Report on the accident to Airbus A-320-231, G-MEDA On approach to Addis Abeba Airport, Ethiopia 31 March 2003

Contents

Glossary of abbreviations used in this report

AAIB	Air Accidents Investigation Branch
aal	above aerodrome level
ADF	Automatic Direction Finder
agl	Above ground level
AIRAC	Aeronautical Information Regulation And Control
amsl	above mean sea level
ATC	Air Traffic Control
CAA	Civil Aviation Authority
CB	cumulonimbus
CFIT	Controlled Flight Into Terrain
CVR	Cockpit Voice Recorder
DME	Distance Measuring Equipment
EGPWS	Enhanced Ground Proximity Warning System
EPE	Estimated Position Error
FAA	Federal Aviation Administration (USA)
FCOM	Flight Crew Operating Manual
FDAU	Flight Data Acquisition Unit
FDR	Flight Data Recorder
FL	Flight Level
FLTA	Forward Looking Terrain Avoidance
FMGC	Flight Management and Guidance Computer
FMS	Flight Management System
FO	First Officer
FOQA	Flight Operations Quality Assurance
FPA	Flight Path Angle
g	gravitational acceleration
GPS	Global Positioning System
HSI	Horizontal Situation Indicator
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organisation
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IRS	Inertial Reference Systems
kg	kilograms
km	kilometre
kt	knots
JAA	Joint Aviation Authorities
JAR	Joint Aviation Requirements
LOC	Localiser (ILS)
m	Metre
mb	millibars (pressure)
MCDU	Multifunction Control and Display Unit
MDA	Minimum Descent Altitude
METAR	Meteorological Aerodrome Report
MHz	Megahertz
mm	millimetre(s)
MPS	Minimum Performance Standards
NAV	Navigation
ND	Navigation Display
NDB	Non-Directional Beacon
nm	nautical miles
NOTAM	Notice to Airmen
OPS	Operations
PDA	Premature Descent Alerting
PFD	Primary Flight Display
PNF	Pilot Not Flying
QAR	Quick Access Recorder
QNH	Corrected mean sea level pressure
RA	Radio Altimeter
RH	Radio Height
RNAV	Area Navigation
RVR	Runway Visual Range
SOP	Standard Operating Procedure(s)
TAD	Terrain Awareness and Display
TAF	Terminal Area Forecast
TAS	True Airspeed
TAWS	Terrain Awareness Warning System
TCF	Terrain Clearance Floor
TRK/FPA	Track/Flight Path Angle
TOM	Take-off mass
UK	United Kingdom
USA	United States of America
UTC	Universal Time Co-ordinates
VCR	Visual Control Room
VHF	Very High Frequency
VOR	VHF Omni-Directional Radio Range
ZFM	Zero Fuel Mass
°T, °M	degrees True, Magnetic
°C	degrees Celsius

Air Accidents Investigation Branch   Incident Ref: EW/A2003/3/1

Registered Owner and Operator:	British Mediterranean Airways Limited
Aircraft Type:	Airbus A-320-231
Manufacturer's Serial No:	0480
Registration:	G-MEDA
Location of incident:	On approach to Runway 25L, Addis Abeba Airport, Ethiopia Latitude: 09° 05'N Longitude: 038° 53'E
Date and Time of incident:	31 March 2003 at 2338 hrs All times in this report are UTC

Synopsis

The United Kingdom Air Accidents Investigation Branch (AAIB) was notified of this incident by the Flight Safety Manger of British Mediterranean Airways. The AAIB then notified the Ethiopian Accident Investigation Authority.

A British Mediterranean Airbus A-320 aircraft, registration G-MEDA operating as flight number LAJ 6711 on a flight from Alexandria (Bourg-el-Arab), Egypt, to Addis Abeba, Ethiopia, carried out two approaches using the Addis Abeba VHF Omni-Directional Radio Range beacon (ADS VOR) and associated Distance Measuring Equipment (DME). On the second approach the aircraft crossed over a ridge of high ground in Instrument Meteorological Conditions (IMC) and came within 56 ft of terrain at a location 5 nm to the northeast of the airport. As the aircraft crossed the ridge the crew, alerted a few seconds earlier by a radio altimeter (RA) height callout, carried out a go-around; at the same time the Enhanced Ground Proximity Warning System (EGPWS) generated a 'TOO LOW TERRAIN' aural alert

The investigation determined that the antenna of the ADS VOR had suffered water ingress and was not functioning correctly. The correct maintenance procedures for the ADS VOR/DME and its associated monitoring equipment were not followed.

The aircraft received erroneous information from the ADS VOR which was fed to the flight deck VOR display, the Flight Management System (FMS), the navigation displays and the EGPWS computer with its associated Terrain Awareness Display (TAD). A single common position source error thus adversely affected all these apparently independent navigation/situational awareness systems.

The existing certification standards for the aircraft navigation systems were met but were not sufficient to protect against this problem.

Six safety recommendations have been made.

1 Factual Information

1.1 History of the flight

The aircraft was operating a scheduled flight, which originated at London Heathrow Airport, carried out an intermediate stop en-route at Bourg-el-Arab Airport, Egypt, and continued to Addis Abeba Airport, Ethiopia. Two VOR/DME approaches and subsequent go-arounds were conducted at Addis Abeba following which the aircraft diverted to land at Djibouti Airport. The history of flight was compiled from information obtained from interviews with the flight crew, recorded data from the Quick Access Recorder (QAR), the EGPWS computer and Air Traffic Control (ATC) voice recordings.

1.1.1 En-route and descent

The commander was the handling pilot for the sector from Bourg-el-Arab to Addis Abeba Airport and for the subsequent diversion to Djibouti. During the final hour of cruise flight to Addis Adeba the aircraft navigation accuracy indicated 'LOW' on the FMS Multifunction Control and Display Unit (MCDU). As the aircraft neared the ADS VOR the navigation accuracy changed to 'HIGH'. The crew carried out a cross check of the aircraft position against the ADS VOR/DME to confirm that the FMS position was accurate. The crew also copied the following weather report from Addis ATC: 'Surface wind from 130° at 4 kt, rain, visibility 8 kilometres, broken cloud at 700 m, broken cloud at 2,400 m, temperature 14°C, dewpoint 12°C pressure 1029 mb. In addition, the aircraft’s weather radar indicated thunderstorm activity to the south and east of the airfield.

