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**Flight simulator evaluation of the safety
benefits of terrain awareness and warning
systems**

R.J. de Muynck and R. Khatwa

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FLIGHT SIMULATOR EVALUATION OF THE SAFETY BENEFITS OF TERRAIN AWARENESS AND WARNING SYSTEMS

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Abstract

This paper focuses on an investigation into the operational safety aspects of advanced Terrain Awareness and Warning Systems (TAWS), conducted under contract to the Netherlands Directorate General of Civil Aviation (RLD). The TAWS depicts graphical terrain information on a Navigation Display (ND) and provides predictive terrain collision alerting. Initially, several ND terrain format displays were evaluated in an exploratory workstation study. The most preferred display format was adopted for follow-up evaluations in a piloted simulation programme. The objective of phase two was to evaluate the independent effects of terrain awareness information and predictive terrain alerting. The NLR Research Flight Simulator employing the Fokker 100 model served as the test facility. Ten evaluation crews flew fourteen scenarios each, primarily in terrain-rich environments.

The subjects generally had little difficulty in becoming accustomed to the displayed terrain information and comments indicated a marked improvement in terrain situational awareness. Analysis shows a significant improvement in terrain situational awareness and speed of detecting potential terrain critical situations. The terrain display provided sufficient spatial awareness to the extent that the conditions generating a predictive alert developed relatively few times. The crews did not perceive a marked improvement in terrain situational awareness from the predictive terrain proximity alerting. However, the additional safety margin provided by this alerting algorithm was still regarded a valuable asset. Relatively few crews noticed anomalies on the terrain display associated with TAWS database errors.

Abbreviations

ATC	Air Traffic Control
CFIT	Controlled Flight Into Terrain
DH	Decision Height
DME	Distance Measuring Equipment
EGPWS	Enhanced Ground Proximity Warning System
FMS	Flight Management System
FSF	Flight Safety Foundation
GCAS	Ground Collision Avoidance System
GPWS	Ground Proximity Warning System
ICAO	International Civil Aviation Organisation
MDA	Minimum Descent Altitude
ND	Navigation Display
PFD	Primary Flight Display
QNH	Altimeter sub-scale setting to obtain elevation relative to mean sea level
RLD	Rijksluchtvaartdienst; Directorate General of Civil Aviation of the Netherlands
RFS	Research Flight Simulator
SOP	Standard Operating Procedures
TAWS	Terrain Awareness and Warning System
TCAS	Traffic Alert and Collision Avoidance System

Introduction

It is generally accepted that Controlled Flight Into Terrain (CFIT) is one of the leading categories of civil aircraft accidents. Recent safety studies include those conducted by the Flight Safety Foundation (FSF)/ICAO CFIT and Approach & Landing Accident Reduction Task Forces^{1,2,3}. These Task Forces recommended the application of advanced technology to improve situational awareness in the cockpit. Currently, several avionics manufacturers are developing and some are already marketing such technology, most notably in the form of depicting graphical terrain information on the already installed EFIS displays. Current regulatory activity from the



FAA and ICAO is focused on rule making for mandating the installation of TAWS. In March 1999, ICAO adopted amendments to Annex 6, Parts I and II, which introduce requirements for a predictive terrain hazard warning function in the GPWS (i.e. EGPWS, GCAS or TAWS). The Society of Automotive Engineers (SAE) has published human factors guidelines⁴ for the development of these systems.

The introduction of such terrain awareness displays as well as predictive terrain warning systems will impact flight crew operational procedures. These systems are likely to influence the crew's spatial awareness as well as their reaction to ground proximity alerts occurring in combination with such displays. For shared displays, in which terrain is one of several types of information that can be depicted, information prioritisation, discrimination of terrain information, consistency of coding and symbology and potential clutter are just some of the issues that need to be addressed.

The investigation, on behalf of the RLD, was carried out into the operational safety aspects of TAWS. The objective was to evaluate the independent effects of terrain awareness information and predictive terrain alerting. More complete details of the study are given in Ref.5. The current study adds to other recent research conducted on the subject of terrain depiction in the flight deck^{6,7}.

Workstation Pilot Study

The objective of the initial phase of the study was to select a representative TAWS type system that could be pursued further in a full mission research simulator. Therefore, prior to the piloted flight simulator evaluation, a workstation experiment was conducted to assess candidate Navigation Display formats depicting terrain. Eight technical airline pilots from local carriers served as test subjects. Evaluation variables included:

- Colour coding schemes to depict terrain altitude relative to aircraft, e.g. grey, green or brown tints, or combinations, as well as current weather radar colours (red, yellow and green);
- Altitude spacing between terrain contours - 500 or 1000ft intervals;
- The relative altitude below the aircraft at which not to depict terrain.

Although the displays presented were "static", pilots were able to vary aircraft altitude and position to mimic a dynamic terrain display. In summary, the subjective workstation evaluation generated the following recommendations:

- The preferred format for the terrain colour coding was based on brown tints, comparable to that for paper navigation charts, e.g. Jeppesen;
- Darker colours to indicate higher terrain elevations, as opposed to dark colours for low terrain, were preferred – just as for paper charts that depict terrain contours;
- 1000ft altitude intervals between terrain contours was the preferred format when compared to the use of 500ft intervals;
- The use of grey colour coding for displaying terrain below the aircraft was not received well. The preferred approach was to maintain a similar colour scheme as used for terrain depiction above the aircraft – since both were considered hazards to ultimately avoid.

