Report for

UK Civil Aviation Authority

on

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

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Contents

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1. 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 (HTAWS) to improve warning times for offshore operations 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 HTAWS 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.

Airbus Helicopters EC225 flight data from Bristow Helicopters' Flight Data Monitoring (FDM) 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 modified warning envelopes to be developed. The new warning envelopes were initially 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 alert rate of less than 1 in 100 flights. A lower nuisance alert rate might be achieved in practice, but a larger sample of data for normal operations would be required to demonstrate this.

The EC225 analysis exercise was repeated for the Bristow Helicopters' Sikorsky S76A+ fleet in order to evaluate the proposed new warning envelopes on an older, less sophisticated helicopter type and a different style of operation. Although the flight path variability inherent in normal operations was greater for the S76A+ as expected, only minor adjustments to the proposed new warning envelopes were required to maintain a nuisance alert rate of less than 1 in 100 flights. The consequent effect on the warning times generated for the four example accidents was minimal. The two helicopter types and associated styles of operation are considered to represent a broad spectrum of offshore operations, indicating that a single set of warning envelopes would have general applicability, avoiding the need to tailor warning envelopes for individual helicopter types and/or types of operation.

Evaluation of the new warning envelopes using flight data for the accident to AS332L2 G-WNSB in August 2013 indicated that the accident would likely not have been prevented. This inspired the development of a totally new warning envelope based on airspeed and total torque which proved effective for the G-WNSB accident and a number of other occurrences. This warning envelope was only effective for the EC225, however, and was unsuitable for the S76A+. Subsequent analysis of additional flight data established that modified versions of the envelope could be defined that were effective for the Sikorsky S92 and Leonardo AW139, but not the Sikorsky S76C++. Although very effective on most aircraft, it appears that helicopter type-specific solutions will be necessary for this warning envelope.

In addition to the accident to G-WNSB, data for a further six occurrences became available to the project. The new and revised warning envelopes were tested on these case examples and found to be effective in all but two incidents. The two incidents in question could be accommodated by adjustment of the warning threshold for the corresponding warning envelope but an additional warning parameter would need to be introduced to prevent excessive nuisance alerts being generated.

The new and revised warning envelopes were implemented in a Honeywell engineering prototype HTAWS computer and evaluated during trials performed in a Bristow Helicopters' flight simulator. The warning envelopes performed as expected and were well received by the trials pilots. The warning envelopes have also been validated for the Sikorsky S92 and Leonardo AW139 helicopter types using data from helicopter operators' FDM programmes. A small modification to the revised Mode 4B warning envelope would be required to constrain the nuisance alert rate on the AW139 and consideration needs to be given as to whether this should be applied generally or only to the AW139.

The success of this project has resulted in an industry-led two-phase voluntary implementation programme:

- Phase 1 comprises changes to existing HTAWS that can be implemented through a simple equipment software modification without affecting any existing mandates or standards, and with minimal effect on the aircraft or any of its systems. This is expected to take the form of optional equipment Service Bulletins which will need to be introduced onto individual helicopter types via optional helicopter manufacturer Service Bulletins. The main impact on aircraft is expected to be the update to the HTAWS supplement to the Rotorcraft Flight Manual that will be required. The objective of Phase 1 is to benefit from the majority of the significant safety enhancements identified and demonstrated as soon as practicable. A standard for the Phase 1 HTAWS update has been produced and, following industry consultation, has been published by the UK CAA in the form of a Civil Aviation Publication (CAP) on its web site.

- Phase 2 is planned to comprise a more extensive update to HTAWS, potentially involving more complex modifications and including a review of the warning forms and formats in the light of the results of the ongoing research at Cranfield University. It is expected that Phase 2 will generate helicopter type-specific integration issues that will need to be addressed. Existing mandates will be reviewed and 'formal' RTCA or EUROCAE Minimum Operating Performance Standards (MOPS) will likely be produced. It is anticipated that any MOPS produced will be adopted by EASA for the 01 January 2019 mandate for Class A HTAWS contained in the European air operating rules for offshore helicopter operations. Phase 2 is considered to represent the ultimate solution but, due to the complexities involved, is expected to form a medium to long term objective.

2. 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 operations in an offshore environment:

- Bell 212 G-BIJF, 1981, N Sea [2]
- S61 G-BEON, 1983, Scilly Isles [3]
- AS332L G-TIGH, 1992, Cormorant Alpha platform [4]
- S76B G-BHYB, 1997, L7A platform [5]
- AS365N G-BLUN, 2006, Morecambe Bay [6]
- EC225 G-REDU, 2009, ETAP platform [7]

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 alert rate.

Following the accident involving the S61 (G-BEON) approaching the Scilly Isles 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 the air operating rules for offshore helicopters in 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[1].

In recent years, however, the Honeywell MKXXII Enhanced Ground Proximity Warning System (EGPWS) has become available as a Class A helicopter TAWS (HTAWS) and has been fitted to a number of helicopter types. Unfortunately the 'Enhanced Mode' has proven not to be very effective for offshore operations because:

- transient obstacles such as large ships and construction barges (some up to 500ft in height) operate within the offshore area;
- it is difficult to maintain the obstacle database to keep track of mobile installations;
- there have been a large number of nuisance warnings (a nuisance warning is defined as an alert generated by a system that is functioning as designed but which is inappropriate or

[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. AW139 and AW189, set to 150ft) differ.

unnecessary for the particular condition[2]) due to the relatively low resolution of the database compared to the large size of many installations;.

- some manufacturers 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.

In order to optimise the EGPWS Classic Modes, and future helicopter Class A HTAWS, data generated by helicopter Flight Data Monitoring (HFDM) programmes has been used to refine the Classic Mode warning thresholds. The implementation of HFDM has resulted in a large amount of real-world operational data being collected. The HFDM database has been 'mined' to determine where Classic Mode thresholds could be set in order to provide the earliest warning to the crew while keeping the false alert rate at an acceptable level.

[2] AC25.1322-1- Flight Crew Alerting. Dated 13th December 2010.

3. Supply of data

The data for the initial Airbus Helicopters EC225 study 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 original DVD contained 300 files from EC225 helicopters.

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, and the extracted files containing the required parameters stored in comma separated value (CSV) format. Take-off files contained data between lift-off and 1,000 ft (radio), landing files contained data for 1,000 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 EC225 data set of approximately 800 flights was processed. This contained 350-400 offshore landings and takeoffs which were used for the main study.

A follow-on study using data from the Sikorsky S76A+ was conducted using 975 files containing 3,354 flights. Once the ‘filter’ process (see Section 5.3) had removed those flights that were not relevant, a total of 1,268 offshore takeoff and 1,345 offshore landings were available for inclusion in the analysis.

4. Applicable EGPWS Modes

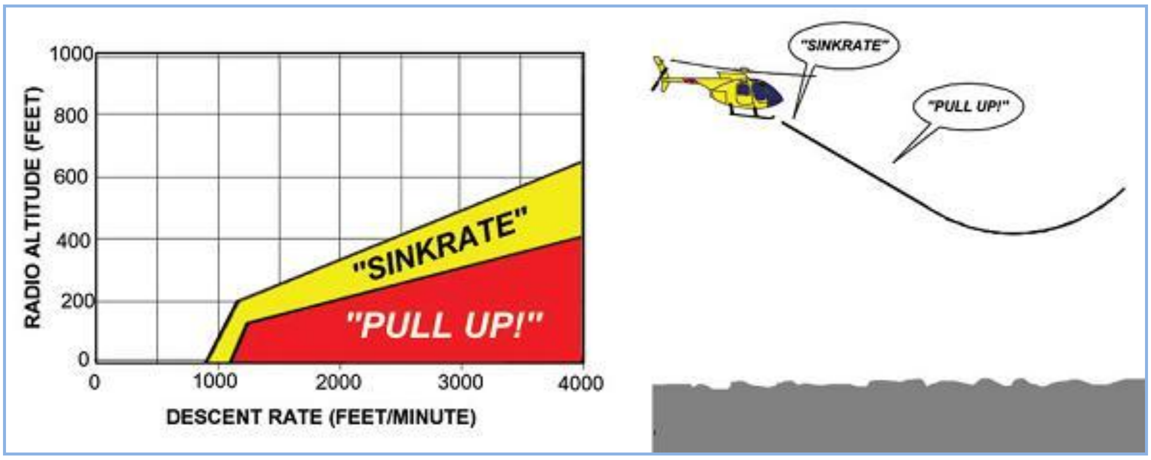
The following descriptions[3] are applicable to the Honeywell EGPWS as installed on the Bristow Helicopters EC225 aircraft.

4.1. Mode 1 – Descent Rate

For Mode 1[4] the voice alert "Sink Rate" will initially 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.



4.2. Mode 2 – Terrain Closure

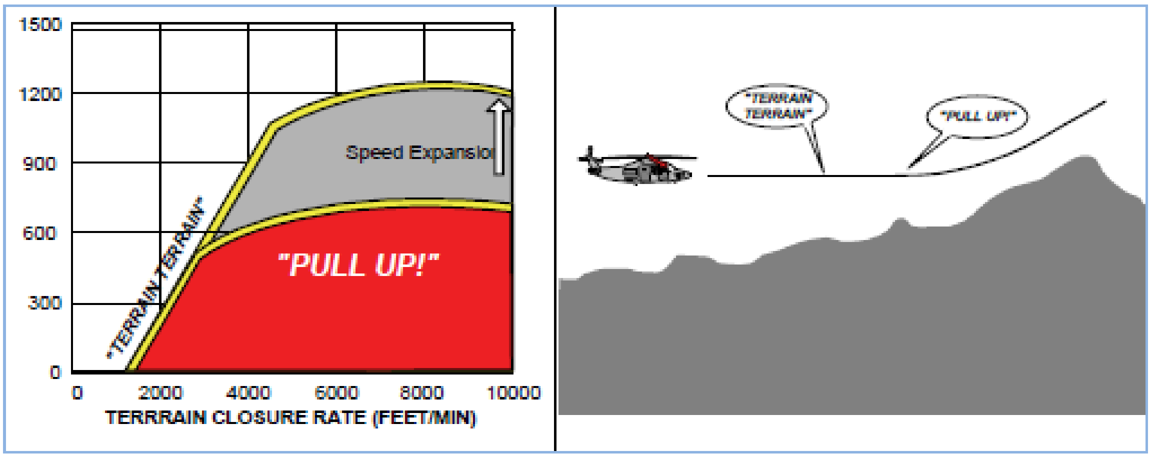
Mode 2 provides alerts[5] when the aircraft is closing with the terrain at an excessive rate. It is not necessary for the aircraft to be descending in order to produce a Mode 2 alert, level flight (or even a climb) towards obstructing terrain can result in a hazardous terrain closure rate. The

[3] Text based on material extracted from [8] by kind permission of Honeywell International Inc.
[4] Mode 1 is permanently inhibited on the Sikorsky S-92.
[5] Mode 2 is inhibited when the 'Enhanced Mode' is operating.

Terrain Closure Rate variable is computed within the EGPWS computer by combining radio altitude and vertical speed.

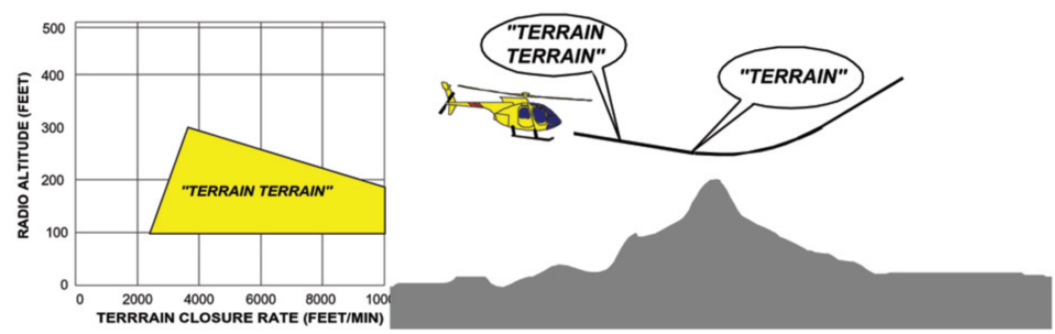
Mode 2 has two sub-modes, referred to as Mode 2A and Mode 2B, the active sub-mode being determined by aircraft configuration and airspeed. Mode 2 uses an integrity view, which indicates how well Terrain Awareness & Display and Geometric Altitude functions are performing in conjunction with the terrain 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.



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 and the red warning generated until the warning envelope is exited. 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.



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.

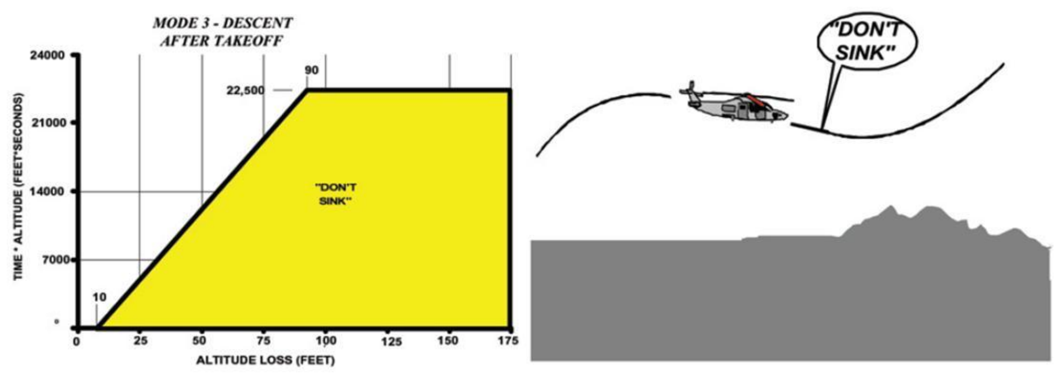
When the Mode 2B warning envelope is penetrated, the aural message "Terrain...." is repeated until the envelope is exited and the amber caution lights are illuminated.

4.3. 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, and the amber caution lights generated. The visual annunciators remain active until a positive rate of climb is re-established.



INADVERTENT DESCENT / LOSS OF ALTITUDE AFTER TAKE-OFF – MODE 3

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.

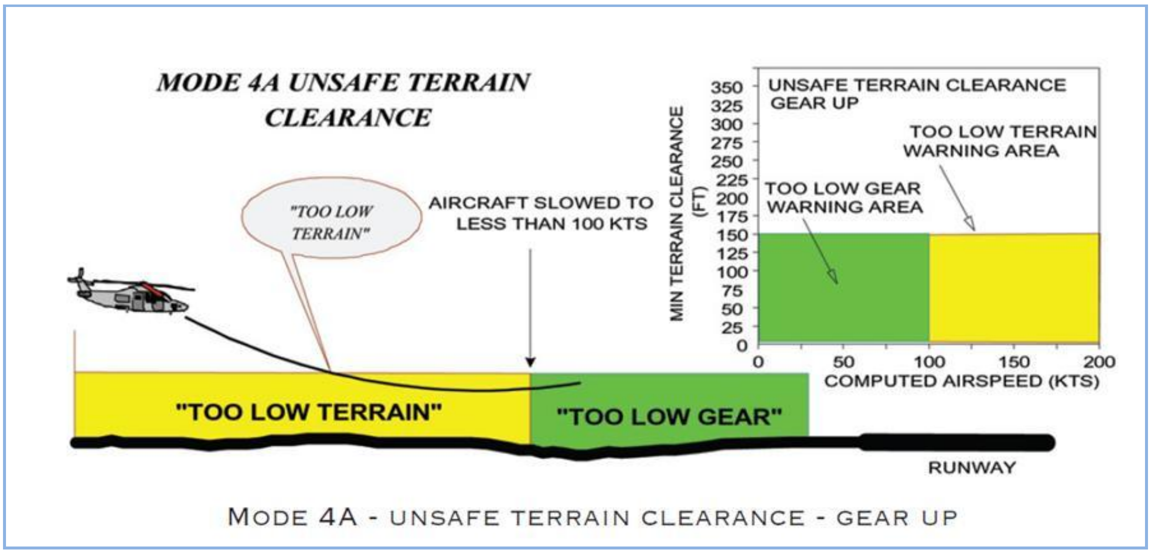
Mode 3 voice alerts are inhibited while the Timed Audio Inhibit is active.

4.4. 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.

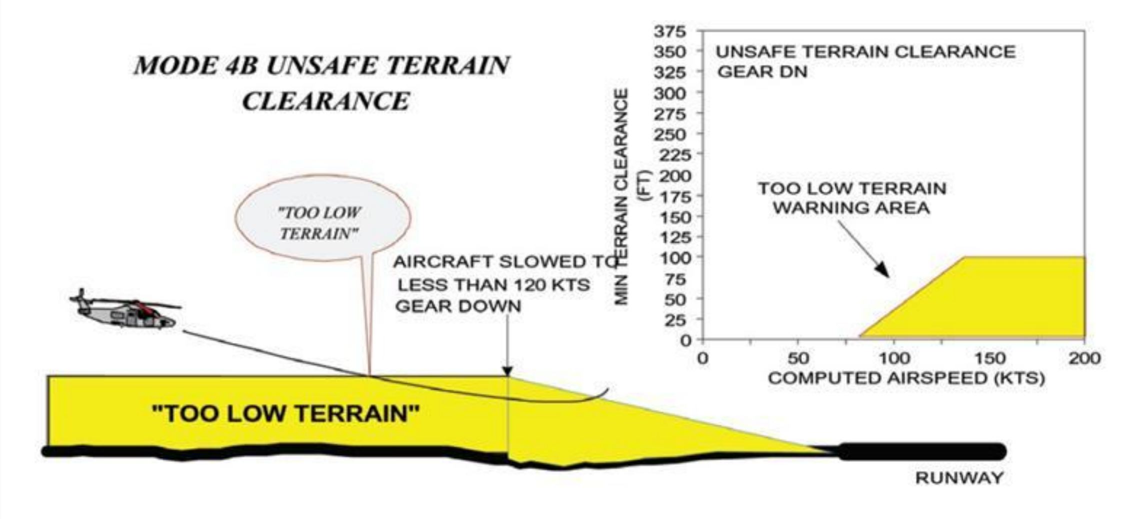
Mode 4 voice alerts are inhibited while the Timed Audio Inhibit is active.

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.

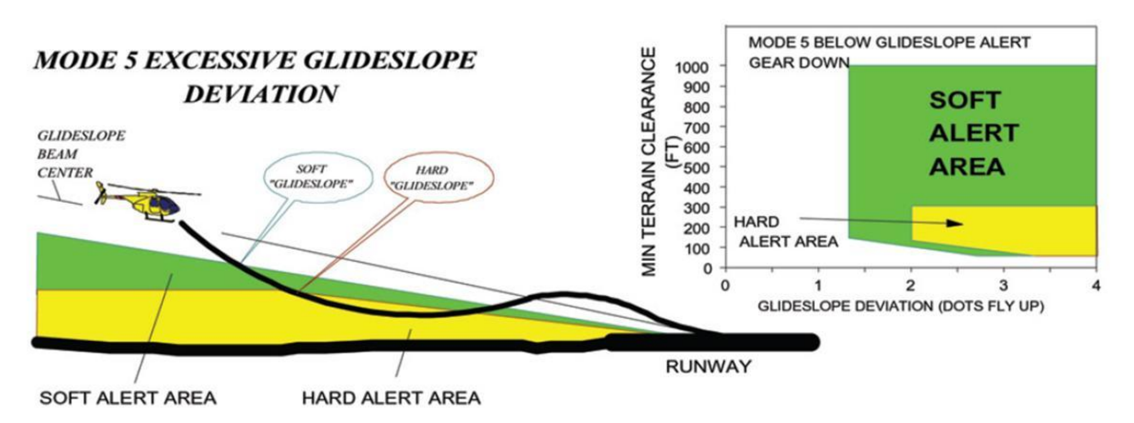
When the landing gear is lowered, Mode 4B becomes active and the boundary decreases to 100 feet when above 120 knots (100 knots for fixed gear). As airspeed decreases below 120 knots (100 knots for fixed gear) the warning boundary decreases to 10 feet at 80 knots. The voice message is "Too Low Terrain".



Mode 4B - Unsafe Terrain Clearance - Gear Down

4.5. 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 increases 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 - Excessive Glideslope Deviation

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 alerts are inhibited while the Timed Audio Inhibit is active.

4.6. 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.

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

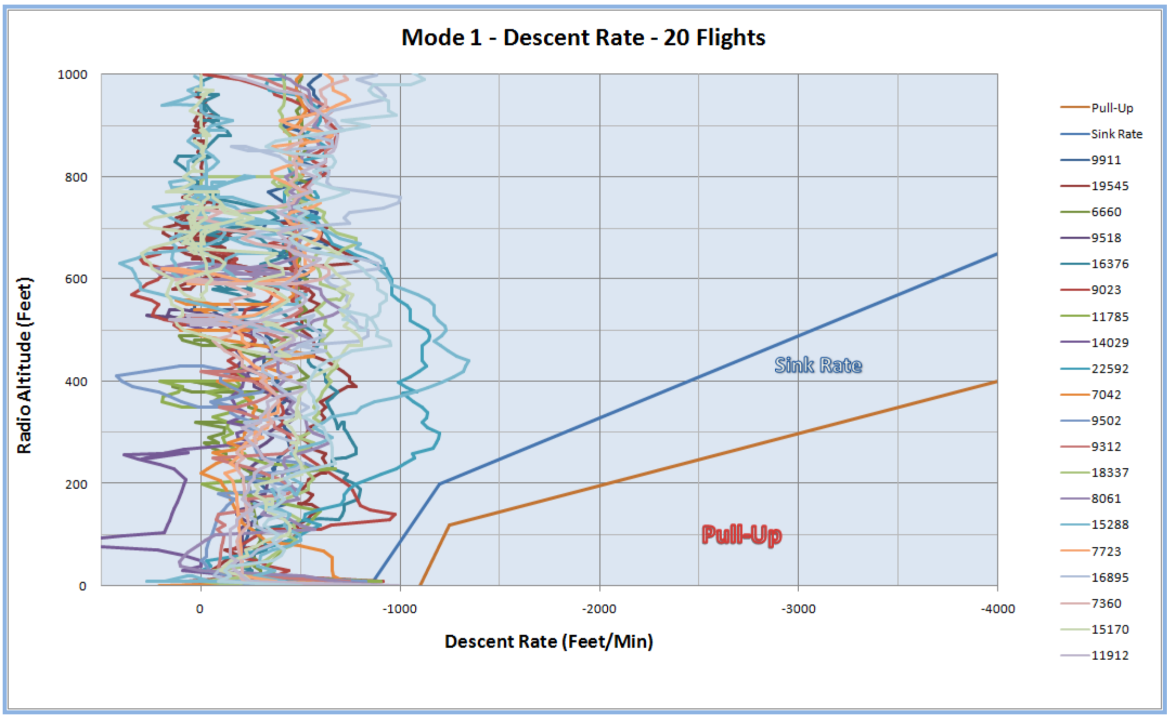
An optional discrete input provides the ability to force the Mode 6 audio level to lower audio volume. This enables operators to control the Mode 6 volume level with activation of windscreen rain removal or if lower volume callouts are desired at all times.

MODE 6 ALTITUDE CALLOUTS

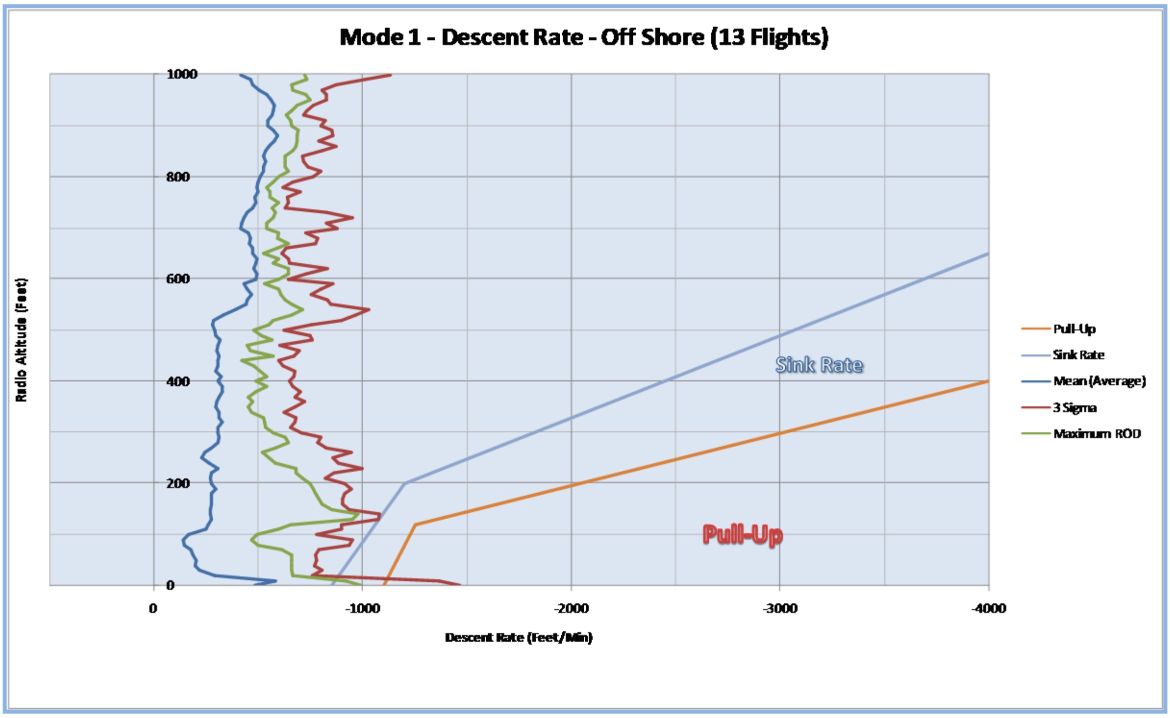
5. Analysis - General

5.1. Pilot Study

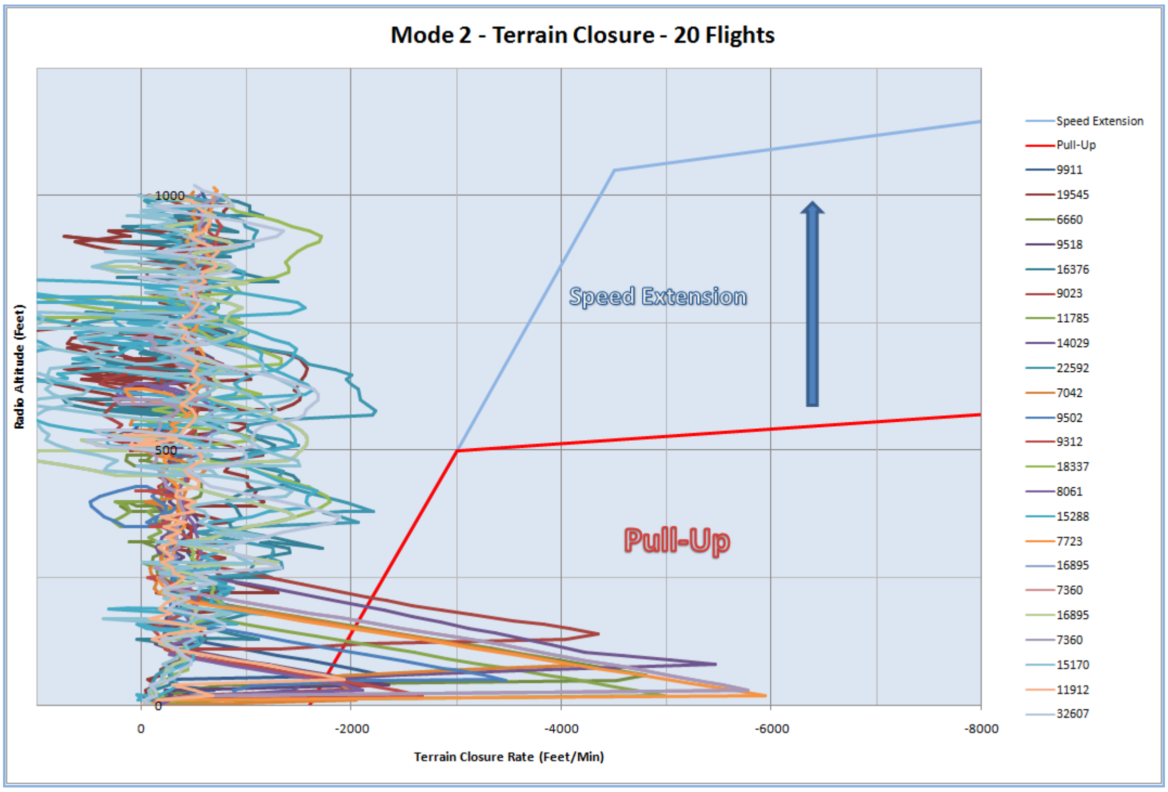
The pilot study EC225 data set of 20 files contained both onshore and offshore operations, all of which was included in the study, albeit separated so that a comparison would be possible. The plot below shows the calculated 'barometric' (pressure) rate of descent (RoD) curve for all 20 flights, plotted on the Mode 1 chart.