1.1.2 First approach and go-around

The aircraft was cleared for descent and for the ADS VOR/DME approach to Runway 25L (Figure 1). The commander selected ROSE VOR on his Navigation Display (ND), with the weather radar displayed, the co-pilot selected the NAV display on his ND with terrain information displayed. At 2315 hrs the aircraft passed overhead the ADS VOR at 13,500 ft amsl and turned outbound on the procedure while descending to 11,200 ft amsl. In order to establish on the 092º radial outbound the crew observed that an unexpectedly large heading correction to the left was required.

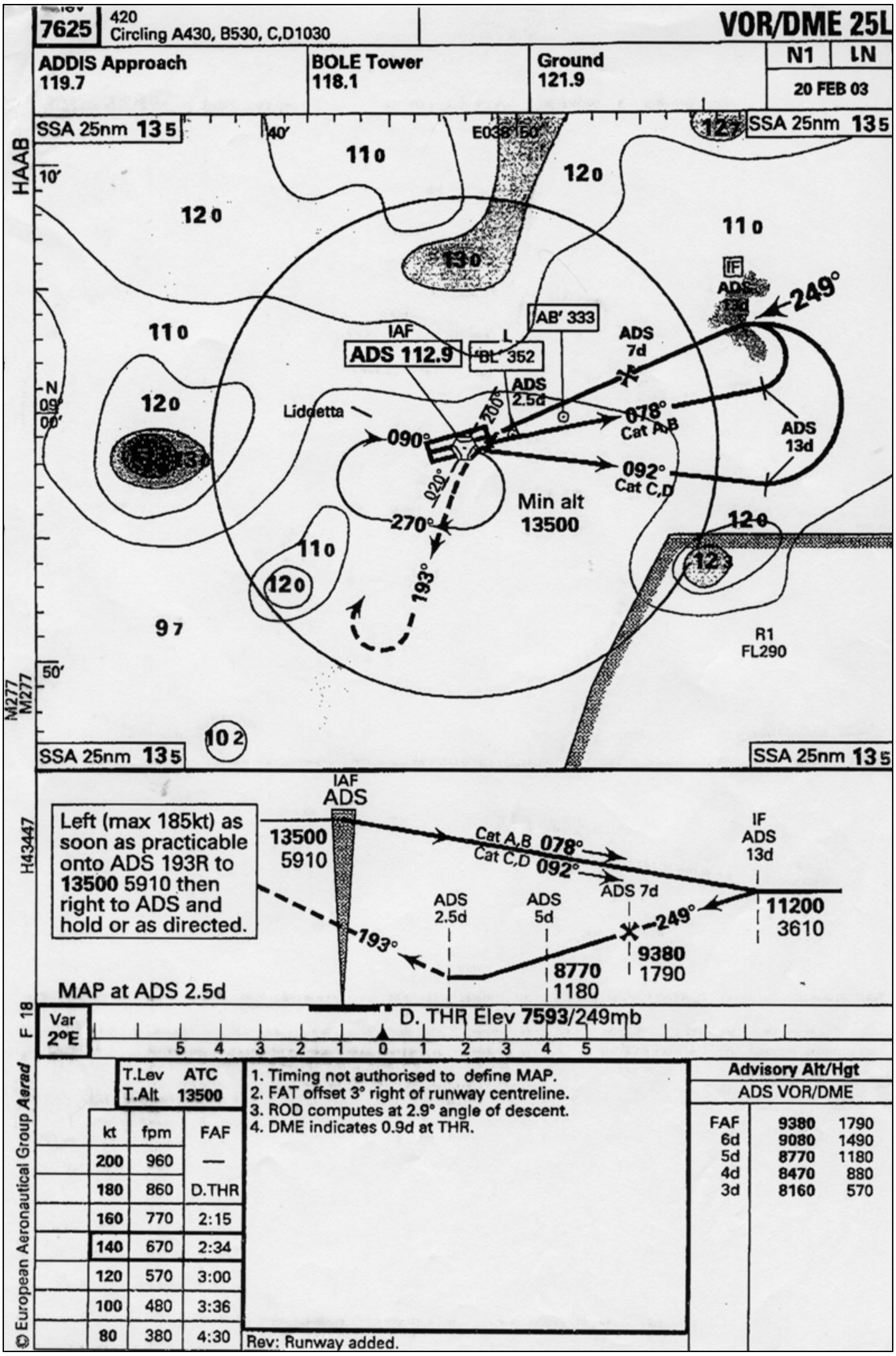


Figure 1
ADS VOR/DME approach plate

The autopilot was engaged throughout the approach. The inbound course was intercepted using track and flight path angle (TK/FPA); flap one and landing gear were selected down and descent commenced at 13 DME in accordance with the procedure. During the descent the crew observed some fluctuations of the VOR beam bar. They also noticed that the Automatic Direction Finder (ADF), tuned to the AB Non-Directional Beacon (NDB), was indicating that the aircraft was to the right of the approach course, however they disregarded this due to cumulonimbus (CB) activity indicated on the weather radar in the same direction. Visual contact with lights on the ground ahead was attained and further flap was selected, but the crew could not make a positive identification of the airport. The beam bar for the VOR on the ND then disappeared from view and the commander carried out a go-around with the aircraft at 1,200 ft above aerodrome level (aal).

The aircraft followed the published missed approach procedure and returned to the ADS VOR at 13,500 ft. As the aircraft crossed over the VOR the beam bar came back into view. A further check on the accuracy of the FMS map was carried out and was satisfactory. The crew then contacted ATC to check that the ADS VOR was serviceable. ATC confirmed that the VOR was serviceable, and it was also established that the ILS for Runway 25R was radiating. There were no approach charts available on the aircraft for this navigation aid, therefore the commander decided to carry out a further VOR/DME approach for Runway 25L.

1.1.3 Second approach

At 2329 hrs the aircraft overflew the ADS VOR and commenced a second approach. This was conducted in a similar method to the first but with the aircraft this time fully configured for landing by 11 DME on the inbound track. From the final approach fix at 7 DME the co-pilot cross checked the published advisory altitudes against the DME to ensure that the aircraft was maintaining the correct vertical profile. The commander heard a "ONE THOUSAND" auto callout and 11 seconds later at around 6 DME there was a "FOUR HUNDRED" auto callout which he also heard. He responded by saying "CHECK" as required by the company Standard Operating Procedure (SOP), but a short time afterwards realised that these height callouts did not correspond with the approach profile and commenced a go-around. The recorded data showed thrust increasing four seconds after the call of 400 ft. As he applied go-around thrust and started to pitch the aircraft nose up he heard an EGPWS "TOO LOW TERRAIN" aural alert. He increased the pitch attitude to a maximum recorded value of 15.1° nose up with an attendant normal acceleration of 1.5g. The go-around commenced at a height of 1,250 ft aal.

