Development of a Terrain Awareness Warning System Tool for Aircraft Operation Monitoring

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Abstract

This work combines two of the most important concepts related to aircraft safety: Flight Data Monitoring and Terrain Awareness Warning Systems (TAWS). Using R programming language algorithms, a tool of analysis was built, capable of detecting TAWS warnings using flight data. This tool complements the daily monitoring that is performed within an airline, by automatically validating such warnings. For developing this tool, the Enhanced Ground Proximity Warning System was carefully studied to understand how warnings were triggered and especially to characterize the particular situations in which they were inhibited. An open source terrain database was implemented in the algorithms to predict conflicts between aircraft and the upcoming terrain based on the aircraft GPS position. All the studies reported in this work used Google Earth as an auxiliary tool to perform a visual analysis of the information under treatment.

Keywords: Safety, Flight Data Monitoring, Warnings, Algorithms, Analysis Tool

1. Introduction

Aviation has become one of the world’s most important industries, mainly due to its immense economical and social benefits. International business and tourism are among the activities that most benefit from air transportation.

Aviation has been growing ever since it exists. Historically, according to Airbus, air traffic has been doubling every 15 years [1]. Figure 1 shows the world annual traffic represented in Revenue Passenger Kilometers (RPK) between 1976 and 2016 and estimations until 2036, where RPK is defined as the product between the number of paying passengers and the distance travelled in km.

Figure 1: World Annual Traffic [1]

In this figure it is possible to observe that air traffic growth is not expected to stop in the medium term. Instead, aviation expansion will continue at a fast pace, mainly due the increased demand of the Asia-Pacific region, especially by countries such as China, India or Indonesia [2]. This demand will bring multiple challenges, the most important of which is to avoid by all means any kind of aircraft accident.

To achieve this goal, it is important to maintain a daily monitoring of the flight data recorded by aircraft, in order to detect deviations from standard procedures that may jeopardize the aircraft or the safety of operation. This is a standard practice in every airline company called Flight Data Monitoring (FDM), whose importance should not be underestimated.

The process starts aboard the aircraft with the recording of a large amount of parameters, such as temperatures, position, altitude or speed of the aircraft, among many others. This data is then sent to the ground workstation where, after being decoded, it is analysed. The result of this analysis may reveal values that are outside the expected range, whether it is a single exceedance in one of the parameters (for instance, aircraft speed), or a continuous trend (for instance, engine deterioration). In such cases, a report may automatically be generated. This procedure helps finding potential problems before they become a threat to the aircraft, and the appropriate solution may be adopted in time.
2. Background

2.1. Radar Altimeter

A radar altimeter is a system used onboard aircraft to measure the height $h$ above the surface currently beneath the plane. The working principle of a radar altimeter is based on measuring the total time $t$ required for a signal to reflect from the surface and return to the aircraft (or a receiver, in general), and converting it to a distance through the signal's velocity (i.e., the speed of light $c$).

$$h = \frac{c}{2} t$$  \hspace{1cm} (1)

The waveforms used in radar altimetry can be divided into continuous waves (CW) or pulsed waves (PW), depending on the distance to the target [3]. CW radars can only measure distances usually up to 1km, nevertheless this type of radars are the ones installed on aircraft. These radars emit electromagnetic radiation continuously, and therefore the transmission signal must be modulated in order to allow having a basis for measuring the time delay between transmitted and received signal.

The most common modulation process is by changing frequency over time, creating a Frequency Modulated Continuous Wave (FMCW). There are many types of Frequency Modulation (FM), such as the linear FM with a triangular symmetric pattern, represented in Figure 2.

![Figure 2: Triangular Frequency Modulation [3]](image)

The time delay $t$ between transmitted and received signals can be computed through the frequency shift between the two waves at any instant, also known as beat frequency $f_b$:

$$t = \frac{T_M f_b}{2 f_{dev}}$$  \hspace{1cm} (2)

where $T_M$ corresponds to the modulation period and $f_{dev}$ to the frequency deviation.

