{p}{\cos \varphi} - N \quad (3.12)$$

Where auxiliary values are:

$$p = \sqrt{X^2 + Y^2} \quad (3.13)$$

$$\theta = \arctan \frac{Za}{pb} \quad (3.14)$$

This is the mathematics foundation of ECEF to LLA transformation. During the project, the specific matlab function was applied to receive LLA information.

### ECEF to Local NED

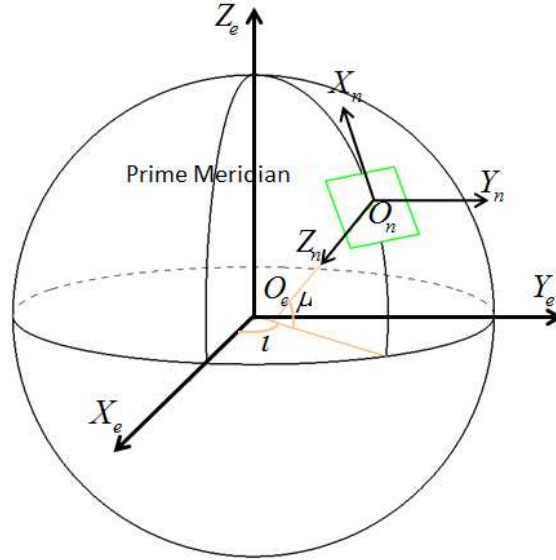
Figure 3.5 illustrates the relationship of ECEF reference frame and NED reference frame. Converting a position in ECEF coordinate to the local NED coordinate, a Direction Cosine Matrix ( $DCM_{ref}$ ) is needed to perform the transformation of a vector in ECEF axes into a vector in NED axes. Correspondingly, its geodetic latitude ( $\mu$ ) and longitude ( $\iota$ ) information is demanded.  $DCM_{ref}$  is derived as below:

1. Rotating around  $Z_e$  through longitude ( $\iota$ ).
2. Continue rotating around  $Y_e$  through latitude ( $\mu$ ).

Combining these two steps,  $DCM_{ref}$  is expressed:

$$DCM_{ref} = \begin{bmatrix} -\sin \mu & 0 & \cos \mu \\ 0 & 1 & 0 \\ -\cos \mu & 0 & -\sin \mu \end{bmatrix} \begin{bmatrix} \cos \iota & \sin \iota & 0 \\ -\sin \iota & \cos \iota & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.15)$$

More specific, the NED position can calculate by:



**Figure 3.5:** The relationship between ECEF reference frame and NED reference frame

$$P_n = DCM_{ref}(P_e - P_{eo}) \quad (3.16)$$

where  $P_{eo}$  is the origin of local NED coordinate indicated in ECEF coordinate.

### Local NED to Body Axis

Rotation about  $Z_n$ ,  $Y_n$  and  $X_n$  axis through Euler angle  $\psi, \theta$  and  $\phi$  separately will transform local NED frame to aircraft body axis which can be presented as follows:

$$R_z(\psi) = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.17)$$

$$R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \quad (3.18)$$

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix} \quad (3.19)$$

Thus the total transformation matrix, normally called *direction cosine matrix DCM* is given by,

$$DCM = R_z(\psi)R_y(\theta)R_x(\phi) = \begin{bmatrix} \cos \psi \cos \theta & \sin \psi \cos \phi & \sin \psi \sin \phi \\ -\sin \psi \cos \theta & +\cos \psi \sin \theta \sin \phi & -\cos \psi \sin \theta \cos \phi \\ \sin \theta & \cos \psi \cos \phi & \cos \psi \sin \phi \\ & -\sin \psi \sin \theta \sin \phi & +\sin \psi \sin \theta \cos \phi \\ & -\cos \theta \sin \phi & \cos \theta \cos \phi \end{bmatrix} \quad (3.20)$$

*DCM* is the rotation matrix that will be used to perform the perspective projection on HUD concept in the following chapter.

## 3.2 Perspective Display Design Method

The view feature of human eyes is called perspective projection. It is easy to understand it through camera working mechanics, projecting the real 3D scenes and objects into a 2D plane. Tunnel-in-the-sky concept development was according to this principle, the HUD 2D plane was looked as the view plane. What happened outside of cockpit was perspective projected on a HUD to improve pilot situational awareness.

### 3.2.1 General Introduction

In order to well explain the perspective projection, several coordinates and related terminology is discussed here.

*Viewing coordinate system V*: viewing coordinate system is defined in accordance with pilot position. Since pilot is sitting in the cockpit, his or her front of view is always along the aircraft body axis, therefore viewing coordinate system coincides with aircraft body axis. As Figure 3.6 shown, the origin, also known as centre of projection, is the same as aircraft centre

of gravity.

*Viewing reference co-ordinate system  $V_f$* : viewing reference co-ordinate system is a 2D frame, used to indicate the information transferred from 3D world. It is perpendicular to the  $X_b$  axis of body coordinate and its origin is the centre of the viewplane. As Figure 3.6 presented, its  $x$  axis is parallel to the  $Y_v$ , its  $y$  axis is parallel to  $Z_v$  while with the opposite orientation.  $V_f$  is used to express HUD plane.

Figure 3.6 illustrated the correlation of these two systems. Viewing coordinate system was used to define the scenes and objects in the real 3D space. Assuming a virtual tunnel existed in the front sky of aircraft, it was the objects belong to frame  $V$ . Viewing reference co-ordinate system was used to express the projection information based on the virtual tunnel in frame  $V$ . Tunnel-in-the-sky symbology on a HUD was the objects belong to frame  $V_f$ .

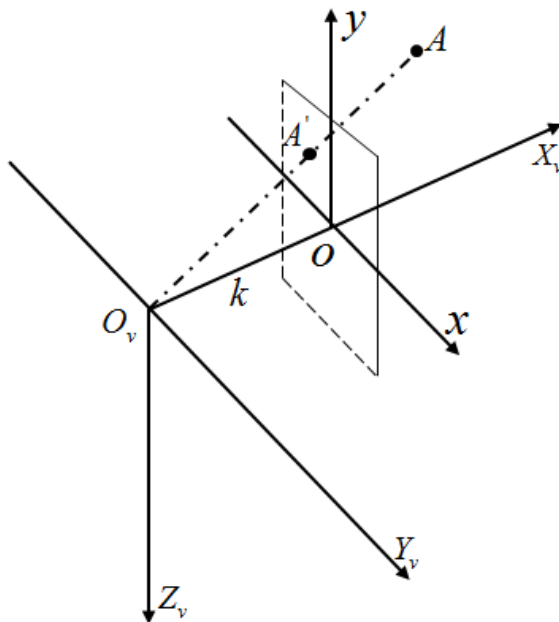


Figure 3.6: The 3D projection method

### 3.2.2 Perspective Projection Method

Refer to Figure 3.6, it explains perspective projection method. Point  $A$  is an object outside of cockpit. According to perspective projection concept, point  $A'$  is the projection of point  $A$  on the viewplane. Image the traffic and virtual tunnel are consisted of countless of  $A$ , correspondingly, immense of

projections  $A'$  can be derived and constructed the view on HUD. The distance away from the projection plane decides its size on the viewplane. The more far away, the smaller appearance compared to the near-by ones. The correlation of point  $A$  and its mapping point  $A'$  were given by Equation 3.21 and 3.22:

$$x^A = k \frac{Y_v^A}{X_v^A} \quad (3.21)$$

$$y^A = -k \frac{Z_v^A}{X_v^A} \quad (3.22)$$

where  $(X_v^A, Y_v^A, Z_v^A)$  is point  $A$  position,  $(x^A, y^A)$  is point  $A'$  position,  $k$  is the distance of the origin  $O_v$  and  $o$ . Point  $A$  was given by a fixed location, when aircraft was flying towards it, the relative distance would become smaller which led to the mapping changed.

Considering aircraft position and virtual tunnel position were defined in NED coordinate, while perspective projection requests the relative viewing coordinate system, thus position of point  $A$ ,  $\underline{P}_v^A = (X_v^A, Y_v^A, Z_v^A)$  could be defined as:

$$\underline{P}_v^A = DCM(\underline{P}_n^A - \underline{P}_n^{cop}) \quad (3.23)$$

which  $\underline{P}_n^A$  is the position of  $A$  in NED coordinate,  $\underline{P}_n^{cop}$  is used to indicate aircraft centre of gravity in NED coordinate, the effect of  $\underline{P}_n^A - \underline{P}_n^{cop}$  is transforming point  $A$  to aircraft centre of gravity,  $DCM$  is direction cosine matrix mentioned before.

### 3.3 TCAS Manoeuvre Display Design Method

TCAS manoeuvre display design is the primary work of this project, not only contains the vertical manoeuvre interface, it also includes the horizontal trajectory guidance interface. It desires to provides pilots the real time anticipated 3D guidance proposition. Thus tunnel-in-the-sky concept was extracted for TCAS manoeuvre display design. Three steps are involved to accomplish it.

1. Define the encouraged flight path.
2. Generate the nominal tunnel in the real 3D space.
3. Address perspective projection method to produce TCAS manoeuvre display based on a HUD.

### 3.3.1 Define Flight Path

The recommended flight path was initialized by collision avoidance logic function, it was applied to generate the flight path appropriate for Manoeuvre Display (named MFP). MFP was defined base on a series of position ( $P_1, P_2, P_3 \cdots P_n, P_{n+1}$ ), the interval between two contiguous points was the space between two virtual tunnel frame, this is the key concern of defining a flight path. The smaller interval will lead to clutter tunnel, the larger interval is not accurate to interpret the suggested flight path which maybe not construct the tunnel image. MFP is the real aircraft LLA or NED position and calculated by aircraft flight dynamics.

### 3.3.2 Generate the nominal tunnel

The centre of the commanded trajectory is the basic information use to produce the nominal tunnel. In this project, the nominal tunnel consisted of a bundle of tunnel frame which was defined to be rectangular shape and perpendicular to the estimated aircraft velocity. As Figure 3.7 shown, points  $P$  are the arbitrary points of centre of the MFP,  $v_n$  is the estimated velocity vector based on the trajectory,  $C_1, C_2, C_3, C_4$  are the vertex of tunnel frame which centre is  $P_n$ .

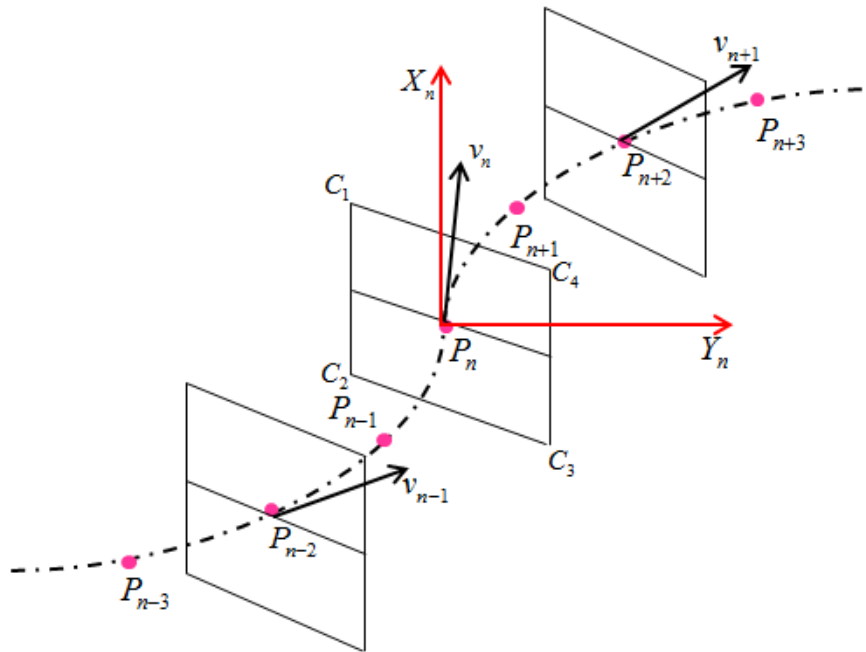


Figure 3.7: Vertices of the tunnel

The instantaneous velocity (the velocity vector) can be calculated by,

$$v = \lim_{D \rightarrow 0} \frac{\Delta D}{\Delta t} = \frac{\delta D}{\delta t} = \frac{P_{n+1} - P_n}{\delta t} \quad (3.24)$$

Where  $\Delta D$  is the aircraft flying distance during time  $\Delta t$  which is the interval of tunnel frame. Supposing the distance between  $P_n$  and  $P_{n+1}$  inclines to 0, the vector from  $P_n$  pointing to  $P_{n+1}$  is equal to velocity vector. The angle between aircraft velocity vector and North is aircraft heading angle, illustrated in Figure3.7.

Tunnel frames were constituted by four vertex, they were defined as follows,

$$C_{1,2,3,4} = P_n + R_z(\psi)R_y(\theta)R_x(\phi) \begin{bmatrix} 0 \\ \pm w \\ \pm l \end{bmatrix} \quad (3.25)$$

which  $w$  is the half width of the tunnel frame and  $l$  is the half length of the tunnel frame,  $\psi, \theta, \phi$  is the aircraft attitude which can be estimated by MFP.

Figure 3.8 illustrated the method used to estimate aircraft attitude based on MFP, they can be calculated by the following equations:

$$\psi = \tan \frac{P_{n+1,2} - P_{n,2}}{P_{n+1,1} - P_{n,1}} \quad (3.26)$$

$$d = \sqrt{(P_{n+1,2} - P_{n,2})^2 + (P_{n+1,1} - P_{n,1})^2} \quad (3.27)$$

$$\theta = \tan \frac{P_{n+1,3} - P_{n,3}}{d} \quad (3.28)$$

To sum up, every centre points generated the MFP, every four vertex consisted of the tunnel frame, all the tunnel frames composed the nominal tunnel in the world.

### 3.3.3 Accomplish TCAS Interface

The 2D tunnel-in-the-sky symbology are accomplished by perspective projecting the real 3D tunnel frames on a HUD. Section 3.2.2 described the projection method. Besides tunnel images, TCAS manoeuvre display also involved horizontal and vertical deviation indicator. Aircraft instance position and the nearest tunnel frame position were compared, the different between them showed pilots the compensation needed to consider.



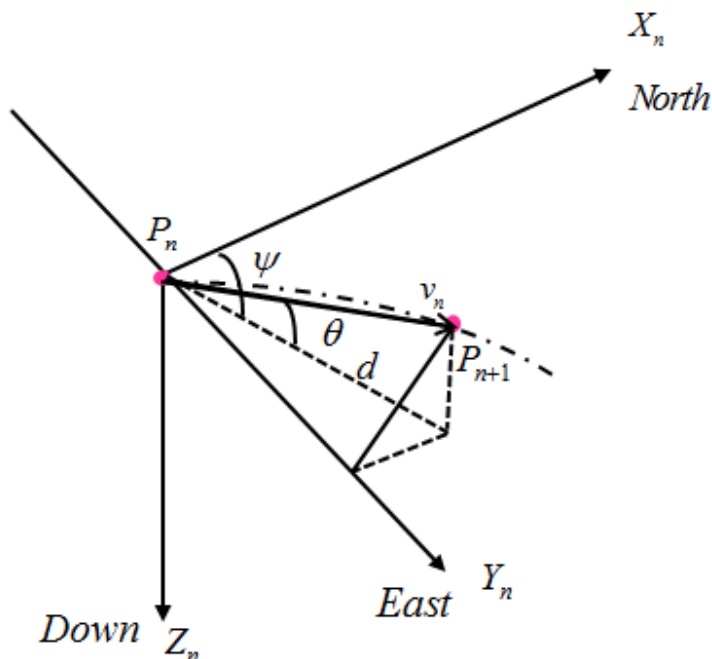


Figure 3.8: Method to estimate attitude based on trajectory position

### 3.4 Flight Path Predictor Design Method

Flight path predictor is similar to the conventional flight director, while with defined time ( $T_{pred}$ ) ahead to predict aircraft future position. Grunwald took the lead to explore the effect of the flight path predictor on a perspective flight path display. He identified the following benefits of using position predictor:

*“the information provided to the pilot by the predictor is optional. This, for example, allows the pilot to leave the predictor for several seconds to scan other parts of the display to return to it later.”*

He also verified the position predictors had the benefit of enhance the flight tracking performance and released pilots workloads[39].

#### 3.4.1 Design Consideration

Refer to Theunissen[42], the predictor is a crucial parameter of the perspective flight path display. The predictor development consideration in this project mainly based on navigation and control requirements. Figure 3.9 illustrates the benefit of predictor based on navigation and control task requirement. The ‘Future desired state & margins’ information is provided

by tunnel-in-the-sky symbology, pilots can naturally understand what is the task and where to flight the aircraft. The ‘Current desired state and actual state’ information is the same as the conventional display, it involves aircraft attitude information and current position information, according to which the pilots could estimate aircraft flight status in future with the help of their experiences. The ‘Prediction’ block is the function performed by the predictor, it directly presents pilot the aircraft position or flight path status with specified time before, also with change trend. It releases the pilots from predicting by themselves instead with the calculation done by the computer. The effects of this kind of control strategy and display format allow pilots to get error information, the predicted flight path and the permitted margins simultaneously, which have the ability to reduce the feedback loop gain and improving the tracking performance[42].

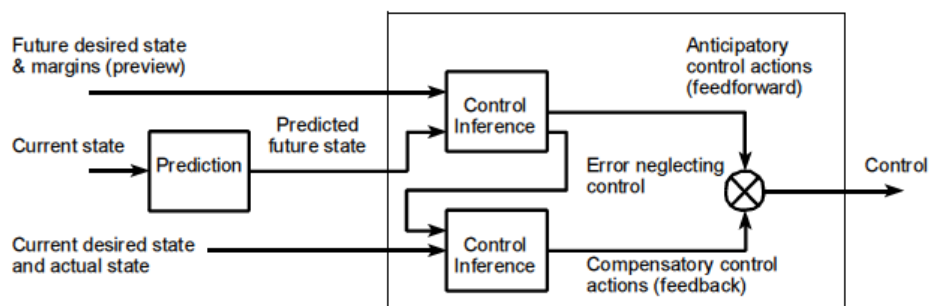


Figure 3.9: Control activities required with predictor symbol[42].

### 3.4.2 Algorithms Development

The predictor for perspective flight path display can be divided into two different kinds, one is called future position predictor, the other is the flight path predictor. The algorithms development of them shared the similar concepts, because of the future position is predicted along the current flight path angle, thus flight path predictor is chosen instead of the future position predictor.

The algorithms development of flight path predictor contains the lateral control and the longitudinal control. The discussion about them is described later in this section. Another important factor need to be consider is the selected time  $T_{pred}$ . Theunissen[42] did the experimental research about predictor time with pilot-in-the-loop simulations. The results indicated the position error increased with the prediction time increasing, while the elevation deflection reacted the contrary way, finally the  $T_{pred} = 5sec$  is determined. Some researchers did similar investigations to decided the prediction time,

which will be discussed in Chapter 4.1.2 that shown  $5sec$  is the choice.

