REDUCING THE CONTROLLED FLIGHT INTO TERRAIN RISK
BY
HUMAN ERROR MANAGEMENT

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Abstract. In the light of the latest airline scheduled airline traffic growth forecasts, significant improvements will have to be introduced to maintain the public's confidence in the safety of air travel. So-called "Controlled Flight Into Terrain", in which airworthy aircraft are inadvertently flown into the terrain (or water) with little or no awareness by the pilots, cause the major part of airline passenger and crew fatalities today. This paper categorises the causes leading to this specific type of aircraft accident and suggests improvements in the area of cockpit man-machine-interface and warning system improvements capable of reducing the CFIT-rate in future.

Keywords. Controlled flight into terrain, Human error management, Ground proximity warning systems, Synthetic/Enhanced terrain displays.

1. INTRODUCTION

Air travel is generally accepted as a safe means of transportation. According to the latest traffic growth forecasts however, the civil aviation safety record, in terms of yearly passenger fatalities or aircraft hull-losses, could deteriorate. Until the year 2003, the International Civil Aviation Organisation (ICAO) assumes a moderate 5% long-term traffic growth for world scheduled passenger traffic. As the averaged annual passenger fatalities and fatal accident rates in the 1984 trough 1993 period did not change substantially, extrapolation, based on the trend in traffic growth and accident statistics over this period of time, presents reasons to be concerned about the future flight safety record. According to this extrapolation, ICAO (Corrie, [4]) expects the number of passenger fatalities to increase with 74% to 1,200 per year, and the number of fatal accidents to increase with 77% to 40 per year by the year 2003. In order to maintain the public's confidence in the safety of air travel, significant safety improvements will have to be introduced.

So-called "Controlled Flight Into Terrain" (CFIT) accidents remain the number one cause of passenger and crew member fatalities today. This paper categorises the causes leading to this specific type of aircraft accident and suggests improvements in the area of cockpit man-machine-interface and warning system improvements capable of reducing the CFIT-rate in future.

2. CONTROLLED FLIGHT INTO TERRAIN

Definition and statistics

Adopting the definition as compiled by the Flight Safety Foundation's CFIT task force, a controlled flight into terrain or CFIT accident occurs when "an airworthy aircraft is inadvertently flown into the terrain (or water) with little or no awareness by the pilots". Since the advent of the jet transport in 1958, well over 9000 lives have been lost in CFIT accidents world-wide. Although reduced in number by the implementation of the ground proximity warning system (GPWS), CFIT accidents continue to occur. GPWS is a terrain warning system that alerts the crew whenever their aircraft's terrain clearance becomes endangered. Recent data (1988-1993 period) show that, in world-wide airline operations, 54% of all passenger and crew fatalities were a result of controlled flight into terrain. These fatalities were caused by 28 CFITs out of a total number of 76 fatal accidents (figure 1). The number of CFIT accidents per million flights by region is depicted in figure 2.
Over the period 1959-1992, the number of hull-losses due to controlled flight into terrain in Europe was five times higher than that in the North America region. This might be a result of earlier implementation of GPWS in the USA and the availability of a terrain-warning system for Air Traffic Controllers, the Minimum Safe Altitude Warning System (MSAWS). MSAWS is a software package for use at Automated Radar Terminal System (ARTS) Air Traffic Control facilities. The MSAWS provides the air traffic controller automatically with aural warnings when aircraft under his or her control penetrate the safety altitude for the region they are flying in. The MSAWS program started in 1977 but still only 50% of the project has been completed in the United States.

63% of all CFIT accidents occurred during the initial approach or final approach and landing flightphase figure 3. The relatively high (67) average number of casualties per CFIT accident can be explained by the high airspeed averaged in CFIT accidents (220 knots, 407 km/h).

Human error

"Experience indicates that most CFIT accidents can be related to poor visibility, navigation error, instrument reading error, visual misconception, vertigo, distraction, confusion and/or inattention. Thus, the expression "controlled flight into terrain" is one applied to those accidents that are normally attributed to "pilot error" as opposed to mechanical failure"

The essence of this quotation by Peter Penny, published in the ICAO BULLETIN of March 1975, still holds for present day aviation operations. It is important however to stress that the causes for aircraft accidents cannot be attributed to one action only. Even when a crew-error directly caused an accident, there usually are several other events which preceded it, and also attributed. According to Professor James Reason (Reason, [9]), aircraft accidents occur as a result of complex interactions between many causal factors. The causal factors may be categorised into three groups: active failures committed by those operating at the "sharp end", which are necessary but insufficient causes for aircraft accidents, local triggering factors such as weather conditions, and latent organisational failures. The total sequence of events leading to Reason's organisational accident is depicted in figure 4.
This paper, however, would like to focus on the human-error side of the CFIT problem. In Reason's diagram this would concern the "Individuals" and "Defences" sections.

