Report for

UK Civil Aviation Authority

on

Class A Terrain Awareness Warning System (TAWS) for Offshore Helicopter Operations

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2. Executive Summary

Controlled flight into terrain is a major cause of accidents in helicopter operations which Terrain Awareness Warning Systems (TAWS) could help to address. However, existing helicopter TAWS are not considered to be optimised for the offshore operations undertaken by the majority of the UK’s medium/large helicopter fleet, and would have offered little or no protection in the case of the accident scenarios that have been experienced in that environment. The objective of the research was therefore to seek to identify improvements to helicopter TAWS to improve warning times offshore without incurring an undue number of nuisance alerts. At the time of conducting the study, the Honeywell MKXXII Enhanced Ground Proximity Warning System (EGPWS) represented the only Class A helicopter TAWS in operational use. Due to the nature of the offshore obstacle environment, only the ‘Classic’ or non-database EGPWS modes are universally effective and this is therefore where the work was focussed.

Eurocopter EC225 flight data from Bristow Helicopters’ Flight Data Monitoring programme was used to establish the limits of normal operations. This enabled the Classic Mode warning envelopes and their associated input parameters to be refined, and also allowed new warning envelopes to be developed. The revised and new warning envelopes were tested using the available data from four accidents and demonstrated a worthwhile improvement in performance in terms of warning time, while maintaining an acceptably low nuisance alert rate of less than 1 in 100. A lower nuisance alert rate might be achieved in practice, but a larger sample of the database of normal operations would be required to demonstrate this.

All of the work was based on the Eurocopter EC225 which has a relatively high performance margin and a sophisticated autopilot. It is possible that the TAWS developments proposed may therefore be unsuitable for other helicopter types which may exhibit greater flight path variability during normal operations. Although not essential, it is highly desirable that any TAWS have the broadest possible applicability in order to avoid the need to tailor the system to each different helicopter type. The study is therefore being extended to a second, dissimilar helicopter type which may result in modifications to the proposed new warning envelopes.

The purpose of this ‘informal’ interim report is to update interested parties on the progress of the project up to the completion of the EC225 study. The need for further work has already been identified and is described in Section 9, some of which (i.e. the extension to a second helicopter type), is under way. It is anticipated that a final overall project report will be published in the form of a CAA Paper on the UK CAA’s website when the project has been concluded. The results contained in this report should therefore be regarded as preliminary and subject to change, and should be treated accordingly.
3. Background

Controlled flight into terrain (CFIT) is a major cause of accidents in helicopter operations [1]. The following CFIT accidents have occurred to helicopters conducting Commercial Air Transport in an offshore environment:

- S76B 1997 – L7A platform [5]

This type of accident has been addressed with some success in fixed-wing operations through the provision of Terrain Awareness Warning Systems (TAWS). In fixed-wing applications, the ‘Enhanced Mode’ or look-ahead database mode forms the primary means of alerting the crew to approaching terrain with the consequence that the thresholds for the ‘Classic Modes’ or non-database modes have been set sufficiently low as to minimise the false alarm rate.

Following the accident involving the S61 approaching the Scilly Isles (G-BEON) the UK CAA mandated the fitting of a low height aural warning system for overwater operations, with the RACAL Automatic Voice Alerting Device (AVAD) becoming the standard system. This requirement was later adopted into JAR OPS 3.660. The combination of radio altitude and AVAD provides a basic form of Ground Proximity Warning System (GPWS) which has one fixed and one pilot selectable low height warning threshold. In recent years, however, the Honeywell MKXXII Enhanced Ground Proximity Warning System (EGPWS) has become available as a Class A helicopter TAWS and has been fitted to a number of helicopter types. Unfortunately the Enhanced Mode has proven not to be very effective for offshore operations: transient obstacles such as large ships and construction barges (some up to 500ft in height) can be within the offshore area; it is difficult to maintain the obstacle database to keep track of mobile installations; and, due to the relatively low resolution of the database compared to the large size of many installations, there have been a large number of nuisance warnings. Some OEMs have chosen to implement EGPWS on their products in a manner which has led to an inadvertent increase in the false alert rate when approaching and departing obstacles. Due to the absence of any ‘terrain’ during offshore operations, the Enhanced Mode provides nothing that could not be achieved utilising existing real-time detection systems (e.g. weather radar, Automatic Identification System (AIS)) and modifying the warning envelopes of the Classic Modes to provide the best compromise between warning time and nuisance alert rate.

1 Note that the AVAD specification in CAP 562, Leaflet 11-35 allows the fixed threshold to be set anywhere between 100 ft and 160 ft. The majority of the North Sea helicopter fleet have this set to 100ft but some (e.g. CHC Scotia AW139, set to 150ft) differ.
In order to optimise the EGPWS Classic Modes, and future helicopter Class A TAWS, HOMP/FDM data has been used to refine the Classic Mode warning thresholds. The implementation of HOMP/FDM has resulted in a large amount of real-world operational data being collected. The HOMP database has been ‘mined’ to determine where Classic Mode thresholds should be set in order to provide the most opportune warning to the crew while keeping the false alarm rate at an acceptable level.

4. Supply of data

The data for the ‘pilot’ study (and the subsequent analysis of a full year of operations) was supplied by Bristow Helicopters on DVD. The files supplied contained multiple flights which were extracted using the British Airways Flight Data Analysis (BAFDA) software. The DVD contained 300 files.

For the purposes of the trial, 20 files were processed from 3 aircraft (G-ZZSA/B/C). Data was extracted for each take-off and landing, the extracted files containing the required parameters stored in comma separated value (CSV) format. Take-off files contained data between lift-off and 1000 ft (radio), landing files contained data for 1000 ft (radio) to touchdown. The BAFDA software was also configured to extract data if the EGPWS Mode 3 or Mode 4 criteria were satisfied.

Once the process of data extraction had been proven by the ‘pilot’ study, the full data set of approximately 800 flights was processed. This data set contained 350-400 offshore landings which were used for the main study.
5. Applicable EGPWS Modes

The following descriptions are applicable to the Honeywell EGPWS as installed on the Bristow Helicopters Eurocopter EC-225 aircraft.

5.1. Mode 1 – Descent Rate

Initially, the voice alert “Sink Rate” will be heard, and an amber caution alert generated. If the aircraft continues in the high rate of descent, the “Sink Rate-Sink Rate” voice alert will be repeated at an increasing frequency. Should the aircraft penetrate the warning boundary, the voice alert “Pull Up” will be heard continuously and the red warning generated.

In both cases, as the pilot reacts to decrease the high rate of descent and the aircraft flight path exits the alerting/warning envelope, the annunciation will extinguish and the voice alerts will cease. Sometimes, the alerting and warning functionality for excessive rate of descent may be overridden by the terrain “Look-Ahead” functionality. This is normal as the “Look-Ahead” function has a higher priority in the MK XXII alerting/warning logic. (See the Alerting/Warning Priority chart later in this guide.)

Mode 1 is inhibited if no Engine Torque input is configured at time of installation. Mode 1 is also inhibited during a detected autorotation on aircraft with a torque input or when Low Altitude is selected. The Mode 1 voices are inhibited during a Timed Audio Inhibit.

5.2. Mode 2 – Terrain Closure

Mode 2 provides alerts when the aircraft is closing with the terrain at an excessive rate. It is not necessary for the aircraft to be descending in order to produce a Mode 2 alert, level flight (or even a climb) towards obstructing terrain can result in hazardous terrain closure rate. The Terrain Closure Rate variable is computed within the EGPWS computer by combining radio altitude and vertical speed.