Finally, substituting Equation 2 into Equation 1, it is possible to verify that the height measured by the radar altimeter is proportional to the frequency beat:

$$h = \frac{c T_M}{4 f_{dev}} f_b$$  \hspace{1cm} (3)

2.2. GPS

The Global Positioning System (GPS) is a space-based radio navigation system managed by the U.S. government that provides real-time accurate position, velocity and time information. While it was originally designed as a military force enhancement system, today its precise position determination capabilities can be used by any civilian and are of extreme importance in the civil aviation industry.

GPS consists of three segments: space, control and user segments. The space segment consists of a constellation of 24 satellites that transmit one-way signals, which are received by the user segment (GPS receivers). The control segment is in charge of monitoring GPS satellites to maintain them in their proper orbits.

To determine a user’s position, GPS uses the concept of one-way time of arrival (TOA) ranging, i.e., measuring the time it takes for a signal transmitted by the emitter at a known location to reach a user receiver [4]. The distance between emitter and receiver is computed multiplying the signal propagation time by the speed of light. Using multiple emitters, and calculating the respective distances to receiver, the user’s position can be unambiguously determined.

2.3. ILS

The Instrument Landing System (ILS) is a precision runway approach aid which provides pilots with instrument indications that enable the aircraft to be manoeuvred along a precise, predetermined, final approach path. ILS is especially useful in conditions of reduced visibility, and it is composed by two main elements – a localizer transmitter and a glide slope transmitter – though marker beacons and high intensity runway lights may also be provided as aids to the use of an ILS.

The ILS localizer is a ground-based radio system located at the end of the runway, designed to give lateral guidance to the aircraft with respect to a runway center line. The localizer transmitters radiate field patterns of 90-Hz and 150-Hz modulated energy on opposite sides of the instrument runway center line, in such a way that the 90-Hz modulation exceeds the 150-Hz modulation when the aircraft is to the left of the course an in this situation an indication is exhibited to the pilot to ”fly right” [5]. The glide slope transmitter works with a very similar principle as the localizer. However, instead of horizontal guidance, it provides vertical guidance, with the on-path line usually set at $3^\circ$.

2.4. Euler angles

Euler angles provide a simple way to represent the attitude of a rigid body using a combination of three rotations about different axis. Each rotation
produces a rotation matrix that defines the orientation of the new set of axis in relationship to the original ones.

When working with Euler angles it is necessary to define two different reference frames, for instance the inertial and the body frame. The Euler angles in this particular problem are yaw \( \psi \), pitch \( \theta \) and roll \( \phi \) angles. The product of the three rotation matrices around the three axes originates a complete rotation matrix (Equation 4) [6] that allows for any vector defined in one of the reference frames to be rotated to the other, as shown in Equation 5.

\[
R^B_I(\phi, \theta, \psi) = R(\phi)R(\theta)R(\psi) \tag{4}
\]

\[
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix}_B = R^B_I(\phi, \theta, \psi)
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix}_I \tag{5}
\]

3. EGPWS Description

The concept of Terrain Awareness Warning System (TAWS) was introduced with the purpose of effectively combating Controlled Flight Into Terrain (CFIT), which is defined as a situation in which there is an unintentional collision of a completely operational aircraft with an obstacle, terrain or water surface, without any indication of loss of control. As of today, TAWS comprises the Ground Proximity Warning System (GPWS), and a more advanced version of GPWS, which will be described in this part, the Enhanced Ground Proximity Warning System (EGPWS).

The EGPWS is a system used in aircraft to warn pilots when the aircraft is in danger of impacting with terrain. To decide if a given situation is considered dangerous, this system uses a combination of aircraft inputs – such as geographic position, altitude, airspeed, or glide slope deviation – and an internal terrain, obstacle, and airport runway database [7]. Once a terrain or obstacle conflict is detected, EGPWS alerts the flight crew with aural and/or visual warnings.

The EGPWS is usually divided in two parts according to the type of warnings generated. On the one hand, there are the basic functions included in GPWS, which are translated in 5 different modes that generate reactive warnings. On the other hand, there are a few additional functions called enhanced functions, which compare the aircraft position with EGPWS internal databases to predict hazardous situations (predictive warnings).