1.1.4 Go-around and diversion

The aircraft flew the published missed approach and joined the holding pattern at the ADS VOR. There was some further discussion with ATC as to whether the localiser was available for an approach to Runway 25R followed by a visual landing on Runway 25L. Although ATC confirmed that the localiser was operating the crew were unable to receive any signals from it. After one holding pattern the commander decided to divert to Djibouti.

At Djibouti the aircraft carried out an successful VOR/DME approach and landed at 0042 hours.

1.1.5 Subsequent return and landing

The following morning the flight returned to Addis Abeba. Before departure the crew carried out a full re-alignment of the Inertial Reference Systems (IRS) and disabled the ADS VOR radio updating function for the FMS. On arrival at ADS VOR the crew were able to maintain visual contact with the airfield and decided to allow the aircraft to follow the approach track in lateral navigation using the FMS. On the outbound leg they noticed that the ADS VOR indications showed that the aircraft was 22º off track to the south, even though the aircraft was on the correct track. Moreover, when established on the correct inbound track the VOR indications showed the aircraft to be 30º off track. Thus, whilst maintaining visual contact throughout with the runway they were able to confirm that the ADS VOR indications were in error and reported the fault to ATC.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	-	-	-
Serious	-	-	-
Minor/none	8	67	-

1.3 Damage to aircraft

None

1.4 Other damage

None

1.5 Personnel information

1.5.1 Flight Crew

Commander:	Male, aged 40 years	
Licence:	Airline Transport Pilot's Licence	
Licence Proficiency Check:	Valid until 31 December 2003	
Operator Proficiency Check	Valid until 30 June 2003	
Annual Line Check:	Valid until 29 February 2004	
Medical certificate:	Issued 29 January 2003	
Flying experience:	Total all types:	4,798 hours
	Total on type:	1,562 hours
	Total last 28 days:	66 hours
	Total last 24 hours:	10 hours

The commander had visited Addis Abeba on a number of previous occasions as detailed below in Table 1.

Date	Type of approach
8 October 2001	VOR
18 February 2002	Localiser
20 May 2002	ILS
1 July 2002	Localiser
2 September 2002	Localiser
12 September 2002	Localiser
14 October 2002	ILS
11 November 2002	VOR
16 January 2003	VOR

Table 1
History of commander’s previous visits to Addis Abeba

Co-pilot:	Male, aged 32 years
Licence:	Airline Transport Pilot's Licence
Licence Proficiency Check:	Valid until 30 November 2003
Operator Proficiency Check	Valid until 31 October 2003

Annual line check:	Valid until 31 October 2003	
Medical certificate:	Class 1 issued 14 May 2002	
Flying experience:	Total all types:	4,000 hours
	Total on type:	1,800 hours
	Total last 28 days:	57 hours
	Total last 24 hours:	10 hours

1.5.2 Flight crew duty time

On duty:	1200 hrs on 31 March 2003
Preceding rest periods	Commander 71 hours / Co-pilot 49 hours
Available flight duty period	12 hours 15 mins

The flight crew reported for duty at 1200 hrs on 31 March 2003 for a planned two sector duty day, the approaches to Addis Ababa occurred on the second sector. At the time of the incident the crew had completed 11 hrs 38 mins of their flight duty period.

1.5.3 Crew reports

Because he had carried out the two go-arounds and received an EGPWS alert the commander filed an Air Safety Report through his company safety reporting system immediately after landing. He also provided a more detailed follow up report on his return to the United Kingdom. The crew remained unaware of the closeness of the proximity of the aircraft to the ground until the data from the Quick Access Recorder was replayed by the operator as part of their Flight Operations Quality Assurance (FOQA) programme.

Both pilots were interviewed in the United Kingdom (UK) some ten days after the incident. They each had a good recollection of the events as represented in the history of flight.

The commander reported that the significant event which alerted him to carry out the go-around was the "FOUR HUNDRED" auto callout. He did remark however that a short period of time elapsed before he recognised and responded to this cue that all was not well.

1.6 Aircraft information

1.6.1 General information

The Airbus A320 aircraft utilises a fly-by-wire, electronically managed, flight control system. At the heart of the system are computers that convert the pilot's commands into electrical impulses delivered to the control surfaces. The commands to the control surfaces are monitored to ensure the aircraft is kept within a safety margin; this is called the 'flight protection envelope'. Thus, the pilot can get the maximum performance out of the aircraft in an emergency without the risk of exceeding the flight envelope or over-stressing the aircraft. For a terrain avoidance pull-up manoeuvre the pilot is required to disconnect the autopilot, select and maintain full back stick pressure and apply Take Off / Go Around (TOGA) thrust.

The aircraft G-MEDA was manufactured in 1994, serial number 0480. In 1998 the aircraft was fitted with a Honeywell EGPWS. The aircraft was not equipped with a Global Positioning System (GPS) receiver.

The Flight Warning Computer on G-MEDA was configured to give automated call outs in the following sequence during an approach "2,500, 1,000, 400, 100, 50, 40, 30, 20, RETARD and 10"

The aircraft was fitted with 124 passenger seats

Actual Take Off Mass (TOM)	65,578 kg
Maximum TOM	73,600 kg
Actual Zero Fuel Mass (ZFM)	51,778 kg
Maximum ZFM	60,500 kg
Calculated mass at second go-around	55,900 kg

1.6.2 Aircraft systems

The aircraft systems pertinent to this incident are the FMS, the NDs, and the Terrain Awareness Warning System (TAWS), which, in this instance was a Honeywell EGPWS.

1.6.2.1 Flight Management System

The FMS provides navigation and performance information to the crew. The system comprises two Flight Management Guidance Computers (FMGC), two Multipurpose Control and Display Units (MCDU), two Primary Flight Displays

(PFD) and two NDs. Pilot inputs to the system are through the MCDU and various display options are available on the ND.

A full description of the navigation function of the FMS is included at section 1.8 of this report.