### Longitudinal Flight Path Predictor Design

The longitudinal flight path predictor model designed here adopts a second order function, which generate the following future position predictor equation.

$$H_{PD}(t) = H_0 + \dot{H}_t T_{pred} + \frac{1}{2} \ddot{H}_t T_{pred}^2 \quad (3.29)$$

where,

$$H(t) = \int_0^{T_{pred}} v \sin(\gamma(t)) dt \quad (3.30)$$

when  $\gamma(t) \ll 0$ ,

$$\dot{H}_t = \frac{dH(t)}{dt} = v\gamma(t) \quad (3.31)$$

$$\ddot{H}_t = \frac{d}{dt} \left( \frac{dH(t)}{dt} \right) = v \frac{d\gamma(t)}{dt} = v\dot{\gamma}(t) \quad (3.32)$$

Finally, the Equation 3.29 can be written as follows:

$$H_{PD}(t) = H_0 + vT_{pred}\gamma(t) + \frac{1}{2}vT_{pred}^2\dot{\gamma}(t) \quad (3.33)$$

Setting the gains for the future position model as follows:

$$G_\gamma = vT_{pred}, G_{\dot{\gamma}} = v\frac{T_{pred}^2}{2} \quad (3.34)$$

then the position of predictor is expressed:

$$H_{PD}(t) = H_0 + G_\gamma\gamma(t) + G_{\dot{\gamma}}\dot{\gamma}(t) \quad (3.35)$$

Equation 3.35 is the most basic second order predictor model to generate a continuation of the flight path. Theunissen[42] discussed and exploited this predictor algorithms in the same way for improving manual control performance.

For flight path predictor model:

$$\gamma_{PD}(t) = \gamma_0 + \dot{\gamma}(t)T_{pred} + \frac{\ddot{\gamma}(t)}{2}T_{pred}^2 \quad (3.36)$$

According to the relationship between attitude rates  $(\dot{\psi}, \dot{\theta}, \dot{\phi})$  and angular velocity  $(p, q, r)$ ,

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi \sec \theta & \cos \phi \sec \theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (3.37)$$

it is easy to get:

$$\dot{\gamma} = \cos \phi q - \sin \phi r \quad (3.38)$$

when aircraft perturbations is small,  $\gamma$  may be treated as small angle, Equation 3.43 can be approximated by,

$$q = \dot{\gamma} \quad (3.39)$$

Thus the final longitudinal flight path predictor algorithm can be wrote as,

$$\gamma_{PD}(t) = \gamma_0 + qT_{pred} + \frac{\dot{q}}{2}T_{pred}^2 \quad (3.40)$$

### Lateral Flight Path Predictor Design

For the lateral flight path predictor design, the same mathematical method was applied.

$$\chi_{PD}(t) = \chi_0 + \dot{\chi}(t)T_{pred} + \frac{\ddot{\chi}(t)}{2}T_{pred}^2 \quad (3.41)$$

From Equation 3.37, we can get:

$$\dot{\chi} = \sin \phi \sec \theta q + \cos \phi \sec \theta r \quad (3.42)$$

when aircraft perturbations is small,  $\chi$  may be treated as small angle, Equation 3.42 can be approximated by,

$$r = \dot{\chi} \quad (3.43)$$

Thus the final lateral flight path predictor algorithm can be wrote as,

$$\chi_{PD}(t) = \chi_0 + rT_{pred} + \frac{\dot{r}}{2}T_{pred}^2 \quad (3.44)$$

Flight path predictor symbology in this project is derived from flight director with defined  $T_{pred}$  time look-forward. It has lateral and longitudinal inputs from aircraft model, its position on a HUD depicts the predicted flight path in future, its movement velocity also indicates the flight path movement trends. Finally, it is essential to understand there will be an offset between the predicted position and the real position after the selected time in front. It is caused by the prediction error and acceptable.

---

## Interface Development and Integration

Through the literature review and considering the integrated display development tendency, it is clear that tunnel-in-the-sky displays can provide pilots a predicted trajectory with fly control information, this idea will be extended for the next generation cockpit. Nevertheless, applying tunnel concept to trajectory-based TCAS system for mid-air collision avoidance guidance and integrating it with HUD is somewhat a new viewpoint.

Visual cueing design for collision avoidance system adopted HUD as the elementary interface, it presented pilots the basic aircraft flight performance, such as pitch angle, roll angle and flight path angle information. While the recommended pitch and roll attitude induced by TCAS system was interpreted via the series of tunnel symbols and the deviation indicator. The purpose of TCAS interface design is showing pilots an accurate, natural and predicted manoeuvre through perspective projection method, helping pilots to manual control the aircraft to avoid conflicts.

### 4.1 General Consideration

Different approaches were referred to and discussed herein aims to accomplish the primary interface design. For HUD, the avionics handbook written by people in Rockwell Collins was introduced. For TCAS interface, the experiment related to tunnel-in-the-sky was applied.

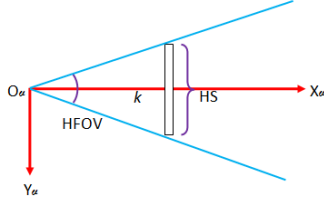
#### 4.1.1 HUD Design Consideration

##### Size Analysis

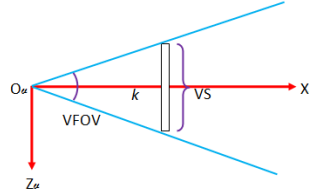
As mentioned in Section 2.2.1, FOV is a crucial parameter for HUD design. The bigger IFOV implies the more flight information pilots can perceive at a glance. Figure 4.1 and Figure 4.2 present the top view and side view of 3D projection method from which geometric FOV is easy to understand. Aslo, it is easy to find HUD screen size and FOV angle decide the parameter  $k$ .  $k$  is defined as the distance between HUD screen and Centre of Projection (aircraft cg), which can be estimated by Equation 4.1.

$$k = \frac{HS}{2 \tan(HFOV/2)}, k = \frac{VS}{2 \tan(VFOV/2)} \quad (4.1)$$

where  $HS$  stands for horizontal size of HUD screen,  $VS$  is the vertical one, and  $HFOV$  represents the horizontal geometrical FOV,  $VFOV$  stands for the vertical one.



**Figure 4.1:** The 3D projection method - Top view



**Figure 4.2:** The 3D projection method - Side view

Thanks to the fast development of high technology, IFOV is never confined by HUD size and its installation, refractive and reflective optical technical was invested to increase the angular of FOV. Figure 4.3 is a good example which describes the typical HUD FOV, and indicates the instantaneous FOV may equal to the total FOV with the reflective optical technology. Look through the figure, it is easy to find the reflective optical system can provide better FOV characteristics than the refractive system, thus the reflective optical HUD are preferred and selected[23] by designer in order to achieve the enhanced capacity. In this project, assuming reflective optical technology is available, so FOV parameter selection is not a problem. To sum up, the smaller FOV could degrade HUD performance, especially for the curved tunnel symbols, which maybe eliminated and leads to control and navigation information lost. A bigger HUD FOV was chosen in this project that was defined to be  $34deg$  for horizontal and  $28deg$  for vertical.

Refer to the definition of  $k$  and the proposed FOV, the relationship of HUD screen length and width can be calculated:

$$\frac{HS}{2\tan(34/2)} = \frac{VS}{2\tan(28/2)} \quad (4.2)$$

Therefore  $\frac{HS}{VS} = 1.2262$ .

	Refractive HUD FOV Characteristics <sup>a</sup>		Reflective HUD Optics FOV Characteristics
	Single Combiner	Dual Combiners	
Total Field Of View	20°–25° Diameter	25°–30° Diameter	22–28° V × 28–34° H
Instantaneous FOV	12° V × 17.8° H	16° V × 17.8° H	22–28° V × 28–34° H
Overlapping	11° V × 6° H	16° V × 6° H	22–26° V × 25–30° H
Monocular FOV	12° Diameter	16° V × 12° H	22–28° V × 30° H

<sup>a</sup> Calculations assume a collimator exit aperture diameter of 5.0", and a distance of 24" between the pilot and the HUD collimator exit aperture.

**Figure 4.3:** Typical HUD Fields-of-View[23].

In this project, instead of the actual size, HUD screen length and width were defined in pixel. According to the calculated proportion, its size was originally defined to be  $1000pix \times 1200pix$ . The parameter  $k$  was discussed and changed based on HUD final performance.

### Selected Symbology

The symbology and layout of HUD were determined by pilots' mission and operation. During the simulation, pilot flight the aircraft at cruising phase. When TCAS RA was functioned, pilots needed to give reaction immediately and control the aircraft to follow the suggested trajectory.

To sum up, the designed HUD symbology and all relative parameters were defined as below:

- Pitch Scale, Horizon Line, Bank Indicator, Flight Path Vector Symbol, Flight Path Predictor Symbol, Aircraft Reference Symbol, Aircraft Digital Speed Indicator, Aircraft Digital Altitude Indicator and Traffic Alert Indicator were the main symbology for HUD concept.
- A round rectangular was defined as HUD outline, restricting all symbology presented inside. It indicated the size of HUD which was supposed to be  $1000pix \times 1200pix$ .
- Geometric FOV is set to  $34degH \times 28degV$ .

### Visual Attention Allocation Analysis

Attention allocation is a considerable factor for display design which influences the efficiency of information processing. The reasonable design (well attention allocation) of HUD allows pilot to perceive aircraft flight situation easily and naturally. It also agrees pilots to perform control tasks and aware environment outside of the cockpit efficiently and accurately. This part will

discuss how to consider pilots attention distribution during HUD and TCAS interface development and integration stage.

Pilots' attention can be classified into two types: 'Focused Attention' and 'Divided Attention', which of them is the dominate attention at a specific condition depending on the flight mission. For instance, the focused attention is required when pilots try to execute approaching and landing, which means pilots need to concentrate on one particular symbol or position, ignoring the less pertinent information. While the divided attention works on the opposite way. Tasks like traffic detecting when pilots carry out avoidance manoeuvre, it requires pilots to allocate their attention to multiple information or regions in space at the same time. Paradoxically, researcher discovered perceptual character cannot handle both kinds of attention simultaneously[24]. The solution principle of this contradiction is to coordinate the focused attention and divided attention by presenting the common missions at the nearby space[43]. Location, format and intensity are the key features to be consider during the display design process to achieve the desired attention allocation.

Considering trajectory-based TCAS manoeuvre requirement, pilots need aircraft attitude information to estimate flight trends, need control information to find out how to fly the aircraft and maintain it within the margin, also need traffic information to 'see and avoid' the conflict traffic. With all these information organized properly on HUD can contribute to quick information processing. Depending on these requirements, focused attention is necessary to control the aircraft to perform the manoeuvre, divided attention is also indispensable for traffic tracking. Thus, pitch scale and horizon line were grouped together and moved synchronically, tunnel-in-the-sky symbology was superimposed upon flight path vector, flight path predictor and attitude indicator aiming to allow pilots to processing these information parallel. In order to enhance pilots situational awareness, switch from selected attention (control information) to distribution attention (adjacent traffic information) smoothly and quickly, different color was adopted for traffic alert indicator (*cyna* is for the approximate traffic, *red* stands for intruder) desiring to disrupt the selected attention and improve divided attention capability.

## Conclusion

As discussed above, the original prospective layout of HUD was shown in Figure 4.4. The whole HUD screen was defined to be  $1000pix \times 1200pix$ . The top middle was the position for Bank Indicator, the big black rectangular in the centre was for Pitch Indicator, True Airspeed Indicator was located on the left bottom just besides Pitch Scale, the Flight Path Vector and Aircraft Reference Symbol were indicated by the small black box in the centre



of the screen. All of this symbology were set to be bright green color similar to commercial aircraft HUD format. In order to improve pilots situational awareness, prevent the cognitive effect due to tunnel-in-the-sky application and eliminate clutter issues, some of symbology were excluded, such as: Air-speed and Altitude Tape, Heading Indicator and Compass. Distinctive color was imposed for Traffic Alert Indicator and Flight Path Predictor desired to divert pilots attention fast and easily.

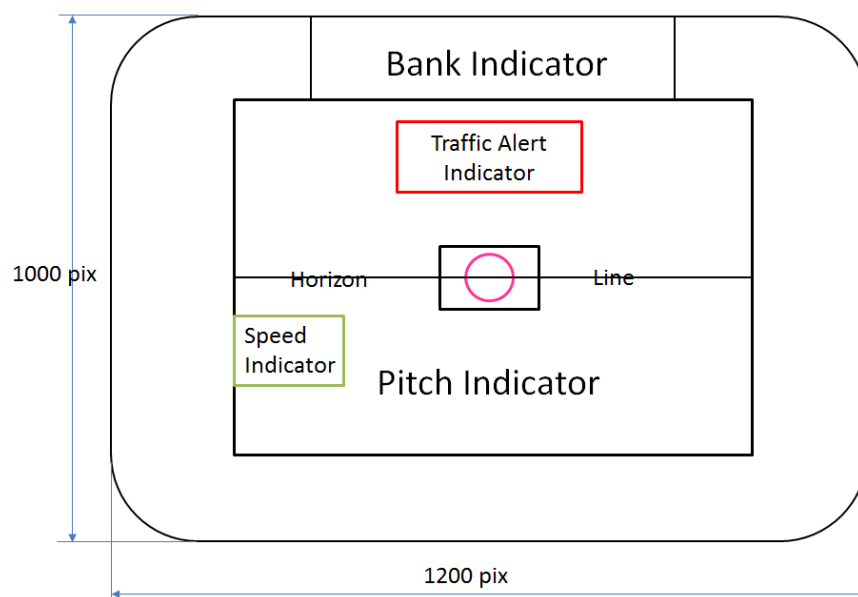


Figure 4.4: The proposed HUD layout.

#### 4.1.2 Tunnel Size Definition

The size of tunnel discussed hither is the geometry dimension of the virtual tunnel in the real world outside of the cockpit. According to the papers of different researchers, the size of tunnel and the prediction time for flight director are determined based on the test experience and the simulation results.

#### Reference to Funabiki's Research

Refer to the visual flight piloted test related to attention allocation in tunnel-in-the-sky on HUD conducted by Kohei Funabiki and his colleague Tomoko Iijima, he described the tunnel size and the other essential parameters in his paper of IEEE 2007. The detailed information was specified in Table 4.1.

**Table 4.1:** Characteristics of Tunnel-in-the-sky[44]

Parameter	Data from experience
Cross Section Size	100 x 100m (above 700ft)
Interval of Frame	250m
Tunnel Visual Presentation	Frame within 0.5NM
Flight Path Predictor (Horizon)	5 seconds prediction with bank angle
Flight Path Predictor (Vertical)	Initial response is slaved to pitch attitude

Here is another study carried out by Kohei Funabiki, he mentioned the parameters of the tunnel and the related data in the 24<sup>TH</sup> INTERNATIONAL CONGRESS OF THE AERONAUTICAL SCIENCES. From his design of tunnel-in-the-sky display for JAXA, he made the following decision based on simulation experiments[10]:

- Lead Time Constant ( $T_l$ ) that stands for the ratio between course error gain and heading error gain, refer to Figure 2.25, 5 seconds was selected.
- The width of the tunnel was 100 metres.
- The intervals between each tunnel frame was 500 metres.
- Tunnel frames that 10 kilometres ahead of the aircraft were hidden and instead with a dotted line at the centre of the tunnel used to guide the pilot to the enter the tunnel.
- The distance error parameter that provoking a distance indication is 200 metre.

### Reference to Other Researchers

Dr. Mulder is the theme leader of air traffic systems in Delft University, the effects of the tunnel size was discussed in his thesis 'Cybernetics of tunnel-in-the-sky displays'. During the experiment, the following parameters were varied:

- The tunnel was consisted of a series of squares, the size of them was defined to different levels to discuss their effects, they were: 80 metres, 40 meters, 20 metres and 10 metres respectively.
- The interval between the squares was fixed at 350 metres.
- Three different levels of aircraft velocity were implemented: 50m/s, 70m/s and 100m/s.

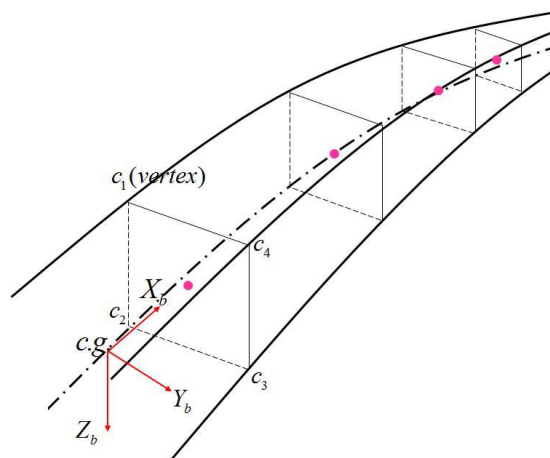
Andrew K. Barrows mentioned in his paper[13] that ‘tunnel in the sky’ prototype display was developed by Stanford University, and he demonstrated the tunnel display had benefits on flight accuracy and situational awareness. The tunnel frame applied in his research was:

*“100 metres wide by 60 metres tall ‘hoops’.”*

The intervals between each frame was 200 metres. The ‘Normal Path Symbol’ and the ‘Predictor Symbol’ were determined 3.5 seconds ahead which were chosen according to the aircraft dynamics. The predicted time was changed based on the aircraft dynamics characteristics, the bigger aircraft with the longer predicted time.

### Conclusion

According to the experiences from other researchers mentioned previously, the tunnel-in-the-sky conception was selected and investigated for trajectory-based TCAS mid-air resolution display. Figure 4.5 described the bird view of preliminary proposal of virtual tunnel in the real space and its parameter were defined in Table 4.2:



**Figure 4.5:** The proposed tunnel in the real world.

**Table 4.2:** Parameter of Tunnel for TCAS

Parameter	Data
Width and Height of the tunnel	80m × 60m
Interval of Frame	250m
Tunnel Visual Presentation	Frame within 0.5NM
Flight Path Predictor (Horizon)	5 seconds prediction with slide angle
Flight Path Predictor (Vertical)	5 seconds prediction with pitch attitude

The tunnel-in-the-sky symbology on a HUD was derived from the real 3D world. As Figure 4.5 presented, the tunnel in the space was defined in aircraft body axis named ‘bird’s eye view of the situation’. The main elements concerned were tunnel frames (the rectangular staffs), the four longitudinal lines hooking up the vertexes of every frame, the pink points represented for the centre of the virtual tunnel. Some researchers implemented the altitude poles for the tunnel used to indicate the aircraft altitude during landing or approaching phase. While they were not applicable in this research because of the manoeuvre was happened during aircraft cruising flight phase, aircraft altitude was high enough so pilots do not need to worry about crashing to the ground or mountains. The visual tunnel-in-the-sky symbology on HUD had two basic color. For tunnel frames and longitudinal outlines, blue color was chosen, while tunnel centre adopted magenta color.