CFIT causal conditions

The factors that contribute to CFIT accidents may be categorised into two groups, identified by two "CFIT causal conditions". The first condition focuses on the aircraft's flightpath:

**The aircraft's flight path will cause it to collide with terrain or water.**

The second condition concentrates on the crew's terrain awareness:

**The crew has no awareness concerning the flightpath condition, or develops this awareness too late to avoid collision.**

Only when both of these conditions have been satisfied, a CFIT accident will occur. In order to construct a fail-proof CFIT protection, however, both of these problem areas will have to be addressed. According to this classification, two classes of CFIT prevention strategies may be distinguished: those which prevent aircraft from flying a flightpath towards terrain and those which make it obvious to the crew that they are flying towards terrain. First we have to understand under what circumstances and due to which error-chains any of these conditions may occur. From accident and incident reports, a number of causes for the two conditions mentioned above can be extracted.

3. ASSESSING THE LINKS IN THE CFIT ACCIDENT CHAIN

Flightpath Condition

As most flightpath deviations leading to CFIT accidents have occurred on the extended centreline of the destination runway (Bateman, [3]), flightpath deviations in the vertical plane seem to pose a greater threat than lateral deviations. In the July '88 through July '93 period, 13 out of 25 CFIT commercial jet aircraft hull losses occurred while executing non-precision1, step-down, approach procedures. When observing the flight path profiles of these accidents it appears that in several cases the crew failed to level off after performing an altitude step (Bateman, [2]). The increased workload induced by performing a large number of step-down altitude changes in a short period of time, as required by some approach profiles, may cause the crew to lose track of their position on the profile. In September 1992 an Airbus A-300 crashed on approach for Kathmandu’s Tribhuvan International airport (figure 5). The step-down approach for this airport comprises no less than 8 altitude steps along a 16 nautical miles long approach path.

![Figure 5: Instrument Approach Plate for Kathmandu's Tribhuvan "Sierra" Approach. Source: [8].](image)

Undetected descents, resulting from erroneous autoflight mode selection have also been a factor in several incidents and accidents.

Misinterpretation of a departure procedure is illustrated by the 1989 accident with a Boeing 737-200. The aircraft crashed into a mountain in Taiwan after misinterpreting the Standard Instrument Departure (SID) chart. The SID for the flown departure called for a right turn after take off, instead the crew flew a left turn and, after being discovered by the copilot, corrected to the right too late.

Premature descent clearances or late heading changes, issued by air traffic control, may also result in flights towards terrain, and may remain undetected by the crew. Although monitoring the terrain separation of aircraft is not a primary responsibility of air traffic controllers, accident and incident reports not seldom cite the crew’s confidence in terrain-free vectors issued by ATC personnel. It may well be that the high workload during the approach flightphase makes it tempting

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1 i.e. Approaches without using precision approach and landing guidance systems like the Instrument Landing System (ILS). Non-precision approaches do not offer vertical approach path guidance.
for the crew to trust controllers rather than to check any issued ATC vector for terrain before accepting it. High confidence in terrain-free vectors on the part of the crew reduces the redundancy, and thus the safety, of the aviation system.

As the altimeters used in aviation are barometric, common approach procedures require the crew to enter the local barometric pressure for the destination airport before commencing the approach. The approach controller of the destination airport provides the crew with current air-pressure data by radio communication. Several CFIT accidents are known to have occurred due to altimeter setting errors. Pilots have entered erroneous digits causing altitude indications with errors of more than 1000 feet (305 meters)! Misunderstanding of the correct data during the radio contact with ATC is also known to have been a factor in several accidents.