3.1. EGPWS Basic modes

All 5 EGPWS basic modes can be described by an envelope, which distinguishes a safe situation from a situation where a warning is emitted, as exemplified by mode 1 envelope in Figure 3.

Mode 1 is active during all phases of flight and it was designed to alert for excessive descent rates of the aircraft. The flight envelope for this mode depends on radio altitude and the aircraft’s descent rate, i.e., the aircraft’s vertical speed. The aural messages generated by this mode are “Sinkrate” and “Pull Up”.

Mode 2 was designed to protect the aircraft from impacting with rapidly rising terrain. Mode 2 is subdivided into mode 2A and mode 2B, depending on the configuration of the flaps.

Both modes are active during climbout, cruise, and initial approach and their envelope depends on radio altitude and Terrain Closure Rate (TCR), which is defined as the rate of change of radio altitude. When the envelopes are broken the aural messages ”Terrain Terrain” and ”Pull Up” are heard in the cockpit.

Mode 3 is active during take-off and low altitude go-around when both landing gear and flaps are not in landing configuration. It was designed to prevent altitude losses when the aircraft is expected to be climbing. Mode 3 envelope depends on radio altitude and the altitude loss of the aircraft, defined as the maximum altitude reached during take-off (or go-around) and the current altitude. This mode is inhibited once the system determines that the aircraft has gained sufficient altitude. When mode 3 envelope is penetrated the aural message ”Don’t Sink” is generated to the cockpit.

Mode 4 is active during cruise and approach and it alerts the crew for insufficient terrain clearance when the aircraft is not in landing configuration. It is usually subdivided into mode 4A, 4B. The envelope of both modes depends on the aircraft’s radio altitude and computed airspeed.

Mode 4A prevents unintentional gear up landings, by emitting ”Too Low Gear” and ”Too Low Terrain” warnings. On the other hand, mode 4B was designed for alerting the crew for landings with the flaps set in a wrong configuration, by generating ”Too Low Flaps” and ”Too Low Terrain” messages.
Mode 5 is active once/if a glide slope beam is received by the aircraft, since its envelope depends on radio altitude and glide slope deviation. There are two levels of alerts in this mode, which produce the same aural message – “Glideslope” – at different sound volumes.

3.2. EGPWS Enhanced functions

The enhanced functions that have been added to the original GPWS are called predictive functions since they use terrain, obstacle and airport databases to anticipate any hazardous situation that could lead to a CFIT accident.

In this section, only one of EGPWS enhanced functions will be explained, since it is the most important and the only one that is mandatory in every EGPWS unit. It is called Collision Prediction Alerting, and it is usually referred to as Terrain Ahead function. As the name indicates this function was designed to predict possible aircraft collisions by looking for terrain ahead of the aircraft.

This predictive function combines a terrain database included in the EGPWS and an envelope attached to the aircraft, and using the airplane’s GPS position, it can compute warnings by detecting possible conflicts between the two virtual objects.

![Figure 4: EGPWS terrain database](image)

As seen in Figure 4, the EGPWS terrain database consists of a set of small terrain cells forming a continuous grid over the world’s land areas, where each cell covers a small area of the Earth’s surface and has a constant altitude defined by the maximum altitude within that area.

This function’s envelope is composed of two different parts (two trapezoids): a short-term propagation of the current Flight Path Angle (FPA) and a long-term prediction of the aircraft’s potential climb gradient [10].

In the final flight phases, “Terrain Ahead” warnings are inhibited if the aircraft predicted trajectory converges with a protected area, known as the convergence envelope, which has a funnel shape and is designed to account for both straight-in and curved approaches.

4. Implementation

The algorithms developed to detect EGPWS warnings during flight used two essential tools for that purpose: flight data files, containing the parameters recorded by the aircraft, and R programming language, which allowed a quick and efficient analysis of the former.