These results were used to code the format used in the flight simulator evaluation described below.

Objectives of the Simulator Evaluation

The objective of phase two was to evaluate the independent effects of terrain awareness information and predictive terrain alerting. In particular the influence on spatial awareness and crew decision making were central to this study.

The basic hypotheses formulated for the experiment design were as follows:

- Crew acceptability of the TAWS function is high;
- The introduction of predictive terrain alerting leads to fewer terrain critical situations than systems with reactive alerting;
- A graphical terrain display leads to earlier crew recognition of potential terrain conflicts and facilitates improved crew decision-making.

The investigation also included the observation of crew behaviour following terrain alerts and when erroneous terrain was displayed due to database anomalies.

The 2x2 matrix below represents the evaluation independent variables (awareness and alerting type). Note that 'alerting type' refers specifically to those aural and visual alerts associated with potential impact with terrain (and not the relative terrain altitude coding for the display).

Table 1: Interface definition matrix

	Standard Nav. Display	Nav. Display & Terrain Data
Reactive alerting	Interface A (GPWS)	Interface B
Predictive alerting	Interface C	Interface D (TAWS)

Interface A represents the GPWS (*reactive* alerting based on current conditions, e.g. Radio altimeter, barometric descent rate, etc). This is also the reference treatment condition. Interface B is a GPWS supplemented by a terrain awareness display (and therefore does not provide predictive alerting). Interface D equates to TAWS with complete system functionality. Interface C represents a TAWS type system minus the terrain awareness display (predictive alerting only). For each of the interfaces in Table 1, GPWS Mk 5 functionality was always provided as standard - the terrain display and predictive alerts supplement the basic GPWS.

Simulation Facility

The piloted evaluation program was executed using the NLR's Research Flight Simulator (RFS). The RFS features a modern civil transport aircraft glass cockpit, with a moving base motion platform and both terrain model board and computer generated visual system. An Air Traffic Control (ATC) controller station is fully coupled to the RFS. The various aircraft simulation models, avionics sub-systems and cockpit displays that are available can be tailored for a specific type of investigation. For the purpose of this evaluation, the RFS was programmed to simulate a Fokker 100 aircraft. Figure 1 presents the RFS cockpit set-up.



Figure 1: Research Flight Simulator Cockpit Layout

Although the cockpit layout does not resemble that of the actual aircraft, system functionality was emulated to the maximum extent possible. The standard Fokker 100 Primary Flight Display (PFD) and Navigation Display (ND) formats, and Engine Indication and Crew Alerting System (EICAS) were used. The Flight Management System, two Control Display Units, integrated Autopilot/Flight Director and Autothrottle were also used for the evaluation. The Flight Control Panel is glareshield mounted as shown above.

Terrain Awareness and Warning System Description

The experimental TAWS comprised the following visual and aural information:

- Graphical depiction of relative terrain elevation on the ND employing brown contours;
- Yellow and red alerting areas on the NDs to provide a visual indication of the predicted collision area associated with terrain cautions and warnings respectively. The caution and warning alerts are based on a 60 and 30 second look-ahead respectively, using current aircraft altitude, position, airspeed, descent rate, turn rate, and an on-board terrain database;
- Aural alerts (“Caution Terrain” and “Terrain Ahead - Pull-up”) combined with the above visual alerts;
- Terrain proximity warnings and cautions annunciated through the master/caution lamp on the glareshield panel;
- Depiction of a lateral trend vector (predicted flight path over next 30 seconds) on the ND in yellow.

In order to pursue the objectives of the current investigation, terrain was displayed full-time (as opposed to pilot selectable). The display range was pilot selectable. As an example, Figure 2 shows the ND during approach into Mexico City.

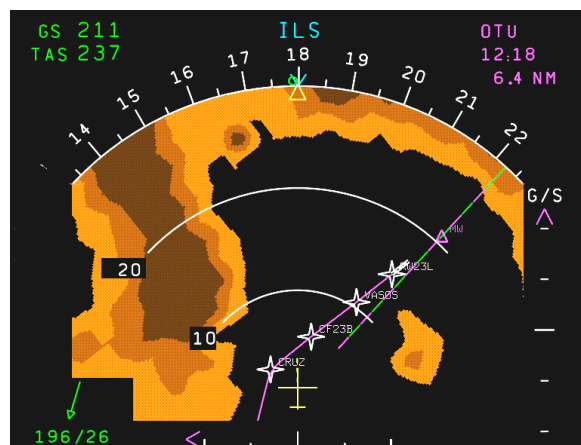


Figure 2: Navigation Display with Relative Terrain Elevation Information

The coding of relative terrain depiction above is defined using the sideview in Figure 3.

