Stephan Josel

Development of the Forward Looking Terrain Avoidance in a Terrain Awareness and Warning System (TAWS)

MASTERARBEIT

zur Erlangung des akademischen Grades
Diplom-Ingenieur

Masterstudium Geomatics Science

Technische Universität Graz

Betreuer:
Ao.Univ.-Prof. Dipl.-Ing. Dr.techn. Manfred Wieser
Institut für Navigation

Graz, September 2012

Deutsche Fassung:
Beschluss der Curricula-Kommission für Bachelor-, Master- und Diplomstudien vom 10.11.2008
Genehmigung des Senates am 1.12.2008

EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt, und die den benutzten Quellen wörtlich und inhaltlich entnommene Stellen als solche kenntlich gemacht habe.

Graz, am ……………………………   ………………………………………………..
(Unterschrift)

Englische Fassung:

STATUTORY DECLARATION

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

……………………………   ………………………………………………..
date   (signature)

Acknowledgements

Since my childhood I have been fascinated by aviation and especially by the navigation in an aircraft. My intimate desire was to become a commercial pilot. However, that dream did not (until now) become true and I got the chance to study Geodesy. The study seemed tailored perfectly to my interests for navigation and that proved true. During my study, I got the chance to gain deeper insight of navigation systems on board a modern aircraft at my work for Axis Flight Training Systems. Finally, the company offered me to develop a new navigation system simulation that is based on this thesis.

In this way, I would like to thank my supervisor Univ.-Prof. Dipl.-Ing. Dr. Manfred Wieser for letting me choose this very special topic and his support.

A big thanks to my (now former) employer Axis Flight Training Systems for gaining all the experience in avionics systems and the chance to write this thesis for the company. The last seven years were great and I will never forget them!

Furthermore I would like to thank my parents for supporting me in my study and my passion in aviation by financing my pilot licenses. Especially I would like to thank my girlfriend Sonja, who gave me motivation and hold during the last six months.

Last, but not least, I would like to thank Christoph Pöllabauer and Martin Steinegger for reviewing this thesis and my colleagues from university for the great friendship and community in the last years!

Abstract

One of the most dominant causes of accidents in aviation is still the Controlled Flight Into Terrain (CFIT), where an airworthy aircraft under complete control of the pilot is inadvertently flown into terrain, water or an obstacle. Since the 1970s, several provisions have been made to avoid CFIT and to mitigate its risk. One of the more recent avionics navigation systems for this purpose is the so-called “Terrain Awareness and Warning System” (TAWS). This system uses position data determined by the Global Positioning System (GPS) and an internal digital terrain database to warn the pilot of a hazardous approach to terrain. In order to detect the approach, the aircraft position is predicted and intersected with the terrain database. This, so-called “Forward Looking Terrain Avoidance” (FLTA) method provides the pilot with an awareness and a warning of the terrain ahead of the aircraft.

This thesis presents the development of the FLTA in a TAWS as used in a full-flight simulator. A mathematical model to predict the aircraft position is formulated. The positions predicted by this model serve as a base for establishing a so-called “Search Volume”. The development of the search volume comprises the design of a volume considering the regulatory requirements as well as the kinematics of an aircraft. The search volume is eventually intersected with the terrain database. Furthermore, a model for a terrain database that allows fast intersection with the search volume is found. Finally, the generation of warnings for the pilot based on the result of the intersection is addressed.

Zusammenfassung

Eine der dominierenden Unfallursachen in der Luftfahrt ist noch immer der "Controlled Flight Into Terrain" (CFIT), bei dem ein voll funktionsfähiges Flugzeug unter der Kontrolle des Piloten versehentlich in das Gelände, ins Wasser oder in ein Hindernis gesteuert wird. Seit den 1970er Jahren wurden Vorkehrungen getroffen CFIT zu vermeiden und das Risiko dessen zu minimieren. Eines der neuesten Avionik-Navigationssysteme zu diesem Zweck ist das sogenannte "Terrain Awareness and Warning System" (TAWS). Mit Hilfe des Globalen Positionierung Systems (GPS) und einer internen digitalen Geländedatenbank warnt das System den Piloten vor einer gefährlichen Annäherung an das Gelände. Das System prädiziert die Flugzeugposition und verschneidet die prädizierten Positionen mit der Geländedatenbank. Diese Methode wird als "Forward Looking Terrain Avoidance" (FLTA) bezeichnet und verbessert das Bewusstsein des Piloten für das vor dem Flugzeug liegende Gelände und warnt diesen gegebenenfalls davor.

Diese Diplomarbeit beschäftigt sich mit der Entwicklung der FLTA in einem TAWS, das in einem Full-Flight Simulator verwendet wird. Es wird ein mathematisches Modell zur Prädiktion der Flugzeugposition entwickelt, das dem Erstellen eines Suchraums dient. Die Erstellung des Suchraums berücksichtigt behördliche Auflagen als auch die Kinematik eines Flugzeugs. Letztendlich wird der Suchraum mit einer Geländedatenbank verschnitten. Dazu wird ein Modell für eine Geländedatenbank vorgestellt, das eine schnelle Verschneidung mit dem Suchraum zulässt. Das Resultat der Verschneidung dient der Entwicklung einer Methode zur Auslösung von Warnungen für den Piloten.

Contents

Abbrevations and Acronyms

ADC Air Data Computer

ANP Actual Navigation Performance

CFIT Controlled Flight Into Terrain

DTM Digital Terrain Model

EGM Earth Gravitational Model

EGPWS Enhanced Ground Proximity Warning System

FAA Federal Aviation Administration (U.S. Department of Air Transportation)

FAF Final Approach Fix

FLTA Forward Looking Terrain Avoidance

GPS Global Positioning System

GPWS Ground Proximity Warning System

HFOM Horizontal Figure of Merit

IAF Initial Approach Fix

ICAO International Civil Aviation Organization

IFR Instrument Flight Rules

ILS Instrument Landing System

IMS Inertial Measurement System

IRS Inertial Reference System

ITI Imminent Terrain Impact

LAD Look Ahead Distance

LOD Level of Detail

MA Moving Average

MIP Multum in Parvo

MOC Minimum Obstacle Clearance

MSL Mean Sea Level

NDB Non Directional Beacon

NED North-East-Down

OAS Obstacle Assessment Surfaces

RA Radio Altimeter

RNAV Area Navigation

ROC Required Obstacle Clearance

RTC Reduced Terrain Clearance

SA Situational Awareness

SRTM Shuttle Radar Topography Mission

TA Terrain Awareness

TAWS Terrain Awareness and Warning System

TERPS Terminal Instrument Procedures (FAA)

VFOM Vertical Figure of Merit

VFR Visual Flight Rules

VOR VHF Omnidirectional Range

1 Introduction

1.1 Background

Since the first flight of a powered aircraft in 1903, aviation has undergone a meteoric rise. Today, traveling by plane has become a matter of course. Air transport has increased significantly since the middle of the last century and will keep on doing so in the future. As with many technical and engineering disciplines, the technological advancement in aviation has been immense over the last 50 years. Aircraft have become larger, faster and safer. Especially safety is of high importance in aviation. Piloting an aircraft can be quite a challenging task. Loosely speaking, as the aircraft moves in three dimensions and at high speed, the human operator can rather quickly become overburdened by his tasks. The human with his “human factor” is therefore the dominant cause of accidents in aviation. Hence, the aim of the aviation industry has always been to support the human operator by introducing new and better technology as well as by enhancing the training of pilots.

Nevertheless, one of the most dominant causes for aircraft accidents is still the Controlled Flight Into Terrain (CFIT), where an airworthy aircraft under complete control of the pilot is inadvertently flown into terrain, water or an obstacle, cf. [10]. The analysis of accidents which happened the 1960s and 1970s lead to the development of a system to prevent these CFIT accidents. This development resulted in the invention of the Ground Proximity Warning System (GPWS), which warns the crew of hazardous terrain closure. GPWS was mandated by the Federal Aviation Administration (FAA) to be installed in all U.S. large turbine and turbojet aircraft in 1974. The introduction of this system lead to a significant decrease in CFIT accidents.

As a consequence of those CFIT accidents that still existed, the GPWS was enhanced in the mid 1990s. New navigation technology such as the Global Positioning System (GPS) and new computer technology lead to the development of the Terrain Awareness and Warning System (TAWS). The TAWS contains the GPWS functionality plus some enhancements. While the GPWS issues warnings based on the radio altimeter, the TAWS additionally uses position information and a digital terrain database to issue warnings. The crew is warned earlier and the Situational Awareness (SA) is improved.

The FAA mandated the installation of a TAWS in March 2000 for all U.S. turbine powered aircraft with six or more passenger seats. The International Civil Aviation Organization (ICAO) mandated the installation for all aircraft of a maximum certified takeoff mass in excess of 5700 kg or authorized to carry more than nine passengers in 2007 [22].

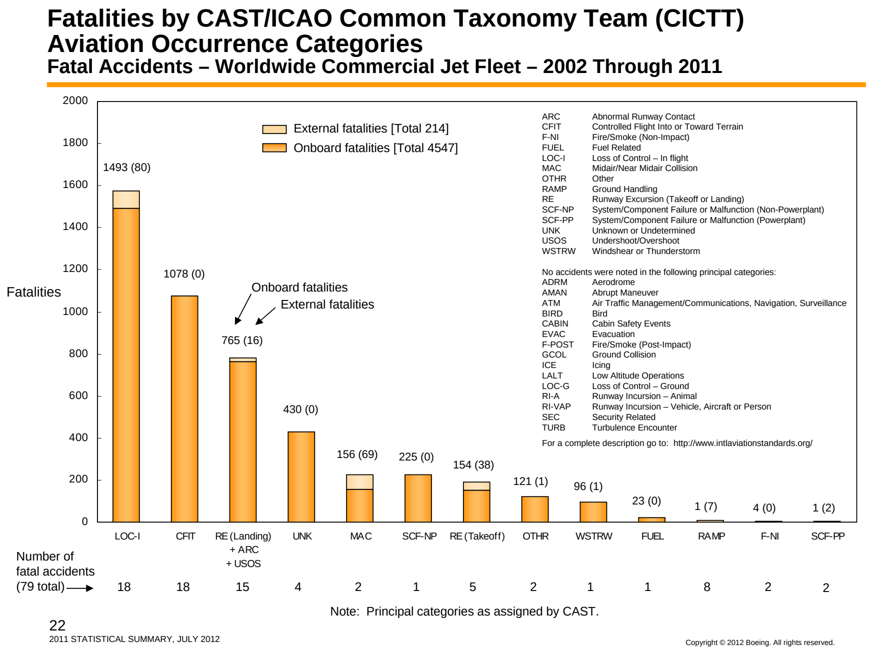


Figure 1.1: Boeing Accident Categories, taken from [3]

1.2 Accidents in Aviation

The investigation of accidents is a key to finding new and better technology to improve safety, which plays an important role in aviation. Reports on the safety of air traffic are released annually. The aircraft manufacturer Boeing for example releases a statistic of commercial jet aircraft accidents [3] every year. Note that this statistic only covers accidents with jet aircraft with a maximum take off weight of over 27 tons and excludes any accidents that happened with aircraft manufactured in the former USSR. Among more than 20 million flights per year, the statistic lists a total of 36 accidents. For a definition of accident consult [3], p. 8. The following enumeration lists the top three causes of accidents with fatalities (see also figure 1.1):

1. Loss of Control in Flight
2. **Controlled Flight Into Terrain (CFIT)**
3. Runway Excursion

These causes are compiled from data gathered between 2002 and 2011. CFIT is still the number two cause of the investigated accidents. CFIT is defined as follows (taken from SKYbrary, a Wiki created by Eurocontrol and ICAO [11]):

> "Controlled Flight into Terrain (CFIT) occurs when an airworthy aircraft under the complete control of the pilot is inadvertently flown into terrain,

> water, or an obstacle. The pilots are generally unaware of the danger until it is too late."

The fact that the aircraft was still airworthy is notable. The crew was just unaware of its position relative to terrain and could not react early enough to avoid a collision. The effect of CFIT is mostly a collision with the ground, resulting in hull loss and fatalities. Hull loss defines the status of an aircraft which has been destroyed or has been determined to have been damaged beyond economic repair, cf. [12].

As the crew was unaware of their position, they might have lost situational awareness (SA) of the surrounding terrain. The term situational awareness plays an important role in aviation since it contributes to the safety of the flight. Situational awareness is defined in literature multiple times, one clear definition from the SKYbrary [13] reads:

> "Situational awareness is defined as the continuous extraction of environmental information, the integration of this information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception and anticipating future events."

In terms of navigational awareness the questions "Where am I?" and "Where to go?" are of relevance ([18], p.2). The crew uses the information gathered from the cockpit environment (e.g. navigation displays) to determine the aircraft position as well as the situation around the aircraft and to finally decide where and how to go next based upon this position. Lack of knowledge of the true aircraft position leads to the loss of situational awareness and the loss of the ability to anticipate future events. Future events may be the start for descent for approach or the approach towards an area with mountainous terrain.

Losing the SA in portions of flight that are close to terrain such as departure or approach can lead to CFIT. Contributory factors for CFIT are [11]:

- Adverse Weather Conditions
- Approach Design and Documentation
- Deficient Crew Resource Management
- Pilot Fatigue and Disorientation

Approaches in adverse weather conditions demand a higher workload of the crew than in good conditions. A typical situation would be when the crew loses visual contact with the runway on a visual approach and enters clouds. The design of an approach procedure in mountainous terrain leads inevitably to predefined flight paths that are close to terrain. Insufficient or bad documentation of the procedure may lead to the loss of SA. Deficient crew resource management (e.g. coordination between crew members and division of workload) is also a contributing factor especially during challenging approaches in mountainous regions. Finally, physiological factors such as fatigue and disorientation lead to reduced pilot performance and ultimately to the loss of SA.

Typical indications of CFIT are the deviation from procedures and/or a desired flight path. During departure, the aircraft may not climb too steeply enough or climb below the desired climb path and thus get close to terrain. The same applies if the aircraft deviates from its desired lateral flight path. During approach, the crew may have a wrong altimeter setting of the local barometric pressure and therefore be too low. Lateral deviation while simultaneously undershooting a minimum safe altitude may also lead to undesired closure to terrain. Lateral deviation may be the result of lost SA or radar vectoring during a radar guided approach by an air traffic controller. Finally, a premature descent on final approach could also cause a CFIT.

Some of the risk factors discussed above can be mitigated or even eliminated by using equipment that helps the crew to improve their SA and that warns them of a hazardous closure or even an impact to terrain. As mentioned above, the GPWS is an equipment of this type and was introduced in the 1970s. Later, as technology progressed, the TAWS was introduced in the mid 1990s to enhance the GPWS. With respect to the risk factors, the following basic requirements can be stated for a TAWS:

- A TAWS should detect any hazardous terrain closure.
- A TAWS should warn the crew early enough to allow for evasive actions and to prevent a CFIT.
- A TAWS should improve the SA of the crew during all phases of flight.

1.3 TAWS System Overview

1.3.1 History

Accident investigations in the early 1970s revealed that CFIT was the most dominant cause for aircraft accidents [27]. Until then, no system preventing these types of accidents was available. By 1974, the GPWS had been developed and mandated by the FAA to be carried on board on all U.S. large turbine and turbojet aircraft. With the introduction of the GPWS, the CFIT rate in the U.S. dropped dramatically (see figure 1.2). The introduction of a GPWS with enhanced functionality in 1996 lead to a further decline in the number of CFIT accidents. 2004 was the first year without any CFIT for jet aircraft at all [5]. In 2006, the loss of control in flight took over as the leading accident cause in aviation for jet aircraft [6]. Reviewing these facts reveals the importance of the system over almost the whole of the last 40 years. However, the number of CFIT accidents for the turboprop aircraft is still significantly high [6].

One of the most recent CFIT accidents in aviation history, despite carrying a functional TAWS, was the accident of a TU-154 in April 2010 near Smolensk (Russia), killing all 96 people on board, among them the Polish president [7]. Another remarkable recent accident was the crash of AirBlue flight 202, Airbus A321, in July 2010 near Islamabad (Pakistan), killing all 152 people on board [1].

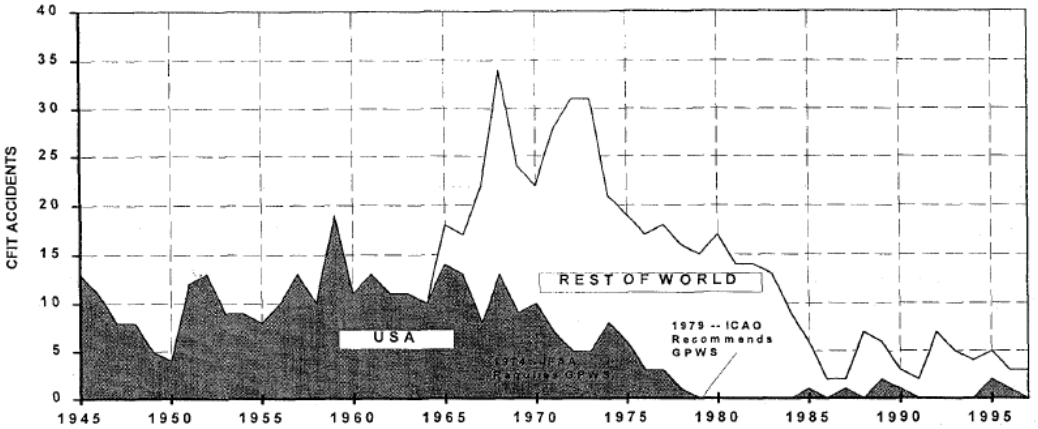


Figure 1.2: CFIT Statistics, taken from [4]

At the time when the GPWS was introduced, the radio altimeter was used as the central sensor for the system. The radio altimeter measures the relative height of the aircraft above ground, the radio altitude. Furthermore, data from the air-data system was used. The air-data system measures the relative velocity of the aircraft in the air. The GPWS incorporates 6 modes. Each mode is responsible for a dedicated task. In principle, a mode's task is to monitor certain parameters and to issue a dedicated alert. There are 2 types of alerts: The caution alert and the warning alert. The caution alert is the weaker one and tells the crew that something is out of order. The warning alert requires immediate action by the crew. The caution alert is always associated with the color amber/yellow whereas the warning alert is associated with the color red. An alert consists of an aural and a visual alert. Aural alerts are issued using loudspeakers in the cockpit, visual alerts using colored lamps.

The most important parameter is the radio altitude. One mode for example is responsible for monitoring the radio altitude and the vertical speed of the aircraft. A criterion is formulated that if the vertical speed of the aircraft is too high when the radio altitude is too low, an alert should be issued. The criteria for each mode are modeled using so-called "envelopes" (see figure 1.3). Using a mapping between the descent rate (vertical speed) and the height above terrain (radio altitude) in a diagram, an envelope is defined as area. Once the combination of both parameters lies inside this area, an alert is triggered. The basic GPWS consists of 6 modes:

1. Excessive Descent Rate

2. Excessive Terrain Closure Rate

3. Altitude Loss after Take-Off

4. Excessive Deviation below Glideslope

5. Excessive Bank Angle and Altitude Callouts

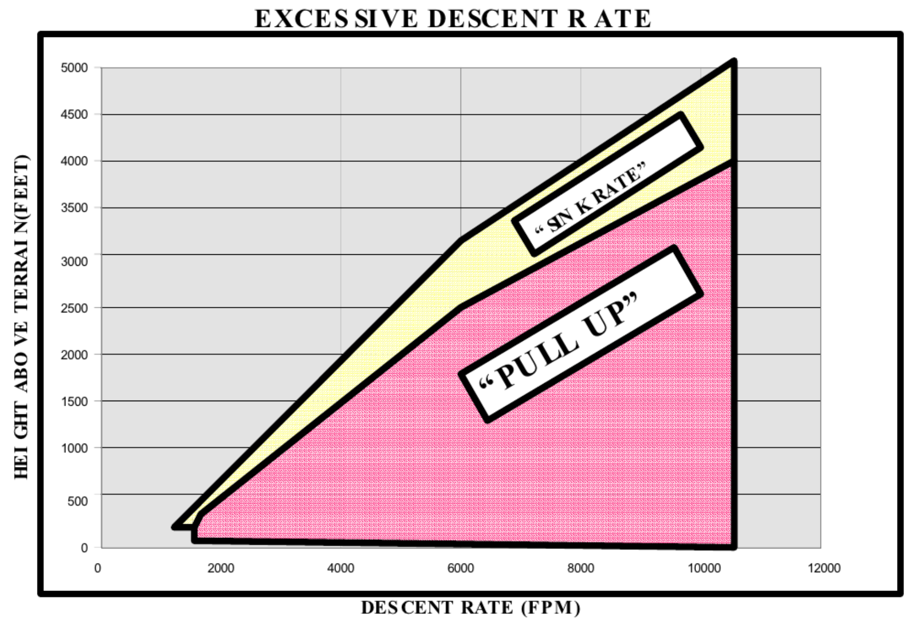


Figure 1.3: GPWS Mode 1 Envelope, taken from [15]

Each mode has its own envelope and alert characteristics. Some modes are active during all phases of flight, while others are active only during, for example, take-off. With respect to the enhanced functionality in a TAWS, mode 2 is of interest.

Mode 2 tries to detect if the aircraft has an excessive terrain closure rate towards terrain. Terrain closure may be caused when the aircraft either descends or when it flies at a certain level or climbs and the terrain is rising as illustrated in figure 1.4. The closure rate is calculated using the differentiated radio altitude with respect to time. When the radio altitude is too low and the terrain closure rate too high (defined by the envelope), mode 2 initially issues the aural caution "Terrain-Terrain", followed by the continuous aural warning "Pull-Up". One drawback of mode 2 is evident: As the radio altimeter measures the relative height of the aircraft above ground, a steep rising terrain ahead of the aircraft may be detected too late to allow for evasive maneuvers. The system simply does not look forward, it only looks down. This is one of the most important factors that eventually caused the advancement to the TAWS.

The requirements for a TAWS are regulated. They define the minimum performance standards that a TAWS must posses in order to certify it for airborne use. They are regulated in the FAA Technical Standard Order (TSO) C151b [15]: "Terrain Awareness and Warning System"

Today, the market for GPWS and TAWS is dominated by Honeywell. Honeywell has pioneered the GPWS with the invention of the system and later on with the enhanced GPWS called Enhanced GPWS (EGPWS). Note that TAWS is the collective term used by the FAA, whereas EGPWS is the implementation of a TAWS by Honeywell. Honeywell has delivered about 70,000 GPWS and EGPWS units. Other manufacturers are Universal Avionics, Thales or Sandel Avionics.

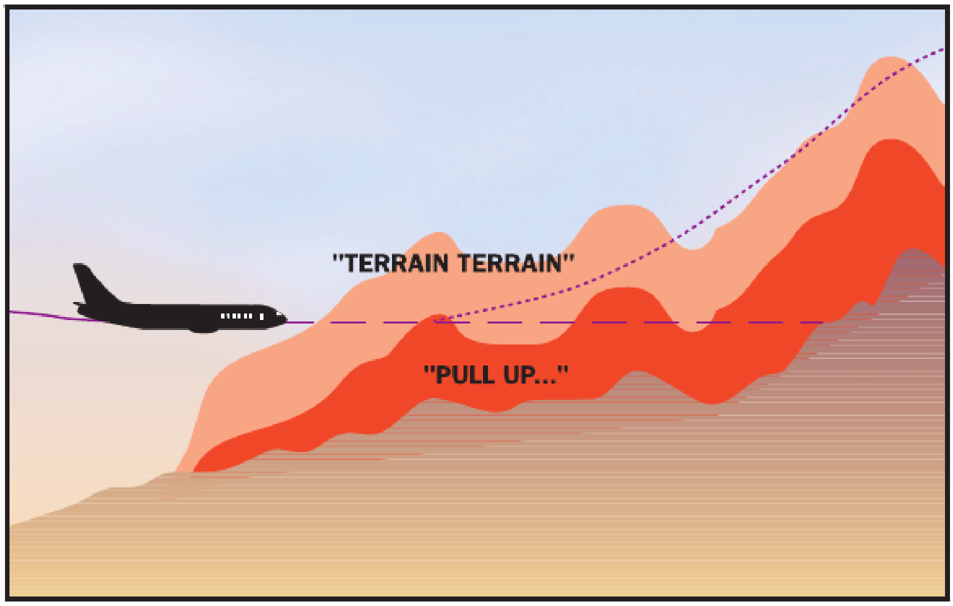


Figure 1.4: GPWS Mode 2 Envelope Illustration, taken from [20]

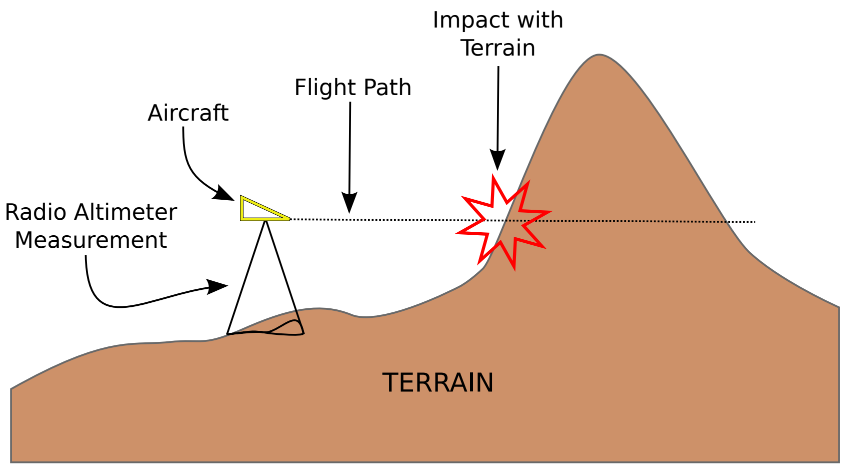


Figure 1.5: Downward Looking Concept

1.3.2 Motivation and Benefits

As discussed in the section above, the GPWS's drawback is the nature of how it works. It simply looks downward by using the radio altitude. There is no anticipation of the terrain closure. Figure 1.5 illustrates this. At the aircraft position, the terrain is rising, but the terrain closure rate is too low to issue a GPWS mode 2 alert. However, terrain obstructs the flight path ahead. If the crew is not warned, a terrain impact is inevitable. This shortcoming that is characteristic of the GPWS lead to the development of the TAWS. Especially with the introduction of GPS, its full operational capability which was achieved in 1995 [19] and the availability of digital terrain databases, the foundation stones for an enhanced system with new capabilities were given.

Some basic requirements for a TAWS that stem from the "lessons learned" in the CFIT accidents are listed in section (1.2). The main drawback of the GPWS - the late issuing

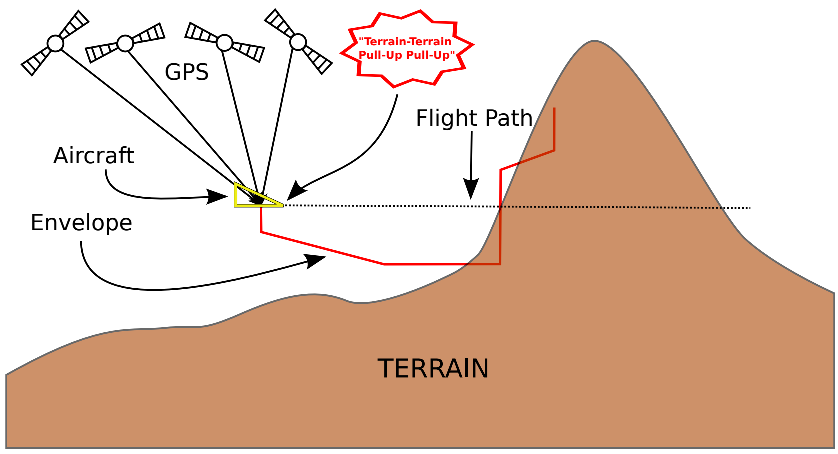


Figure 1.6: Forward Looking Concept

of an alert - is eliminated by introducing a concept that looks ahead of the aircraft. Looking ahead requires knowing the aircraft position and predicting the flight path. While the GPWS measures the radio altitude to detect alerts, the TAWS uses a digital terrain database and tries to find conflicting terrain that lies within the predicted flight path. This method is called "Forward Looking Terrain Avoidance" (FLTA). In figure 1.6 the same situation as in figure 1.5 is depicted. Figure 1.6 shows the enhancement of the GPWS. The aircraft position is determined using GPS, a virtual envelope is established and as the envelope penetrates the terrain, an aural alert, approximately 30-60 seconds ahead of the terrain, "Terrain-Terrain Pull-Up Pull-Up" is issued. The crew can react early enough and initiate an evasive maneuver. Note that the basic GPWS modes are still operating, they are just enhanced by the FLTA. The situational awareness is improved by generating a picture of the terrain in the vicinity of the aircraft on the navigation display in the cockpit. This generated picture is called terrain display. The combined functionality of the FLTA and the terrain display is denoted as "Terrain Awareness" (TA).