Aviation is highly dependent on human-to-human voice communication. This is also a leading source of error in the system, and one that is difficult to combat. Communication in aviation operations can be divided into intra-cockpit and extra-cockpit or radio communication. Intra-crew communications provide the only way for captain, first officer, and flight engineer (in three-crew cockpits) of working as a team, they include requests by the pilot flying for specific action by the pilot not flying, and acknowledgements to these requests. Typical extra-cockpit communications are requests to and from air traffic control, and confirmation of reception of the message (readback). Radio communication between air traffic control and crew provides clearance, weather, and traffic information that is not available by other means. Two examples of error in communication:

En route from Colombia to Seattle, the crew of a Metro III aircraft received this descent clearance: "Nectar one six nine three Metro, you are cleared to cross Hobart at 8,000, Seattle at or above 4,000. Maintain 4,000. No delay expected. Contact Seattle Approach Control over Hobart for further clearance, over." The captain, who was experienced on the route replied: "Roger, this is uh nine three Metro is cleared to... uh... Hobart... to cross there 4,000 or above, the range station at 4,000, and we report to you at uh Hobart, over." Control replied: "Negative. Report Hobart to Seattle Approach Control", thus correcting the last and least important of the two mistakes in the repeat-back. The aircraft descended to 4,000 feet and crashed into a mountain.

A Boeing 747 approaching Nairobi in the middle of the night was cleared by the controller to "seven zero zero zero" feet. The first officer repeated back "five zero zero zero". The controller should have corrected the mistake, but it was allowed to continue. Fortunately the captain saw the ground through intermittent cloud and carried out an overshoot.

In general, errors made in communication arise from non-standard or ambiguous phraseology, lack of communication between crew members or mishearing words with similar pronunciation. Lack of information exchange between crew members has also led to several accidents in the history of aviation. Cockpit voice recorders (CVRs), tapping the last seconds before the accident often show the pilot's chilling inability to say the words that might save them.

**Terrain Awareness Condition**

The primary factor leading to the loss of the crew's terrain situational awareness is of course the outside visibility. No flight towards terrain will remain undetected for long during operation in daylight Visual Meteorological Conditions (VMC). Under Instrument Meteorological Conditions (IMC) pilots have to determine their position by relating their current position and flightpath vector with the approach plate's terrain information. This process involves mental conversion of the north-up oriented approach plates towards a track-up "mental terrain picture". Under high workload situations this may involve too much time to be correctly performed, mental terrain pictures constructed prior to the initial approach may fade during the relatively high number of actions needed to complete this flight-phase. The CVRs of crashed aircraft often expose expressions of uncertainty by crew-members concerning the whereabouts of the surrounding terrain.

When flying under Visual Flight Rules (VFR) in deteriorating weather conditions, pilots may have the tendency to try and maintain visual contact with the ground, instead of cancelling VFR and continuing under an Instrument Flight Rules (IFR) flight plan. Several accidents have been attributed to

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*Instrument Approach Plates are paper maps that contain all information for successfully performing an approach to one specific airport runway.*
this phenomenon, most of which occurred to aircraft of small regional operators, whose pilots were used to fly under VFR during almost all flights. An example:

In December 1991 a Beechjet Be 400 collided with a mountain summit near Rome, Georgia, US, shortly after take-off. The aircraft was told by ATC to "remain VFR because we have traffic four and five right now south-east of Rome". The crew had trouble maintaining VFR in the fog, but did not inform the controller. The cockpit voice recorder installed in the aircraft indicated that the pilots recognised that the aircraft was close to obscured terrain. At 9.39:39 (nine minutes past half ten and 39 seconds) the Captain told the First Officer: "We're gonna have to get away from that mountain down there pretty soon", and at 9.39:52: "You're getting close. You're gonna (have to) go to the right". The First Officer answered that he could not "see over there". The captain then stated that if they maintained their present course, they could run into an airplane on approach to Rome and pointed out there was a mountain in one direction and an antenna in another that would be hidden by fog. At 9.40:07 the captain directed the first officer to fly "back to the right" and the first officer stated "I can't see over there that's why I wanted to go the other way". The CVR recording stopped at 9.40:55. The accident report stated that the probable cause of the accident was:

"the captain's decision to initiate visual flight into an area of known mountainous terrain and low ceilings and the failure of the flight crew to maintain awareness of their proximity to the terrain".