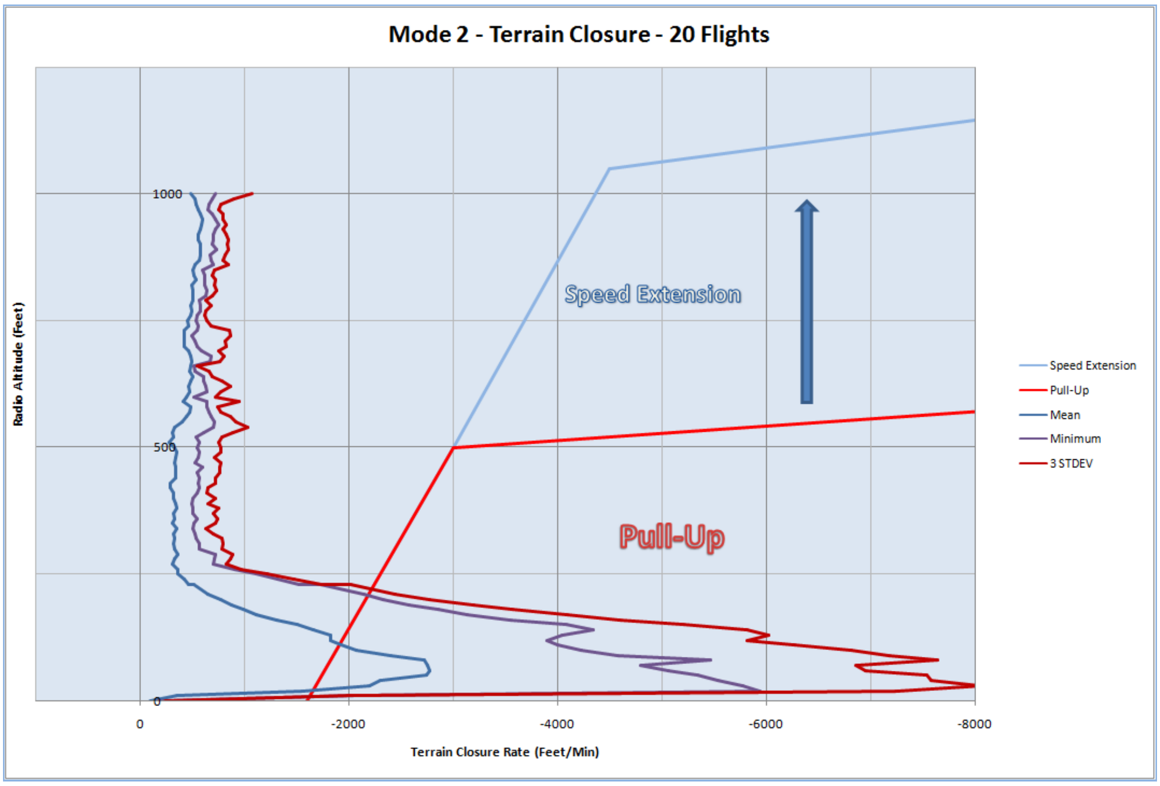
The next plot shows offshore data only (13 flights) displayed on the Mode 1 chart. This data was assumed to be 'normally distributed' and is shown as 3 descent rate curves - mean, 3σ and maximum, derived from the radio RoD values.



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, 3σ and maximum, derived from the radio RoD values.

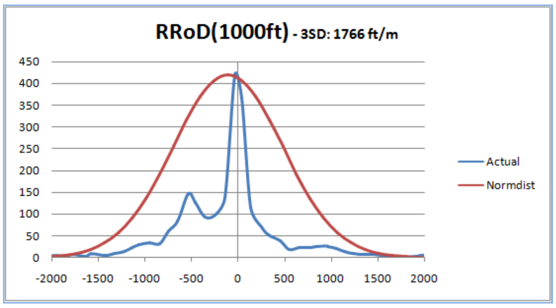


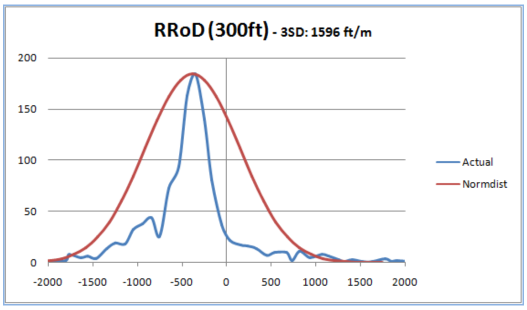
In the above example, it can be seen that the plots did not appear as expected, with the 3σ curve exceeding the maximum. This is indicative that the data is not normally distributed, although the small dataset used in pilot study is believed to also have contributed to this result (see Section 5.2.1).

5.2. Issues Raised by Trial Analysis

5.2.1. 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, 3σ 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.





5.2.2. Presentation of Aggregate Data

Having discounted presentation of the data as if normally distributed, it was decided to revert to plotting the n^{th} 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 alert rate. The corresponding false alert rate would not be exceeded provided that this curve and the warning envelope did not impinge on each other. Although the false alert 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 initial analysis based on Bristow EC225 data (approximately 400 offshore landings), it was decided to plot the 99^{th} percentile curve, representing a potential alert rate of 10^{-2}.

5.2.3. 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 data was used. It should be noted however that the process of excluding the onshore data was not considered to be foolproof (insufficient indicators in the data) and there may be a small number remaining. However, any effect on the results is considered to be insignificant.

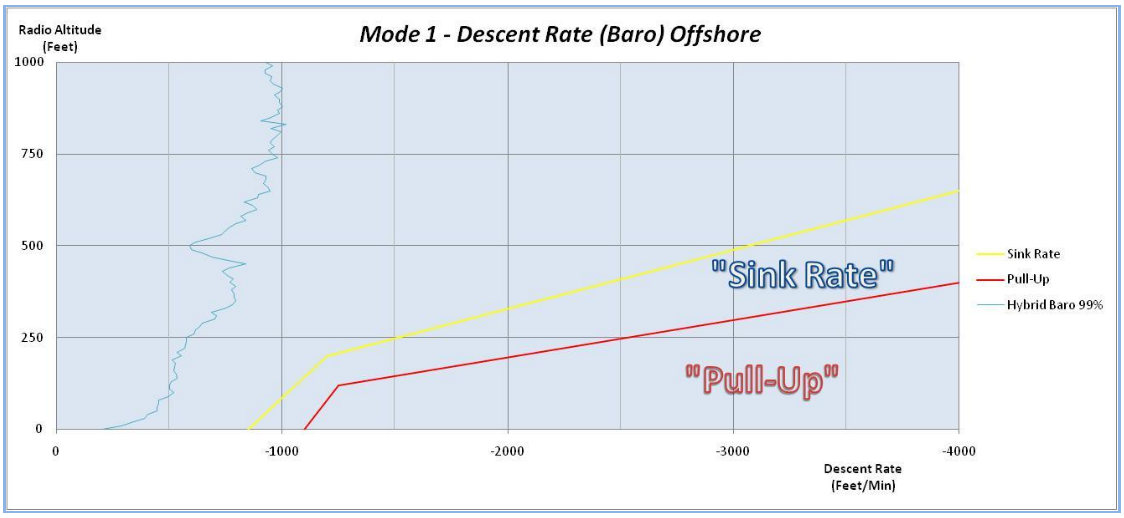
5.2.4. Low Airspeed & Deck Edge Effect

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 affecting the pressure 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.

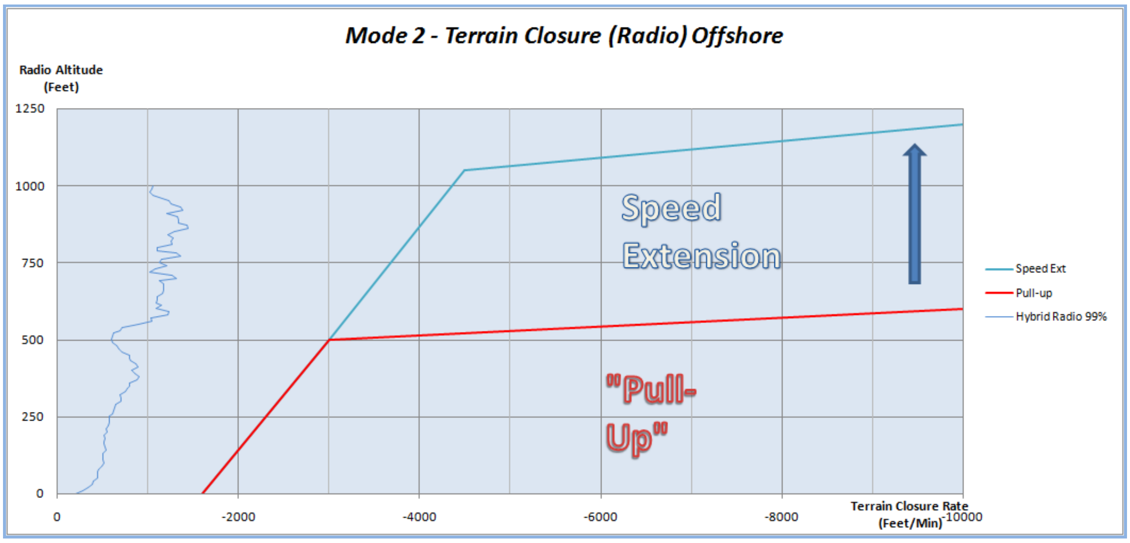
In order to address these issues, consideration was given to using the ALTRATE parameter from the recorded dataframe. On the EC225, ALTRATE is the vertical speed parameter from the Attitude & Heading Reference System (AHRS) comprising a hybrid of barometric and inertial data with long term error-elimination 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.[6]



[6] 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.



5.2.5. Training Flights & Autorotation

Where possible, training flights and flights including autorotation were excluded from the data set. Training flights were mostly identified by take-off and landing locations, i.e. flights taking off and landing at the same location, indicating that the flight in question was not a revenue operation. HTAWS is automatically inhibited during autorotation, when both engine torques fall below 7.5%; 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 HTAWS during autorotation, i.e. the rates of descent are significantly in excess of normal operations and the warnings generated would be unhelpful. Training flights, airtests and autorotations are usually conducted over land where envelopes designed specifically for offshore operations would not be active. Overwater training is almost always performed in accordance with standard operating procedures hence offshore specific envelopes would be valid.

5.2.6. 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 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 decided that descent after lift-off should continue to be monitored.

5.2.7. 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 and the landing gear position. 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; 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 4.4).

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 not considered to be relevant to this study, which is targeted at offshore operations.

5.3. Data Filtering

Some of the issues raised in Section 5.2 above were addressed through the use of filters which excluded the relevant records from the analysis. Many lessons were learned during the processing of the EC225 data, which meant that the filtering was performed in a relatively 'ad-hoc' manner for that type. It was possible to take a more automated approach in the case of the S76, however, and the list below shows the types of filter check that were applied.

- Autorotation – Eliminate records where both engine torque levels are below the autorotation trigger value.
- Unbelievable descent rate – Eliminate records where ALTRATE, or the calculated rate of descent (ROD or RROD) exceed a defined limit.
- Training flights – Eliminate records from flights with same take-off and landing locations.
- Onshore landings – Eliminate records from flights that land at onshore locations.

- Spurious heights – Eliminate records that have a negative value of radio height (RALT).

Further details of the filtering performed are given in Appendix A.

6. Analysis Results

6.1. General

This section addresses each of the warning modes and, where applicable, shows how the operational and accident data relate 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 existing HTAWS warning envelope boundaries, permitting modification of the envelopes to provide an earlier warning to the crew.

For Modes 1 and 2, 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 calculated from ALT (barometric) for Mode 1 and RALT (radio) for Mode 2. Below this height the recorded value of ALTRATE is used.

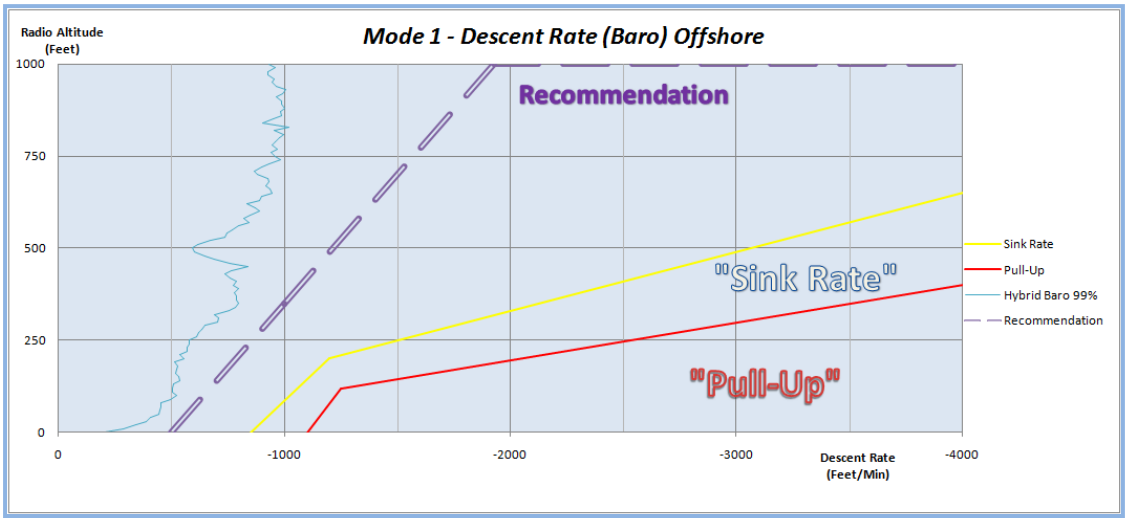
Flight path data from the G-BLUN [6], G-TIGH [4], G-BEON [3] and G-REDU [7] accidents is presented on the relevant plots to indicate the amount of warning time that could be expected with the existing and proposed warning envelopes. The flight path data was derived from the FDR in all four accidents 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 flight path data.

6.2. 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 6 on page 22) in relation to height above the surface (radio height). A more detailed description of Mode 1 warning is given in Section 4.1.

6.2.1. Existing Warning Envelope

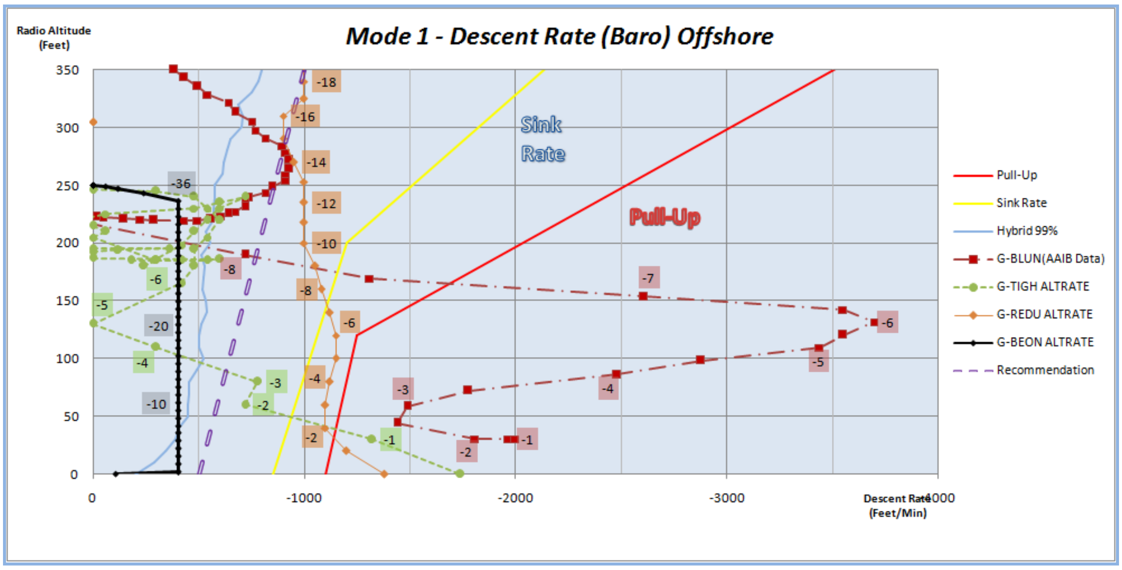
The two diagrams below show the results of the rate of descent analysis and the accident data plotted on the Mode 1 warning envelope. The first of the two diagrams shows only the 99 percentile line (light blue) and clearly indicates the potential to re-define the envelope without significant risk of an unacceptable false alert rate. This is illustrated by the purple dashed line which represents the recommended new warning envelope.



For clarity the second diagram shows only the last 350ft of the rate of descent profile, to which the flight path data from the four accident cases has been added. The key to the 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 estimated.



As can be seen, useful warnings are generated by current HTAWS at 7.5 seconds ('Sink Rate') and 7 seconds ('Pull Up') in the case of G-BLUN, and at 7 seconds ('Sink Rate') for G-REDU. With the proposed new warning envelope, the G-BLUN warning time would be improved slightly to 8 seconds but, more significantly, a large increase in warning time from 7 to 16 seconds would be realised in the case of G-REDU.

6.2.2. Summary of Results for Mode 1

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.

Accident	Warning Time (sec)		
	Current Mode 1		Recommended Mode 1
	'Sink Rate'	'Pull-Up'	
G-BEON	0.0	0.0	0.0
G-TIGH	1.5	1.5	3.5
G-BLUN	7.5	7.0	8.0
G-REDU	7.0	1.5	16.0

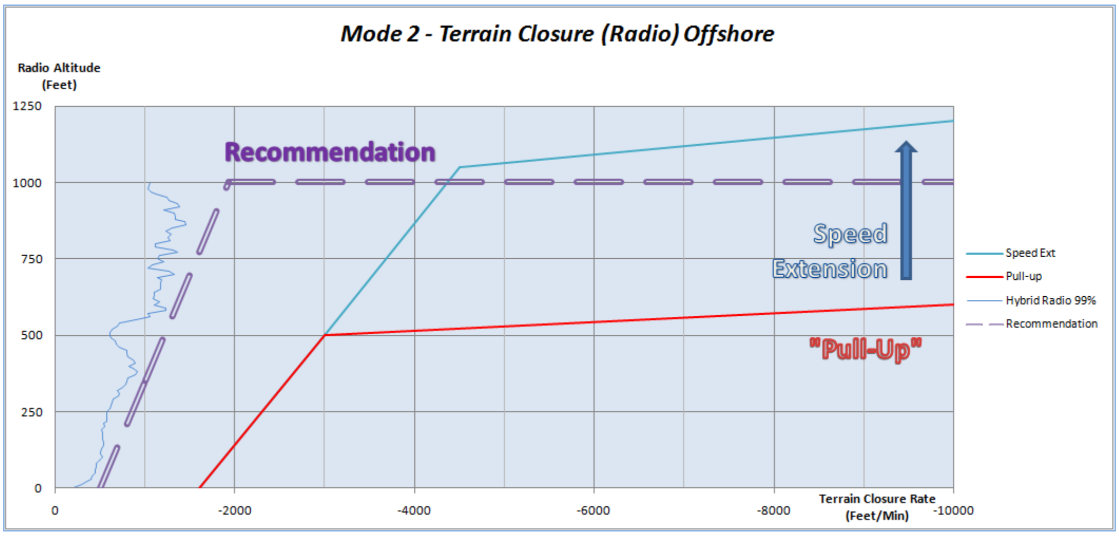
6.3. Mode 2 – Terrain Closure

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 is given in Section 4.2.

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 related to the envelope of normal operations which is the same for both Mode 2A and Mode 2B.

6.3.1. Existing Warning Envelope

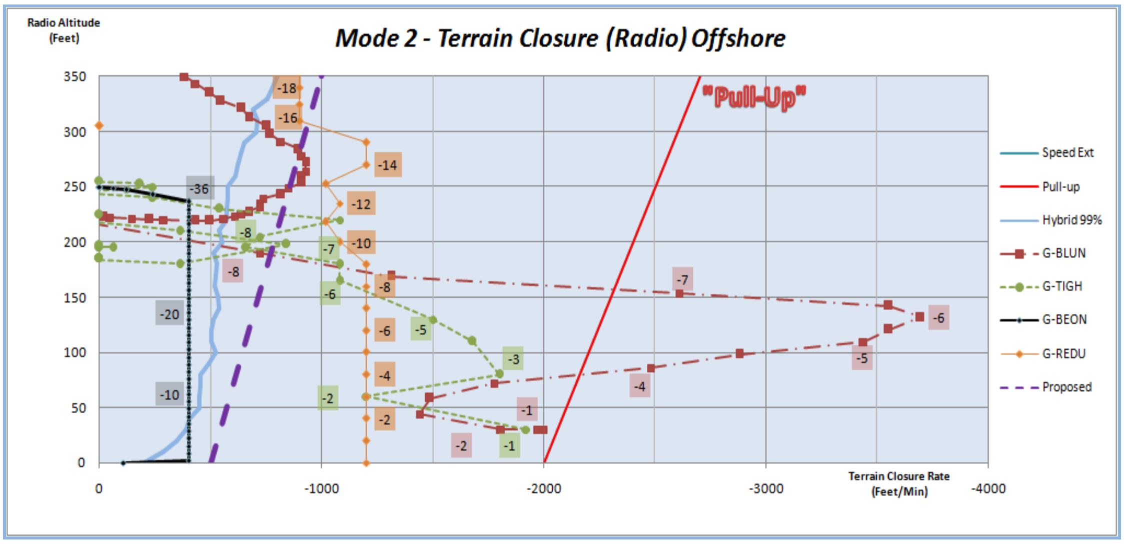
The two diagrams below show the results of the rate of descent analysis and the accident data plotted on the Mode 2A warning envelope. The first of the two diagrams shows only the 99 percentile line (light blue) and clearly indicates the potential to re-define the envelope without significant risk of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



For clarity the second diagram only shows the last 350ft of the rate of descent profile, to which has been added the flight path data from four accident cases. The key to the 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 estimated.



As can be seen, a warning is generated by current HTAWS for one accident case only (G-BLUN) and this is of limited use as it triggers at 7 seconds prior to impact and then ceases three seconds later; the flight crew might interpret this as meaning the danger had passed. With the proposed new warning envelope, the G-TIGH warning time would be increased from 1 to 8 seconds and the G-BLUN warning time would be improved slightly to 8 seconds. More significantly, however, a 16 second warning would be generated in the case of G-REDU. The G-BEON scenario remains outside of the revised warning envelope.

6.3.2. Summary of Results for Mode 2

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

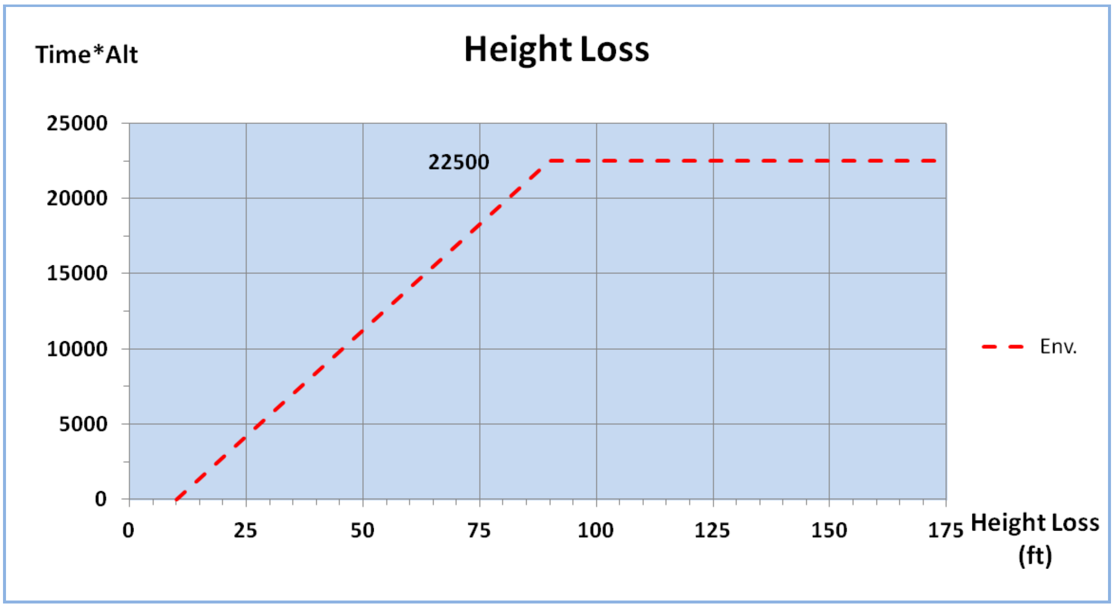
Accident	Warning Time (sec)	
	Current Mode 2A	Recommended Mode 2
G-BEON	0.0	0.0
G-TIGH	1.0	8.0
G-BLUN	7.0	8.0
G-REDU	0.0	16.0

6.4. 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 is given in Section 4.3.

6.4.1. Existing Warning Envelope

The existing warning envelope, taken from Honeywell EGPWS Pilot's Handbook is shown below. There were a few instances of descent after take-off in the data available for analysis, however these all occurred during the 'transition' from hover to forward flight and there were insufficient examples to present statistically meaningful percentile lines on the plot.



The second diagram shows the FDR data from the only take-off accident case for which data is available.

- G-TIGH - Eurocopter AS332 - Green

The plot has been identified with timings to indicate seconds prior to impact. By relating these figures to the warning envelope, the approximate warning time that would have been given can be estimated.

Note that IAS falls below 50kt at -19 seconds and does not recover prior to impact which will inhibit Mode 3.

It can be seen that there are two periods of descending flight, the first of which occurred approximately 28 seconds prior to impact. However, as this descent was successfully arrested, it is presumed that the loss of height was detected by the crew and, for the purposes of this analysis, it is the second uncorrected descent which is judged to be relevant. This would have triggered a warning 10 seconds prior to impact.