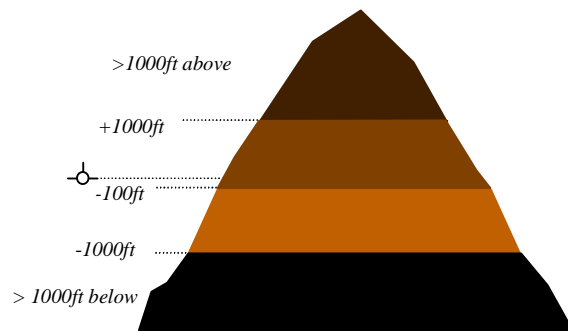


Figure 3: Colour Coding for Relative Terrain Depiction on ND

Experimental Design

A great challenge in the experimental design was the expected anticipation by test subjects that terrain collisions and/or dangerous proximity to terrain would occur during the experiment - as the pilots would be aware of the nature of the evaluation. Similarly, it was anticipated that subject pilots were unlikely to frequently encounter situations involving terrain alerts during the experiment since they would adhere to given clearances and also strictly follow prescribed Standard Operating Procedures. Reproduction of the complex accident causal chains in an experimental set-up is difficult to achieve. In addition, it was anticipated that there would be a significant learning effect for a particular crew in cases where they were exposed to abnormal situations and emergencies more than once. Exposing subjects to these latter conditions with more than one candidate interface was therefore avoided.

For the reasons stated above, a *mixed experimental design* was adopted. Two subject groups, each of five crews (Captain and First Officer), were each exposed to only two interfaces in Table 1. Each subject group evaluates the two interfaces in a repeated measures fashion, and the two subject groups themselves are involved in a randomised subject design. The evaluation of the individual effects of both terrain display information and that of predictive terrain proximity alerting could be investigated in this way.

Scenario Matrix Selection

An attempt was made to include scenarios representative of typical CFIT accidents^{1,2,3,8} within the constraints of an experimental set-up. Secondary tasks (e.g. full engine fire drill) were employed to introduce distractions and increase workload. The scenarios were primarily flown in a high terrain environment (Mexico City and Innsbruck), but a number of approaches were also flown in a flat terrain area (Amsterdam Airport Schiphol). Moreover, it is known that CFIT accidents also involve landing short and do occur in areas absent of

high terrain¹. All scenarios were flown under low visibility conditions, obscuring terrain features. All approach scenarios were initiated at an altitude of 16000ft and indicated airspeed of 250kts, which resulted in average flight times of 15 minutes to touchdown. The departure scenarios involved a take-off and subsequent routing along the published standard instrument departure. These simulations were stopped once the aircraft had safely climbed above the surrounding terrain, i.e. above 14000ft. The scenarios employed are described below and presented in Table 2.

Normal, uneventful flights Radar vectoring, published SIDs, STARs and both precision and non-precision approaches. See scenarios 2-4 in Table 2.

Incorrect radar vectors towards rising terrain Scenarios 5a-b. The engine fire in scenario 5a introduced distractions and additional workload. A given crew tested one interface only for each scenario. This scenario addresses display and alerting effects.

Incorrect altimeter settings/incorrect QNH Crews were unknowingly presented with incorrect QNH, placing the aircraft lower than indicated on the altimeter. See scenarios 6a-b in Table 2. A given crew tested one interface only for each scenario. Scenario 6 addresses the effect of the display.

Terrain database integrity There has been some debate in industry regarding crew response in cases where the system presents information based on erroneous terrain data. Scenario 7a included incorrect co-ordinate data, laterally shifting terrain below the departure route on the ND. Scenario 7b included incorrect (i.e. higher) altitude information of some elevated terrain below the arrival route. A given crew tested one interface only for each scenario.

False/nuisance GPWS terrain alerts Scenario 8 included a false "terrain" alert shortly before reaching the Minimum Descent Altitude (MDA). The scenario was selected to analyse crew tactical decision making following a terrain alert under instrument meteorological conditions (IMC). In several fatal CFIT accidents the crew continued descent despite a valid terrain warning, potentially as a result of loss of trust in the system due to earlier nuisance alerts¹.

Missed approaches The scenario involving crew exposure to missed approaches was combined with that involving false GPWS terrain alerts in scenario 8. After completing the required terrain evasive

manoeuvre, the specific terrain situation required the crew to continue on the published missed approach procedure.

Subject pilot group I was exposed to a sequence of scenarios using interfaces *A* and *B*, whereas group II used interfaces *C* and *D* (see Table 1 and 3). Within each pilot group, all were exposed to identical scenarios, the only difference being the scenario order was randomised. The scenarios flown per interface were identical with the exception of those scenarios that could not be realistically repeated with the alternative interface (for a given crew) because of the learning effect. In those cases an alternative scenario with similar generic characteristics was used - see scenarios 5-7, Table 3.