## 4.2 System Integration

### 4.2.1 Introduction

Figure 4.6 illustrated the block diagram of the whole simulation model and the integration process, it involved *Boeing 747* aircraft model, TCAS system, HUD display and FlightGear environment. During the simulation, the information flow was depicted as follows:

- Aircraft model sends flight data to HUD to display aircraft flight status.
- Aircraft model sends flight data to FlightGear to get the flight environment.
- TCAS system receives flight data from aircraft model, monitoring the distance between host aircraft and the tracked traffic, producing traffic alert and resolution advisory when necessary. Its output goes into HUD and supports HUD to generate the TCAS manoeuvre display.
- HUD is the only display offers pilots the needful information. It contains flight information from aircraft model and flight control and navigation information from TCAS system.
- Pilots receive information from HUD and perceive flight environment from flight gear, they use joystick to control host aircraft to complete the flight task.

The detailed information about every block was presented later.

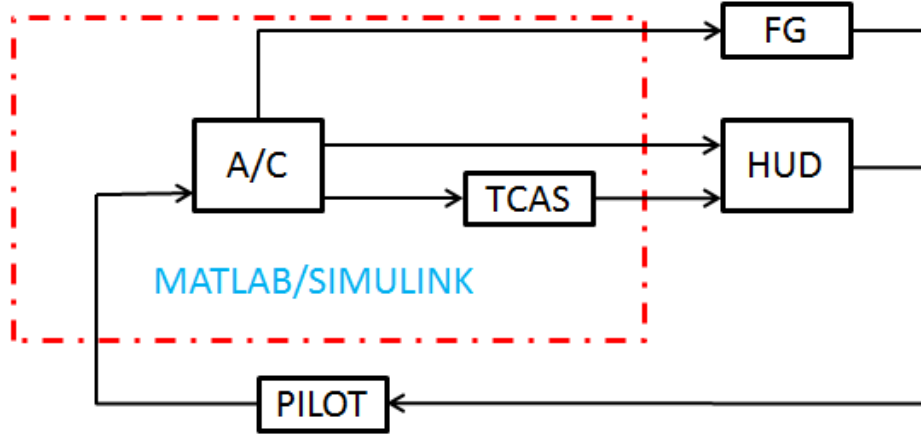


Figure 4.6: Integration block

### 4.2.2 Aircraft Model

One Mach number of 0.8 cruise flight configuration of the *B747* aircraft is selected to carry out the simulation. At a flight altitude of 20000ft and a Mach number of 0.8M, longitudinal and lateral dynamics can be modelled by the following equations referred to [45] derived from [46], the following scenario implementations and discussions were based on this flight condition.

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.006 & 0.026 & -9.980 & 32.130 \\ -0.095 & -0.633 & 906.20 & 0 \\ 0.00 & -0.001 & -0.860 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 0.0001 \\ -33.178 & 0 \\ -2.073 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_\tau \end{bmatrix} \quad (4.3)$$

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{a}_z \\ \dot{a}_{z_p} \\ \dot{C}^* \\ \dot{h} \\ \dot{h}_p \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -0.096 & -0.633 & 13.049 & 0 \\ -0.079 & -0.516 & 85.299 & 0 \\ -0.079 & -0.516 & 82.299 & 0 \\ 0 & -1 & 0 & 893.160 \\ 0 & -1 & 84 & 893.160 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -33.178 & 0 \\ 140.951 & 0 \\ 140.951 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_\tau \end{bmatrix} \quad (4.4)$$

$$\begin{bmatrix} \dot{\beta} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -0.12 & 0 & -1 & 0.036 & 0 \\ -4.12 & -0.974 & 0.292 & 0 & 0 \\ 1.62 & -0.0157 & -0.232 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ p \\ r \\ \phi \\ \psi \end{bmatrix} + \begin{bmatrix} 0 & 0.0124 \\ 0.31 & 0.183 \\ 0.0127 & -0.922 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_\tau \end{bmatrix} \quad (4.5)$$

$$\begin{bmatrix} \beta \\ p \\ r \\ \phi \\ \psi \\ v \\ a_y \\ a_{yp} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 893.160 & 0 & 0 & 0 & 0 \\ -107.179 & 0 & 0 & 0 & 0 \\ 28.901 & -1.319 & -19.488 & 0 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ p \\ r \\ \phi \\ \psi \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 11.075 \\ 1.067 & -66.373 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_\tau \end{bmatrix} \quad (4.6)$$

The control surface actuators and throttle actuator were modelled as second order transfer function with actuator rate and limits in the aircraft model.

### 4.2.3 TCAS system

TCAS system defined in this project could perform surveillance, tracking, traffic advisory, threat detection, resolution advisory and advisory annunciation function. Figure 4.7 describes the basic elements of TCAS system. TCAS receives position information and velocity of host aircraft and the intruder to estimated the time to CPA. Time is the core parameter to determine conflict, 48sec before CPA is the point TCAS issues traffic advisory and announce ‘Traffic, Traffic’, 35sec before CPA TCAS decides resolution advisory and provides prompt alert.

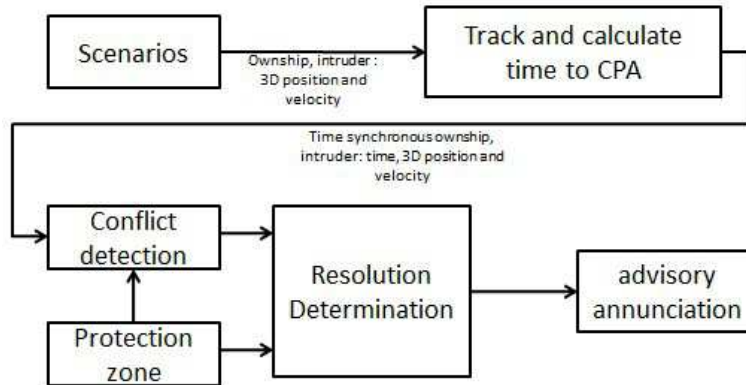


Figure 4.7: Overview TCAS system logic.

### 4.2.4 FlightGear

FlightGear is considered to be a sophisticated, professional and open source flight simulator developed by talented volunteers over the internet[47, 48]. It supports different platforms, such as Windows, Mac, etc. and updated constantly. The detailed information and latest software can be download from the official website: ‘www.flightgear.org’. FlightGear introduced and

discussed herein is version 2.6.

FlightGear provides extensive and accurate world scenery data base, a mass of flight dynamics models, dependable and detailed sky model[47]. In this project, FlightGear is included to offer operation environment for the collision avoidance scenario. During the simulation, two aircraft models(Boeing B747 and Airbus A380), were chose from FlightGear. The pack named *net-fdm Packet* from simulink FlightGear block generates the data necessary to run and control aircraft motion, all data is sent to FlightGear through *Send net-fdm Packet to FlightGear* block which allows to connect local host computer to the FlightGear server. Multiplayer feature allows B747 and A380 two aircraft are displayed on the screen simultaneously to vivid simulate the disaster happened in 2002. The main setting for multiplayer is described as follows:

- aircraft callsign: *test747*, *test380*.
- Hostname: in order to get the best performance, the geographically nearest server (UK: *mpserver04.flightgear.org*) was chosen.
- In/Out port: one instance used in port 5001, the other was 5002. The out port was 5000 for both.

The corresponding arguments in fgfs file were these:

*test747*

```
fgfs -callsign=test747 -multiplay=in,10,192.168.0.2,5001 -multiplay  
=out,10,mpserver05.flightgear.org,5000
```

*test380*

```
fgfs -callsign=test380 -multiplay=in,10,192.168.0.2,5002 -multiplay  
=out,10,mpserver05.flightgear.org,5000
```

### 4.2.5 Integration Process

#### Aircraft to HUD

The main consideration for integration was the interface between aircraft model and HUD block. Matlab s-function was the solution to connect aircraft Simulink model with Java programming. The detailed information stream from Simulink to Java was depicted in Figure 4.8. The information of aircraft roll angle, heading angle, pitch angle, flight path angle, predictor 5sec ahead, side drift angle, aircraft speed, altitude and aircraft position are straight from Simulink block. The flight data were sent to Java through MATLAB function, while their arrangement on HUD and their size were decided in Java. To sum up, the Java only generated all symbology on HUD,

while MATLAB/Simulink were responsible for the real time simulation and updating the appearance.

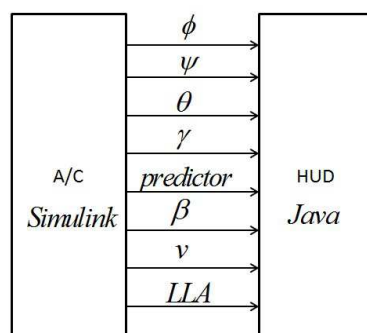


Figure 4.8: Information from aircraft model.

### TCAS to HUD

The interface between TCAS and HUD included Traffic Alert Indicator, Avoidance Manoeuvre Display. TCAS calculated the slant distance between host aircraft and the intruder to determine if TCAS TA or RAs was necessary. When the situation was satisfied, TCAS sent the following information to initialize HUD providing pilots visual cueing to increase traffic awareness and guide pilots to avoid the imminent collision. As Figure 4.9 presented, the position information which indicated the centre of recommended trajectory included *longitudinal*, *latitudinal*, *altitude* data. The applicable traffic alert type involved 'Climb', 'Descend', 'Turn Right', 'Turn Left'. TCAS was responsible to determine the suitable alert type compliance with the tunnel extend tendency.

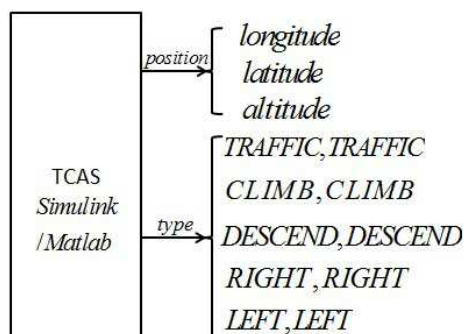


Figure 4.9: Information from TCAS.



### 4.3 Display Symbolology

The display symbolology described and discussed in this section was the final interface developed in this research project, involving basic HUD symbolology and tunnel-in-the-sky symbolology. The operator was required to fly the aircraft to avoid the imminent mid-air collision referring to the developed visual cueing methods. Java JDK software was the basic tool used to develop the HUD interface.

#### 4.3.1 HUD Symbolology

Taking into account the current HUD layout of Rockwell Collins and Thales, considering HUD clutter issues and pilots' flight task requirements, finally the HUD symbolology and its layout in this project were defined as Figure 4.10 shown. It included bank angle symbolology, pitch attitude indicator, flight path vector, flight path predictor, the artificial horizon, digital airspeed indicator and digital altitude indicator.

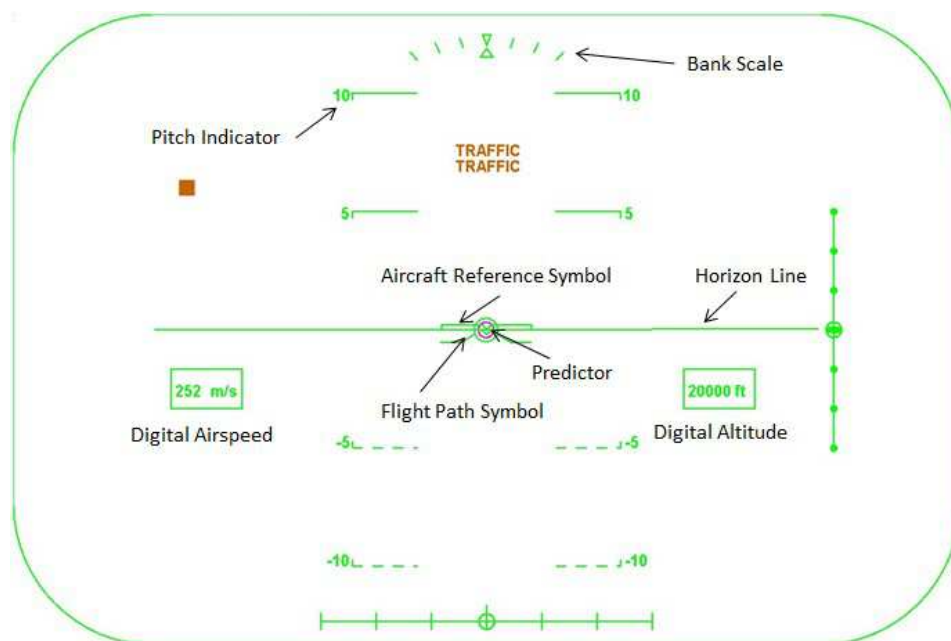


Figure 4.10: The primary symbols of the developed HUD concept.

#### Pitch Attitude Indicator

The consideration of pitch attitude indicator designation referred to the pitch scale implemented on commercial airliner today, commonly it increases or decreases with  $5deg$  interval above and below the horizontal line. As Figure 4.10 shown, it was presented in the centre of HUD and symmetrically

arranged on the left and right. The pitch attitude display range was designed from  $-20deg$  to  $20deg$ , while only  $-10deg$  to  $10deg$  were displayed at the initial flight stage, the bigger attitude indicator would be displayed when the bigger aircraft pitch attitude was required. The positive attitude was indicated by solid horizontal lines with tiny solid vertical lines pointed down to the artificial horizon on left/right edge. The negative attitude was illustrated by dotted horizontal line with little vertical lines pointed up to the artificial horizon. In this project, the right side of the pitch attitude indicator was particularly designed could be hidden from the display for de-cluttered purpose. While which mode was chosen depended on the pilot's prefer, the default mode was the whole attitude indicator with both left side and right side.

### Horizon Line

One difference between a HUD and a PFD is that HUD has no artificial sky and ground, while the horizontal line was implemented to help pilots distinguish them. Typically, the horizon reference line was required to located at or near the actual horizon looking through the windshield, and it moved according to the aircraft pitch attitude in order to overlies the horizon. The horizon line worked as a reference for aircraft reference symbol, flight path vector and flight path predictor to indicate aircraft flight status, it could move up and down and also rotate with pitch scale indicator. During the integration and simulation, the HUD interface was superposed on the flight gear environment, the horizon line was supposed to coincide with horizon in the far domain of flight gear. At this situation, it was easier for pilots to perceive aircraft attitude information and the scenes outside compared with the conventional head down displays.

### Bank Scale Indicator

The bank scale indicator was fixed on top of HUD and labelled at  $0deg$ ,  $10deg$ ,  $20deg$ ,  $30deg$ . The 'triangular' was the bank pointer, the relative location between the triangular and the bank scale indicated aircraft roll angle. The pitch scale and horizon line rotated the same degrees as bank pointer. When they rotated towards left implied the aircraft was rolling left, otherwise was the opposite direction. The bank pointer got the input from aircraft model and indicated aircraft  $\phi$  angle.

### Flight Path vector Symbol

Flight path vector symbol displayed on HUD predicted pilots where the aircraft would flight to shortly from their current position without any control commands were given. The position of the flight path symbol on a HUD indicated the aircraft flight status. Typically, The input data for the flight

path vector was from the calculation in the IRS/AHRS and FMS.

The flight path vector symbol designed in this project referred to the flight path vector symbol used by commercial aircraft HUD, the vertical distance between flight path symbol and horizon line determined the attitude between aircraft velocity vector and the horizon line, named flight path angle ( $\gamma$  angle). It helped pilots to perceive the vertical deflection naturally and simply to estimate the aircraft climbing or descending trends and rate. The distance between the centre of the flight path symbol and centre vertical line of the HUD indicated aircraft drift angle ( $\beta$  angle) with respect to heading angle. The pilots can recognize the lateral attitude information of aircraft and keep situational awareness of aircraft tracking angle ( $\chi = \psi + \beta$ ).

When conducting pilot-in-the-loop test, the pilots need to manual control the aircraft with flight path symbol. In this project, when flight path symbol was below the horizon line meant the aircraft was descending, otherwise indicating the aircraft was climbing. If flight path angle was located on the right hand of the pitch attitude indicator, it showed pilots the aircraft was drifting to the right, conversely the aircraft was drifting to the left.

### **Flight Path Predictor Symbol**

Flight Path Predictor Symbol was defined to be a magenta circle used to predict the aircraft future position with  $5sec$  look forward. Its operating principle was the same as flight path vector, its relative position with pitch scale and horizon line anticipated the flight status in future. Comparing with flight path vector, the predictor anticipated the flight path angle  $5sec$  ahead which allowed the pilots to foresee the flight condition without predicting by themselves. It was more facilitated and easier for pilots to complete the control task than flight path vector, especially for the tough manoeuvre.

As discussed in Section 3.4.2, flight path predictor had the separate input for the vertical and horizontal location. For the pitch axis, the predictor not only got the flight path angle form aircraft model, also was accelerated by pitch rate  $q$  and  $\dot{q}$  which helped pilots feel the control from the joystick. For the roll axis, flight path predictor received the slide angle data and accelerated by roll rate  $r$  and  $\dot{r}$ . Thus, the predictor had the capability to predict aircraft future situation, also allowed pilots to feel the control effects when they were trying to control the aircraft.

### **Aircraft Reference Symbol**

The aircraft reference symbol designed here referred to the symbol from commercial aircraft nowadays, it was fixed on the HUD. The distance be-

tween the horizon line and the aircraft reference symbol decided the aircraft pitch attitude ( $\theta$  angle), its location on the pitch scale illustrated the aircraft  $\theta$  value at that moment. Its initial relative position was determined by the aircraft flight performance, it indicated aircraft cruising pitch angle. According to the aircraft model used in this project, the pitch angle ( $\theta$  angle) was  $0deg$  during cruising phase, so the initial position of aircraft reference symbol was located at the horizon line.

### **Airspeed Indicator**

Airspeed Indicator presented pilots the digital aircraft true airspeed instead of the traditional Airspeed Tape. It had the advantage to provide pilots the decluttered format HUD layout but still afforded pilots enough flight information. The precision of airspeed here was decided to units digital while eliminated the decimals. The airspeed data was straight received from *B747* aircraft model.

### **Altitude Indicator**

Altitude indicator was similar with airspeed indicator, it presented pilots the digital altitude on right hand of HUD instead of the conventional Altitude Tape. The digital altitude indicator indicated real time altitude of the aircraft, its precision was defined to units digital while eliminated the decimals. The altitude input was directly from *B747* aircraft model.