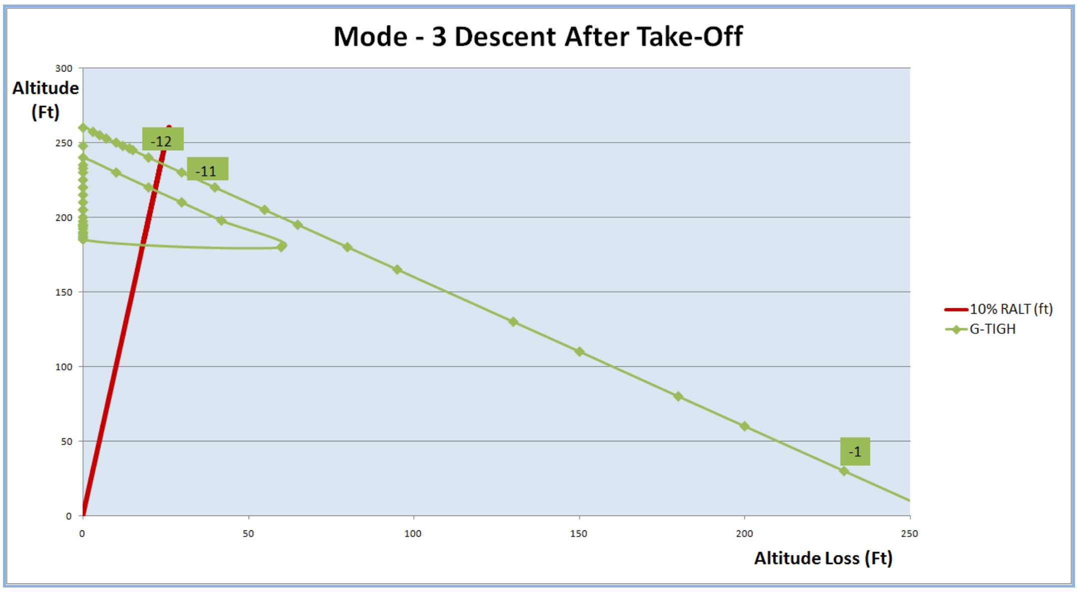
6.4.2. Alternative Warning Envelopes

Two modifications to the existing Mode 3 warning envelope were investigated.

6.4.2.1. Simplification of Existing Envelope

The existing HTAWS envelope, which is based on height loss as a function of altitude and time (altitude * time), would have given a 10 second warning to the fight crew of G-TIGH. The need for the time element was questioned, however, and the use of a simple envelope based only on altitude was investigated. In this case the warning envelope was arbitrarily set to trigger when there is a height loss greater than 10% of the current radio altitude. It can be seen that the warning time for G-TIGH is marginally increased to 11.5 seconds. Adoption of a lower threshold, e.g. 5%, would increase the warning time further but due consideration would need to be given to the frequency of nuisance alerts.

The effect of the modified Mode 3 warning envelope on the warning time is a modest increase the warning time from 10 to 11.5 seconds.

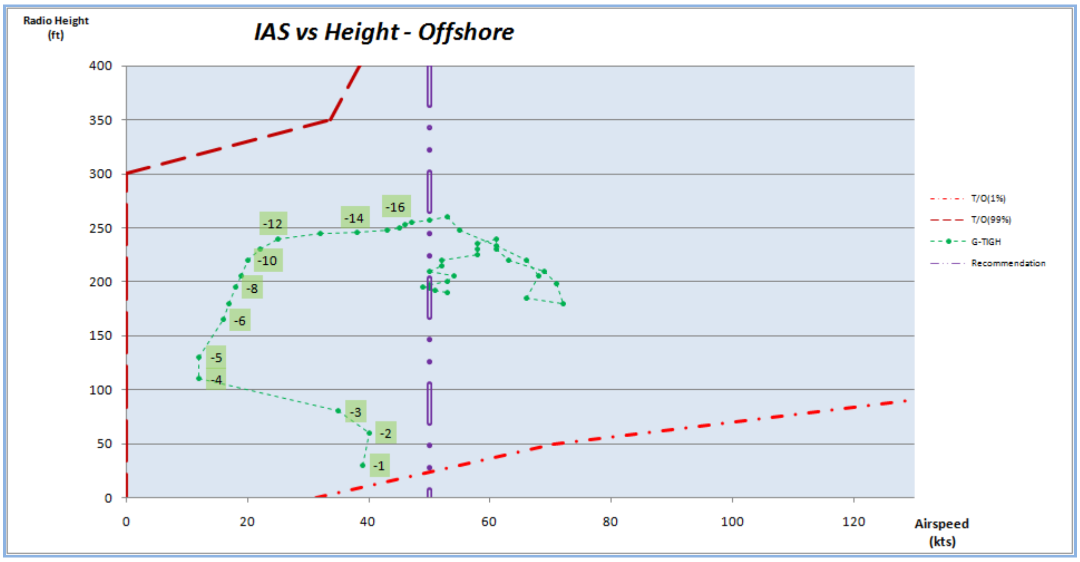


6.4.2.2. Additional Mode 3 – Loss of Airspeed after Take-off

The accident aircraft under consideration in the Mode 3 analysis above (G-TIGH) suffered a significant loss of airspeed after take-off and, while this ultimately resulted in a loss of height, it was considered that a warning based on airspeed could potentially result in earlier detection and a greater warning time. Rather than replace the current Mode 3 envelope, it was proposed that Mode 3 be separated into two sub-modes; Mode 3A – Loss of Height after Take-off (with the simplified warning envelope recommended in 6.4.2.1 above), and Mode 3B – Loss of Airspeed after Take-off as described below.

The new Mode 3B would be activated as for the current Mode 3, i.e. at gear retraction after take-off or on achieving 50kt after take-off, remaining active for about 60 seconds thereafter (see Section 4.3). Any reduction in airspeed during this time would result in a 'Check Airpeed' caution, any fall in airspeed below 50kt would result in a 'Check 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.

The effect of implementing a new Mode 3B warning envelope to detect low airspeed after take-off on the warning times for the one relevant example accident case, G-TIGH, is to increase the warning time from 10 to 17 seconds.



6.4.3. Summary of Results for Mode 3

The effects of the modifications to the Mode 3 warning envelope on the warning times for the G-TIGH accident are shown in the table below.

Accident	Warning Time (sec)		
	Current Mode 3	Recommended Mode 3A	Recommended Mode 3B
G-TIGH	10.0	11.5	17.0

6.5. Mode 4 – Terrain Clearance

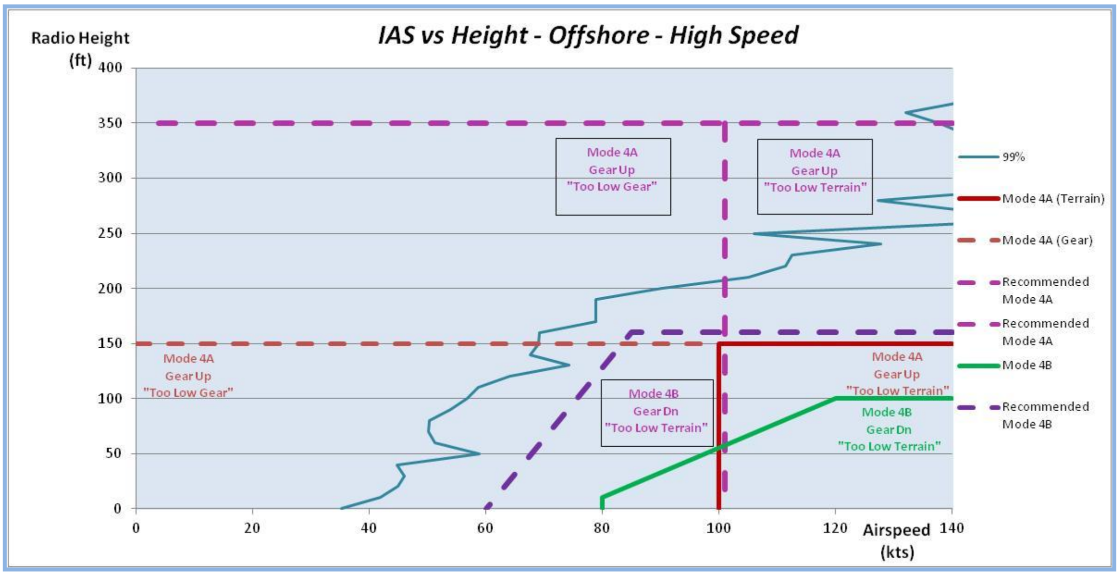
Mode 4 provides alerts for insufficient terrain clearance with respect to phase of flight and airspeed. This mode requires radio height, airspeed and landing gear position. A more detailed description of the Mode 4 warning is given in Section 4.4.

6.5.1. Existing Warning Envelopes

The two diagrams below show the results of the height vs airspeed analysis and the accident data plotted on the Mode 4 warning envelope. The first of the two diagrams shows only the 99 percentile line (light blue), the existing Mode 4A (red line) and Mode 4B (green line) envelopes, and the recommended new Mode 4A (pink dashed line) and Mode 4B (purple dashed line) warning envelopes.

As regards the current Mode 4A, the height threshold of 150ft is too low to provide effective warnings for operations to elevated decks which can be as high as 300ft; the average is over 100ft. 'Too Low Gear' warnings are not generated until the helicopter crosses the edge of the helideck which is very late. It is therefore proposed that the height of the Mode 4A threshold be raised to 350ft as shown by the pink dashed line. The incursion into the 99 percentile envelope is of no significance as most of the data relates to gear down flight.

In view of the position of the '99 percentile' curve, there would appear to be scope to extend the Mode 4B 'Too Low 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).



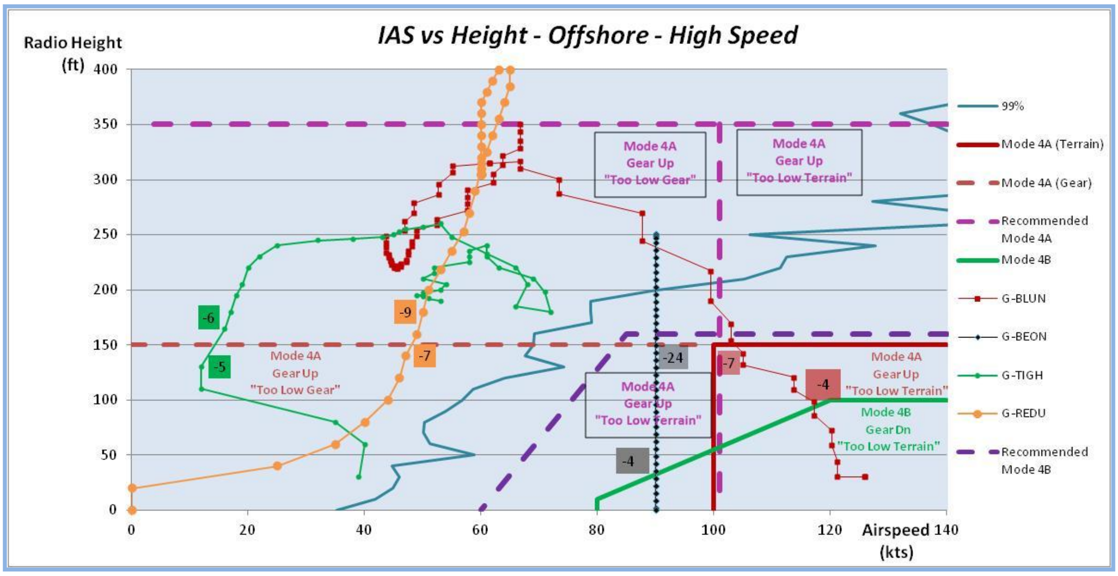
The flight path data for the four accidents has been added to the diagram below. The key to the descent rate plots for the accident data is as follows:

- 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 have 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 generated no warnings.

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 estimated. As can be seen, in both cases the airspeed remains high throughout and it would appear that, with current HTAWS, both G-BLUN and G-BEON would have received a Mode 4B warning at 4 seconds prior to impact. Mode 4A warnings would not have been generated as the landing gear was down in both accidents.

The recommended new Mode 4B envelope provides a generous warning of 24 seconds for the G-BEON accident case. Although this accident scenario is catered for by AVAD/Mode 6 (see Section 6.7 below), the effectiveness of these warnings is compromised to some extent as they are routinely triggered during normal operations, with the fixed height warning triggered every approach. Having the additional discriminant of airspeed, the proposed modified Mode 4B envelope would not suffer from this disadvantage. Although almost doubling the warning time for G-BLUN to 7.5 seconds, the improvement is of no consequence as a Mode 1 'Sink Rate' warning would have been generated by current HTAWS. The adoption of the modified Mode 4 envelopes is nevertheless considered desirable as they should not suffer from the same nuisance alert rate as the present Mode 6 and will cater for a broader range of accident scenarios.



6.5.2. Summary of Results for Mode 4

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.

Accident	Warning Time (sec)	
	Current Mode 4B	Recommended Mode 4B
G-BEON	4.0	24.0
G-TIGH	0.0	0.0
G-BLUN	4.0	7.5
G-REDU	0.0	0.0

6.6. Mode 5 – ILS Mode

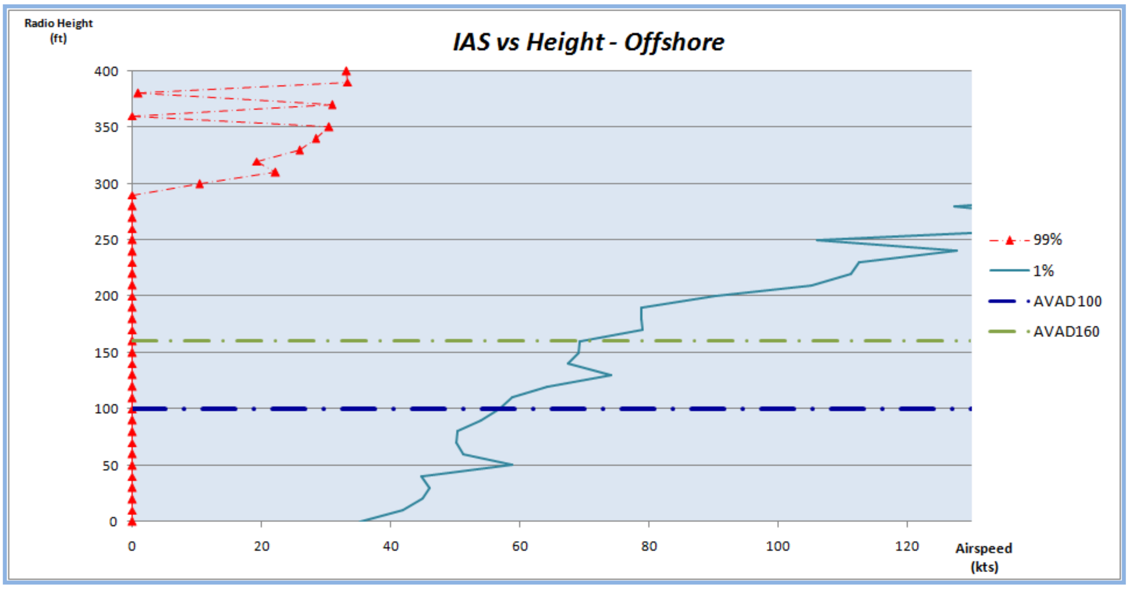
This mode is associated with ILS Glideslope deviation and therefore has no current relevance to offshore operations. It is understood that the SBAS Offshore Approach Procedure (SOAP) will, in future, provide ILS 'look-alike' guidance and thus Mode 5 should be reconsidered at that time. It is noted that the thresholds for 'soft' and 'hard' warnings may need to be revised.

6.7. 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 is given in Section 4.6.

6.7.1. Existing Warning Envelopes

The first figure below is a height-speed diagram showing the upper (green dashed line) and lower (blue dashed line) limits of the current Mode 6 (AVAD[7]) warning envelope, the 1 percentile curve (red line representing the low airspeed end of the distribution), and the 99 percentile curve (light blue line representing the high airspeed end of the distribution). As can be seen, the AVAD warning is triggered on every flight which could be considered undesirable.



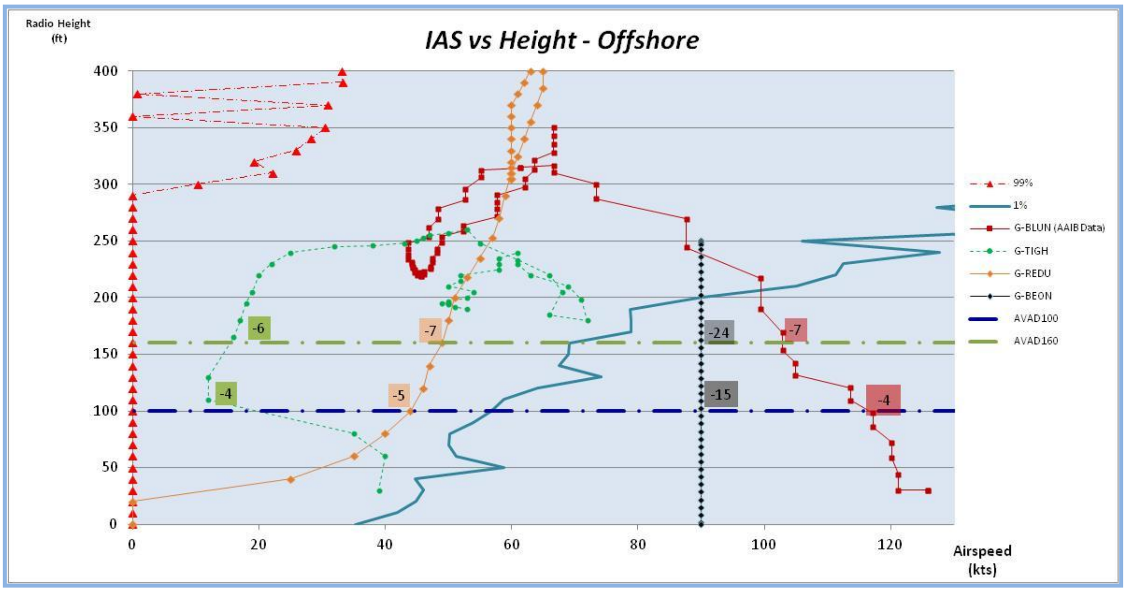
The flight path data from the four accidents has been added to the diagram below. The key to the descent rate plots for the accident data is as follows:

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

[7] 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 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 estimated.

As expected, 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. However, with reference to the review of Mode 4 in Section 6.5 above, it is noted that the altitude call-out functionality of Mode 6 could usefully be replaced with a modified version of Mode 4 which would be more effective and less prone to nuisance alerts.



6.7.2. Summary of Results for Mode 6

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.

Accident	Warning Time (sec)	
	Current 100ft	Current 160ft
G-BEON	15.0	24.0
G-TIGH	4.0	6.0
G-BLUN	4.0	7.0
G-REDU	4.5	7.0

6.8. Exploratory Analysis

As well as investigating improvements possible through the modification of the existing HTAWS 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 RoD.

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

6.9. TAWS Inhibit Function

The existing EGPWS warning envelopes are subject to activation/enabling logic that is only partially described in Section 4. The purpose of this logic is essentially to minimise the nuisance warning rate and will likely be product specific, at least to some degree. The proposed new warning envelopes are based on FDM data, and these have been set such that an acceptable nuisance warning rate of less than 1 in 100 flights will be achieved provided that the FDM data is fully representative of 'normal' operations. If the new envelopes are adopted, therefore, it follows that the current activation/enabling logic should be reviewed and any unnecessary/superseded logic deleted or modified as appropriate.

6.10. Sikorsky S76A+ Analysis

Following completion of the EC225 analysis it was recognised that this aircraft would not necessarily be representative all types currently in use in offshore operations. It was therefore agreed that it would be highly desirable to verify the results from the EC225 with those from a different type, preferably one with different operational characteristics.

The Eurocopter EC225 is a modern helicopter with a relatively high performance margin and a sophisticated autopilot. Being an older type, the Sikorsky S76A+ was judged to represent the opposite end of the spectrum in terms of performance and specification, and thus ideally suited as the second helicopter type to analyse. In addition, the Bristow S76A+ fleet were operated quite differently to the EC225 fleet. Being based in the southern North Sea, the operation involved a lot of shuttling and manual flying. Between them, therefore, the EC225 and S76A+are considered to adequately encompass all offshore helicopter types and operations.

Prior to running the analysis on the S76A+, it was expected that the type would exhibit a wider spread in flight profiles during the first and last 1000ft of offshore flights, which would potentially require a re-positioning of the proposed HTAWS envelopes for the false alert rate of 1 in 100 to be maintained. The results of the analysis for the Sikorsky S76A+ are detailed in Appendix C. Although it can be seen that the predicted increase in the spread of the rate-of-descent measurements was realised, the amount by which the proposed HTAWS envelopes need to be moved to maintain the false alert rate is in fact quite small. The impact on estimated warning times for the modifications to the existing HTAWS warning envelopes is consequently minimal.

6.11. Airspeed vs Total Torque Solution

Analysis of the flight data from the accident to AS332L2 G-WNSB on approach to Sumburgh in August 2013 indicated that the best warning time provided by current HTAWS (Mode 1 'Sink Rate') would have been 7 seconds[8]. The proposed new HTAWS envelopes would have provided a greater warning time of 8 seconds, however the pilot had already recognised the situation and was starting to react at this point as evidenced by the onset of increasing collective pitch. Furthermore, the aircraft manufacturer has since confirmed that modelling results suggest that the aircraft was not recoverable from this point.

Taking a similar approach to that adopted for the accident to G-TIGH at the Cormorant A platform in 1992 and looking for the precursor to the onset of adverse height/rate of descent, a long period of flight at abnormally low collective pitch and airspeed combinations was noted. It was therefore decided to re-analyse the available operational flight data in order to investigate the potential to create a new warning envelope based on airspeed and collective pitch. The analysis was performed on the EC225 data set first as this aircraft is similar to the accident aircraft, with a view to extending it to the S76A+ data if the results showed promise. In the event, the S76A+ data was also re-analysed.

Although the original concept was for a warning envelope based on collective pitch and airspeed, for logistical reasons (i.e. the data could be produced more efficiently) an envelope based on total torque and airspeed was initially investigated. Collective pitch and total torque are generally well correlated and, for most practical purposes, are effectively interchangeable. Collective pitch data would be extracted and used to define a warning envelope if the results using total torque showed promise and this was the case.

[8] A warning time of 5.7 seconds was obtained during a laboratory simulation test at Honeywell using the Mk XXII HTAWS based on an EC225 configuration with the latest (as of June 14) -030 software and the accident flight data with data samples linearly interpolated.

The results of the analysis are detailed in Appendix D. The airspeed vs total torque warning envelope based on the EC225 flight data significantly improves the warning times for the G-WNSB and G-BLUN accidents, particularly in the case of the latter. This is especially important as none of the other warning envelopes, current or proposed, are very effective for either of these accident scenarios. There remains, however, the question of the general applicability of this new envelope. Significant differences between the EC225 and S76A+ FDM data were discovered such that a warning envelope designed to respect the 99 percentile line for the S76A+ would be ineffective.

An airspeed vs collective pitch envelope was investigated and found to offer no advantage compared to airspeed vs total torque. The use of collective pitch in place of total torque did, however, highlight differences in scaling between helicopter types which would necessitate individually tailored envelopes for each type. This is much less of an issue when using total torque as it has a common natural physical datum.

In view of the results obtained for the S76A+, the analysis was extended to additional helicopter types. FDM data was obtained from CHC for the S92, S76C++ and AW139, as well as data from Bristow for the AW139. This study is reported in Appendix E. Effective envelopes were identified for both the S92 and the AW139 which were similar to the EC225, and it is possible that a single ‘average’ envelope might represent an efficient solution. The S76C++ results were similar to the S76A+ and the envelope does not appear to be suitable for this family of helicopters. It appears that, although very effective on most types, the airspeed vs total torque envelope differs between helicopter types and is not suitable for some.

Consideration should therefore be given as to whether and how best such a warning envelope might be implemented. Individual, tailored warning envelopes could be provided for each helicopter type, selected by pin programming. Alternatively, if a single envelope could be defined that was adequate for most helicopter types, that envelope could be implemented in a standard HTAWS and disabled by pin programming where necessary to prevent excessive false alerts (e.g. for the S76 series). Both of these options are possible; the tail strike function of Mode 6 is already tailored to individual helicopter types and some modes are already disabled on some helicopter types (e.g. Mode 1 on the Sikorsky S92). Further helicopter types are to be evaluated (e.g. Airbus Helicopters H175 and Leonardo AW189) and the optimum solution determined once the results are available.

6.12. Additional Accident/Incident Data Analysis

Since the completion of the work reported in the main body of this report, there have been a number of additional occurrences that are relevant to the study and, in addition, the data for an earlier incident became available. Although the total number of actual occurrences remains limited, the addition of these occurrences more than doubles the size of the data base and introduces a new accident scenario. These occurrences are:

- AS332L2 G-WNSB, 2013 – N Sea [9]

- EC155 OY-HJJ 2013 – N Sea [10]
- Sikorsky S92 C-GQCH, 2011 – St. John's, Newfoundland [11]
- Sikorsky S92 incident
- EC225 incident 1
- EC225 incident 2

The latter three incidents were provided to the project in confidence so no formal references are available.

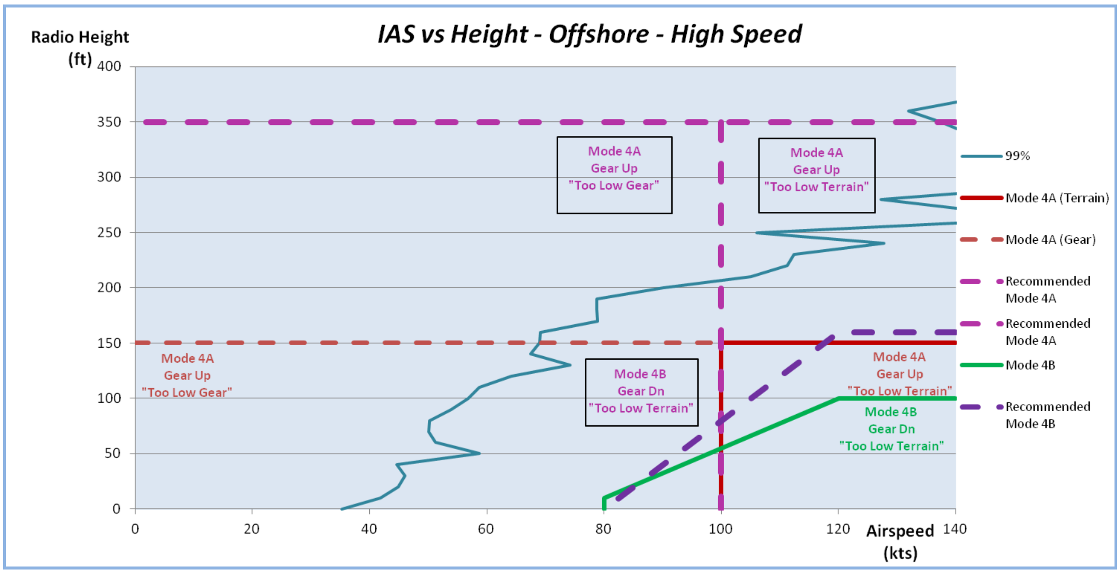
Overall, the analysis of the additional occurrences detailed in Appendix F supports the adoption of the recommended envelopes. Worthwhile improvements in warning time are indicated for four of the six occurrences. For the remaining two, a revision (reduction in airspeed threshold) of the recommended Mode 3B envelope would result in useful warnings, however additional filters would be required to avoid excessive false alerts.