4. GROUND PROXIMITY WARNING SYSTEMS

To alert the crew whenever their loss of terrain-awareness has developed into a hazardous situation, the ground proximity warning system (GPWS) has been developed. Development of GPWS started in 1967, when it was recognised that the radio altimeter, a requirement for the Category II "All Weather Landing" instrument package, did not encompass the maximum alerting for exposure to collision with the ground under all types of flying conditions. The GPWS concept was unique in a number of respects. It was the first warning system in general use to combine information of a number of hitherto unrelated aircraft sensors to produce a single warning output. It was also the first cockpit warning system to use a synthesised human voice to provide the primary warning to the crew. The ground proximity warning system computer unit accepts inputs of radio altitude, barometric altitude rate, ILS glide slope deviation and landing gear and flap discrete, which it manipulates mathematically to determine the onset of terrain proximity. Audible warnings or alerts are operator specified synthesised voice commands such as "WHOOP WHOOP, PULL UP!" or "TERRAIN! TERRAIN!". Red "PULL UP", "GND PROX" and/or "BELOW G/S" lights, flashing in the glareshield, form the visual output of the GPWS. The GPWS functions only when the radio altitude is less than 2,500 feet above ground level. Power to the system is controlled only by a circuit breaker, pilot inputs are not required and, when the aircraft is flown in normal profiles, the GPWS warning should never be heard. Modern ground proximity warning systems offer four warnings for a (predicted) dangerous situation with respect to the terrain: modes 1 (excessive rate of descent), mode 2 (excessive terrain closure rate), mode 3 (altitude loss following take off), mode 4 (insufficient terrain clearance). Another two warning modes include a warning for excessive deviation below the glideslope of an ILS approach (mode 5) and for a descent below a minimum radio altitude selected by the crew (mode 6). Although its introduction has significantly reduced the CFIT rate, incident and accident reports, indicate that GPWS is not capable of providing a fail-proof safety-net against CFIT. More than half of the aircraft lost in CFIT accidents during the July '88-July '93 period had been equipped with GPWS (figure 6).

3 The radio altimeter uses continuous or pulsed radar signals to measure the distance to terrain directly below the aircraft.

![Figure 6: GPWS Effectiveness](image-url)
procedures and crew vigilance have failed to assure a safe terrain clearance. Secondly, when safety is likely to be endangered, the system should be capable of alerting the crew under all circumstances. Present GPWS models are known to be subject to both primary and secondary error: there are circumstances under which the system issues unnecessary warnings, as well as situations in which the system does not alert the crew for a potentially dangerous situation with respect to terrain. These two areas do not include all deficiencies of current GPWS equipment however. Accidents have occurred in which the GPWS did issue terrain warnings, but too late for the crew to complete a successful recovery. Simulated GPWS warning time prior to projected impact has been depicted in figure 7.

![Figure 7](image)

**Figure 7.** GPWS warning time prior to projected impact. Data from computer simulation with “GPWS SIM” (Dijkgraaf [6]).

For the flightpath of an aircraft flying horizontally towards a single mountain with a constant slope angle the GPWS warning time was measured. When the aircraft was configured for landing (landing gear down and locked, landing flaps selected) warning times did not exceed 5 seconds in advance of a possible impact!

In other cases a timely GPWS warning was issued, but the crew responded too late (or even not at all). The most severe limitation of the GPWS however, is its inability to guarantee a safe recovery from any warning. In other words: even when a procedural evasive manoeuvre will be initiated immediately after the first warning, GPWS does not guarantee sufficient terrain clearance throughout the recovery flight path. Due to the lack of a “forward looking” sensor input, present ground proximity warning systems have to determine terrain hazard by extrapolating the slope angle of the terrain directly below the aircraft. Warnings will then be issued some time prior to a projected collision with an extrapolated mountain slope. It is this technique, in use since the introduction of GPWS in the late 1960s, that lies at the basis of most of the GPWS drawbacks. Whenever terrain steepness increases along the trajectory the aircraft is flying, the system will alert the crew relatively late, on the other hand when the aircraft flies at a safe altitude over sheer cliffs, the system will issue unwanted alerts.

### 5. MANAGING THE ERRORS LEADING TO CFIT

Having summarised the numerous human-error related causal factors which form the CFIT chain-of-events, and having observed that the ground proximity warning system is not a fail-proof CFIT safety-net, what can be done do to reduce the CFIT-rate in future?

In his report “Intervention Strategies for the Management of Human Error” (Wiener [11]), Earl Wiener of the University of Miami hands several lines of defence against human error. In his terms, “error management” must be distinguished from “error reduction” or “elimination”. “Management” in this sense means that one strives to build into systems and operator methods by which one can either eliminate or reduce human error, or if this is not possible, to minimise its consequences. According to Wiener:

> “The Human remains a vital component in complex systems found in aviation and elsewhere because he/she possesses remarkable perceptual capabilities, among them the ability to detect subtle deviations from normal. This capability should be assigned to the front end of the lines of defence against human error. Human error is the price we pay for the flexibility of the human brain. It is a price that must be minimised by effective intervention strategies and lines of defence.”