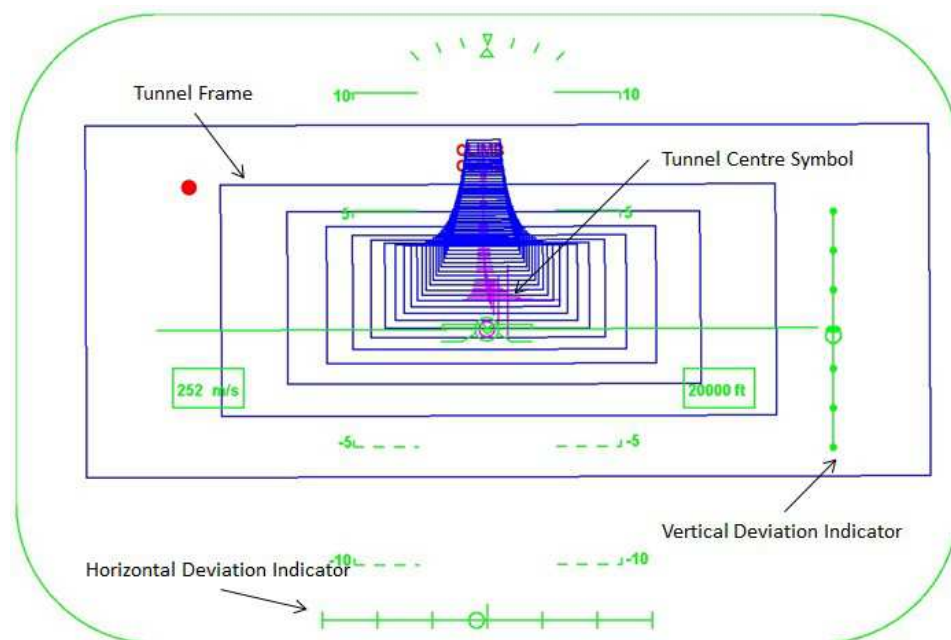
## **4.3.2 Avoidance Manoeuvre Symbology**

The avoidance manoeuvre display for TCAS system applied tunnel-in-the-sky concept that consisted of a series of hoops and crosses to describe the predicted and recommended flight path. It was superposed on HUD and represented the perspective projection of the virtual tunnel in the real 3D space based on pilots' forward field of view. Besides tunnel symbology, it also included a lateral distance deviation indicator and a vertical altitude deviation indicator. The final avoidance manoeuvre display for TCAS system was illustrated in Figure 4.11. Its detailed function were described as below.

### **Tunnel-in-the-sky**

As Figure 4.11 presented, the bundle of blue color rectangular and the magenta crosses consisted of the tunnel-in-the-sky symbology.

Every rectangular represented the real tunnel frame looking through aircraft windshield which was defined in Section 4.1.2. The real size of every hoop



**Figure 4.11:** Avoidance manoeuvre symbology with HUD

was  $80m \times 60m$ , while the size and shape of them on HUD after the perspective projection depended on their relative position and orientation compared with host aircraft. The more far away from the aircraft, the smaller the hoop was. When the aircraft was flying towards the tunnel, the hoops would become bigger and bigger and moving to the aircraft. The hoops that arrived at or passed aircraft nose were excluded and disappeared from the screen. The interval between each hoops on HUD depended on its distance away from aircraft *cg*.

The magenta crosses were derived from the centre of every hoops in the real world which real size is  $10m \times 10m$ . They were the targets for pilots flying to, the specific color aimed to enhance pilots situational awareness and reduce the position deviation. During the preliminary design, they were not supposed to be applied. While without them, it was difficult to perceive the tunnel centre and track the recommended trajectory, aircraft frequently flies outside of the constrains.

As Figure 4.11 shown, the whole tunnel-in-the-sky symbology consisted of the recommended trajectory and indicated the up trends. It implied TCAS issued a 'CLIMB' advisory and guided pilots to follow it and fly climbing. As Figure 4.12 illustrated the 'TURN RIGHT' advisory, the tunnel-in-the-sky symbology presented pilot the turn right tendency. From HUD, pilots

could roughly understand how much heading angle he need to change and which direction he need to fly to.

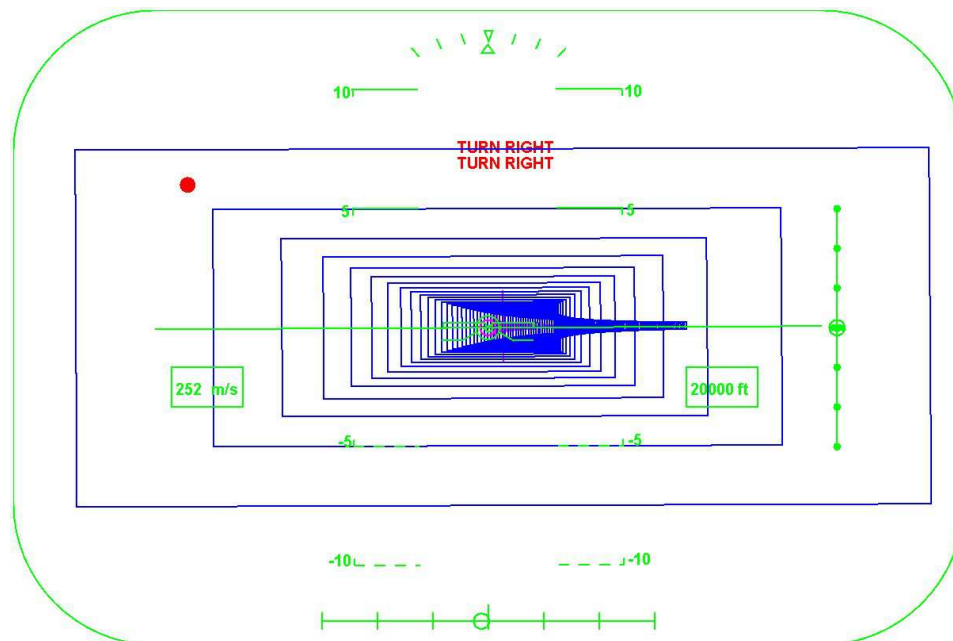


Figure 4.12: Turn right Advisory display

### Deviation Indicator

The green color vertical and horizontal scale located on the right hand and at the bottom of HUD are named Vertical and Horizontal Deviation Indicator respectively. They are used to indicate the current aircraft position error compared with the suggested trajectory. The scales were defined according to the size of the virtual tunnel frame which determined the flight boundary of aircraft. The centre of the scale stood for 0 position error, the relative distance between the indicator and the scale illustrated the magnitude of aircraft position deviation. When the indicator was beyond of the hoops, it implied the aircraft was flying exceeding of the constrains. As Figure 4.11 shown, the lateral deviation circle was located on the left side of the middle meant the aircraft was on the left hand of the tunnel centre, pilots needed to right roll joystick to made the aircraft slight right change. When the vertical indicator was under the centre of the scale, it implied the aircraft altitude was under the recommended tunnel centre, pilots needed to pull up the joystick and made sure the aircraft was climbing steadily. The input for deviation indicator was calculated from the host aircraft current position and the nearest tunnel centre. The mission of the pilots was trying to make sure the deviation was minimum, it meant the indicator was around the

middle of the scaler.

## 4.4 Final Display Information Analysis

### 4.4.1 Guidance to the Tunnel Consideration

At the beginning of tunnel image design, centre of the hoop symbology was not involved. While a remarkable problem was noticed when trying to fly back into tunnel centre. The scenario defined, originally host aircraft was at the centre of the hoop and its velocity vector was perpendicular to the tunnel plane. But once the aircraft was flying outside of the nominal trajectory with a big deviation, it was hard to control the aircraft back into the tunnel frame due to the indistinct centre indication.

One idea came out trying to solve this problem. A magenta dotted line was added to connect every centre of the hoops, the nearest hoop was connected with the flight path predictor. The benefit of indicating the centre clearly helped pilots to aware the target easily. The line connecting the predictor and the most nearby hoop also presented pilots the way get back to the centre. However the magenta dotted line made the whole HUD sort of cluttered compared to without it. Finally, the idea of continue centre line was cancelled.

Another solution was indicating the tunnel centre with the magenta crosses instead of the previous connected dotted line. The series of independent crosses form the centre of the tunnel and extended accompany with the trajectory. It had the advantage to provide pilots an obvious view of the goal while get rid of confusion. The idea of connect the nearest tunnel frame and flight path predictor was given up, instead of instructing pilots directly to the tunnel centre, pilot had the duty to decide which way to flight back.

The horizontal deviation and vertical deviation indicator was one more idea aimed to improve the guidance performance. They were proposed due to pilots prefer to have them. How to arrange them was considered during the development. The horizontal error indicator was decide to locate at the bottom of the HUD while the vertical one was defined to be on the right hand of the HUD. The reason to separate them was in order to divide pilots' attention to eliminate tunnel-in-the-sky brought the cognitive problem. The separate error indicator not only presented pilots the explicit error needed to compensate, but also it compelled pilots to switch their attention around half HUD which should help pilots to be conscious of other traffic if needed.

All in all, the avoidance manoeuvre format was determined to be with tunnel-in-the-sky symgology to present the predictive flight path, with tun-

nel centre symbology to guide pilots fly back to the target position, with deviation indicator to improve mission accuracy.

#### 4.4.2 Traffic Display Consideration

The design of TCAS system was based on ‘see and avoid’ principle, supposing flight crews could see the intruder in advance, it will enormous improved pilots capability and confidence to follow TCAS instruction to avoid the collision. The idea to display the conflict aircraft accompany with tunnel symbology came out with the purpose to let pilots capture the other traffic’s position with respect of ownship.

Based on the commercial traffic display for TCAS version 7.1, two kinds of different traffic symbols are adopted. One is particularly for TA which is square shaped cyan color symbol, the other one is for all RAs which are circular shaped red color symbol. The intruder’s position is defined in the real world based on geodetic coordinate then project on HUD via perspective projection method. The symbol stood for the intruder and its position was updated according to the real time simulation. During the simulation, it found only when the intruder was coming from the front of the ownship, the traffic symbol worked with the tunnel. While the intruder was flying from the other direction to the ownship, the position of intruder’s symbol on HUD did not make sense and confused pilots. While the intruder was out of HUD’s FOV, traffic symbol could not be projected on HUD. Finally, the idea of updating intruder position with tunnel-in-the-sky was cancelled, pilots can get the other traffic information from the conventional traffic display while not from HUD. The intruder’s indication symbol was given by a fixed size and fixed position on HUD.



---

## Collision Avoidance Scenario

In order to verify the accuracy and effectiveness of the developed visual cueing for collision avoidance system and discover its advantage compared with the conventional interface, three different mid-air collision avoidance scenarios were defined herein. Scenario one described the traditional function of TCAS, providing vertical manoeuvre guidance with pull up or push down instruction. Scenario two presented new function of trajectory-based TCAS system which could issue horizontal manoeuvre advisory. The setup of scenario three was the same as scenario one, while TCAS issued a 3D resolution advisory which required both roll and pitch control to complete the task. The scenarios focused on flying different trajectories with the new developed real time 3D TCAS interface on a HUD to avoid the adjacent collision, intended to explore the effectiveness, accuracy or other benefits of the new display for trajectory-based TCAS system.

### 5.1 Mid-air Collision Definition

Mid-air collision rarely happened with respect to the collisions occurred during approaching and landing flight phase, especially at high cruising altitude. However it would bring massive disasters once took place, the tragedy crash between *Tu – 154* commercial aircraft and *Boeing 757 – 200* was a typical example. In addition, because of the dramatic increasing aviations, experts of aviation Jim Eckes expressed the chances of such mid-air collision would increase naturally[49]. Thus, researches about mid-air collision became more necessary and meaningful.

Firstly, ‘Near Mid-air Collision (NMAC)’ definition was introduced, then collision scenarios were described and implemented through mathematical method.

*“A near midair collision is defined as an incident associated with the operation of an aircraft in which a possibility of collision occurs as a result of proximity of less than 500 feet to another aircraft, or a report is received from a pilot or a flight crew member stating that a collision hazard existed between two or more aircraft[50].”*

According to AOPA study, 26% NMAC emerged due to climbing and descending at cruise stage. And National Guard indicated 27% mid-air collision took place in cruise and 17% happened while performing manoeuvre[51]. Based on these data, we can discover the probability of a mid-air collision was not so rare. And with the free flight concept was open, the amount of mid-air collision would be imaged rising up, especially with the bad weather or low visibility condition. The investigations by National Transportation Safety Board (NTSB) indicated the main reason of mid-air collision was ‘pilot in command failed to see and avoid other aircraft’. Solutions needed to be considered to help pilots easily catch the intruders in order to maintain or even enhance the flight safety.

## 5.2 Scenario Description

The three scenarios described herein were about two aircraft involved in a collision course. If pilots took no additional actions, the two aircraft were supposed to get collision at CPA. The similar setup of these three scenarios were presented as follows:

- The host aircraft and intruder were both level at  $FL200$  with initial velocity 0.8 Mach.
- From host aircraft point of view, only one intruder was under tracking.
- Both aircraft were supposed to have TCAS installed and worked well.

The differences came from the different RAs, reflected by different pilots control tasks. Three types of RAs (Climb, Turn Right and 3D Trajectory RA) were involved and issued respectively for every scenario, pilots of host aircraft followed the new developed TCAS manoeuvre display guidance to complete the flight task.

### 5.2.1 Scenario One Description

Scenario one referred to the disaster happened between *Tu-154* and *Boeing 757-200* aircraft described in Section 2.3.6. Assuming *Boeing 757-200* was the host aircraft and simulated by a *Boeing 747* aircraft model that provided by Dynamics, Simulation & Control Group of Cranfield University. The host aircraft was controlled by pilots through joystick. *Tu-154* was the intruder and simulated by a fixed flight path. Figure 5.1 illustrated the situations of these conflicted aircraft. The host aircraft was heading from East to West, the intruder was from South to North and they were supposed to get collided in future. The two cylinders indicated the 3D protected volume of TCAS as mentioned in Section 2.3.3. The outer cylinder defined TA covered area which was 48sec before CPA, and the inside one

was special for RAs which was 35sec before CPA, the vertical separation was defined to be 600ft high. The protected volume was decided according to the performance of TCAS II, version7.1. When aircraft entered the protected volume, TCAS TA or RA would be initialized which generated aural or/and visual prompt to catch pilots' awareness and assisted pilots to resolve the conflict.

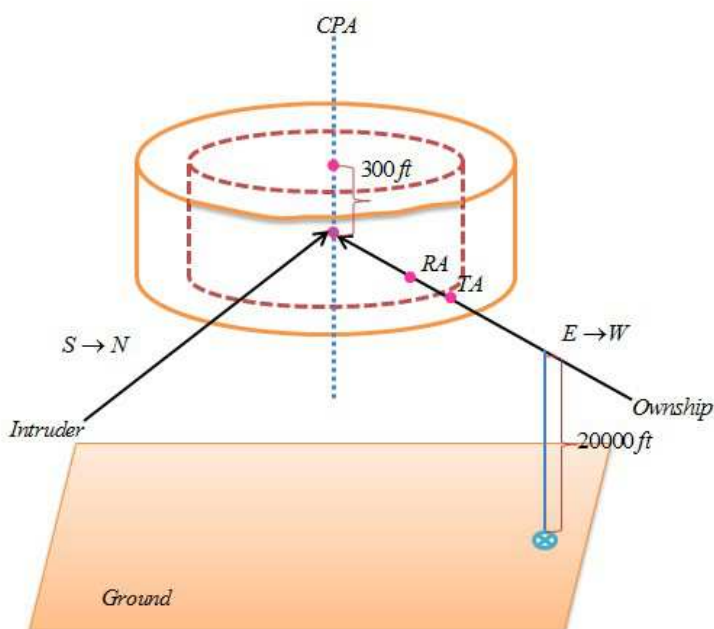


Figure 5.1: Flight status of two conflict aircraft.

Figure 5.2 indicated the procession of TCAS operation, summarized as follows. The dotted arrows indicated the supposed flight path without collision alert from TCAS, the solid arrows described the flight condition if TCAS RA was followed properly.

1. Firstly, the aircraft was flying under control of autopilot, pilots were free from operation and monitoring the display. TCAS system were tracking the position of intruder and estimated the time two aircraft got collided.
2. 48sec before arriving at CPA, TCAS system found the approximate and issued a Traffic Advisory on HUD and a 'TRAFFIC TRAFFIC' aural announcement to catch pilots' attention.
3. TCAS system continued tracking the intruder and monitoring the slant range between two aircraft.

4. 35sec before arriving at CPA, TCAS issued Resolution Advisory to both aircraft, recommending pilots of host aircraft to pull up joystick and pilots of intruder to push down.
5. TCAS system continued monitoring the performance of two aircraft, in case the reversal RA was necessary.
6. Collision course was cleared and TCAS display was eliminated.

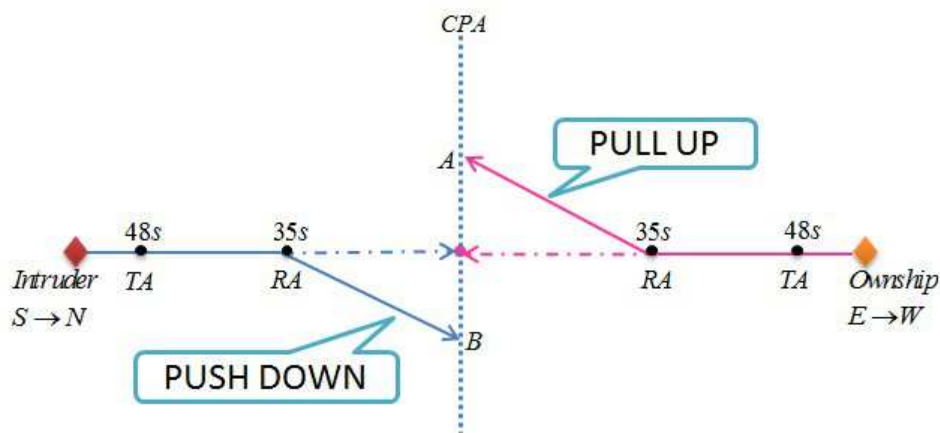


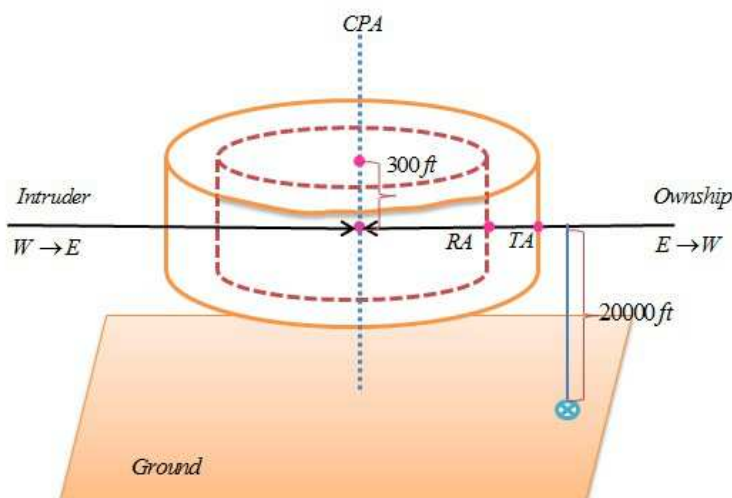
Figure 5.2: Conventional RA (pull up or push down).