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2 Text based on material extracted from [8] by kind permission of Honeywell International Inc.
3 Mode 2 is inhibited when the ‘Enhanced Mode’ is operating.
Mode 2 has two sub-modes, referred to as Mode 2A and Mode 2B, the active sub-mode being determined by aircraft configuration and airspeed. Mode 2 uses an integrity view, which indicates how well Terrain Awareness & Display and Geometric Altitude functions are performing in conjunction with the terrain data integrity. When these conditions are satisfied Mode 2 functions are inhibited.

*Mode 2 is inhibited by the Low Altitude Mode and during an Autorotation. The Mode 2 voices are inhibited during a Timed Audio Inhibit.*

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**Mode 2A - Excessive Terrain Closure Rate**

Mode 2A is enabled when the conditions for enabling Mode 2B are not satisfied (see below). If the aircraft penetrates the Mode 2A alerting envelope, the aural message “Terrain Terrain” is generated initially, and the amber caution generated. If the aircraft continues to penetrate the envelope, then the aural message “Pull Up!” is repeated continuously until the warning envelope is exited and the red warning generated. As shown in above, the upper boundary of the Mode 2A alert envelope varies as a function of aircraft speed. As airspeed increases from typically 90 knots to 130 knots, the boundary expands to provide increased alert times at higher airspeeds. Expansion airspeeds are varied for some aircraft types.

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**Mode 2B - Excessive Terrain Closure Rate**

Mode 2B provides a “desensitized” alert envelope, permitting normal landing approach manoeuvring close to the terrain without producing unwanted alerts. Mode 2B is enabled for three conditions:
Whenever the Landing Gear is down or for fixed gear aircraft, when less than 80 knots and less than 200 ft. AGL.

- If the aircraft is performing an ILS approach and is within ±2 dots of the Glideslope centreline.
- For the first 60 seconds after takeoff.

When the Mode 2B warning envelope is penetrated, the aural message “Terrain....” is repeated until the envelope is exited and the amber caution lights are illuminated.

5.3. **Mode 3 – Descent after Take-off**

Mode 3 provides alerts when the aircraft loses a significant amount of altitude immediately after takeoff or during a missed approach. Mode 3 is enabled after takeoff or go-around when landing gear is not in landing configuration, or when the airspeed is greater than 50 knots. The mode stays enabled until the EGPWS computer detects that the aircraft has gained sufficient altitude that it is no longer in the takeoff phase of flight which in normal conditions is about 60 seconds.

The Altitude Loss variable is based on the Altitude value from the time of the beginning of the inadvertent descent. The amount of altitude loss, which is permitted before an alert is given, is a function of the height of the aircraft above the terrain and the length of time since takeoff.

If the aircraft penetrates the Mode 3 boundary, the aural message “Don’t Sink” is generated, the amber caution lights generated. The visual enunciators remain active until a positive rate of climb is re-established.

As the pilot adjusts the flight path of the aircraft and a positive rate of climb is re-established, the voice alert “Don’t Sink” will cease and the amber caution annunciation will extinguish. Note: To prevent nuisance “Don’t Sink” warnings while manoeuvring around an airport where airspeeds may exceed 50 knots it is recommended that the Low Altitude Mode be selected.

*Mode 3 voices are inhibited while the Timed Audio Inhibit is active.*
5.4. Mode 4 – Unsafe terrain Clearance

Mode 4 provides alerts for insufficient terrain clearance with respect to phase of flight and airspeed. Mode 4 exists in three forms, 4A, 4B and 4C. Mode 4A is active during cruise and approach with the gear not in landing configuration. Mode 4B is also active in cruise and approach, but with the gear in landing configuration. Mode 4C is active during the takeoff phase of flight with the gear not in landing configuration. The amber caution is illuminated during all Mode 4 warnings.

*Mode 4 voices are inhibited while the Timed Audio Inhibit is active.*

As shown in the figure below the standard boundary for Mode 4A is at 150 feet radio Altitude. If the aircraft penetrates this boundary with the gear still up and less than 100 knots, the voice message will be “Too Low Gear”. Above 100 knots the voice message is “Too Low Terrain”. For aircraft with a torque input, that can detect autorotation, during an Autorotation the gear warning boundary is raised to 400 feet AGL and the “Too Low Terrain” speed region is removed.

Fixed, non-retractable landing gear aircraft do not provide Mode 4A.

When the landing gear is lowered, Mode 4B becomes active and the boundary decreases to 100 feet when above 120 knots (100 knots for fixed gear). As airspeed decreases below 120 knots (100 knots for fixed gear) the warning boundary decreases to 10 feet at 80 knots. The voice message is “Too Low Terrain”.

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*Figure: Mode 4A and Mode 4B diagrams showing terrain clearance boundaries and voice messages.*
5.5. **Mode 5 – Below Glideslope**

Mode 5 provides two levels of alerting when the aircraft flight path descends below the Glideslope beam on front course ILS approaches with the gear down. The first alert activation occurs whenever the aircraft is more than 1.3 dots below the beam and is called a “soft” Glideslope alert. That is because the volume level of the “Glideslope” alert is approximately one half (-6 dB) that of the other alerts. On a normal approach where the aircraft is established on the Glideslope prior to reaching 1000 feet AGL the upper warning boundary is 1000 feet AGL. However as long as the aircraft is in level flight the upper boundary is set at 500 feet AGL. The upper boundary will increase linearly to 1000 feet AGL as descent rate raises from 0 to 500 FPM or greater. This allows intercepting the Glideslope at less than 1000 feet AGL without getting nuisance warnings. A second alert boundary occurs below 300 feet radio altitude with greater than 2-dot deviation and is called “loud” or “hard” Glideslope alert because the volume level is increased to that of the other alerts. The amber Caution is also illuminated during both soft and hard Glideslope alerts.

Mode 5 is enabled when all of the following are present: ILS selected with valid GS signal (flag not in view); valid radio altitude less than 1000 ft. AGL; Landing Gear Down retractable gear helicopters only); Glideslope Cancel is off. The EGPWS computer must be sensing it is in the Approach Mode (not Takeoff) or the groundspeed is less than 40 kts with the above conditions met. In some installations the localizer signal is used to enable ‘Envelope Modulation’, to prevent nuisance warnings at certain airports.

*The Glideslope voice is inhibited while the Timed Audio Inhibit is active.*

5.6. **Mode 6 – Altitude Callout**

Mode 6 provides aural callouts for descent below predefined altitudes and Minimums. No Caution or Warning lights are illuminated. The actual callouts are selected from a menu at installation time.

A “minimums-minimums” callout is provided based upon the decision height discrete with the landing gear down or less than 90 knots in fixed gear aircraft. When Low Altitude is selected or gear is up or greater than 90 knots in fixed gear aircraft the
message “Altitude Altitude” is provided when transitioning below the selected decision height.

An optional discrete input provides the ability to force the Mode 6 audio level to lower audio volume. This enables operators to control the Mode 6 volume level with activation of windscreen rain removal or if lower volume callouts are desired at all times.
6. Analysis - General

6.1. Pilot Study

The pilot study data set of 20 files contained both onshore and offshore operations, all of which was included in the study, albeit separated so that a comparison would be possible. The plot below shows the calculated ‘barometric’ (pressure) rate of descent (RoD) curve for all 20 flights, plotted on the Mode 1 chart.