Table 2: Overview of Evaluation Scenarios

Scenario code/description	Anomaly/Event
#2 Amsterdam VOR/DME Alfa approach runway 24	None
#3 Innsbruck LOC/DME East approach runway 26	None
#4 Mexico Jusco2 departure from runway 23L	None
#5a Mexico Visos1 departure from runway 05R	Radar vectors toward rising terrain after engine failure
#5b Mexico Coapa4 arrival with rwy 23L approach	Radar vectors toward rising terrain off the standard arrival route
#6a Mexico Otumba2 arrival with rwy 23L approach	Altimeter setting error imposed on the crew
#6b Innsbruck LOC/DME west approach runway 26	Altimeter setting error imposed on the crew
#7a Mexico Arcos1 departure from runway 05R	Terrain database error mountain next to airport is shown under departure route on ND
#7b Mexico Otumba2 arrival with rwy 23L approach	Terrain database error terrain next to route is depicted higher on ND
#8 Innsbruck LOC/DME East approach runway 26	False GPWS "Terrain" alert

Table 3: Scenarios Per Subject Group and Interface

Subject group Interface Scenario	Group I (Crews 1-5)		Group II (Crews 6-10)	
	A	B	C	D
2	x	x	x	x
3	x	x	x	x
4	x	x	x	x
5a	x*	x*	x*	x*
5b	x*	x*	x*	x*
6a	x			x
6b		x	x	
7a		x	x	
7b		x		x
8	x	x	x	x
Runs/crew	6	8	7	7

- * only one, either scenario 5a or 5b for each interface per crew

Operational Procedures

To reduce experimental variability a number of variables were controlled, including operational variables discussed here. All flight crews were furnished with a generic set of Standard Operating Procedures (SOPs) (only those relevant to the experiment) in advance. The SOPs were based on the aircraft operations manual of a major European Fokker 100 operator. Crew co-ordination procedures for take-off & climb, approach & landing, go-around and GPWS & TAWS recovery were provided. For all GPWS and TAWS warnings, the crews were required to execute an immediate maximum performance climb until the warning ceased and the crew determined that terrain clearance was assured. The only exception to the immediate climb was for clear daylight Visual Meteorological Conditions when the flight crew could immediately and unequivocally confirm a false warning. This procedure is consistent with a recent FSF Safety Alert. For a TAWS *Caution Terrain* alert crews were required to correct flight path or perform the terrain avoidance if safe terrain clearance was in doubt. Full details are given in Ref. 5. Subjects were clearly briefed that the intended use of terrain display was for "pilot awareness" only, not for "navigation" or "escape guidance".

For all evaluation runs the Captain was designated pilot flying.

KLM navigation charts that depict brown terrain contours were employed. As the terrain display was displayed full-time for the purposes of the experiment, weather radar was not available.

Test Subjects

Ten European airline flight crews with jet transport experience conducted the evaluation. The 20 subjects, all with glass cockpit experience, were familiar with GPWS operation and related procedures for their current aircraft. Average Captain experience and age were 10000 hours (range 3300-22000 hours) and 44 years respectively. Average First Officer experience and age were 3300 hours (range 1700-5000 hours) and 31 years respectively.

Evaluation Procedure

The simulator evaluation was conducted during August 1997 and each crew was required to attend the NLR simulation facility for a single day. Each crew was furnished with a written briefing guide prior to their arrival. Following a pre-test verbal briefing, a training session in the RFS familiarised crews with the simulator, evaluation systems and procedures. The remainder of the day was used to conduct the crew's schedule of 14 evaluation runs.

Data Collection

Data collection before, during and after the evaluation runs consisted of:

- A pre-experiment questionnaire, i.e. pilot's flying background, experience and opinion/knowledge of onboard terrain warning systems;
- Subjective comments following each scenario;
- Quantitative data per run such as aircraft states (e.g. altitude, position, body attitudes), system parameters (e.g. AP modes engaged, alerts generated) power plant data (throttle position, engine indications), configuration data (e.g. flap, gear), etc;
- Qualitative interface rating questionnaire after completing the series of runs using one interface type;
- A post-experiment questionnaire to qualitatively compare the interfaces tested and assess overall pilot acceptability.

Results and Discussion

Qualitative Analysis

The post-test questionnaire for each interface type considered the following factors:

- the amount of information to assure sufficient terrain clearance;
- the degree of (spatial) situational awareness;
- terrain depiction: ease of interpretation and coding for terrain above/below the aircraft; and
- overall rating for the interface tested.

The overall ratings are based on a modified Cooper-Harper scheme. Statistical tests were applied to the combined data from the subjects to determine the

individual effect of both the terrain display as well as predictive terrain proximity alerting algorithms.

The ratings were processed using non-parametric Wilcoxon (for effect of terrain display) and Mann-Whitney tests (for effect of alert type). An ANOVA (analysis of variance) test was also applied for verification of the nonparametric test results. A sample of the results is shown below. The results in the figures indicate a (statistically) significant difference ($p < 0.001$), between ratings given with and without the terrain information display (Figure 4 & Figure 6) In contrast, a significant effect ($0.19 < p < 0.85$) was not observed for the forward-look (predictive) terrain alerting (Figure 5 & Figure 7). This is probably due to the fact that the terrain display aided the subject's spatial situational awareness to the extent of preventing the development of conditions generating