One of the most important parameters used in the EGPWS warning detection algorithm is the radio altitude. However, the radio altitude data provided by flight recorders must be properly treated before being used. In TAP Air Portugal most aircraft can only record radio altitudes up to 1024ft, due to the maximum number of bits available for the recording of that parameter. Once the radio altitude exceeds 1024 ft, the recorded value will not correspond to the real value, since the count has been reset to 0 at an altitude of 1024 ft. This means that a value of RALTD1 – the altitude measured by radar altimeter one – of x could correspond to a real altitude given by:

\[ \text{radio altitude} = \left( x + 1024 \right) i, \quad i = 0, 1, 2 \]  

Radar altimeters used onboard aircraft have a maximum range of about 1km, or equivalently 3281 ft, which means that for radio altitudes above this limit (which would correspond approximately to \( i > 2 \) in Equation 6) the recorded information cannot be trusted, since it is incorrect. Therefore, the corresponding information was not analysed, which will not interfere with the warning detection because no warnings can be triggered at such altitudes.

To find the value of \( i \) in Equation 6, the difference of consecutive RALDT1 values was computed. Whenever this difference was abnormally high, it would mean that a reset to 0 would have occurred, and thus the value \( i \) should be adjusted to obtain the true radio altitude value.

4.1. Basic modes

The warning detection algorithm for basic modes consisted in making a direct comparison at each second between the relevant flight parameters and the envelope of the mode in analysis.

However, in some of the modes it was required to perform additional computations when the necessary parameters were not available in flight data files, since they were not recorded during flight.

As an example, the analysis of mode 3 requires the computation of a parameter known as altitude loss, which measures the difference between the maximum altitude achieved during take-off or go-around and the current altitude.

Another example consists of the flap landing configuration parameter, which is essential to detect mode 4 warnings. During a flight, pilots introduce in the Multi-function Control and Display Unit (MCDU) the flap configuration in which it is
intended to land the aircraft. However, this information is not recorded, and so this parameter had to be obtained by directly extracting the flap configuration from the flight data file in the moment when the aircraft actually lands.

$$t_i = t_0$$

Extract relevant parameters

Is the mode active?

Yes

Warning detection at $$t = t_i$$

No

Make additional computations if necessary

Time update: $$t_i = t_i + 1$$ (until $$t_f$$)

Was the envelope broken?

Yes

No

Figure 5: Warning detection flow chart

The warning detection method for basic modes follows the flow chart represented in Figure 5.

4.2. Terrain Ahead - Funchal case study

This predictive EGPWS function uses a combination of a worldwide terrain database and an envelope to generate a warning when an aircraft is dangerously headed towards terrain.

Unlike basic modes, where entire flights were analysed to check for EGPWS warnings, in this function only a specific case was studied – the approach to runway 05 in Cristiano Ronaldo Airport (Funchal - "FNC" code). This is an ideal case study to test the Terrain Ahead function for two reasons.

First, this single approach is responsible for the great majority of "Terrain Ahead" warnings in all of TAP’s operation, which makes it the perfect case to be tested. Second, warnings in this approach are always triggered around the same area, and therefore only a very small part of the flight must be analysed. Since the computations required to test this function take a much longer time when compared to the basic modes, it would be unpractical to search for these warnings throughout an entire flight.

The first step to recreate the Terrain Ahead function is to create a Digital Elevation Model (DEM) of Madeira Island. The DEM is a digital model or 3D representation of a terrain’s surface, created from terrain elevation data. To simulate the EGPWS terrain database, the mesh obtained with DEM must have one simplification: each element of the mesh must have a constant altitude equivalent to the maximum altitude of terrain within that area element. Each element must cover an area of $15 \times 15$ arcsec, the resolution commonly used for mountainous areas near airports, like the one in Funchal.

The DEM was created using an R function that takes NASA’s SRTM terrain database as an input, and provides the user with discrete terrain elevation data for a certain location. This R function returns a much greater number of points per area than the resolution of the EGPWS database. The altitude assigned to each $15 \times 15$ arcsec element in the DEM is the maximum altitude that is provided by the R function for all points comprised in that element. Selecting the number of points needed to match the EGPWS database resolution, and generating 4-noded rectangular elements around those points, the DEM shown in Figure 6 is obtained.

$$t_i = t_i + 1$$

Figure 6: Final DEM

There is one other crucial element to recreate this predictive function: the envelope. The envelope’s characteristics are presented in Figure 7.