1.3.3 System Design

A high level system design of a TAWS is shown in figure 1.7. The TAWS receives inputs from various aircraft systems and processes them in the main modules GPWS and terrain awareness. The GPWS and the terrain awareness modules generate alerts and the terrain display. The alerts are presented within the cockpit environment on loudspeaker and lamps, the terrain is displayed on the navigation display.

The following aircraft systems are commonly used:

- GPS
- Inertial Reference System (IRS)
- Air Data Computer (ADC)

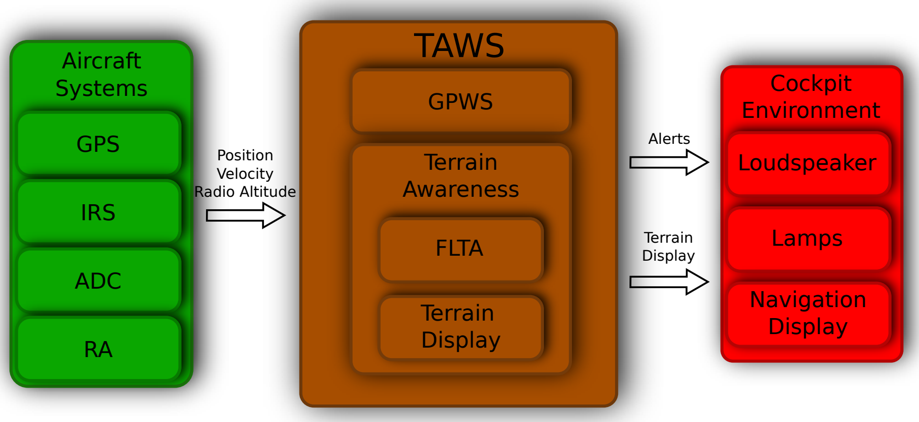


Figure 1.7: High Level TAWS System Design

- Radio Altimeter (RA)

The GPS provides position data and the velocity vector. The IRS supplies position, kinematic data (e.g velocity vector, angular rates) and attitude data. The ADC provides airspeed, barometric altitude and temperature data, the RA provides radio altitude. The data provided by the IRS are supplemental to the GPS to increase position accuracy. In addition, the IRS provides data at a significant higher rate (e.g. 1 Hz from GPS vs. 60 Hz from IRS).

The terrain awareness module is divided into the FLTA and the terrain display. The FLTA module is responsible for

- Prediction of the current Aircraft Position
- Construction of a Search Volume
- Intersection of the Search Volume with a Terrain Database
- Generation of Alerts

The prediction of the aircraft position is the first step. The prediction uses the current aircraft position and the velocity vector to calculate the future positions. One important question is how far ahead the future should be predicted. Another important question is how to predict. Since the TSO-C151b requires the FLTA to handle curved flight, provisions must be made to predict the position along a curved flight path.

After the positions have been predicted, a so-called “search volume” (defined in TSO-C151b) is established using the predicted positions. The search volume has a lateral extent to the left and right of and a vertical extent along these positions. The search volume depends mostly on the predicted positions and the flight phase. The flight phase depends on the distance to the nearest runway. Therefore, a search for the nearest runway is necessary. The search volume is dynamic and must adapt optimally to the current situation. The layout of the volume is significant for the overall performance of a TAWS.

Once the search volume has been constructed, the next step is to intersect it with a terrain database. The TAWS contains a dedicated terrain database. The task is to find all terrain that penetrates the volume. The terrain database is modeled to allow effective access with the searchvolume - terrain intersection in mind.

Finally, if terrain that penetrates the volume was found, the alert generation is responsible for examining this terrain and issues an alert. Again, as described above (section 1.3.1), two types of alert exist: The caution and the warning alert. Both types of alert are announced through the cockpit environment's loudspeaker and lamps.

1.3.4 Challenges in System Design

The objective of a TAWS is to be a reliable navigation system that warns the crew early enough against hazardous terrain closure and to improve the crew's situational awareness. However, when designing a TAWS, one must especially take care of the reliability of the system. One major problem of a TAWS is the generation of false alerts or so-called "nuisance alerts"[1] (defined in TSO-C151b [15], appendix 1, p. 3). These alerts occur inappropriately during normal safe operations. The crew may lose confidence in the system if these alerts occur too often. The challenge in designing the system is to construct a search volume that does not cause nuisance alerts on the one hand but on the other hand does not discard a potential hazardous terrain closure.

Another challenge is to handle the large amount of terrain data contained in the terrain database. Since a TAWS may be used globally, effective methods for storing and accessing the data have to be designed.

1.4 Objective of this Thesis

The objective of this thesis is to find solutions for the tasks executed by the FLTA. This means to find a solution for the following points:

- Aircraft Position Prediction (chapter 2)
- Construction of a Search Volume (chapter 3)
- Method to find the nearest Runway (chapter 4)
- Intersection of the Search Volume with a Terrain Database (chapter 5)
- Method to generate Alerts (chapter 6)

The solutions found are used to develop a TAWS for a Full-Flight Simulator which is used for pilot training.

The chapter "Position Prediction" explores how to predict the aircraft position with a given set of parameters. This involves the setup of an appropriate algorithm.

[1] An inappropriate alert, occurring during normal safe procedures, that occurs as a result of a design performance limitation of TAWS.

The chapter "Search Volume" deals with the design of a search volume that generates a minimum of nuisance alerts. Several parameters that influence the shape of the volume are considered.

In the chapter "Intended Runway Search" a solution is found for detecting the nearest runway in the vicinity of the aircraft.

Chapter "Search Volume - Terrain Intersection" defines a design for a terrain database that is well fitted for the intersection with the search volume. Furthermore, an effective method for the intersection of the search volume with the terrain database is described.

Chapter "Alert Generation" presents a method to generate alerts based on the results from the search volume - terrain intersection.

The last chapter "Implementation and Outlook" describes briefly the development and implementation process.

1.5 Definitions

For the sake of completeness, table 1.1 lists the units and their description used throughout this thesis:

Table 1.1: Units used

Unit Name	**Description**
ft	Feet
kt	Knots (Nautical Miles per Hour)
NM	Nautical Miles
deg	Degrees
secs	Seconds
G	Earth's Gravity

Figure 1.8 shows the symbology used for the aircraft in this document.

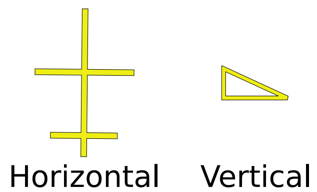


Figure 1.8: Aircraft Symbology

2 Position Prediction

2.1 General

The aim of the position prediction is to determine the aircraft position in the near future. Depending on the speed of the aircraft, the position is predicted for about 30 sec to 1 min ahead in time. The prediction accounts for straight and turning flight. Vital aspects are the accuracy and integrity of the predicted position. The following chapter will give a short introduction into the kinematics of an aircraft and will then deal with the position prediction itself.

2.2 Kinematics of an Aircraft

A TAWS requires input from various aircraft systems. The sensors of the systems (directly or indirectly) measure the kinematics of an aircraft. The kinematics of an aircraft is described by a set of parameters that are the result of the underlying dynamics. For the prediction in the TAWS the following parameters are needed:

- Position
- Horizontal Velocity
- Flightpath
- Yaw Rate

These parameters are used to find a suitable simplified "dynamics model" that forms the base for the prediction. Precise information about the underlying dynamics is not available and not desirable since the prediction should work for any aircraft.

2.2.1 Position

The position is given in form of latitude (φ), longitude (λ) and altitude (h). The latitude and longitude together define the horizontal position.

The altitude has to be treated separately. The primary altitude reference in aviation is barometric. The instruments in the cockpit display the altitude measured by barometers. These measurements are subject to various factors such as the local pressure or temperature. As a TAWS primarily relies on the GPS position and altitude, it is complemented with other systems that measure for example the barometric altitude. With

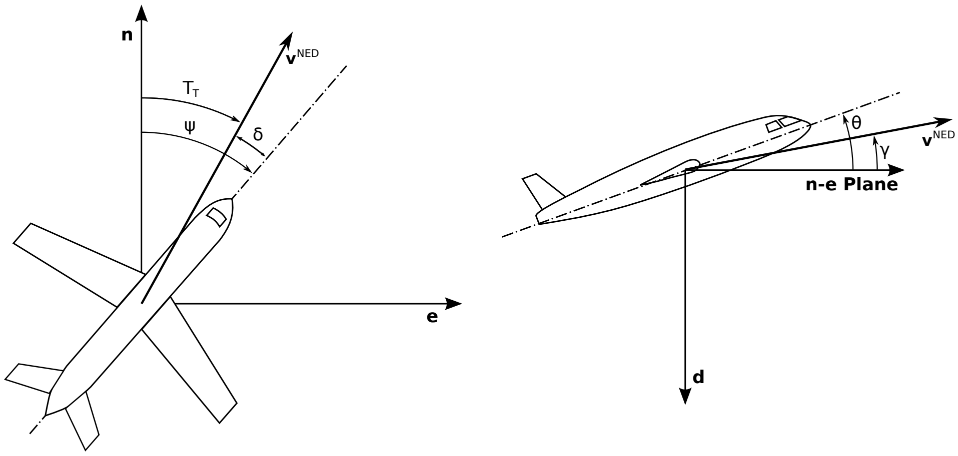


Figure 2.1: Illustration of Velocity Vector and associated Angles

respect to a terrain database, it is very important to find a common altitude reference system.

For the sake of completeness, the horizontal and vertical datum of the position must match the horizontal and vertical datum of the used terrain database (see chapter 5).

2.2.2 Horizontal Velocity

For defining the velocity, a local level frame is introduced. The local level frame's origin is arbitrary. It is defined by a three-dimensional, right-handed Cartesian system with the $\mathbf{x}_1$ axis pointing north, the $\mathbf{x}_2$ axis pointing east and the $\mathbf{x}_3$ axis pointing down in direction of the nadir. A vector in this system is comprised of components in north (n), east (e) and down (d) direction, indicated by the subscripts $_n$, $_e$ and $_d$. The frame is denoted as N(orth)-E(ast)-D(own)-frame (NED).

The velocity vector contains the velocities along each axis of the NED-frame:

$$\mathbf{v}^{NED} = \begin{bmatrix} v_n \\ v_e \\ v_d \end{bmatrix} \tag{2.1}$$

Horizontal velocity ($\mathbf{v}_{hor}^{NED}$) is derived from the individual components of the vector:

$$v_{hor}^{NED} = \sqrt{v_n^2 + v_e^2} \tag{2.2}$$

2.2.3 Flightpath

The flightpath of an aircraft is derived from the velocity vector. The flightpath is defined as the direction in which the aircraft is flying with respect to the NED-frame. Therefore, the direction of the flightpath is split into a horizontal and a vertical component. The vertical component is described by the angle γ, the horizontal component by the angle T_T. γ is also known as the flightpath angle and T_T is known as true track (subscript $_T$

denotes true). The angles are calculated as follows (see also figure 2.1):

$$\gamma = \arcsin \frac{v_d}{\|\mathbf{v}^{NED}\|} \tag{2.3}$$

$$T_T = \arctan \frac{v_e}{v_n} \tag{2.4}$$

As one can see from equation 2.3, the flightpath angle is the angle between the n-e plane of the NED frame and the velocity vector. The true track expresses the direction of the velocity vector with respect to the true (not the magnetic) north direction.

2.2.4 Yaw Rate

The yaw rate ($\dot{\psi}$) of an aircraft is derived from the yaw (heading) angle of the attitude (see figure 2.1 left hand side). The attitude describes the orientation of the body frame (b-frame) relative to the NED-frame by three angles:

- ψ (Yaw or Heading)
- θ (Pitch)
- ϕ (Roll or Bank)

The yaw rate is simply the time-derivative of the yaw angle. Note that the actual yaw angle is not of interest for the prediction, the true track angle is used instead (see 2.4). Figure 2.1 depicts a typical situation where the true track T_T does not coincide with the yaw angle ψ. The difference angle δ is the drift angle, which is caused by the influence of the wind.

2.3 Sensor Data

Various sensors in the aircraft provide the parameters mentioned above directly or indirectly. The TSO-C151b [15] states requirements for the horizontal and the vertical position information. The minimum required and most typical equipment is an onboard GPS-receiver that meets the requirements of TSO-C129a [14]. However, to improve accuracy and integrity, the use of other means such as an IRS is recommended. When multiple sensors are used for determining a parameter, a suitable integration method (e.g. Kalman Filter, complementary filter) has to be used. Following, various on board systems are listed that are used within a typical TAWS setup to determine the parameters:

2.3.1 Global Positioning System (GPS)

The GPS provides the following information to the TAWS:

- Horizontal Position

- Altitude
- Horizontal Figure of Merit (HFOM)
- Vertical Figure of Merit (VFOM)
- True Track
- Flight Path Angle
- Ground Speed

The horizontal position contains the latitude and longitude in WGS84 coordinates. The altitude is ellipsoidal and must be converted finally to the same vertical datum as that of the terrain database, otherwise errors due to the different datums may occur later in the FLTA. The HFOM expresses the accuracy of the horizontal position in nautical miles, the VFOM the accuracy of the altitude in ft. Both represent the accuracy on a 95% confidence level and are important factors to determine the reliability of the supplied information. The true track is provided along with the ground speed. The true track and ground speed contain some lag because these informations are derived from positions over time.

2.3.2 Inertial Reference System (IRS)

The IRS provides the following information to the TAWS:

- Horizontal Position
- Horizontal Figure of Merit (HFOM)
- True Track
- Flight Path Angle
- Ground Speed
- Yaw Rate

Similar to the GPS, the IRS provides information about the horizontal position and attitude. However, the IRS provides the information at a much higher rate than GPS (about 60Hz in case of IRS) and is also denoted as Inertial Measurement System (IMS) in geodesy.

2.3.3 Air Data Computer (ADC) and Radio Altimeter (RA)

The ADC provides barometric altitude to the TAWS. The barometric altitude must be handled with care because it is influenced by atmospheric conditions and pilot settings. The RA provides the radio altitude, which is the relative height of the aircraft above the ground.

2.4 Aircraft Position Prediction

The aircraft position prediction predicts the horizontal position of the aircraft. The objective is to know where the aircraft will be in the future. The result of the prediction is a series of positions. The positions are sampled with a certain time step. The prediction must account for straight ($\dot{\psi} = 0$) and turning flight ($\dot{\psi} \neq 0$). The altitude is not predicted, since a kind of vertical prediction is done via construction of the vertical part of the search volume. In general, the prediction is kept simple to minimize the computational effort. In the following section the model for prediction in straight and turning flight will be developed.

2.4.1 Navigation Frame

A special navigation frame is chosen for the model. Since the prediction is intended for short term only, the earth is regarded as a non-rotating inertial frame. Terms resulting from the earth's rotation, more precisely the coriolis and centrifugal acceleration, are neglected. These terms only have an impact if one predicts the position for long term. The navigation frame has its origin at the current aircraft position and the axes coincide with the axes of the NED-frame.

2.4.2 Detection of Straight and Turning Flight

The prediction for both straight and turning flight is a requirement of the TSO-C151b [15]. The following requirement (appendix 1, chapter 3.1) is stated: "The FLTA function should be available during all airborne phases of flight including turning flight." and "The lateral search volume should expand as necessary to accommodate turning flight". As the lateral search volume is built from the predicted positions, the prediction uses different algorithms for straight and turning flight. Before the prediction algorithm can predict the position, the type of flight (straight or turning flight) is detected.
In general, an aircraft is considered to be in turning flight when $\phi \neq 0$, meaning that the aircraft is rolling. As a consequence of the rolling, the aircraft's yaw angle ψ will change with a certain rate $\dot{\psi}$. Now, one may choose either ϕ or $\dot{\psi}$ to detect whether the aircraft is turning or not. This detection uses $\dot{\psi}$. The main reason for that is that ϕ may be erratic during flight in turbulences, whereas $\dot{\psi}$ is more steady. A disadvantage emerges when using $\dot{\psi}$, because $\dot{\psi}$ lags behind in time. The result of the detection is the flight type. The flight type can either be straight or turning flight. The detection filters the incoming $\dot{\psi}$ and then applies a hysteresis function to the filtered $\dot{\psi}$. The hysteresis function's result is the flight type. The usage of a filter and a subsequent hysteresis function is necessary to avoid erratic and wrong detection results.

The main reason for filtering $\dot{\psi}$ are the possible influences of turbulences. Furthermore, pilot inputs that lead to a short-term change in $\dot{\psi}$ are suppressed. The result is a smoothed yaw rate. The influences that need to be filtered are high frequency components compared to the main signal $\dot{\psi}$. Therefore, the used filter must provide the characteristics of a low pass filter. The frequency characteristics of the disturbing influences are not known or vaguely known. An α-β-filter has been chosen as the filter that fulfills the requirements. The α-β-filter is a filter often used in navigation applications to smooth data. It is closely related to the Kalman filter. The main advantage of the α-β-filter is that it does not require a detailed system model and that the computational effort is very small compared to a moving average filter for example. The α-β-filter is based on the same "predict-update" concept as the Kalman filter. The main difference lies in the static weight factors that are applied when the prediction is updated with new measurements.

2.4.2.1 Filter Algorithm

The α-β-filter assumes that the system is described by two states. The first state is obtained by the integration of the second state. The first state is called x, the second is called v. x can be interpreted as a position, v as a velocity. Integrating v over time yields x. The filter assumes that the system is the outcome of a motion with constant velocity. As we will see, this is not true for all applications. However, by keeping the integration interval small, the condition of motion with constant velocity can be achieved. The filter for epoch k with the measured position x, the estimated position $\hat{x}$ and predicted position $\tilde{x}$ works as follows:

Initialization:

$$\hat{x}_0 = \textit{initial position} \tag{2.5}$$

$$\hat{v}_0 = 0 \tag{2.6}$$

Step 1: Prediction of the states:

$$\tilde{x}_k = \hat{x}_{k-1} + \Delta T \hat{v}_{k-1} \tag{2.7}$$

$$\tilde{v}_k = \hat{v}_{k-1} \tag{2.8}$$

Step 2: Calculation of a residual position:

$$\hat{r}_k = x_k - \tilde{x}_k \tag{2.9}$$

Step 3: Measurement update (correction):

$$\hat{x}_k = \tilde{x}_k + \alpha\, \hat{r}_k \tag{2.10}$$

$$\hat{v}_k = \tilde{v}_k + \frac{\beta}{\Delta T}\, \hat{r}_k \tag{2.11}$$

The filter is initialized with an initial position and velocity 0. The first step of the filter predicts the position of epoch $k-1$ to the current epoch k. It therefore uses the previously calculated velocity $\hat{v}_{k-1}$ and the time step ΔT, which is the time that elapsed between the epoch $k-1$ and the current one. As the velocity is assumed to be constant, it is not predicted at all. The velocity from the last epoch is used. In the second step, a residual position error is calculated. This error arises from measurement noise and changes in the dynamics that have not been considered in this simple model. The residual position error can be compared to the innovation in terms of Kalman Filtering (see [18], chap. 3.6.3). The last step involves the calculation of an estimated position $\hat{x}_k$ and velocity $\hat{v}_k$. This calculation uses two static gain factors: α for the position and β for the velocity. Both factors are determined experimentally (see 2.4.2.2). The residual position error is used with the gain factors to correct the predicted position and velocity.

2.4.2.2 Choosing suitable Gain Factors

The gain factors α and β steer the behavior of the filter. They should lie in the range of 0 to 1 in order to have a converging filter. α controls how new position measurements are weighted compared to the predicted ones. The more α approaches 1, the more the output of the filter resembles the original data, since $\tilde{x}_k$ (equ. 2.10) will vanish. β is responsible for weighting the influence of the residual position error on the predicted velocity. For the case when $\beta = 0$, the estimated velocity stays constant. This will have the effect that the residual position error becomes larger since the prediction assumes a constant velocity which might be a wrong assumption for most cases. The gain factors for the yaw rate filter were found empirically. Flight tests using a flight dynamics simulation were conducted and recorded. The following situations were examined to evaluate suitable gain factors:

- Flight in turbulent air
- Direction change (from left turn to right turn)
- Pilot errors (yawing inputs from the pilot)

The α-β-filter was additionally compared to a standard moving average (MA) filter. As one can see, the chosen gain factors of $\alpha = 0.08$ and $\beta = 0.002$ fit very well for the intended application. The influence of turbulences is well reduced (see figure 2.2). The filter also performs well and does not lag behind much in case of rapid direction changes (see figures 2.3 and 2.4).

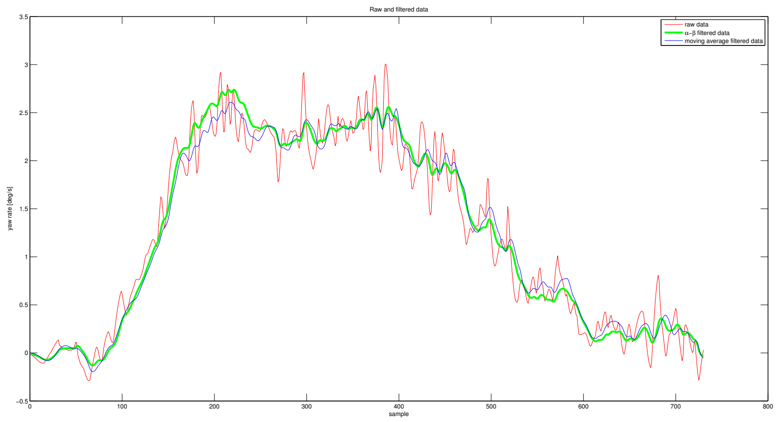


Figure 2.2: Flight Test with Turbulence, $\alpha = 0.08$, $\beta = 0.002$, 15 samples MA Filter

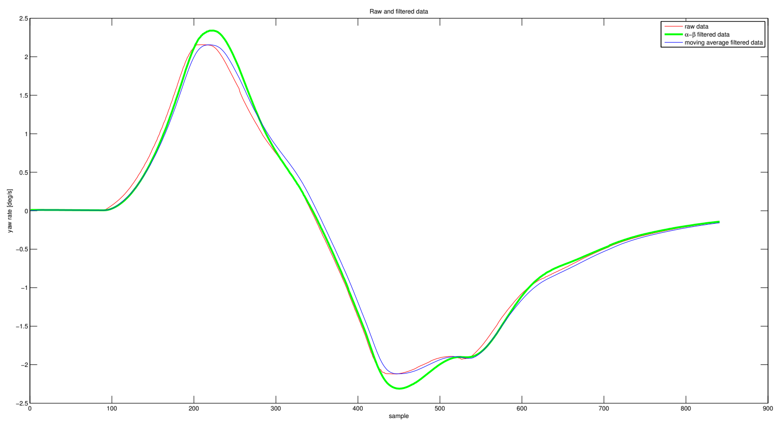


Figure 2.3: Flight Test with Direction Change, $\alpha = 0.08$, $\beta = 0.002$, 15 samples MA Filter

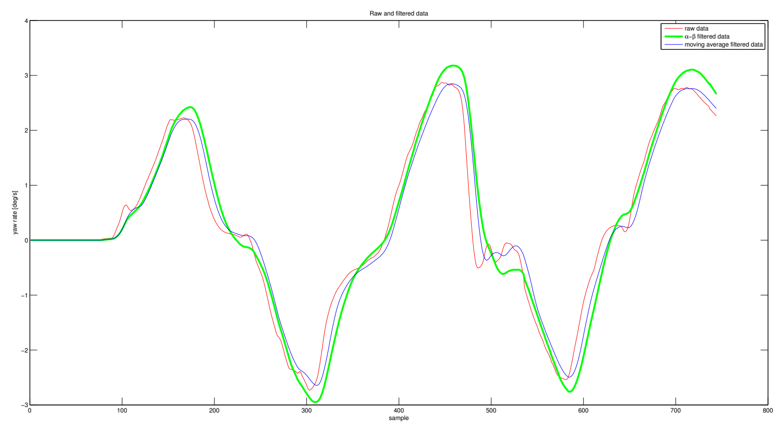


Figure 2.4: Flight Test with Pilot Yawing, $\alpha = 0.08$, $\beta = 0.002$, 15 samples MA Filter

2.4.2.3 Hysteresis Function

The flight type is determined with a hysteresis function applied to the filtered yaw rate. The flight type is considered turning when the yaw rate exceeds 0.5 deg/s and is considered straight again when the yaw rate drops below 0.3 deg/s. These values were found empirically.

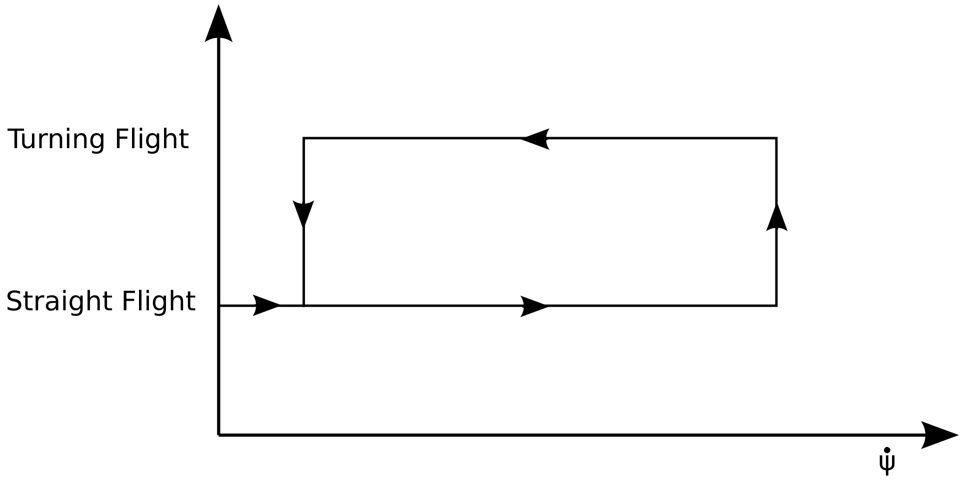


Figure 2.5: Hysteresis Function

2.4.3 Look Ahead Distance (LAD)

The prediction is restricted to a certain time or distance ahead of the aircraft. The choice of this time or distance is important, since it will directly influence the performance of the system in detecting real threats and discarding false threats. A real threat is considered as a serious, highly probable, hazardous terrain closure, whereas a false threat is considered as terrain closure that was wrongly interpreted as hazardous due to the design limitations of the TAWS system. If the time or distance chosen is too long, the system is prone to false threats. If the time or distance chosen is too short, the system may discard real threats. The definition of the LAD is made from a geometric point of view and considers an escape maneuver in the horizontal plane. An escape maneuver in the vertical plane, that is considering the current aircraft performance (e.g. available thrust and kinetic energy), is not taken into account. The following approach corresponds for the most part to the implementation of the LAD in Honeywell's EGPWS.