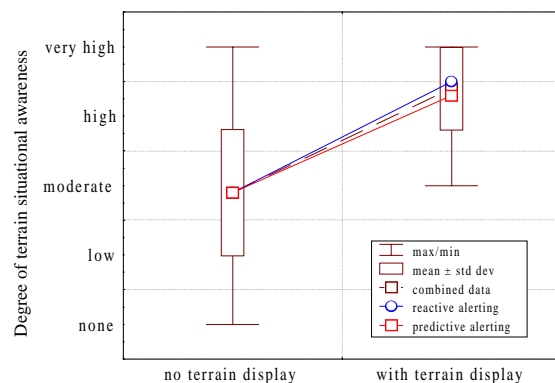


Figure 4: Influence of Graphical Terrain Display on Situational Awareness

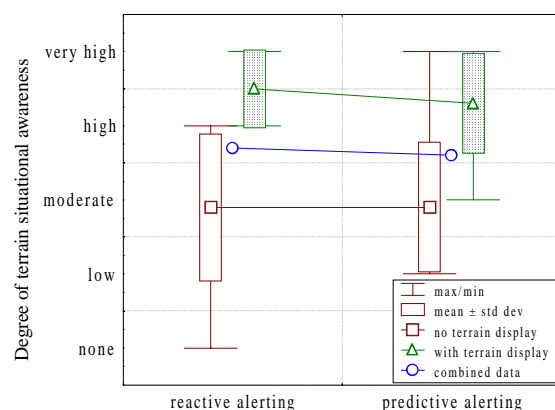


Figure 5: Influence of Forward-Look Terrain Alerting on Situational Awareness

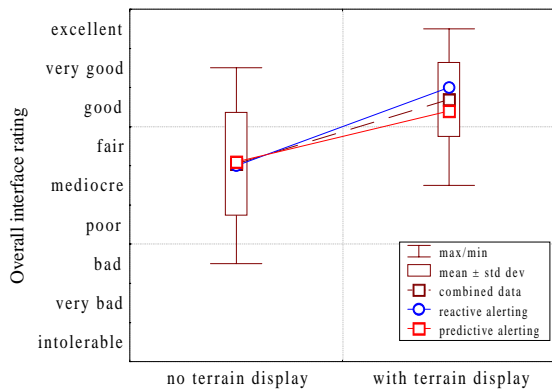


Figure 6: Overall Interface Rating - Effect of use of Graphical Terrain Display

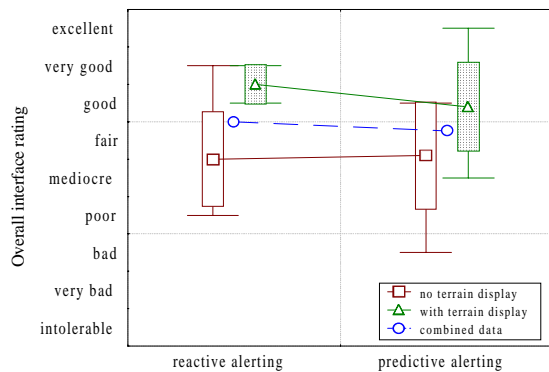


Figure 7: Overall Interface Rating - Effect of Alerting Type

predictive alerts in most scenarios. Relatively few predictive alerts were generated in the experiment (see next section) and it is specifically in those tactical conditions that the alert is of value.

Figure 8 presents the distribution for use of colour for the terrain depiction (note missing data). Colour for the display of terrain *above* the aircraft was considered satisfactory, but approximately one-third of subjects did not fully appreciate the selected colour for terrain *below* the aircraft.

The ratings presented in Figure 9 confirm that the displayed terrain information could be used with sufficient ease, although the interpretation of terrain information *below* the aircraft was rated less favourably by a number of pilots. Subjects indicated that the depiction of the terrain below the aircraft presented undesired distraction and cluttering with the displayed navigation data, during a number of approaches. Some comments also suggested a possible difficulty to discriminate the darkest brown colour, used to indicate high terrain, from the (black) ND background. Several pilots expressed a preference for displaying only terrain above the aircraft, although this would actually remove some

trend information during climb and descent, which are crucial phases of flight with respect to terrain clearance.

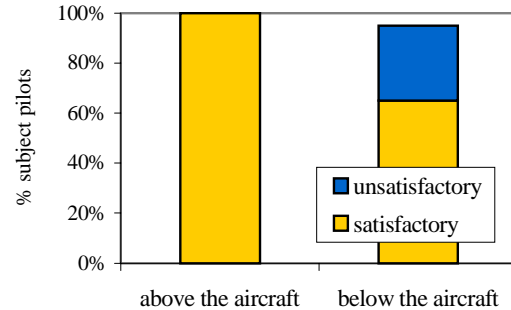


Figure 8: Use of Colour for Terrain Depiction Above and Below the Aircraft

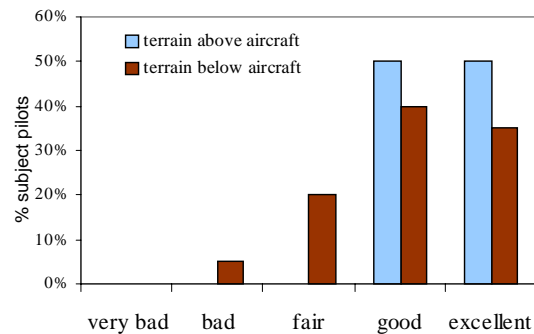


Figure 9: Ease of Interpretation of Terrain Contours
The post-test comparative rating data in

Figure 10 indicate that pilots considered that they were able to detect terrain critical situations significantly faster with the graphical display ($p < 0.01$). Subjects were unanimous in their opinion that the terrain display contributed to reducing workload for terrain separation during flight.