1.6.2.1.1 Navigation Display

The ND has a number of different displays of navigation information available for the pilot. In ROSE NAV or ARC mode a horizontal moving map is displayed, in ROSE VOR mode a lateral deviation pointer is displayed when bearing data is available. When the bearing data is not valid the beam bar disappears and a red VOR flag flashes.

Either weather radar or Terrain Awareness Display (TAD) can be selected on an individual ND. Weather radar information and terrain are both displayed relative to the nose of the aircraft. The weather display is derived from sensors looking ahead of the aircraft, whereas the TAD represents a prediction of the probable terrain using positional information derived from FMS 1.

1.6.2.2 Terrain Awareness and Warning System

Ground proximity warning system (GPWS) installations on aircraft have been effective, in the past, in preventing some accidents involving controlled flight into terrain (CFIT). GPWS Mode 2 is the feature which alerts the crew to an excessive terrain closure rate. However a weakness of the GPWS is that it has no look ahead function, so that if an aircraft is flying towards steeply rising terrain the system may not be able to detect it in time for an escape manoeuvre to be performed. This shortcoming has been recognised for many years and new systems have now been developed which give an aircraft a predictive capability. This is achieved by comparing the aircraft position with on board databases of terrain and runways. The first such system developed was the Honeywell EGPWS, the general term for all these systems is now Terrain Awareness and Warning Systems (TAWS).

TAWS is thus the onboard safety net designed to detect a variety of CFIT threats. The system deals with the CFIT threats relevant to this incident in a number of ways:

- Mode 2 classic GPWS alerting - an alerting algorithm that uses the radio altimeters to look below the aircraft and provide an alert when the rate at which terrain clearance is reducing is too high for a given terrain clearance.

- Premature Descent Alerting (PDA) - an alerting algorithm that uses a runway database, radio altimeter and aircraft positional information to provide an alert when the aircraft is too close to the ground in relation to the distance to the nearest runway.

- Forward Looking Terrain Avoidance (FLTA) - an alerting algorithm that uses databases of terrain and runways, together with aircraft position and heading data, to look forward of the aircraft and provide an alert to terrain hazards without physically sensing ahead of the aircraft.

- Terrain Display - a display of the terrain ahead of the aircraft, colour coded relative to aircraft height, to improve crew situational awareness.

Standards and certification

The minimum performance standards of the TAWS equipment were defined by Federal Aviation Administration (FAA) document TSO-C151b. Subsequently the Joint Aviation Authorities (JAA) issued a virtually identical document, JTSO-C151 and later the European Aviation Safety Agency (EASA) published ETSO-C151a. There is little difference between these documents and they will be referred to as 'the TSO' for the purpose of this report. These performance standards stipulate minimum alert times for given scenarios and stress the need to avoid nuisance alerts.

The certification of the TAWS aircraft installation was guided by the JAA document "*Section One: General Part 3: Temporary Guidance Leaflets LEAFLET NO 12: Certification Considerations for the Terrain Awareness Warning System: TAWS*." – referred to as TGL12. This allowed the use of the aircraft navigation system, which was designed for area navigation, to be the source of positional information for the TAWS. The capabilities of such area navigation systems vary from very poor to very good. There are no minimum positional accuracy requirements imposed on the source of positional information for TAWS, other than by reference to relatively relaxed area navigation requirements, and no requirements to supply TAWS with relevant indicators of navigational data quality. There is no requirement to have GPS as a source of positional information for the TAWS. The standard GPWS alerts, pre-TAWS, are viewed as fall back protective modes in the event of a failure of the new TAWS database based modes.

This aircraft (G-MEDA) was a non-GPS equipped aircraft. Its area navigation system had an allowable equipment cross track error of 0.5nm (with 95% probability) when using VOR/DME collocated at the supported airfield, and 0.3nm when using other equipment.

The aircraft was fitted with an EGPWS. The actual performance of the system that was fitted to the aircraft at the time is defined in the associated Honeywell document, "Product Specification for the Enhanced Ground Proximity Warning System, DWG No. 965-0976-6093 rev M".

Mode 2 implementation

Mode 2 is divided into modes 2A and 2B in order to allow terrain closure during landing without degrading take-off or cruise alerting capabilities. During this incident the aircraft was configured for landing, so the less sensitive mode 2B was active.

The current standards for mode 2 were set in the 1970s under RTCA/DO-161A. This provided nominal alert envelopes and allowed deviation from these to cope with radio altimeter problems that would otherwise trigger nuisance alerts. The equipment manufacturers placed considerable effort into achieving a balance between useful alert times and counterproductive nuisance alert rates. One of the main means of achieving this is by adjusting the complex filtering of the input signal to reduce alerts triggered by spurious signals. In practice no acceptable balance has yet been achieved within the RTCA/DO-161A parameters.

The mode 2 limitations to GPWS, amongst others, were influential in the development of the enhanced features introduced with EGPWS.

In later standards of EGPWS software, triggers other than flaps are used to push mode 2 to the less sensitive mode 2B and this mode is also desensitised from the original DO-161A standard. This occurs when the look ahead system is operating with a high level of confidence (reference document 965-0976-603 rev M). Another manufacturer of TAWS equipment, suppresses modes 1 and 2 entirely whilst the look ahead system is fully operational. This is a design 'feature' to reduce nuisance alerting.

Honeywell reviewed the recorded data and were satisfied that mode 2B was operating in accordance with its design criteria; that is that the necessary rate filtering prevented an alert in this case.

Premature Descent Alerting (PDA) implementation

PDA is a new TAWS alerting mode targeted to overcome the limitation of mode 2 that allows a properly configured aircraft to land even where there is no runway. Terrain Clearance Floor (TCF) is the Honeywell term for PDA. TCF combines information on the aircraft location and terrain clearance (radio altitude), with reference to a database of all usable runways, to provide an alert when an aircraft is too close to terrain when not close enough to a runway. Triggering the alert yields a 'TOO LOW TERRAIN' aural alert with an associated red visual display. The generic TCF standard, as applicable to the EGPWS software standard fitted, is presented in Figure 2. The actual distances applicable at Addis Abeba are presented in Figure 3.