The envelope consists of two trapezoids that are constantly attached to the aircraft’s nose and aligned with the aircraft’s track. With an initial width of $480m$, the envelope diverges at a $1.5^\circ$ angle on either side as it extends outward in front of the aircraft.

(a) Top view

(b) Side view

Figure 7: Envelope features
Both trapezoids have a length that corresponds to a distance of 20 seconds times the Ground Speed (GS). The first trapezoid makes an angle equal to the aircraft’s FPA with the horizontal direction, while the second trapezoid makes an angle of 16° with this direction.

In this predictive function, at every second of the flight a different portion of terrain in the EG-PWS database is analysed, according to the GPS position of the aircraft and the aircraft’s track.

Naturally, only terrain cells that are directly below/above the envelope of the aircraft can potentially produce a warning. However, it is not possible to directly select such cells, since a great amount of computation is required to identify them. Therefore, an initial cell selection was made through the maximum and minimum values of latitude and longitude of the 4 corner points of the envelope, even though this selection includes many cells that are not within the envelope area, as shown by the green cells of Figure 8.

Figure 8: Selected terrain cells

Usually only the 4 nodes of each cell were used in the conflict detection between cells and envelope, as these are the points that are most likely to break the envelope. However, when the envelope only covers a small part of the cell, an extra point belonging to the cell’s edges is added in the conflict search. The use of a variable mesh allows a time reduction in R computation, yet maintaining a high accuracy in the analysis made.

The conflict detection between the envelope and terrain cells consists in an altitude comparison between the two objects, that can only be performed if both are defined in the same reference frame and the same units, which is currently not the case.

On the one hand, the envelope is given in meters and it is aligned with a reference frame known as the wind axis. On the other hand, terrain cells are given by their three geodetic coordinates (latitude, longitude and altitude) defined on a geodetic system, which is a conversion from an Earth-Centered Earth-Fixed (ECEF) reference frame.

The conversion process from geodetic coordinates to meters is not a direct one because the length of a degree of latitude and longitude depends on the latitude of the area that is being considered, since latitude influences both the meridian radius of curvature $M$ and the prime vertical radius of curvature $N$, as shown by equations 7 and 8 [11].

$$M = \frac{a \left(1 - e^2\right)}{\left(1 - e^2 \sin^2 \phi\right)^{3/2}}$$

$$N = \frac{a}{\left(1 - e^2 \sin^2 \phi\right)^{1/2}}$$

where $e$ and $a$ represent, respectively, the first eccentricity and the semi-major axis of an ellipsoid representing planet Earth.

The radius of curvature of the parallel that passes through a point with latitude $\phi$ is given by:

$$R_\phi = N \cos \phi$$

Finally, multiplying equations 7 and 9 by $(2\pi)/360$, one can obtain the length of one degree of latitude and longitude, respectively.

Introducing an auxiliary reference frame centered in the aircraft position, known as the local North-East-Down frame (shown in a green color in Figure 9), it is possible to compute the position vector’s components of each node of a terrain cell. As the aircraft position is always known, this computation process consists in calculating the differences of latitudes, longitudes and altitudes between the cell nodes and the aircraft, and then converting the two former to meters using the equations shown above.

Figure 9: Position vectors in NED frame

Having the position vectors defined in the NED axis, it is now necessary to either rotate them into the wind axis, or rotate the envelope to the NED reference frame. Both solutions were implemented, due to the different advantages that each one offers.

In solution 1, the altitude comparison was done in the wind axis. The great advantage of this solution is the fast computation that is involved. However, this method loses some of its accuracy when either the aircraft’s FPA or the aircraft’s bank angle are not negligible. In solution 2, the altitude
comparison is performed using the local NED axis. Although its accuracy does not depend on the attitude of the aircraft nor the velocity vector direction, the computations made in R are more complex, thus requiring considerably more time until finding out if a warning was triggered or not.

As in the two solutions both frames are centered in the same point, a rotation from one frame to another was performed using the Euler angles and rotation matrices. In this problem, the 3 Euler angles $\psi$, $\theta$ and $\phi$ correspond, respectively to the track angle, the FPA, and the bank angle.