The next plot shows offshore data only (13 flights) displayed on the Mode 1 chart. This data was assumed to be ‘normally distributed’ and is shown as 3 descent rate curves - mean, 3σ and maximum, derived from the radio RoD values.
Radio RoD from the 20 pilot study files, containing both onshore and offshore operations, is also shown plotted on the Mode 2 chart below.
The next plot shows offshore data only (13 flights) displayed on the Mode 2 chart. Again, this data was assumed to be ‘normally distributed’ and is shown as 3 descent rate curves - mean, $3\sigma$ and maximum, derived from the radio RoD values.

In the above example, it can be seen that the plots did not appear as expected, with the $3\sigma$ curve exceeding the maximum. This is indicative that the data are not normally distributed, although the small dataset used in pilot study is believed to also have contributed to this result. (See Section 6.2.1)

### 6.2. Issues Raised by Trial Analysis

#### 6.2.1. Review of plots from multiple flights

The original brief for the trial was to produce ‘scatter plots’ depicting the RoD profile for each height band (10 ft increments). However, it was recognised that plotting the calculated descent rates for individual flights is not particularly helpful and that plots of aggregated results were required. Initially, the assumption was made that the data would be normally distributed and thus it would be meaningful to present curves for the mean, $3\sigma$ and maximum RoD covering the height bands. However, in order to validate the assumption of the data being ‘normal’, plots were produced for a range of height bands showing the distribution of RoDs. The plots below show the distribution of RoDs (blue line) and the corresponding normal distribution (red line) having the same mean value and standard deviation as the actual data at heights of 1000ft and
300ft. It is clear from inspection that the data is not normally distributed and that the use of the 3σ curve would therefore not meaningfully represent the statistical variability of the data.

**RoD Distribution - 1000ft and 300ft**

![RoD Distribution Graphs](image)

**6.2.2. Presentation of Aggregate Data**

Having discounted presentation of the data as if normally distributed, it was decided to revert to plotting the n<sup>th</sup> percentile in order to present the data in a way that would be statistically relevant. The objective of this approach was to provide a curve which would define an acceptable false alarm limit. The corresponding false alarm rate would not be exceeded provided that this curve and the warning envelope did not impinge on each other. Although the false alarm rate should be as low as practical, it is also necessary to provide adequate warning of an impending collision and it was expected that a compromise solution would be needed. It was anticipated that the style of plots proposed would facilitate the process of establishing the best compromise.

Due to the limited data set available for the analysis (approximately 400 offshore landings), it was decided to plot the 99<sup>th</sup> percentile curve, representing a potential false alarm rate of 10⁻². A larger data set would be required in order to draw curves for lower false alarm rates.

**6.2.3. Onshore vs Offshore**

Initially, during the proof-of-concept trial, data was extracted from a small number of flights, and descent rates were investigated for both on and offshore landings. However, with effective enhanced modes available and the limited time that offshore helicopters spend over land, it was decided that the study should focus on offshore operations.

Thus, for the purposes of the full study, only offshore landing data was used. It should be noted however that the process of excluding the onshore landings was not considered to be foolproof (insufficient indicators in the data) and there may be a small number remaining. However, this issue is not thought to be significant enough to invalidate the results.
6.2.4. Low Airspeed & Deck Edge Effect

The basic measures of height and airspeed recorded by the Flight Data Recorder (FDR), and used for the purposes of this study, are subject to errors when the aircraft is travelling at low airspeeds. This is a known phenomenon caused by the downwash from the main rotor impacting the pressure measurements at the pitot and static vents where these parameters are measured. Thus, rates of change of pressure altitude and airspeed data cannot be relied upon below 30-40 knots and an alternative is required. Also, when operating offshore the radio altitude measurement is subject to a ‘step change’ as the aircraft crosses the edge of the helideck. Both of these effects were seen in the data from the FDR and affected the reliability of the RoD calculation at low altitudes.

In order to address these issues, consideration was given to using the ALTRATE parameter from the recorded dataframe. On the EC225, ALTRATE is the vertical speed parameter from the Attitude &Heading Reference System (AHRS) comprising a hybrid of barometric and inertial data with long term error-elimination provided by rate of change of pressure altitude performed within the AHRS using Air Data Computer (ADC) data. The weighting of the hybrid is primarily inertial, and so does not suffer from ground effect or rotor downwash. Since there is no contribution from radio altitude, it is not affected by deck edge crossing either.

Given the difficulty of calculating rates of descent from other recorded parameters, and keeping in mind that only offshore data would be assessed in the full study, the decision was taken to use ALTRATE at altitudes lower than 350 ft where it gave demonstrably better results than either barometric altitude (ALT) or radio altitude (RALT).

The results of this modification can be seen below on the revised Mode 1 and Mode 2 plots, showing the 99 percentile curves. These curves use the calculated RoDs (baro on Mode 1 and radio on Mode 2) above 350 ft and the recorded ALTRATE below 350 ft.\(^4\)

\(^4\) Note that Honeywell use inertial vertical speed if available, baro blended with GPS vertical speed if not. Inertial vertical speed is never blended with GPS vertical speed.
6.2.5. Training Flights & Auto-rotation

Where possible, training and autorotation was excluded from the data set. Training flights were mostly identified by take-off and landing locations, indicating that the flight in question was not a revenue operation. TAWS is automatically inhibited during autorotation, when both engine torques fall below 7.5%, thus a similar test was used to eliminate flights from the data set. The examples of autorotation (during training flights) observed during the trial analysis confirmed the desirability of inhibiting TAWS during autorotation, i.e. the rates of descent are significantly in excess of normal operations and warnings generated would be unhelpful.

6.2.6. Mode 3 – Descent after Take-off
The purpose of this mode is to detect descent after lift-off and before the aircraft has reached 60 knots IAS, therefore BAFDA was configured to output an ‘Event’ each time a height loss was detected in this flight regime. From the total flights processed, there were just two instances detected of descent after lift-off, both of these occurring during the transition from hover to forward flight and the height loss in both cases was less than 20 ft. It was suggested that, while this is not surprising for the EC225, for other types with a lower power/weight ratio there could be a different picture. It was therefore recommended that descent after lift-off continue to be monitored.

6.2.7. Mode 4 – Low Height

The purpose of this mode is to detect flight below a trigger altitude and the warning message is dependent on the speed of the aircraft. Thus, Mode 4 comprises the following:

**Mode 4A**

Below 150 ft, with an airspeed of over 100 kts, the warning “Too Low Terrain” is given.

Below 150 ft, with an airspeed below 100 kts and landing gear not selected down, the warning “Too Low Gear” is given.

The analysis was configured to record an event each time the Mode 4A criteria were satisfied and no events were detected for the dataset used.

**Mode 4B**

With airspeed above 120 kts and landing gear selected down, Mode 4B becomes operative at a height of 100 ft and the warning “Too Low Terrain” is given. Below 120 kts, the attitude boundary reduces to 10 ft at 80 kts (as detailed in Section 5.4).

The analysis was configured to record an event each time the airspeed was recorded to be above 100 kts with height less than 150 ft, no events were detected for the dataset used.