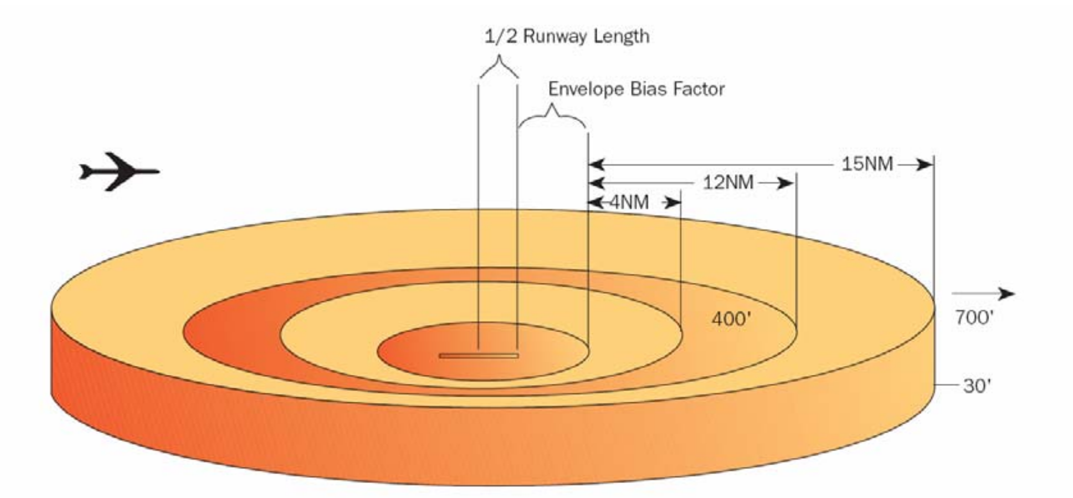


Figure 2

Honeywell TCF alert envelope for the standard of EGPWS fitted. This alerts against insufficient terrain clearance for any given distance form the runway.

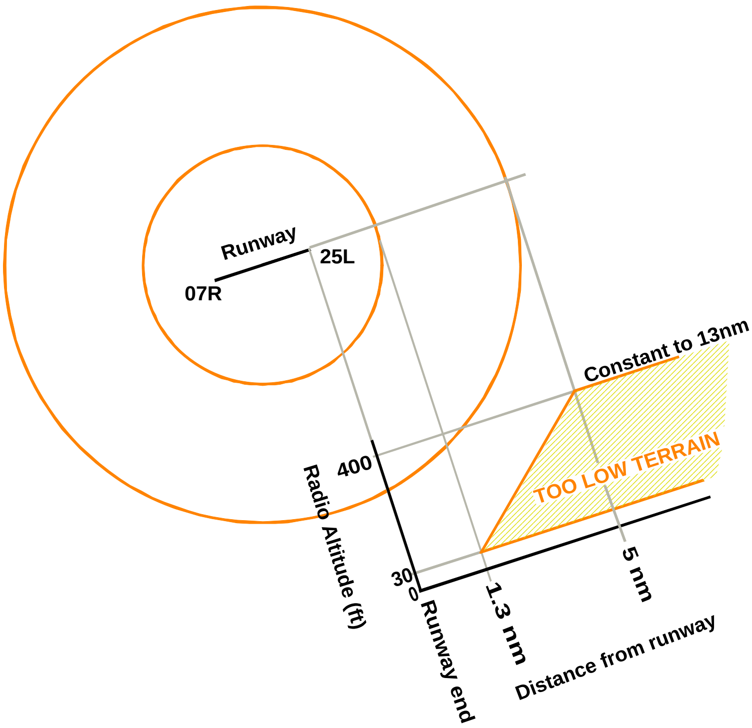


Figure 3

Honeywell TCF as applicable to the incident aircraft EGPWS installation and the location

When provided with direct GPS together with the latest software, one of the effects is to move the TCF envelopes closer to the runway, providing more protection close to the airport.

The standards for PDA are described by the intent of the alert mode but do not prescribe alert envelopes or methods. The effectiveness of the TCF alert mode depends on the accuracy of the runway database, radio altimeter sensors and aircraft position data.

Forward Looking Terrain Avoidance (FLTA) implementation

Improved memory technology made it possible to store within the EGPWS a database of global terrain elevation. The EGPWS uses algorithms that test the terrain database ahead of the aircraft with reference to aircraft position, heading and speed. However, whilst allowance is made for some navigation error, the effectiveness of this alert mode depends on the accuracy of these parameters. This overcomes the limitations with classic GPWS of short alert times by providing alerts up to 60 seconds ahead of a potential conflict. An illustration of the alert algorithms is shown in Figure 4.

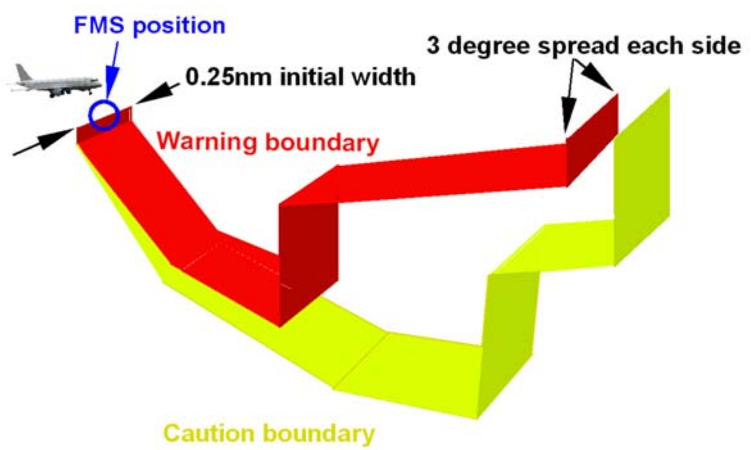


Figure 4

Illustration of the Honeywell algorithms for FLTA that “fly” ahead of the aircraft looking for terrain (not to scale). The geometry varies by aircraft type, configuration and flight parameters

The TSO provides test conditions for the look ahead alerting in Appendix 3 of the TSO. During this incident the aircraft was in the Terminal area as defined by the document and descending therefore the relevant test requirements are defined by section 1.4 of Appendix 3. Table C of that Appendix gives the maximum and minimum alerting times to ensure a level off can be carried out with sufficient terrain clearance, this is reproduced in Figure 5.