2.4.3.1 LAD Calculation

The aircraft is considered to be in straight flight, flying a certain track angle (see figure 2.6). There is terrain ahead. It is the ultimate aim to warn the pilot of the terrain ahead in such a manner that there is enough time for a horizontal escape turn. The radius of the escape turn depends mainly on the flown bank angle (ϕ) and groundspeed (v_{hor}^{NED}). The system issues a caution alert, the pilot may then have some time to react and bank the aircraft to the desired bank angle, resulting in the aircraft flying distance

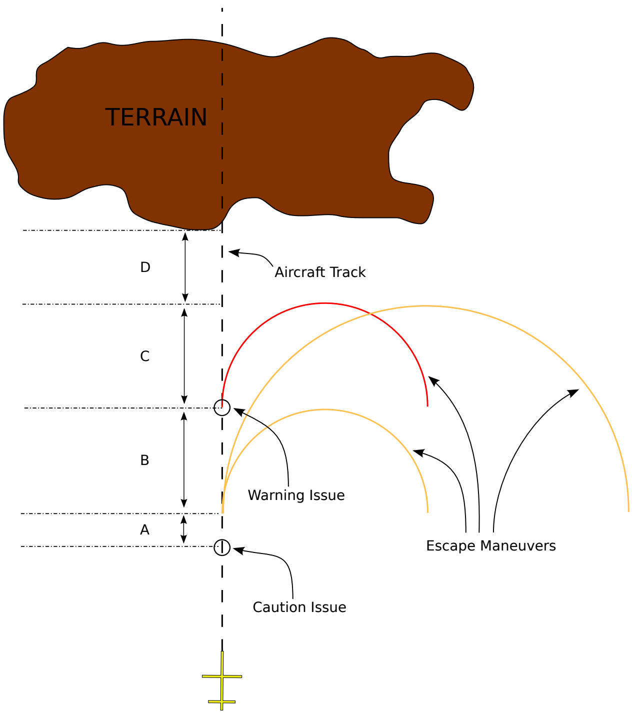


Figure 2.6: Illustration of Look Ahead Distance (LAD)

A meanwhile (figure 2.6). The pilot may turn with a high or low bank angle, resulting in a small or large escape turn. The small turn needs distance B, while the large turn needs distance B + C. If the pilot does not initiate a turn after the caution alert, he is urged to do so when a warning is issued. This turn is assumed to be of high bank angle resulting in distance C. Finally, a safety margin distance D is introduced that is called minimum terrain clearance. The total distance required is:

$$\text{LAD} = \text{A} + \text{B} + \text{C} + \text{D}$$

Distance A is calculated depending on a certain pilot response time t_{Pilot}:

$$A = t_{Pilot}\, v_{hor}^{NED} \tag{2.12}$$

Distance B and C correspond to the turning radius R with a certain escape maneuver bank angle ϕ_{escape}:

$$R = \frac{{v_{hor}^{NED}}^2}{G\,\tan\phi_{escape}} \tag{2.13}$$

The LAD is finally calculated as:

$$LAD = A + 2\,R + D \tag{2.14}$$

Table 2.1 lists and figure 2.7 displays a comparison of the LAD and associated Look Ahead Times for different speeds.

Table 2.1: Comparison of LAD Values

Speed [kt]	LAD [NM]	Look Ahead Time [secs]
100	0.7	27
150	1.4	35
200	2.4	43
250	3.6	52
300	5.1	61
350	6.8	70
450	10.9	88
550	16.1	106
600	19.1	115

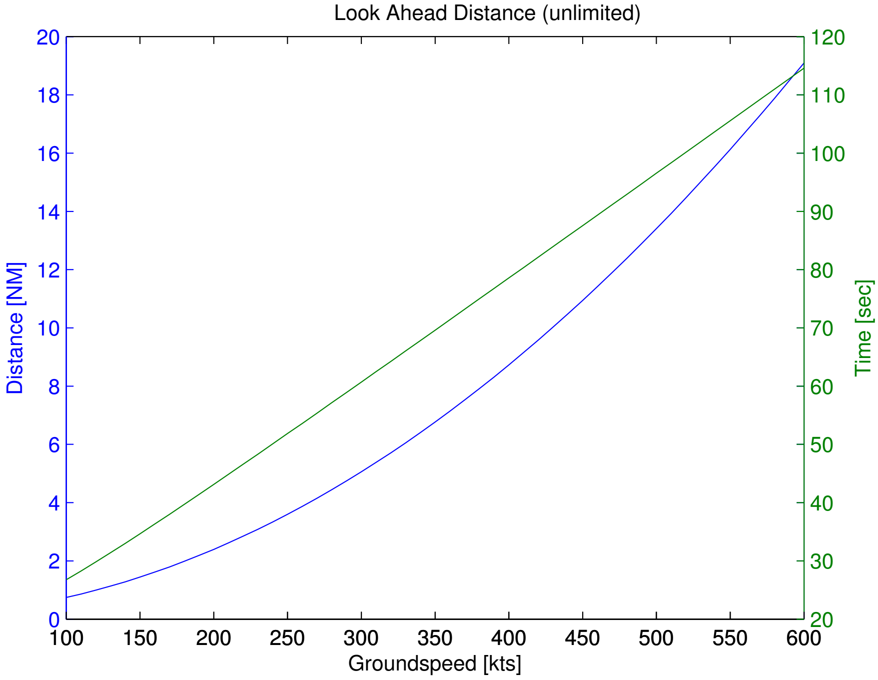


Figure 2.7: Plot of LAD and Look Ahead Times (Unlimited)

Table 2.2: Comparison of LAD values, limited between 1 NM and 8 NM

Speed [kts]	LAD [NM]	Look Ahead Time [secs]
100	1.0	36
150	1.4	35
200	2.4	43
250	3.6	52
300	5.1	61
350	6.8	70
450	8.0	64
550	8.0	52
600	8.0	48

2.4.3.2 LAD Limitation

As one can see from table 2.2, the LAD may become too short or too long when it is dependent on speed only. Therefore, a minimum LAD and a maximum LAD are introduced (see table 2.2 and figure 2.8). The minimum LAD is 1 NM and the maximum LAD is 8 NM. At speeds where the LAD is bounded by the maximum LAD, the aircraft would normally have enough energy to perform a climb in order to avoid the terrain. At speeds where the LAD is too short the aircraft may not have so much energy to perform a climb. Therefore, it is reasonable to enlarge the LAD. This solution provides a good compromise and Look Ahead Times of less than 80 seconds.

2.4.4 Straight Flight Prediction

This algorithm predicts the aircraft's path along an orthodrome for a certain time and is sampled at a certain time step. This results in N predicted positions. The algorithm uses the following inputs:

- Current Aircraft Position and Altitude ($\varphi_{A/C}$, $\lambda_{A/C}$, $h_{A/C}$)
- Current True Track (T_T)
- Current Horizontal Velocity (v_{hor}^{NED})
- Time to predict (t_{pred})
- Sample Time (Δt_{pred})

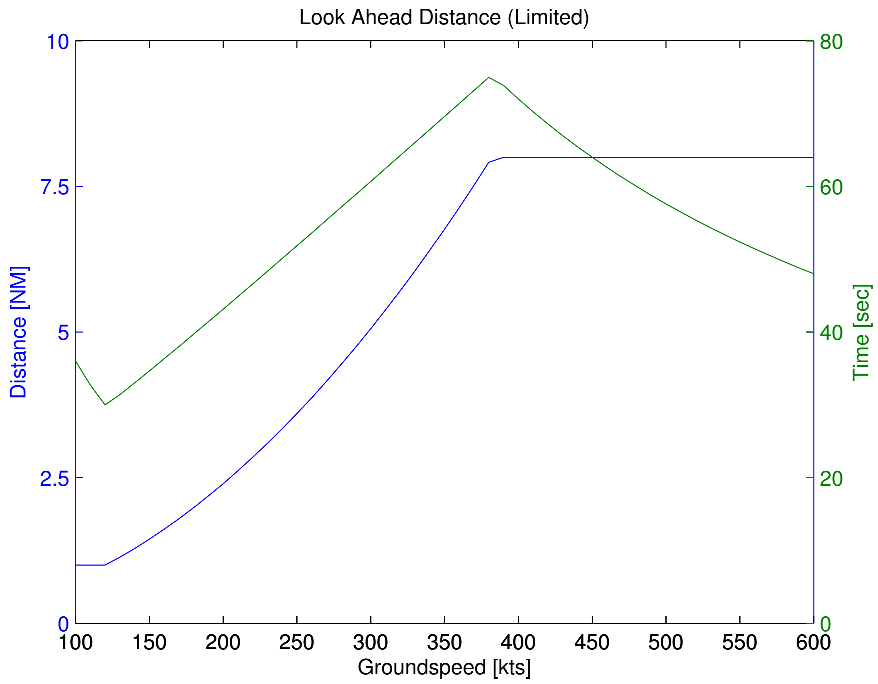


Figure 2.8: Plot of LAD and Look Ahead Times limited between 1 NM and 8 NM

The result of the algorithm is a vector with predicted positions. A predicted position in this vector is calculated as:

$$t_{pred} = \text{Look Ahead Time} \tag{2.15}$$

$$N = \frac{t_{pred}}{\Delta t_{pred}} \tag{2.16}$$

$$d_{step} = \frac{\Delta t_{pred} \cdot v_{hor}^{NED}}{R_{EARTH} + h_{A/C}} \tag{2.17}$$

FOR EACH PREDICTED POSITION i from 1 to N:

$$\varphi_{pred_i} = \varphi_{A/C} + \arcsin(\sin(\varphi_{A/C})\cos(i \cdot d_{step}) + \cos(\varphi_{A/C})\sin(i \cdot d_{step})\cos(T_T)) \tag{2.18}$$

$$\lambda_{pred_i} = \lambda_{A/C} + \arctan\left(\frac{\sin(T_T)\sin(i \cdot d_{step})\cos(\varphi_{A/C})}{\cos(i \cdot d_{step}) - \sin(\varphi_{A/C})\sin(\varphi_{pred_i})}\right) \tag{2.19}$$

The predicted positions coincide with the actual flown track if the wind does not change along the predicted path. Since the prediction is calculated at least once per second, accelerations of the aircraft do not have much impact.

2.4.5 Turning Flight Prediction

If the flight type is turning, an algorithm for predicting the aircraft position along a curved flight path is chosen. The algorithm considers the aircraft to be on an unaccelerated curved flight path with constant bank angle. This assumption can be made since the prediction is calculated at least once per second. Any changes in velocity and/or bank angle will thus influence the predicted positions instantly. Unaccelerated flight and constant bank angle yields a constant turn radius. The radius of a flown curve depends on the horizontal velocity and the bank angle:

$$R = \frac{{v_{hor}^{NED}}^2}{g\,\tan\phi} \tag{2.20}$$

The turn radius may also be expressed as:

$$R = \frac{v_{hor}^{NED}}{\dot{\psi}} \tag{2.21}$$

2.4.5.1 Turning Flight Model

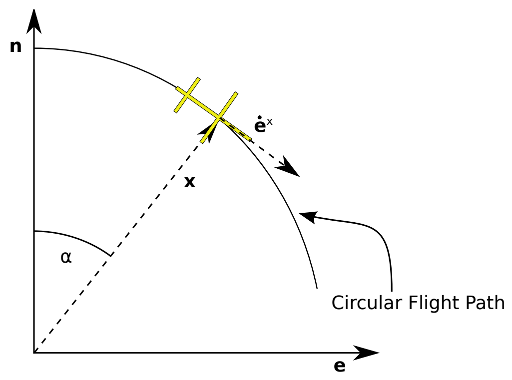


Figure 2.9: Turning Flight Model

In the following, a NED-frame as origin of the curve is considered. Then, a position on the curved flight path is expressed as:

$$\mathbf{x} = \begin{bmatrix} x_n \\ x_e \end{bmatrix} = R \cdot \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = R \cdot \mathbf{e}^x \tag{2.22}$$

where α is the angle between the north axis and the vector to the position on the curve. $\mathbf{e}^x$ denotes the unit vector. Note that both R and α depend on time. To propagate a position to a future point in time one may use a taylor series and truncate it after the quadratic term:

$$\mathbf{x}_{t_0+dt} = \mathbf{x}_{t_0} + \dot{\mathbf{x}}_{t_0}\,dt + \frac{1}{2}\,\ddot{\mathbf{x}}_{t_0}\,dt^2 \tag{2.23}$$

The first and second derivative of $\mathbf{x}$ are needed:

$$\dot{\mathbf{x}} = \dot{R}\,\mathbf{e}^x + R\,\dot{\mathbf{e}}^x\dot{\alpha} \tag{2.24}$$

Assuming the unaccelerated flight with constant bank angle, the Radius remains constant, hence the first term vanishes:

$$\dot{\mathbf{x}} = R \cdot \begin{bmatrix} -\sin(\alpha) \\ \cos(\alpha) \end{bmatrix} \cdot \dot{\alpha} = v_{hor}^{NED} \cdot \begin{bmatrix} -\sin(\alpha) \\ \cos(\alpha) \end{bmatrix} \tag{2.25}$$

The term $R \cdot \dot{\alpha}$ is the radial velocity which is the horizontal velocity v_{hor}^{NED} (see equation 2.21). The second derivative reads as follows:

$$\ddot{\mathbf{x}} = \dot{v}_{hor}^{NED}\,\dot{\mathbf{e}}^x + v_{hor}^{NED}\,\ddot{\mathbf{e}}^x\,\dot{\alpha} \tag{2.26}$$

Since $\dot{v}_{hor}^{NED} = 0$ (unaccelerated flight) only the second term remains:

$$\ddot{\mathbf{x}} = v_{hor}^{NED} \cdot \begin{bmatrix} -\cos(\alpha) \\ -\sin(\alpha) \end{bmatrix} \cdot \dot{\alpha} \tag{2.27}$$

The taylor series finally is:

$$\mathbf{x}_{t_0+dt} = \mathbf{x}_{t_0} + v_{hor}^{NED}\,\dot{\mathbf{e}}^x\,dt + \frac{1}{2}\,v_{hor}^{NED}\,\dot{\alpha}\,\ddot{\mathbf{e}}^x\,dt^2 \tag{2.28}$$

2.4.5.2 Algorithm

The prediction algorithm for turning flight takes the same input as the one for the straight flight (see 2.4.4) and additionally the aircraft's yaw rate $\dot{\psi}$. This algorithm predicts the aircraft's path along a circular path using small segments of orthodromes. The result of the algorithm is again a vector containing the predicted positions. Again, the aircraft position $\varphi_{A/C}$,$\lambda_{A/C}$ serves as starting point. The algorithm uses a cumulated track angle ψ_c to accumulate the track angle change of each orthodrome segment.

INITIALIZATION:

$$\begin{aligned} \varphi_{pred_0} &= \varphi_{A/C} \\ \lambda_{pred_0} &= \lambda_{A/C} \\ \psi_c &= T_T \end{aligned} \tag{2.29}$$

FOR EACH PREDICTED POSITION i from 1 to N:

Calculate new center angle α and update cumulated track angle ψ_c:

$$\alpha = \psi_c - \frac{\pi}{2} \tag{2.30}$$
$$\psi_c = \psi_c + \dot{\psi}\,\Delta t_{pred}$$

Calculate the orthodrome segment:

$$\mathbf{dx} = \begin{bmatrix} dn \\ de \end{bmatrix} = v_{hor}^{NED} \cdot \begin{bmatrix} -\sin(\alpha) \\ \cos(\alpha) \end{bmatrix} \cdot \Delta t_{pred} - \frac{1}{2} \cdot v_{hor}^{NED} \cdot \dot{\psi} \cdot \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} \cdot \Delta t_{pred}^2 \tag{2.31}$$

Calculate the new predicted position:

$$\varrho = \frac{|\mathbf{dx}|}{R_{EARTH} + h_{A/C}} \tag{2.32}$$
$$\vartheta = \arctan(\frac{de}{dn}) \tag{2.33}$$
$$\varphi_{pred_i} = \varphi_{pred_{i-1}} + \arcsin(\varphi_{pred_{i-1}} \cos(\varrho) + \cos(\varphi_{pred_{i-1}}) \sin(\varrho) \cos(\vartheta)) \tag{2.34}$$

$$\lambda_{pred_i} = \lambda_{pred_{i-1}} + \arctan\left(\frac{\sin(\vartheta) \sin(\varrho) \cos(\varphi_{pred_{i-1}})}{\cos(\varrho) - \sin(\varphi_{pred_{i-1}}) \sin(\varphi_{pred_i})} \right) \tag{2.35}$$

As one can see, the small orthodrome segments are made of the previously introduced result vector of the taylor series (see equation 2.28). Note that it is important to use small enough time steps to yield accurate results. The yaw rate $\dot{\psi}$ is limited to a maximum

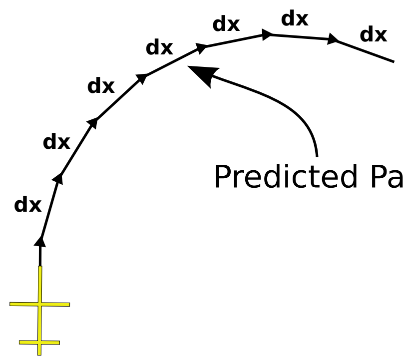


Figure 2.10: Turning Flight Prediction

yaw rate $\dot{\psi}_{max}$ to prevent inappropriate predicted flight paths. This is important since the horizontal search volume (see chapter 3) depends on the predicted positions.

2.4.6 Prediction Performance

The performance of the prediction is mainly influenced by three factors:

- Sensor Data Quality
- Wind
- Sampling Interval

2.4.6.1 Sensor Data Quality

The quality of the sensor data ultimately affects the quality of each predicted position. The quality of the current aircraft position, which is the starting point of the prediction, is of great importance. A typical TAWS installation uses a GPS and/or an IRS for determination of the current aircraft position. Typical values of position accuracies (95% confidence level) are 0.04 to 0.15 NM [8] for a system using GPS and IRS. As the predicted positions are the base for building the search volume (see chapter 3), the search volume considers the accuracy of the current aircraft position. Appropriate modification of the size and/or shape of the search volume will be made depending on the accuracy.

2.4.6.2 Wind Influence

Wind influences mainly the turning flight prediction. As the aircraft turns, it changes its heading and thus the influence of the wind on the ground track also changes. Figure 2.11 shows a 180° left turn from heading north (360°) to heading south (180°). The positions with and without wind are shown. One can clearly see the influence of the wind. It is remarkable that the distance between the final no wind (end of nominal 180° curve) and wind position (end of wind deformed ground track) is constant for different speeds. For the simulation of the wind influence a wind speed of 40 kt was chosen. This gives a distance of about 1.3 NM. Unfortunately wind information is not available in the TAWS. Therefore, the turning flight model does not consider any wind when predicting. However, the search space is normally large enough to compensate for the wind influence.

2.4.6.3 Sampling Interval

The sampling interval Δt_{pred} is chosen to be in balance with computational effort and effectivity. It should not introduce any errors due to insufficient spacing of the samples. The sampling interval should consider the resolution of the terrain database.

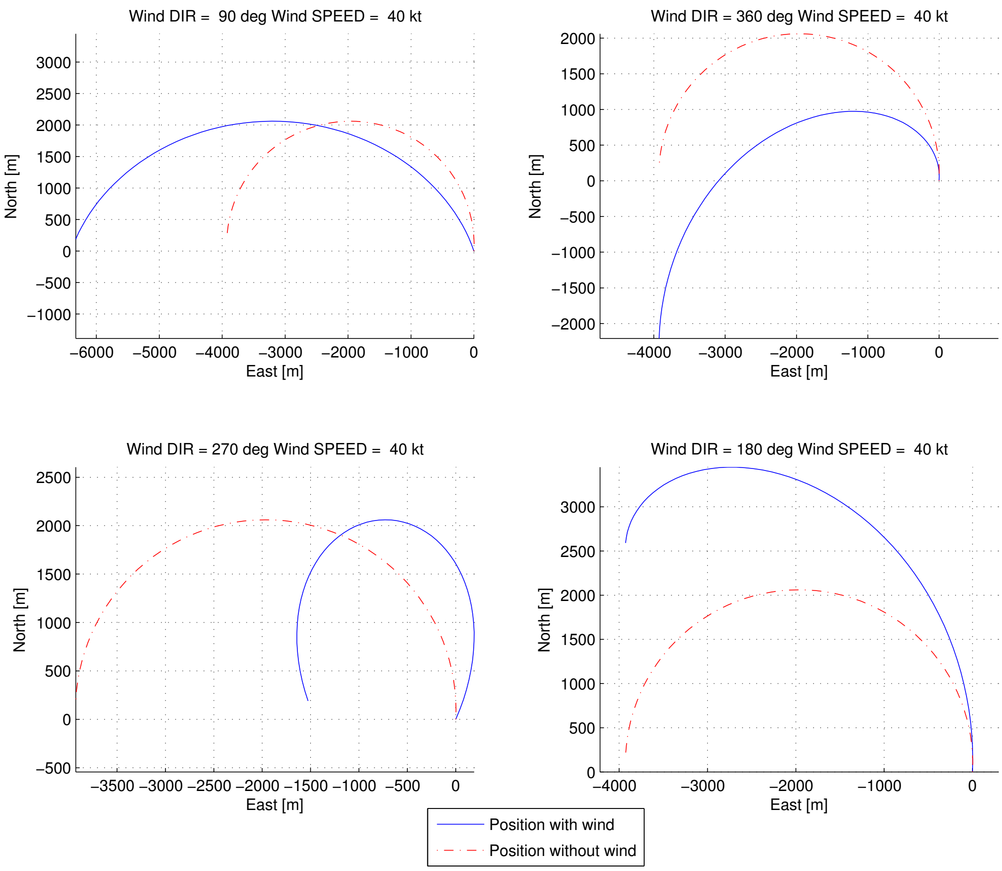


Figure 2.11: Wind Influence on a 180° left Turn from North to South, Aircraft Speed = 200 kt

3 Search Volume

3.1 General

A so-called “Search Volume” is needed, where the TAWS searches for a potential hazardous approach of the aircraft to terrain. The search volume is constructed ahead of the current aircraft position, along the predicted positions. It has a certain shape in the horizontal and vertical plane depending on various parameters. The volume is finally intersected with the terrain database. The result of the intersection is evaluated and alerts may be generated.

The TSO-C151b [15] states the following requirement:

> “The search volume consists of a computed look ahead distance, a lateral distance on both sides of the airplane’s flight path, and a specified look down distance based upon the airplane’s vertical flight path. This search volume should vary as a function of phase of flight, distance from runway, and the required obstacle clearance (ROC) in order to perform its intended function and to minimize nuisance alerts. The lateral search volume should expand as necessary to accommodate turning flight. The TAWS search volumes should consider the accuracy of the TAWS navigation source. The TAWS lateral search area should be less than the protected area defined by the United States Standard for Terminal Instrument Procedures (TERPS), FAA Handbook 8260.3B and ICAO PANSOPS 8168, volume 2, to prevent nuisance alerts.”

In accordance with the requirement above, this chapter provides the necessary steps to construct the search volume. The search volume is separated into a horizontal and a vertical envelope. Each envelope is subject to varying input parameters that will be examined in this chapter. The main and possibly most difficult objective when designing the search volume is the prevention of nuisance alerts. A nuisance alert is defined in TSO-C151b [15] as:

> “An inappropriate alert, occurring during normal safe procedures, that occurs as a result of a design performance limitation of TAWS.”

A nuisance alert will in most cases arise from the design of the search volume (other reasons may be errors in the terrain database for example). On the one hand, when the search volume is designed too large, it is prone to generate nuisance alerts, on the other hand, when the search volume is designed too small, it may discard real threats and thus no alert will be generated.

Testing of the search volume and detection of design limitations that may cause nuisance alerts is not easy. The large range of the varying input parameters, above all the aircraft position, and the resulting intersection with the terrain database anywhere on earth are elaborate.

3.2 Flight Phase Concept

The search volume requires to adapt to the current situation as the flight progresses. A flight undergoes different flight phases. For this reason, the TSO-C151b [15] defines a set of phases. The requirements and thus the search volume change depending on these phases. The phases are (in chronological order of a flight):

- Departure
- Enroute
- Terminal
- Approach

The definition of the phases is based on the distance to a runway in the vicinity of the aircraft position and the aircraft altitude. The TAWS must contain a flight phase logic to switch between these phases. As the phases depend on the distance to a runway in the vicinity, the TAWS searches for such runways. The runways are ordered by distance and a nearest runway is chosen for the flight phase logic. This search is treated separately in chapter 4.

The departure phase is defined from power-up of the system until the aircraft reaches 1500 ft above the departure runway (which is the nearest runway). The logic also has to determine whether the aircraft is airborne by using the ground speed and height above the departure runway. During the departure phase, the aircraft performs the initial climb.

The enroute phase is defined as when the aircraft is more than 15 NM away from the nearest runway or whenever the conditions for the other phases are not met. Since this definition is vague, the aircraft may be in climb, in cruise or in descent, having left the airway, towards the terminal area.

The terminal phase is defined as: The aircraft is within 15 NM of the nearest runway, the distance to this runway is decreasing and the aircraft altitude is below a certain altitude profile starting at the nearest runway. The altitude profile is defined to be 3500 ft above the nearest runway at 15 NM and then linearly decreasing to 1900 ft above the nearest runway at 5 NM. The aircraft in this flight phase is in climb on a standard instrument departure route or in descent on a standard arrival route respectively or rather on initial approach.

The approach phase is defined as when the aircraft is less than 5 NM away from the nearest runway, the distance to this runway is decreasing and the aircraft's height above the nearest runway is below 1900 ft. In this phase, the aircraft is on final approach.

3.3 Horizontal Envelope

The shape describing the search volume in the horizontal plane is called horizontal envelope. It changes its shape depending on the following parameters:

- Type of Flight (straight / curved)
- Flight Phase
- Aircraft Position Accuracy

Figure 3.1 illustrates the horizontal envelope. Basically, the shape of the envelope is trapezoidal for straight flight and tubular for turning flight. It is built based on the predicted positions and has a certain width, called basic across track width. The length of the envelope is determined by the LAD. The envelope splays at a certain lead angle to account for the parameters listed above.

The section TERPS / ICAO Requirements discusses the influence of airspace design on the envelope, the section ANP (Actual Navigation Performance) discusses the influence of the position accuracy on the envelope.

3.3.1 TERPS / ICAO Requirements

The TSO-C151b [15] requires that the search volume varies as a function of flight phase, based on requirements defined by TERPS and ICAO:

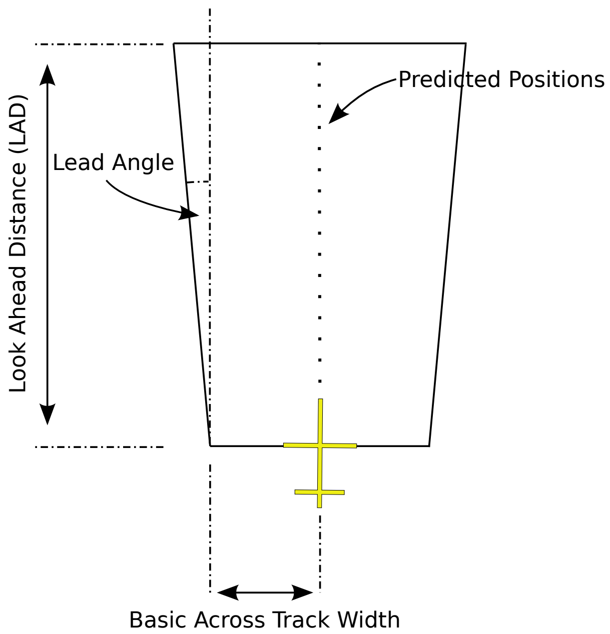
> "The TAWS lateral search area should be less than the protected area defined by the United States Standard for Terminal Instrument Procedures (TERPS), FAA Handbook 8260.3B and ICAO PANSOPS 8168, volume 2, to prevent nuisance alerts."

and

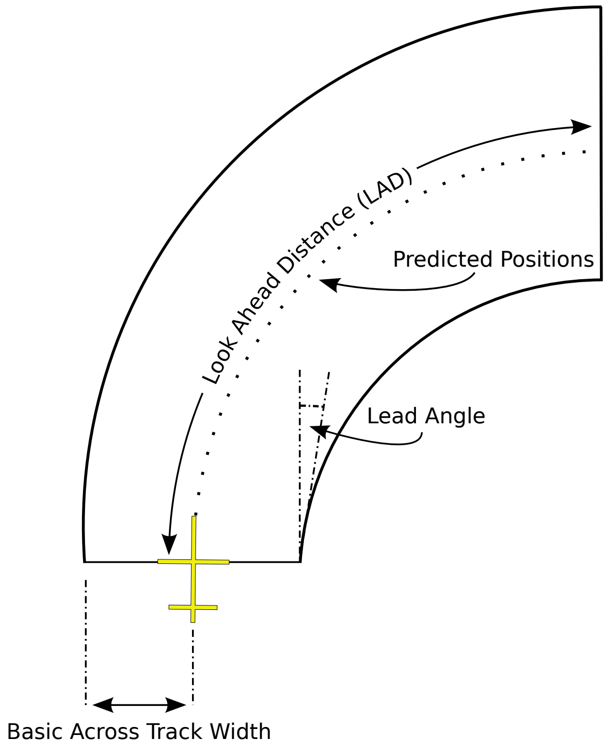
> "The TAWS equipment search volumes and alerting thresholds should vary as necessary to be compatible with TERPS and other operational considerations. For that reason, a set of definitions is offered for Enroute, Terminal, Approach and Departure Phases of Flight."