**Mode 4C**

Mode 4C is specifically designed to detect flight towards rising terrain after take-off. It is thus deemed not to be relevant to this study, which is targeted at offshore operations.
7. Analysis Results

7.1. General

This section addresses each of the warning modes and, where applicable, shows how the operational and accident data relates to the warning envelopes. In general, it can be seen that there is a significant margin between 'normal operation', as defined by the 99 percentile lines, and the warning envelope boundaries permitting modification of the envelopes to provide an earlier warning to the crew.

Each point on the 99 percentile lines representing 'normal operations' contains 99% of the calculated RoD values for the corresponding 10ft height bands. Above 350 ft, RoD is a calculated value from ALT (barometric) or RALT (radio) is used depending on whether Mode 1 or Mode 2 is under consideration. Below this height the recorded value of ALTRATE is used.

Flight path data from the G-BLUN [6], G-TIGH [4], G-BEON [3] and G-REDU [7] accidents is shown on the relevant plots to indicate the amount of warning time that could be expected with the existing warning envelopes. The flight path data was derived from the FDR in all four accidents except for G-BEON where it was estimated from the reported flight path; no flight path data is available for G-BIJF [2] or G-BHYB [5]. It should be noted that in none of the accidents for which the data is shown was there an ‘active’ EGPWS, hence warning times have been estimated from the FDR data.

7.2. Mode 1 – Descent Rate

Mode 1 monitors descent rate throughout the flight and compares it with the warning envelope. The envelope is based on the rate of change of barometric (pressure) altitude (see footnote 4 on page 19) in relation to height above the ground (radio height). A more detailed description of Mode 1 warning can be found in Section 5.1.

7.2.1. Existing Warning Envelope

The two diagrams below show the results of the rate of descent analysis and the accident data plotted on the Mode 1 warning envelope. The first of the two diagrams shows only the 99 percentile line and clearly indicates the potential to re-define the envelope without significant risk of an unacceptable false alarm rate. This is illustrated by the dashed purple line which represents the recommended new warning envelope.
For reasons of clarity the second diagram only shows the last 350ft of the rate of descent profile, to which the FDR data from the four accident cases has been added. The key to the descent rate plots for the accident data is as follows:

- **G-BEON** - Sikorsky S61N - Black
- **G-TIGH** - Eurocopter AS332 - Green
- **G-BLUN** - Eurocopter AS365N - Red
- **G-REDU** - Eurocopter EC225 - Orange

The respective plots for the accident cases have been identified with timings to indicate seconds prior to impact. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be deduced. As can be seen, a useful warning (seven seconds) is generated by current TAWS in one accident case only (G-BLUN).
7.2.2. Recommendations

The effect of the modified Mode 1 warning envelope on the warning times for the four example accident cases is shown in the table below.

<table>
<thead>
<tr>
<th>Accident</th>
<th>‘Sink Rate’</th>
<th>‘Pull-Up’</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-BEON</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>1.5</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>7.5</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td>G-REDU</td>
<td>7.0</td>
<td>1.5</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The modified warning envelope significantly improves the warning time for the G-REDU accident, and provides modest improvements for the G-TIGH and G-BLUN accidents. It is therefore recommended that consideration be given to the adoption of the revised envelope.

7.3. Mode 2 – Terrain Closure

Mode 2A monitors terrain closure rate throughout the flight and compares it with the warning envelope. The envelope is based on the rate of change of radio altitude in relation to height above the ground (radio height). A more detailed description of the Mode 2 warning can be found in Section 5.2.

Mode 2B was ignored for the purposes of the study. Forming a desensitised version of Mode 2A, any improvements in warning times for Mode 2A would be even greater for Mode 2B, and the nuisance alert rate is referenced to the envelope of normal operations.

7.3.1. Existing Warning Envelope

The two diagrams below show the results of the rate of descent analysis and the accident data plotted on the Mode 2A warning envelope. The first of the two diagrams shows only the 99 percentile line and clearly indicates the potential to re-define the
envelope without significant risk of an unacceptable false alarm rate. This is illustrated by the dashed purple line which represents the recommended new warning envelope.

For reasons of clarity the second diagram only shows the last 350ft of the rate of descent profile, to which has been added the FDR data from four accident cases. The key to the descent rate plots for the accident data is as follows:

- G-BEON - Sikorsky S61N - Black
- G-TIGH - Eurocopter AS332 - Green
- G-BLUN - Eurocopter AS365N - Red
- G-REDU - Eurocopter EC225 - Orange

The respective plots for the accident cases have been identified with timings to indicate seconds prior to impact. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be deduced. As can be seen, a warning is generated by current TAWS for one accident case only (G-BLUN) and this is of limited use as it triggers at seven seconds prior to impact and then ceases three seconds later; the flight crew might interpret this as meaning the danger had passed.
7.3.2. Recommendations

The effect of the modified Mode 2A warning envelope on the warning times for the four example accident cases is shown in the table below.

<table>
<thead>
<tr>
<th>Accident</th>
<th>Current</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-BEON</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>1.0</td>
<td>8.0</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td>G-REDU</td>
<td>0.0</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The modified warning envelope significantly improves the warning time for the G-REDU and G-TIGH accidents, and provides modest improvement for the G-BLUN accident. It is therefore recommended that consideration is given to the adoption of such a revised envelope.
7.4. **Mode 3 – Height Loss After Take-off**

Mode 3 is applicable and requires radio height to monitor height loss after take-off as a function of height. A more detailed description of the Mode 3 warning can be found in Section 5.3.

7.4.1. **Existing Warning Envelope**

The existing warning envelope, taken from Honeywell EGPWS Pilot's Handbook is shown below.

![Height Loss Graph](image)

There were no significant instances of descent after take-off in the data available for analysis. However, it is recognised that the EC225 operation is not necessarily representative of other aircraft types in that it has a high power/weight ratio and normal operational practice is to use AFCS 'Go-Around' mode for all take-offs. Thus, Mode 3 warnings may have a greater relevance to other types.

Furthermore, one of the accident aircraft under consideration (G-TIGH) suffered a significant loss of airspeed after take-off (see below) and while this ultimately resulted in a loss of height, a warning based on airspeed would potentially result in earlier detection and a greater warning time. It is therefore recommended that consideration is given to separating Mode 3 into two sub-modes; Mode 3A – Loss of height after Take-off (as per current definition) and Mode 3B – Loss of Airspeed after Take-off (as described in Section 7.4.2 below).
7.4.2. Mode 3B – Loss of Airspeed after Take-off

The new Mode 3B would be activated as for the current Mode 3A, i.e. at gear retraction after take-off or on achieving 50kt after take-off, remaining active for 60 seconds thereafter. Any reduction in airspeed during this time would result in a ‘Check Speed’ caution, any fall in airspeed below 50kt would result in a ‘Low Airspeed’ warning. G-TIGH was the only take-off accident under consideration and it can be seen from the plot of airspeed vs height that the 50kt ‘Low Airspeed’ warning would have been activated at 250 ft, 17 seconds prior to impact.

![IAS vs Height - Offshore](image)

7.4.3. Recommendations

The effect of the modified Mode 3 warning envelope on the warning times for the four example accident cases is shown in the table below.
<table>
<thead>
<tr>
<th>Accident</th>
<th>Current</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-BEON</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>0.0</td>
<td>17.0</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>G-REDU</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The modified warning envelope significantly improves the warning time for the G-TIGH accident, and providing nearly twice the warning time generated by the proposed new Mode 2A envelope. It is therefore recommended that consideration is given to the adoption of the additional Mode 3 (Mode 3B) envelope.