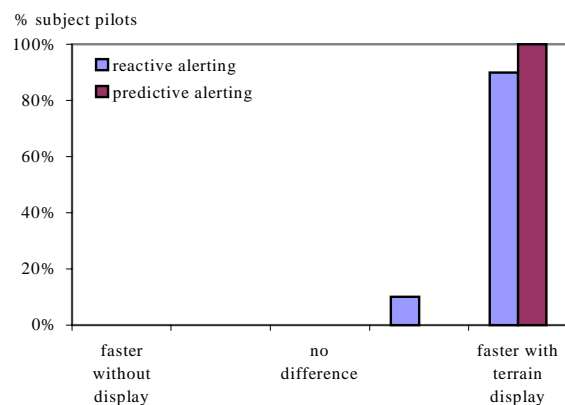


Figure 10: Speed of Detecting Terrain Critical Situations

Quantitative Analysis

A total of 140 scenarios were flown. The main parameters of interests for the quantitative analysis for each scenario included:

- Perceived terrain awareness (crews were asked whether they felt comfortable with respect to terrain clearance at the termination of runs);
- Crew recognition of unsafe vectors and/or current terrain clearance;
- Terrain alert(s) generated;
- The overall quality of the crew decision (safe vs. unsafe consequences);
- Compliance with the required SOP for escape manoeuvres.

For the purposes of this paper only a selection of results is presented. In the ensuing discussion, the term “safe” refers specifically to collision with terrain and/or marginal terrain clearance indicated by a GPWS/TAWS alert.

Nominal scenarios

Scenarios 2-4 comprised a total of 60 evaluation trials. As expected crew performance for all four interface types (display vs. no terrain display, and reactive vs. predictive alerting) was similar - all scenario outcomes being “safe”. Subjects clearly favoured the terrain display for conducting operations in the terrain rich environments exposed to them.

Radar vectoring towards rising terrain

Figure 11 presents an overview of scenario 5a involving radar vectoring towards rising terrain. The scenario involved an engine failure shortly after take-off from Mexico City airport, which required an immediate return. While the engine failure was introduced to pose extra workload to the crew, the aircraft returned to the airport via radar vectors given by the experiment ATC controller. Part of the radar vectoring involved flight towards rising terrain. With the terrain display, terrain critical situations did not arise. Subjects clearly recognised potential threats in advance and requested alternative vectors (consistent with subjective data in). The outcome was “safe” in 100% of the runs with a display. Without the display two-thirds of the scenarios involved an “unsafe” situation.

For the alternative scenario (to reduce learning effect), the crew was initially briefed on a standard arrival routing into Mexico City. Radar vectors off the standard routing were given to place the aircraft in the proximity of rising terrain. The results from this scenario (5b) are summarised in Figure 12. Forty three percent of the crews without a terrain display encountered an “unsafe” situation – terrain alert. All

runs with a terrain display resulted in “safe” outcomes.

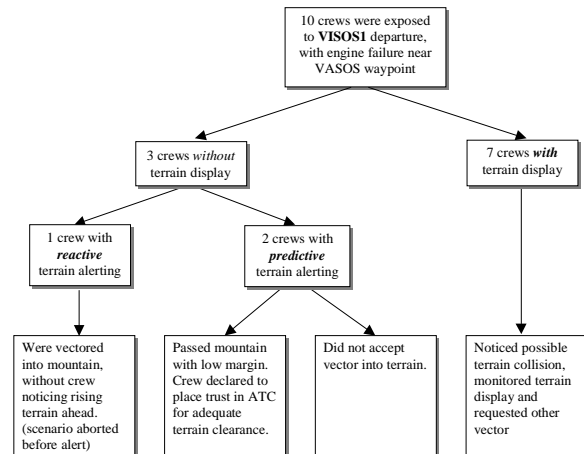


Figure 11: Crew Response to Terrain Critical vectors by ATC Following Engine Failure

For all terrain vectoring scenarios combined (5a-b), the outcome for 100% of terrain display aided scenarios was “safe”, whereas 50% of those without a display resulted in an “unsafe” encounter. For those crews with a display, no predictive alerts were generated. It appears that the terrain display provided sufficient spatial awareness to prevent the development of conditions that would trigger a predictive alert. It is likely that subject behaviour (not uncommon for experiments of this type, see Ref.6-7) also played a role, e.g. often refusing descents, requesting new vectors.