In solution 1, after rotating the cells to the wind axis, a warning is triggered by the first trapezoid of the envelope if the cell’s position vector meets Equations 10, 11 and 12.

$$0 < x < 20\, GS$$ (10)
$$z < 0$$ (11)
$$-\tan(1.5^\circ)x - \frac{480}{2} < y < \tan(1.5^\circ)x + \frac{480}{2}$$ (12)

For a warning to be triggered by the second trapezoid of the envelope, Equations 12, 13 and 14 must be true.

$$20GS < x < 20GS + 20GS \cos(16^\circ - FPA)$$ (13)
$$z < -(x - 20\, GS) \tan(16^\circ - FPA)$$ (14)

In solution 2, the envelope was transferred to the local NED frame, which means that all 6 corner points that fully define the envelope were rotated to that frame. Once again, the Euler rotation matrix was used, with the same Euler angles of solution 1 (track angle, FPA and bank angle). However, this time, since the rotation is happening in the opposite direction, the rotation matrix is the transpose of the one used for solution 1.

The volume above the envelope, where a terrain cell must lie for a warning to be triggered, can be defined making use of geometry and the general equation of a plane:

$$a\, x + b\, y + c\, z = d$$ (15)

For each trapezoid defining the envelope, it is possible to find, in the NED axis, the equation of the plane that contains the trapezoid (since three points define a plane), and the equations of 4 auxiliary planes, each containing an edge of the envelope and being parallel to the vertical direction. Finally, transforming these 5 equations into inequalities, it is possible to mathematically define the required volume.

5. Results

In this section the results of this work – obtained using the algorithms explained in the previous chapter – will be compared with the actual data concerning EGPWS warnings that was recorded in flight.

Every aircraft has a flight recorder which records multiple parameters, including the activation of an EGPWS warning, using different parameters for each mode, thus allowing for an individual analysis of each mode and an identification of the modes with the best and worst results.

The comparison between a real warning and the computed warning is done, for each mode, through the seconds in which both have occurred. Unless otherwise indicated, a computed warning is considered correct if the time difference to the actual warning is not greater than 5 seconds.

5.1. Basic modes

For the EGPWS basic mode analysis, two different flight batches were considered: one having all flights with an EGPWS basic mode warning in the period between January 2016 and June 2018, and another containing all flights occurred in January 2018, except those already included in the first batch.

To have a better comprehension of the results, 4 indicators were used: the Percentage of True Warnings Detected ($PTWD$), the Percentage of Valid Warnings Computed ($PVWC$), a Global Percentage ($GP$), and the Percentage of Correctly Computed Flights ($PCCF$),

$$PTWD = \frac{TWC}{RW} \times 100$$ (16)
$$PVWC = \frac{TWC}{ToWC} \times 100$$ (17)
$$GP = \frac{TWC}{RW + Out} \times 100$$ (18)
$$PCCF = \frac{CCF}{F} \times 100$$ (19)

where $TWC$ stands for true warnings computed, $RW$ corresponds to the number of real warnings, $ToWC$ is the number of total warnings computed, $Out$ stands for outliers, $CCF$ is the number of correctly computed flights, and $F$ corresponds to the total number of flights.

5.1.1 Mode 1

Mode 1 had excellent results, as $PTWD = 96.43\%$, $PVWC = 100\%$, $GP = 96.43\%$ and $PCCF = 99.97\%$. This corresponds to 0 outliers, and only 2 undetected warnings. The undetected cases for this mode occurred with a combination of
vertical velocity and radio altitude very close to the boundaries of the envelope. It may have happened that the envelope was broken for a short moment between two consecutive recorded seconds.

5.1.2 Mode 2

Mode 2 was considered one of the greatest flaws of GPWS, due to the excessive number of nuisance warnings emitted, that led to a disbelief in this system by some pilots. This problem was fixed with the introduction of the EGPWS, due to an enhanced function called envelope modulation. This function was created to avoid false warnings at well-identified locations where warnings were generated during maneuvers that were consistent with the airplane’s operation [12].