6.13. Additional Helicopter Types

The FDM data for additional helicopter types collected for developing airspeed vs total torque envelopes (see Section 6.11 above) was also used to evaluate all of the new and revised warning envelopes except for Mode 1. The Mode 1 envelope was not checked due to some issues experienced in programming the warning envelope in the operators' FDM systems. However, Mode 1 is not expected to generate excessive nuisance alert rates as helicopter operators' standard operating procedures and the procedures contained in Rotorcraft Flight Manuals are well aligned with the envelope.

The data set comprised: 7,343 AW139 flights and 4809 S92 flights from Babcock Mission Critical Systems Offshore Ltd.; 39,168 AW139 flights from Bristow Helicopters Ltd.; 44,346 AW139 approaches, 36,976 S92 approaches and 35,475 S76C++ approaches from CHC. The only issue identified apart from the customisation required for the airspeed vs total torque envelopes was an excessive nuisance alert rate for Mode 4B for the AW139. This could be addressed by modifying the revised Mode 4B warning envelope detailed in the figure below (compare with figure in Section 6.5.1).

Although solving the nuisance alert rate on the AW139, the modification significantly reduces the warning times for G-BEON and G-REDU which is undesirable and might preclude the deletion of Mode 6A were this version of Mode 4B to be applied generally. Alternatively, this envelope might be implemented on the AW139 only. Analysis of FDM data for further helicopter types (e.g. Airbus Helicopters H175 and Leonardo AW189) will help to identify the best solution.



6.14. Flight Simulator Study

A simulator trial was conducted on the Bristow EC 225 simulator using a modified EGPWS MKXXII unit supplied by Honeywell. During the trial, test pilots from Babcock, CHC and Bristow conducted an assessment of the revised warning envelopes whilst replicating the incidents and accidents above. Overall, the assessment concluded that the warning envelopes were satisfactory and provided timely warnings.

The following scenarios were investigated:

- Scenario 1: ILS – 3° approach flown at 150 kt still air – MDH 200 ft with an automatic transition to level flight over the runway.

  Result: The automatic transition down to 80 ft over the runway had a slow deceleration and so a Mode 4, “Too Low Terrain”, alert was triggered as expected.

- Scenario 2: ILS – 3° approach flown at 150 kt still air – MDH 200 ft with a manual transition to the hover.

  Result: The manually flown deceleration was more aggressive and did not result in any alerts being triggered.

- Scenario 3: LOC/DME/NDB to RW 24 at Scatsta. Nominal descent angle of 4° from FAF flown as a 4-axis approach at 120 kt.

  Result: The rate of descent was 800 ft/min. No alerts were triggered as expected.

- Scenario 4: LOC/DME/NDB to RW 24 at Scatsta. Nominal descent angle of 4° from FAF flown in 3 axis with ROD controlled by collective.

  Result: Maximum rate of descent 1000 ft/min reduced to 800 ft/min below 500 ft agl. No warnings generated as expected.

- Scenario 5: ARA Flown to a MDH of 200 ft. Flown in 4-axis with a Go_Around selected at the MAP.

  Result: Flown at 70 kt GS. Still air. ROD 500 ft/min. No alert generated as expected.

- Scenario 6: ARA Flown to a MDH of 200 ft. Flown in 3 axis with ROD controlled by collective. At the level sector allow the airspeed to bleed by not selecting sufficient power.

  Result: When the airspeed reduced the aircraft protection modes were activated and no alerts generated. Repeating the exercise with the upper modes disengaged during the level sector (i.e. protection modes inhibited), an airspeed low warning was triggered at 20 kt as expected.

- Scenario 7**:** Helipad reject following OEI.

  Result: This scenario should have triggered a Mode 1 warning but no warning was generated. A lack of Mode 1 alert is most probably due to the erroneous GPS vertical speed provided to the EGPWS, i.e. a simulator integration issue.

- Scenario 8: High speed >50 kt reject following an engine failure during take-off.

  Result: During the aggressively flown high speed reject the Airspeed Low warning occurred repeatedly. This warning could be a distraction during a critical phase of flight. The gently flown reject did not result in a warning. Note that this exercise was performed over land where the offshore envelopes would not be active.

- Scenario 9: C-GQCH without upper modes engaged, pitch the aircraft 9° nose up with 1000 ft/min ROC at 65KTIAS. Release the controls and recover when a TAWS warning is given after the test conditions have been achieved.

  Result: Due to the protection modes embedded in the EC225 autopilot, Scenario 9 had to be manually flown. The aerodynamic response of the EC225 when released to trim is different to the S92 (G-GQCH) and so emulating the incident scenario was problematical. The exercise demonstrated that a loss of airspeed after take-off will generate relevant warnings when Mode 3 is invoked.

- Scenario 10: G-TIGH take-off into a 55 kt wind level at 250 ft and keep the collective fixed. Turn downwind maintaining the collective fixed and recover when a TAWS warning is given after the test conditions have been achieved.

  Result: The points above demonstrate that a warning is provided in timely manner.

- Scenario 11: G-BLUN Start at 90 kt wings level at 400 ft and then push the nose forward and increase power to increase speed, 38° left roll, 38° pitch down with a ROD of -2000 ft min at 300 ft AMSL. Recover when a TAWS warning is given.

  Result: Due to the dynamic nature of this accident the conditions were hard to replicate. The type of warnings given and their sequence varied with the rates of pitch and roll selected. The Mode 1 performance was significantly affected by the erroneous GPS vertical speed provided to the EGPWS by the simulator. Mode 1 alerts would have been triggered earlier if GPS vertical speed were properly computed.

- Scenario 12: G-REDU Manoeuvre to achieve 60 kt, 10° nose up with a ROD of -1000 ft/min at 350 ft AMSL. Recover when a TAWS warning is given after the test conditions have been achieved.

  Result: The alerts were given in a timely manner.

- Scenario 13: G-WNSB Configure the aircraft in 3-axis with pitch controlled on cyclic pitch and airspeed on collective. Set Alt Pre to 300 ft. Commence an approach from 1000 ft 80 kts with 20% torque set. Recover when a TAWS warning is given after the test conditions have been achieved.

  Result: The alert was given in a timely manner.

The following conclusions were drawn:

- Two deficiencies in the simulator and simulator/EGPWS interface were noted. The terrain database and position became offset which impacted on the second and third sorties. It was discovered that the simulator did not provide a properly computed/modelled GPS vertical speed input to the EGPWS. The GPS vertical speed was always set to 0 fpm and valid. The EGPWS blends GPS vertical speed and barometric altitude rate, thus erroneous GPS vertical speed led to an offset (delay) between the simulator rate of descent and that internally generated by the EGPWS unit.
- Some of the accident scenarios were difficult to replicate, in particular Scenario 11, G-BLUN.
- Some test points had to be manually flown due to the EC225 autopilot protection modes which are not present in most other types.
- In Scenario 6 the “Airspeed Low” warning was given at 20 kt which is unsatisfactory. The airspeed torque warning envelope is a straight line, whilst the FDM shows the relationship to be non-linear below 35 kt. Maintaining a straight line might reduce the effectiveness of the warning envelope below 35 kt.
- The “Airspeed Low” warning was issued repeatedly whilst the condition existed. In the case of a high speed reject or recovery, Scenarios 8 and 10, the repeating warning became a distraction. The optimum means of delivering the warning whilst not becoming a distraction should be investigated as part of the Human Factors phase of this project.
- In general the warnings provided were an enhancement over those currently provided.

7. Conclusions and Recommendations

7.1. Warning Times

The overall benefit of adopting the proposed warning envelope modifications are summarised in the following tables. Results are presented for the proposed new envelopes based on EC225 data only (EC225 Env.), and for the proposed new envelopes adjusted to include the S76A+ and maintain a nuisance alert rate of less than 1 in 100 (S76 Env.).

The first table compares the performance of the proposed new HTAWS warning envelopes with what could be achieved with the existing AVAD (HTAWS/EGPWS Mode 6) both at the current most common setting of 100ft, and with the maximum setting allowed of 160ft.

Accident	Current AVAD (HTAWS/EGPWS Mode 6)		Proposed HTAWS			Δ	
	100ft	160ft	Warning Time (EC225 Env.)	Warning Time (S76 Env.)	Mode(s)	100ft AVAD	160ft AVAD
G-BEON	15.0	24.0	24.0	24.0	4B	+9.0	+0.0
G-TIGH	4.0	6.0	17.0	17.0	3B	+13.0	+11.0
G-BLUN	4.0	7.0	35.0	8.0	TT/IAS (EC225) 1 & 2A (S76A+)	+31.0 (+4.0)*	+28.0 (+1.0)*
G-REDU	4.5	7.0	16.0	15.0	1 & 2A	+11.5 (+10.5)*	+9.0 (+8.0)*
G-WNSB	3.5	5.0	13.0	8.0	TT/IAS (EC225) 1 & 2A (S76A+)	+9.5 (+4.5)*	+8.0 (+3.0)*
OY-HJJ	0.0	0.0	35.0	35.0	3B	+35.0	+35.0
C-GQCH	9.0	12.5	32.0	32.0	3B	+23.0	+19.5
S92 incident	0.0	1.0	18.0	11.4	TT/IAS (EC225) 1 & 2A (S76A+)	+18.0 (+11.4)*	+17.0 (+10.4)*
EC225 incident 1	0.0	0.0	0.0	0.0	-	0.0	0.0
EC225 incident 2	0.0	0.0	0.0	0.0	-	0.0	0.0

* S76A+ envelope improvement

Significant improvements in warning times compared to the present 100ft AVAD setting are evident for eight of the 10 occurrences using the EC225 envelopes. The same is true for the comparison with a 160ft AVAD setting although with slightly smaller increases in warning times and for only seven of the 10 occurrences.

The results for the S76A+ warning envelopes are also very encouraging, except that the ineffectiveness of the airspeed vs total torque envelope in this case constrains the improvements in warning times to six out of 10 occurrences for the 100ft AVAD setting and five out of 10 occurrences for the 160ft AVAD setting. Even where the new envelopes provide only a nominal increase in warning time over the 160ft AVAD setting however, there is additional benefit in the reduction in nuisance alert rate that would be expected.

The second table (below) compares the performance of the proposed new 'Classic' Mode HTAWS warning envelopes with those of existing HTAWS (Honeywell EGPWS).

Accident	Current HTAWS (EGPWS) excl. Mode 6		Proposed HTAWS			Δ
	Warning Time	Mode(s)	Warning Time (EC225 Env.)	Warning Time (S76A+ Env.)	Mode(s)	
G-BEON	4.0	4B	24.0	24.0	4B	+20.0
G-TIGH	1.5	1	17.0	17.0	3B	+15.5
G-BLUN	7.5	1	35.0	8.0	TT/IAS (EC225) 1 & 2A (S76A+)	+27.5 (+0.5)*
G-REDU	1.5	1	16.0	15.0	1 & 2A	+14.5 (+13.5)*
G-WNSB	7.0	1	13.0	8.0	TT/IAS (EC225) 1 & 2A (S76A+)	+6.0 (+1.0)*
OY-HJJ	5.0	1	35.0	35.0	3B	+30.0
C-GQCH	18.0	1	32.0	32.0	3B	+14.0
S92 incident	6.8	1	18.0	11.4	TT/IAS (EC225) 1 & 2A (S76A+)	+11.2 (+4.6)*
EC225 incident 1	0.0	-	0.0	0.0	-	0.0
EC225 incident 2	0.0	-	0.0	0.0	-	0.0

* S76A+ envelope improvement

Significant improvements in warning times (*) are provided for all of the occurrences except for EC225 incidents 1 and 2, where the airspeed achieved was insufficient to activate the proposed new Mode 3B. In addition, it should be noted that a generic airspeed vs total torque envelope (i.e. based on the S76A+) would not be effective for either the G-WNSB or G-BLUN accidents, and would provide only a nominal benefit in the case of the S92 incident.

Subject to evaluation using data for additional accident/incident scenarios, the results presented in the tables above are considered to provide worthwhile improvements in warning times available to flight crews while ensuring an acceptably low false alert rate of less than 1 in 100. This alert rate is believed to represent an improvement over current HTAWS.

Between them, the results of the EC225 and S76A+ studies are considered to be suitably representative of all offshore operations, and this is generally supported by the analysis of FDM data for a further three helicopter types and also from an additional two helicopter operators. Consequently, with the exception of the new airspeed vs total torque mode and possibly the revised Mode 4B, a common set of new 'Classic' Mode envelopes could be implemented for application to all offshore helicopter types and operations. It is possible that a common airspeed vs total torque envelope could be devised that provides an acceptable compromise between warning time and nuisance alert rate for the majority of helicopter types. Some modes may have to be disabled via pin programming on a minority of helicopter types as is currently the case (e.g. Mode 1 is disabled on the S92).

7.2. Proposals for HTAWS Modifications

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

- Remove all offshore obstacles from the database to address the high nuisance alert rate currently experienced with the 'Enhanced Mode'. Note that this modification has already been incorporated in Honeywell HTAWS.
- Replace the current 'Classic' Mode 1 with the new warning envelope detailed in Appendix C.1.
- Delete the current 'Classic' Mode 2. As there is no 'terrain' at sea Mode 2 effectively provides the same protection as Mode 1 and is therefore redundant. Note also that Mode 2 is usually inhibited while the 'Enhanced Mode' is active.
- Modify the current 'Classic' Mode 3 as detailed in Section 6.4.2.1, renaming it 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 as detailed in Section 6.4.2.2.
- Replace the current 'Classic' Modes 4A, 4B and 4C with the new 'Classic' Mode 4A and 4B warning envelopes as detailed in Section 6.5.

- Delete the altitude call-out section of the existing ‘Classic’ Mode 6 where this functionality is provided by Mode 4.
- Implement the new airspeed vs total torque envelopes on helicopter types for which satisfactory envelopes can be identified.

8. Further Work

This report covers the research performed to date which has necessarily been focussed on the technical challenge of modifying HTAWS 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 HTAWS modifications that would be required to realise an effective system.

8.1. Further Validation of Warning Envelopes

The evaluation of the new and revised warning envelopes will be extended to additional helicopter types (e.g. H175 and AW189). The purpose of this exercise will primarily be to identify airspeed vs total torque warning envelopes for these types, and determine whether a single standard envelope could represent the best solution. Further evaluation of the other envelopes will be performed with a particular focus on Mode 4B to establish whether the AW139 is unusual. The main focus of the evaluation will be the nuisance alert rate, although incidents may occur providing additional case studies.

8.2. 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 attenson, voice, and tone + voice. Any tone or attenson 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 G for information.

The aspect of warning annunciation options is being addressed under an associated programme of work which has been contracted to Cranfield University. The results of this work will be reported when available.

8.3. 'Soft' Warnings

This study has focused on the apparent large gap that exists between 'normal operation' and the existing HTAWS 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' HTAWS warnings, limiting the amount of warning time that can be provided. Higher nuisance alert rates might be acceptable for 'soft' HTAWS warnings, however, which could allow warning times to be extended further. It is therefore proposed that the use of 'soft' warnings be investigated as part of the work on warning annunciation discussed in Section 8.2 above.

9. References

[1] CAA Paper 97004 –Investigation and Review of Helicopter Accidents Involving Surface Collision– Civil Aviation Authority, London, 2004.

[2] UK AAIB Report No: 10/1982. Report on the accident to Bell 212, G-BIJF in the North Sea South-east of Dunlin Alpha Platform, 12 August 1981.

[3] UK AAIB Report No: 8/1984. Report on the accident to British Airways Sikorsky S61N, G-BEON in the sea near St Mary's Aerodrome, Isles of Scilly on 16 July 1983.

[4] UK AAIB Report No: 2/1993. Report on the accident to AS 332L Super Puma, G-TIGH near the Cormorant 'A' platform, East Shetland Basin, on 14 March 1992.

[5] UK AAIB Report No: 5/1988. Report on the incident to Sikorsky S76A, G-BHYB near Fulmar A Oil Platform in the North Sea, 9 December 1987.

[6] UK AAIB Report No: 7/2008. Report on the accident to Aerospatiale SA365N, registration G-BLUN, near the North Morecambe gas platform, Morecambe Bay on 27 December 2006.

[7] UK AAIB Report No. 1/2011. Report on the accident to Eurocopter EC225 LP Super Puma, G-REDU near the Eastern Trough Area Project (ETAP) Central Production Facility Platform in the North Sea on 18 February 2009.

[8] Honeywell EGPWS MK XXII Helicopter EGPWS Pilot Guide (Ref: 060-4314-200 Rev. C March 2004).

[9] UK AAIB Special Bulletins: S6/2013, S7/2013, and S1/2014 - AAIB investigation to AS332 L2 Super Puma, G-WNSB.

[10] UK AAIB Bulletin: 7/2014 – AAIB investigation to Eurocopter EC155B1, OY-HJJ.

[11] Canadian TSB Aviation Investigation Report A11H0001, Inadvertent descent during departure, Cougar Helicopters Inc. Sikorsky S92A (Helicopter), C-GQCH, St. John's, Newfoundland and Labrador, 200 NM E, 23 July 2011.

[12] Dutch Safety Board report - Inadvertent loss of altitude during approach; Sikorsky S61N, PH-NZG, Waddenzee near Den Helder, 30 November 2004

Nomenclature

ADC	Air Data Computer
AGL	Above Ground Level
AHRS	Attitude & Heading Reference System
AVAD	Automatic Voice Alerting Device
BAFDA	British Airways Flight Data Analysis Program
CAA	Civil Aviation Authority (UK)
CFIT	Controlled Flight into Terrain
CSV	Comma Separated Variable
EGPWS	Enhanced Ground Proximity Warning System
FDM	Flight Data Monitoring
FDR	Flight Data Recorder
FPM	Feet per Minute
GPWS	Ground Proximity Warning System
GS	Glide Slope (ILS vertical axis)
HOMP	Helicopter Operations Monitoring Programme (form of FDM)
HTAWS	Helicopter Terrain Awareness Warning System
IAS	Indicated Air Speed
ILS	Instrument Landing System
RoD	Rate of Descent
SBAS	(Global Positioning System) Space-Based Augmentation System
TAWS	Terrain Awareness Warning System

Appendix A – Values used in Data Filtering

A.1 – Eurocopter EC225

The following flights were removed from landing analysis:

```
DELETE FROM LANDING WHERE TRQ1<7.5 AND TRQ2<7.5
DELETE FROM LANDING WHERE ALTRATE<-5000 OR ALTRATE>5000
DELETE FROM LANDING WHERE ISNULL(INTRALT,-1)=-1
DELETE FROM LANDING WHERE charindex('EGPD00044',fn)>0        (Aberdeen)
DELETE FROM LANDING WHERE charindex('EGPE00044',fn)>0        (Inverness)
DELETE FROM LANDING WHERE RROD<-7000 OR RROD>5000
DELETE FROM LANDING WHERE ROD<-5000 OR ROD>5000
DELETE FROM LANDING WHERE INTRALT<0 OR INTRALT>1100
```

The following flights were removed from take-off analysis:

```
DELETE FROM TAKEOFF WHERE TRQ1<7.5 AND TRQ2<7.5
DELETE FROM TAKEOFF WHERE ALTRATE<-5000 OR ALTRATE>5000
DELETE FROM TAKEOFF WHERE IAS>100
DELETE FROM TAKEOFF WHERE ISNULL(INTRALT,-1)=-1
DELETE FROM LANDING WHERE charindex('EGPD00044',fn)>0        (Aberdeen)
DELETE FROM LANDING WHERE charindex('EGPE00044',fn)>0        (Inverness)
DELETE FROM TAKEOFF WHERE RROD<-7000 OR RROD>5000
DELETE FROM TAKEOFF WHERE ROD<-5000 OR ROD>5000
DELETE FROM TAKEOFF WHERE INTRALT<0 OR INTRALT>1100
```

A.2 – Sikorsky S76A+

The following flights were removed from landing analysis:

```
DELETE FROM LANDING WHERE TRQ1<7.5 AND TRQ2<7.5
DELETE FROM LANDING WHERE ALTRATE<-5000 OR ALTRATE>5000
DELETE FROM LANDING WHERE ISNULL(INTRALT,-1)=-1
DELETE FROM LANDING WHERE charindex('EGSH00044',fn)>0        (Norwich)
DELETE FROM LANDING WHERE charindex('EGNM00044',fn)>0        (Leeds)
DELETE FROM LANDING WHERE charindex('CAIS00044',fn)>0(Caister)
DELETE FROM LANDING WHERE charindex('EGKR00044',fn)>0        (Redhill)
DELETE FROM LANDING WHERE RROD<-7000 OR RROD>5000
DELETE FROM LANDING WHERE ROD<-5000 OR ROD>5000
DELETE FROM LANDING WHERE INTRALT<0 OR INTRALT>750
```

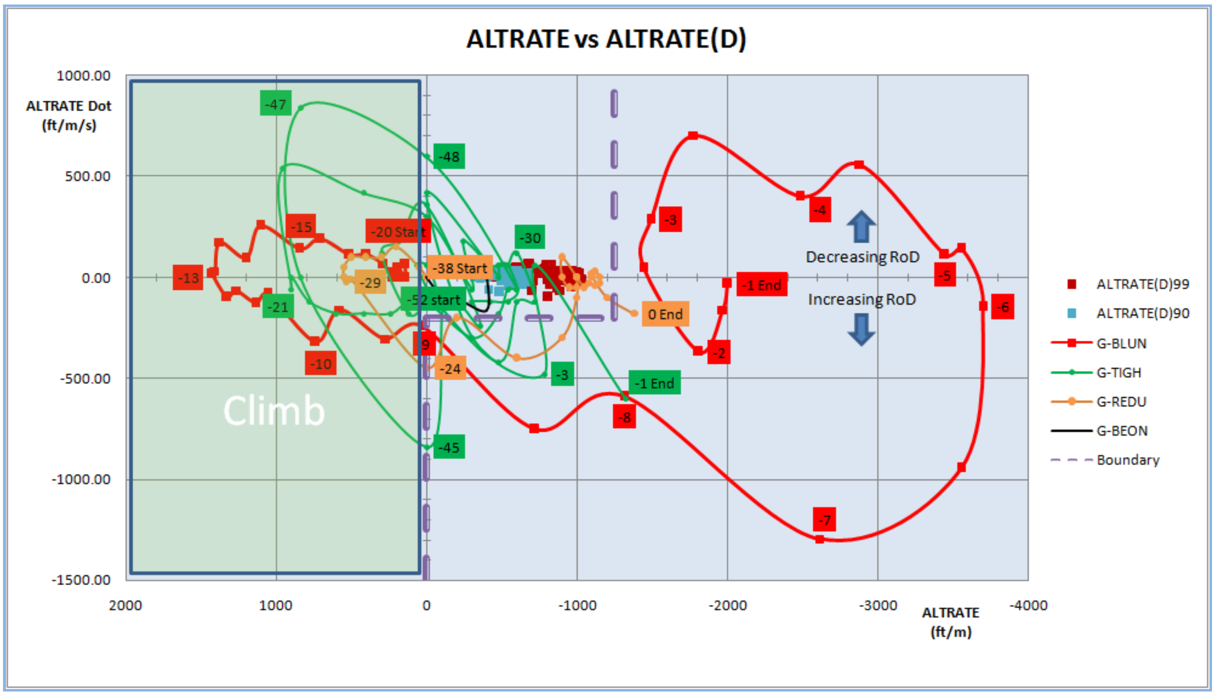
The following flights were removed from take-off analysis:

```
DELETE FROM TAKEOFF WHERE TRQ1<7.5 AND TRQ2<7.5
DELETE FROM TAKEOFF WHERE ALTRATE<-5000 OR ALTRATE>5000
DELETE FROM TAKEOFF WHERE IAS>100
DELETE FROM TAKEOFF WHERE ISNULL(INTRALT,-1)=-1
DELETE FROM TAKEOFF WHERE SUBSTRING(FN,24,4)='EGSH'(Norwich)
DELETE FROM TAKEOFF WHERE SUBSTRING(FN,24,4)='EGNM'          (Leeds)
DELETE FROM TAKEOFF WHERE SUBSTRING(FN,24,4)='CAIS'  (Caister)
DELETE FROM TAKEOFF WHERE SUBSTRING(FN,24,4)='EGKR'(Redhill)
DELETE FROM TAKEOFF WHERE RROD<-7000 OR RROD>5000
DELETE FROM TAKEOFF WHERE ROD<-5000 OR ROD>5000
DELETE FROM TAKEOFF WHERE INTRALT<0 OR INTRALT>750
```

Appendix B – Exploratory Analyses

B.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 drawn 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.

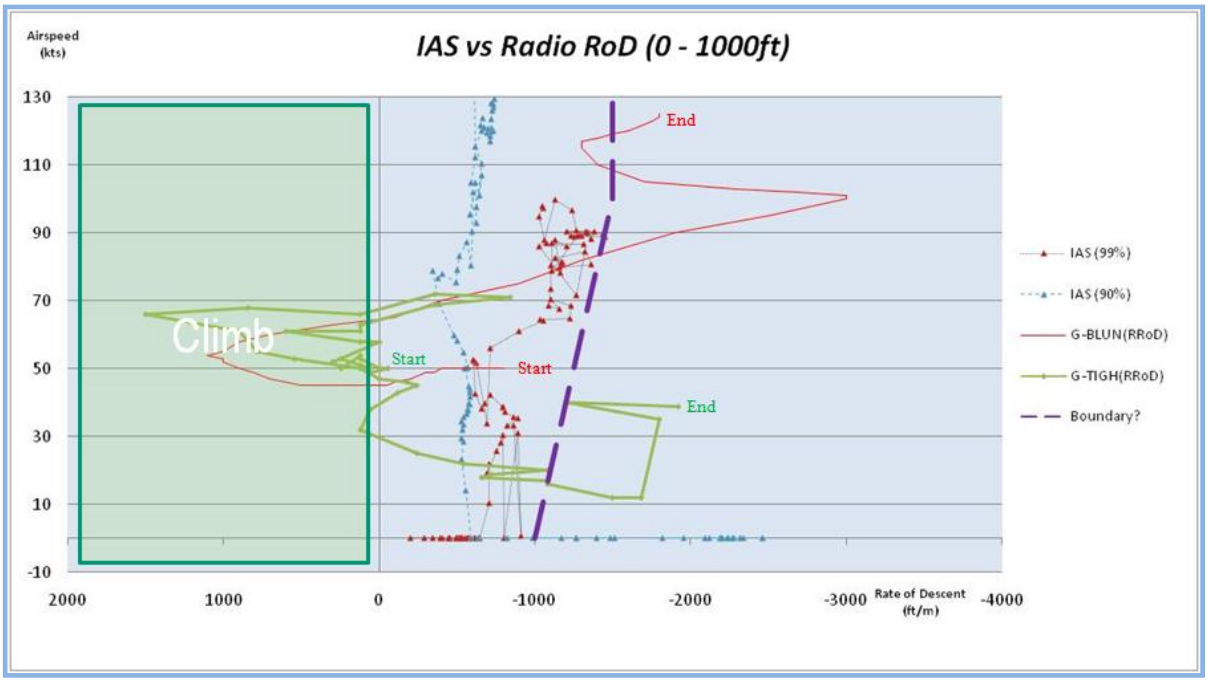
It was found that this would have provided a useful warning for G-BLUN only, but no significant benefit in terms of warning time would have been obtained for G-TIGH, G-REDU or G-BEON, as shown below. G-TIGH would have received warnings of one second duration at 43, 33, and 13 seconds from impact, a two 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. No warning would have been generated for G-BEON.