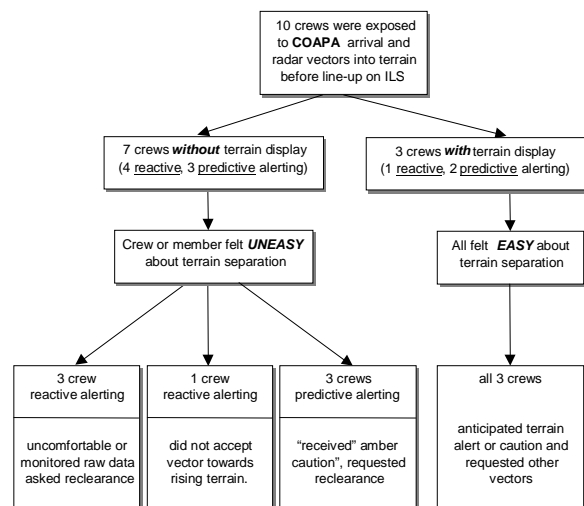


Figure 12: Crew Responses to Terrain Critical vectors by ATC during Approach vectoring

Observations of crew behaviour during these two scenarios clearly suggest that the graphical terrain information significantly improved the “comfort level” of the crews during radar vectoring with non-standard routing. However, it was also observed

during the high workload engine failure scenario, that at least two subjects used the terrain display for navigating away from significant terrain. (This was deduced from the communications in the flight deck and subsequent crew actions). When the terrain display was not available during these scenarios, observations suggest that subjects found it more challenging to efficiently correlate their actual position with the approach charts to verify sufficient terrain separation. Crew requests to ATC such as “state intentions” or revised clearances generally occurred earlier in those scenarios aided with a terrain display (consistent with subjective data in Figure 10).

Incorrect altimeter setting/QNH

The QNH given to crews in scenarios 6a-b placed the aircraft to within 1000 ft of terrain. Results for scenario 6a are show in Figure 13. Three of the ten crews noticed the anomaly at the termination of the run. Note that in half of these cases (including the TAWS trials) the basic GPWS “too low terrain” alert was generated and standard terrain recovery was executed.

Scenario 6b was a challenging approach in a terrain rich area with a steep descent using LOC and DME guidance to (overhead) the airport, followed by visual manoeuvring including course reversal to the runway. The vertical clearance during the approach was sufficient to prevent alerts being generated, and none of the ten crews exposed to this scenario noticed the QNH anomaly. The outcome of all 6b trials was “safe”.

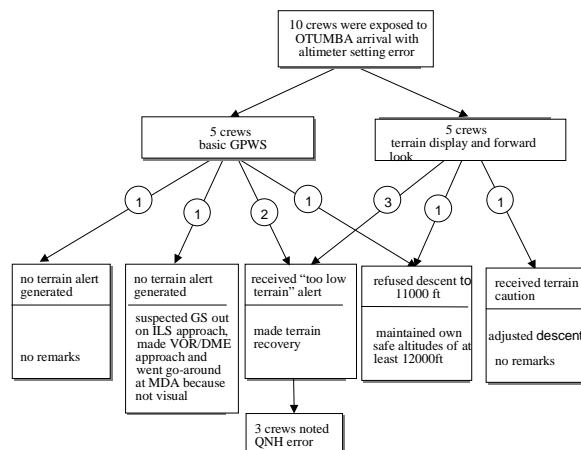


Figure 13: Altimeter Setting Error - Scenario 6a

Detection of terrain database errors

The potential for erroneous terrain data and the integrity issues of the onboard database have been heavily debated in industry. Current systems are developed on the basis that the information is

supplemental to the basic GPWS and that the intended use of terrain display is for “pilot awareness” only, not for “navigation” or “escape guidance. There is also speculation in some quarters that the terrain information presented is extremely compelling and that a potential exists whereby the system may be inadvertently misused for navigation. Scenario 7b included a database error with incorrect terrain elevation for an area beside the arrival path, on the published Otumba 2 arrival into Mexico City. The display presented the mountain as being 2000 ft higher than actual. The crews were cleared to descend to an altitude such that the terrain would be presented on the ND (under normal circumstances it would not be displayed).

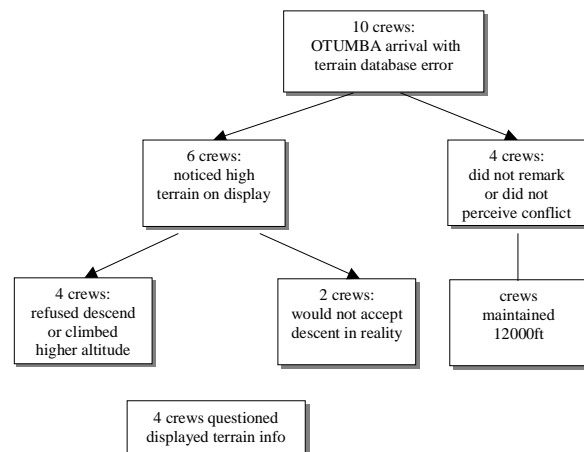


Figure 14: Crew reaction to terrain database anomaly

Figure 14 indicates that 40% of the crews did not question the presentation of information that posed a potential terrain separation conflict. At the termination of the scenario, when questioned about terrain separation, these crews indicated that they felt “comfortable” with respect to terrain separation.

In scenario 7a, a mountain located approximately 5 NM north of the take-off runway was laterally displaced (within the TAWS database) below the published departure routing. It was therefore visible on the ND below the departure route. Crews were also in possession of the published SID that depicted the correct terrain. None of the crews noticed the database anomaly prior to or during take-off and departure, even though it was located below the departure route. An established procedure for briefing about terrain database errors before takeoff was not included in the experiment. Note that for some airports it is not unusual to take-off towards high terrain. In today’s operations, the assumption is that following SOPs, SIDs and Climb Procedures will provide the necessary terrain clearance if followed.