The FAA and ICAO have set up requirements for instrument and visual procedures. Instrument procedures are used to safely guide an aircraft flying under Instrument Flight Rules (IFR) through various phases of flight. Visual procedures using Visual Flight Rules (VFR) are used to safely visually guide an aircraft on the final segment of an approach to the runway. The requirements contain constraints on

- Obstacle and Terrain Clearance Altitudes
- Lateral Protection Areas against Terrain and Obstacles
- Navigation Aids Performance



(a) Horizontal Envelope for straight Flight



(b) Horizontal Envelope for curved Flight

Figure 3.1: Illustration of Horizontal Envelope

The FAA publishes the requirements through a "U.S. Standard for Terminal Instrument Procedures (TERPS)" [28], the ICAO through "ICAO DOC 8168 Aircraft Operations - Volume II: Construction of Visual and Instrument Flight Procedures" [23].

The protection of the aircraft from obstacles and terrain is the most important consideration. The ICAO defines a primary and a secondary area for obstacle clearance along any route that is part of an instrument procedure. The primary area is one half of the total width, located in the middle of the route. The secondary area is actually split into two parts, each spreading over one quarter of the total width, located at the side of the route. See figure 3.2 for an illustration. As one can see from figure 3.2, the primary area guarantees a Minimum Obstacle Clearance (MOC). In the secondary area, the MOC decreases from the full MOC to 0. The actual MOC values with respect to the design of the search volume are treated in 3.4.1. The total width varies as a function of the procedure that the route is part of. Procedures for departure, enroute, approach and arrival have different requirements for the lateral protection areas. There are too many considerations regarding the protection areas made in the ICAO DOC 8168 [23] in order to be fully discussed within this thesis. However, the minimum widths for departure, approach and enroute are given in the following sections.

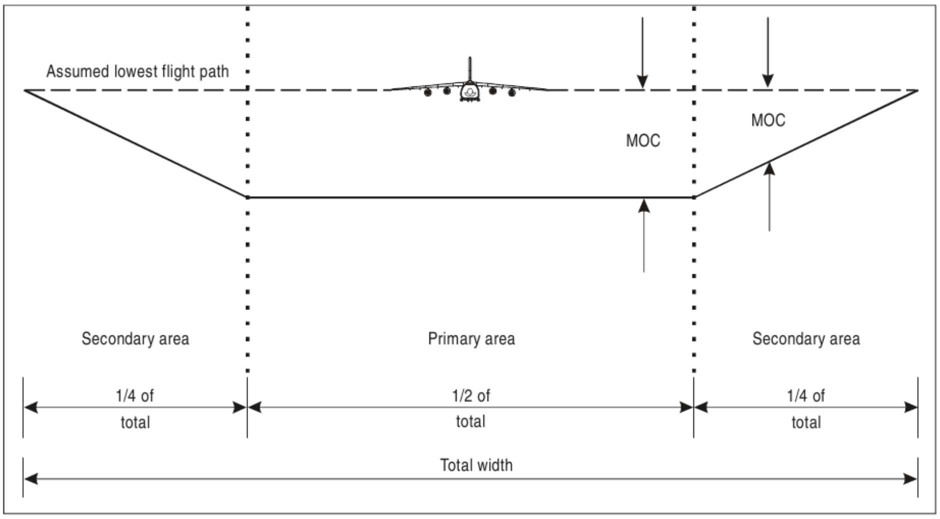


Figure 3.2: Route Obstacle Clearance (taken from ICAO DOC 8168 PANS-OPS [23])

3.3.1.1 Departure Requirements

For a straight departure without track guidance procedures, for example when the aircraft does not navigate along a track provided by a navigation facility as a VOR, the protection area begins at the Departure End of Runway (DER) with a total width of 300 m (0.16 NM) centered around the runway center line. It then splays at an angle of 15° on each side. This would give a total width of approx. 2.8 NM after 5 NM. See figure 3.3 for illustration.

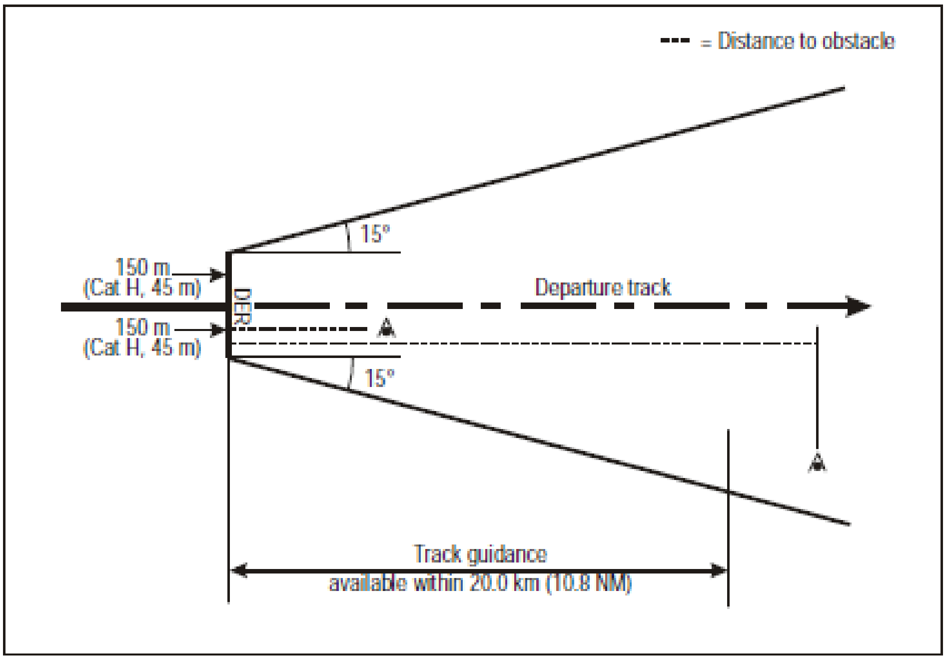


Figure 3.3: Straight Departure Without Track Guidance Area (taken from ICAO DOC 8168 PANS-OPS [23])

3.3.1.2 Approach Requirements

An instrument approach may have five separate segments (see figure 3.4):

- Arrival
- Initial Approach
- Intermediate Approach
- Final Approach
- Missed Approach

Each of the segments end at designated fixes and for each segment the ICAO DOC 8168 PANS-OPS defines its own area width. The initial approach width extends for 3.6 km (2.5 NM) laterally on each side of the track and ends at the Initial Approach Fix (IAF). The IAF may be defined by a VOR, NDB or RNAV waypoint, and for a VOR IAF for example has a width of 3.7 km (2.0 NM). The initial approach is succeeded by the intermediate approach. The width at the beginning of the intermediate approach is the width at the IAF. It then reduces linearly so as to match the width of the final approach at the Final Approach Fix (FAF). The width of the final approach at the FAF depends on the considerations made for different so-called “Obstacle Assessment Surfaces” (OAS). The OAS are used for assessing any obstacles within the final approach area. The surfaces start at the runway and the shape (e.g. lateral, longitudinal and vertical coverage) is defined by the ICAO DOC 8168 PANS-OPS (see page 330). It must be ensured that no obstacles penetrate the OAS. For example, the basic ILS surface

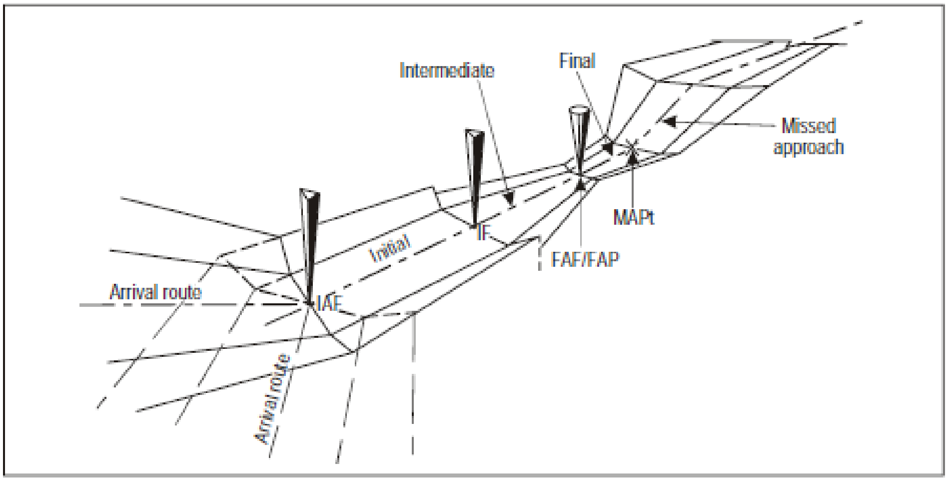


Figure 3.4: Approach Segments (taken from ICAO DOC 8168 PANS-OPS [23])

initially extends 150 m (0.08 NM) on each side of the runway and then splays out at 15% of the distance to a runway. This would give a width of 2.6 km (1.4 NM) on each side of the runway center line after 5 NM (see figure 3.5).

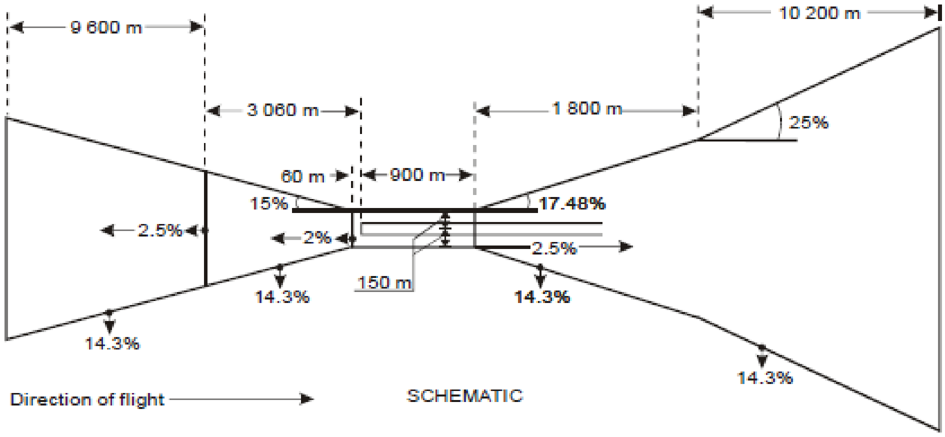


Figure 3.5: ILS Surface (taken from ICAO DOC 8168 PANS-OPS)

3.3.1.3 Enroute Requirements

For straight enroute legs between two navigation fixes that are less than 100 NM long, a primary area of 5 NM on either side of the leg is used.

3.3.2 ANP (Actual Navigation Performance)

The TSO-C151b [15] requires the consideration of the TAWS navigation source:

> "The TAWS search volumes should consider the accuracy of the TAWS navigation source."

Table 3.1: Typical HFOM Values, taken from [8]

Sensors	Range of HFOM Values
IRS/VOR/DME	0.50 - 1.65 NM
IRS/DME/DME	0.20 - 0.48 NM
IRS/GPS	0.04 - 0.15 NM

Table 3.2: Basic Across Track Widths

Flightphase	Basic Across Track Width
Departure	0.50 NM
Enroute	0.75 NM
Approach	0.25 NM

The accuracy of the horizontal position directly influences the shape of the horizontal envelope. Any position uncertainty should be compensated for by enlarging the area that is covered by the horizontal envelope. The accuracy of the horizontal position is expressed as HFOM. This value represents the 95% confidence in the horizontal position accuracy. Typical values for today's navigation systems are listed in table 3.1. The lead angle of the horizontal envelope is modified depending on the ANP.

3.3.3 Construction of the Envelope

The envelope is constructed using the predicted positions (see figure 3.6). At each predicted position, at a specific lateral distance left and right, a point on the envelope is calculated. At the aircraft position, this distance is the basic across track width. This lateral distance changes with respect to the longitudinal distance, which is the LAD, and a certain lead angle. The lead angle is used to extend the area of the envelope and to account for the position accuracy (ANP). The lead angle is increased when the ANP gets worse and thus leads to a larger area that is covered by the envelope. The area of the envelope is designed to be smaller than the associated current flight phase's protection area width by using the values of the basic across track width in table 3.2.

The envelope consists of a lists of points which are relative to the current aircraft position. The list constitutes a polygon. This polygon is later used for the intersection with the terrain database.

3.4 Vertical Envelope

The shape describing the search volume in the vertical plane is called vertical envelope. The vertical envelope is constructed starting at the current aircraft position and proceeding ahead of the aircraft until a certain distance is reached.

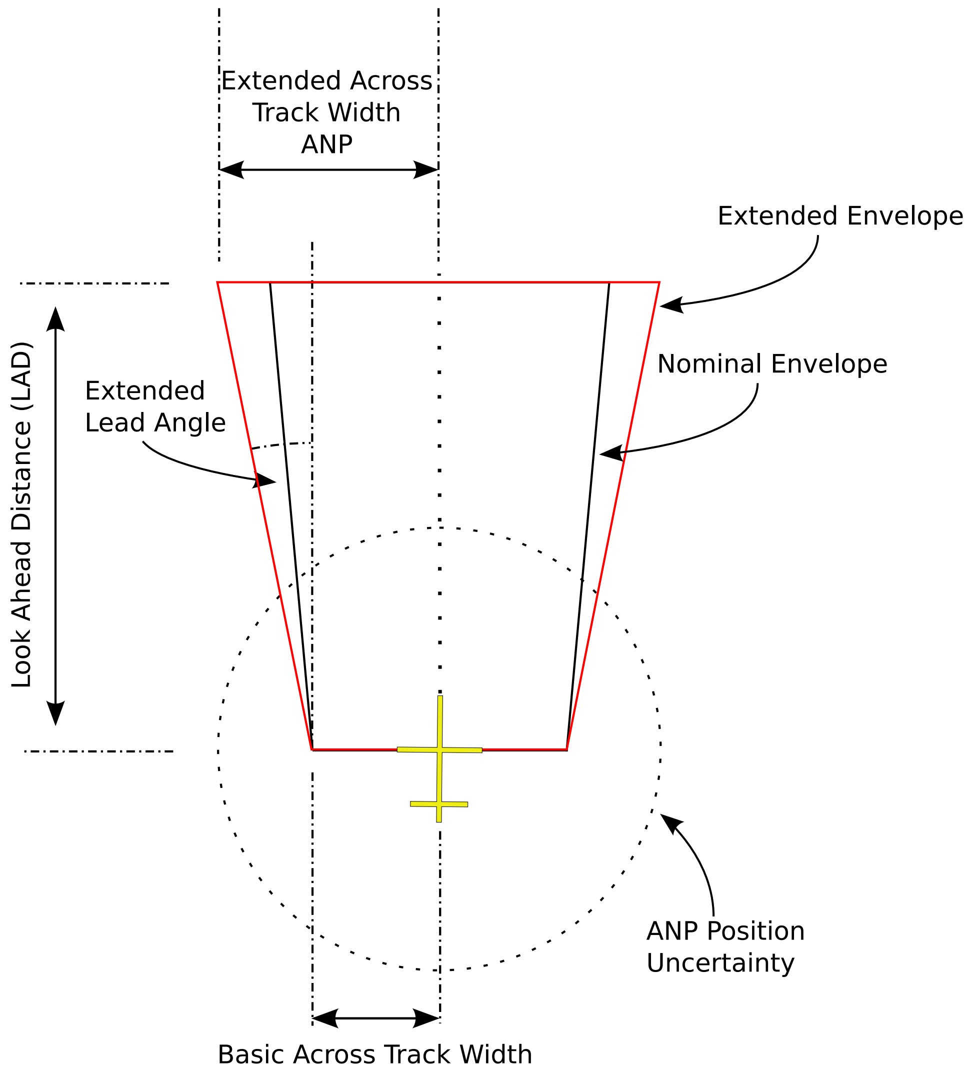


Figure 3.6: Horizontal Envelope modified with respect to ANP

The design depends on the following parameters:

- Flight Phase
- Flight Path Angle
- Alert Type

All of the dependencies listed above are derived from the requirements stated in TSO-C151b [15]. This document lists minimum terrain clearances depending on the flight phase. The vertical envelope must consider these clearances. As the clearances and/or the flight path angle changes, the envelope changes accordingly. The document also distinguishes between caution and warning alert and lists different minimum terrain clearances for each type. Therefore, a caution and a warning envelope for the respective alert exists.

Section TSO-C151b Requirements discusses two concepts listed in TSO-C151b [15] of how an aircraft may undershoot a minimum safe height. The actual construction of the

Table 3.3: TAWS RTC by Flightphase (taken from TSO-C151b [15, table 3.1]

Flightphase	**ROC**	**TAWS (RTC) Level Flight**	**TAWS (RTC) Descending**
Enroute	1000 ft	700 ft	500 ft
Terminal (Intermediate Segment)	500 ft	350 ft	300 ft
Approach	250 ft	150 ft	100 ft
Departure	48 ft/NM	100 ft	100 ft

envelope is discussed in section 3.4.2.

3.4.1 TSO-C151b Requirements

The requirements listed in TSO-C151b [15] basically define two scenarios of how an aircraft may undershoot a minimum safe height above terrain. The first scenario or concept is the so-called "Reduced Required Terrain Clearance" (RTC) [15, sect. 3.1.1], the second one is the so-called "Imminent Terrain Impact" (ITI) [15, sect. 3.1.2]. The construction of the vertical envelope must consider both concepts. As described in the following section, the concepts may be combined.

3.4.1.1 RTC (Reduced Required Terrain Clearance) Concept

The RTC concept considers the case when the aircraft is currently above the terrain but the amount of terrain clearance at some position along the flight path is considered unsafe for the particular flight phase. In figure 3.7 you can see an illustration of the RTC concept. The aircraft on the left is flying level, the flight path is horizontal. A certain offset distance below and always parallel to the flight path, a margin line is established. The offset distance is the required terrain clearance (RTC). The definition of the required terrain clearance is listed in the TSO-C151b [15] and is derived from the TERPS Required Obstacle Clearances (ROC, see also 3.3.1), which considers airspace design. The RTC and ROC depend on the flight phase and on the question whether the aircraft is flying level or descending. The exact values are listed in table 3.3. As one can see from table 3.3, the values for the RTC are slightly reduced so as to be lower than those for the ROC. The values for the ROC are associated with the caution envelope and the values for the RTC are associated with the warning envelope. The reduction leaves a margin between the minimum obstacle clearance from airspace design and the required terrain clearance that is used. This margin serves to desensitize the generation of alerts. Furthermore, the values for descending flight are lowered in order to prevent nuisance alerts in the case of the pilot performing a level off.

In the situation depicted in figure 3.7, the aircraft at its present position is safe above terrain and clears any terrain by a vertical distance of at least the RTC. However, if it continues to fly level, it will violate the RTC at some point along the flight path because

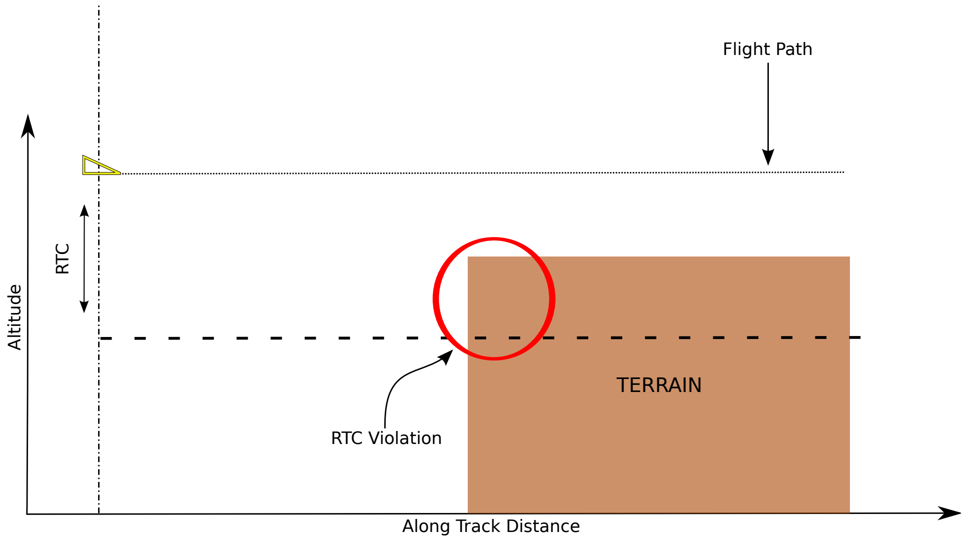


Figure 3.7: Reduced Required Terrain Clearance Concept

of the terrain that lies ahead and beneath.

3.4.1.2 ITI (Imminent Terrain Impact) Concept

The ITI concept considers the case when the aircraft is currently below the terrain but the amount of terrain clearance at some position along the predicted flight path is considered unsafe for the particular flightphase. The required amount of terrain clearance used here is the RTC for level flight (see table 3.3). In figure 3.8 an illustration of the ITI concept can be seen. The aircraft on the left is currently below any terrain, the flight path is slightly climbing. At a certain offset distance below the aircraft and at a certain angle, the ITI-angle, a margin line is established. The offset distance is the RTC. The ITI angle is at least the flight path angle of the minimum climb performance of the aircraft. However, when the current flight path angle becomes larger than the minimum climb performance flight path angle, the ITI angle becomes the current flight path angle. This is the main difference between the RTC and the ITI concepts: The margin line in the case of the ITI is not necessarily parallel to the flight path, whereas in the case of the RTC, the margin line is always parallel to the flight path.

In the situation depicted in figure 3.8, the aircraft at its present position is safe above any terrain but below some terrain that lies ahead of it. If it continues to fly along the present predicted flight path it will violate the RTC at some point because of the terrain that lies ahead and above.

3.4.1.3 The Pull-Up Maneuver

Once the flight crew receives a caution or warning alert, they may take immediate action. Possible actions comprise a vertical or horizontal escape maneuver. In the case of the vertical maneuver a so called “Pull-Up” is executed (see figure 3.9). The pull-up maneuver is initiated by pulling on the elevator control. The pulling is done with a

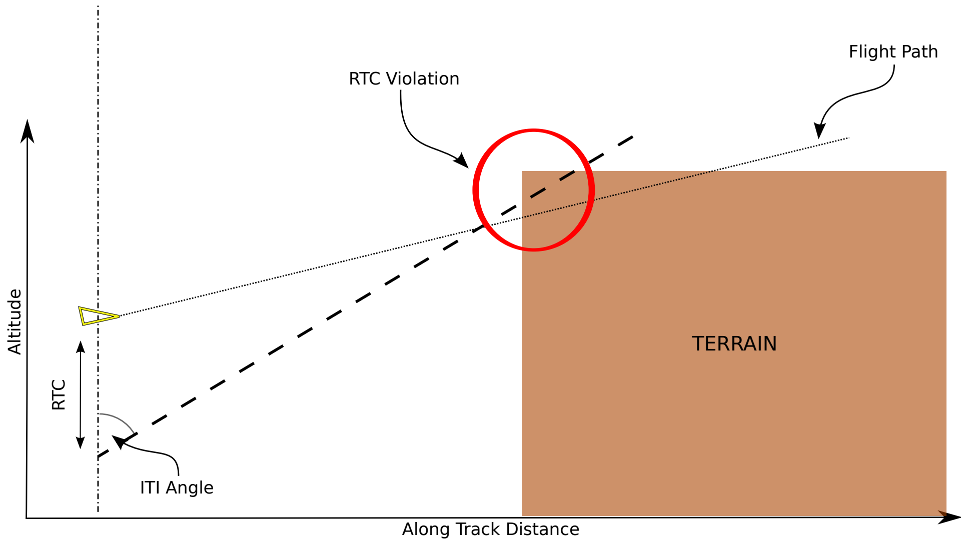


Figure 3.8: Imminent Terrain Impact Concept

certain load factor. The load factor is the vertical acceleration that acts on the aircraft and depends on the magnitude of the pull on the elevator control. Typically, the pilot should not exceed a pull of 1.25 G. During the pulling the flight path angle increases and the aircraft begins to climb. The pulling is stopped when the TAWS cancels the alert or when a maximum flight path angle is reached. The maximum flight path angle during such a pull-up maneuver depends on various factors, the most important one being the airspeed. Under no circumstances, a safe airspeed, i.e. one that is well above the stalling airspeed must not be undershot.

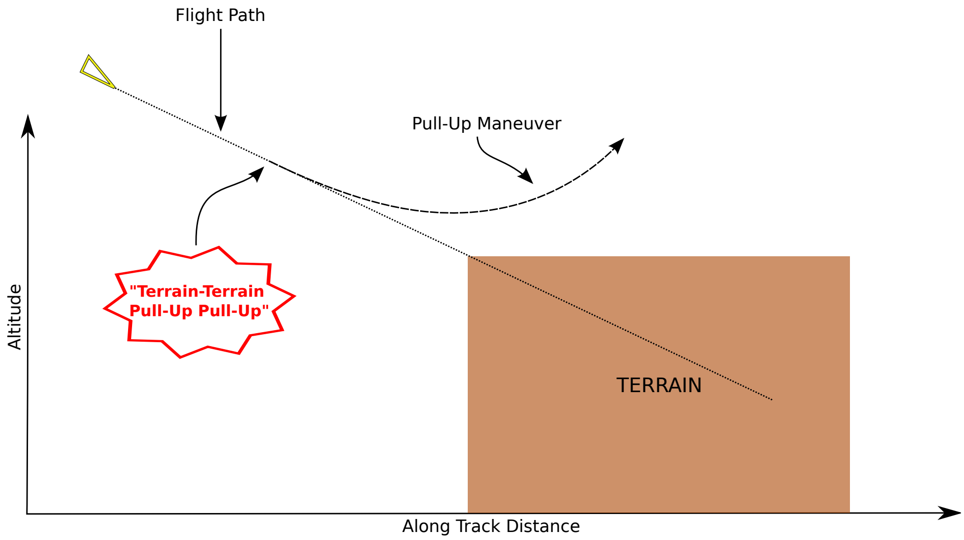


Figure 3.9: Pull-Up Maneuver

3.4.2 Construction of the Envelope

The final envelope is constructed out of a combination of both of the aforementioned concepts. The combination of the two concepts yields optimal protection: By using the RTC concept, the aircraft is protected against terrain threats that lie beneath the current aircraft altitude. By using the ITI concept, the aircraft is protected against terrain threats that lie above the current aircraft altitude. A dedicated envelope is constructed for both the caution alert and the warning alert. The caution envelope has, in principle, a larger extent since a caution alert precedes a warning alert.

The construction and thus the shape of the envelope is not static. It depends on various factors, the most important ones being the ground speed and vertical speed (which determine the flight path angle γ). Furthermore, the flight phase and the accuracy of the used input data play an important role. Note that the following construction examples employ "perfect data". In a concrete implementation of a TAWS, the construction is slightly modified to incorporate the accuracy of the input data.

The test cases given in TSO-C151b [15, Appendix 3, chap. 2 and 3] directly influence the construction of the envelope. They discriminate between different flight phases as well as between descending and level flight. To fulfill the requirements of the TSO-C151b, it must be shown that the test results of the TAWS implementation correspond with the expected results.

3.4.2.1 RTC Protection in Level Flight

According to TSO-C151b [15], level flight is defined as when the aircraft having a vertical speed that is within -500 feet/minute to +500 feet/minute. An example envelope for level flight that provides the RTC concept is shown in figure 3.10. Two envelopes are established:

- Warning Envelope (red envelope)
- Caution Envelope (amber envelope)

Both envelopes start at the aircraft position and extend vertically by the RTC value. The vertical extent of the envelope is called warning floor for the warning envelope and caution floor for the caution envelope respectively. The RTC value depends on the flight phase (see table 3.3). The warning envelope extends horizontally, parallel to the flight path, until the so-called "Warning Look Down Distance" is reached, the caution envelope until the so-called "Caution Look Down Distance" is reached. The warning look down distance is always calculated as: $0.5 \cdot \text{LAD}$ whereas the caution look down distance is calculated as $1 \cdot \text{LAD}$.