Accident	Possible Warning
G-BEON	0
G-TIGH	Negligible
G-BLUN	9
G-REDU	Negligible

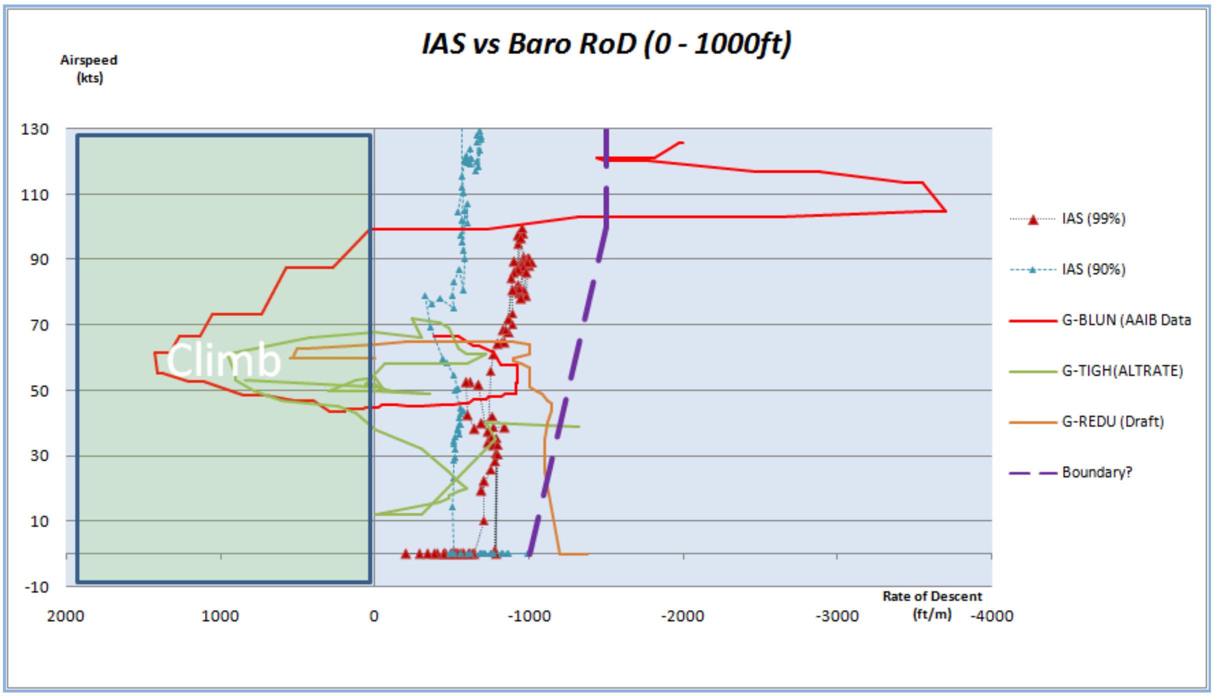
B.2 Indicated Airspeed vs Rate of Descent

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.

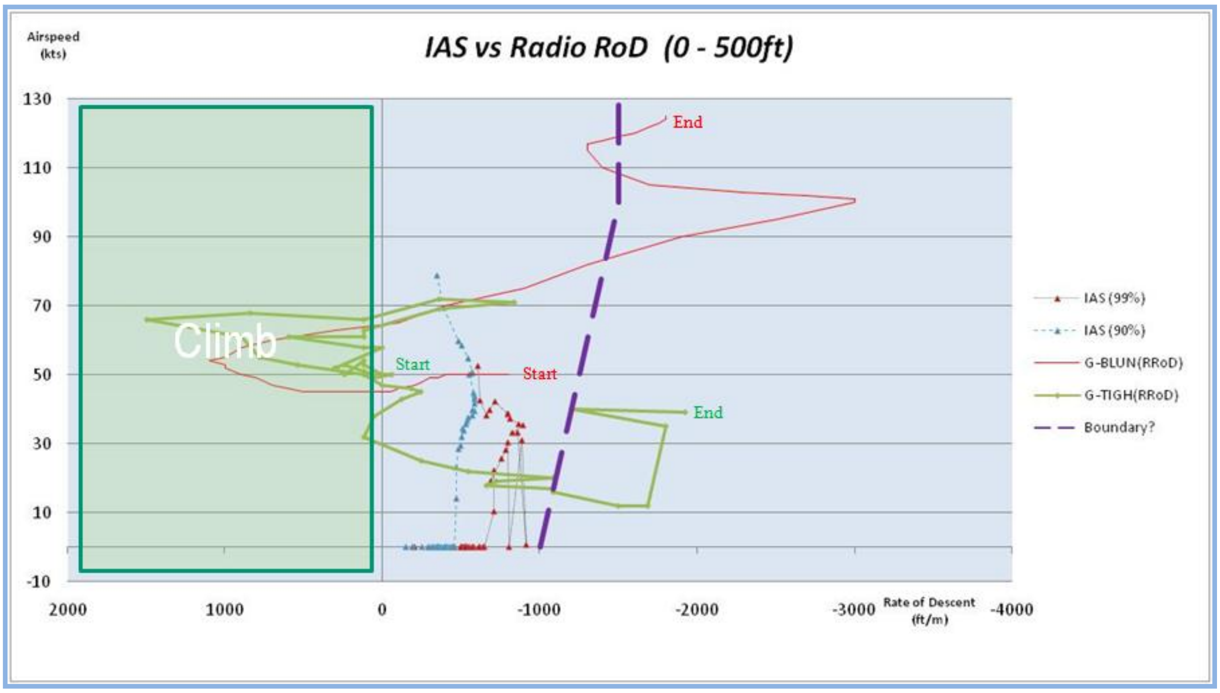
In the case of IAS vs radio RoD (see plot below), it was noted that a boundary from 1000ft/min at 0kts to 1500ft/min at 100kts would separate the accidents and provide a reasonable warning times, comparable to Mode 2A.

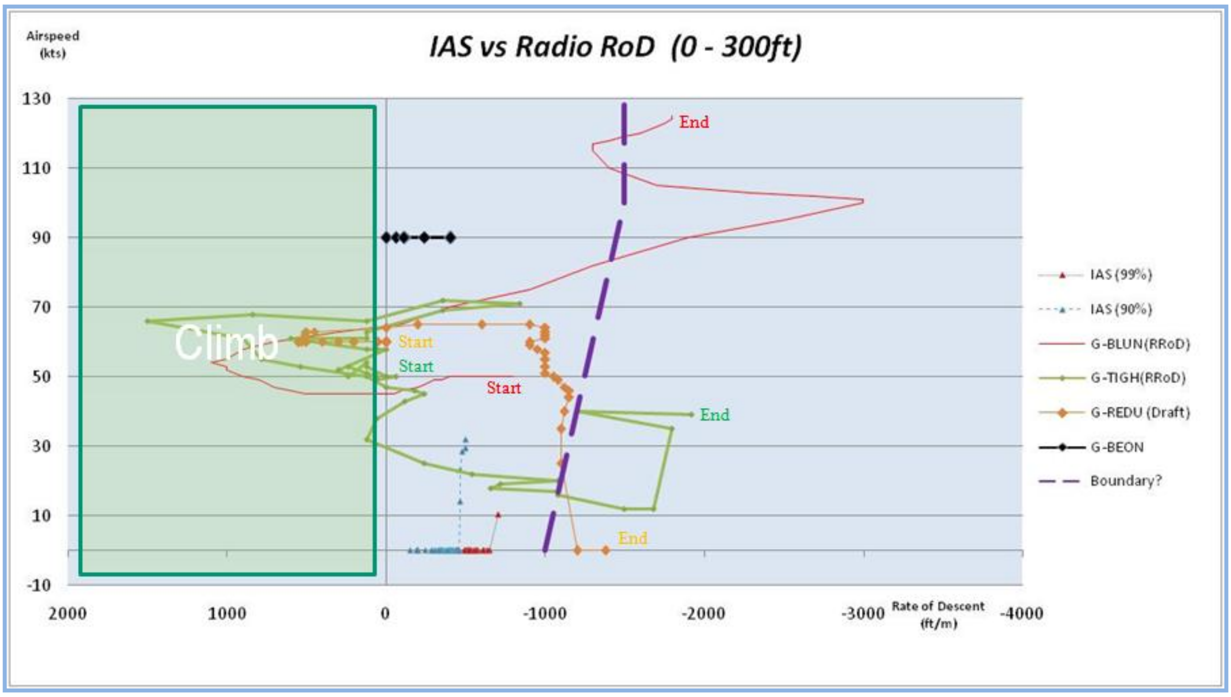


The results for IAS vs baro RoD (see plot below) were similar but less pronounced, presumably due to the lag inherent in baro RoD.



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.)





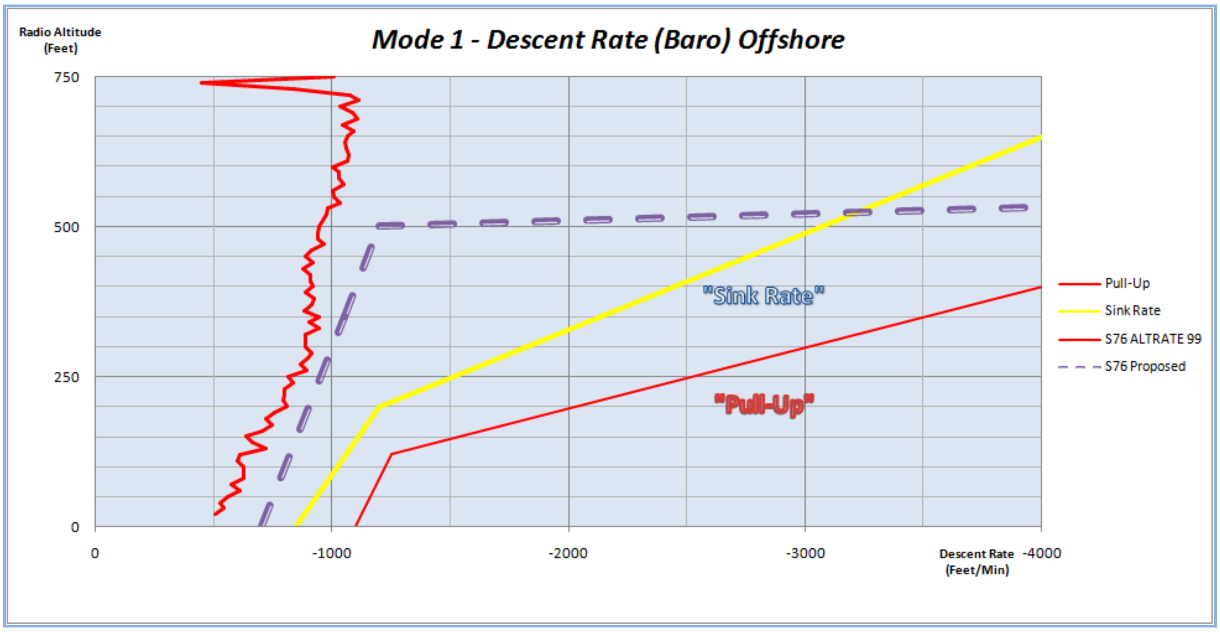
As can be seen, no additional discrimination resulted and, overall, envelopes based on IAS vs RoD did not appear to offer any advantage over existing envelopes.

Appendix C – Sikorsky S76A+ Analysis Results

C.1 – Mode 1 – Descent Rate

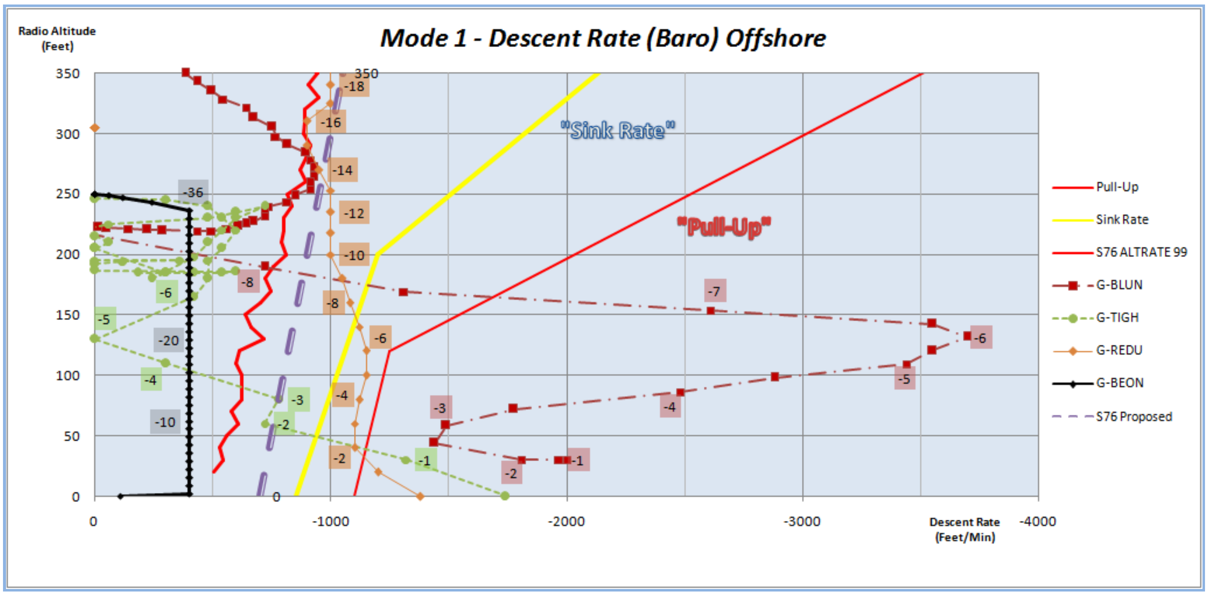
NB: For full explanation of analysis results and recommendations see Section 6.2 Mode 1 – Descent Rate.

The two diagrams below show the results of the S76A+ 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 (red) for the S76A+ and clearly indicates the potential to re-define the envelope without significant risk of an unacceptable false alert rate. This is illustrated by the purple dashed line which represents the recommended new warning envelope.



For 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



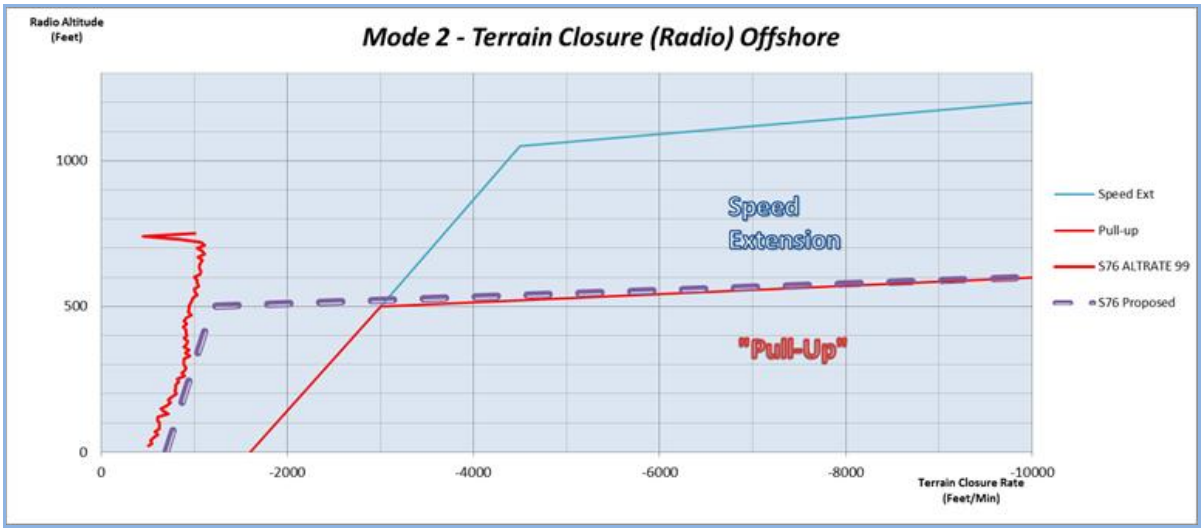
The effect of the modified Mode 1 warning envelope on the warning times for the four example accident cases is shown in the table below. The S76A+ analysis showed slightly higher rates of descent than the EC225 data at each altitude, which required a corresponding 'shift' in the position of the recommended envelope. The impact of this 'shift' was to slightly reduce the improvement in warning time for G-TIGH and G-REDU, as shown in the table below.

Accident	Warning Time (sec)			
	Current Mode 1		Recommended Mode 1	
	'Sink Rate'	'Pull-Up'	(S76A+)	EC225
G-BEON	0.0	0.0	0.0	0.0
G-TIGH	1.5	1.5	2.0	3.5
G-BLUN	7.5	7.0	8.0	8.0
G-REDU	7.0	1.5	14.0	16.0

C.2 – Mode 2 – Terrain Closure

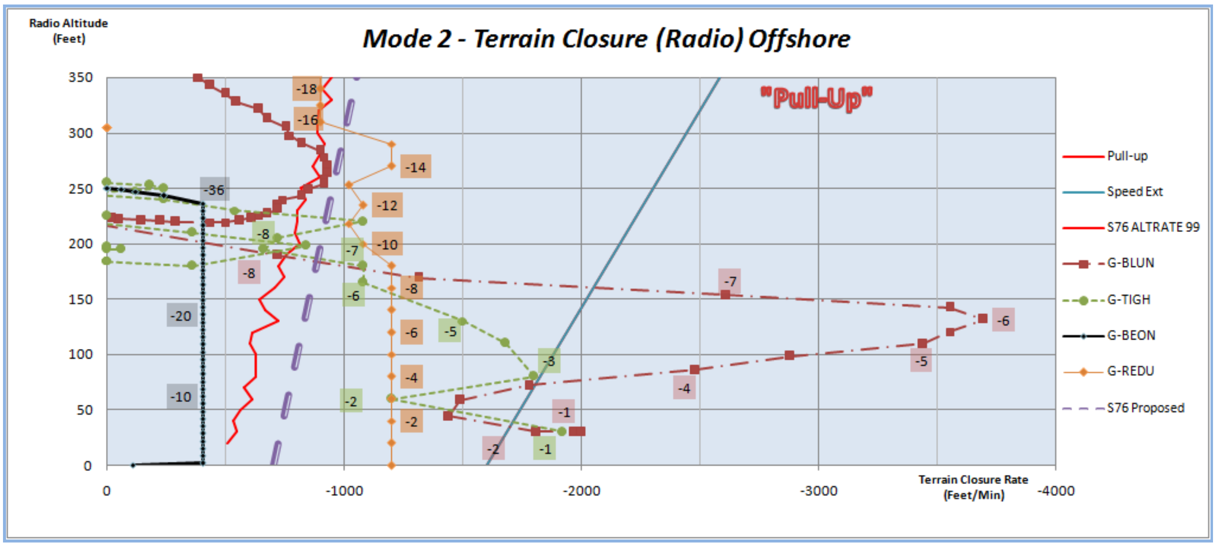
NB: For full explanation of analysis results and recommendations see Section 6.3

The two diagrams below show the results of the S76A+ 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 (red) for the S76A+ and clearly indicates the potential to re-define the envelope without significant risk of an unacceptable false alert rate. This is illustrated by the purple dashed line which represents the recommended new warning envelope.



For 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 effect of the modified Mode 2A warning envelope on the warning times for the four example accident cases is shown in the table below. The S76A+ analysis showed slightly higher rates of descent than the EC225 data for each height, which required a corresponding 'shift' in the position of the recommended envelope. The impact of this 'shift' was to slightly reduce the improvement in warning time for G-TIGH and G-REDU, as shown in the table below.

Accident	Warning Time (sec)		
	Current Mode 2A	Recommended Mode 2A	
		S76A+	EC225
G-BEON	0.0	0.0	0.0
G-TIGH	1.0	7.5	8.0
G-BLUN	7.0	8.0	8.0
G-REDU	0.0	15.0	16.0

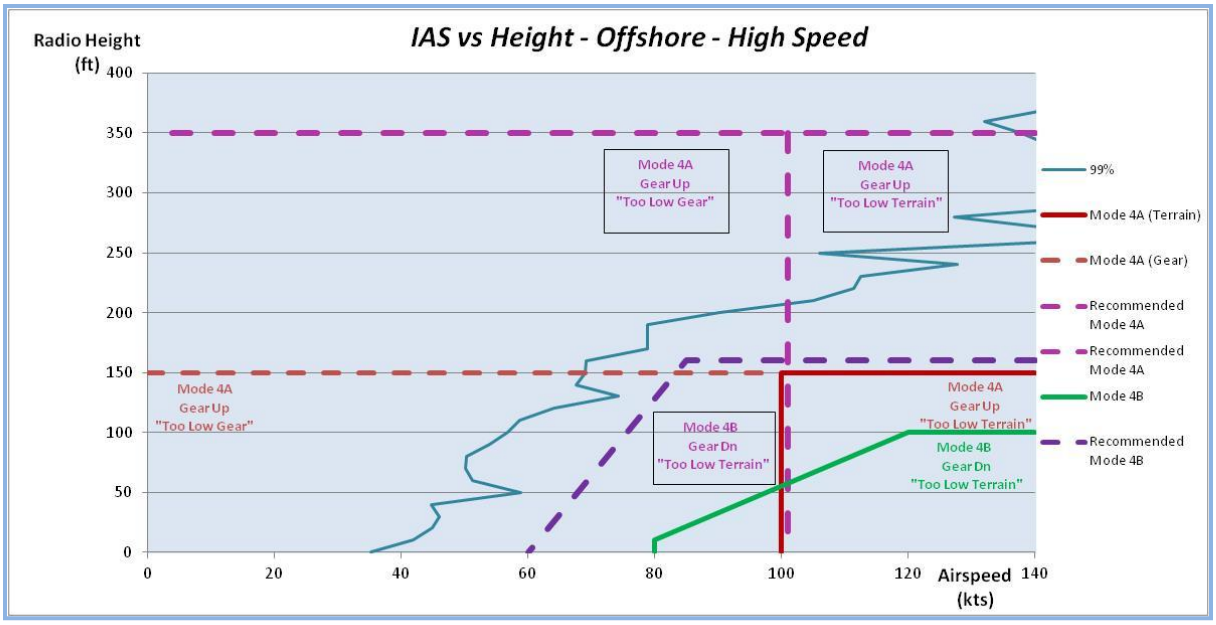
C.3 – Mode 3 – Height Loss After Takeoff

The S76A+ data analysis does not impact the recommendations detailed in Section 6.4, i.e. the EC225 envelope definitions would result in a false alarm rate of less than 1:100 flights.

C.4 – Mode 4 – Terrain Clearance

NB: For full explanation of analysis results and recommendations see Section 6.5.

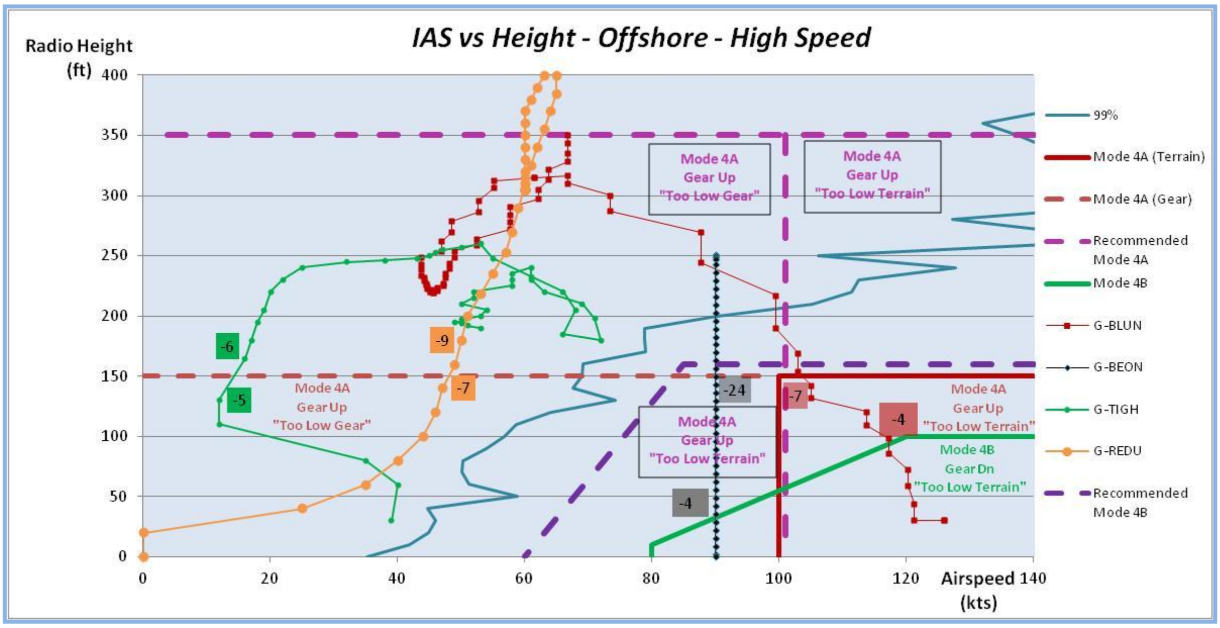
The first figure below is a height vs speed diagram, onto which the '99 percentile' high airspeed line (light blue), the existing Mode 4A (red) and Mode 4B (green) envelopes and the recommended new Mode 4A (pink dashed line) and Mode 4B (purple dashed line) envelopes have been plotted.



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 S76A+ data analysis has no impact the recommendations detailed in Section 6.5.



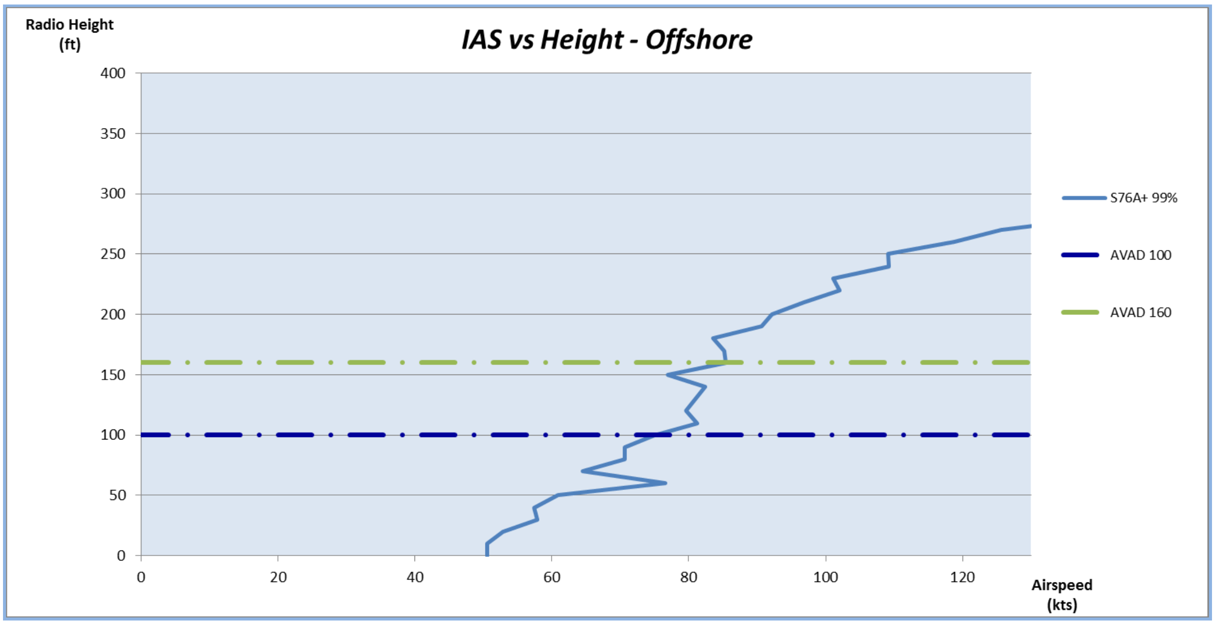
C.5 – Mode 5 – ILS mode

See Section 6.6.