7.5. **Mode 4 – Terrain Clearance**

Mode 4 provides alerts for insufficient terrain clearance with respect to phase of flight and airspeed. This mode requires radio height, airspeed and landing gear position. A more detailed description of the Mode 4 warning can be found in Section 5.4.

7.5.1. **Existing Warning Envelopes**

The first figure below is a height vs speed diagram for the EC225, onto which the ‘99 percentile’ high airspeed curve (BLUE), and the existing Mode 4A (RED) and Mode 4B (GREEN) envelopes have been plotted.
The data from the four accidents has been added to the diagram below. The key to the descent rate plots for the accident data is as follows:

- **G-BEON** - Sikorsky S61N - Black
- **G-TIGH** - Eurocopter AS332 - Green
- **G-BLUN** - Eurocopter AS365N - Red
- **G-REDU** - Eurocopter EC225 - Orange

The data from G-TIGH and G-REDU has been included in this plot for reference, however both aircraft were configured for landing (gear down) with a relatively low airspeed (i.e. below the lower limit of the existing Mode 4B envelope) and thus would have received no warning.

The plots for G-BEON and G-BLUN have been identified with timings to indicate seconds prior to impact. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be deduced. As can be seen, in both cases the airspeed remains high throughout and it would appear that G-BLUN would have received a 7 second Mode 4A warning. G-BEON was configured for landing with gear down and would have received a Mode 4B warning 4 seconds prior to impact.
In view of the position of the ‘99 percentile’ curve, there would appear to be scope to extend the Mode 4A ‘Terrain’ warning envelope as indicated by the purple dashed line. (N.B. The height boundary has been increased to coincide with the 160ft upper limit of the AVAD fixed height warning that is currently available). This would have provided a generous warning of 24 seconds for the G-BEON accident case. Although this accident scenario is catered for by AVAD/Mode 6, the effectiveness of these warnings is compromised to some extent as they are routinely triggered during normal operations. Having the additional discriminant of airspeed, the proposed modified Mode 4A envelope would not suffer from this disadvantage.

7.5.2. Recommendations

The effect of the modified Mode 4 warning envelope on the warning times for the four example accident cases is shown in the table below.
### Warning Time (sec)

<table>
<thead>
<tr>
<th>Accident</th>
<th>Current</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-BEON</td>
<td>4.0</td>
<td>24.0</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>7.0</td>
<td>7.5</td>
</tr>
<tr>
<td>G-REDU</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The modified warning envelope significantly improves the warning time for the G-BEON accident, although it is noted that an adequate Mode 6 warning (15 sec) would have been provided (see 7.7 below). The adoption of the modified Mode 4 envelope is nevertheless recommended as it should not suffer from the same nuisance alert rate as the present Mode 6 and will cater for a broader range of accident scenarios. In addition, it is recommended that consideration be given to inhibiting the existing Mode 4B when offshore.

#### 7.6. Mode 5 – ILS Mode

This mode is associated with ILS Glideslope deviation and therefore has no current relevance to offshore operations.

##### 7.6.1. Existing Warning Envelopes

See Section 5.5.

##### 7.6.2. Recommendations

It is understood that the SBAS Offshore Approach Procedure (SOAP) will, in future, provide ILS ‘look-alike’ guidance and thus Mode 5 should be reconsidered at that time. It is noted that the thresholds for ‘soft’ and ‘hard’ warnings may need to be revised.
7.7. Mode 6 – Altitude Call-Outs

The current Mode 6 provides ‘AVAD-style’ fixed radio height threshold (operator pin programmable between 100 and 160ft). It also provides excessive bank angle and tail strike warnings, however, the study was limited to the altitude call-out functionality. A more detailed description of the Mode 6 warning can be found in Section 5.6.

7.7.1. Existing Warning Envelopes

The first figure below is a height-speed diagram, onto which has been plotted the current AVAD warning envelopes. In addition, the diagram shows the 99 percentile curve - RED (representing the low airspeed end of the distribution) and the 1 percentile curve – BLUE (representing the high airspeed end of the distribution). Finally, the diagram shows the upper (GREEN dashed line) and lower (BLUE dashed line) limits of the existing Mode 6 (AVAD⁵) warning envelope.

---

⁵ The term AVAD is used here, and elsewhere in the report, to signify a fixed boundary at which an alert is generated. It does not necessarily imply that an independent AVAD device is fitted.
The data from the four accidents has been added to the diagram below. The key to the descent rate plots for the accident data is as follows:

- G-BEON - Sikorsky S61N - Black
- G-TIGH - Eurocopter AS332 - Green
- G-BLUN - Eurocopter AS365N - Red
- G-REDU - Eurocopter EC225 - Orange

The respective plots for the accident cases have been identified with timings to indicate seconds prior to impact. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be deduced. As can be seen, Mode 6 warnings are generated for all four accidents with the higher fixed height threshold of 160ft providing earlier warnings than the 100ft threshold currently in common usage as expected.

7.7.2. Recommendations

The effect of raising the Mode 6 fixed height threshold from 100ft to 160ft on the warning times for the four example accident cases is shown in the table below.
Warning Time (sec)

<table>
<thead>
<tr>
<th>Accident</th>
<th>Current 100ft</th>
<th>Current 160ft</th>
<th>Recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-BEON</td>
<td>15</td>
<td>24</td>
<td>N/A</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>4</td>
<td>6</td>
<td>N/A</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>4</td>
<td>7</td>
<td>N/A</td>
</tr>
<tr>
<td>G-REDU</td>
<td>4.5</td>
<td>7</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The raised threshold significantly improves the warning time for the G-BEON accident, and provides modest improvement for the G-TIGH, G-BLUN and G-REDU accidents. It is therefore recommended that consideration is given to adopting a higher Mode 6 fixed height threshold of 160ft if Mode 6 is to be retained.

With reference to the review of Mode 4 in Section 7.5 above, however, consideration should be given to replacing the altitude call-out functionality of Mode 6 with a modified version of Mode 4 which would be more effective and less prone to nuisance alerts.

7.8. Exploratory Analysis

As well as investigating improvements possible through the modification of the existing TAWS warning envelopes, a number of alternative warning envelope designs were explored in order to seek greater discrimination between normal operations and accident scenarios. These included the following combinations of parameters:

- The four permutations of Radio RoD, baro RoD, rate of change of Radio RoD, rate of change of baro RoD.
- ALTRATE vs rate of change of ALTRATE.
- Airspeed vs Radio RoD.
- Airspeed vs baro rate of descent.

None of the combinations evaluated provided any benefit in terms of warning time compared to the results obtained by modifying the existing TAWS warning envelopes. The rationale for each of the combinations evaluated and the results obtained are presented in Appendix A for completeness and interest.
8. Conclusions

8.1. Warning Times

The overall benefit of adopting the proposed warning envelope modifications are summarised in the following tables.

The first table compares the performance of the proposed new TAWS warning envelopes with what could be achieved with the existing AVAD (TAWS/EGPWS Mode 6) both at the current most common setting of 100ft, and with the maximum setting allowed of 160ft. Significant improvements in warning times compared to the present 100ft AVAD setting are evident for three of the accident scenarios, and a worthwhile improvement is obtained in the case of the G-BLUN accident. The benefits are lower when compared to an AVAD setting of 160ft but still significant for two of the accident scenarios, and the proposed TAWS warning envelopes would be expected to generate significantly fewer nuisance alerts than an AVAD set to 160ft.