Since this enhanced feature was not recreated for this analysis, mode 2 had very poor results, with several outliers. Nevertheless, it is interesting to note that these outliers tended to happen in specific areas, creating clouds of computed warnings (Figure 10), thus confirming that such areas are probably inhibited by the envelope modulation feature.

![Figure 10: Mode 2 computed warnings in Lisbon](image)

Even if the results were not good, the tool detected all real warnings. One of the flights with real warnings was extensively studied. This flight was chosen as the warning was emitted in an area where several warnings had been wrongly computed, which suggests that this might correspond to an inhibited area. However, this study showed that when the warning was generated the aircraft's heading was greater than in any other flight that has gone through the same area. This seems to indicate that the envelope modulation inhibitions were set using not only the GPS position but also the aircraft's heading.

5.1.3 Mode 3

Mode 3 is responsible to warn for situations when the aircraft is descending in periods where it was supposed to be climbing. It is active during take-off and low altitude go-around, until the aircraft gains sufficient altitude. The biggest challenge in mode 3 was to identify the altitude that was sufficient to reset the mode. Using a height level reset of 1500ft the results were \( PTWD = 69.57\% \), \( PVWC = 36.36\% \), \( GP = 31.37\% \) and \( PCCF = 99.84\% \). The poor results that were obtained were caused by an enormous number of outliers and some undetected warnings, which means the height level reset was not correctly implemented.

A detailed case-to-case inspection revealed that many outliers occurred after a period where the aircraft’s height remained approximately constant. Therefore, a stabilization period reset, defined as 65 seconds with the aircraft’s vertical speed modulus below 500 ft/min, was added.

Additionally, it was also noted that when the aircraft is climbing and the crew pulls the flaps up, any subsequent change in the flaps configuration is interpreted by the EGPWS as conscious will of the pilot to land the aircraft, and thus no warnings are emitted. Finally, the height level was increased to 1650 ft in order to detect extra real warnings.

The results using this modified reset conditions were much better, with \( PTWD = 91.30\% \), \( PVWC = 67.74\% \), \( GP = 63.64\% \) and \( PCCF = 99.90\% \).

5.1.4 Mode 4

Mode 4 results are \( PTWD = 64\% \), \( PVWC = 94.12\% \), \( GP = 61.54\% \) and \( PCCF = 99.85\% \).

In this mode there were 9 undetected warnings that can all be explained by a FDM limitation. In fact, in this mode an important parameter, known as flap landing configuration, is not recorded.

To overcome this problem the flap configuration in which the aircraft actually landed was adopted. However, this solution was not completely effective, since in those 9 situations the warning was generated when the aircraft had landing gear down and its flaps in this computed landing configuration.

If these 9 flights are ignored, the results improve significantly, with \( PTWD = 100\% \), \( PVWC = 94.12\% \), \( GP = 94.12\% \) and \( PCCF = 99.99\% \).

5.1.5 Mode 5

Mode 5 warnings are the most common EGPWS warnings. This mode serves to alert pilots when the advised 3 degree approach is not being correctly followed, and it is active between 1000ft and 30 ft when a valid glideslope beam is being received.

In the analysis of mode 5, an extra condition for this mode to be active was added, which consisted in the aircraft’s recorded HEIGHT parameter also
being above 30 ft. HEIGHT is a computed parameter which measures altitudes above the airport’s altitude using barometric altitudes. With this new condition, warnings that are triggered at very low altitudes are inhibited. At such low altitudes, not only the glide signal is not very reliable, as the presence of a warning would probably have a negative effect on the pilot’s behavior.

The results for this mode are $PTWD=99.4\%$, $PVWC=83.76\%$, $GP=83.33\%$ and $PCCF=99.55\%$.

5.2. Terrain Ahead enhanced function

This function was recreated with the intention of discovering if a given approach to FNC airport had triggered a warning or not. In Figure 11 the trajectories of all 232 flights were smoothed and plotted in Google Earth using a green color for warning-free flights and a red color for flights with warning.

![Figure 11: Smoothed trajectories landing on FNC](image)

In this figure, a middle zone with similar trajectories for both red and green colors can be seen. This is an indicator of the extreme difficulty of recreating this function in this particular case study, since a very small modification of one of the aircraft parameters could be the difference between a safe flight and a flight with warning.