3.4.2.2 RTC Protection in Descending Flight

According to TSO-C151b [15], descending flight is defined as the aircraft having a vertical speed that is less than -500 feet/minute. In figure 3.11 an example envelope for

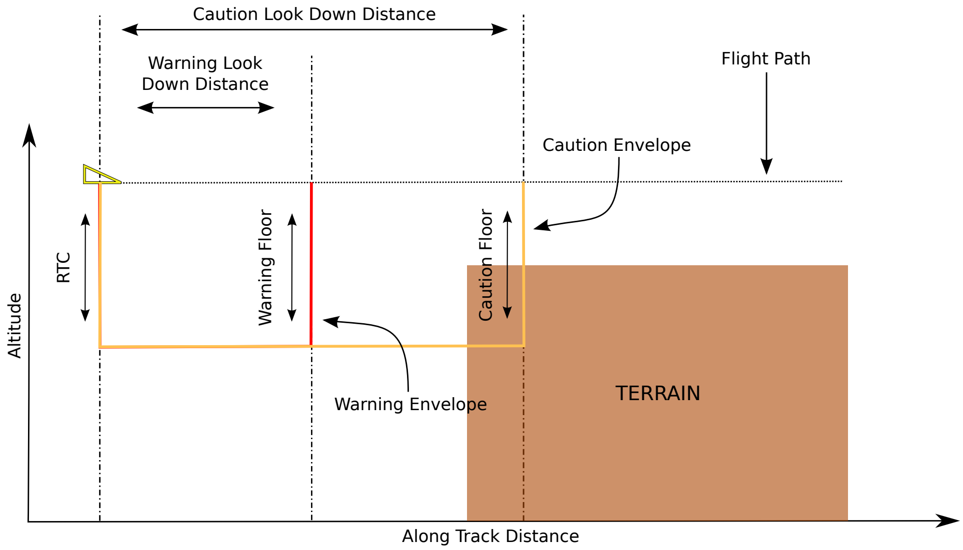


Figure 3.10: RTC Protection in Level Flight

descending flight is shown. As for the level flight case, a dedicated envelope for both warning (red) and caution (amber) is established. As can be seen from the figure, the envelopes again start at the aircraft position and reach down to the RTC value, then continue parallel to the flight path until reaching the warning or the caution floor respectively. When the corresponding floor is reached, the envelope continues horizontally to either the warning or the caution look down distance respectively.

The calculation of the caution and the warning floor plays an important role. As one can see from figure 3.11, the point in time of penetration of the envelope is determined mainly by the vertical extent of the floors. When comparing this to the situation during level flight (figure 3.10), one can see that there the penetration is determined mainly by the LAD and thus by the horizontal extent of the envelope. The alerting criterion that is bound to the LAD, which considers horizontal escape maneuvers, therefore has to be complemented by vertical criteria that directly influence the vertical extent of the floors.

The requirements for the floors are derived from test cases for descending flight described in TSO-C151b [15, Appendix 3, chap. 2 and 3]. As an example the test case for enroute descent is considered here (TSO-C151b [15, Appendix 3, chap. 1.2, Enroute Descent Requirement]). The main requirement of this test case is to ensure that the TAWS issues a warning alert that make sure that the crew can react early enough and level the aircraft off with a minimum of 500 ft altitude clearance above the terrain, which is the value for the RTC for enroute descending (see table 3.3). This requirement must be fulfilled within the operational flight envelope of the aircraft (operational range of vertical and ground speed). Therefore, the test case contains a table (see TSO-C151b [15, Appendix 3, chap. 1.2, Table A]) that defines the minimum height above terrain when a warning alert must occur and the maximum height above terrain when a caution alert may occur (see table 3.4).

Figure 3.12 illustrates the calculation of the warning floor. After receiving the warning alert, the crew may (in the worst case) not respond to the alert immediately. Therefore,

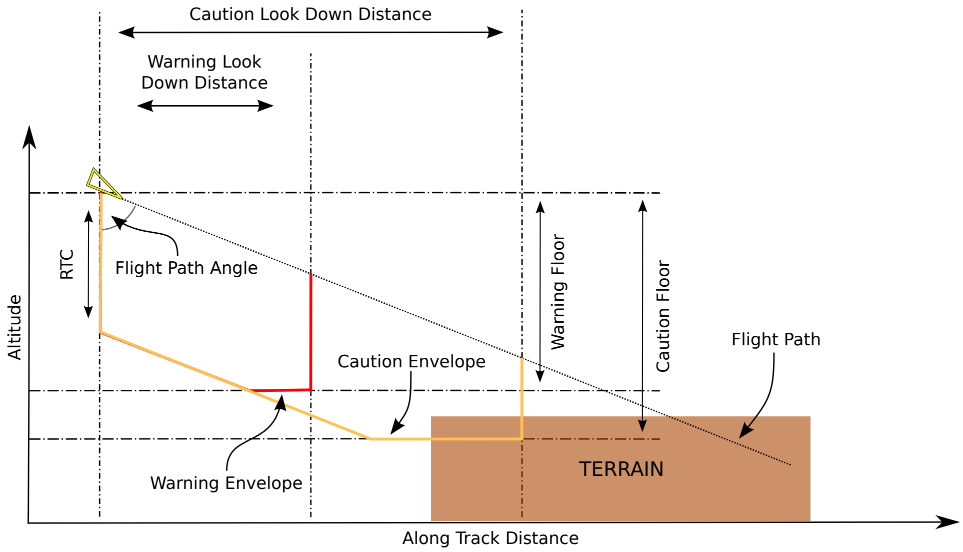


Figure 3.11: RTC Protection in Descending Flight

Table 3.4: Enroute Descent Requirements

Vertical Speed [ft/min]	Minimum Warning Alert Height (above terrain) [ft]	Maximum Caution Alert Height (above terrain) [ft]
1000	567	1200
2000	669	1400
4000	978	1800

the test assumes a response time ($t_{Response}$) of 3 seconds. This yields, using the current vertical speed v_d, the altitude lost due to pilot delay:

$$h_{Pilot} = v_d \cdot t_{Response} \tag{3.1}$$

When 3 seconds have elapsed, the crew starts the pull-up maneuver. The pull-up maneuver assumes a constant acceleration of 0.25 G until level flight (0 feet/minute vertical speed) is established. To calculate the altitude lost during the pull-up maneuver a constant acceleration motion in the vertical plane is assumed. The distance x traveled during a constant acceleration motion is defined as follows (a being the acceleration and t time):

$$x = \frac{1}{2} \cdot at^2 \tag{3.2}$$

After eliminating time and introducing velocity v, it reads:

$$x = \frac{1}{2} \cdot \frac{v^2}{a} \tag{3.3}$$

Finally the altitude lost during the pull-up maneuver to level flight is calculated as follows:

$$h_{Pull-Up} = \frac{1}{2} \cdot \frac{v_d^2}{(0.25 \cdot G)} \quad (3.4)$$

The main requirement was to level off at 500 ft (the value for the RTC). Therefore, both altitude losses plus the RTC value yields the warning floor:

$$h_{Warn\,Floor} = RTC + h_{Pilot} + h_{Pull-Up} \quad (3.5)$$

This warning floor guarantees that the warning envelope penetrates the terrain when the crew still has the chance to pull-up and level the aircraft off. This calculation method for the warning floor adheres to the required values for the minimum warning alert height above terrain (see TSO-C151b [15, Appendix 3, chap. 1.2, Table A] or table 3.4).

The calculation of the caution floor is similar. Instead of using the RTC, the ROC is used.

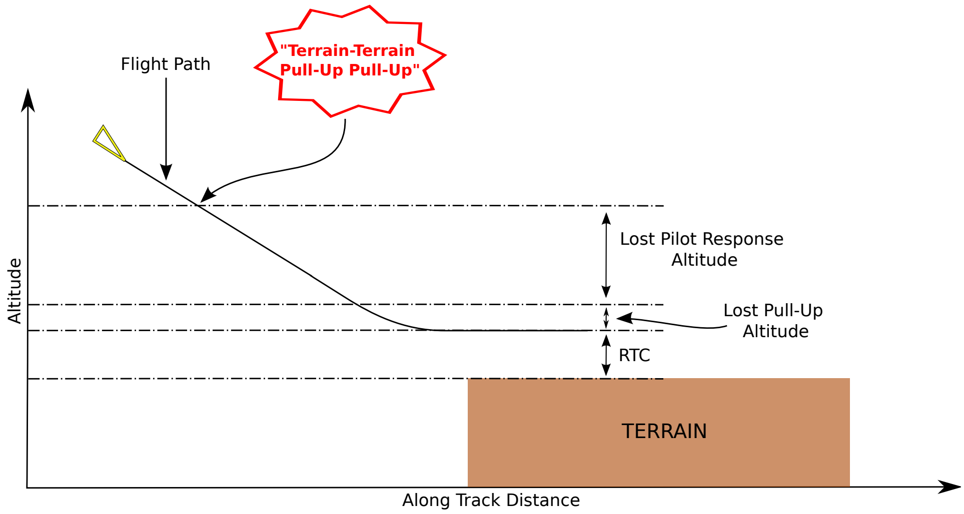


Figure 3.12: Floor Calculation

3.4.2.3 ITI Protection

As explained in section 3.4.1.2, the ITI concept protects the aircraft against terrain threats that lie above the current aircraft altitude. The ITI protection must work for any kind of flight, so for descending as well as for level and climbing flight. The test cases for the ITI protection are described in TSO-C151b [15, Appendix 3, chap. 2]. In figure 3.13 one can see the basic constitution of the envelope. Again, an envelope for both warning and caution exists. The warning envelope extends horizontally until the so-called “Warning Look Up Distance” is reached, the caution envelope until the so-called “Caution Look Up Distance” is reached. The look up distances look beyond the look down distances and are therefore typically $1.3 \cdot$ LAD for the warning and $1.5 \cdot$ LAD for the caution envelope. The altitude where the envelope starts is determined by the climb out floor. The slope is determined by the ITI-Angle.

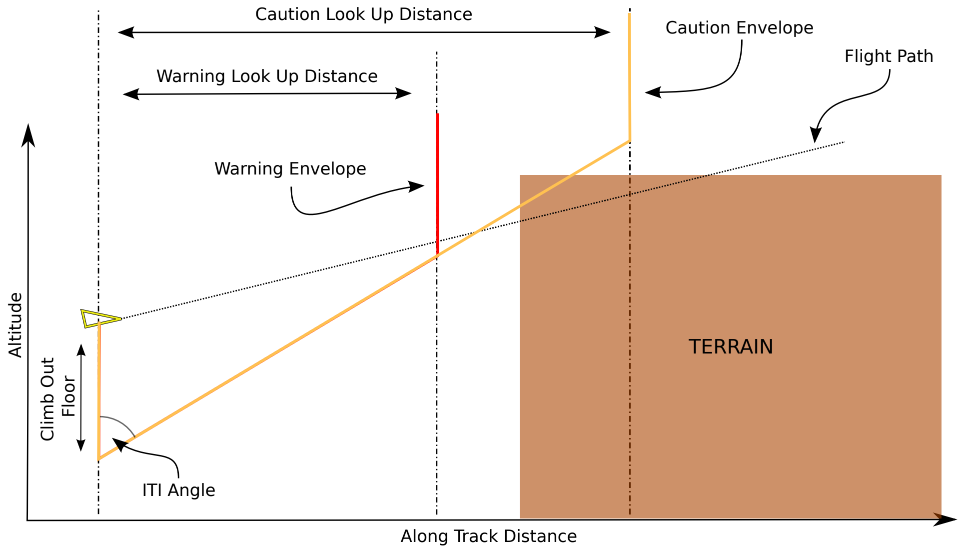


Figure 3.13: ITI Protection

The envelope in the vertical plane is constructed in order to model a vertical escape maneuver. The constraints for this maneuver are stated in the test case. A pilot delay of one second and a succeeding 0.25 G incremental pull to a constant 6.0 degree climb gradient ($\gamma_{desired}$) are required. As long as the aircraft has not reached the 6.0 degree climb gradient, the altitude lost until the gradient is established is of importance (see figure 3.14).

In case the aircraft descends (position A in figure 3.14, vertical speed less than -500 feet/minute), the gross altitude lost is the pilot delay (see equation 3.1) plus the pull-up (see equation 3.4). However, equation 3.4 only applies for pull-up to level flight. The altitude lost for reaching the desired 6.0 degree climb gradient is calculated very similar to equation 3.4, however the desired vertical speed for the 6.0 degree climb gradient is used. The desired vertical speed can be calculated from equation 2.3:

$$v_{desired} = \sin \gamma_{desired} \left\| \mathbf{v}^{NED} \right\| \tag{3.6}$$

The gross altitude lost using equation 3.4 once for the pull-up to level flight and then for the pull-up to the desired climb rate, assuming both a 0.25 G acceleration, then is:

$$h_{Pull-Up\,Descend} = \frac{1}{0.5 \cdot G} \cdot \left(v_d^2 + v_{desired}^2 \right) \tag{3.7}$$

Note that figure 3.14 shows a situation where the aircraft's current vertical (descent) speed is the same in magnitude as the desired vertical (climb) speed. This yields a parable.

When the aircraft is in level flight (position B in figure 3.14, vertical speed within -500 feet/minute to +500 feet/minute), only the pull-up for attaining the 6.0 degrees climb gradient is considered. Thus, the required pull-up to the desired vertical speed is used as altitude lost:

$$h_{Pull-Up\,Level} = \frac{1}{2} \cdot \frac{v_{desired}^2}{(0.25 \cdot G)} \tag{3.8}$$

In case the aircraft climbs (position C in figure 3.14, vertical speed is larger than 500 feet/minute) and does not have a climb gradient of 6.0 degree, the difference between the desired and the actual vertical speed is taken for calculating the altitude lost:

$$h_{Pull-Up\,Climb} = \frac{1}{2} \cdot \frac{(v_{desired} - v_d)^2}{(0.25 \cdot G)} \tag{3.9}$$

When the aircraft's actual vertical speed exceeds the desired vertical speed no altitude loss is calculated.

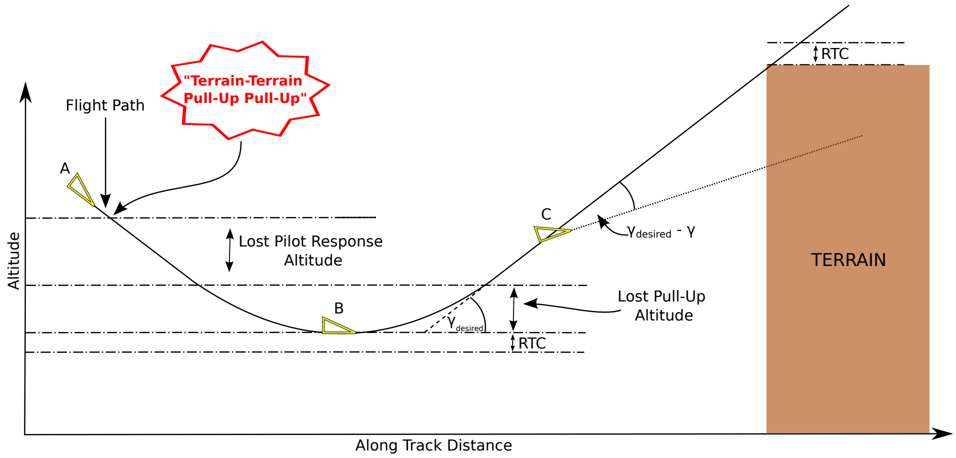


Figure 3.14: Climb Out Floor Pull-Up

Finally, the climb out floor is calculated considering the altitude lost for pilot delay of one second and for attaining the desired climb gradient. The RTC is added in case of the warning envelope or the ROC in case of the caution envelope. Adding one of these values has the aim of protecting the aircraft from undershooting the terrain clearance either by the RTC or the ROC. Again, the warning envelope is considered in the following floor calculations.

In case the aircraft is in level flight (see figure 3.15, position B), the climb out floor is calculated as:

$$h_{Climb\,Out\,Floor\,(Level)} = RTC + h_{Pull-Up\,Level} + h_{Pilot\,Level} \tag{3.10}$$

The altitude lost due to pilot delay ($h_{Pilot\,Level}$) is the altitude that would have been gained if the aircraft had climbed with the desired climb gradient for one second. Adding the pull-up altitude to the RTC means the following: The aircraft has not reached the desired climb gradient and is therefore always lower than when flying with the desired climb gradient. Figure 3.15 illustrates the floor and the envelope (red path). The figure shows that the envelope penetrates the terrain and would finally cause a warning.

In case the of the aircraft descending, the climb out floor calculation is based on the calculation for the level flight. As one can see in figure 3.15, position B is the position where the aircraft is leveled off. Equation 3.10 shows how to calculate the climb out floor at this position. At this position, the aircraft still has not reached the desired climb gradient. Going further back to position A, the aircraft is still in descent and has not even leveled off. This means that the aircraft is always lower than when flying with the desired climb gradient until the desired climb gradient is reached. The time needed to reach the desired climb gradient is even longer than in the case of the level flight. This means that the aircraft has a negative altitude budget that consists of the $h_{Pull-Up\,Descend}$ and $h_{Pilot(Descent)}$. $h_{Pilot(Descent)}$ is defined here as the altitude lost when the aircraft descends with the current vertical speed for one second. Note that this is a different definition than in the case of the level flight. The climb out floor in case the aircraft descends is finally calculated as follows:

$$h_{Climb\,Out\,Floor\,(Descent)} = RTC + h_{Pull-Up\,Level} + h_{Pull-Up\,Descent} + h_{Pilot(Descent)} \quad (3.11)$$

When the aircraft climbs, the floor is calculated as:

$$h_{Climb\,Out\,Floor\,(Climb)} = RTC + h_{Pull-Up\,Climb} + h_{Pilot(Climb)} \quad (3.12)$$

The altitude lost due to pilot delay ($h_{Pilot(Climb)}$) is defined here as the altitude that would have been gained if the aircraft had climbed with a climb rate of $v_{desired} - v_d$. When the climb rate is equal to or exceeds the desired climb rate, $h_{Pilot(Climb)}$ and $h_{Pull-Up\,Climb}$ is set to zero, thus setting the floor equal to the RTC (see position C in figure 3.15).

The envelope is then established starting from the aircraft altitude and going down the distance of the respective climb out floor. From this point, a slope with an angle corresponding to the ITI-angle is established. The ITI-angle depends on the desired climb gradient $\gamma_{desired}$ and the current climb gradient γ. If the current climb gradient exceeds the desired climb gradient, the ITI-angle is calculated as follows:

$$\text{ITI-angle} = 90 - \gamma \quad (3.13)$$

otherwise:

$$\text{ITI-angle} = 90 - \gamma_{desired} \quad (3.14)$$

As one can see in figure 3.15, the construction of the envelope in this manner ensures protection in each case (Position A (Descend), Position B (Level), Position C (Climb)). In each case the envelope would penetrate the terrain and thus cause a warning.

The construction of the caution envelope is similar. Instead of the RTC, the ROC is used.

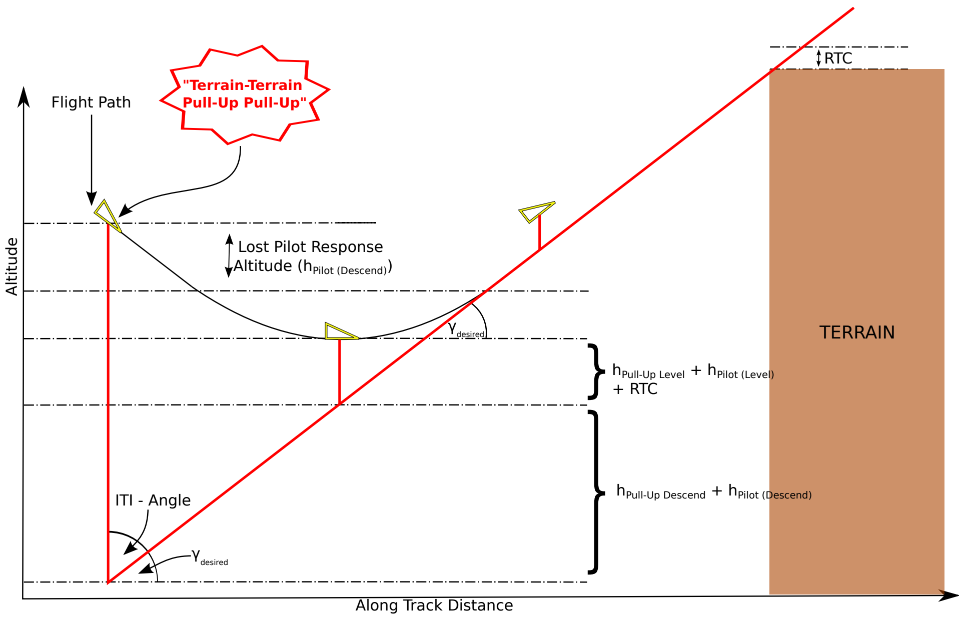


Figure 3.15: ITI Envelope

3.4.2.4 Combination of RTC and ITI Protection

Finally, both concepts are combined into a common envelope. This envelope provides the desired protection against any kind of terrain threats that lie below and/or above the current aircraft altitude. As previously mentioned, the envelope is not static and depends on the following factors/parameters:

- Vertical Speed and Ground Speed (which determine the flight path angle γ)
- Flightphase
- Desensitization
- Accuracy of input data

The envelope is defined by the points labeled A-H (see figure 3.16) that are continuously calculated with respect to the above mentioned parameters. With this definition by points (which yields a path), one can easily calculate the altitude of the envelope at any point ahead of the aircraft. This will be important for the terrain-search volume intersection.

In figures 3.16, 3.17 and 3.18 one can clearly see the difference in the envelope during different types of flight. The main steering (and most changing) parameter is the flight path angle. As this angle decreases, the space below the aircraft is of more importance as opposed to the level or climbing flight.

The flight phase mainly controls how sensitive the system should be by changing the minimum terrain clearance distance (RTC and ROC). The more sensitive it should be, the larger the vertical extent is. As the flight phase mainly depends on the distance to the nearest runway (see also 3.2), the volume gets smaller as the aircraft approaches a runway and larger as the aircraft departs a runway.

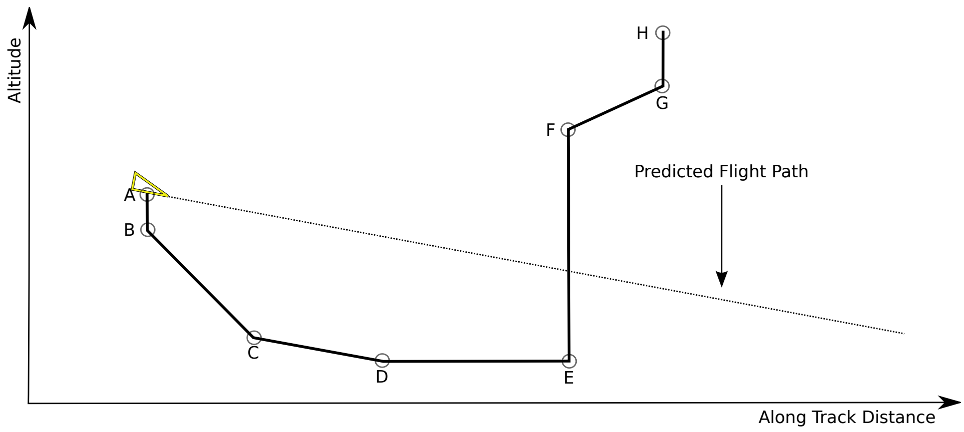


Figure 3.16: Example of the combined Envelope during descending Flight

As the aforementioned concepts use perfect input data, the real envelope has to be desensitized and adapted with respect to the accuracy of the input data. Desensitization takes places especially near the aircraft by shifting the envelope or parts of it upwards. Adaption with respect to the accuracy of the input data happens by shifting the envelope or parts of it downwards.

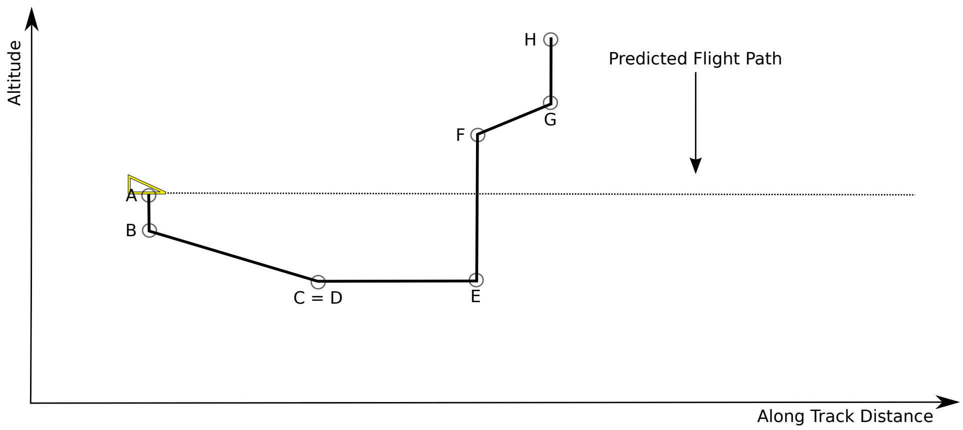


Figure 3.17: Example of the combined Envelope during level Flight

3.5 Combination of horizontal and vertical Envelope

Having examined the horizontal and the vertical envelope separately, both envelopes are now combined to build a volume. This volume is used as a so-called "Search Volume" to search for terrain that penetrates this volume. The search volume is separated in the horizontal plane by a closed polygon (see 3.3.3) and in the vertical plane by an open path (see 3.4.2.4). See figure 3.19 for illustration. As there are dedicated vertical envelopes for both the caution and the warning alert, a dedicated search volume for each envelope also exists.

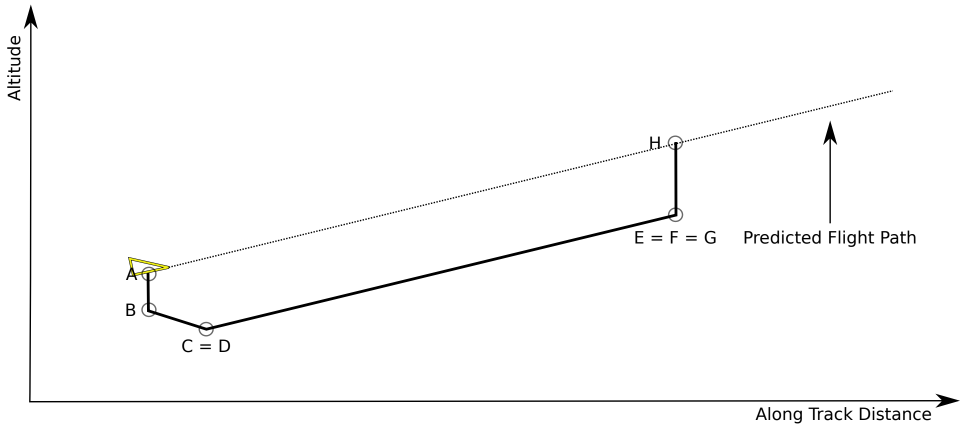


Figure 3.18: Example of the combined Envelope during climbing Flight

3.5.1 Modeling the Volume

One approach would be to model the volume by taking all points that enclose the volume (see figure 3.20). This approach models the volume exactly. However, for calculation of an intersection with the terrain, the model must be divided into smaller volumes (e.g. cubes or other geometric volumetric primitives) to apply standard point in volume testing. The division can be seen on the right hand side in the figure. One drawback of this approach is that the division must constantly adapt to the shape of the envelope. The division might work for simple combinations of the horizontal and the vertical envelope. However, if the horizontal envelope becomes curved (see figure 3.1(b)) or the vertical envelope is subject to change (see figures 3.16, 3.17 and 3.18) the division will not work. To overcome this problem, the volume is finally not modeled as groups of volumes, but rather sampled at certain positions. At the sampled positions, a query for the height of the envelope takes place. This procedure is dealt with in chapter 5 since it is closely related to the intersection of the search volume with the terrain.