TABLE C

Terminal Descent Area Alerting Criteria					
A	B	C	D	E	F
VERT SPEED (FPM)	ALT LOST WITH 1 SEC PILOT DELAY	ALT REQ'D TO L/O WITH 0.25G	TOTAL ALT LOST DUE TO RECOVERY MANEUVER	MINIMUM TAWS WARNING ALERT HEIGHT (ABOVE TERRAIN)	MAXIMUM TAWS CAUTION ALERT HEIGHT (ABOVE TERRAIN)
1000	17	17	34	334	700
2000	33	69	102	402	900
3000	50	156	206	506	1100

Figure 5

Extract from JTSO-C151a Appendix 3 Table C. Maximum and minimum alert heights when descending in the terminal area

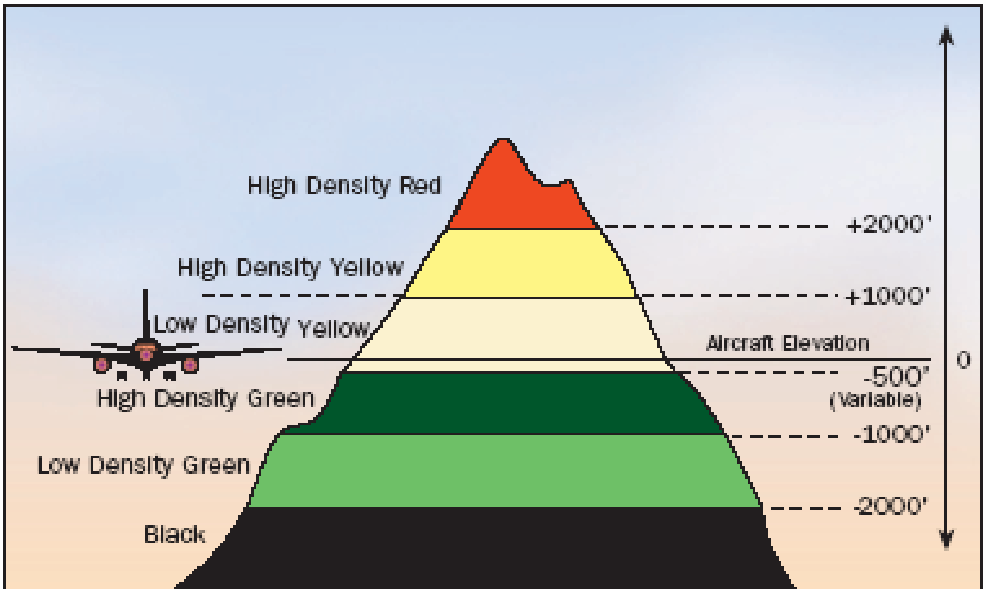
Terrain display implementation

The terrain display uses the same parameters as the FLTA protection described above but instead of using alert algorithms to detect threats, the terrain is displayed to improve the situational awareness for the pilot. Figure 6 and Figure 7 illustrate the terrain display.

The certification requirements state that the probability of providing misleading information should be less than 1 X 10^{-5} per flight hour. However, this requirement does not include external error sources such as incorrect information from a VOR. The conditions under which the display would be considered misleading are not defined and so it is difficult to measure performance against the requirement.

System performance objectives

TGL 12 certification objectives are shown in Figure 8. These were created before any TAWS mandates were in force. In order to keep the costs of the voluntary installation viable, the objectives were interpreted so that not all the limitations of the systems providing TAWS with data were included in the assessment of the objectives. To have included all external influences would have required GPS to be fitted, significantly increasing the costs of installation and so reducing the number of systems being fitted.



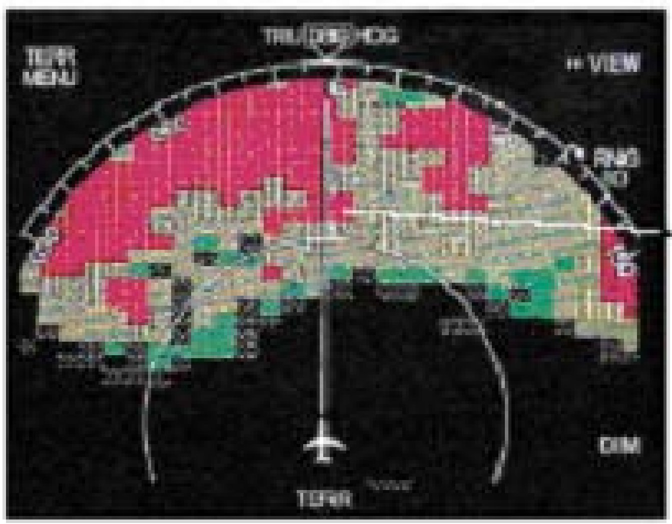
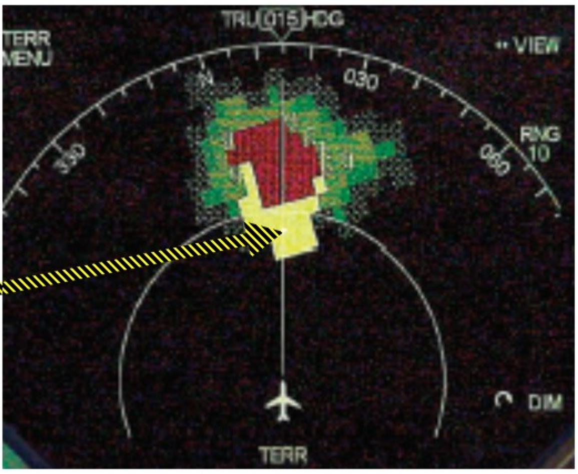


Figure 6
Terrain Display colour coding - no alert (not Airbus display)

CAUTION
60 seconds from projected impact.

The terrain in high-density red is high enough, relative to the aircraft, to show it as high density red but has not yet penetrated the warning boundary and so is not solid red.

The terrain that has been encountered by the caution boundary is highlighted in solid yellow.



WARNING
30 seconds from projected impact.

The terrain in solid red has been encountered by the warning boundary of the EGPWS.

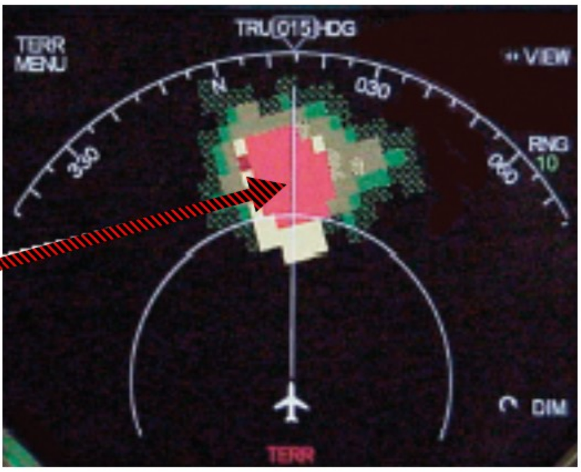


Figure 7

Terrain display - illustration of a reaction to alerts (not Airbus display)

4 CERTIFICATION OBJECTIVES

4.1 The probability of failure of the installed system to perform its intended function from a reliability and availability perspective shall be shown to be no greater than 1 X 10^{-3} per flight hour.