<table>
<thead>
<tr>
<th>Accident</th>
<th>Current AVAD (TAWS/EGPWS Mode 6)</th>
<th>Proposed TAWS</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100ft</td>
<td>160ft</td>
<td>Warning Time</td>
</tr>
<tr>
<td>G-BEON</td>
<td>15.0</td>
<td>24.0</td>
<td>24.0</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>4.0</td>
<td>6.0</td>
<td>16.0</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>4.0</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td>G-REDU</td>
<td>4.5</td>
<td>7.0</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The second table (below) compares the performance of the proposed new 'Classic' Mode TAWS warning envelopes with those of existing TAWS (Honeywell EGPWS). Significant improvements in warning times are provided for all of the accident scenarios except for G-BLUN, where only a modest improvement has proven possible.
8.2. Proposals for TAWS Modifications

Taking account of all of the results obtained during the study, the following changes to the existing Helicopter Class A TAWS are proposed for use when the aircraft is offshore (as determined by GPS position):

- Disable all ‘Enhanced’ Mode functionality when offshore.

- Delete the current ‘Classic’ Mode 1/replace the current ‘Classic’ Mode 1 with the new warning envelope recommended in Section 7.2.1.

- Replace the current ‘Classic’ Mode 2 with the new warning envelope recommended in Section 7.3.1.

- Retain the current ‘Classic’ Mode 3 as Mode 3A, and add a new ‘Classic’ Mode 3B with the same activation logic but monitoring for speed loss rather than height loss after take-off (see Section 7.4.2).

- Replace the current ‘Classic’ Modes 4A, 4B and 4C with the new ‘Classic’ Mode 4 warning envelope recommended in Section 7.5.1.

- Delete the altitude call-out section of the existing ‘Classic’ Mode 6.

<table>
<thead>
<tr>
<th>Accident</th>
<th>Current TAWS (EGPWS) excl. Mode 6</th>
<th>Proposed TAWS</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warning Time</td>
<td>Mode(s)</td>
<td>Warning Time</td>
</tr>
<tr>
<td>G-BEON</td>
<td>4.0</td>
<td>4B</td>
<td>24.0</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>1.5</td>
<td>1</td>
<td>16.0</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>7.0</td>
<td>1, 2A &amp; 4A</td>
<td>8.0</td>
</tr>
<tr>
<td>G-REDU</td>
<td>1.5</td>
<td>1</td>
<td>16.0</td>
</tr>
</tbody>
</table>
9. Further Work

This report covers the research performed to date which has necessarily been focussed on the technical challenge of modifying TAWS to provide timely warnings for foreseeable accident scenarios. It is considered that this initial objective has been met and that worthwhile improvements are possible in principle. It is recognised, however, that further work is required to fully define the TAWS modifications that would be required to realise an effective system.

9.1. Further Aircraft Types

All of the work in this study is based on the Eurocopter EC225 which has a relatively high performance margin and a sophisticated autopilot. It is possible that the TAWS developments recommended may therefore be unsuitable for other helicopter types which may exhibit greater flight path variability during normal operations. Although not essential, it is highly desirable that any TAWS have the broadest possible applicability in order to avoid the need to tailor the system to each different helicopter type. The study has therefore been extended to a second, dissimilar helicopter type which may result in modifications to the recommended new warning envelopes, or may result in the need for helicopter type-specific envelopes. The results of this work will be added to this report at a future update.

9.2. Further Case Studies

It is recognised that, at only four, the database of accidents is very limited and efforts have already been made to secure data for additional, relevant accidents. So far this exercise has been met with only limited success, but the search will continue and it is hoped that further case studies can be added to this report at a future update.

9.3. Warning Annunciation Options

Although very important, warning time represents only one aspect of an effective warning system. Any warnings generated must be clear, unambiguous and direct the pilot towards making the correct response quickly and efficiently. Warning type and content must therefore be considered both for existing Modes and for the new Modes proposed. There are choices to be made between visual, auditory and tactile warnings.

In the case of auditory warnings, the designer must choose between tone or attension, voice, and tone + voice. Any tone or attension used must be carefully designed to be easily distinguishable from others, and the content of voice warnings must clearly and quickly convey the action required of the pilot. The type of voice used is also very important. This subject has already received much attention and the report on the
literature review performed for the JAA Helicopter Sub-Sectorial Team (HSST) is attached at Appendix B for information.

The aspect of warning annunciation options will be addressed as the project progresses, and the results of this work will be added to this report at a future update.

9.4. Simulator Study

It is proposed that simulator trials be undertaken to re-enact accident scenarios to evaluate the usefulness of the proposed TAWS modifications. The warning envelopes, and warning annunciations could then be refined if necessary prior to completion of the project and publication of the results. It is not entirely clear how the modified warnings could be implemented in a training simulator, but one option might be to arrange for the production of a ‘red label’ modified EGPWS computer for installation in a level D simulator.

9.5. ‘Soft’ Warnings

This study has focused on the apparent large gap that exists between ‘normal operation’ and the existing TAWS warning envelopes, and proposals have been put forward as to how that gap can be reduced to increase warning times without the generation of a significant number of nuisance warnings. As yet however, there has been no significant discussion on the use of ‘soft’ warnings (e.g. EGPWS Mode 1 “Sink Rate” as opposed to the ‘hard’ “Pull Up” warning) and how these could be accommodated in the revised envelopes.

Due to their nature, only a relatively low nuisance alert rate can be tolerated for ‘hard’ TAWS warnings, limiting the amount of warning time that can be provided. Higher nuisance alert rates might be acceptable for ‘soft’ TAWS warnings, however, which could allow warning times to be extended further. It is therefore proposed that the use of ‘soft’ warnings be investigated.
10. References


### 11. Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Air Data Computer</td>
</tr>
<tr>
<td>AGL</td>
<td>Above Ground Level</td>
</tr>
<tr>
<td>AHRS</td>
<td>Attitude &amp; Heading Reference System</td>
</tr>
<tr>
<td>AVAD</td>
<td>Automatic Voice Alerting Device</td>
</tr>
<tr>
<td>BAFDA</td>
<td>British Airways Flight Data Analysis Program</td>
</tr>
<tr>
<td>CAA</td>
<td>Civil Aviation Authority (UK)</td>
</tr>
<tr>
<td>CFIT</td>
<td>Controlled Flight into Terrain</td>
</tr>
<tr>
<td>CSV</td>
<td>Comma Separated Variable</td>
</tr>
<tr>
<td>EGPWS</td>
<td>Enhanced Ground Proximity Warning System</td>
</tr>
<tr>
<td>FDM</td>
<td>Flight Data Monitoring</td>
</tr>
<tr>
<td>FDR</td>
<td>Flight Data Recorder</td>
</tr>
<tr>
<td>FPM</td>
<td>Feet per Minute</td>
</tr>
<tr>
<td>GPWS</td>
<td>Ground Proximity Warning System</td>
</tr>
<tr>
<td>GS</td>
<td>Glide Slope (ILS vertical axis)</td>
</tr>
<tr>
<td>HOMP</td>
<td>Helicopter Operations Monitoring Programme</td>
</tr>
<tr>
<td>IAS</td>
<td>Indicated Air Speed</td>
</tr>
<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
</tr>
<tr>
<td>RoD</td>
<td>Rate of Descent</td>
</tr>
<tr>
<td>TAWS</td>
<td>Terrain Awareness Warning Systems</td>
</tr>
</tbody>
</table>
Appendix A – Exploratory Analyses

A.1 Rate of Descent vs Rate of Change of Rate of Descent

Warning envelopes based on RoD vs rate of change of RoD were proposed for investigation in an attempt to increase the warning time for the G-TIGH accident. It was thought that the increase in RoD evident in the RoD profile for the accident might provide an opportunity for early detection that could be discriminated from normal operations. The four permutations of radio and baro RoD and rate of change of RoD were plotted but the results appeared to be affected by deck edge crossing (radio RoD) and the effects of rotor downwash on baro RoD at low airspeeds. These four plots were consequently replaced with the single plot of altrate vs rate of change of altrate shown below.