3.5.2 Examples

For the sake of completeness, some details on the dimensions of the volume are given (see figure 3.21 for explanation of measures) here. Note that these measures are taken

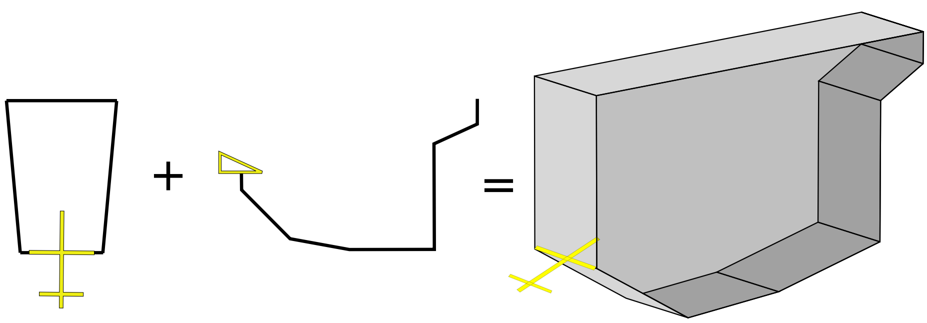


Figure 3.19: Combination of horizontal and vertical Envelope

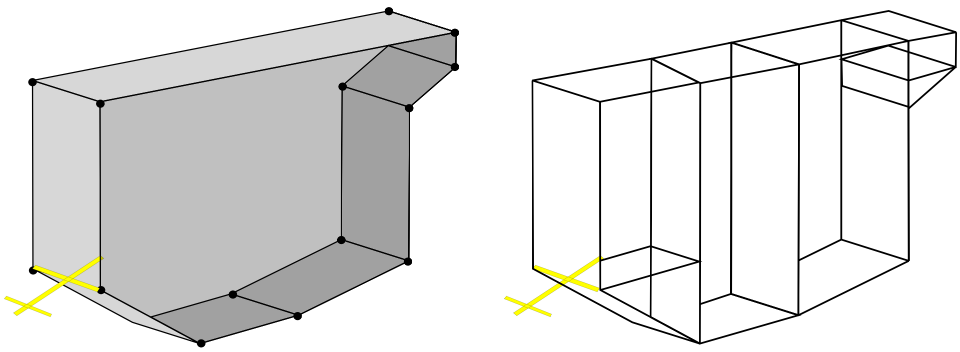


Figure 3.20: Search Volume defined by Points (left) and Division (right)

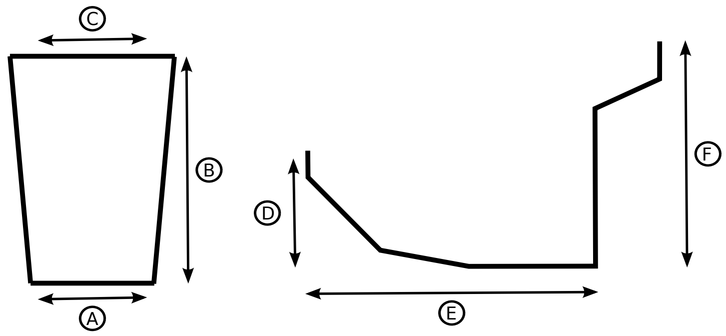
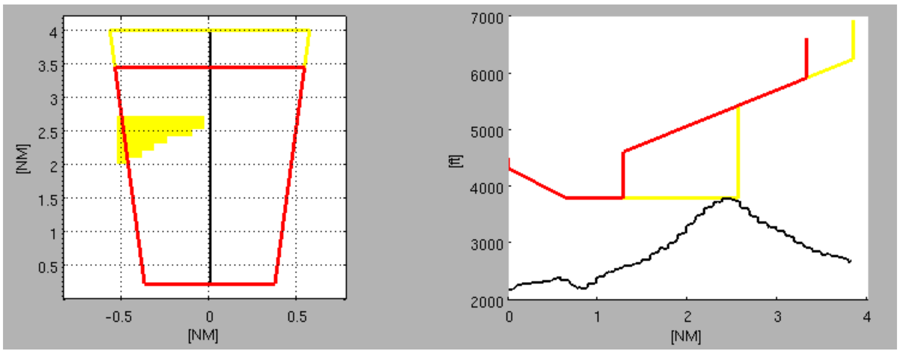


Figure 3.21: Annotation of Measures

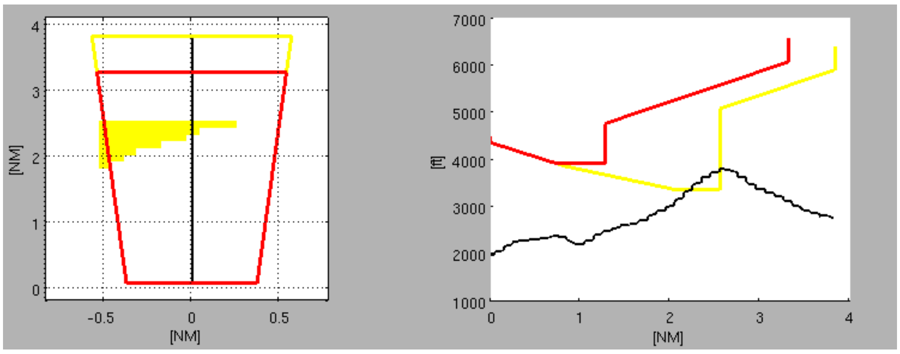
from the caution search volume. Typical measures for the volume with a ground speed of 200 kt are listed in table 3.5 (see figure 3.22 for graphical representation). Typical measures for the volume with a ground speed of 150 kt are listed in table 3.6 (see figure 3.23 for graphical representation).

Table 3.5: Measures of Enroute Search Volume

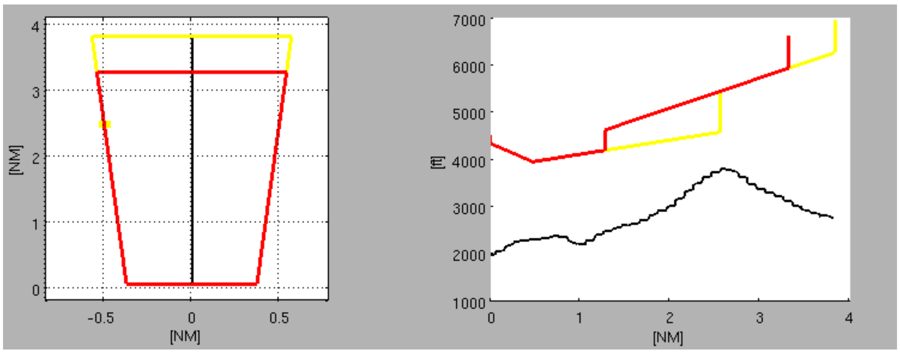
Type	**A [NM]**	**B [NM]**	**C [NM]**	**D [ft]**	**E [NM]**	**F [ft]**
Level Flight	0.75	3.7	1.1	700	2.5	3144
Descending Flight (-1000 ft/min)	0.75	3.7	1.1	1113	2.5	3023
Climbing Flight (1000 ft/min)	0.75	3.7	1.1	560	2.5	3005



(a) Level Flight



(b) Descending Flight

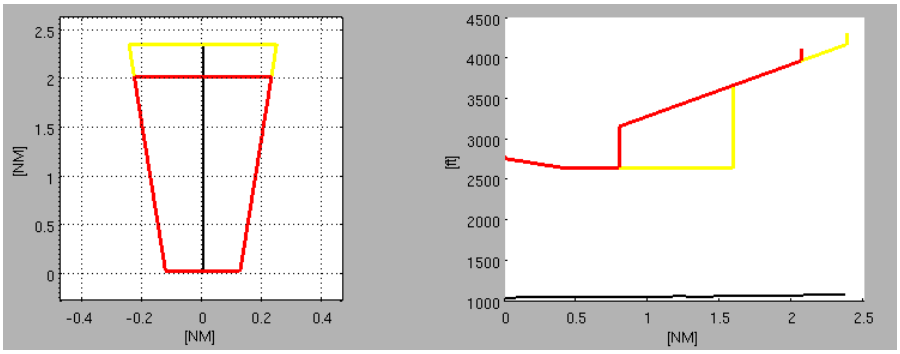


(c) Climbing Flight

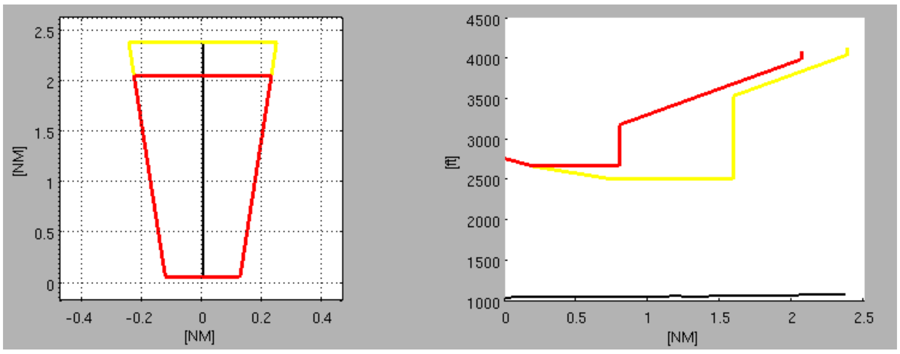
Figure 3.22: Envelopes for Flight Phase Enroute. The red Path represents the Warning Envelope, the yellow path the Caution Envelope.

Table 3.6: Measures of Approach Search Volume

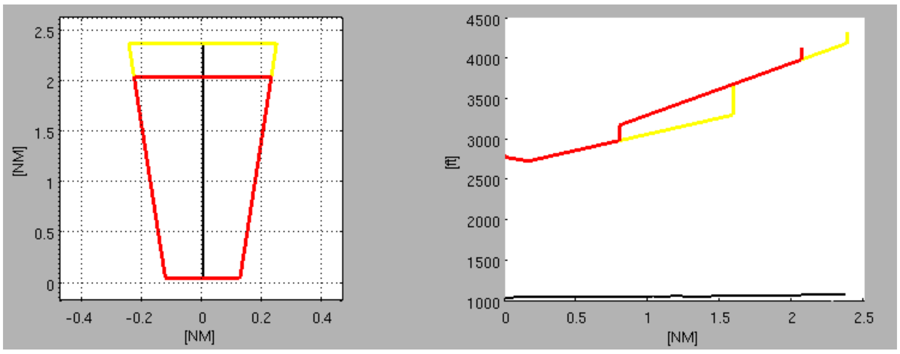
Type	A [NM]	B [NM]	C [NM]	D [ft]	E [NM]	F [ft]
Level Flight	0.25	2.3	0.49	150	1.6	1669
Descending Flight (-600 ft/min)	0.25	2.3	0.49	256	1.6	1633
Climbing Flight (1000 ft/min)	0.25	2.3	0.49	85	1.6	1653



(a) Level Flight



(b) Descending Flight



(c) Climbing Flight

Figure 3.23: Envelopes for Flight Phase Approach. The red Path represents the Warning Envelope, the yellow path the Caution Envelope.

4 Intended Runway Search

4.1 General

As previously mentioned in section 3.1, the search volume depends amongst other things on the distance from a runway. The distance from a runway directly influences the selected flight phase (see section 3.2) and hence the shape of the search volume.

The runway search tries to solve the following questions:

- What and where is the nearest runway?

- Is the aircraft on an approach to a runway?

The first question is necessary primarily for detecting the flight phase. The second question is necessary to distinguish if the aircraft is approaching a runway or is heading towards terrain. The runway that is most probably approached (for landing) is defined as the intended runway. This is necessary to turn off the system on final approach and to prevent any nuisance alerts during landing. See also figure 4.1 for an illustration of the problem.

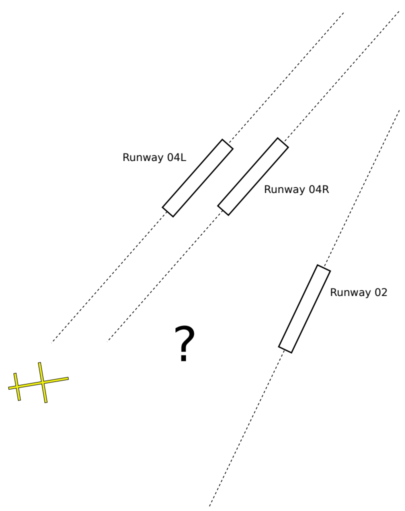


Figure 4.1: Runway Search Illustration. Which runway is the Aircraft approaching?

The TAWS has a dedicated runway database on which it periodically performs the search. The basic search is performed as follows:

1. Load all runways in the vicinity of the current aircraft position (φ, λ) from the database
2. Determine the nearest runways
3. Determine the intended runway

The search uses the current aircraft position and true track (T_T) as input.

4.2 Search Algorithm

4.2.1 Runway Database

The runway database provides runway data for a specific area. Each runway has an entry with the following properties:

- Runway Identifier
- Airport Identifier
- Runway Threshold Position
- Runway Threshold Elevation
- Runway True Bearing
- Runway Length

Note that this database does not have a primary key since the search is based on the position. The runway database is queried to load an area of interest within the vicinity of the current aircraft position into a cache. As the aircraft moves, the area of interest changes and so does the cache. Typically, the cache area is quite large (e.g. 600 x 600 NM) in order to minimize the number of reloads. The runways contained in the cache serve as a base for the actual search.

4.2.2 Calculated Parameters

To detect the nearest and the intended runway, a couple of parameters are calculated constantly for each runway in the cache. Each parameter depends on the relative position between the aircraft and the runway. See figure 4.2 for illustration.

Distance to Runway

The distance to the runway threshold is calculated using spherical geometry and is denoted as d_{RWY}.

Relative Bearing

The bearing from the aircraft to the runway threshold is calculated using spherical geometry. The difference angle between the bearing aircraft to runway threshold and the runway true bearing is the relative bearing, denoted as α.

Cross Track Error (XTE) and Along Track Error (ATE)

The cross track error is defined as the lateral deviation from the runway axis. The along track error is defined as the distance from the threshold along the runway axis. Both are calculated using d_{RWY} and α. The XTE determines how well the aircraft is aligned with the runway axis.

Distance and Cross Track Error and Rate

Rates for d_{RWY} and XTE are constantly calculated and are denoted as $\dot{d}_{RWY}$ and $X\dot{T}E$ respectively. The signs of the rates are used to distinguish if the aircraft is approaching or departing the runway.

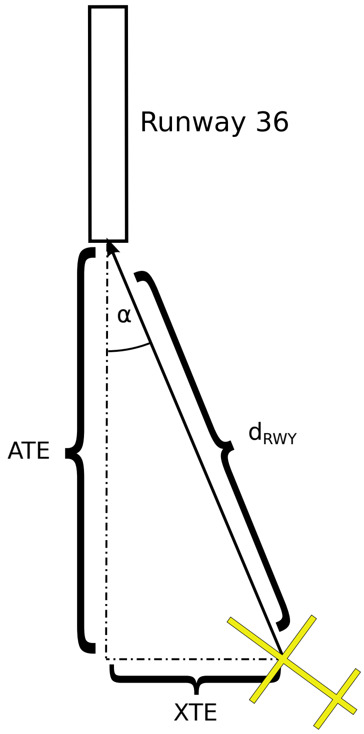


Figure 4.2: Runway Search Parameters

4.2.3 Score Function

A score function that determines a certain score value for each runway is used. The score values express the probability of the aircraft departing or landing on a certain runway. The higher the value, the more probable it is that the crew has chosen the runway to depart or land. The algorithm uses the parameters given above to calculate a score. The calculation of the score is mathematically expressed as:

$$s = f_1(d_{RWY}) + f_2(XTE, ATE) + f_3(\dot{d}_{RWY}, X\dot{T}E) \tag{4.1}$$

Equation 4.1 contains three functions (f_{1-3}) that all contribute to the total score.

The first function f_1 calculates the score depending on the distance, e.g. the score increases the closer the aircraft is to the runway. This simple approach acts as a coarse filter to discard any distant runways.

The second function f_2 determines the score based on how well the aircraft is aligned with the runway axis. The alignment with the axis is determined by the XTE. When the XTE approaches 0, the aircraft is perfectly aligned with the axis. The smaller the XTE gets, the more score is generated. The ATE is initially used to determine if the aircraft is on the correct side of the runway by checking the sign. If it is on the wrong side, the score is decremented significantly. The smaller the ATE gets, the more score is generated, which means that the aircraft is closer to the runway threshold.

Note that the last two described functions focus on parameters that are rather static and that do not contain dynamic information. Using the rates $\dot{d}_{RWY}$ and $X\dot{T}E$ the last function, f_3, considers the dynamic information. The function uses the rate information (especially the sign of the rates) to detect if the aircraft is heading towards a runway or not. The sign of the rate $X\dot{T}E$ signals if the XTE is getting smaller or not, which means that the aircraft is approaching the runway axis. The rate's sign of $\dot{d}_{RWY}$ provides information as to whether the aircraft is departing or approaching the runway. If the sign of the rates signals an approach, the score is incremented, otherwise it is decremented.

4.2.4 Selection of Runways

Finally, the selection of the nearest and the intended runway takes place. The nearest runway is simply selected by arranging the runways in an ascending order by the parameter d_{RWY}. The selection of the intended runway is based on the score. The runway with the highest score is chosen as the intended runway. However, before the intended runway is finally selected, the aircraft altitude is compared against an altitude profile that starts at the supposed runway. This profile defines a standard approach profile. The examined runway is chosen as the intended runway only if the aircraft altitude is below this profile.

5 Search Volume - Terrain Intersection

5.1 General

The previous chapters mainly dealt with the construction of a search volume. The search volumes for caution and warning are now intersected with the terrain to detect any terrain that penetrates the volumes. The penetration of the terrain may eventually lead to a caution- or a warning alert. For the intersection, the following questions are of relevance:

- Which terrain lies within the horizontal boundary of the search volume?
- Does the terrain that lies within the horizontal boundary penetrate the search volume?

In order to be able to answer these questions, the TAWS must have a terrain database as well as methods available to effectively access this database during the intersection. The terrain database contains a Digital Terrain Model (DTM) for a specific region. Furthermore, a method must be developed to effectively intersect the search volume with the terrain database. All operations must work in real time, i.e. during flight.

5.2 Terrain Database

5.2.1 Definition

What is described in a terrain database is not clearly defined in the document TSO-C151b [15]. There is no definition of the term “terrain”. Since terrain and geographic information in general play an important role in aviation, provisions have been made to establish standardization for the gathering, storing and exchanging of terrain, obstacle and aerodrome mapping information. Standardization documents provide the necessary definitions. The most important ones are:

- ICAO Annex 15: Aeronautical Information Services [21]
- ICAO Document 9881: Guidelines for Electronic Terrain, Obstacle and Aerodrome Mapping Information [24]
- Eurocontrol: Terrain and Obstacle Manual [9]
- RTCA DO-200A / EUROCAE ED 76: Standards for Processing Aeronautical Data [16]

One definition can be found in the ICAO Document 9881 on page 33 [24]:

> "Terrain: The surface of the Earth containing naturally occurring features such as mountains, hills, ridges, valleys, bodies of water, permanent ice and snow, excluding obstacles."

This is stated by one definition, however, depending on the sensor used to generate the terrain database it may also contain vegetation and cultural features. Nevertheless a strict division should be made between man-made obstacles that are significantly higher than any other features in their surrounding and the terrain. Figure 5.1 illustrates the definition quoted above.

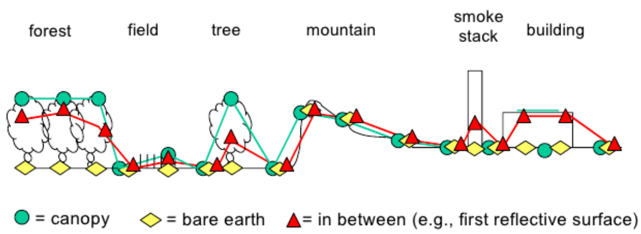


Figure 5.1: Terrain Definition, taken from [24]

A terrain database within the TAWS is defined as: a digital representation of the surface of the earth representing natural features within an area sampled at discrete points. The discrete points are sampled at a fixed angular spacing, each having an assigned elevation. The discrete points yield a grid of adjacent quads named cells. In each cell, the maximum elevation of the whole cell is assigned to the lower left corner. Note that this definition is necessary since the system wants to detect a potential threat that may be caused by any elevation point within the cell. This also plays an important role if the database is re-sampled. If the maximum elevation is not be used, a potential threat may be ignored. In figure 5.2 an explanatory area can be seen. The area is sampled at a fixed angular spacing and each lower left corner of a cell has the maximum elevation of the terrain, in this case a 10000 ft high mountain peak, assigned. Note that this model does not need to know the coordinate of the lower left corner of each cell. The coordinate is implicitly given by the fixed angular spacing and by the knowledge which area is covered. This plays an important role on the physical layout of the data in memory (see 5.2.5.2).

5.2.2 Reference System

The horizontal reference system used for positioning of the grid is WGS84. The vertical reference datum for elevations is Mean Sea Level (MSL). The mean sea level is defined by the Earth Gravitational Model (EGM) EGM96. These reference systems are the ones prescribed by the ICAO ([24], p. 31). Note that the intersection algorithm must take into account the usage of the correct reference system. As the GPS provides geometric height above the WGS84 ellipsoid, a geoid model for transferring this height to an orthometric height referenced to EGM96 must exist in the TAWS.

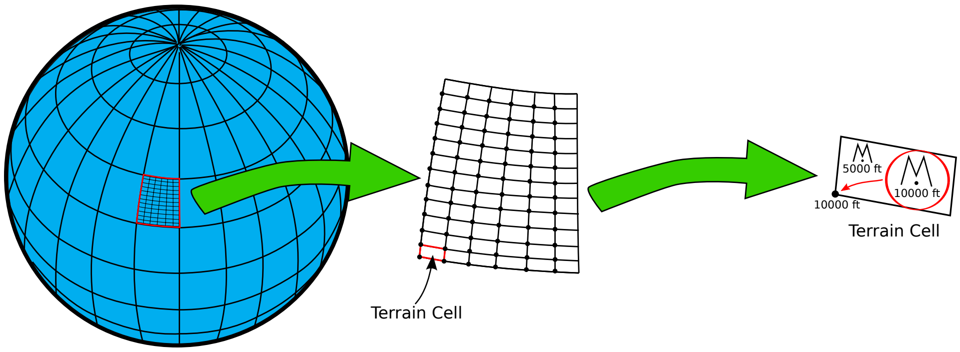


Figure 5.2: Terrain Grid

5.2.3 Terrain Data Attributes and Quality Requirements

Terrain Data Attributes

When creating a terrain database for a real TAWS, a minimum set of terrain data attributes that are described in the ICAO document 9881 are necessary. These attributes are present right from the creation and throughout the entire life cycle of the data. This ensures that the data's characteristics and quality satisfies the requirements of a concrete application.

Table 5.1 lists the attributes that the terrain data must possess. Some of them are discussed in the following.

The post spacing expresses the angular (e.g. arc-seconds) or linear (e.g. meters) distance between two adjacent points in the grid. If an angular distance is used and a linear distance has to be maintained, the post spacing in latitude will differ from the post spacing in longitude at higher latitudes due to the departure of the meridians.

One of the most important attribute defining the quality is the declaration of the accuracy. Here, the accuracy can be judged by the attribute horizontal/vertical accuracy and the associated horizontal/vertical confidence level. The accuracy expresses the degree of conformance between the estimated or measured value and the true value, cf. [24]. The standard deviation must be provided here. The confidence level is the probability that errors in the data are within the limit specified by the accuracy, cf. [24]. The probability is declared as percentage.

The elevation reference holds information about how to interpret the associated elevation value of a point in the grid. The elevation may be interpreted as the elevation of the corner or the center of the cell, the average or the maximum elevation of the cell.

The recorded surface describes whether the data contains information about the elevation of the bare earth (usually acquired by land surveying) or the reflective surface (acquired via remote sensing).

The integrity defines the level of assurance that states that the data has not been altered in such a way that it no longer reflects the original value, cf. [9]. The integrity is expressed as the probability of any single data element of the terrain data having been changed inadvertently since the creation of the terrain data.

The ICAO specifies three levels of integrity ([24], p. 16):

1. Critical: 10^{-8}
2. Essential: 10^{-5}
3. Routine: 10^{-3}

A change in the data could occur in the processing chain. As example, assuming a standard 3 arc seconds Shuttle Radar Topography Mission (SRTM) tile of 1° x 1° along latitude/longitude that contains 1440000 elevation points, only 14 points may have changed when provisions were made to have an integrity of the level Essential. The question about integrity plays an important role especially with SRTM and its characteristic voids and filling of them. See [25] for examination of the integrity level of SRTM-based terrain databases for aviation use.

Table 5.1: Minimum Set of Attributes for Terrain Data, taken from [24], Table 2.1

Attribute Name
Area of Coverage
Data Source Identifier
Acquisition Method
Post Spacing
Horizontal Reference System
Horizontal Resolution
Horizontal Accuracy
Horizontal Confidence Level
Horizontal Position Data
Elevation
Database Units
Elevation Reference
Vertical Reference System
Vertical Resolution
Vertical Accuracy
Vertical Confidence Level
Surface Type
Recorded Surface
Penetration Level
Known Variations
Integrity
Date and Time Stamp

Quality Requirements

The ICAO document states recommended requirements for the use of terrain data in aviation applications. Among them is the GPWS with forward looking terrain avoidance.

The document lists requirements for the following areas:

- Area 1: Entire Territory of a State
- Area 2: Terminal Control Area
- Area 3: Aerodrome/Heliport Area
- Area 4: Category II or III Operations Area

The detailed requirements are listed in table 5.2. However, the document points out that these requirements should not be construed as system level or application specific requirements, rather as recommendation. That's because current TAWS systems use terrain data for advisories only, but not for primary navigation. The TSO-C151b [15] provides some requirements for the resolution of the terrain database but none for the accuracy or the confidence level.

Table 5.2: Quality Requirements for Terrain Data, taken from [24], Table 2.6

Quality Attributes	Area 1 The State	Area 2 Terminal Control Area	Area 3 Aerodrome/ Heliport Area	Area 4 CAT II/III Operations Area
Horizontal Accuracy [m]	50.0	5.0	0.5	2.5
Data Integrity	Routine (10^{-3})	Essential (10^{-5})	Essential (10^{-5})	Essential (10^{-5})
Vertical Accuracy [m]	30.0	3.0	0.5	1.0
Vertical Resolution [m]	1.0	0.1	0.01	0.1
Confidence Level (1σ)	90%	90%	90%	90%
Post Spacing [arc seconds]	3.0	1.0	0.6	0.3
Maintenance Period	as required	as required	as required	as required

5.2.4 Resolution

One of the most outstanding requirements for a terrain database is the resolution. This concerns the horizontal as well as the vertical resolution. The TSO-C151 [15] defines some requirements for the resolution of a terrain database used within a TAWS:

> "Terrain and airport information must be of the accuracy and resolution suitable for the system to perform its intended function. Terrain data should be gridded at 30 arc seconds with 100 foot resolution within 30 nautical miles of all airports with runway lengths of 3500 feet or greater and whenever necessary (particularly in mountainous environments) 15 arc seconds with 100 foot resolution (or even 6 arc seconds) within 6 nautical miles of the closest runway. It is acceptable to have terrain data gridded in larger segments over oceanic and remote areas around the world."

The requirement mentions gridded terrain data. This gridded nature of the data is of importance and will be discussed below in 5.2.5. The resolution requirement is nowadays easily fulfilled by the most common databases. One example would be the SRTM database that provides an almost global coverage with a 3 arc seconds horizontal and 1 m vertical resolution.

5.2.5 Database Model

Figure 5.2 shows an explanatory detail of the terrain database. If we now return to the initial question, which terrain lies within the horizontal boundary of the search volume, this leads to the problem of how to query the terrain database for elevation data. This problem requires the introduction of a model that allows effective access. Effective access in this context means primarily

- Fast Access
- Memory Saving Access

Fast access is necessary since the query happens in real time. Memory saving access is needed due to limited memory during runtime. The greatest challenge for the model is to deal with the immense amount of data. Imagine a TAWS having a global terrain database and thus allowing global operation. Finding the elevation data lying within the volume would require a search across the whole database. For the effective access, spatialization and a spatial structure for addressing the elevation data are introduced (see also [2], chapter 8.2).

5.2.5.1 Logical Layout

Spatialization

As illustrated in the example above, the TAWS contains in the worst case a global database. A short assessment of the amount of data contained in the database shows the problem even more clearly:

Again, assuming a standard 3 arc seconds global coverage of tiles with dimension 1° x 1° along latitude/longitude, each containing 1440000 elevation points, would yield approximately $9.33 \cdot 10^{10}$ points.