Concluding his report Wiener presents 5 levels at which technology and humans may combine to manage rather than necessarily prevent error. These lines global of defence are:

1. Prevent the error in the first place, or make it as unlikely as possible. This is done by training, procedures, management, and quality assurance.
2. If an error is introduced into the system, make it as conspicuous as possible through display design and traditional human factors (“error-evident displays”).
3. If the first two methods fail to block or remove the error, design the system, probably through software, to trap the error and prevent it from affecting the system. This level of defence may or may not require further developments of artificial intelligence.
4. Provide sophisticated warning and alerting systems.
5. Make certain that there is a recovery path from any error.

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Returning to the controlled flight into terrain problem, Wiener's global lines of defence (see also figure 8) indicate several shortcomings with respect to CFIT avoidance in the present aviation system.

figure 8, Lines of defence against CFIT.

The first defence line (training, management etc.) is currently being promoted by the ICAO and the Flight Safety Foundation's CFIT Task Force in the form of CFIT awareness programmes and GPWS training aids. It is of extreme importance that pilots learn to understand CFIT "traps" and learn to perform a successful recovery from any GPWS warning. "Error-evident" displays, the second line of defence Wiener proposed, may be introduced in the form of some sort of terrain display that could improve the crew's terrain awareness. Such a display could increase the probability of detection by the crew of an inadvertent flight towards terrain. It may also take over the crew's task of mental conversion of the north-up oriented paper approach plates towards a track-up oriented picture. The error-evident display does not have the intelligence to detect errors.

It is merely a display system, and the management of human error ultimately depends on human intelligence to detect the error. As stated earlier in this paper, in many CFIT accidents from the past, pilots expressed their doubts concerning the position of high terrain relative to the aircraft. An example of terrain display depicted on the aircraft's navigation display is presented in figure 9. The terrain data required for terrain displays could be "synthetic", in the form of a terrain elevation database stored in a computer's memory, or obtained via various "enhanced-vision" sensors that depict real terrain. Using a terrain elevation database would require a reliable and accurate navigation system to align the synthetic terrain and the real world, but might well be more cost-effective than installing expensive infra red sensors, millimeter-wave radar and low-light-level television equipment. Enhanced vision equipment is not dependent of navigation accuracy and does not hold the dangers hidden in database-errors, but is hindered by weather-conditions. Combining the two systems, enhancing real sensor data with synthetic terrain information could be a solution but will get even more expensive.

Future ground proximity warning systems should assure the success of procedural escape manoeuvres, eliminate unwanted warnings and no-warning situations and improve crew response to warnings. In order to achieve these requirements, the use of a coarse digital terrain elevation database is expected to offer the best cost/performance ratio. By using terrain elevation data, aircraft performance and pilot response time as GPWS input, it should be possible to continuously compute escape flightpaths, both in the vertical and horizontal plane. Postponing terrain warnings until the last of these flightpaths intersects a safety margin above terrain, will considerably reduce the number of unwanted warnings while assuring a recovery from every warning. By using approach recognition logic, the warning system should be able to distinguish between stabilised approaches towards an airport and stabilised approaches towards terrain. Besides these system improvements, it will still be necessary to assure timely and efficient crew response to terrain warnings. To achieve this, the terrain preview capability as used for the ground proximity warning computer should also be offered to the crew by means of a terrain display. It is assumed that the preview capability offered by this display will cause the crew to discover developing terrain hazards long before the GPWS warning is issued and, in case the GPWS still catches the crew by surprise, reduces pilot response time by indicating the position of the
terrain causing the alert. MSAWS software for air traffic control or enhanced vision equipment could in that case be used as an independent monitor.

6. CONCLUSIONS

Rather than to try and eliminate human error as a controlled flight into terrain cause, efforts should be directed towards human error management, thus avoiding the error where possible while reducing the severity of the consequences of any unavoidable errors. Well-designed procedures, man-machine-interfaces, training programmes and CFIT awareness programmes should avoid human error where possible. In addition, pilots should be provided real-time terrain information to make flightpath deviations towards terrain obvious. Acting as a final line of defence, improved terrain-warning systems should incorporate “forward looking” capability and take into account the pilot’s inherent response delay to unexpected warnings, thus offering a fail-proof controlled flight into terrain safety net.

7. LIST OF ABBREVIATIONS

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<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
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<td>CFIT</td>
<td>Controlled Flight Into Terrain</td>
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<td>GPWS</td>
<td>Ground Proximity Warning System</td>
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<td>ICAO</td>
<td>International Civil Aviation Organisation</td>
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<td>IFR</td>
<td>Instrument Flight Rules</td>
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8. LITERATURE