From the above plot, it appears as though normal operations are confined to a relatively small area defined by the cluster of light blue (90%) and red (99%) points to the right of the origin. With this in mind a possible boundary line was draw which excluded all climbing flight as well as the 99% data and would produce a warning where either rate of descent is abnormally high, or is increasing abnormally. It was found that this would have provided significant warnings for G-BLUN and G-REDU, but no significant benefit in terms of warning time would be obtained for G-TIGH or G-BEON, as shown below.
G-TIGH would have received warnings of one second duration at 43, 33, and 13 seconds from impact, a two second warning at 4 seconds from impact and a further warning at one second from impact.

G-REDU would have received a three second warning at 24 seconds from impact, but no further warning until one second prior to impact.

### A.2 Indicated Airspeed vs Rate of Descent

Warning envelopes based on IAS vs RoD were proposed for investigation also in an attempt to increase the warning time for the G-TIGH accident. The principle behind this initiative was that the cause of the accident was suspected to be due to entry of the aircraft into vortex ring condition which is known to occur within a specific IAS / RoD envelope.

In the case of IAS vs radio RoD (see plot below), it was noted that a boundary from 1000ft/min at 0kts to 1500ft/min at 100kts would separate the accidents and provide a reasonable warning times, comparable to Mode 2A.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>RoD</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-BEON</td>
<td>0</td>
</tr>
<tr>
<td>G-TIGH</td>
<td>Negligible</td>
</tr>
<tr>
<td>G-BLUN</td>
<td>9</td>
</tr>
<tr>
<td>G-REDU</td>
<td>24</td>
</tr>
</tbody>
</table>
The results for IAS vs baro RoD (see plot below) were similar but less pronounced, presumably due to the lag inherent in baro RoD.

![IAS vs Baro RoD (0 - 1000ft)](image)

It was further thought that the RoD boundary ought to be a function of height and that this might allow more discrimination and increased warning times. The following two plots cover IAS vs radio RoD data for heights up to 500ft only, and heights up to 300ft only (NB: This exercise was not performed for baro RoD due to its inferior performance compared to radio RoD.)

![IAS vs Radio RoD (0 - 500ft)](image)
As can be seen, no additional discrimination resulted and, overall, envelopes based on IAS vs RoD did not appear to offer any advantage over existing envelopes.
Appendix B – Auditory Displays – Review of Literature

INTRODUCTION

Nearly every aircraft system has associated indications, annunciations, and status messages which pilots must monitor and understand; a list of current fixed wing FAR warning system requirements is at Appendix 1. It is generally understood that humans are poor monitoring agents and that operator monitoring performance will degrade with boredom and loss of attention [1,2]. One method of bringing to the attention of the crew Warnings, Alerts, Cautions and Advisories is use of auditory displays or audio warnings: in this paper the term warning will be used generically to refer to warnings, alerts, cautions and advisories. Fixed wing aircraft have harmonised guidance material available both in FAA and EASA literature [3,4], unfortunately specific guidance is not available for helicopters and FAR 25/JAR 25 advisory material is not wholly relevant to all helicopter operations. Operational Regulations can state equipment requirements [5], for example “an audio voice warning, or other means acceptable to the Authority”, but no guidance is available on how “other means acceptable to the Authority” could be implemented: this problem occurs when operational requirements are not harmonised with airworthiness requirements.

In addition to the standard aircraft system warnings, helicopters are being increasingly equipped with a range of avionics that include their own auditory warnings; these include GPWS, EGPWS, AVAD and TCAS. When new aircraft are designed or the equipment is fitted at initial aircraft build, integration of the various systems is usual. Unfortunately retrofit equipment is generally certified in isolation and a holistic assessment of any impact on the overall cockpit environment usually does not take place, nor is currently required to take place. The general lack of relevant guidance on how auditory warning systems should be embodied in helicopters is a current problem that will increase with equipment being retrofitted to older aircraft with the attendant flight safety implications.

AIM

The aim of this review is to identify relevant material that could be used to draft helicopter specific guidance on the implementation of auditory warning systems. No attempt will be made to differentiate between operational and airworthiness material at this point as the juxtaposition of these aspects of regulations will lead to some overlap and some repetition in both sets of material might be necessary.

DISCUSSION

Audio Processing

Auditory warnings display great advantage over visual displays in that they are not dependent on the direction of gaze of the user in order to convey information [6]. The Short Term memory is used to process auditory warnings, which leads to a number of limitations in their use. The Short Term Memory has limited capacity, typically 7 ± 2 “chunks” of information. Additionally,
information held in Short Term Memory is held in Auditory, Verbal, and Linguistic code that can lead to acoustic confusion. A successful auditory warning has to achieve 2 tasks: firstly, it has to attract the attention of the crew; secondly, it has to be discriminated from other signals and then acted upon [6].

Two types of sounds have commonly been used as auditory warnings: speech and abstract sounds such as simple tones [8]. Speech warnings have the advantage of being suitable for conveying complex information and requiring little or no learning. However, if they are used where there is a high level of background speech then they might be masked [7]. The transmission of a speech message might require a relatively long period of time and are therefore better suited to situations where immediate action is not required and the number of alternative warnings is large.

When conveying an auditory warning to the pilot two types of masking have to be overcome; frequency and amplitude [6]. Frequency (pitch) masking occurs when the target signal is masked by other tones of a similar frequency in the cockpit. A helicopter cockpit tends to be a noisy environment with a large range of aircraft generated frequencies apparent to the crew; if a pure tone is used as an auditory warning then a limited set of suitable frequencies will be available to the system designer and the system might not be transferable between helicopters or even suitable for the same helicopter in different roles. In order to reduce this problem, an assessment of the cockpit noise spectrum could be used to select the most suitable frequencies for the auditory warning(s) and a combination of frequencies combined in a tone can be utilised to reduce the masking. Amplitude masking occurs when the amplitude of the ambient cockpit noise is much greater than the auditory warning and masks it. For this latter problem it might be tempting to increase the amplitude of the auditory warning, but research [6] has shown that this can lead to a startle reaction which has the effect of narrowing the attention of the pilots and decreasing their cognitive capacity.

Once the crew has detected the warning sound, they then have to discriminate it from other warning sounds in the cockpit. As the Short Term memory has a typical capacity of 7 ± 2 “chunks” of information, where an individual warning sound is a “chunk”, it is important to minimise the number of individual tone alerts as the meaning of each sound has to be learned [7]. In many offshore helicopter cockpits, Nr low, Nr high, engine fire warning and landing gear raised audio tone alerts are already implemented. When the number of audio alerts to be remembered exceeds 5 it may exceed the likely memory of some pilots and be wrongly identified, especially when similar tones are used for different warnings on diverse systems.