The funnel-shaped convergence envelope, explained in section 3.2, could not be accurately simulated, due to the complicated shape of the convergence envelope and the advanced computations that the EGPWS uses to predict if the aircraft will converge to the envelope’s area or not. Instead, an alternative approach was used to define the inhibition period of this function.

Statistical studies revealed that no warnings occurred for an aircraft position with a true bearing greater than 213° nor a heading angle less than 50°. Therefore, these two conditions were established to inhibit warnings, roughly simulating the convergence envelope.

<table>
<thead>
<tr>
<th>RW</th>
<th>$CW^V$</th>
<th>$0$</th>
<th>$1^{(1)}$</th>
<th>$1^{(0)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>97</td>
<td>–</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>77</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Terrain ahead results

The results of this function can be found in Table 1, where $RW$ stands for real warnings, $CW$ stands for computed warnings, and the superscript $V$ indicates the number of valid warnings, among the computed ones. Using the usual 4 indicators, the results were $PTWD=72.6\%$, $PVWC=65.8\%$, $GP=57\%$ and $PCCF=75\%$.

Table 1 was built using solution 1. However, the results were very similar using solution 2, with only one flight having a different warning outcome. This proves the good accuracy of both methods and leads to the conclusion that the flaws in this function are not caused by the actual conflict detection method.

Among possible errors, one can highlight the use of the SRTM terrain database, which may not be the database used in the EGPWS internal computer, the set of inhibitions that probably do not correctly simulate the convergence envelope, and possible wrong envelope features.

6. R_TAWS tool

All algorithms developed in this work were aggregated in a single interactive application created using Shiny Dashboard R package. This package is capable of producing an app with an appealing output that is dependent on a user’s input.

The R_TAWS tool that was created in Shiny is divided in three tabs. The first one displays statistical data of all EGPWS warnings in TAP’s operation for a period of time selected by the user.

![Figure 12: R_TAWS - Second tab - Mode 1](image)

In the second tab the user is asked to load a file and the envelopes of EGPWS basic modes are shown with all warnings marked with small dots (see Figure 12).
Finally, in the last tab, the user is asked to load a file whose landing runway corresponds to FNC runway 05 in order to see if a Terrain Ahead warning (Figure 13) was generated. In such cases, the tool is able to link R and Google Earth through a feature that automatically generates KML files. These files can be used to perform a visual analysis of the conflict between terrain cells and the envelope of the Terrain Ahead function. (yellow pin in Figure 14).

![Figure 13: R_TAWS - Third tab - RGL window](image)

**Figure 13: R_TAWS - Third tab - RGL window**

Finally, in the last tab, the user is asked to load a file whose landing runway corresponds to FNC runway 05 in order to see if a Terrain Ahead warning (Figure 13) was generated. In such cases, the tool is able to link R and Google Earth through a feature that automatically generates KML files. These files can be used to perform a visual analysis of the conflict between terrain cells and the envelope of the Terrain Ahead function. (yellow pin in Figure 14).  

**Figure 14: KML file read by Google Earth**

### 7. Conclusions

This work sought to understanding one of the most complex and important TAWS systems used in aircraft nowadays – the EGPWS. The different algorithms developed were assembled in a complete and unique tool capable of detecting EGPWS warnings using only flight data files. This tool allows automatically validations of EGPWS occurrences recorded in flight within an airline’s operation. In the development of the tool, one of the greatest concerns was to understand the inhibition periods for each EGPWS mode in order to avoid the triggering of warnings in safe situations.

With this work it was also possible to build and integrate a terrain database into an airline’s FDM programme, allowing to recreate the Terrain Ahead Alerting function. An extensive study on the problematic approaches to Funchal was made, by establishing an algorithm to detect conflicts between the terrain database and a previously studied envelope, replicating the function’s actual behaviour.

Finally, the tool has the ability to automatically generate KML files to be read by Google Earth and used to perform a visual analysis on the case study of Terrain Ahead warnings in Funchal.

### References