This is an example of traditional TCAS system operation principle. During the simulation, TCAS provided TA and RA (CLIMB and Descend) according to the estimated time to CPA as the commercial TCAS system did. HUD with TCAS manoeuvre interface was the only method to provide pilot the complete and natural guidance information. The pilot of host aircraft had the responsibility to discover the TCAS conflict reminder, followed the instruction provided by TCAS system and controlled the aircraft through joystick to fly the aircraft out of the intruder's protective zone. The new developed TCAS manoeuvre display was the core of the testing, as Figure 4.11 shown, it presented pilots the whole trajectory and helped pilots to understand the flight mission - climbing. The purpose of this scenario was to explain effectiveness and accuracy of the new visual cueing through conventional pull up and push down commands, and discover its specific performance compared with traditional TCAS display.

### 5.2.2 Scenario Two Description

Scenario two described two aircraft involved in a collision course. The same as scenario one, one aircraft was defined to be host aircraft and could operated by pilots, the aircraft model was provided by Dynamics, Simulation &

Control Group of Cranfield University. The other aircraft was defined to be intruder which was generated by a fixed flight path. As Figure 5.3 shown, scenario two was similar with scenario one except the intruder heading direction. In scenario two, the two aircraft flight face to face. For host aircraft, it was levelled from East towards West, while the intruder was cruising from West to East. Scenario two desired to demonstrate the horizontal manoeuvre display of trajectory-based TCAS system.



**Figure 5.3:** Flight status of two conflict aircraft (face to face).

Figure 5.4 described the horizontal function of TCAS system. Based on the flight condition of ownship and intruder, this time TCAS issued ‘TURN RIGHT’ advisory to ownship, correspondingly dispatched ‘TURN RIGHT’ advisory to the intruder. Thus these two aircraft would change their flight path to the opposite side and avoided the head to head collision. The desired horizontal separation between two conflicts was defined to be  $0.8NM$ . During simulation processing, the developed TCAS turn right manoeuvre display was superimposed on HUD, presenting pilots the turn right instruction via the predicted tunnel images.

TCAS operation procedure was summarized as follows, referred to Figure 5.4. The dotted arrows indicated the supposed flight path without collision alert from TCAS, the solid arrows described the condition if TCAS RA was followed properly.

1. Firstly, the aircraft was flying under control of autopilot, pilots were free from operation and monitoring the display. TCAS system were tracking the position of intruder and estimated the time two aircraft

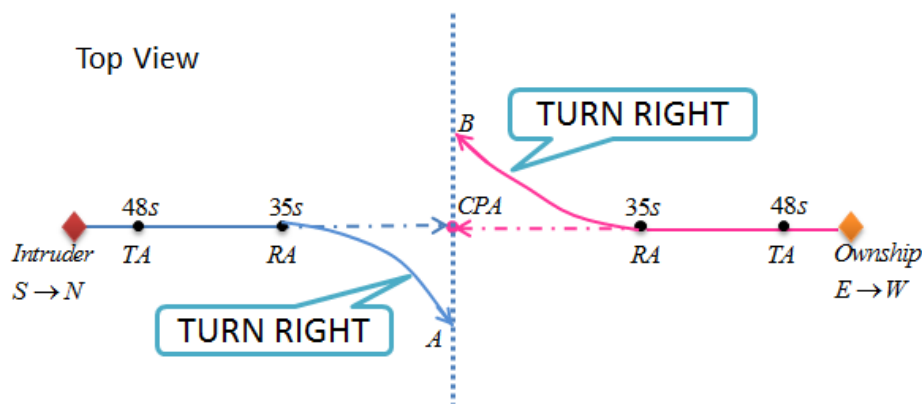


Figure 5.4: Horizontal RA (turn left or turn right).

got collided.

2. 48sec before arriving at CPA, TCAS system found the approximate and issued a Traffic Advisory on HUD and a 'TRAFFIC TRAFFIC' aural prompt to catch pilots' attention.
3. TCAS system continued tracking the intruder and monitored the slant range between two aircraft.
4. 35sec before arriving at CPA, TCAS issued Resolution Advisory to both aircraft, recommending pilots of host aircraft turning to the right side and pilots of intruder turning to the right too.
5. TCAS system continued monitoring the performance of two aircraft, in case the reversal RA was necessary.
6. Collision course was cleared and all TCAS interface was eliminated.

### 5.2.3 Scenario Three Description

The initial condition of scenario three was exactly the same as status in scenario two, two aircraft flight head to head and involved in a collision course. While TCAS system in scenario three provided pilots a 3D guidance, pilots needed both pitch control and roll control to accomplish the mission. As Figure 5.5 depicted, host aircraft and the intruder were both transformed from LLA coordinate to NED. The green arrow indicated the relative velocity of the two aircraft, the cylinder defined the intruder protected zone, the dotted arrows constructed the 3D margin which inhabited host aircraft entered into. The blue error presented the recommended trajectory issued by TCAS system. It was tangent to the right top margin of cylinder, which

guided host aircraft to achieve both horizontal and vertical separation. Although it was not the optimized trajectory, while generating the optimized trajectory was not belong to this project. The 3D trajectory applied herein was used to demonstrate the new developed TCAS manoeuvre display was natural, predictable, robust, and providing more crucial information which maybe prevent the catastrophe in future. The operation of TCAS system herein referred to scenario two discussed before.

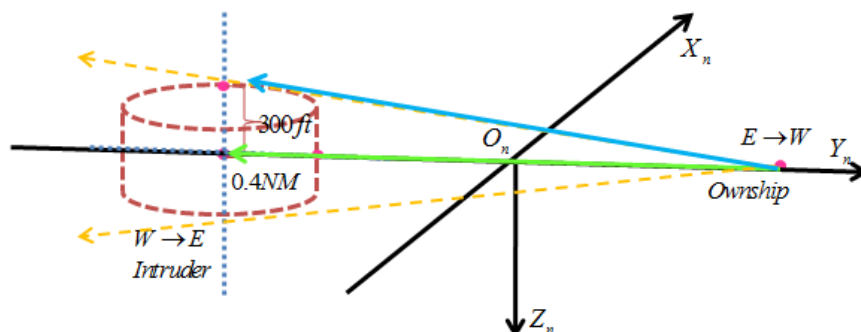


Figure 5.5: Trajectory-based RA (climb and turn right).

The TCAS RA in scenario three was named ‘3D TRAJECTORY’ which implied it contained both horizontal and vertical manoeuvre requirement. The key point and the object of this project was providing pilots a proper manoeuvre display and demonstrating its effectiveness. Therefore, the principle of trajectory generation was not discussed and applied herein. In order to make the imitation easily, the recommended trajectory defined by TCAS system was simply assembled by changing flight path angle and heading angle.

### 5.3 Scenario Implementation

Two steps were involved to implement the scenarios described before. Firstly, defining flight dynamics for two aircraft and make sure they were in a collision course. Secondly, setting the needed function for TCAS system and make sure the two aircraft could release from the collision course with TCAS guidance. The most important thing was to predefine a proper recommended trajectory for TCAS system.

### 5.3.1 Basic Pull-up Scenario One Implementation

#### Collision Scenario Design

For host aircraft, as described in Section 4.2.2, the original flight data and its dynamics status from aircraft model were presented as follows:

1. **True Airspeed:** 0.8 Mach.
2. **Altitude:** 20000 feet.
3. **Pitch Angle:** 0 degree.
4. **Heading Angle:** -90 degree.
5. **Roll Angle:** 0 degree.
6. **Position:** Latitude 51.4775 degree, Longitude 0.4614 degree.

For intruder, a particular fixed flight path was defined and made it collide with host aircraft some time later. The initial condition were depicted as below:

1. **True Airspeed:** 0.8 Mach.
2. **Altitude:** 20000 feet.
3. **Pitch Angle:** 0 degree.
4. **Heading Angle:** 0 degree.
5. **Roll Angle:** 0 degree.
6. **Position:** Latitude 51.47695 degree, Longitude 0.0819 degree.

The intruder's trajectory was implemented through Simulink, and defined to fly straightly from South to North. If no collision avoidance system was installed, pilots could not aware the critical situation timely. In this scenario, supposing pilots of two aircraft dd not perform the manoeuvre, they definitely got collide around 50 seconds after the simulation.

#### TCAS Recommended Trajectory for Ownship

According to CAS logic discussed in Section 2.3.3, TCAS interrogated with other traffic by transponder to estimate the slant range, altitude and bearing. Assuming it issued a TA 48sec before CPA and a RA 35sec before CPA. Thus a new trajectory initialized by TCAS system was display on HUD with traffic information to show pilots how to fly the aircraft to avoid the imminent collision.



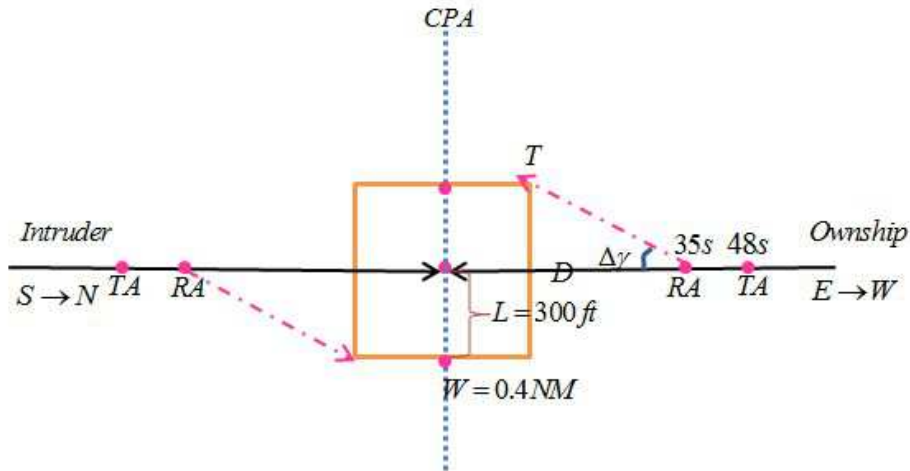


Figure 5.6: Manoeuvre strategy (PULL UP).

Figure 5.6 illustrated the side view of pull up manoeuvre issued by TCAS system. The orange color rectangular described the minimum horizontal and vertical protected zone which size was  $400NM \times 300ft$ , the host aircraft/intruder was forbidden to arrive into this area. The size of protected zone was defined according to the minimum separation requirement. The dotted line represented the opposite advisory (recommended trajectory) initiated by TCAS logic.  $\Delta\gamma$  stood for the minimum required flight path angle quantity which allowed host aircraft to arrive at point  $T$  if it flight with constant flight path angle ( $\gamma(t) = \gamma_0 + \Delta\gamma$ ) since TCAS RA was issued.  $\Delta\gamma$  was the flight path angle variation that could be estimated by the following two equations:

$$D = \int_0^{35} (V_0 \cos \gamma(t) \sin \psi(t)) dt - W \quad (5.1)$$

$$\tan \Delta\gamma = \frac{L}{D} \quad (5.2)$$

where  $W$  was aircraft horizontal protected distance,  $L$  represented the vertical protected distance,  $D$  stood for the horizontal distance to point  $T$ , it was the distance along with aircraft longitudinal direction.

Refer to host aircraft original flight performance, supposing its heading angle and roll angle kept constant during the manoeuvre, only flight path angle got changed to accomplish the climbing advisory, thus  $\Delta\gamma$  was estimated to 0.6 degree. This estimated flight path angle was used to implement the suggested trajectory. The 0.6 degree was calculated during an ideal status

which required pilots to react and change aircraft flight path angle immediately when TCAS initialized the RA. While this was not practical during the simulation trials. For aircraft model, it cannot achieve flight path angle  $0.6deg$  step changed. So the estimated  $0.6deg$  was considered as a reference value, the defined flight path angle should increase gradually and smoothly, the important thing was make sure the protective volume was satisfied before arriving at CPA. The final flight path angle was determined through simulating process.

In this project, TCAS RA manoeuvre trajectory was defined in geodetic coordinate and represented by aircraft speed, flight path angle and heading angle. Define  $\vec{P}_{Traj}(t)$  as trajectory's position vector, which can be presented as follows,

$$\vec{P}_{Traj}(t) = [ X(t) \quad Y(t) \quad Z(t) ] \quad (5.3)$$

Where  $X(t)$ ,  $Y(t)$ ,  $Z(t)$  was the instance position information related with simulation time.

The recommended flight path issued by TCAS system was approximated by the integration of aircraft velocity and initial position, described as below,

$$\vec{P}_{Traj}(t) = \vec{P}_{Traj}(t_0) + \int_{t_0}^t \vec{V}_t dt \quad (5.4)$$

Here  $t_0$  prescribed the time that TCAS system provided trajectory on HUD during the whole simulation, it was decided to be  $35sec$  before CPA. Correspondingly,  $\vec{P}_{Traj}(t_0)$  specified the original position of trajectory. The velocity integration calculated the length of the trajectory based on host aircraft flight performance. Aircraft velocity and simulation time were the only variables determine the future flight path.  $\vec{V}_t$  stood for host aircraft instantaneous velocity vector, relative to aircraft attitude angles which defines in Equation 5.5,

$$\vec{V}_t = \vec{V}_0 \begin{bmatrix} \cos \gamma(t) \cos \psi(t) \\ \cos \gamma(t) \sin \psi(t) \\ \sin \gamma(t) \end{bmatrix} \quad (5.5)$$

where  $\gamma(t)$  was host aircraft flight path angle that decided by TCAS system and estimated referring to  $0.6$  degree. During the climbing process, ownship bank angle  $\psi$  kept constant and was equal to  $-90$  degree. The format of  $\gamma(t)$  angle was the key point of tunnel frame. As we defined in Section 4.1.2, the tunnel interval in the real world is  $250m$ , thus the defined of  $\gamma(t)$  should satisfy this requirement. Finally,  $\gamma(t)$  was defined to be a series of digital

data to achieve the interval and implemented by MATLAB function as follows:

```
'gammamax = 1.5 * pi/180;
psi = -90 * pi/180;
gamma = [zeros(1,3)'linspace(0, gammamax, 105)];'
```

Therefore the finally tunnel frame centre was expressed in LLA reference frame and presented in Appendix 1. The distance between the adjacent frame was around  $250m$ , the vertical altitude between the first tunnel frame and point  $T$  was  $300ft$  which complied with the required minimum separation.

Refer to scenario one's description and Figure 5.6, the whole simulation was defined to be  $51sec$  in this project. Firstly, aircraft was cruising as expected and TCAS kept measuring the distance;  $2sec$  later, TCAS issued TA, traffic alert 'TRAFFIC TRAFFIC' and its indicator were displayed on top centre of HUD, aural prompt was broadcasting;  $15sec$  later, TCAS climbing RA was issued, traffic alert 'CLIMB CLIMB' substituted 'TRAFFIC TRAFFIC' on HUD, traffic indicator substituted intruder indicator, at the same time the suggested trajectory was superimposed on HUD predicting the flight path for pilots, also aural prompt was broadcasting; finally,  $50sec$  after the simulating, collision risk was cleared and all traffic display was removed from HUD.

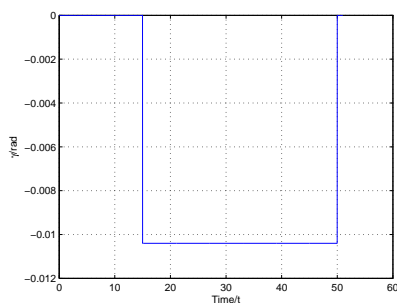
### TCAS Recommended Trajectory for Intruder

When TCAS issued 'Climb, Climb' to ownship, the opposite advisory 'Descend, Descend' was provided to the intruder. The intruder was implemented by a fixed flight path and could not be controlled manually. Thus we supposed the intruder followed TCAS advisory and performed descending as soon as RA was initialized. As presented in Equation 5.4 and Equation 5.5, supposing the intruder's heading angle and roll angle kept constant during the whole simulation, only the flight path angle got changed to accomplish the descending advisory. The intruder's trajectory was defined by its flight path angle whose absolute value was the same as ownship's but with an opposite direction.  $\gamma(t)$  value was defined as below and illustrated by Figure 5.7:

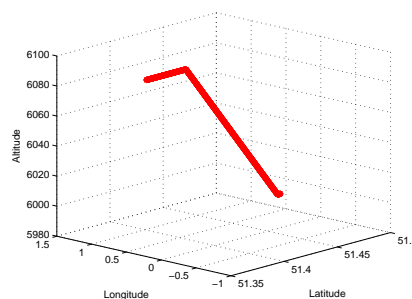
$$\gamma(t) = \begin{cases} 0 & t_0 < t < t_1 \\ m(t - t_1) & t_1 < t < t_2 \\ 0 & t > t_2 \end{cases} \quad (5.6)$$

Where  $t_1 = 15sec$ ,  $t_2 = 50sec$ ,  $m$  was expressed by radians and equal to  $-0.0104rad$  or  $-0.6deg$ .

The intruder's flight path was generated by Simulink block, the flight path angle was defined by a consecutive signal creator. The two  $\gamma$  profiles defined herein could maintain the minimum vertical separation between two aircraft. Finally, the proposed intruder's trajectory was shown in Figure 5.8.



**Figure 5.7:** Flight path angle of intruder.



**Figure 5.8:** Intruder's descending trajectory.

Comparing the virtual tunnel produced by TCAS system, we can find at point  $T$ , the horizontal separation between two aircraft was  $0.8NM$  and the vertical separation was  $740ft$ . Both of them satisfied the required minimum separation. Thus TCAS logic could provide validate trajectory, then only need to verify the manoeuvre display was designed the right way and could help pilots to fly outside of the predefined protected zone.

The fixed aircraft trajectory calculated by velocity integration was belong to the flat earth reference frame, while the relative position between ownship and intruder usually adopted longitudinal, latitudinal and altitude position information which was also needed by FlightGear. So coordinate transformation from Flat Earth to LLA was required and necessary which could be achieved by Simulink block named 'Flat Earth to LLA'.

### 5.3.2 Turn Right Scenario Two Implementation

Turn right scenario was the second scenario implemented in this project. Refer to its description in Section 5.2, the algorithm implementation was described as follows:

#### Collision Scenario Design

For host aircraft, the original flight data and its dynamics status were the same as scenario one and derived from the aircraft model.

1. **True Airspeed:** 0.8 Mach.

2. **Altitude:** 20000 feet.
3. **Pitch Angle:** 0 degree.
4. **Heading Angle:** -90 degree.
5. **Roll Angle:** 0 degree.
6. **Position:** Latitude 51.4775 degree, Longitude 0.4614 degree.

For intruder, except its heading angle and aircraft position were set to a new condition, the other status were the same as scenario one.