The combined data for scenarios 7a-b indicate that in 70% of the cases, crews did not notice the anomalies on the terrain display.

Crew adherence to procedures after terrain alerts

Scenario 8 investigated the crew reaction to a false GPWS terrain alert during an approach into Innsbruck without visual external reference. The expected reaction was an immediate standard terrain evasive manoeuvre, i.e. a wings-level, maximum performance go-around.

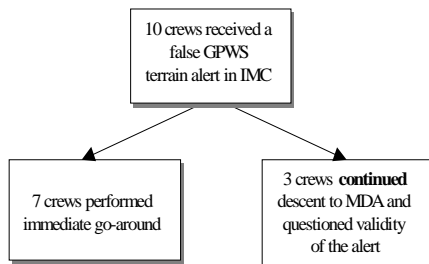


Figure 15: Crew reaction to false GPWS alert

Additionally, the 180° course reversal for the published missed approach procedure implies a rather demanding manoeuvre given the nature of surrounding terrain. Although the SOPs called for an immediate go-around upon receiving any GPWS warning in IMC, three crews (30%) continued the approach without performing a go-around. At the termination of the scenario, the crews stated that the GPWS alert was disregarded since the aircraft appeared well stabilised on path, and with the correct speed. They questioned the validity of the GPWS warning and stated that terrain clearance appeared to be satisfactory. These crews were at a heightened state of alertness carefully monitoring all raw data. Whilst in the latter scenarios a terrain threat did not exist, statistics show that failure to respond to GPWS alerts has played a role in previous accidents^{1,3}. This has generally been the result of inadequate SOPs and/or training, and reduced trust in the system due to previous false/nuisance alerts^{1,3,8}.

Conclusions

For the 20 scenarios involving radar vectoring towards terrain, the outcome for all terrain display aided runs was “safe”, whereas 50% of those without a display resulted in an “unsafe” encounter. For those crews with a display, predictive alerts were not generated.

- Observations of crew behaviour and subjective comments during scenarios in which crews were radar vectored close to rising terrain suggest that those pilots presented with a terrain display generally felt more comfortable with respect to terrain clearance, than those without the display.
- For the 20 scenarios where crews were furnished with incorrect QNH data, three crews (15%)

noticed the anomaly. In five (25%) cases GPWS terrain alerts were generated, resulting in execution of appropriate terrain recovery manoeuvres.

- In 70% of 20 scenarios crews did not notice anomalies on the terrain display associated with TAWS database errors.
- Three of 10 crews (30%) continued the approach without performing a go-around upon receiving a false GPWS warning in IMC and in a terrain-rich environment. Whilst these crews questioned the validity of the alert, this action was not consistent with the SOPs provided.
- Subjective ratings indicate that the terrain information on the ND gave rise to a significant improvement in spatial situational awareness and speed of detecting terrain critical situations. The graphical terrain information on the navigation display was regarded as the most helpful safety item in providing terrain situational awareness.
- Subjective ratings did not show a significant effect in terrain awareness resulting from the predictive alerting. The terrain display provided sufficient spatial awareness to the extent that the conditions generating a predictive alert developed relatively few times. Also the heightened awareness of crew in an experimental set-up potentially contributed to this effect. Crews clearly stated their desire for the predictive alerting capability.
- Many subjects indicated that the terrain display was so compelling that it would not be difficult to use the information for navigation, specifically during high workload situations. This was observed at times during the evaluation. Issues concerning the terrain database integrity and the required high position accuracy, especially in an obstacle rich environment, currently preclude this function.
- Overall, the terrain display format and selected colour coding were generally regarded as easy to understand and use. It should be noted, however, that the depiction of terrain below the aircraft was not unanimously appreciated.
- Subjects had little difficulty learning to use the terrain display and commented about the major improvement in terrain awareness compared to the current *no terrain display* situation in most current flight decks.
- Many subjects expressed concern about a cluttering of data on the navigation display close to the airport, which could obscure essential navigation information during this critical phase of flight.
- During poor weather conditions in mountainous terrain, it was regarded as essential to have the weather radar data available on the navigation display. Currently, weather and terrain are selected on alternate NDs.

Recommendations

- a) Product designers should ensure that terrain information is distinguishable from other display elements such as traffic, FMS flight path, data and weather. The importance of background terrain and terrain alerting information should be specified relative to these other data on the display. The use of colour should not result in the erroneous interpretation of terrain information. Means to deal with potential clutter, especially at low altitudes/during approach, should be addressed. Strategies to allow the flight crew to manipulate the shared display of information may need to be provided.
- b) States and operators should support the implementation of TAWS as proposed by ICAO, FAA and the FSF CFIT/ALAR Task Force.
- c) Operators should provide flight crews with adequate CFIT awareness and avoidance training e.g. FSF CFIT Training Aid.
- d) Operators employing TAWS/GPWS equipment should provide flight crews with the necessary SOPs and training. Correct terrain recovery procedures and limitations of the TAWS/GPWS system being utilised should be emphasised. Both initial and recurrent training should expose flight crews to high workload scenarios that demonstrate navigation strategies independent of the TAWS display.

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