4.2 The probability of failure of the system to provide the required aural and visual alerting functions without a failure indication shall be shown to be no greater than 1 X 10^{-4} per flight hour.

4.3 The probability of false alerts due to a failure of the system when no terrain hazard exists shall be shown to be no greater than 1 X 10^{-4} per flight hour.

4.4 The probability of failure of the terrain display alone shall be shown to be no greater than 1 X 10^{-3} per flight hour.

4.5 The probability of displaying misleading information on the terrain display without a failure indication shall be shown to be no greater than 1 X 10^{-4} per flight hour.

Note 1: This level of integrity does not allow the terrain display system to be used for navigational purposes.

Note 2: Database errors need not be considered in this assessment. Database integrity aspects are addressed in EUROCAE 76 / RTCA DO-200A, See section 9.

4.6 The probability of nuisance alerts when the system is functioning in accordance with its specification but when no terrain hazard exists, should be minimised. To avoid loss of crew confidence in the system, the probability of nuisance alerts should be shown to be less than 1 X 10^{-4} per flight hour.

Figure 8

TGL 12 certification objectives

1.7 Meteorological information

The meteorological report received by the crew prior to commencing the first approach at Addis Abeba was as follows:

> *Surface wind from 130º at 4 kt, rain, visibility 8 km, broken cloud at 700 m, broken cloud at 2,400 m, temperature 14ºC, dewpoint 12º C and pressure 1029 mb.*

The crew reported that the weather radar indicated thunderstorm activity to the south and east of the airfield. Local night commenced at 1605 hrs.

1.8 Aids to navigation

1.8.1 General

At the time of the incident Addis Abeba Airport was equipped for ADS VOR/DME approaches to Runway 25L (frequency 112.9 MHz), and daylight visual approaches to Runway 25R. There was a localiser installation for Runway 25R but it was not promulgated in the active Aeronautical Information and Control (AIRAC) cycle and neither approach charts nor frequencies for it were available on the aircraft. (The AIRAC cycle for documentation is designed to ensure the co-ordinated publication of information is achieved using a common set of internationally agreed dates for provision, distribution and effective dates.) An ILS was in the process of being installed for Runway 25L but had not yet been commissioned. There was a published GPS approach for Runway 07R however the aircraft was not fitted with a GPS and at the time GPS approaches had not been approved by the United Kingdom (UK) Civil Aviation Authority (CAA). There were two NDBs, AB (333 KHz) and BL locator beacon (352 KHz), which were located respectively at 3 nm and 0.5 nm on the extended centreline of Runway 25R. The crew had the AB NDB tuned, identified and displayed on the ND.

1.8.2 Non directional beacons

NDBs are subject to a number of errors one of which is as a result of electrical interference associated with thunderstorms.

The aircraft was fitted with two ADF receivers for NDBs; the FMS navigation system does not use NDB data.

1.8.3 VOR/DME information

The DME systems calculate the distance between the aircraft and the ground station and the VOR systems calculate the relative bearing of the aircraft from the ground station. These two pieces of information are provided to the crew and to the aircraft navigation systems and are combined to give the position of the aircraft. In this case the DME was located on the top of the VOR antenna assembly in the VOR/DME antenna protective housing.

There are two types of VOR, a Doppler VOR (DVOR) and a Conventional VOR (CVOR). The methods used to generate the reference and rotating signals are different but this difference is transparent to the receiver. The VOR at Addis Abeba was a CVOR.

The VOR transmits two signals. One is a reference signal that is transmitted uniformly around the ground station. The other signal is rotated 30 times a second. The difference in phase of the two signals at any point around the ground station will equate to the bearing of the receiver relative to the ground station.

The CVOR ground station uses a stationary four slot antenna for transmitting both the stationary and rotating signals. The four slots are spaced at 90 degrees to each other, one each in the north-east, south-east, south-west and north-west positions. The four antenna slots are driven with the reference signal and opposite antenna pairs are driven with two varying signals. The antenna radiation patterns combine in space to produce the required stationary reference signal and the rotating signal. The antenna assembly is protected from the elements within a waterproof housing. The reference signal and the two varying signals for the antenna pairs are generated in the ground station main building and coupled to the antenna via capacitors.

1.8.4 ADS VOR Installation

The ADS VOR/DME installed at Addis Abeba airport was a Wilcox 585B Conventional VOR (CVOR). The VOR consists of a building containing the electronics with a large ground plane mounted on top and the antenna, with radome, on top of that. Figure 9 contains a photograph of the ADS VOR/DME installation.

A few weeks prior to this incident the ADS VOR antenna radome had been accessed during a programme of work to fit a new DME. This required that the protective housing be removed from the around the antenna assembly and later re-instated and resealed against water ingression. The first heavy rainfall following this work was on the night of 31 March 2003.

Figure 9
ADS VOR antenna radome on top of the ground plane

Physical inspection of the ADS VOR ground station, in the days after the incident involving G-MEDA, revealed water ingress in the capacitors used to couple the signal generators to the antennas. It was reported that the impedance matching capacitor of the NE/SW variable signal was full of water; the affected area was cleaned and dried. A transistor in the control unit was also found to be faulty and was replaced. Changing the characteristics of one of these capacitors will affect the power output and/or phase of the varying signal used to drive the corresponding antenna pair. Figure 10 illustrates the effects of changing the power and phase of the NE/SW antenna signal. The errors generated by these types of faults are not uniform. For some bearing ranges, large changes in actual bearing will result in relatively small changes in the bearing sensed at the aircraft.

There was little deviation from ADS VOR bearing of 069º (heading 249º) observed by the crew on either approach during the incident flight, though there were intermittent signal failure indications. As the flight was at night and in poor weather, there were no external visual cues when these observations were made.

The day after the incident, with the aircraft outbound from the ADS VOR on a heading of 092º, the crew observed a 22º error. With the aircraft inbound on a heading of 249º, a VOR error of 30º was observed. The crew made these observations when in good visual contact with the runway and the surrounding terrain. These errors were reported to ATC.