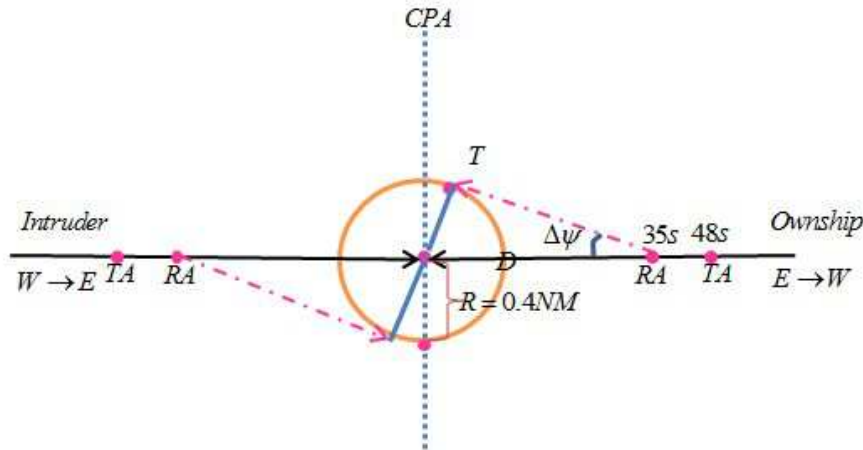
1. **True Airspeed:** 0.8 Mach.
2. **Altitude:** 20000 feet.
3. **Pitch Angle:** 0 degree.
4. **Heading Angle:** 90 degree.
5. **Roll Angle:** 0 degree.
6. **Position:** Latitude 51.47695 degree, Longitude 0.0819 degree.

Keeping cruising condition, these two aircraft were supposed to get collision around 50sec after the simulation. During the simulation, the next generation TCAS system detected the hazardous, the new developed turn right manoeuvre display was provided on a HUD to remind pilots of host aircraft. The pilots controlled the aircraft through joystick with pitch and roll commands to avoid the imminent collision risk.

### TCAS Recommended Trajectory for Ownship

In this scenario, the two aircraft were levelled at the same altitude and flying face to face. Different from the traditional TCAS system, the trajectory-based TCAS system issued 'TURN RIGHT, TURN RIGHT' advisory 35sec before CPA. Simultaneously, the turn right manoeuvre display (turn right trend tunnel-in-the-sky) was overlay on the HUD and aural prompt 'RIGHT, CLIMB' was broadcasting to catch pilot attention.

Figure 5.9 was the top view of turn right advisory strategy issued by TCAS system. The orange color circle defined the minimum horizontal protected area whose diameter was 0.8NM, intruder was forbidden to arrive into this area. The dotted magenta line was tangent to the protected zone and illustrated the suggested optimized trajectory provided by TCAS. They were the expected aircraft heading angle with which the collision risk can be removed.  $\Delta\psi$  stood for the minimum required bank angle variation which



**Figure 5.9:** Manoeuvre strategy (TURN RIGHT).

meant host aircraft would arrive at point  $T$  if it kept flying the new heading angle ( $\psi(t) = \psi_0 + \Delta\psi$ ) since TCAS RA was issued.  $\Delta\psi$  could be estimated by the following two equations:

$$D = \int_0^{35} (V_0 \cos \gamma(t) \sin \psi(t)) dt \quad (5.7)$$

$$\sin \Delta\psi = \frac{R}{D} \quad (5.8)$$

where  $R$  was aircraft horizontal protected distance,  $D$  stood for the horizontal distance to collision point, it was the distance along with aircraft longitudinal direction.

Refer to the mentioned host aircraft original flight performance,  $V_0 = 0.8M$ , assuming aircraft flight path angle kept constant during the manoeuvre and equal to 0, only aircraft bank angle got changed to avoid collision, thus  $\Delta\psi$  was estimated to  $4.5deg$ . This estimated bank angle was used to define the suggested trajectory. The same method as the estimated flight path angle  $\Delta\gamma$ , here 4.5 degree was calculated during an ideal status, while it was not practical in the real test process. Considering the bank angle was achieved by roll control, rudder control was prohibited, thus the bank angle variation  $\Delta\psi$  needed to be implemented gradually and smoothly.

The trajectory implementation algorithm for host aircraft was presented by Equation 5.4 and Equation 5.5. Where  $\psi(t)$  was host aircraft heading angle which was determined by TCAS system and estimated referring to  $4.5deg$ .

While aircraft flight path angle kept constant and was equal to  $0deg$  during the whole simulation. In order to receive the tunnel frame with  $250m$  interval,  $\psi(t)$  was defined by a series of digital data and implemented by MATLAB function as below:

```
'gamma = 0 * pi/180;
psimax = -(90 - 12) * pi/180;
psi = [-90 * pi/180 * ones(3, 1)']linspace(-90 * pi/180, psimax, 105);'
```

Therefore, the final tunnel frame centre in the real world was presented in Appendix 2.

### TCAS Recommended Trajectory for Intruder

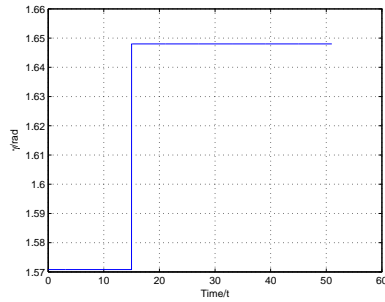
When TCAS issued 'TURN RIGHT, TURN RIGHT' to host aircraft, the same advisory 'TURN RIGHT, TURN RIGHT' was provided to the intruder. The intruder was defined to follow TCAS instruction and changing its heading angle to the right side. Consequently, a fixed flight path with specific bank angle was given to the intruder which was defined in Equation 5.9 and presented as Figure 5.10 shown.

$$\psi_{Intd}(t) = \begin{cases} \pi/2 & t_0 < t < t_1 \\ \pi/2 - n(t - t_1) & t_1 < t < t_2 \\ \pi/2 - n(t - t_1) & t > t_2 \end{cases} \quad (5.9)$$

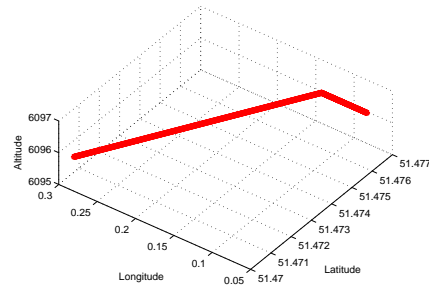
Where  $t_1 = 15sec$ ,  $t_2 = 50sec$ ,  $n$  was expressed by radians and equal to  $4.5deg$ .

The intruder's recommended heading angle was generated by Simulink block and was defined by a consecutive signal creator. The two  $\psi$  profiles defined herein could maintain the minimum horizontal separation between two aircraft. Finally, the proposed intruder's trajectory was shown in Figure 5.11.

Comparing the virtual tunnel produced by TCAS system, we can find at point  $T$ , the horizontal separation between two aircraft is  $0.8NM$ , satisfying the required minimum separation. Thus TCAS logic could provide validate trajectory, then only need to verify the manoeuvre display was designed the right way and could help pilots to fly outside of the predefined protected zone.



**Figure 5.10:** Heading angle of intruder.



**Figure 5.11:** Intruder's turn right trajectory.

### 5.3.3 Trajectory-based Manoeuvre Scenario Three Implementation

#### Collision Scenario Design

The collision scenario three design adopted the same collision scenario described in Section 5.3.1.

#### TCAS Recommended Trajectory for Ownship

As described in Section 5.2, manoeuvre trajectory for scenario three could be looked as the combination of trajectories for scenario one and scenario two. Aircraft needed to change its flight path angle and heading angle to follow the recommended trajectory. The protected zone was defined to be a  $0.8NM \times 600ft$  cylinder, the TCAS trajectory for host aircraft was tangent to the cylinder from the top view and just passed the cylinder top point from the side view, shown as Figure 5.2 and Figure 5.4. The algorithm of trajectory was depicted in Equation 5.4 and Equation 5.5. The estimated flight path angle variation and heading angle variation was  $0.6deg$  and  $4.5deg$  respectively. In order to receive the tunnel frame with  $250m$  interval,  $\gamma(t)$  and  $\psi(t)$  was defined by a series of digital data and implemented by MATLAB function as below:

```
'gammamax = 1.5 * pi/180;
psimax = -(90 - 12) * pi/180;
gamma = [-90*pi/180*ones(3, 1)'linspace(-90*pi/180, gammamax, 105)];'
psi = [-90 * pi/180 * ones(3, 1)'linspace(-90 * pi/180, psimax, 105)];'
```

Therefore, the final tunnel frame centre in the real world was presented in Appendix 3.



### TCAS Recommended Trajectory for Intruder

When TCAS issued ‘RIGHT, CLIMB’ to host aircraft, advisory ‘RIGHT, LEFT’ was provided to the intruder. Supposing the intruder followed TCAS 3D trajectory to perform the manoeuvre, a fixed flight path with specific bank angle and flight path angle were given to the intruder as defined in Equation 5.6 and Equation 5.9. Where  $t_1 = 15sec$ ,  $t_2 = 50sec$ ,  $m$  was expressed by radians and equal to  $-0.0104rad$ ,  $n$  was expressed by radians and equal to  $4.5deg$ .

The intruder’s recommended heading angle was generated by Simulink block and was defined by a consecutive signal creator. Finally, the proposed intruder’s trajectory was shown in Figure 5.12.

Comparing the virtual tunnel produced by TCAS system, we can find, the horizontal separation between two aircraft was  $0.8NM$ , the vertical separation was  $600ft$ , satisfied the required minimum separation. Thus TCAS logic could provide validate trajectory, then only need to verify the manoeuvre display was designed the right way and could helped pilots to fly outside of the predefined protected zone.

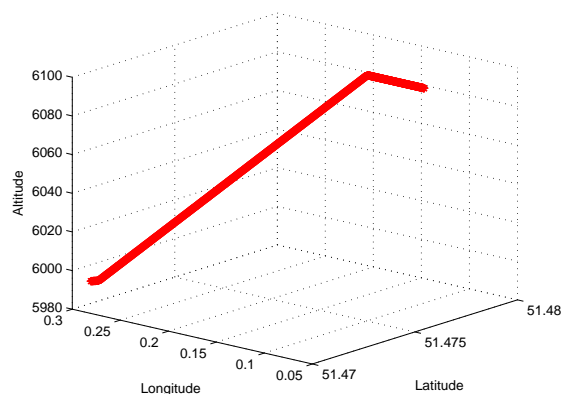


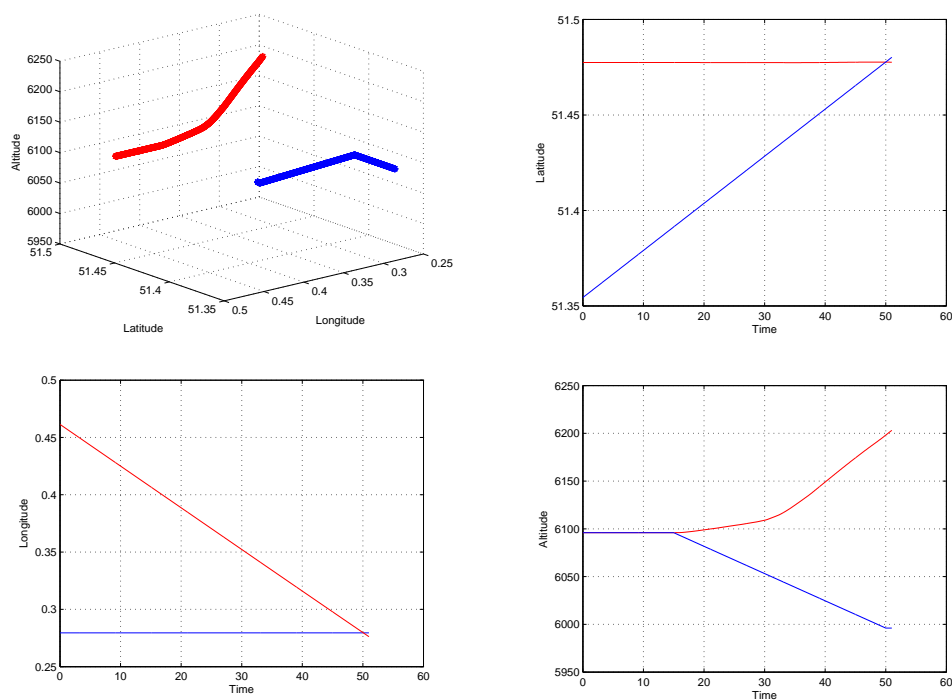
Figure 5.12: Intruder’s 3D trajectory.

## 5.4 Discussion

The whole simulation process was recorded by videos. The simulation was performed by operator instead of pilots. During the simulation, most of the time, the operator could follow the presented tunnel and complete the flight task successfully. The simulation results were described as follows:

### Scenario One Simulation Results

The host aircraft and intruder's flight status in scenario one was depicted in Figure 5.13. It compared host aircraft and its intruder's latitude, longitude and altitude position along with simulation time separately. The red color indicated host aircraft and the blue one represented the intruder. From these figures, it found the host aircraft successfully follow TCAS RAs, started to climbing at 15sec in simulation. The two aircraft arrived at the same latitude and longitude at 50sec while with vertical separation 663ft, thereinto the host aircraft contributed 335ft which satisfied TCAS resolution display design.

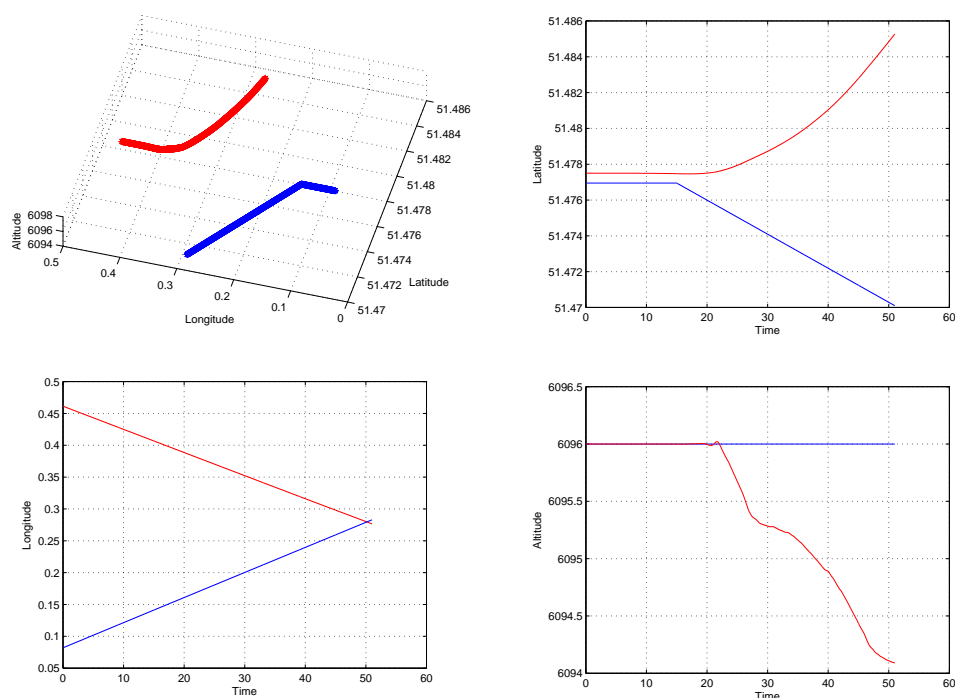


**Figure 5.13:** Vertical collision avoidance manoeuvre (3D, Latitude, Longitude and Altitude status).

### Scenario Two Simulation Results

The host aircraft and intruder's flight status in scenario two was depicted in Figure 5.14. It compared host aircraft and its intruder's latitude, longitude and altitude position along with simulation time separately. The red color indicated host aircraft and the blue one represented the intruder. From these figures, it found the host aircraft successfully follow TCAS RAs, starting to turn right around 15sec in simulation. The two aircraft arrived at the

same longitude with almost the same altitude at 50sec, while the horizontal separation was 0.872NM, therinto the host aircraft contributed 0.433NM which satisfied TCAS manoeuvre display design. Particularly referred to the latitude figure.

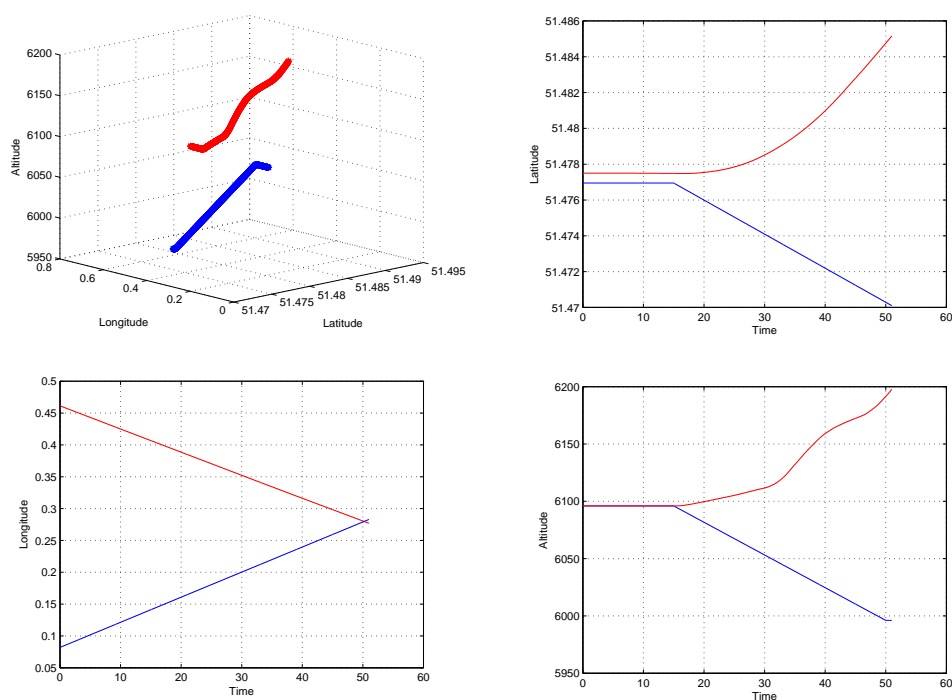


**Figure 5.14:** Horizontal collision avoidance manoeuvre (3D, Latitude, Longitude and Altitude status).

### Scenario Three Simulation Results

The host aircraft and intruder's flight status in scenario three was depicted in Figure 5.15. It compared host aircraft and its intruder's latitude, longitude and altitude position along with simulation time separately. The red color indicated host aircraft and the blue one represented the intruder. From these figures, it found the host aircraft successfully follow TCAS RAs, starting to climbing and turn right simultaneously at 15sec in simulation. The two aircraft arrived at the same longitude at 50sec. while their vertical separation was 641.4ft, among the host aircraft contributed 313.3ft; the horizontal separation was 0.872NM, therinto the host aircraft contributed 0.433NM, which satisfied TCAS 3D resolution display requirement.