C.6 – Mode 6 – Altitude Call-Outs (S76A+)

NB: For full explanation of analysis results and recommendations see Section 6.7 Mode 6 – Altitude Call-Outs.

The first figure below is a height-speed diagram showing the upper (green dashed line) and lower (blue dashed line) limits of the current Mode 6 (AVAD[9]) warning envelope. In addition, the diagram shows, for the S76A+, the 99 percentile curve (light blue line) representing the high airspeed end of the distribution.

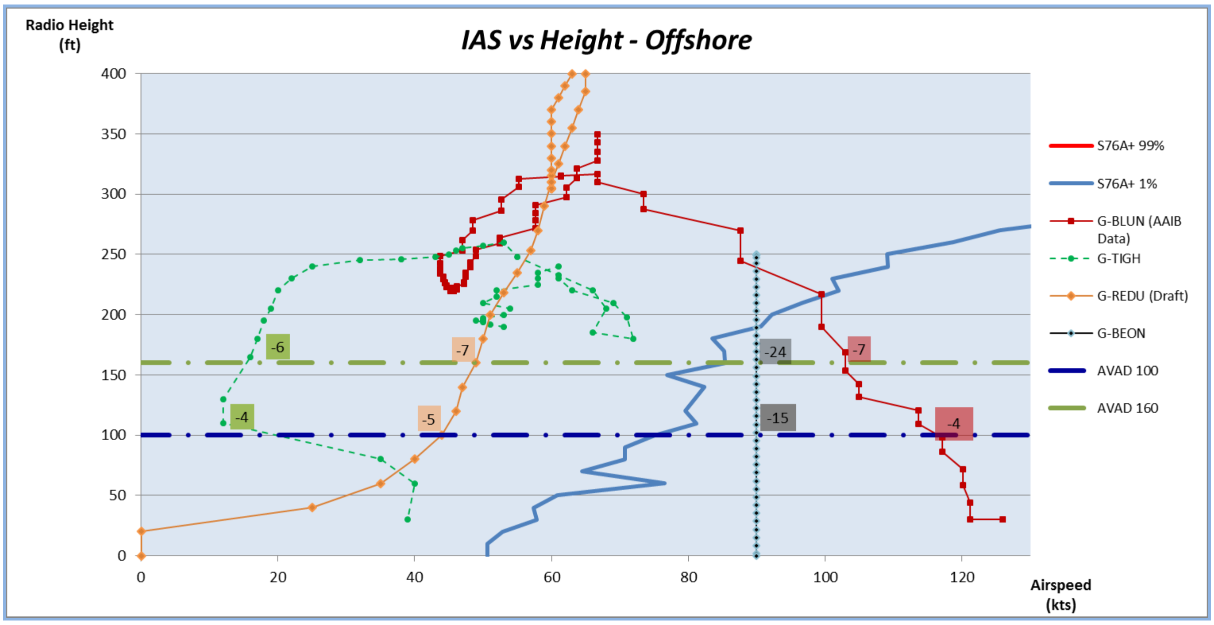


The data from the four accidents has been added to the diagram below. The key to the descent rate plots for the accident data is as follows:

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

[9] 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.

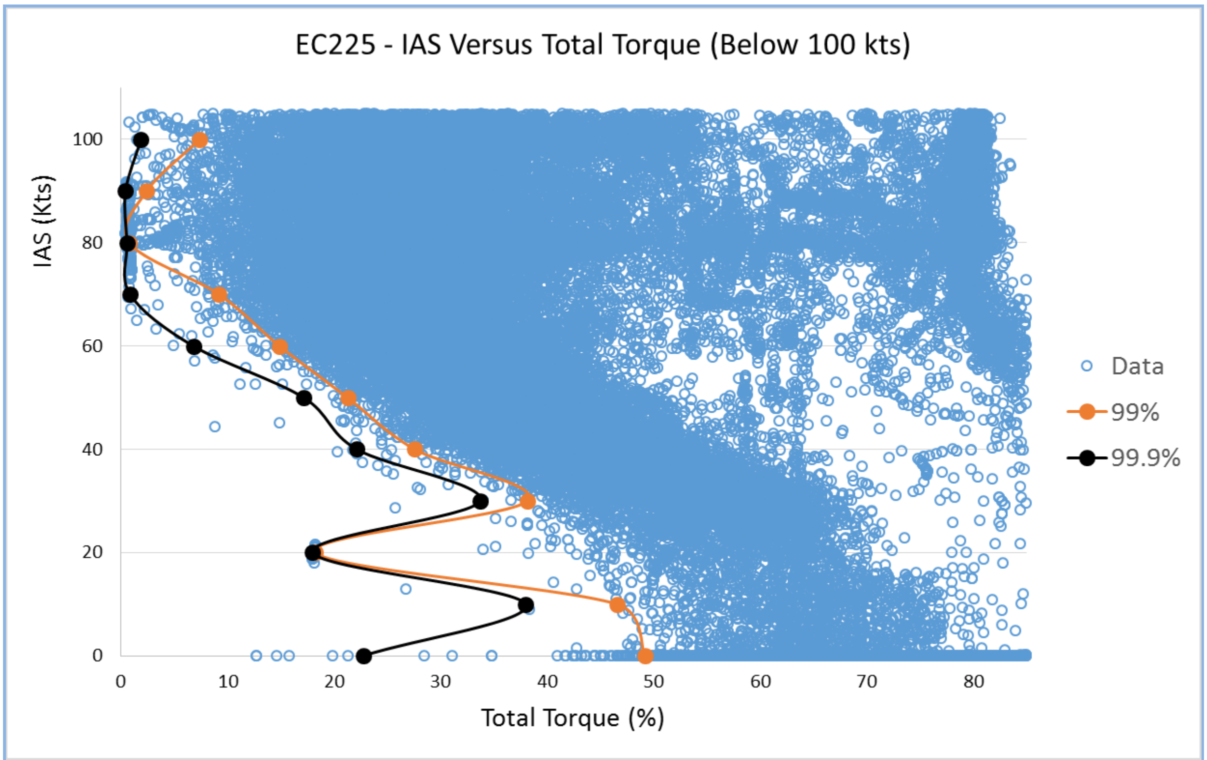
The S76A+ data analysis does not impact the warning times or recommendation detailed in Section 6.7 to raise the Mode 6 fixed height threshold from 100ft to 160ft.



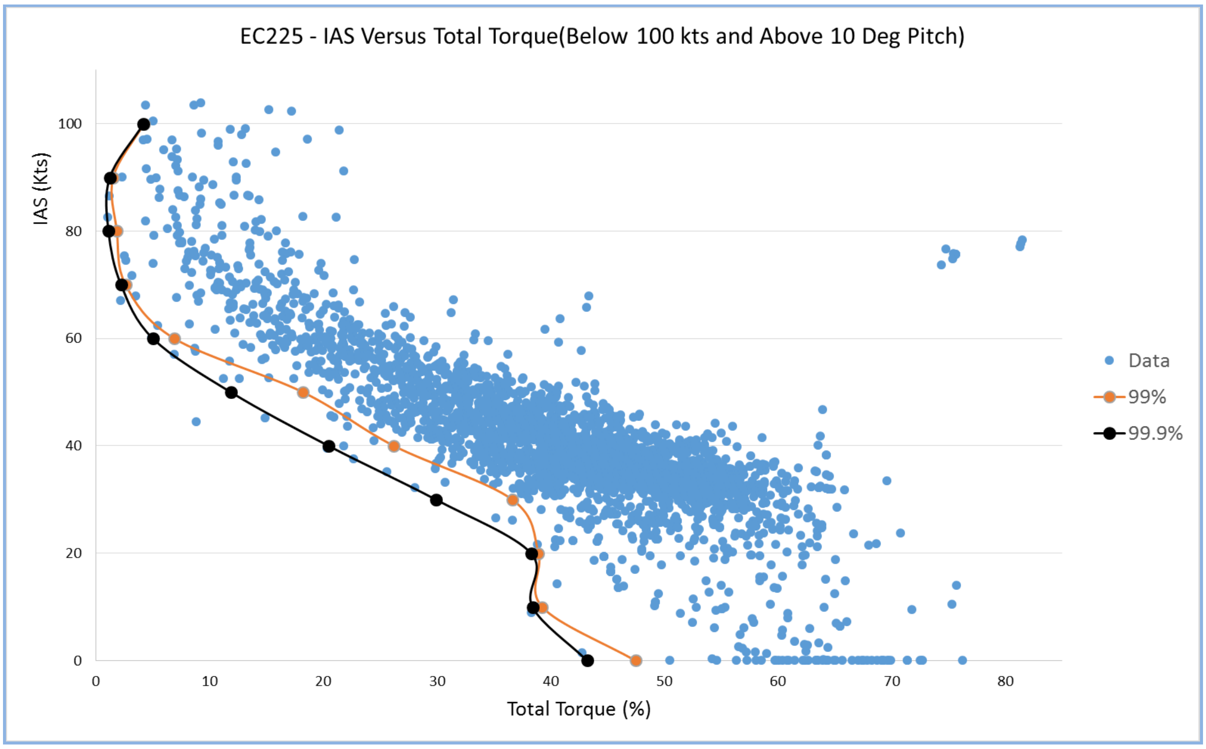
Appendix D – Airspeed vs Total Torque Solution

D.1 Data for Total Torque EC225

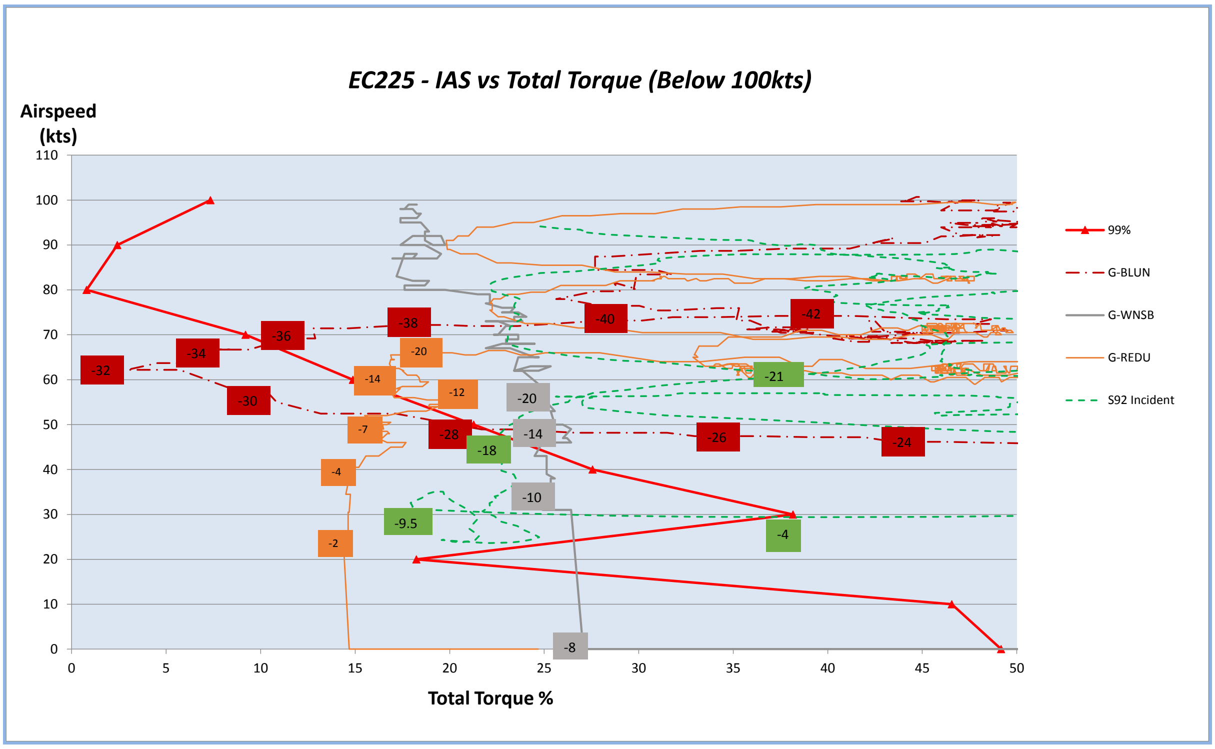
The figure below presents the result of plotting over 250,000 data points resulting from analysis of the EC225 data set described in Section 3 of the main report. These were processed from approaches conducted during normal EC225 operations below 100kts indicated airspeed. The 99 percentile line (orange) and 99.9 percentile (black) are also shown. The results were considered to show sufficient potential for the development of a new warning envelope, although there was some concern over the number of 'outlier points' confirmed to be associated with normal operations. Even if a warning envelope could be defined which circumvented these points, the possibility of other outliers not captured in the data sample analysed would remain. In any event, it is normal practice to specify simple envelopes and not over fit the data so, one way or another, the presence of outliers is likely to result in a slightly higher than ideal false alert rate.



In order to attempt to improve the warning time the data was also plotted with a filter to eliminate pitch attitude values less than 10 degrees, the results of which are shown in the figure below. The hypothesis was that a high nose up attitude would result in faster deceleration and would be indicative of adverse speed trend/rate. Focussing the envelope on high pitch attitude conditions was expected to improve discrimination between normal and abnormal situations. However, this resulted in large reduction in the data set and an adverse shift in the 99 percentile line, leading to a reduction in warning time for the G-WNSB accident case. This refinement was therefore not pursued.



To illustrate the potential that a warning envelope based on airspeed and total torque may have, the 99 percentile envelope was used to determine warning times for the G-BLUN, G-REDU and G-WNSB accidents and an incident provided to the project in confidence (S92 incident). The resultant plot and a table of the warning times are presented below.



Occurrence	Warning Time (sec)				
	Existing HTAWS			Recommended EC225	
	Mode 1 'Sink Rate'	Mode 1 'Pull Up'	Mode 2A	Mode1/2A	IAS/TT Envelope
G-BLUN	7.5	7.0	7.0	8.0	35.0
G-REDU	7.0	1.5	0.0	16.0	13.0
G-WNSB	7.0	1.0	0.0	8.0	13.0
S92 incident	6.8*	6.1*	5.0	11.4	18.0

* Note that Mode 1 is disabled on the S92 hence no warning would have been generated. However, the same incident could happen to a helicopter type on which Mode 1 is used hence the notional warning times are relevant.

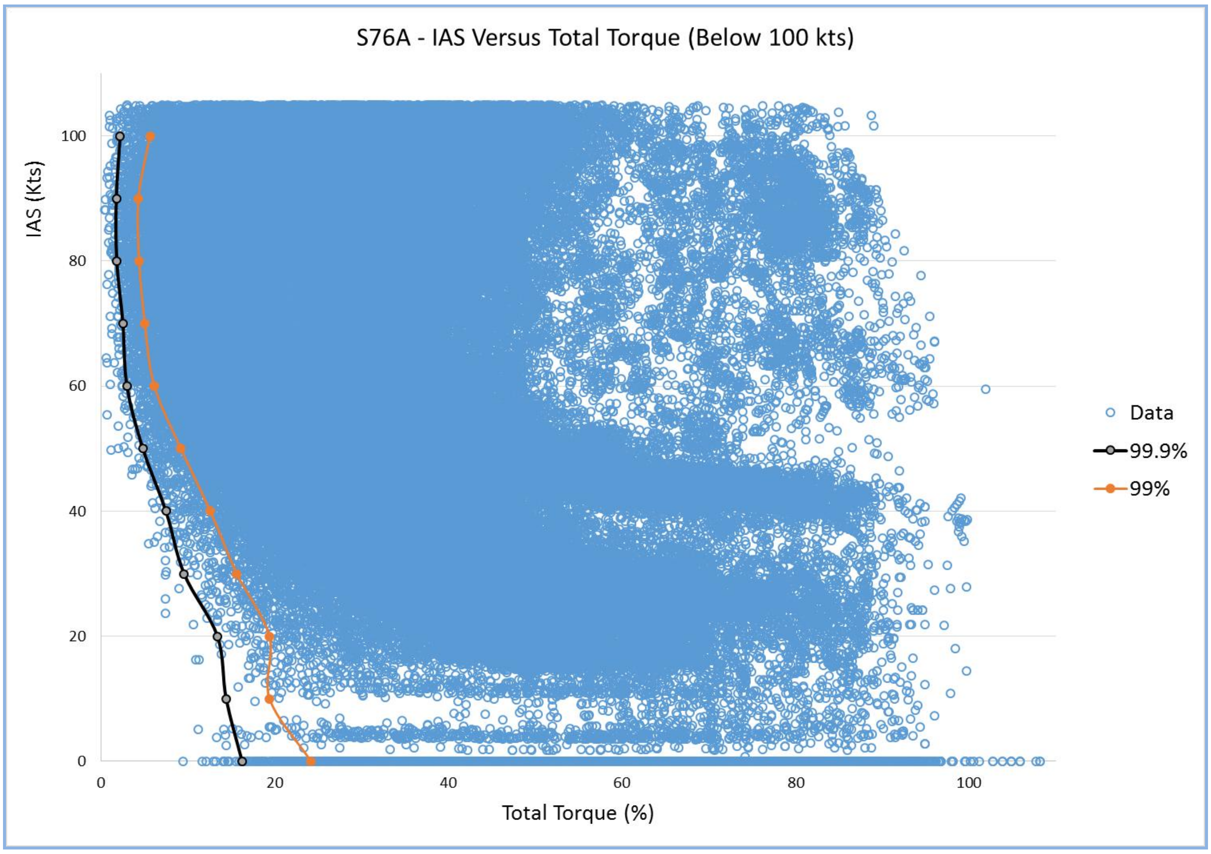
It should be noted that the warning times above are based on a warning envelope determined using the 99 percentile line drawn from analysis of the EC225 data only. Thus, although the development of a new envelope appears feasible, it must first be established that other helicopter types exhibit the same operational characteristics.

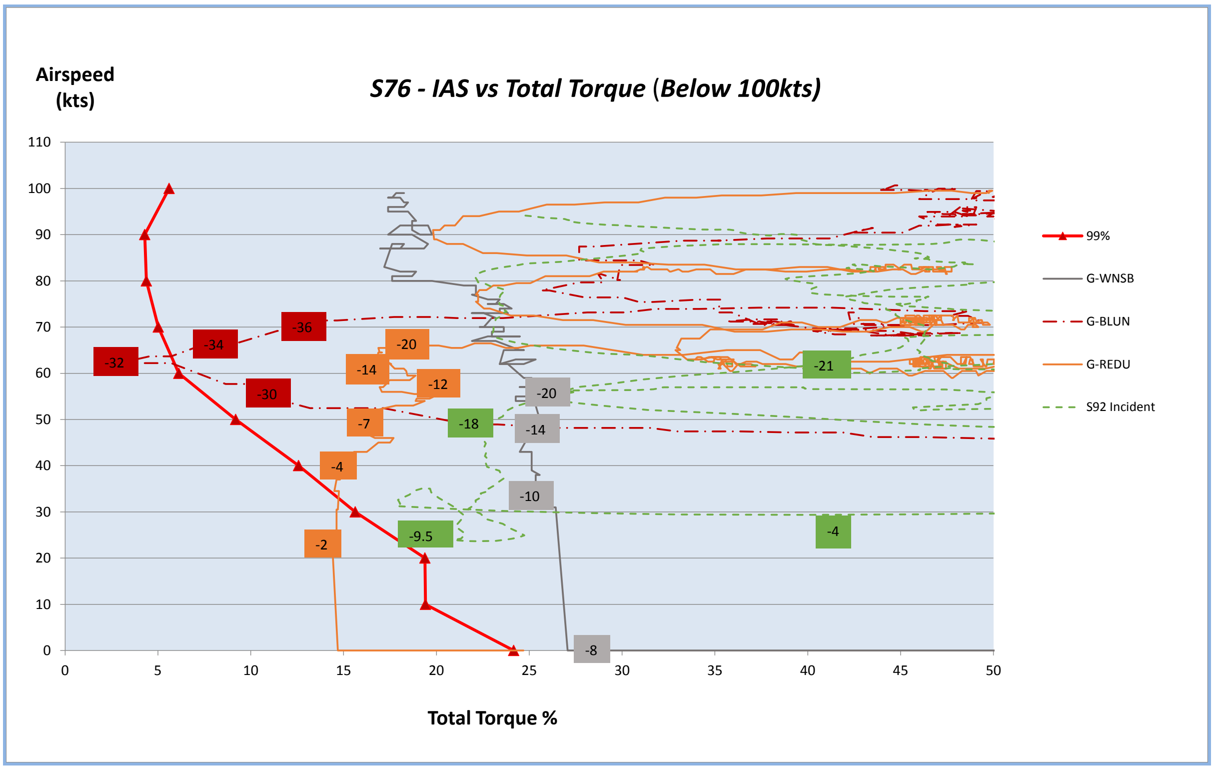
D.2 Data for Total Torque S76A+

As a first step to establishing the broader applicability of a total torque vs airspeed warning envelope, the S76A+ flight data set described in Section 3 of the main report was processed in the same way as the EC225 data and the results are plotted in the first figure below. The data comprises over 250,000 data points from approaches conducted during normal S76A+ operations below 100kts indicated airspeed. The 99 percentile line (orange) and 99.9 percentile (black) are also shown.

It is immediately apparent that this data is significantly different to that for the EC225. This result was unexpected as it was thought that the control characteristics of the S76A+ would be broadly similar to those of the EC225. The high number of data points with low airspeed and low total torque was investigated, however, and found to be a genuine characteristic of normal operation of the S76A+.

From the second figure and table of warning times below it is clear that it would not be possible to create a warning envelope that would address the G-WNSB accident scenario without generating excessive false alerts, and that the 99 percentile line for the S76A+ would offer significantly less protection than the 99 percentile boundary derived from the EC225 data.





Occurrence	Warning Time (sec)		
	Existing Mode 2A	Proposed Mode 2A	S76A+ IAS/TT Envelope
G-BLUN	7.0	8.0	33.0
G-REDU	0.0	16.0	3.0
G-WNSB	0.0	8.0	0.0
S92 incident	5.0	11.4	0.0

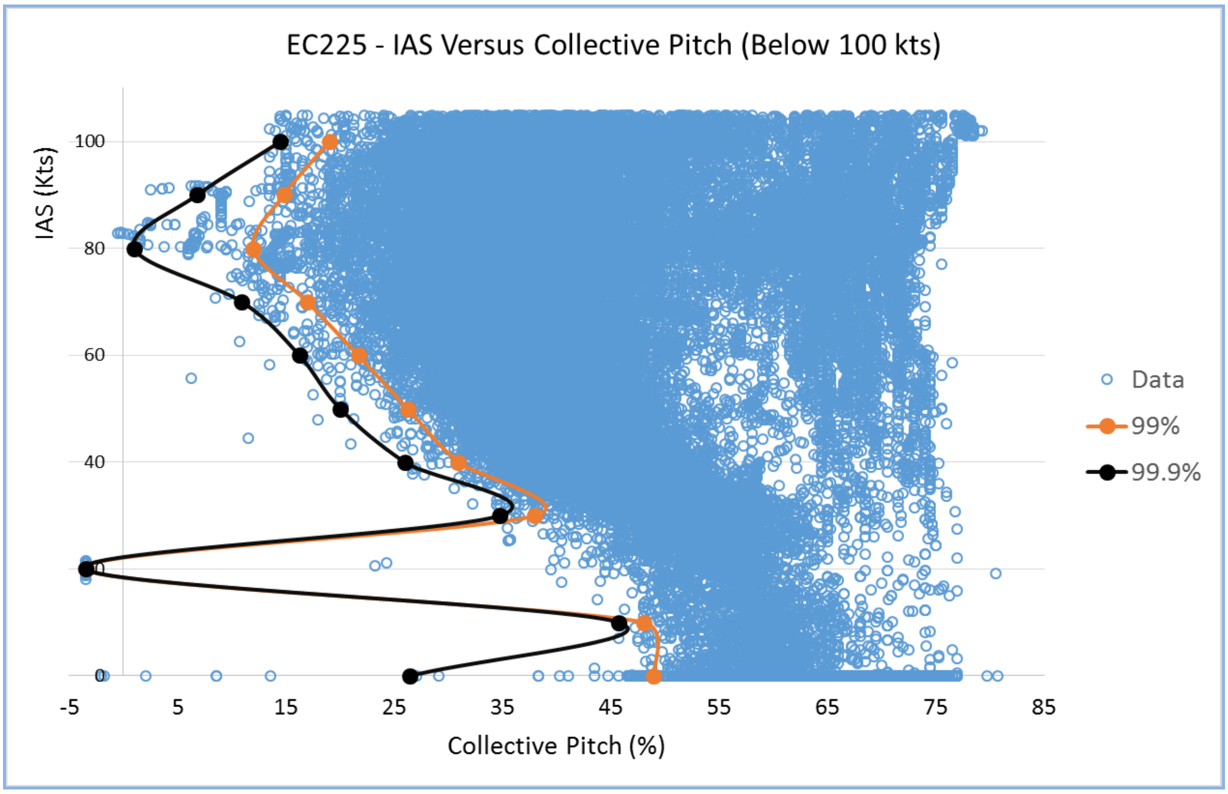
Unlike all of the other warning envelope developments, therefore, it would be necessary to either generate two or more individual warning envelopes to cover variations between aircraft types or, if only the S76 is significantly different, disable the mode on the S76 to prevent excessive false alerts. Equivalent data for additional helicopter types needs to be analysed to allow the best approach to be determined.