Table 5.3: Level of Detail (LOD) Structure

Level	Angular Spacing	Number Child Segments
0	3”	1200 x 1200
1	6”	600 x 600
2	15”	240 x 240
3	30”	120 x 120
4	60”	60 x 60
5	1.5’	40 x 40
6	3’	20 x 20
7	6’	10 x 10
8	12’	5 x 5
9	30’	2 x 2
10	1°	1 x 1

The spatialization of the data is done by dividing the global database recursively into smaller segments. Each segment correspond to a specific Level of Detail (LOD). As the segment gets smaller, more details appear. A top level and a bottom level of detail exist. The top LOD represents the lowest terrain resolution whereas the bottom LOD represents the highest terrain resolution. The spatialization is done from top (global scale) to bottom (local scale). Figure 5.3 illustrates this process. In the top LOD, which is also called the parent segment, each segment covers an area with a dimension of 1° x 1° along latitude/longitude. In the next step, the segment is divided by two in latitude and longitude. Four new child segments are the result, each having a dimension of 30’ x 30’. This division is repeated until the segment has a dimension of 3” x 3”. Note that the division is not entirely done by factor 2, but rather is adapted to the requirements of the TAWS and with respect to the spatial structure for addressing. With this parent-child architecture, one may access the desired LOD recursively. Once the parent segment is known, the child segments are easily found. Table 5.3 shows the numerical values for the LODs used within this system. In the third column, the number of child segments contained in the top LOD (1° x 1°) for the respective LOD (e.g. 3” x 3”) can be seen. This division process is very similar to a quad-tree structure (see [2], chapter 8.2.1).

The transition from a segment that contains a geographic feature to terrain data is seamless. Since terrain data as previously defined in 5.2.1 is treated as a cell, each segment becomes a terrain cell. It is assumed that the terrain data is available in a resolution that is a multiply of 3 arc seconds. Then, each terrain cell can be used in the segment structure above by simply re-sampling the terrain data to the desired LOD. As mentioned earlier, the cell’s maximum elevation is stored in the lower left corner of the cell. This lower left corner will later on play an important role in addressing the cell. Figure 5.4 shows a sample terrain area of 1° x 1° that is re-sampled from 3 arc seconds to a resolution of 30 arc minutes. The figure illustrates clearly that the maximum elevations are forwarded to the next level. Finally, the top LOD contains only 4 terrain cells that, however, represent the maximum elevation of the whole area.

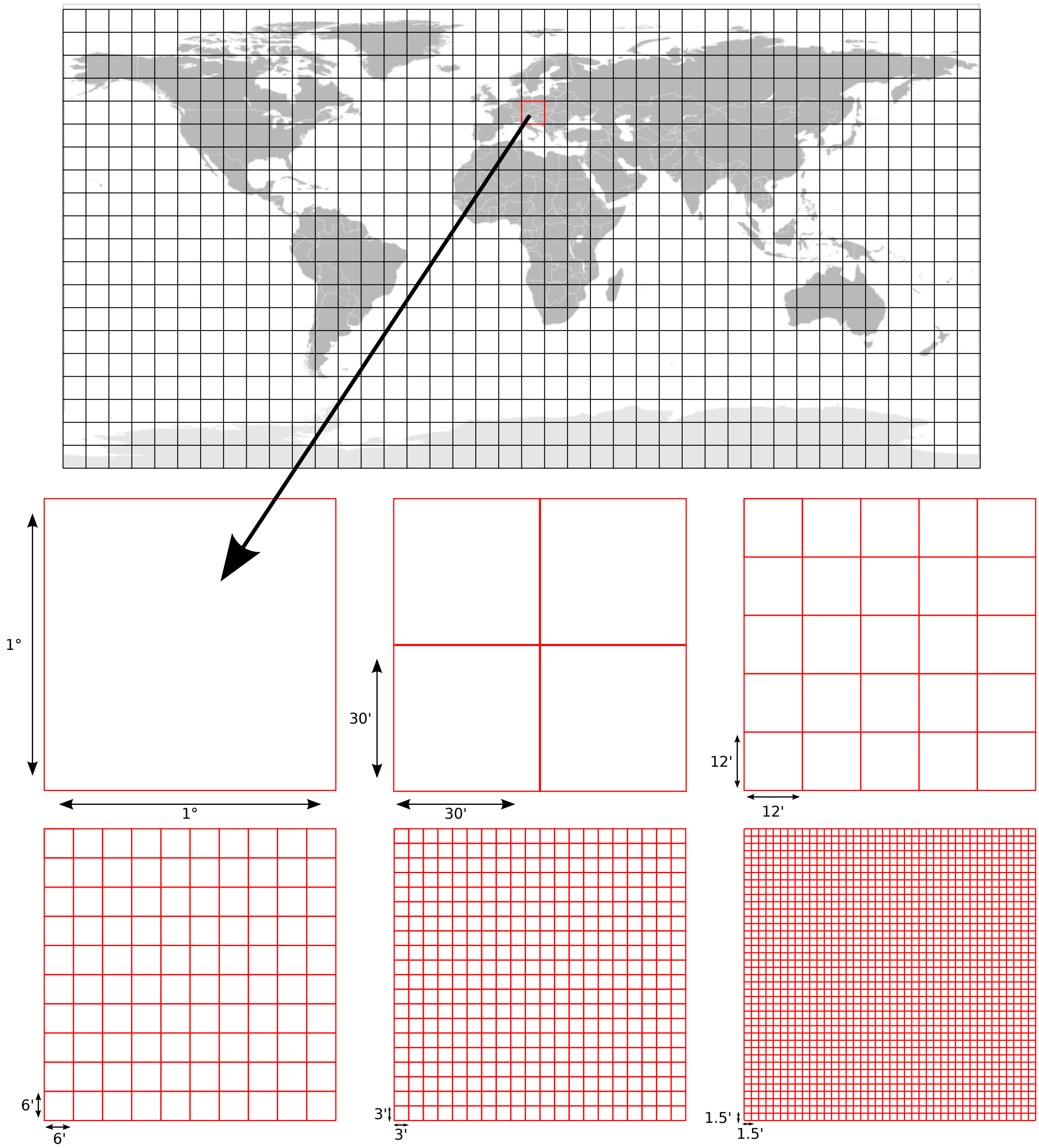
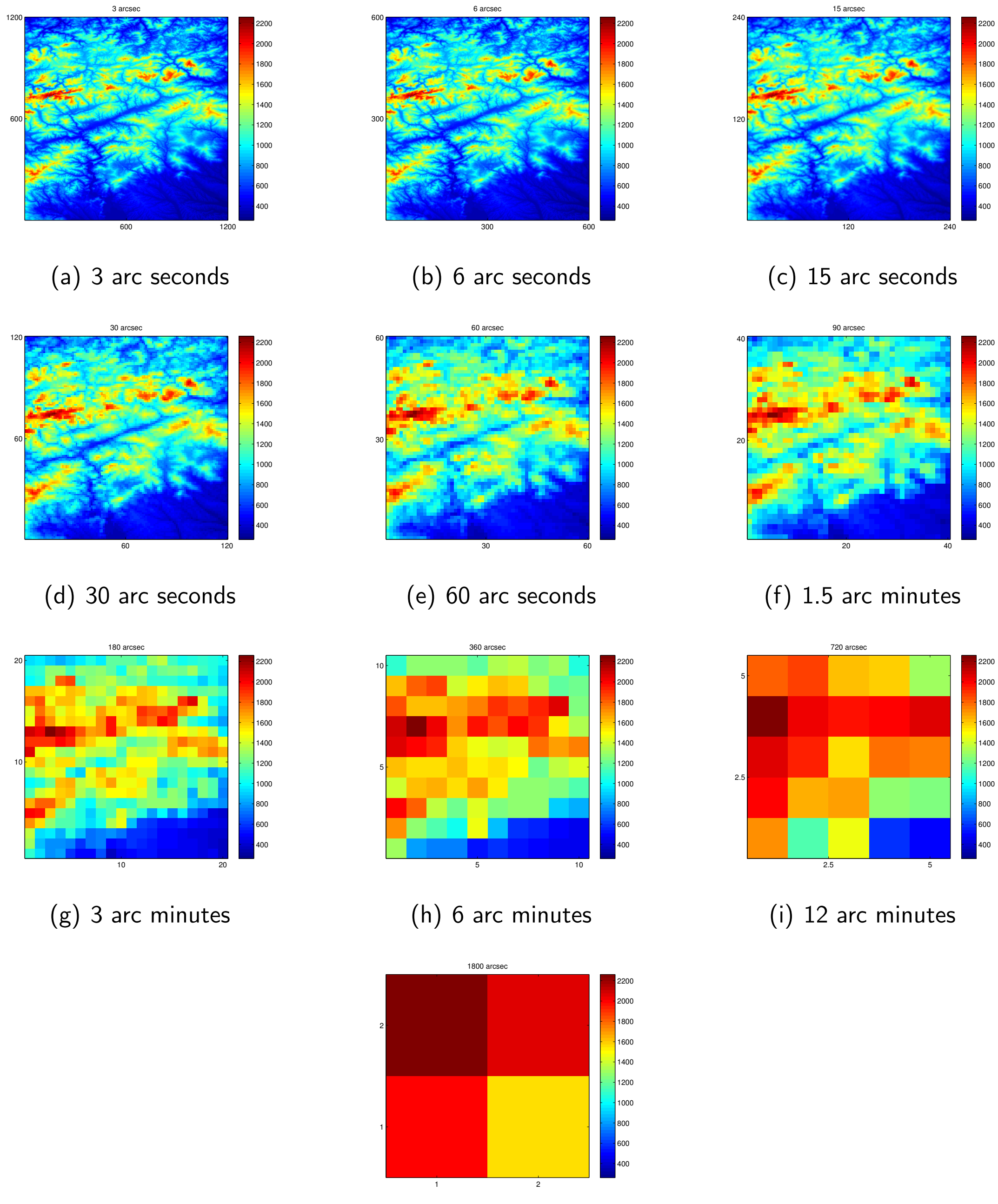


Figure 5.3: Spatialization. The resolution is increased from left to right, starting in the upper row.



(a) 3 arc seconds (b) 6 arc seconds (c) 15 arc seconds

(d) 30 arc seconds (e) 60 arc seconds (f) 1.5 arc minutes

(g) 3 arc minutes (h) 6 arc minutes (i) 12 arc minutes

(j) 30 arc minutes

Figure 5.4: Explanatory Visualization of the LOD for an Area with a lower left corner of N47°/E015° (Styria/Austria). Colors represent Elevation in meters

Spatial Structure for Addressing

The previous sections discussed the division of an area into smaller segments and finally into terrain cells. The question that arises is: How can the terrain cells be addressed? Given a position (φ, λ), the next question would be: Which terrain cell is the nearest one and which elevation does it have?

The spatialization already provides the key feature for establishing a spatial structure for addressing a terrain cell. Finding an addressing scheme is easy as the terrain cells are laid out in a grid. As in the addressing scheme EXCELL (see [2], chapter 8.2.2), an address space is introduced. The address space utilizes the already existing grid structure. The grid structure is considered as a matrix. Each element of a matrix A, with n rows and m columns, i (row) and j (column) has a unique linear index k defined as:

$$k = i * m + j \tag{5.1}$$

The calculation of the linear index is used as a hash function ([2], p. 280) to map the row index i and the column index j to a unique value k. Applying the hash function to the terrain cells, the following addressing scheme is introduced:

Each terrain cell is uniquely addressed using two indices:

- Global Index (GI)
- Sub Index (SI)

The global index is defined as the linear index of the 1° x 1° terrain cells that cover the whole earth. As the earth is defined by 180 parallels and 360 meridians, the hash function for the global index (using φ, λ in degrees) is:

$$GI = (floor(\varphi) + 90) \cdot 360 + floor(\lambda) + 180 \tag{5.2}$$

The $floor$ function returns the largest integer not greater than the argument. The global index runs from 0 to a maximum index of $180 \cdot 360 = 64800$ and maps a position within a 1° x 1° terrain cell to the lower left corner of that cell. The position N47° 3' 51.51" / E15° 27' 11.40" for example has a global index of 49515.

Within a 1° x 1° terrain cell, the sub index is used to address any child terrain cell. As discussed before, it is important to take into account the division factor for each LOD. Table 5.3 shows the angular spacing. A closer look at the angular spacing reveals, that each level has an integer multiply angular spacing of the base level, which is 3 arc seconds. This makes it possible to address any position within the 1° x 1° terrain cell with a linear index that is based on 3 arc seconds. As one 1° x 1° terrain cell consists of 3600 x 3600 1 arc seconds cells, the hash function for the sub index, using minutes (m)

and seconds (s) of φ and λ and the angular spacing Δ_{ang} in arc seconds is defined as:

$$N_{\text{Samples per Row}} = \frac{3600}{\Delta_{ang}}$$
$$SI = floor\left(\frac{m_\varphi \cdot 60 + floor(s_\varphi)}{\Delta_{ang}}\right) \cdot N_{\text{Samples per Row}} + floor\left(\frac{m_\lambda \cdot 60 + floor(s_\lambda)}{\Delta_{ang}}\right) \tag{5.3}$$

Fractional seconds are rounded to the largest previous integer second using the floor function. The result of the division by Δ_{ang} is also rounded down to the nearest integer. Note that when φ or λ is negative, the calculation of the total seconds for φ becomes $m_\varphi \cdot 60 + floor(s_\varphi) + 3600$ instead of $m_\varphi \cdot 60 + floor(s_\varphi)$ and for λ it becomes $m_\lambda \cdot 60 + floor(s_\lambda) + 3600$ instead of $m_\lambda \cdot 60 + floor(s_\lambda)$.

For position N47° 3' 51.51" / E15° 27' 11.40" and an angular spacing of 3 arc seconds (which yields $N_{\text{Samples per Row}} = \frac{3600}{3} = 1200$) for example, the sub index is 92944. This addressing scheme can be used for the LOD defined in table 5.3. The transformation from one resolution level to another is also easy since all angular spacings are an integer multiply of 3 arc seconds.

Using the global and sub index, an arbitrary position on earth can be mapped to a terrain cell in the database. Note that this mapping not necessarily returns the nearest terrain cell since the mapping involves rounding using the $floor$ function. This drawback is acceptable since the mapping error lies in the range of a maximum of 3 or 6 arc seconds if the intersection uses these resolutions. The calculation of the indices paired with a sophisticated physical layout grants a fast access.

5.2.5.2 Physical Layout

The choice of the correct physical layout is of great importance. As stated above, a fast and memory saving access is required. With the knowledge gained in the previous section, the logical layout is now transformed into a corresponding physical layout.

As mentioned above, in the worst case the TAWS might use a global database. Assuming a 3 arc seconds resolution, one 1° x 1° terrain tile file has 1440000 elevation points. If each point requires 2 bytes of storage, the file requires 2812.5 kBytes. A database for the whole earth (360 · 180 files) requires approximately 173.81 GBytes. However, if terrain tile files that contain only sea level (assuming as an estimation that 71% of the earth are covered by sea) are discarded, the amount of storage needed is reduced to approximately 50 GBytes. This amount of data cannot be loaded into memory by a program during runtime. Therefore, two methods are used to overcome this problem:

- Caching
- Memory Mapping

The caching is dealt with in section 5.2.6 and is a method of transferring a section of the terrain database to a temporary memory. The memory mapping allows access to terrain tile files without extra consumption of runtime memory.

As mentioned in the section above, for a fast access to terrain data it is necessary to have a sophisticated physical layout. The physical layout should integrate with the logical layout seamlessly. The logical layout uses a spatialization in form of a LOD and terrain at high resolution is sampled to lower resolution. With respect to the FLTA and the terrain display, this LOD structure is also used for the physical layout. The FLTA acts in the immediate vicinity and therefore uses a high resolution terrain. As the terrain display shows the terrain in the vicinity depending on the pilot's selected display range (up to 320 NM), the resolution of the terrain has to be lower for large ranges than for short ranges.

All the LOD levels are stored in one LOD file. This technique is very similar to the "Multum in Parvo" (MIP) mapping technique [26], where a high resolution texture image is sampled down to lower resolution texture images in order to have a fast access on computer graphics cards. Storing the LOD levels in one LOD file needs a preprocessing step, where the high resolution terrain tile file (e.g. 3 arc seconds) is successively sampled to each LOD level shown in the table 5.3. Starting from level 0, all elevations of one level are packed into a contiguous memory block, ordered by the sub index and finally stored in the file. The ordering by the sub index is important since this facilities fast access. During runtime, when the sub index is calculated through equation 5.3, a pointer pointing to the first elevation in the memory block can easily be shifted by the sub index. The shifted pointer then points to the elevation that corresponds to a certain position. No search has to be performed and the only complex operation is the calculation of the sub index. Finally, a LOD file for each 1° x 1° terrain cell exists. Each LOD file contains a header representing the positions in the file memory where each LOD level starts and ends. The collection of all the LOD files constitutes the terrain database.

To save runtime memory, the content of a LOD file, the elevations, are not loaded into a runtime memory buffer. A runtime memory buffer would require the dynamic allocation of memory, which is a time and memory costly method. However, the content of a LOD file is mapped into the runtime memory using a method called "memory mapping". When a file is memory mapped, the program has access to the content of the file as if it was available in runtime memory buffer, but does not use up any time and memory as would be the case if the file was loaded.

5.2.6 Terrain Caching

The amount of data in the terrain database, as discussed previously, can be tremendous. One technique to overcome this problem was memory mapping the LOD files. As the terrain database is constituted by a collection of LOD files, which may cover the whole earth, the TAWS must schedule the memory mapping of the files. This is necessary since the mapping cannot address an unlimited amount of memory, which has to do with the underlying computer architecture (e.g. 32 bit versus 64 bit).

The caching makes sure that LOD files needed for the FLTA and the terrain display are memory mapped. Therefore, a cache area and a reload area are defined. Both areas use the arrangement of the 1° x 1° terrain cells and the associated global index.

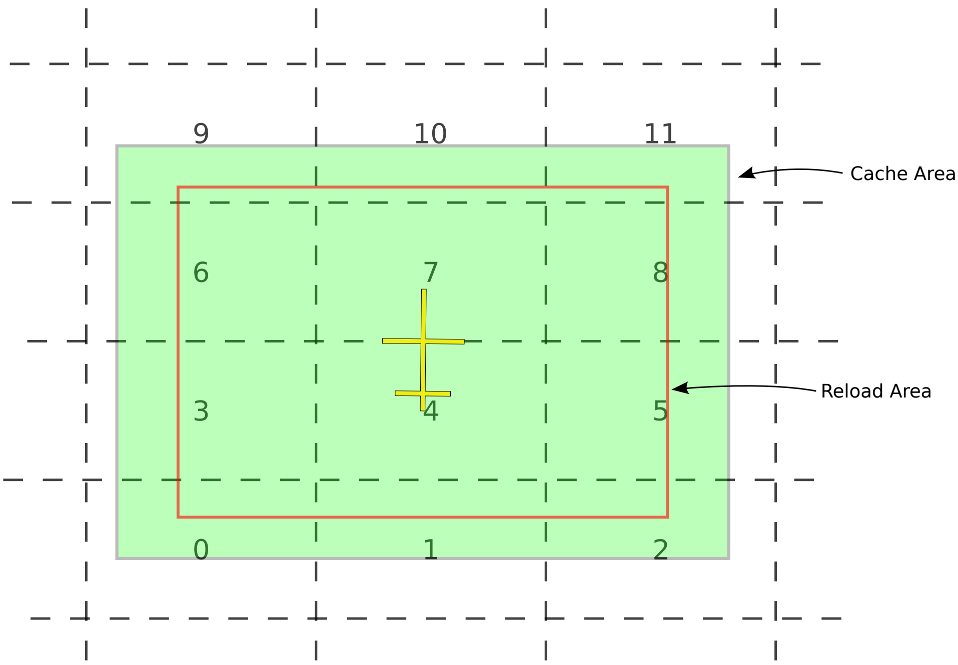


Figure 5.5: Cache and Reload Area

As there is a LOD file for each 1° x 1° terrain cell, all the LOD files associated to a terrain cell within the cache area are memory mapped. The cache area is not static and moves as the aircraft moves. A continuous moving of the cache area would result in a continuous memory mapping operation of the LOD files. However, most of the time this is not necessary, since the movements of the aircraft are relatively small compared to the dimension of the cache area. To avoid a continuous memory mapping operation, the reload area is used for triggering when new LOD files need to be memory mapped. Figure 5.5 illustrates both areas. The reload area (seen in red in the figure) is smaller than the cache area (seen in green in figure, usually 80%) and moves constantly with the aircraft. As the aircraft moves, the reload area is intersected with the cache area and it is checked if the reload area is contained in the cache area. If the reload area is not contained in the cache area, the memory mapping is triggered. For each 1° x 1° terrain cell lying within the cache area, the corresponding LOD file is memory mapped. A pointer to this memory mapped file is stored in a lookup table that maps the global index of the LOD file to the pointer.

5.3 Intersection

The questions "Which terrain lies within the horizontal boundary of the search volume?" and "Does the terrain that lies within the horizontal boundary penetrate the search volume?" still remain. Chapter 3 dealt with the design and definition of the search volume. In section 5.2, the logical and physical structure for the terrain database was introduced. Next, a method must be found to intersect the search volume with the terrain database.

As the search volume is constituted by a horizontal and a vertical envelope, the intersection is also divided into a horizontal and a vertical part. The horizontal envelope is defined by a closed polygon, the vertical one by an open path (see 3.5). For the horizontal part, all the terrain cells lying within the horizontal envelope have to be found, for the vertical part, the elevation of a terrain cell has to be compared with the altitude of the envelope at the cell's position.

5.3.1 Terrain Cell Search

The search for terrain cells that lie within the horizontal envelope uses the terrain cell structure as a raster. The raster is spaced at an angular distance of Δ_{ang}. The envelope is available as a polygon that is defined as a set of points with ellipsoidal coordinates φ and λ. This definition is analytical. By regarding the cell structure as a raster (the terrain cells being the pixels) and the envelope polygon as vector graphic, the most simple solution for finding all terrain cells within the envelope is to convert the envelope polygon to a raster representation. The intersection uses the highest terrain resolution of the terrain database, which is 3 arc seconds.

Before the conversion can take place, a mutual mapping between the ellipsoidal coordinates and the raster coordinates has to be defined. A mapping between ellipsoidal coordinates (φ, λ) and raster coordinates (u, v) is defined using the latitude φ_0 of the most southern point and the longitude λ_0 of the most western point of the envelope as origin of the raster coordinate system and the angular spacing of the used terrain resolution (Δ_{ang}):

$$\begin{aligned} u &= \Delta_{ang} \cdot (\lambda - \lambda_0) \\ v &= \Delta_{ang} \cdot (\varphi - \varphi_0) \end{aligned} \tag{5.4}$$

$$\begin{aligned} \varphi &= \varphi_0 + \Delta_{ang} \cdot v \\ \lambda &= \lambda_0 + \Delta_{ang} \cdot u \end{aligned} \tag{5.5}$$

Each point of the envelope can now be converted to the corresponding raster coordinates u and v, and the raster coordinates to the corresponding ellipsoidal coordinates φ and λ.

The conversion of the envelope polygon to a raster representation is a standard task of computer graphics. It is better known as vector-raster conversion and is used in every graphics card to convert geometric primitives such as lines or polygons to their pixel representation on the monitor. In this case, the task is to find all the pixels that lie within the envelope polygon (see figure 5.6 for illustration). This task is accomplished by using a so called “Scan-Line Algorithm”. This algorithm uses horizontal lines (“scan-lines”), spaced apart in 0.5 pixels vertically, to scan the vector geometry (see figure 5.7). Scanning means that the algorithm searches for intersections of the vector geometry with the horizontal lines. Such an intersection can comprise an entry and an exit, or only a single point. Between the entry and the exit point, the horizontal scan line is sampled

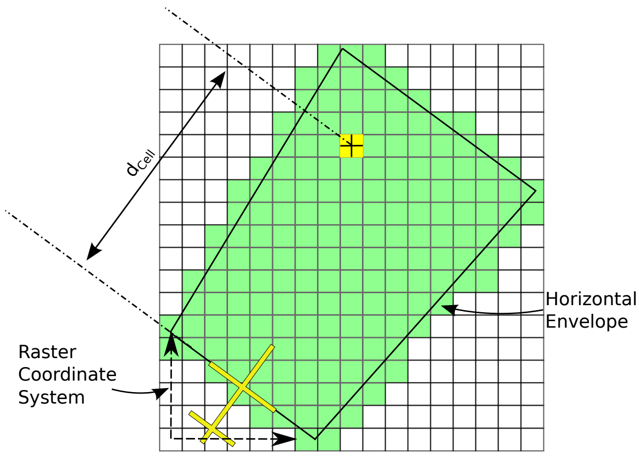


Figure 5.6: Terrain Cell Search

at each pixel position. These pixels are considered to lie inside the polygon. An example algorithm can be found in [17].

The scan-line algorithm returns a list of pixels that lie within the envelope polygon. The position of each pixel is converted to ellipsoidal coordinates using equation 5.5 and is stored in a so-called called hit list. For each position, the global and the sub index are calculated (see equation 5.2 and 5.3 respectively) and stored in the hit list. Knowing the indices, it is now possible to access the corresponding terrain cell from the database and thus also the elevation.

5.3.2 Threat Detection

In the previous section, the search for the terrain cells that lie within the horizontal envelope was described. The result of this search is the hit list. Each entry in the hit list contains the position, the global and the sub index of a terrain cell and is called a hit cell. Using this information, the elevation H_{Cell} of the hit cell can be looked up. As described in section 5.2.6, the terrain caching supplies a lookup table between the

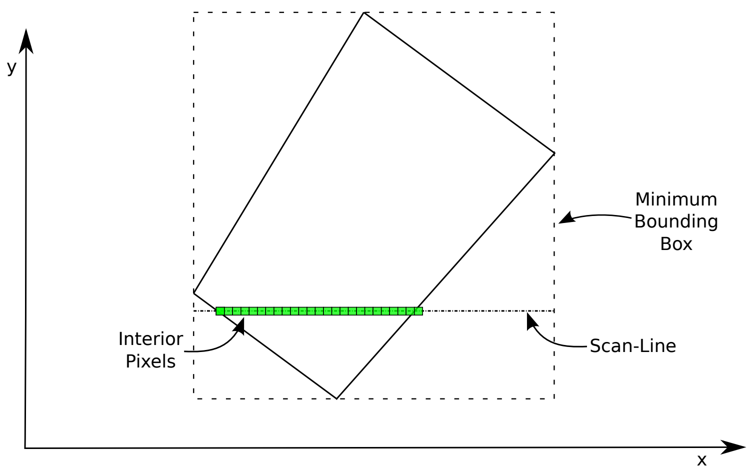


Figure 5.7: Scan Line Algorithm

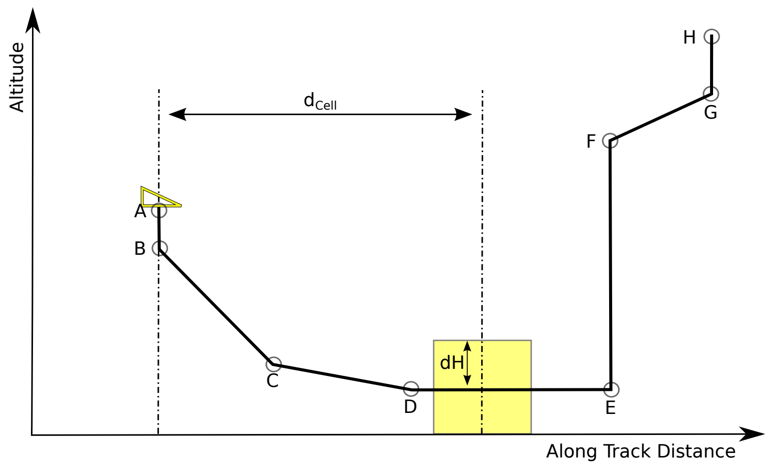


Figure 5.8: Threat Detection using vertical Envelope

global index and a pointer to a memory mapped LOD file. Using the global index of a hit cell as a key, the associated pointer to the memory mapped LOD file is retrieved. By dereferencing the pointer, the LOD file is accessed. The sub index serves to finally find the elevation of the hit cell. Therefore, a second pointer that points to the elevation data of the file is used. It is shifted by the sub index. Dereferencing the second pointer yields the elevation H_{Cell} of the hit cell.