The montages of the simulation is described in Figure 5.16,



**Figure 5.15:** Trajectory-based collision avoidance manoeuvre (3D, Latitude, Longitude and Altitude status).

### 5.4.1 Problem Discussion and solution

One problem was discovered during the simulation. When aircraft flight out of the suggested trajectory far away, it was not easy to fly back to the tunnel, it was also difficult to decide which way to fly back was efficiency and safety. To solve this problem, a new function was designed for TCAS system. When aircraft horizontal position was two times outside of the original tunnel centre or its vertical position was one time out, TCAS would generate a new trajectory and correspondingly update its display on HUD.

Figure 5.17 illustrated the strategy how to generate a new trajectory. The original tunnel centre line was issued by TCAS system and indicated by solid line. The aircraft was supposed to fly from position  $P_{n-3}$  towards position  $P_{n+\dots}$ . The new trajectory was issued by TCAS too, its centre line was illustrated by a set of new tunnel frames' centre position  $(p_{n-3}, p_{n-2}, p_{n-1}, \dots)$ . The new issued trajectory was generated according to the aircraft's current position and adhered to the original trajectory gradually. The new trajectory coincided with the original one at the last tunnel frame.

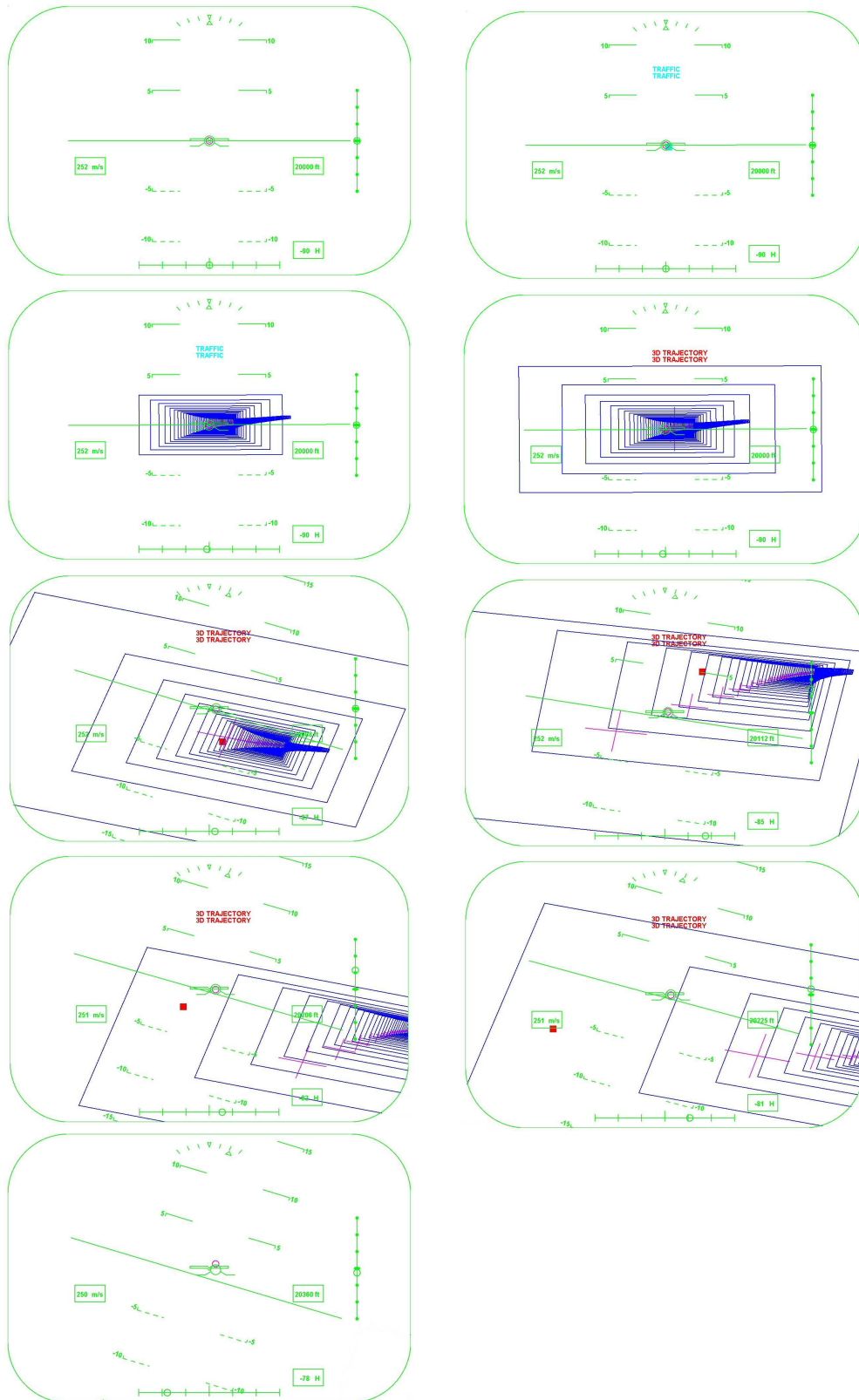


Figure 5.16: Trajectory-based manoeuvre montages.

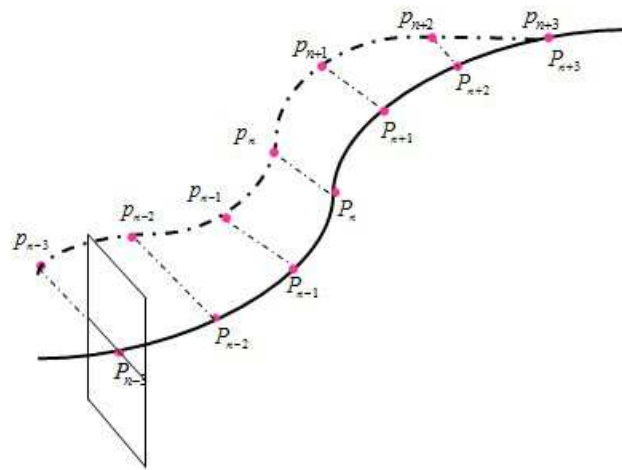


Figure 5.17: New trajectory generation strategy.

---

## Conclusion and Future Work

### 6.1 Summary of the Research

The research presented in this thesis has explored a novel visual cueing method for trajectory-based TCAS system. In order to achieve a more advanced and suitable display system, a literature review was done on different aspects to understand glass cockpit development requirement and trends to help locate the final approach. The literature review indicated a gap within the perspective flight display and TCAS system, therefore the idea of applying tunnel-in-the-sky concept to mid-air collision came to bare and was carried out afterwards.

Secondly, HUD layout, current & future CAS resolution and function of separate tunnel-in-the-sky symbology design consideration were accomplished. It contributed to the preliminary design of the research.

Thirdly, the development of HUD concept, TCAS manoeuvre display, traffic alert display and traffic oral announcement were performed. It was then integrated with *Boeing 747* aircraft model in MATLAB/Simulink environment.

Finally, three scenarios were implemented to assess and evaluate the developed idea. The optimisations and conclusions were described there after.

### 6.2 Conclusive Remarks

Let us bring this research to a *terminare* with some overall conclusions:

The developed tunnel-in-the-sky symbology has the capability to present pilots a natural and effective predictive flight path, from which pilots can understand the whole task immediately;

The horizontal and vertical deviation indicator is helpful to describe the aircraft's deviation from the anticipated trajectory, thus relieving pilots from estimating it themselves. Furthermore it shall draw the pilots attention, alleviating the cognitive problem.

The predictor shows its benefits when the pilot controls *Boeing 747* aircraft model (pitch and roll control with joystick). The predictor moves faster than the flight path vector as its speed depends on the pilots control force where pilots can adjust their physical strength in accordance with the predictor movement. It works in conjunction with tunnel-in-the-sky and deviation indicator symbology, from which pilots can estimate the position error and determine if any compensation is required.

Most of the time, during the simulation, it is easy to fly the aircraft inside of the tunnel and perform the collision avoidance manoeuvre as TCAS indicated successfully. The manoeuvre display also has the ability to present a new trajectory when the deviation falls out of bounds. The new trajectory is generated according to the aircraft's current position and adheres to the original trajectory gradually.

### 6.3 Future Work

The future works maybe describe with the following pragmatic items:

- Analytic prescreening assessment and pilot-in-the-loop experimental evaluation could be carried out to profoundly evaluate the effectiveness and accuracy of the developed visual cueing method.
- The mathematical description of the static curved tunnel in the real world could adopt successive tunnel geometry with circular turn strategy.
- Different formats of resolution display symbology could be proposed to explore their advantages and disadvantages, aims to find more appropriate display for trajectory-based TCAS system.
- Gibson's Ecological approach to visual perception could be a completely new research direction for tunnel-in-the-sky concept design.



---

## Bibliography

- [1] J.M. Hoekstra. Free Flight with Airborne Separation Assurance, An executive summary of: NLR-TP-2001-313, Designing for Safety: the Free Flight Air Traffic Management concept. Technical report, National Aerospace Laboratory NLR, 2002.
- [2] G. Dowek and C. Munoz. Tactical Conflict Detection and Resolution in a 3-D Airspace. Technical report, ICASE, NASA Langley Research Center, 2001.
- [3] D.W. Burgess, S.I. Altman, and M.L. Wood. TCAS: Maneuvering Aircraft in the Horizontal Plane. *THE LINCOLN LABORATORY JOURNAL*, 7:296–312, 1994.
- [4] *A Novel 3D Geometric Algorithm for Aircraft Autonomous Collision Avoidance*, San Diego, CA, USA., 2006.
- [5] J.G. Rajvanshi and K. Subbarao. Aircraft Conflict Detection and Resolution Using Mixed Geometric And Collision Cone Approaches. In *American Institute of Aeronautics and Astronautics*, 2004.
- [6] G. Dowek. Conflict Detection and Resolution for 1,2,... ,N Aircraft. In *7th AIAA Aviation Technology, Integration and Operations Conference*, 2007.
- [7] R. Chamlou. Future airborne collision avoidance - Design principles, analysis plan and algorithm development. In *Digital Avionics Systems Conference, 2009. DASC'09. IEEE/AIAA 28th*, pages 6.E.2–1 –6.E.2–17, 2009.
- [8] Andrew D. Zeitlin, W. Dwight Love, and James J Cieplak. Enhancements to the next generation collision avoidance system: opportunities for greater safety and efficiency. In *Digital Avionics Systems Conference*, 1995.
- [9] A.K. Barrows and K.W. Alter. Alaskan flight trials of a synthetic vision system for instrument landings of a piston twin aircraft. In *Proceedings of SPIE - The International Society for Optical Engineering*, volume 3691, 1999.

- 
- [10] K. FUNABIKI. Design of tunnel-in-the-sky display and curved trajectory. In *24TH INTERNATIONAL CONGRESS OF THE AERONAUTICAL SCIENCES*, 2004.
- [11] M. Mulder. *Cybernetics of tunnel-in-the-sky displays*. PhD thesis, Delft University Press, 1999.
- [12] A.K. Barrows and K.W. Alter. Operational experience with and improvements to a tunnel-in-the-sky display for light aircraft. In *Proceedings of ION GPS*, volume 1, pages 791–799, 1997.
- [13] A.K. Barrows and J.D. Powell. Tunnel-in-the-sky cockpit display for complex remote sensing flight trajectories. In *Fourth International Airborne Remote Sensing Conference and Exhibition*, 1999.
- [14] FAA Federal Aviation Regulations (FARS, 14 CFR), Part 25, Airworthiness standards: Transport category airplanes.
- [15] Primary flight display. [http://en.wikipedia.org/wiki/Primary\\_flight\\_display](http://en.wikipedia.org/wiki/Primary_flight_display). Accessed: Dec.14,2012.
- [16] Collins proline4 style multi-function display. <http://secure.simmarket.com>. Accessed: Aug.24,2012.
- [17] S.N. Roscoe. *Human Factors: Airborne Displays for Flight and Navigation*. Human Factors and Ergonomics Society, 1968.
- [18] D.C. Foyle and A.J. Ahumada. Enhanced/Synthetic Vision Systems: Human Factors Research and Implications for Future Systems. *SAE Transactions : Journal of Aerospace*, pages 59–66, 1992.
- [19] R.B. Wood and P.J. Howells. *Head-Up Displays*, 2001.
- [20] R.L. Newman. *Head-up displays: Designing the way ahead*. Gower Technical, 1995.
- [21] J.J. Gibson. *The Ecological Approach to Visual Perception*. Lawrence Erlbaum Associates, Inc.
- [22] Minimum Performance Standard for Airborne Head Up Display (HUD), 1999.
- [23] R.B. Wood and P.J. Howells. *The Avionics Handbook , Chapter 4 Head-Up Displays*. CRC Press, 2000.
- [24] P.M. Ververs and C.D. Wickens. Conformal Flight Path Symbolology for Head-Up Displays: Defining the Distribution of Visual Attention in Three-Dimensional Space. Technical report, Aviation Research Lab Institute of Aviation, 1998.

- [25] Transport Category Airplane Head Up Display (HUD) Systems, May 1999.
- [26] Rockwell Collins. *HGS Pilot Guide Boeing 737 NG*, b edition, 2003.
- [27] L.J. PrinzellIII. Head-Up Displays and Attention Capture. *NASA/TM-2004-213000*, page 1, 2004.
- [28] P.M. Ververs and C.D. Wickens, editors. *Designing head-up displays (HUDs) to support flight path guidance while minimizing effects of cognitive tunneling*. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2000.
- [29] C.D. Wickens and L.J. Long, editors. *Conformal Symbology, Attention Shifts, and the Head-Up Display*, volume 38. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1994.
- [30] J. Crawford and A. Neal. A Review of the Perceptual and Cognitive Issues Associated With the Use of Head-Up Displays in Commercial Aviation. *THE INTERNATIONAL JOURNAL OF AVIATION PSYCHOLOGY*, 16(1):1–19, 2006.
- [31] TCAS Home Page. <http://adsb.tc.faa.gov/TCAS.htm>. Accessed: Apr.18,2012.
- [32] Ed Williams. Airborne collision avoidance system. In *Proceedings of the 9th Australian workshop on Safety critical systems and software - Volume 47*, SCS '04, pages 97–110, Darlinghurst, Australia, Australia, 2004. Australian Computer Society, Inc.
- [33] EUROCONTROL. ACAS II Guide, January 2012.
- [34] J.K. Kuchar and A.C. Drumm. The Traffic Alert and Collision Avoidance System. *MIT Lincoln Laboratory Journal*, 16(2):277–296, 2007.
- [35] Introduction to TCAS II Version 7.1. <http://www.faa.gov/documentLibrary>, February 2011. Accessed: Apr.06,2012.
- [36] Passagierliste Flug 2937 der verunglueckten Tu-154 der Bashkirian Airlines. [http://www.aktuell.ru/russland/hintergrund/\\_information/passagierliste](http://www.aktuell.ru/russland/hintergrund/_information/passagierliste). Accessed: Apr.4,2012.
- [37] Fur Flugunfalluntersuchung and Bundesstelle. Investigation Report AX001-1-2. Technical report, German Federal Bureau of Aircraft Accidents Investigation, 2004.
- [38] A.J. Grunwald. Tunnel display for four-dimensional fixed-wing aircraft approaches. *Journal of Guidance, Control, and Dynamics*, 7:369–377, 1984.

- [39] A.J. Grunwald and J.B. Robertson. Evaluation of a computer-generated perspective tunnel display for flight path following. Technical report, NASA, 1980.
- [40] M.V. Cook. *Flight Dynamics Principles*. Elsevier Ltd., second edition, 2007.
- [41] Datum Transformations of GPS Positions. <http://www.nalresearch.com>. Accessed: Oct.15,2012.
- [42] Erik Theunissen, U. Sennes, and G. Sachs. PREDICTIVE FLIGHT-PATH DISPLAYS FOR IMPROVED MANUAL CONTROL PERFORMANCE. ICAS, 2000.
- [43] C.D. Wickens and C.M. Carswell. *The Handbook of Human Factors and Ergonomics*, chapter Informatio, pages 89–129. John Wiley, 1997.
- [44] K. Funabiki and T. Iijima. Attention allocation in tunnel-in-the-sky on HUD and HDD for visual flight. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, pages 6A31–6A310, 2007.
- [45] M.M. Lone, N. M. Rouyan, and A.K. Cooke. A MATLAB/Simulink suite for the real-time flight simulation of large aircraft. Technical report, Cranfield University, 2012.
- [46] R.K. Heffley and W.F. Jewell. Aircraft handling qualities data. Technical report, Technical Report NASA CR-2144, NASA, Hawthorne, California, 1972.
- [47] FlightGear. <http://www.flightgear.org>. Accessed: Aug.31,2012.
- [48] M.B. Spott and S. B. Walisser. *The FlightGear Manual*, 2012.
- [49] J. Havely. Midair collisions: A rare nightmare scenario. <http://articles.cnn.com/2002-07-02>. Accessed: Dec.14,2012.
- [50] Federal Aviation Administration. *Aeronautical Information Manual: Section 6. Safety, Accident, and Hazard Reports*, 2012.
- [51] Mid-air Collisions. [gp2.cawg.cap.gov/doc/Mid-air.ppt](http://gp2.cawg.cap.gov/doc/Mid-air.ppt). Accessed: Nov.16,2012.