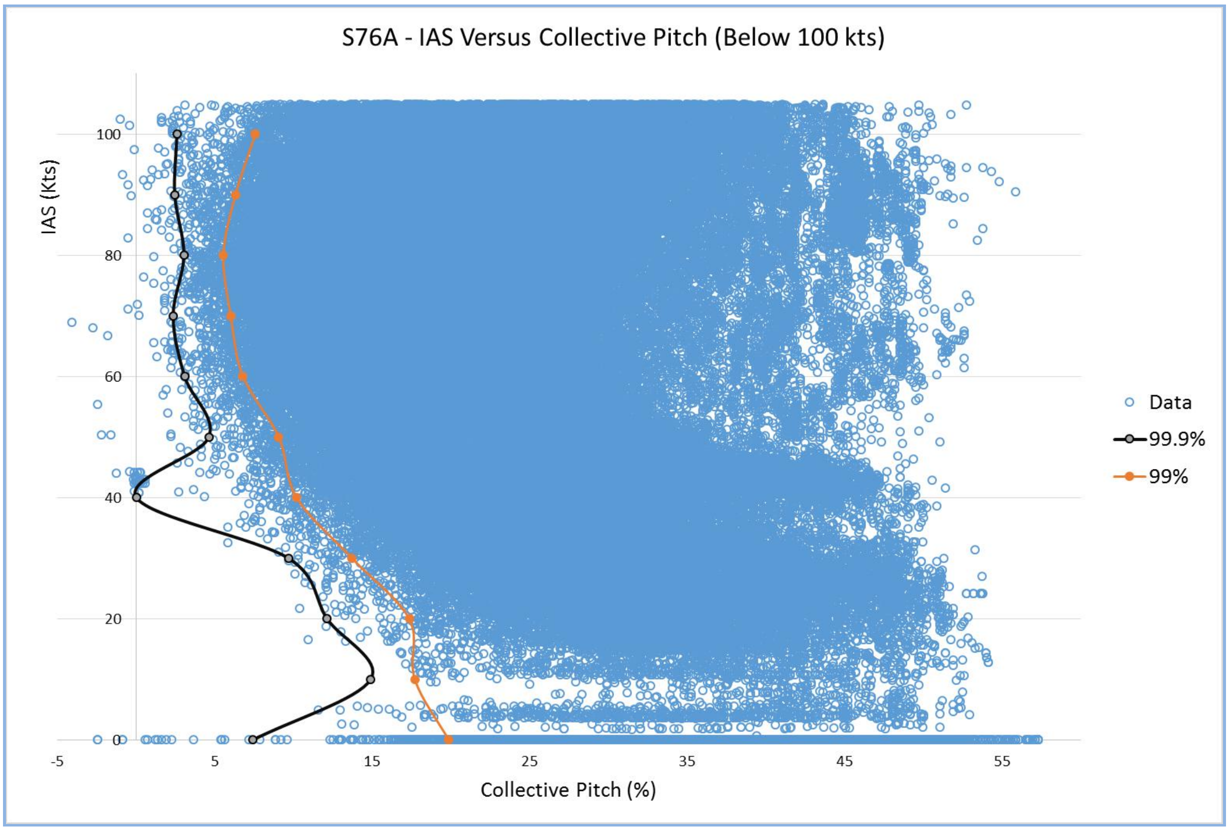
D.3 Data for Collective Pitch Position

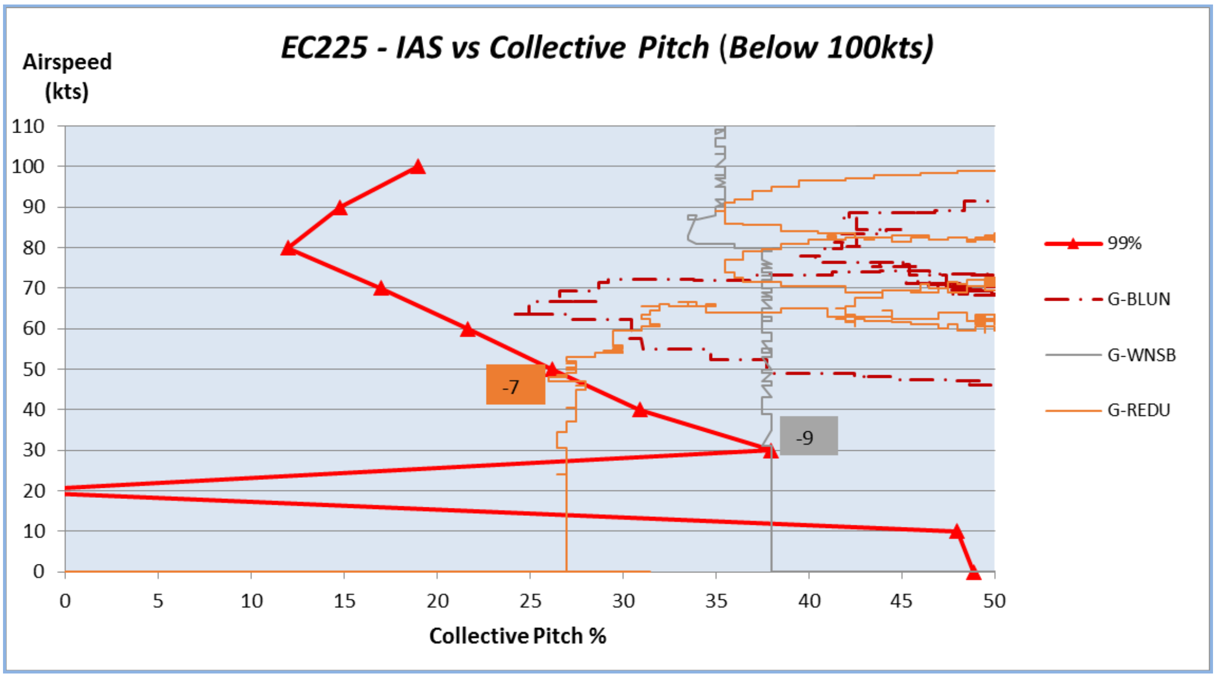
Despite the less encouraging results obtained for the S76, the analysis was completed by extracting collective pitch data from the operational data sets and plotting collective pitch vs airspeed for both the EC225 and S76A+ as presented below.

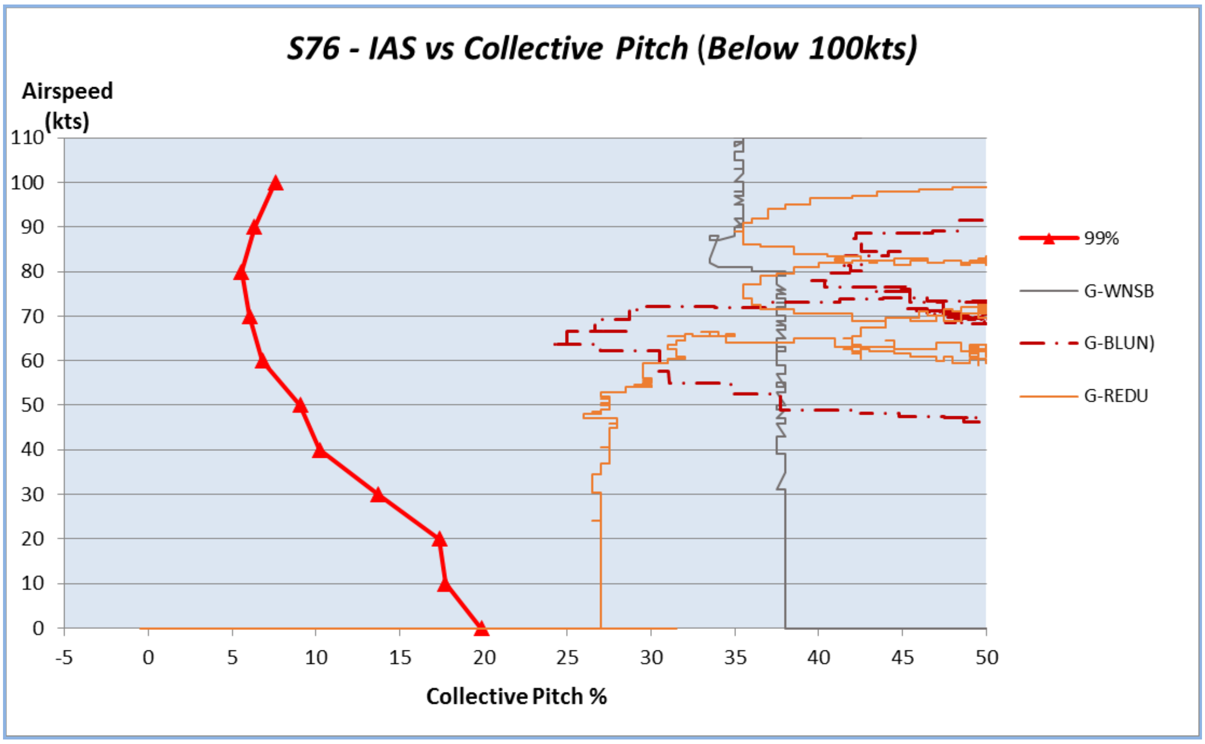
The switch from total torque to collective pitch does not improve the situation with outlier points, and the S76A+ and EC225 plots are significantly different from each other as in the case of total torque vs airspeed. For completeness, however, the 99 percentile envelopes were used to determine warning times for the G-BLUN, G-REDU and G-WNSB accidents. The S92 incident is not included as collective pitch data was not available. The resultant plots are presented below.

From inspection, the S76A+ based envelope would not have generated any warnings and the EC225 envelope would have generated a warning only for the G-REDU accident, but with a significantly shorter warning time than the total torque vs airspeed envelope. In addition, it was noted that there are differences in the scaling of collective pitch between helicopters types; this is less likely with total torque which has a common natural, physical datum.


EC225 - IAS Versus Collective Pitch (Below 100 kts)
IAS (Kts)
Collective Pitch (%)
Data
99%
99.9%


S76A - IAS Versus Collective Pitch (Below 100 kts)
IAS (Kts)
Collective Pitch (%)
Data
99.9%
99%


EC225 - IAS vs Collective Pitch (Below 100kts)
Airspeed (kts)
110
100
90
80
70
60
50
40
30
20
10
0
-7
-9
0
5
10
15
20
25
30
35
40
45
50
Collective Pitch %
99%
G-BLUN
G-WNSB
G-REDU


S76 - IAS vs Collective Pitch (Below 100kts)
Airspeed (kts)
110
100
90
80
70
60
50
40
30
20
10
0
-5
0
5
10
15
20
25
30
35
40
45
50
Collective Pitch %
99%
G-WNSB
G-BLUN)
G-REDU

Appendix E – Identification of Airspeed vs Total Torque Warning Envelopes for additional Helicopter Types

E.1 General

Data was provided by CHC for the S92, AW139 and S76C++. The S76C++ data is discussed separately below. For the AW139 and S92 data there were a larger number of low torque data points at higher airspeeds than at lower airspeeds, which was reassuring from a safety standpoint. Values of the 99th Percentile torque (torque value containing 99% of all values) for each airspeed were plotted and a best fit straight line drawn.

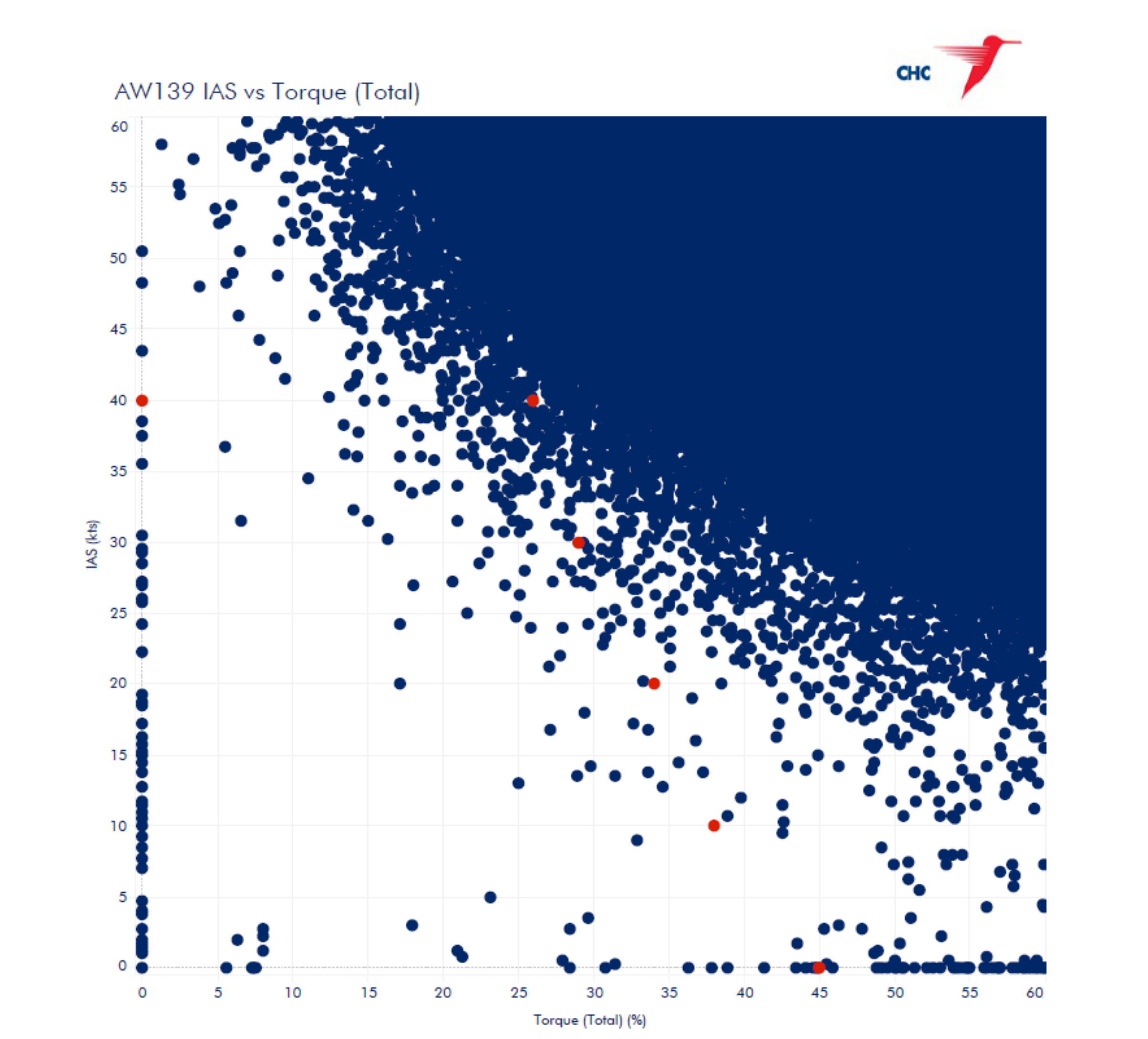
As discussed below, the minimum airspeed for this mode should be 20 kts due to airspeed inaccuracy at lower values. The maximum airspeed is limited by the variability of the torque data as the aircraft decelerates below Vy onto the reverse side of the drag curve; this tends to drive the 99th Percentile value close to zero. When a HTAWS has an autorotation mode this is usually activated below 10% torque and so would override the airspeed vs total torque envelope at higher speeds where the 99th Percentile threshold is below 10% torque. Therefore, the maximum practical airspeed for this warning coincides with 10% torque which is typically around 60 kts.

E.2 Leonardo AW139

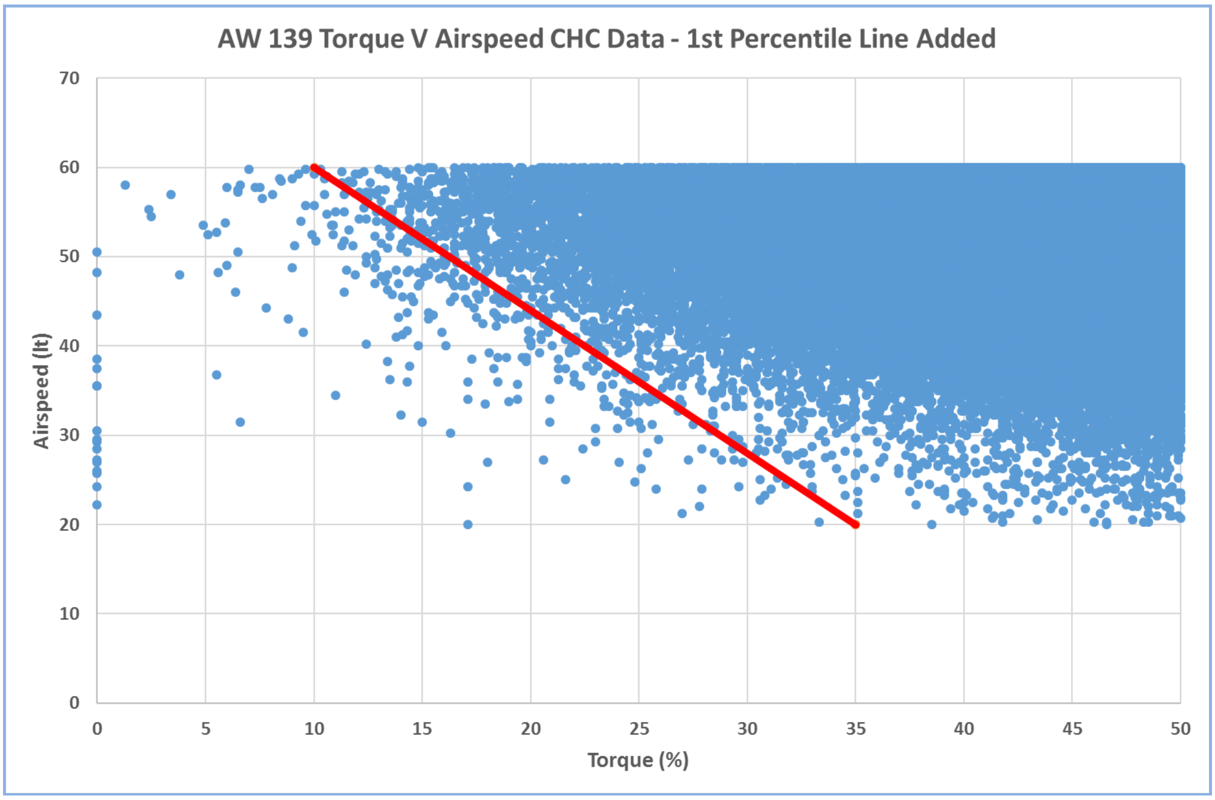
The initial CHC AW139 data set comprised 44,346 approaches made between January and November 2016. Onshore approaches were not explicitly filtered out as had been the case for the initial CAA analysis using approximately 1,000 flights per type. Due to the large dataset, it was not considered necessary to remove onshore approaches as the operators now apply similar stabilised approach criteria to all approaches. In addition, the 60 kt and 60% torque filters would remove onshore IFR approaches as they are typically flown at higher speeds and powers, except for the final stage where the crew would be converting to a visual approach. The first figure below shows the scatter plot for the 44,346 approaches, filtered below 60 kts and 60% torque.

The data displayed a lot of noise below 20 kts which is believed to be caused by inaccuracies in the pitot static system, and the typical nose high attitude at low airspeed which result in an airspeed vector which does not reflect the actual flight path of the aircraft. The caution envelope was therefore set to a minimum airspeed of 20 kts.

As explained in E.1 above, the practical upper limit of this mode is 60 kts, and below 20 kts the data is noisy. Airspeeds outside of these values were therefore removed, as were all data point above 50% torque. This resulted in 115,416 data points which are plotted in the second figure below. The 99th Percentile line was drawn on the data to denote the caution threshold which is further defined in the table.



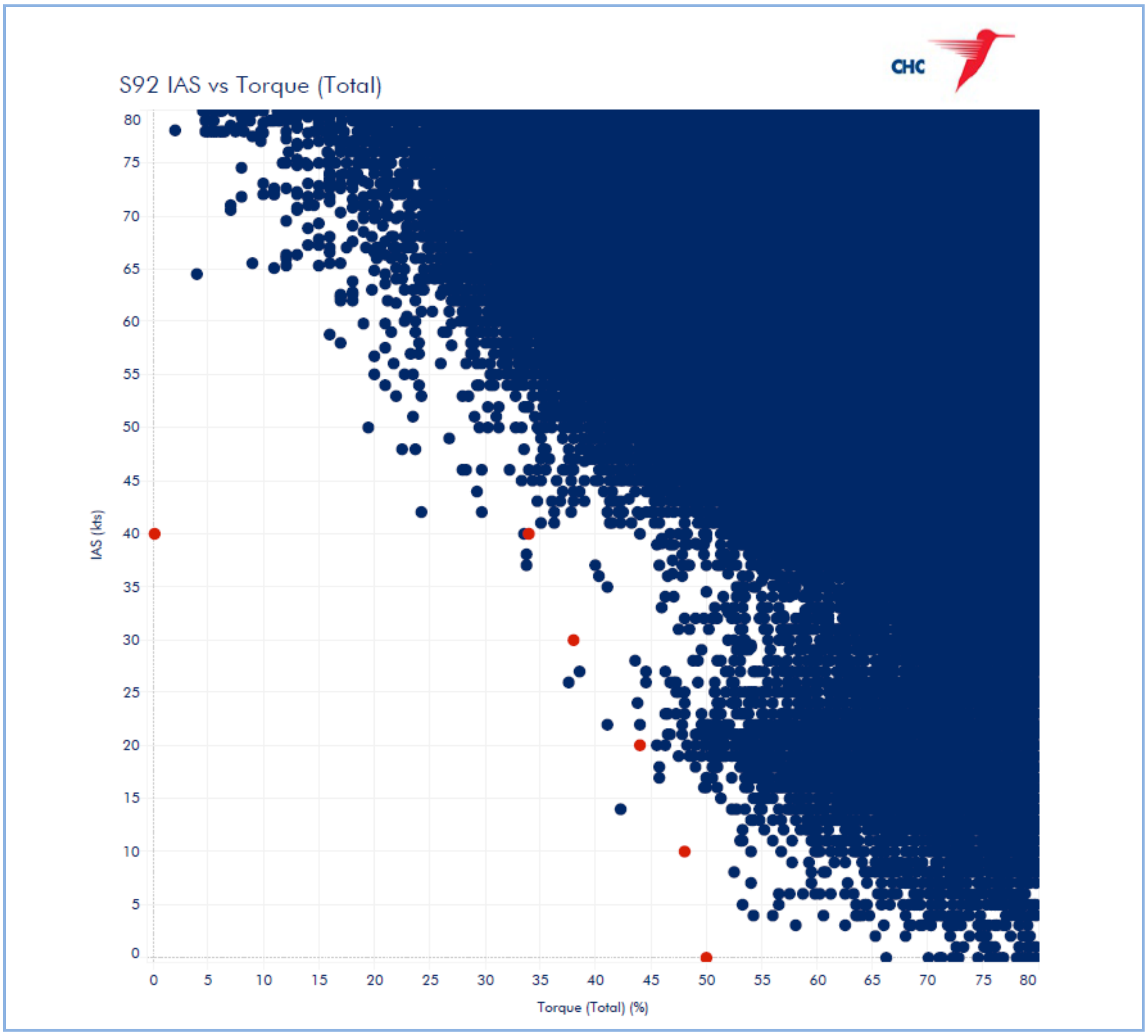
Y Axis IAS (kt)	X Axis Total Torque (%)
"Check Airspeed" caution	
60	10
20	33



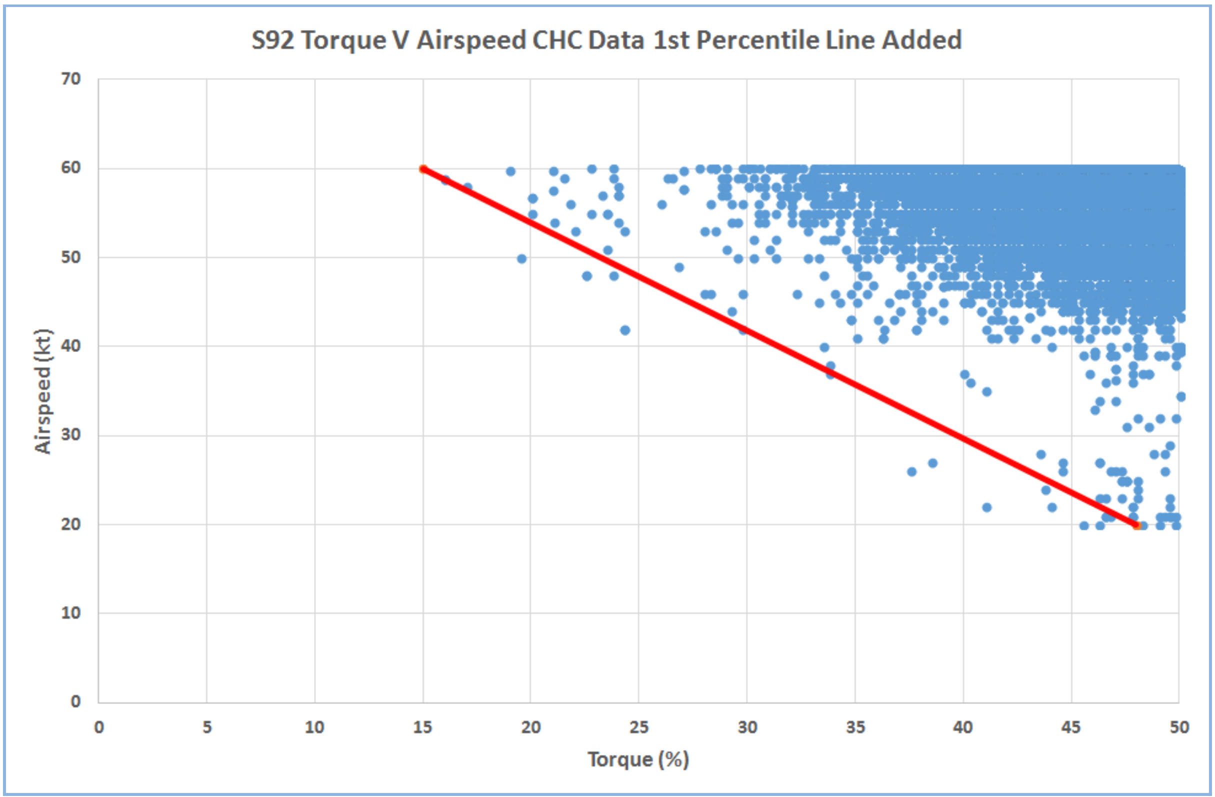
E.3 Sikorsky S92

The initial S92 data was taken from 36,976 approaches performed during the period January to November 2016 and is presented in the first figure below.

Of interest is the small number of low torque values below 60 kts. This could be due to the aerodynamic characteristics (drag in particular) of the aircraft and the profiles flown. Although the S92 data was less noisy than the AW139 below 20 kts, due to the general unreliability of all helicopter pitot static systems below 20 kts, all points below this value were removed. The dataset was therefore filtered to include data points with airspeed values between 60 and 20 kts, and with torque values below 50% only. The resulting scatter plot is presented in the second figure below. The 99th Percentile line was drawn on the data to denote a caution threshold which is further defined in the table below.