A hit cell that may cause a hazardous terrain closure is considered a threat cell. The detection of a threat cell is done using the vertical envelope. A threat cell's elevation penetrates the vertical envelope by a height of dH. Figure 5.8 shows such a threat cell (depicted as yellow rectangle). The distance d_{Cell} to the threat cell is measured along the track as shown in figures 5.6 and 5.8. Having the along track distance d_{Cell} to the threat cell, the height of the envelope at that distance is calculated. This involves a search for the previous and the next point among points A-H. Using these points, the height of the envelope is interpolated linearly at a distance of d_{Cell}. Then, the aircraft altitude is added to the calculated height to yield an absolute altitude $H_{Envelope}$. Finally, dH can be calculated as:

$$dH = H_{Envelope} - H_{Cell} \tag{5.6}$$

If dH is negative, the hit cell becomes a threat cell. To avoid transient alerts, a threat cell does not necessarily lead to an alert and is handled by the alert generation. Therefore, each hit cell with a negative dH is stored in a threat list. Since the intersection intersects both search volumes, i.e. caution and warning, a cell might be a threat cell that penetrates the caution and warning search volume. Each threat cell therefore carries a specific type of information that describes which search volume is penetrated by the threat cell. The threat list is examined by the alert generation and a caution or warning alert may be triggered.

6 Alert Generation

6.1 General

The alert generation is responsible for the generation of caution and warning alerts. Caution alerts are issued when the caution search volume penetrates the terrain, whereas warning alerts are issued when the warning search volume penetrates the terrain. The alert generation logic uses the threat list produced by the search volume - terrain intersection (see 5.3.2) to trigger an alert. A penetration of the caution and warning search volume can be active concurrently, which would yield both alerts. However, the warning alert has priority over the caution alert. The logic tries to suppress possible nuisance and transient alerts with delays, thresholds and hysteresis.

6.2 Logic

The logic for the alert generation is based on two tasks:

- Alert Triggering
- Alert Cancellation

The alert triggering is responsible for examining each threat cell and triggering a caution or warning alert. It uses a certain kind of hysteresis that delays the triggering of alerts. In order to cancel present alerts, the alert cancellation task also examines each threat cell and also applies a certain kind of hysteresis that delays the cancellation of alerts. Figure 6.1 illustrates the described high level logic. On each TAWS execution cycle, the alert triggering is executed first, followed immediately by the alert cancellation.

6.2.1 Alert Triggering

In figure 6.1, the alert triggering logic can be seen on the left hand side. Each threat cell on the threat list is examined. A threat cell can become an alert cell. In order for this to happen, a threat cell must fulfill some conditions. When a threat cell becomes an alert cell, the cell is saved in a separate list, called the “alert list”. Furthermore, each threat cell also has a “hit count”, that may be incremented or decremented by the logic on each TAWS execution cycle.

The first step of the logic is to check whether the threat cell is already an alert cell. If this is the case, and if the alert cell previously caused a caution alert, it may now cause a warning alert since the threat cell may already have penetrated the warning search

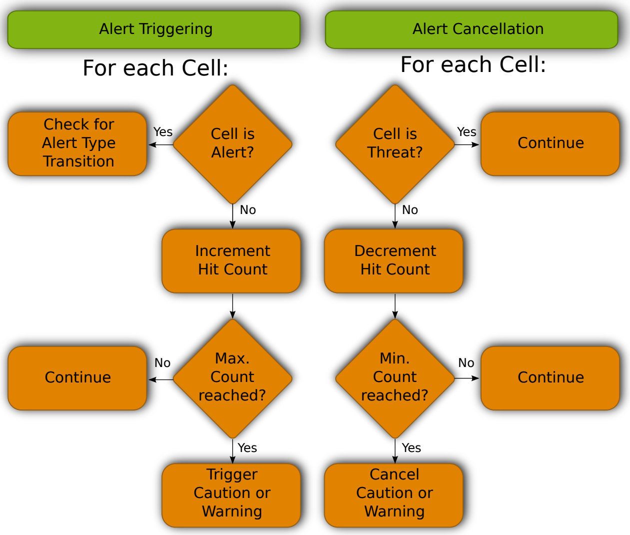


Figure 6.1: Alert Generation and Cancellation Logic (High Level)

volume. Therefore, a check exists that may cause a transition from a caution alert to a warning alert.

If the cell is not yet an alert cell, the hit count is incremented based on some particular elaborate conditions. The next step is to check if the hit count has reached a certain maximum hit count. If this is the case, a caution or warning alert, depending on which search volume was penetrated by the threat cell, is triggered. The threat cell now becomes an alert cell and is stored in the alert list. The hit count serves as hysteresis and tries to prevent transient alerts. An alert is only triggered, if a threat cell remains in a search volume for a certain amount of time.

6.2.2 Alert Cancellation

On the right hand side of figure 6.1, the logic for the alert cancellation can be seen. All the cells in the alert list are examined. The first step is to check if the alert cell still poses a threat. If so, the next cell is examined.

If it is no longer a threat, the hit count is decremented. This is followed by a check, that determines whether the cell's hit count is below a minimum hit count. If the minimum hit count has been reached, the alert cell is released. A different minimum and maximum hit count has the effect of a hysteresis. A threat cell must have for example a hit count of 5 to become an alert cell, but to vanish it must have a hit count of 2.

Finally, if no alert cells exist, the alert is released.

7 Implementation and Outlook

7.1 General

The knowledge covered in the last six chapters was developed iteratively. First, theoretical considerations and then prototype implementations based on these considerations were made. The prototype implementations used the programming languages Matlab and Python. Findings were acquired using the prototype implementations that helped to enhance the theoretical part. Some of the functionalities were not implemented as prototype because of performance issues of the aforementioned programming languages.

The final (real-time) implementation was made using the programming language C++ under the Linux operating system and was integrated into three full-flight simulators of the company "Axis Flight Training Systems GmbH" in Lebring, Austria.

7.2 Prototype Development

The prototype of the core functionality was made using Matlab as it provides a good high level framework (e.g. plotting) with a lot of functionality. The design of the prototype is strictly procedural and not object-oriented nor event driven. The prototype does not run in real-time due to performance limitations encountered with Matlab.

The prediction model was tested with recorded aircraft kinematics generated by Axis. The vertical envelope model was developed alongside the TSO-C151b [15] test cases using an interactive test GUI (see figure 7.1). A provisional SRTM terrain database was used and a primitive caching mechanism implemented. However, the final terrain database functionality was implemented in C++ because of performance issues. The search volume - terrain intersection with the vector to raster conversion was also implemented in the prototype. Finally, the alert generation logic was developed iteratively in the prototype until the logic delivered acceptable results. The logic was unit tested using automated test procedures.

The functionality of the prototype was controlled using a dedicated GUI (see figure 7.2). The GUI facilitates

- Starting and Stopping of the Prototype
- Loading of recorded Aircraft Kinematics
- Interactive control of the Aircraft Kinematics
- Inspection of internal Variables

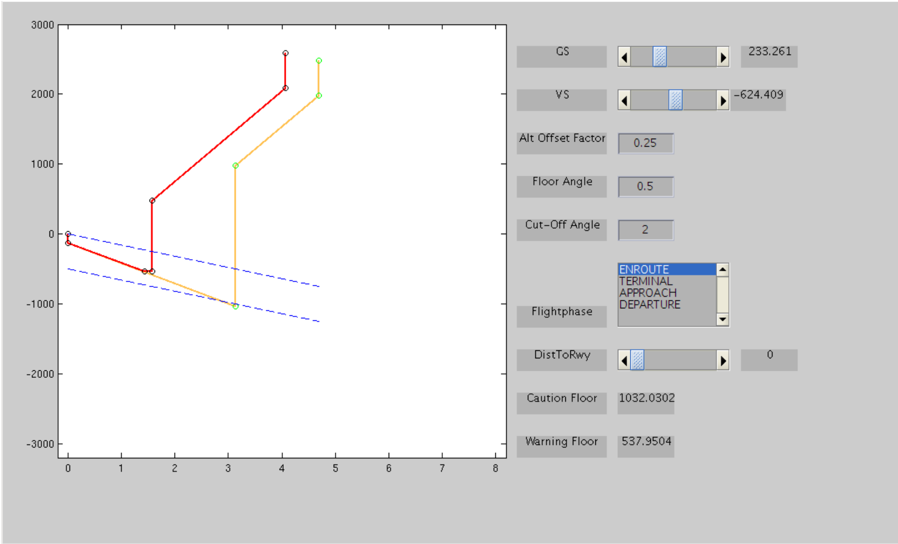


Figure 7.1: Vertical Envelope Interactive Test GUI

- Visualization of the horizontal and vertical Envelope
- 2D-Visualization of the Search Volume-Terrain Intersection
- 3D-Visualization of the Search Volume-Terrain Intersection

The prototype is driven by aircraft kinematics either coming from a recorded flight path or from aircraft kinematics generated in the prototype. In the latter case, the GUI allows the interactive control. The GUI shows the internal variables as well as a visualization of the horizontal and vertical envelope. A 2D and a 3D-visualization of the search volume - terrain intersection provide better understanding of the algorithm. The 2D-visualization shows the threat cells in the horizontal envelope plot and a terrain profile in the vertical envelope plot (see upper part of figure 7.2). The 3D-visualization shows a three-dimensional view of the search volume - terrain intersection (see figure 7.3).

7.3 Final Implementation

The final real-time implementation was done using C++ under the Linux operating system and resulted in a dedicated TAWS program. Most of the Matlab code was ported to C++ seamlessly. The TAWS program is interfaced with the rest of the full-flight simulator in order to receive data from the subsystems. Outputs of the TAWS are used to control the aural alerts and the lamp alerts. Furthermore, the TAWS program incorporates the generation of a terrain picture of the terrain in the vicinity of the aircraft. This picture is shown on the navigation displays in the cockpit. The picture is transferred to these displays using the weather radar interface.

An example of the terrain picture is shown in figure 7.4. The terrain ahead of the aircraft is depicted using different patterns and colors depending on the relative altitude between the aircraft and the terrain. Every four seconds the picture is refreshed like a

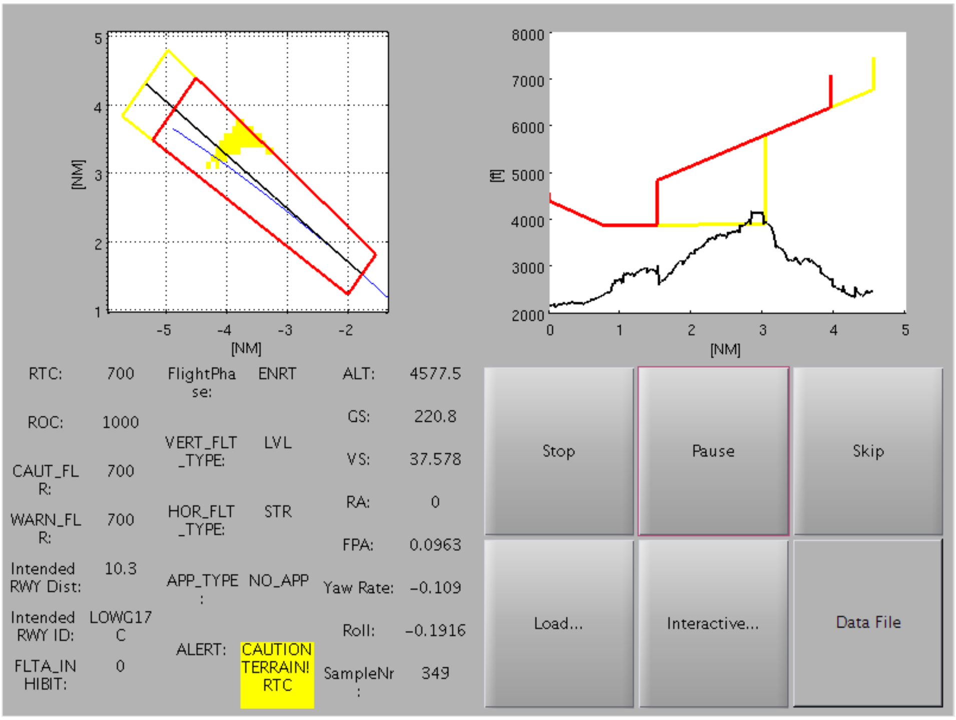


Figure 7.2: Prototype GUI showing the threat Cells and a Terrain Profile

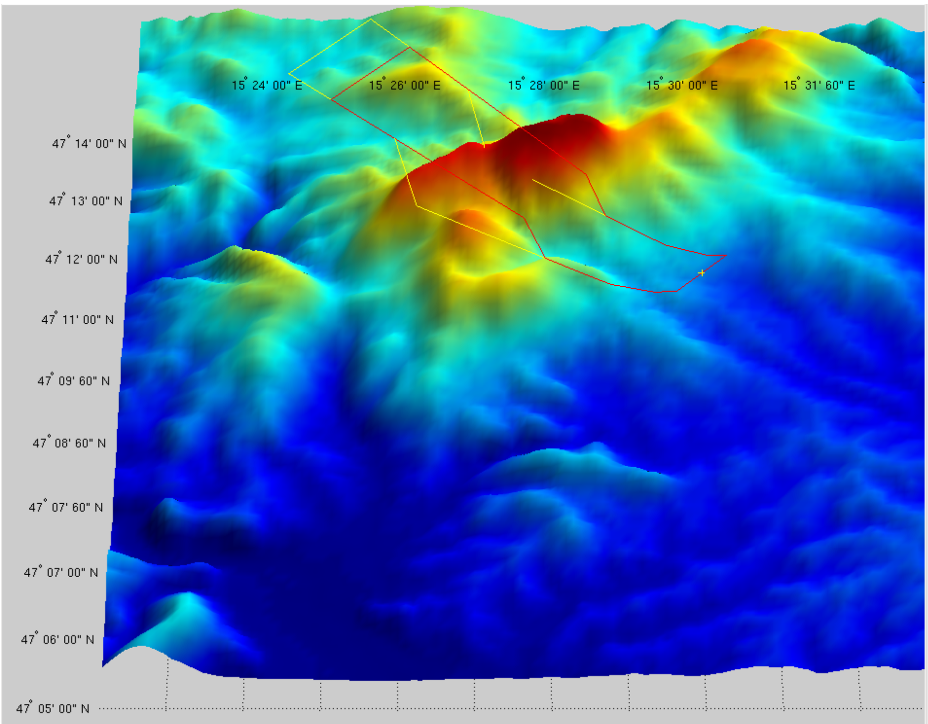


Figure 7.3: 3D-Visualization of the Search Volume-Terrain Intersection showing the mountain "Schoeckl" near Graz (Austria)

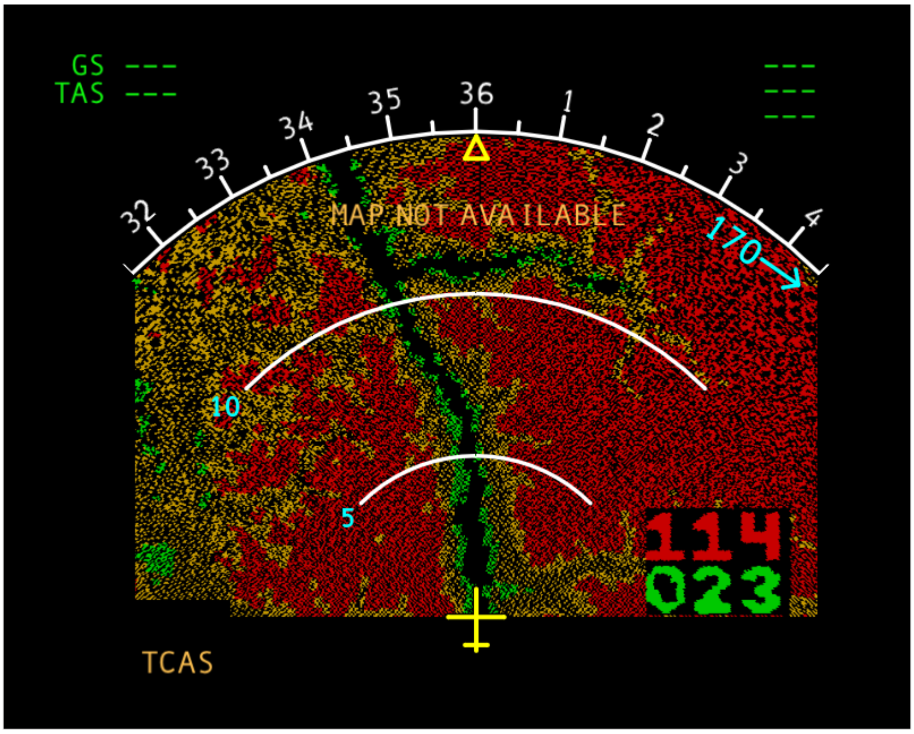
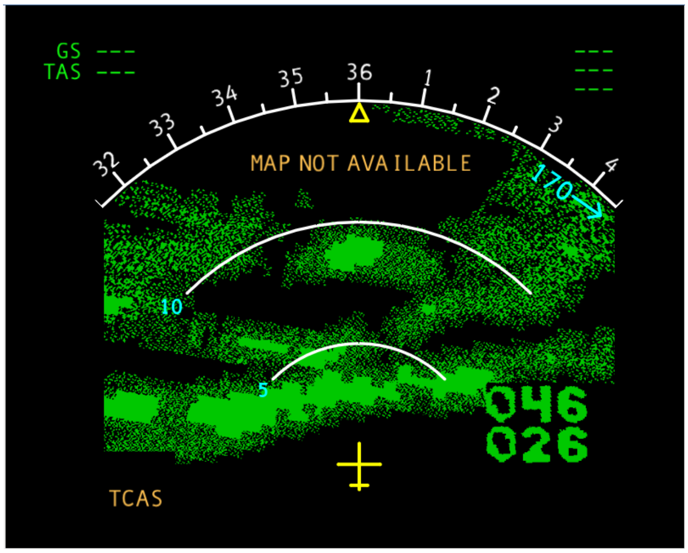


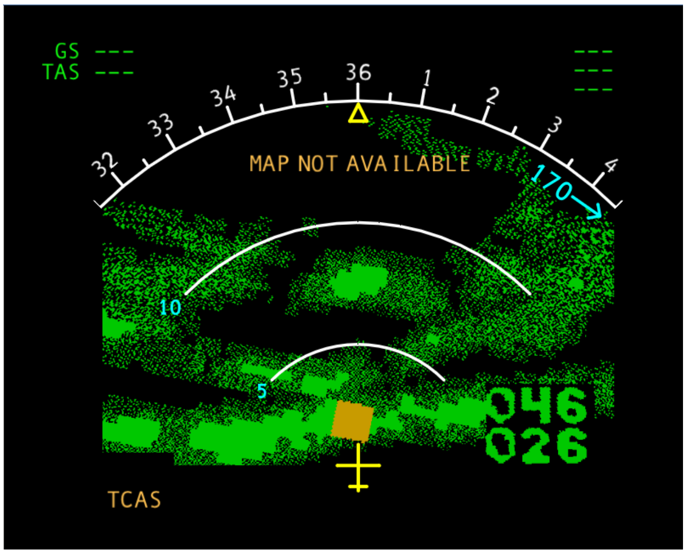
Figure 7.4: Terrain Picture shown on a Navigation Display at Innsbruck (Austria), looking east towards the Inntal valley

weather radar sweep. On the lower right corner in the terrain picture, the minimum and maximum terrain elevation of the terrain shown in the picture are presented. The lower number shows the minimum, the upper number the maximum elevation in hecto feet. The color of the numbers corresponds to the color of the terrain depicted.

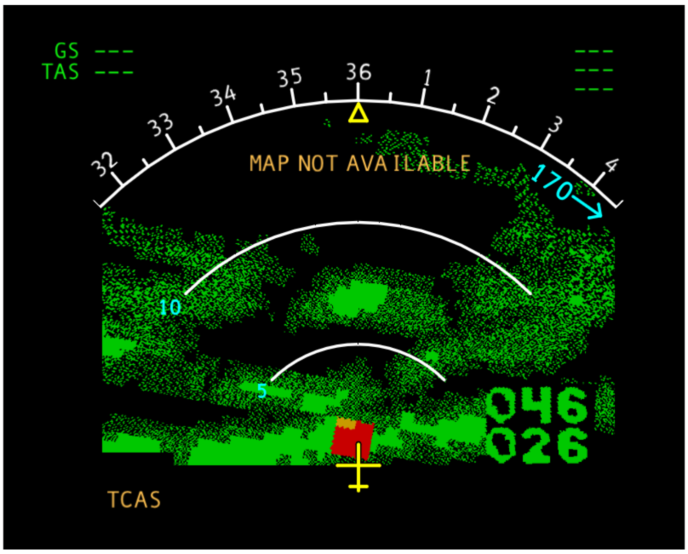
Figure 7.5 shows the terrain picture during a test flight towards the peak "Hasenmatt" in Switzerland. In picture 7.5(a) the aircraft is far away from the peak, thus the picture shows only green terrain. As the aircraft approaches the peak and the terrain penetrates the caution search volume, a caution alert is issued approximately 50 seconds before the peak. The associated terrain cell is marked solid yellow in the terrain picture as shown in figure 7.5(b), a repetitive aural alert "Caution Terrain, Caution Terrain" is issued and a warning lamp illuminates. Finally, the aircraft gets even closer and the terrain penetrates the warning search volume causing a warning alert approximately 30 seconds before the peak. The associated terrain cell is now marked solid red in the terrain picture as it can be seen in figure 7.5(c) and the aural alert changes to a repetitive "Terrain-Terrain Pull-Up".



(a) Approaching the Peak



(b) The Caution Alert is issued



(c) The Warning Alert is issued

Figure 7.5: Terrain Picture shown on a Navigation Display during a Test Flight towards the peak "Hasenmatt" (Switzerland)

7.4 Outlook

The TAWS has proven its capabilities to sufficiently enhance the terrain and situational awareness of a crew sufficiently. Since the system has been introduced, it has had a noticeable impact on the accident statistics as in 2006 the CFIT was replaced by the loss of control in flight as the number one cause of accidents in aviation. New developments and enhancements in automation have made flying still safer. One of the latest technologies introduced into modern aircraft cockpits is the Synthetic Vision System which provides a 3D-depiction of the terrain ahead of the aircraft on the navigation display (see figure 7.6). This intuitive presentation combined with the features of a TAWS enhances the situational awareness even more and hence makes flying safer.

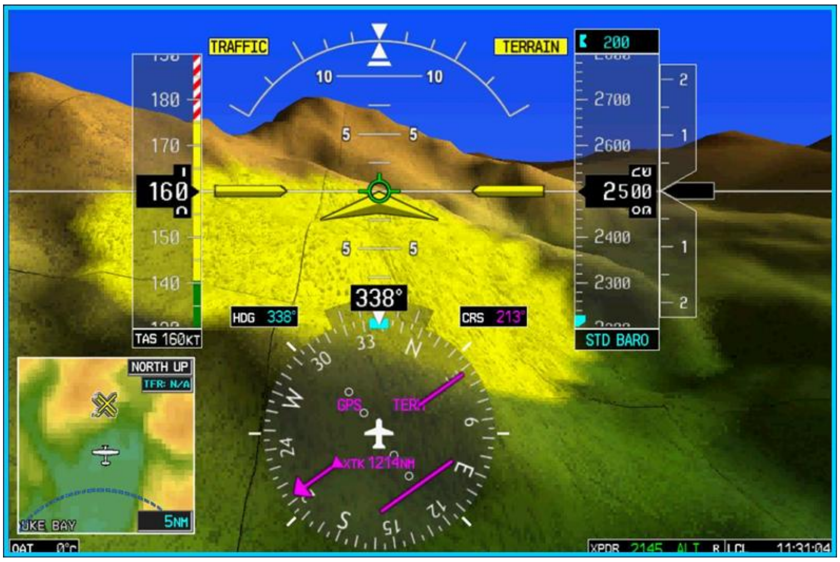


Figure 7.6: Synthetic Vision Display, developed by Garmin

List of Figures

List of Tables

Bibliography

[1] Pakistan Civil Aviation Authority. Investigation Report Air Blue Flight ABQ-202, Crashed on 28 July 2010 at Islamabad. `http://www.caapakistan.com.pk/investigation.aspx`, 2011.

[2] Norbert Bartelme. *Geoinformatik - Modelle, Strukturen, Funktionen.* Springer, Berlin, 4th edition edition, 2005.

[3] Boeing. *Statistical Summary of Commercial Jet Airplane Accidents.* 2011.

[4] Barry C. Breen. Controlled Flight Into Terrain and the Enhanced Ground Proximity Warning System. *IEEE AES Systems Magazine*, January 1999.

[5] Jim Burin. 2005: The year in review - return of the killers. *AeroSafety World*, July 2006.

[6] Jim Burin. Leveling off. *AeroSafety World*, February 2011.

[7] Interstate Aviation Comittee. Accident Report of TU-154M, Aircraft Tail Number 101, of the Republic of Poland on April 2010 near Smolensk. `http://www.mak.ru/english/info/tu-154m_101.html`, 2011.

[8] Boeing Dave Nakamura. *FMS RNAV Workshop.* February 2000.

[9] Eurocontrol. *Terrain and Obstacle Manual.* 2.0 edition, November 2011.

[10] Eurocontrol and International Civil Aviation Organization (ICAO). SKYbrary (Wiki). `http://www.skybrary.aero`.

[11] Eurocontrol and International Civil Aviation Organization (ICAO). SKYbrary (Wiki), CFIT Definition. `http://www.skybrary.aero/index.php/Controlled_Flight_Into_Terrain`.

[12] Eurocontrol and International Civil Aviation Organization (ICAO). SKYbrary (Wiki), Hull Loss Definition. `http://www.skybrary.aero/index.php/Hull_Loss`.

[13] Eurocontrol and International Civil Aviation Organization (ICAO). SKYbrary (Wiki), Situational Awareness Definition. `http://www.skybrary.aero/index.php/Situational_Awareness`.

[14] Federal Aviation Administration (FAA). *Technical Standard Order TSO-C129a, Airborne Supplemental Navigation Equipment using the Global Positioning System (GPS).* February 1996.

[15] Federal Aviation Administration (FAA). *Technical Standard Order TSO-C151b, Terrain Awareness and Warning System.* December 2002.

[16] Radio Technical Commission for Aeronautics (RTCA). *DO-200: Standards for Processing Aeronautical Data.* 2002.

[17] Paul S. Heckbert. Concave Polygon Scan Conversion. *Graphics Gems I*, 1993.

[18] B. Hofmann-Wellenhof, K. Legat, and M. Wieser. *Navigation - Principles of Positioning and Guidance.* Springer, 2003.

[19] B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins. *GPS - Theory and Practice.* Springer, 5th edition, 2001.

[20] Honeywell. *MK VI and MK VIII, Enhanced Ground Proximity Warning System (EGPWS), Pilot's Guide.*

[21] International Civil Aviation Organization (ICAO). *Annex 15 to the Convention on International Civil Aviation: Aeronautical Information Services.* 12th edition, 2004.

[22] International Civil Aviation Organization (ICAO). *Annex 6 to the Convention on International Civil Aviation: Operation of Aircraft*, volume Part I. 12th edition, 2004.

[23] International Civil Aviation Organization (ICAO). *Procedures for Air Navigation Services, DOC 8168: Aircraft Operations - Volume II: Construction of Visual and Instrument Flight Procedures.* 2006.

[24] International Civil Aviation Organization (ICAO). *Doc 9881: Guidelines for Electronic Terrain, Obstacle and Aerodrome Mapping Information.* Undated.

[25] Jeppesen. *Got Mountains? Challenges of Modeling SRTM and Other Terrain Data to Suit Aviation Applications*, 2008.

[26] Dave Shreiner, Mason Woo, Jackie Neider, and Tom Davis. *OpenGL Programming Guide.* Addison Wesley, 4th edition, 2004.

[27] FAA U.S. Department of Transportation. *Installation of Terrain Awareness and Warning System (TAWS) Approved for Part 23 Airplanes.* June 2000.

[28] FAA U.S. Department of Transportation. *United States Standard for Terminal Instrument Procedures (TERPS).* August 2011.