Speech Warnings

Speech warnings have the advantage that they have a meaning attached to them and so help overcome the limited capacity of the Short Term Memory. However alone, they are susceptible to both frequency and amplitude masking. Additionally, speech warnings take a finite period to pass a message and so may not be suitable for warnings where an immediate response is required. However, speech alone is often not sufficiently compelling to alert the crew under all conditions [7,11], with voice alone tending to be masked by cockpit discussions and radio traffic.
Attenson

An “Attenson” [9] is commonly used to introduce the aural warning. Ideally the attenson should have a sound that conveys the relative importance/urgency of the warning. It should be louder than the ambient noise environment, have a broad frequency range and unique temporal characteristics such that it does not blend in. Finally, it should have a shaped onset to prevent a startle reaction. Following the attenson, a gap is required to prevent forward masking, where the attenson masks the initial part of the voice message [9,10,12]. This gap between the Attenson and speech message further increases the length of time necessary to inform the crew of a given event.

Tone Warnings

It could be argued that an aural warning consisting of an Attenson and then a voice message takes too long to convey a message to the pilot and that an audio alert is faster in critical cases. In order for a tone alert to be effective it must be unambiguous. However, most tone warnings currently used are abstract in nature and have to be learned [8,12]. If the cause of a warning is not readily discernable to the crew when a warning is triggered, then time will be wasted whilst a visual search is made to confirm the cause of the warning. Therefore, under some circumstances using a tone warning can increase crew reaction time and workload following a warning. Only a limited number of tone warnings can be used in a given cockpit as the crew will be unable to accurately differentiate between different tones [6,8,12,13]. Indeed some recommend that only 4 different tone warnings should be used in a given cockpit [12]. As tone warnings can suffer from frequency and amplitude masking, ideally they should be composed of a combination of frequencies to reduce the chance of being totally masked and be sufficiently loud to avoid amplitude masking whilst not startling the crew or inhibiting communication. An example of the “communication window” [12] is shown below:
Trendson, Earcon and Auditory Icons

A number of research projects have been identifying methods of conveying information by nonverbal sound. One method is to use environmental sounds that have a semantic link with the object or action they represent, and another is to use a caricature of a naturally occurring sound. An example of an environmental sound would be a screech of brakes. A caricature of a naturally occurring sound would be a low rotorspeed warning that had a lowering frequency and cadence as the rotor slowed giving an impression of slowing and reducing energy in the rotor: such a system is fitted to some military SA330 helicopters. They have been shown to be an effective form of presenting information in sound [14,15,16,17]. Such auditory warning systems could convey information faster than an Attenson/Speech combination, but require to be learned and so could suffer from some of the problems of traditional tone warnings [8].

Prioritisation of Warnings

Emergency situations can result in two or more auditory warning being triggered, possible resulting in a confusing melange of tones that are at risk from mutual frequency masking. An additional problem is that two auditory alarms can combine to form a third that does not convey either of the meanings of its constituent alarms. It is also noted that there is a lack of
standardisation for tone warnings, a tone on one aircraft could mean something different on another aircraft

Some form of prioritisation of warnings needs to take place so that only the most urgent warning appropriate for the operational circumstance is presented to the crew at a given time. However, the overall warning system must not “lose” the less critical failures that are often a secondary result of the primary fault, but must be dealt with in time. The auditory display can also indicate the degree of urgency, for example by use of appropriate Attensons[22]. General guidance on the priority of various alarms is available for fixed wing aircraft [3,4] and warning systems in general [18] but some modification to these priorities might be needed for certain helicopter roles.

Enhancing Situational Awareness

A number of research projects have investigated the use of directional (3D) sound in enhancing situational awareness [19, 20, 21]. Although some of these projects are relevant to tactical military requirements, the technology could be used to enhance situational awareness during a critical situation in helicopters. Further investigation will need to be made to confirm if lightweight headsets commonly used in civil aviation are compatible with such system or if more advanced headsets with head tracking are required.

SUMMARY

Current guidance on implementing auditory warnings is deficient for helicopters. Fixed wing guidance material could be used but it may not be relevant to all helicopter operations and regimes of flight.

Tone and voice warnings have traditionally been used, but both have their limitations. Tone warnings have to be learned, only a limited number should be used in a given cockpit and they can be confusing under high workload situations. Voice warnings convey a message but need an Attenson to improve their attention-getting-qualities and take longer to convey a message.

Research has identified means of conveying information in sound, such as auditory icons. This offers a means of overcoming some of the limitations of tone and speech warnings.

Warnings have to be prioritised to prevent concurrent warnings being generated, causing confusion, and to ensure that the crew are alerted to the most serious warning.

References:

3. AC/ACJ 25.1322 – revised April 2204
4. EASA NPA Number 15/2004
5. JAR OPS 3.660
8. Learning and Retention of Auditory Warnings. Leung YK, Smith S, Parker S, Martin R
12. DEF STAN 00-25 (Part 8)/Issue 128th April 1989
15. Brewster SA, Wright PC and Edwards ADN. A Detailed Investigation into the Effectiveness of Earcons. HCI Group Department of Computer Science University of York


21. Haas EC. Can 3-D auditory warnings enhance helicopter cockpit safety?

22. Edworthy J, Loxley S, Dennis I. Improved Auditory Warning Design: Relationship between warning sound parameters and perceived urgency. Department of Psychology, Polytechnic South West, Plymouth
### Appendix 1 to AUDITORY DISPLAYS – REVIEW OF LITERATURE

The following list identifies the warnings required by AC 25.1322 for fixed wing aircraft:

<table>
<thead>
<tr>
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CFR/JAR 25, Appendix I Section 25.6  Installation of an Automatic Takeoff Thrust Control System (ATTCS) Powerplant Instruments

| CFR/JAR 33.71(b)(6)     | Lubrication system.                  |
| CFR/JAR 91.219          | Altitude alerting system or device: Turbojet powered civil airplanes |
| CFR/JAR 91.221          | Traffic alert and collision avoidance system equipment and use |
| CFR/JAR 91.223          | Terrain awareness and warning system |
| CFR/JAR 91.603          | Aural speed warning device           |

CFR/JAR 91, Appendix A Section 91.2(b)(1)  Required instruments and equipment

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14 CFR 121.356(b)  Traffic alert and collision avoidance system

CFR/JAR 121.358  Low-altitude windshear system equipment requirements

CFR/JAR 121.360(a)
CFR/JAR 121.360(e)
CFR/JAR 121.360(f)  Ground proximity warning-glide slope deviation alerting system

CFR/JAR 125.187  Landing gear: Aural warning device.

CFR/JAR 125.205(d)  Equipment requirements: Airplanes under IFR.

CFR/JAR 125.221(a)  Traffic alert and collision avoidance system

CFR/JAR 135.150(b)(7)  Public address and crewmember interphone system

14 CFR 135.153(a)  Ground proximity warning system.

14 CFR 135.154  Terrain awareness and warning system

14 CFR 135.163(d)  Equipment requirements: Aircraft carrying passengers under IFR.

14 CFR 135.180(a)  Traffic alert and collision avoidance system

14 CFR 135, Appendix A Section A135.1  Additional Airworthiness Standards for 10 or More Passenger Airplanes