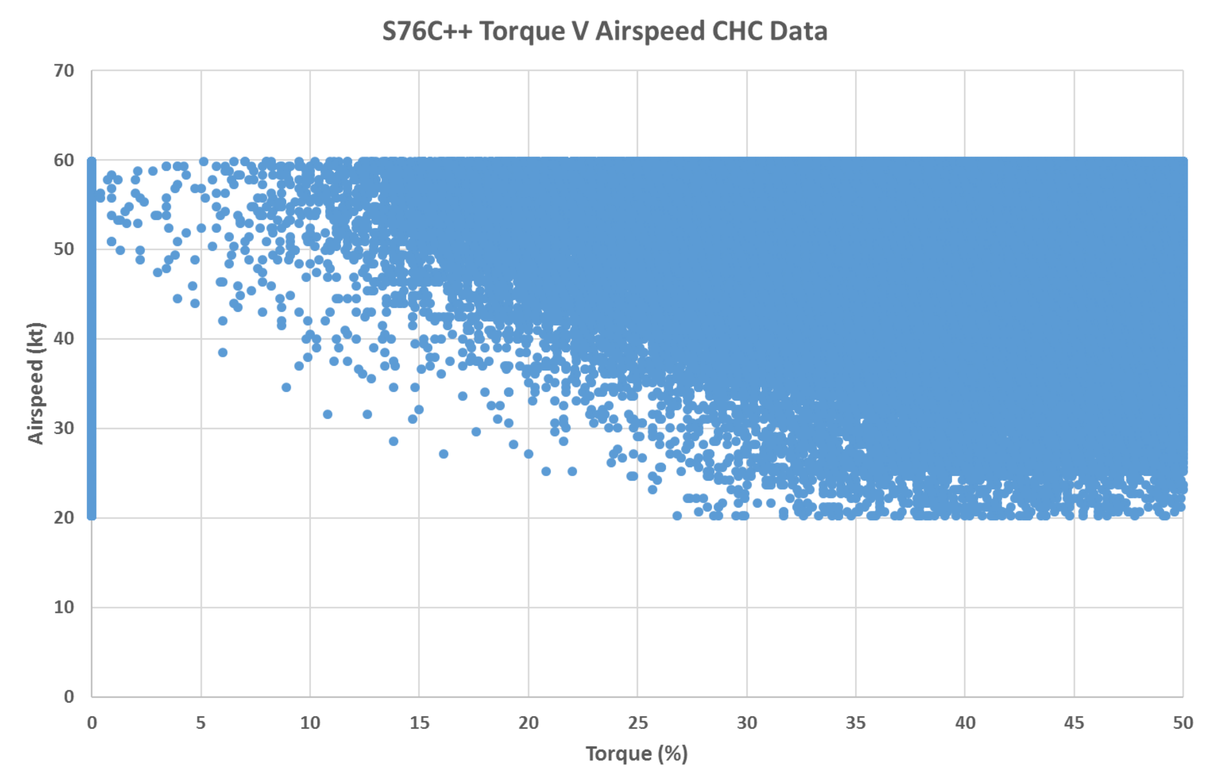


Y Axis IAS (kt)	X Axis Total Torque (%)
"Check Airspeed" caution	
60	15
20	48



E.4 Sikorsky S76C++

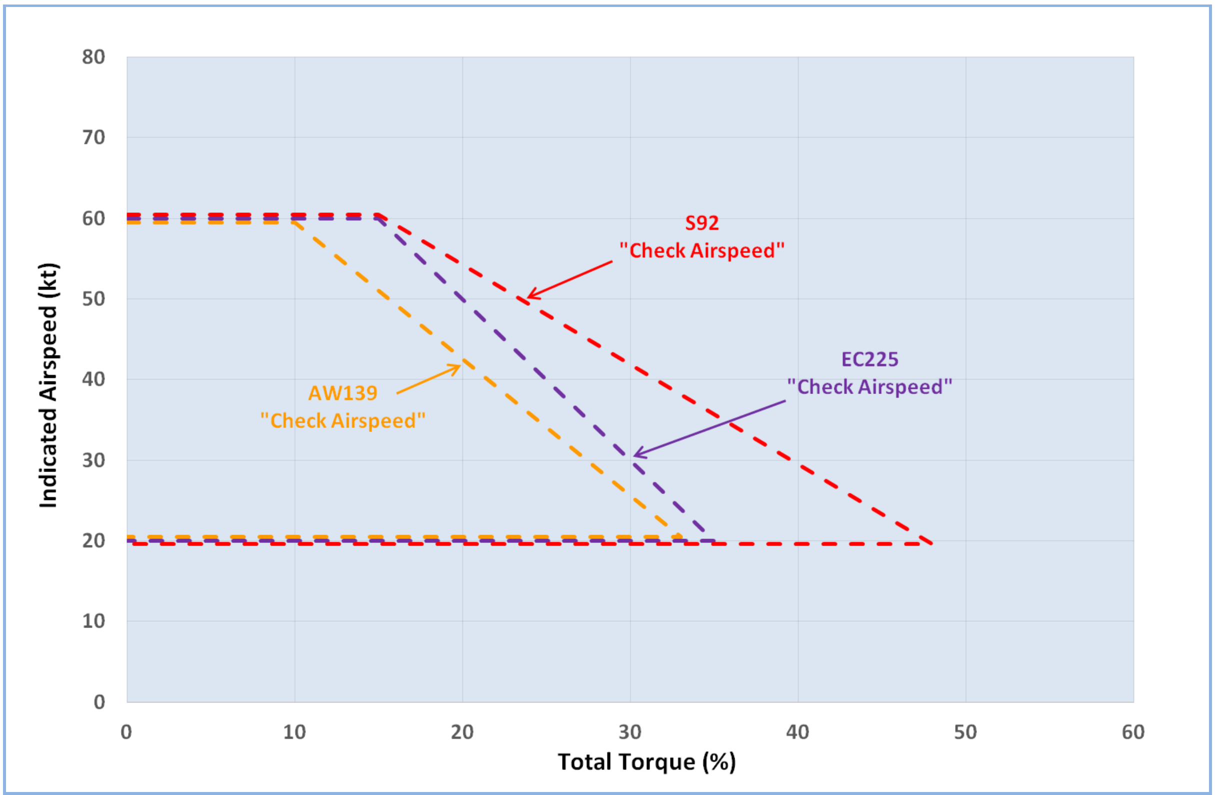
S76C++ data from 35,475 approaches performed between January and November 2016 was made available to the project. These data contained a large number of zero torque data points, similar to the study of the S76A+ data. The data sets for the S76A+ and S76C++ were recorded using different avionic and FDM systems and therefore it is assumed to be a characteristic of the aircraft type rather than faulty recording. It is concluded that, unlike the AW139, S92 and EC225, the airspeed vs total torque warning envelope is not viable for the S76 family of helicopters.



E.5 Conclusions

Using data from 44,346 AW139 approaches, 35,475 S76C++ approaches and 36,976 S92 approaches, the following was concluded:

- It is not possible to set a viable caution envelope for the S76C++. This conclusion supports the conclusion based on S76A+ data.
- The S92 and AW139 data showed that a viable warning envelope can be set. These are shown below together with the previously determined values for the EC225 envelope.



Y Axis IAS (kt)	X Axis Total Torque (%)
EC225 *“Check Airspeed”* caution	
60	15
20	35
AW139 *“Check Airspeed”* caution	
60	10
20	33
S92 *“Check Airspeed”* caution	
60	15
20	48

Appendix F – Additional Accident/Incident data Assessment

F.1 Mode 1 Occurrences

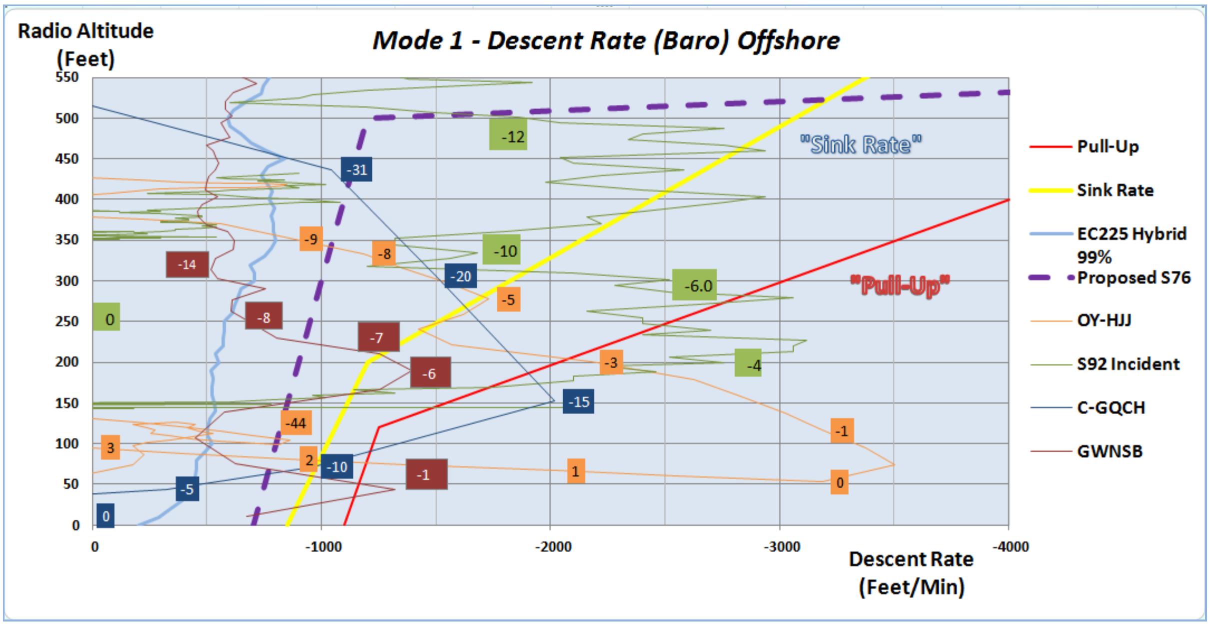
The key to the Mode 1 plots for the relevant occurrences is as follows:

- G-WNSB - Eurocopter AS332L2 - Brown
- OY-HJJ - Eurocopter EC155 - Orange
- C-GQCH - Sikorsky S92 - Dark Blue
- S92 incident - Sikorsky S92 - Green

The respective plots for the occurrences have been identified with timings to indicate seconds prior to impact or the lowest height above the sea achieved as appropriate. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be estimated. The plots and the warning times are presented in the figure and table below.

As can be seen, current HTAWS would have generated relatively short warning times for three of the occurrences, very likely too short to be of any practical use. In the case of C-GQCH, however, useful 'sink rate' and 'pull up' warnings would have been generated.

The proposed new Mode 1 envelope produces increases in warning time for all four occurrences, but the resulting warning times are not especially significant compared to the 'sink rate' warning times except in the case of C-GQCH and possibly the S92 incident. However, taken together with the result for G-REDU from the original four accidents (see Section 6.2.2 of the main report) these results support the case for implementing the proposed new Mode 1 warning envelope.



REGISTERED OFFICE: As above. REGISTRATION No. 6965887 ENGLAND

Occurrence	Current Mode 1		Recommended Mode 1
	'Sink Rate'	'Pull-Up'	
G-WNSB	7.0	1.0	8.0
OY-HJJ	5.0	3.0	9.0
C-GQCH	18.0	16.0	31.0
S92 incident	6.8	6.1	11.4

F.2 Mode 2 Occurrences

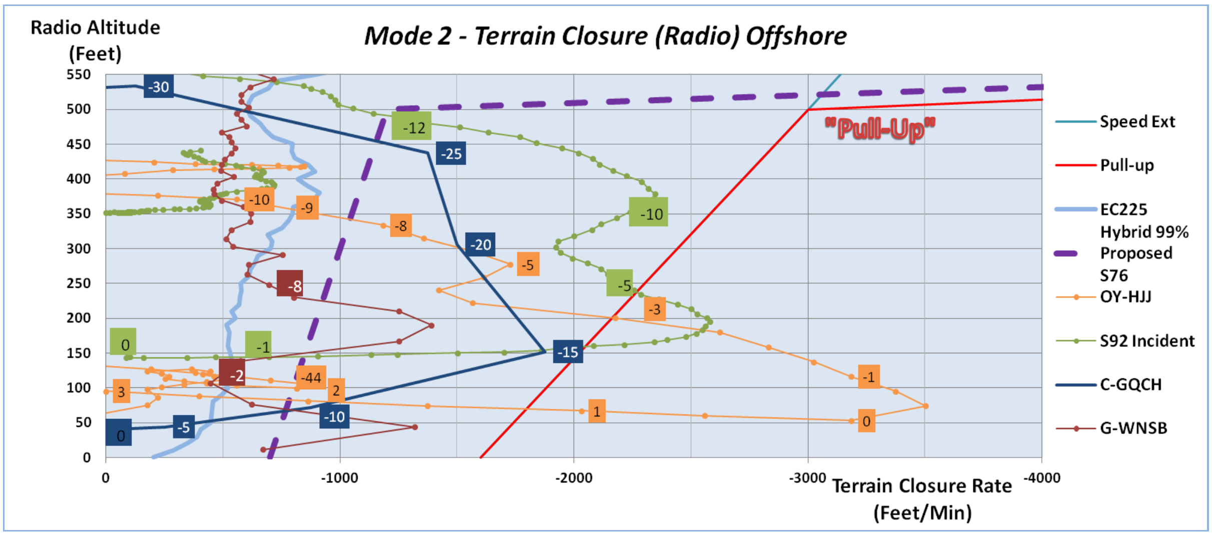
The key to the Mode 2 plots for the relevant occurrences is as follows:

- G-WNSB - Eurocopter AS332L2 - Brown
- OY-HJJ - Eurocopter EC155 - Orange
- C-GQCH - Sikorsky S92 - Dark Blue
- S92 incident - Sikorsky S92 - Green

The respective plots for the occurrences have been identified with timings to indicate seconds prior to impact or the lowest height above the sea achieved as appropriate. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be estimated. The plots and the warning times are presented in the figure and table below.

As can be seen, current HTAWS would have generated relatively short warning times for three of the occurrences, very likely too short to be of any practical use. In the case of C-GQCH and G-WNSB, no warning would have been generated.

The proposed new Mode 2 envelope produces good increases in warning time for G-WNSB and OY-HJJ, but the resulting warning times were unlikely to have been sufficient to affect the outcome. However, a useful increase is produced for the S92 incident, and a very significant increase in warning time for C-GQCH. Viewed in conjunction with the result for G-REDU in the original four accidents (see Section 6.3.2 of the main report), these results support the case for implementing the proposed new Mode 2 warning envelope. It is noted, however, that the warning times for all four occurrences are identical to those provided by the new Mode 1 envelope.



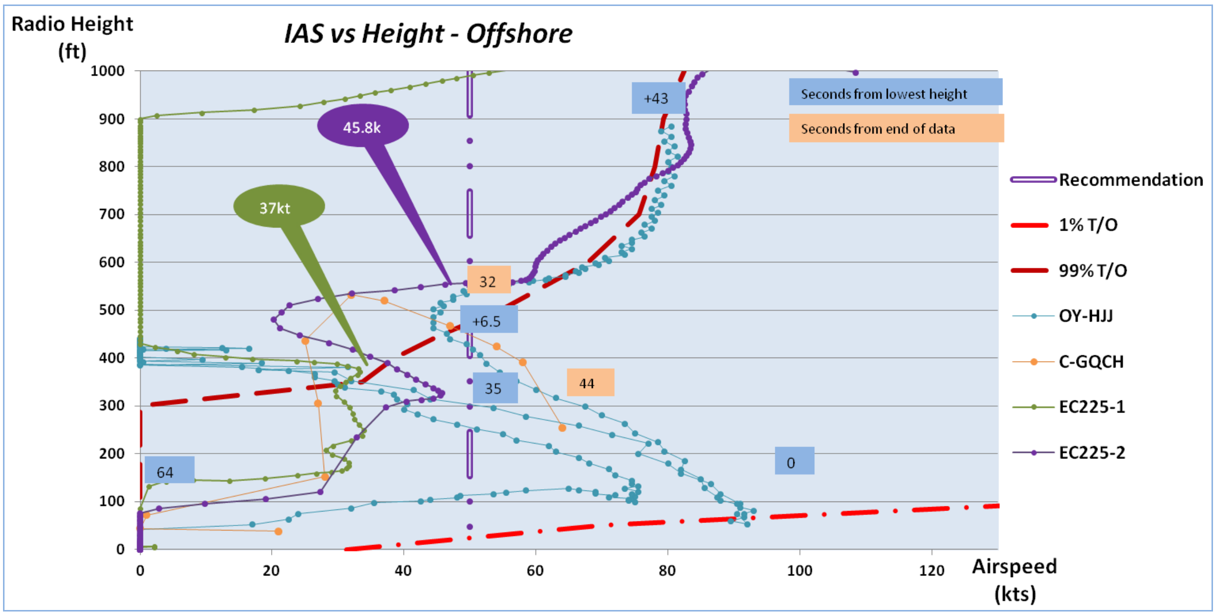
Occurrence	Current Mode2A	Recommended Mode 2
G-WNSB	0.0	8.0
OY-HJJ	3.5	9.0
C-GQCH	0.0	31.0
S92 incident	5.0	11.4

F.3 Mode 3 Incidents

The key to the Mode 3B plots for the relevant incidents is as follows:

- OY-HJJ - Eurocopter EC155 - Light Blue
- C-GQCH - Sikorsky S92 - Orange
- EC225 incident 1 - Eurocopter EC225 - Green
- EC225 incident 2 - Eurocopter EC225 - Purple

The respective plots for the incidents have been identified with timings to indicate seconds prior to the lowest height above the sea achieved as appropriate. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be estimated. The plots and the warning times are presented in the figure and table below.



Incident	Warning Time (sec)	
	Current Mode 3	Recommended Mode 3B
OY-HJJ	0.0	35.0
C-GQCH	0.0	32.0
EC225 incident 1	0.0	0.0
EC225 incident 2	0.0	0.0

The results clearly demonstrate significant and useful warning times for both the OY-HJJ and C-GQCH incidents. For the other two incidents, the new Mode 3B would not have been activated as the landing gear had not been retracted and the airspeed had not passed through 50kt.

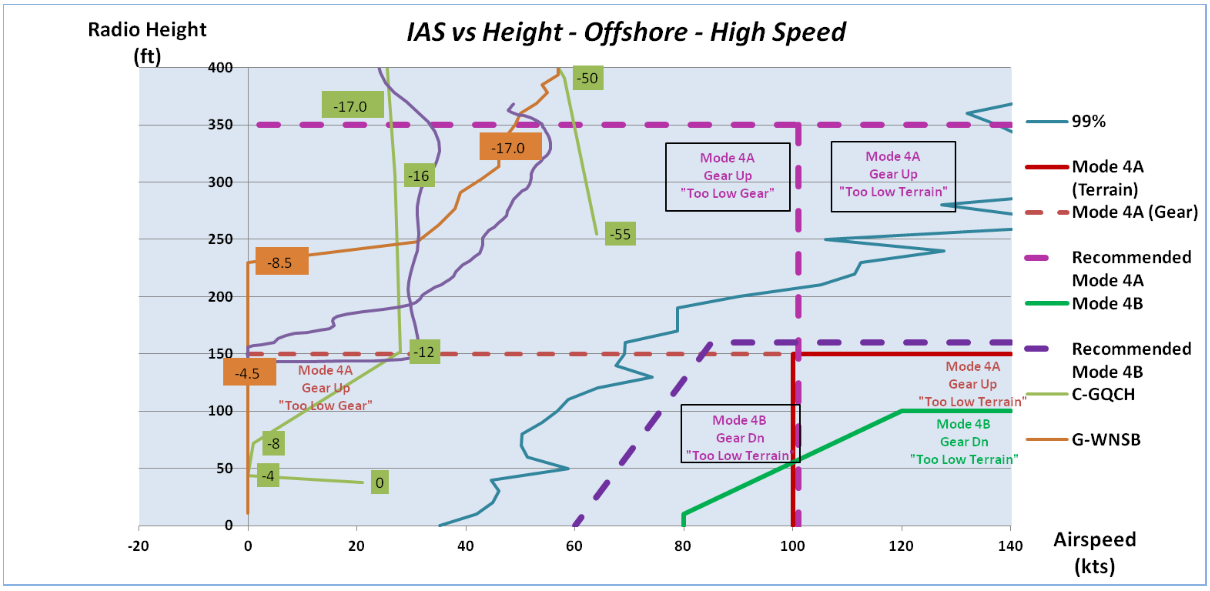
Viewed in conjunction with the results for G-TIGH (see Section 6.4.2.2 of the main report), these results support the case for implementing the proposed new Mode 3B warning envelope. Consideration should be given to lowering the airspeed for activation of Mode 3B, e.g. to 40kt in order to 'capture' incidents such as EC225 incident 2. However, care needs to be taken to avoid nuisance alerts due to the high wind speeds typically encountered during offshore operations. This might be accomplished by applying an additional condition based on radio height, e.g. airspeed > 40kt and radio altitude > 50ft.

F.4 Mode 4 Occurrences

The key to the Mode 4 plot for the relevant occurrences is as follows:

- C-GQCH - Sikorsky S92 - Green
- G-WNSB - AS332L2 - Orange
- S92 incident - Sikorsky S92 - Lilac

The respective plots for the occurrences have been identified with timings to indicate seconds prior to the lowest height above the sea achieved as appropriate. By relating these figures to the warning envelopes, the approximate warning time that would have been given can be estimated. The plots and the warning times are presented in the figure and table below.



Occurrence	Warning Time (sec)				
	Current			Recommended	
	Mode 6 (100ft)	Mode 6 (160ft)	Mode 4	Mode 4A	Mode 4B
C-GQCH	9.0	12.5	12.0 (4A)	17.0	0.0
G-WNSB	3.5	5.0	0.0	0.0	0.0
S92 incident	0.0	1.0	0.0	0.0	0.0

Warnings would have been generated by current HTAWS in the case of C-GQCH and a Mode 4A “Too Low Gear” warning is confirmed in the accident report [11]. However, all would have been generated after the aircraft had broken cloud at 200ft and the flight crew were already aware of the situation and responding. No Mode 4A warnings would be generated for G-WNSB or the S92 incident as the landing gear was down in both cases; the Mode 6 warnings are too late to be of any assistance.

As in the case of the original four accidents (see Section 6.5.2 of the main report), the revised Mode 4 envelope does not have any significant impact on warning time, but it’s adoption would remove the nuisance alert rate associated with the current Mode 6.

F.5 Further Occurrence

Following completion of the analysis reported in this appendix, a further incident of interest came to light. The incident occurred to Sikorsky S61N registration PH-NZG on approach to Den Helder over the sea on 30 November 2004, and was investigated by the Dutch Safety Board [12]. The incident involved a slow loss of airspeed with an associated increase in descent rate that went unnoticed by the flight crew for some time. The aircraft was successfully recovered but did contact the sea.

Neither AVAD (even set to the maximum of 160 ft) nor any of the current HTAWS modes would have generated a timely warning. The proposed revised Modes 1 and 2 and the new airspeed vs total torque mode would have generated warnings. Initial analysis indicates that the revised Mode 1 and 2 warning envelopes would have generated a warning 7 seconds prior to contact with the sea and after the flight crew had already been alerted to the situation. However, the new airspeed vs total torque envelope would have provided a warning time of around 25 seconds which was 7 seconds prior to the flight crew’s first reaction. It is considered that this could have prevented contact with the sea and reduced or eliminated the over-torque that resulted from the later, more aggressive intervention that was required.

Appendix G – Auditory Displays – Review of Literature

G.1 – General

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 F.2. 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:

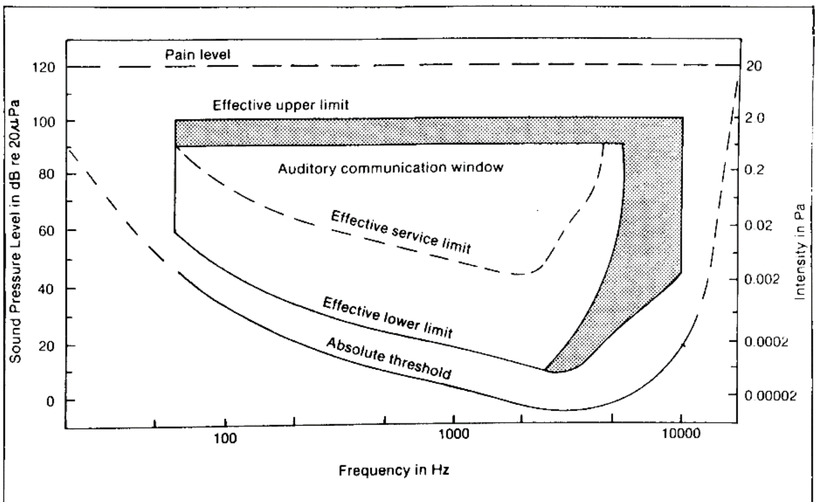


Figure 1 THE AUDITORY COMMUNICATION WINDOW

Trendson, Earcon and Auditory Icons

A number of research projects have been identifying methods of conveying information by non verbal 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 as 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, possibly 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.

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G.2 – Warnings

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

CFR/JAR 25.207	Stall warning
CFR/JAR 25.253(a)(2)	High-speed characteristics
CFR/JAR 25.672(a)	Stability Augmentation…
CFR/JAR 25.679(a)	Control system gust locks
CFR/JAR 25.703	Takeoff warning system
CFR/JAR 25.729(e)	Retracting mechanism
CFR/JAR 25.783(e)	Doors
CFR/JAR 25.812(f)(2)	Emergency lighting
CFR/JAR 25.819(c)	Lower deck service compartments
CFR/JAR 25.841(b)(6)	Pressurized cabins
CFR/JAR 25.854(a)	Lavatory fire protection
CFR/JAR 25.857(b)(3)	Cargo compartment classification
CFR/JAR 25.857(c)(1)	Cargo compartment classification
CFR/JAR 25.857(e)(2)	Cargo compartment classification
CFR/JAR 25.859(e)(3)	Combustion heater fire protection
CFR/JAR 25.863(c)	Flammable fluid fire protection
CFR/JAR 25.1019(a)(5)	Oil strainer or filter
CFR/JAR 25.1165(g)	Engine ignition systems
CFR/JAR 25.1203(b)(2)	Fire-detector system
CFR/JAR 25.1203(b)(3)	Fire-detector system
CFR/JAR 25.1203(f)(1)	Fire-detector system
CFR/JAR 25.1303(c)(1)	Flight and navigation instruments
CFR/JAR 25.1305(a)(1)	Powerplant instruments
CFR/JAR 25.1305(a)(5)	Powerplant instruments
CFR/JAR 25.1305(c)(7)	Powerplant instruments
CFR/JAR 25.1309(c)	Equipment, systems, and installations
CFR/JAR 25.1309(d)(4)	Equipment, systems, and installations
CFR/JAR 25.1322	Warning, caution, and advisory lights
CFR/JAR 25.1326	Pitot heat indication systems
CFR/JAR 25.1331(a)(3)	Instruments using a power supply
CFR/JAR 25.1353(c)(6)(ii)	Electrical equipment and installations
CFR/JAR 25.1419(c)	Ice protection
CFR/JAR 25.1517(3)	Rough air speed, V_{RA}
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 airplanes
CFR/JAR 91.221	Traffic alert and collision avoidance system
CFR/JAR 91.223	Terrain awareness and warning system
CFR/JAR 91.603	Aural speed warning device
CFR/JAR 91, Appx A Sectn 91.2(b)(1)	Required instruments and equipment
CFR/JAR, 91 Appx G Sectn 91.2(c)(3)	Ops in RVSM Airspace - Aircraft approval
CFR/JAR 91, Appx G Sectn 91.3(c)(6)	Instruments and Equipment Approval

CFR/JAR 121.221(c)(1)	Fire precautions
CFR/JAR 121.221(d)(1)	Fire precautions
14 CFR 121.221(f)(2)	Fire precautions
14 CFR 121.289	Landing gear: Aural warning device
14 CFR 121.307(k)	Engine instruments
14 CFR 121.308(a)	Lavatory fire protection.
14 CFR 121.319(b)	Crewmember interphone system
14 CFR 121.354	Terrain awareness and warning system
14 CFR 121.356(b)	Traffic alert and collision avoidance system
CFR/JAR 121.358	Low-altitude windshear system
CFR/JAR 121.360(a)	Ground proximity warning-glide slope deviation
CFR/JAR 121.360(e)	Ground proximity warning-glide slope deviation
CFR/JAR 121.360(f)	Ground proximity warning-glide slope deviation
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 rqmnts: Aircraft carrying passengers under IFR
14 CFR 135.180(a)	Traffic alert and collision avoidance system
14 CFR 135, Appx A Sectn A135.1	Additional Airworthiness Standards for 10 or More Pax