## Appendix 1

The manoeuvre trajectory of host aircraft (climb) is presented in LLA reference frame:

Ptraj =

1.0e+003 \*

0.051477499992818	0.000405000000000	-6.096000000000000
0.051477499992818	0.000403671149499	-6.096000000000000
0.051477499992818	0.000402342298997	-6.096000000000000
0.051477499992818	0.000401013448496	-6.096000000000000
0.051477499992818	0.000399684598018	-6.096012394723418
0.051477499992818	0.000398355747636	-6.096049578892782
0.051477499992818	0.000397026897446	-6.096111552505408
0.051477499992818	0.000395698047544	-6.096198315556830
0.051477499992818	0.000394369198024	-6.096309868040791
0.051477499992818	0.000393040348984	-6.096446209949249
0.051477499992818	0.000391711500518	-6.096607341272373
0.051477499992818	0.000390382652723	-6.096793261998547
0.051477499992818	0.000389053805695	-6.097003972114365
0.051477499992818	0.000387724959529	-6.097239471604635
0.051477499992818	0.000386396114321	-6.097499760452380
0.051477499992818	0.000385067270167	-6.097784838638831
0.051477499992818	0.000383738427162	-6.098094706143436
0.051477499992818	0.000382409585403	-6.098429362943852
0.051477499992818	0.000381080744986	-6.098788809015952
0.051477499992818	0.000379751906005	-6.099173044333822
0.051477499992818	0.000378423068558	-6.099582068869754
0.051477499992818	0.000377094232739	-6.100015882594263
0.051477499992818	0.000375765398644	-6.100474485476068

0.051477499992818 0.000374436566370 -6.100957877482108  
0.051477499992818 0.000373107736013 -6.101466058577527  
0.051477499992818 0.000371778907667 -6.101999028725688  
0.051477499992818 0.000370450081429 -6.102556787888164  
0.051477499992818 0.000369121257394 -6.103139336024742  
0.051477499992818 0.000367792435659 -6.103746673093420  
0.051477499992818 0.000366463616320 -6.104378799050410  
0.051477499992818 0.000365134799471 -6.105035713850136  
0.051477499992818 0.000363805985209 -6.105717417445237  
0.051477499992818 0.000362477173629 -6.106423909786561  
0.051477499992818 0.000361148364828 -6.107155190823171  
0.051477499992818 0.000359819558901 -6.107911260502344  
0.051477499992818 0.000358490755945 -6.108692118769567  
0.051477499992818 0.000357161956054 -6.109497765568540  
0.051477499992818 0.000355833159324 -6.110328200841181  
0.051477499992818 0.000354504365852 -6.111183424527612  
0.051477499992818 0.000353175575734 -6.112063436566174  
0.051477499992818 0.000351846789064 -6.112968236893419  
0.051477499992818 0.000350518005940 -6.113897825444114  
0.051477499992818 0.000349189226456 -6.114852202151234  
0.051477499992818 0.000347860450708 -6.115831366945971  
0.051477499992818 0.000346531678793 -6.116835319757728  
0.051477499992818 0.000345202910806 -6.117864060514122  
0.051477499992818 0.000343874146842 -6.118917589140980  
0.051477499992818 0.000342545386998 -6.119995905562346  
0.051477499992818 0.000341216631370 -6.121099009700475  
0.051477499992818 0.000339887880053 -6.122226901475832

0.051477499992818 0.000338559133143 -6.123379580807100  
0.051477499992818 0.000337230390737 -6.124557047611170  
0.051477499992818 0.000335901652928 -6.125759301803149  
0.051477499992818 0.000334572919814 -6.126986343296356  
0.051477499992818 0.000333244191491 -6.128238172002324  
0.051477499992818 0.000331915468053 -6.129514787830796  
0.051477499992818 0.000330586749598 -6.130816190689729  
0.051477499992818 0.000329258036220 -6.132142380485295  
0.051477499992818 0.000327929328016 -6.133493357121877  
0.051477499992818 0.000326600625081 -6.134869120502071  
0.051477499992818 0.000325271927510 -6.136269670526684  
0.051477499992818 0.000323943235401 -6.137695007094743  
0.051477499992818 0.000322614548849 -6.139145130103477  
0.051477499992818 0.000321285867949 -6.140620039448339  
0.051477499992818 0.000319957192797 -6.142119735022988  
0.051477499992818 0.000318628523489 -6.143644216719295  
0.051477499992818 0.000317299860121 -6.145193484427352  
0.051477499992818 0.000315971202789 -6.146767538035454  
0.051477499992818 0.000314642551588 -6.148366377430116  
0.051477499992818 0.000313313906615 -6.149990002496063  
0.051477499992818 0.000311985267964 -6.151638413116233  
0.051477499992818 0.000310656635733 -6.153311609171779  
0.051477499992818 0.000309328010016 -6.155009590542064  
0.051477499992818 0.000307999390909 -6.156732357104668  
0.051477499992818 0.000306670778509 -6.158479908735377  
0.051477499992818 0.000305342172910 -6.160252245308200  
0.051477499992818 0.000304013574209 -6.162049366695351

0.051477499992818 0.000302684982502 -6.163871272767259  
0.051477499992818 0.000301356397885 -6.165717963392569  
0.051477499992818 0.000300027820452 -6.167589438438134  
0.051477499992818 0.000298699250300 -6.169485697769026  
0.051477499992818 0.000297370687526 -6.171406741248525  
0.051477499992818 0.000296042132223 -6.173352568738126  
0.051477499992818 0.000294713584489 -6.175323180097538  
0.051477499992818 0.000293385044419 -6.177318575184682  
0.051477499992818 0.000292056512109 -6.179338753855692  
0.051477499992818 0.000290727987655 -6.181383715964916  
0.051477499992818 0.000289399471152 -6.183453461364914  
0.051477499992818 0.000288070962696 -6.185547989906462  
0.051477499992818 0.000286742462383 -6.187667301438546  
0.051477499992818 0.000285413970309 -6.189811395808365  
0.051477499992818 0.000284085486570 -6.191980272861331  
0.051477499992818 0.000282757011261 -6.194173932441075  
0.051477499992818 0.000281428544478 -6.196392374389433  
0.051477499992818 0.000280100086317 -6.198635598546460  
0.051477499992818 0.000278771636874 -6.200903604750422  
0.051477499992818 0.000277443196244 -6.203196392837797  
0.051477499992818 0.000276114764524 -6.205513962643281  
0.051477499992818 0.000274786341808 -6.207856313999776  
0.051477499992818 0.000273457928194 -6.210223446738404  
0.051477499992818 0.000272129523776 -6.212615360688496  
0.051477499992818 0.000270801128650 -6.215032055677598  
0.051477499992818 0.000269472742913 -6.217473531531472  
0.051477499992818 0.000268144366659 -6.219939788074087



0.051477499992818 0.000266815999985 -6.222430825127630

0.051477499992818 0.000265487642987 -6.224946642512501

0.051477499992818 0.000264159295760 -6.227487240047312

0.051477499992818 0.000262830958400 -6.230052617548888

## Appendix 2

The manoeuvre trajectory of host aircraft (turn right) is presented in LLA reference frame:

Ptraj =

1.0e+003 \*

0.051477499992818	0.000405000000000	-6.096000000000000
0.051477499992818	0.000403708062012	-6.096000000000000
0.051477499992818	0.000402416124025	-6.096000000000000
0.051477499992818	0.000401124186037	-6.096000000000000
0.051477500805152	0.000399832249360	-6.096000000000000
0.051477503242149	0.000398540317922	-6.096000000000000
0.051477507303801	0.000397248396962	-6.096000000000000
0.051477512990090	0.000395956491722	-6.096000000000000
0.051477520300994	0.000394664607439	-6.096000000000000
0.051477529236483	0.000393372749354	-6.096000000000000
0.051477539796520	0.000392080922704	-6.096000000000000
0.051477551981064	0.000390789132731	-6.096000000000000
0.051477565790063	0.000389497384671	-6.096000000000000
0.051477581223463	0.000388205683765	-6.096000000000000
0.051477598281201	0.000386914035251	-6.096000000000000
0.051477616963208	0.000385622444366	-6.096000000000000
0.051477637269408	0.000384330916350	-6.096000000000000
0.051477659199718	0.000383039456440	-6.096000000000000
0.051477682754049	0.000381748069873	-6.096000000000000
0.051477707932307	0.000380456761888	-6.096000000000000
0.051477734734389	0.000379165537720	-6.096000000000000
0.051477763160186	0.000377874402607	-6.096000000000000
0.051477793209583	0.000376583361784	-6.096000000000000

0.051477824882458 0.000375292420488 -6.096000000000000  
0.051477858178682 0.000374001583955 -6.096000000000000  
0.051477893098122 0.000372710857419 -6.096000000000000  
0.051477929640634 0.000371420246114 -6.096000000000000  
0.051477967806071 0.000370129755276 -6.096000000000000  
0.051478007594278 0.000368839390137 -6.096000000000000  
0.051478049005094 0.000367549155931 -6.096000000000000  
0.051478092038350 0.000366259057890 -6.096000000000000  
0.051478136693873 0.000364969101247 -6.096000000000000  
0.051478182971481 0.000363679291233 -6.096000000000000  
0.051478230870986 0.000362389633078 -6.096000000000000  
0.051478280392195 0.000361100132014 -6.096000000000000  
0.051478331534905 0.000359810793270 -6.096000000000000  
0.051478384298911 0.000358521622074 -6.096000000000000  
0.051478438683997 0.000357232623656 -6.096000000000000  
0.051478494689944 0.000355943803242 -6.096000000000000  
0.051478552316524 0.000354655166060 -6.096000000000000  
0.051478611563504 0.000353366717335 -6.096000000000000  
0.051478672430643 0.000352078462294 -6.096000000000000  
0.051478734917694 0.000350790406160 -6.096000000000000  
0.051478799024404 0.000349502554158 -6.096000000000000  
0.051478864750513 0.000348214911510 -6.096000000000000  
0.051478932095755 0.000346927483438 -6.096000000000000  
0.051479001059856 0.000345640275165 -6.096000000000000  
0.051479071642536 0.000344353291909 -6.096000000000000  
0.051479143843510 0.000343066538891 -6.096000000000000  
0.051479217662484 0.000341780021329 -6.096000000000000

0.051479293099160 0.000340493744441 -6.096000000000000  
0.051479370153230 0.000339207713443 -6.096000000000000  
0.051479448824384 0.000337921933550 -6.096000000000000  
0.051479529112301 0.000336636409978 -6.096000000000000  
0.051479611016656 0.000335351147940 -6.096000000000000  
0.051479694537117 0.000334066152648 -6.096000000000000  
0.051479779673345 0.000332781429313 -6.096000000000000  
0.051479866424996 0.000331496983146 -6.096000000000000  
0.051479954791716 0.000330212819357 -6.096000000000000  
0.051480044773148 0.000328928943152 -6.096000000000000  
0.051480136368926 0.000327645359739 -6.096000000000000  
0.051480229578680 0.000326362074324 -6.096000000000000  
0.051480324402032 0.000325079092111 -6.096000000000000  
0.051480420838596 0.000323796418302 -6.096000000000000  
0.051480518887981 0.000322514058101 -6.096000000000000  
0.051480618549791 0.000321232016708 -6.096000000000000  
0.051480719823620 0.000319950299322 -6.096000000000000  
0.051480822709058 0.000318668911141 -6.096000000000000  
0.051480927205689 0.000317387857362 -6.096000000000000  
0.051481033313087 0.000316107143180 -6.096000000000000  
0.051481141030823 0.000314826773790 -6.096000000000000  
0.051481250358460 0.000313546754384 -6.096000000000000  
0.051481361295554 0.000312267090153 -6.096000000000000  
0.051481473841656 0.000310987786287 -6.096000000000000  
0.051481587996308 0.000309708847974 -6.096000000000000  
0.051481703759049 0.000308430280401 -6.096000000000000  
0.051481821129409 0.000307152088753 -6.096000000000000

0.051481940106911 0.000305874278215 -6.096000000000000  
0.051482060691074 0.000304596853968 -6.096000000000000  
0.051482182881407 0.000303319821193 -6.096000000000000  
0.051482306677416 0.000302043185069 -6.096000000000000  
0.051482432078599 0.000300766950773 -6.096000000000000  
0.051482559084446 0.000299491123482 -6.096000000000000  
0.051482687694444 0.000298215708369 -6.096000000000000  
0.051482817908069 0.000296940710608 -6.096000000000000  
0.051482949724795 0.000295666135368 -6.096000000000000  
0.051483083144086 0.000294391987820 -6.096000000000000  
0.051483218165402 0.000293118273130 -6.096000000000000  
0.051483354788195 0.000291844996464 -6.096000000000000  
0.051483493011910 0.000290572162986 -6.096000000000000  
0.051483632835988 0.000289299777857 -6.096000000000000  
0.051483774259861 0.000288027846239 -6.096000000000000  
0.051483917282956 0.000286756373290 -6.096000000000000  
0.051484061904692 0.000285485364165 -6.096000000000000  
0.051484208124483 0.000284214824020 -6.096000000000000  
0.051484355941736 0.000282944758008 -6.096000000000000  
0.051484505355852 0.000281675171279 -6.096000000000000  
0.051484656366225 0.000280406068982 -6.096000000000000  
0.051484808972241 0.000279137456264 -6.096000000000000  
0.051484963173283 0.000277869338270 -6.096000000000000  
0.051485118968725 0.000276601720144 -6.096000000000000  
0.051485276357935 0.000275334607025 -6.096000000000000  
0.051485435340275 0.000274068004052 -6.096000000000000  
0.051485595915100 0.000272801916363 -6.096000000000000

0.051485758081759 0.000271536349093 -6.096000000000000

0.051485921839593 0.000270271307373 -6.096000000000000

0.051486087187940 0.000269006796334 -6.096000000000000

0.051486254126128 0.000267742821105 -6.096000000000000

### Appendix 3

The manoeuvre trajectory of host aircraft (climb and turn right) is presented in LLA reference frame:

Ptraj =

1.0e+003 \*

0.051477499992818	0.000405000000000	-6.096000000000000
0.051477499992818	0.000403708062012	-6.096000000000000
0.051477499992818	0.000402416124025	-6.096000000000000
0.051477499992818	0.000401124186037	-6.096000000000000
0.051477500805152	0.000399832249383	-6.096012050425546
0.051477503242149	0.000398540318061	-6.096048201701316
0.051477507303800	0.000397248397405	-6.096108453824702
0.051477512990086	0.000395956492746	-6.096192806791362
0.051477520300985	0.000394664609418	-6.096301260595213
0.051477529236463	0.000393372752753	-6.096433815228436
0.051477539796484	0.000392080928083	-6.096590470681473
0.051477551981003	0.000390789140741	-6.096771226943031
0.051477565789966	0.000389497396057	-6.096976084000077
0.051477581223316	0.000388205699365	-6.097205041837841
0.051477598280985	0.000386914055996	-6.097458100439814
0.051477616962902	0.000385622471281	-6.097735259787752
0.051477637268987	0.000384330950551	-6.098036519861673
0.051477659199152	0.000383039499137	-6.098361880639856
0.051477682753305	0.000381748122370	-6.098711342098842
0.051477707931344	0.000380456825580	-6.099084904213437
0.051477734733162	0.000379165614097	-6.099482566956706
0.051477763158644	0.000377874493249	-6.099904330299977
0.051477793207669	0.000376583468367	-6.100350194212844

0.051477824880109 0.000375292544779 -6.100820158663161  
0.051477858175829 0.000374001727813 -6.101314223617040  
0.051477893094685 0.000372711022797 -6.101832389038864  
0.051477929636530 0.000371420435057 -6.102374654891271  
0.051477967801206 0.000370129969922 -6.102941021135166  
0.051478007588551 0.000368839632716 -6.103531487729714  
0.051478048998395 0.000367549428766 -6.104146054632343  
0.051478092030561 0.000366259363397 -6.104784721798744  
0.051478136684865 0.000364969441932 -6.105447489182869  
0.051478182961117 0.000363679669696 -6.106134356736934  
0.051478230859118 0.000362390052012 -6.106845324411417  
0.051478280378664 0.000361100594203 -6.107580392155056  
0.051478331519544 0.000359811301589 -6.108339559914856  
0.051478384281539 0.000358522179493 -6.109122827636082  
0.051478438664424 0.000357233233234 -6.109930195262258  
0.051478494667966 0.000355944468132 -6.110761662735178  
0.051478552291927 0.000354655889505 -6.111617229994891  
0.051478611536059 0.000353367502671 -6.112496896979714  
0.051478672400111 0.000352079312948 -6.113400663626221  
0.051478734883821 0.000350791325652 -6.114328529869256  
0.051478798986924 0.000349503546097 -6.115280495641916  
0.051478864709145 0.000348215979598 -6.116256560875568  
0.051478932050204 0.000346928631469 -6.117256725499840  
0.051479001009812 0.000345641507021 -6.118280989442620  
0.051479071587676 0.000344354611567 -6.119329352630060  
0.051479143783494 0.000343067950416 -6.120401814986573  
0.051479217596957 0.000341781528879 -6.121498376434837



0.051479293027750 0.000340495352263 -6.122619036895792  
0.051479370075552 0.000339209425876 -6.123763796288637  
0.051479448740032 0.000337923755024 -6.124932654530840  
0.051479529020855 0.000336638345012 -6.126125611538125  
0.051479610917679 0.000335353201144 -6.127342667224482  
0.051479694430152 0.000334068328722 -6.128583821502162  
0.051479779557919 0.000332783733048 -6.129849074281681  
0.051479866300616 0.000331499419423 -6.131138425471814  
0.051479954657872 0.000330215393145 -6.132451874979602  
0.051480044629310 0.000328931659512 -6.133789422710346  
0.051480136214545 0.000327648223821 -6.135151068567611  
0.051480229413188 0.000326365091366 -6.136536812453222  
0.051480324224838 0.000325082267442 -6.137946654267270  
0.051480420649092 0.000323799757342 -6.139380593908108  
0.051480518685538 0.000322517566355 -6.140838631272349  
0.051480618333756 0.000321235699773 -6.142320766254871  
0.051480719593322 0.000319954162882 -6.143826998748814  
0.051480822463803 0.000318672960971 -6.145357328645581  
0.051480926944759 0.000317392099324 -6.146911755834834  
0.051481033035744 0.000316111583225 -6.148490280204506  
0.051481140736305 0.000314831417956 -6.150092901640782  
0.051481250045982 0.000313551608798 -6.151719620028119  
0.051481360964308 0.000312272161031 -6.153370435249229  
0.051481473490810 0.000310993079931 -6.155045347185093  
0.051481587625007 0.000309714370776 -6.156744355714951  
0.051481703366411 0.000308436038839 -6.158467460716306  
0.051481820714529 0.000307158089392 -6.160214662064925

0.051481939668858 0.000305880527707 -6.161985959634836  
0.051482060228891 0.000304603359054 -6.163781353298331  
0.051482182394113 0.000303326588699 -6.165600842925965  
0.051482306164003 0.000302050221908 -6.167444428386554  
0.051482431538031 0.000300774263946 -6.169312109547177  
0.051482558515662 0.000299498720075 -6.171203886273178  
0.051482687096354 0.000298223595554 -6.173119758428162  
0.051482817279559 0.000296948895643 -6.175059725873997  
0.051482949064719 0.000295674625598 -6.177023788470812  
0.051483082451272 0.000294400790674 -6.179011946077002  
0.051483217438648 0.000293127396124 -6.181024198549223  
0.051483354026272 0.000291854447198 -6.183060545742394  
0.051483492213559 0.000290581949146 -6.185120987509697  
0.051483631999920 0.000289309907214 -6.187205523702576  
0.051483773384758 0.000288038326648 -6.189314154170739  
0.051483916367468 0.000286767212690 -6.191446878762156  
0.051484060947441 0.000285496570581 -6.193603697323060  
0.051484207124058 0.000284226405560 -6.195784609697947  
0.051484354896696 0.000282956722863 -6.197989615729577  
0.051484504264724 0.000281687527726 -6.200218715258970  
0.051484655227504 0.000280418825380 -6.202471908125411  
0.051484807784391 0.000279150621056 -6.204749194166449  
0.051484961934733 0.000277882919981 -6.207050573217892  
0.051485117677873 0.000276615727381 -6.209376045113815  
0.051485275013145 0.000275349048481 -6.211725609686554  
0.051485433939878 0.000274082888501 -6.214099266766708  
0.051485594457394 0.000272817252660 -6.216497016183140

0.051485756565005 0.000271552146174 -6.218918857762974

0.051485920262021 0.000270287574259 -6.221364791331598

0.051486085547743 0.000269023542127 -6.223834816712664

0.051486252421464 0.000267760054986 -6.226328933728086