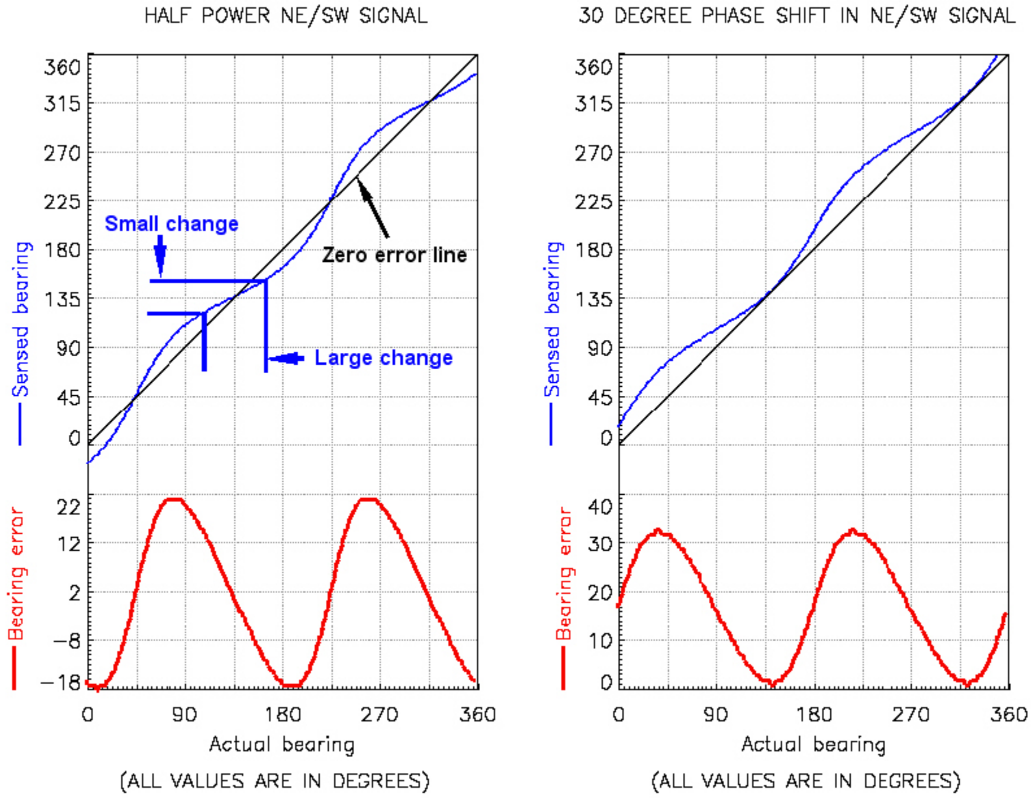


Figure 10

Simplistic models of VOR behaviour with altered signal power and phase for the NE/SW VOR signal

The sealant used on the antenna assembly had been supplied by a contracting firm and was established to have been of an incorrect type; the sealant was replaced. Technicians used a hand-held receiver to test the signal strength, identification and navigation guidance of the ADS VOR. This test indicated normal operation; however, since the test was not conducted from a surveyed position the accuracy of the ADS VOR could not be determined. A serviceability report was requested from an aircraft in flight, which confirmed that the ADS VOR was operating.

The Ethiopian CAA has the required inspection equipment for flight checking navigation aids, but does not have a dedicated aircraft to carry such equipment. The CAA has an arrangement with the Ethiopian Air Force to provide an aircraft for scheduled flight inspections of navigation aids; however, this did not extend to unscheduled post-maintenance inspections. Therefore, no post-maintenance calibration flight check was conducted.

1.8.5 VOR monitor systems

Monitor systems are in place to detect errors in the signals, alert the airfield authorities of such problems and switch to alternative signal drivers or switch the navigation aid off.

The standards regarding VOR monitoring of ground stations are given in ICAO Annex 10, VOLUME I, PART I, section 3.3.7. This states the following:

"3.3.7.1 Suitable equipment located in the radiation field shall provide signals for the operation of an automatic monitor. The monitor shall transmit a warning to a control point, and either remove the identification and navigation components from the carrier or cause radiation to cease if any one of a combination of the following deviations from the established conditions arises:

a) a change in excess of 1 degree at the monitor site of the bearing information transmitted by the VOR;

b) a reduction of 15 per cent in the modulation components 0of the frequency signals voltage level at the monitor of either the subcarrier, or 30 Hz amplitude modulation signals, or both..

3.3.7.2 Failure of the monitor itself shall transmit a warning to a control point and either;

a) remove the identification and navigation components from the carrier; or

b) cause radiation to cease."

It was reported that cables associated with the ADS VOR monitor system, which ran across the airport, had been severed during construction work rendering the monitoring system inoperative.

1.8.6 Aircraft navigation systems

The aircraft was equipped with FMGCs which contain FMS navigation functions. One of the FMS functions is to combine the outputs of various positional sensors to provide a consolidated horizontal aircraft position to the pilot and aircraft systems. How an FMS does this varies according the FMS and aircraft type, and also with aircraft equipment and unit serviceability. This description is only relevant to the installation as it was configured at the time of the event.

On G-MEDA the FMS uses data from three Inertial Reference Systems (IRS), which measure aircraft attitude and accelerations to determine its position, in conjunction with various radio navigation aids. GPS data was not available on the aircraft. The FMS applies various reasonableness checks to select the data sources most likely to provide the best position fix. These are then smoothly combined to drive the cockpit NDs and other aircraft systems where navigation data is required.

In simple terms inertial positions are always available but errors build up slowly over time between the sensed position and the actual position. These errors are in random directions relative to the actual position of the aircraft. Mixing multiple sources means that some of the directional errors cancel each other out, so three independent inertial sources are mixed to provide a triple-mix inertial position.

The triple mix inertial position is always available and only builds up errors slowly; therefore this is used in conjunction with an error correction bias as the FMS position. When other positional information, such as a radio update, is available, the FMS updates the error correction bias. When new information indicates that the bias needs to be amended, rather than jump the calculated position of the aircraft to the new location, it is slowly slewed to the new location by altering the bias to a new target value. The rate of change of the bias is dependant on altitude; at the altitudes involved in this incident, the FMS will take 2 minutes to slew the bias from the old value to the new one. This is illustrated in Figure 11.

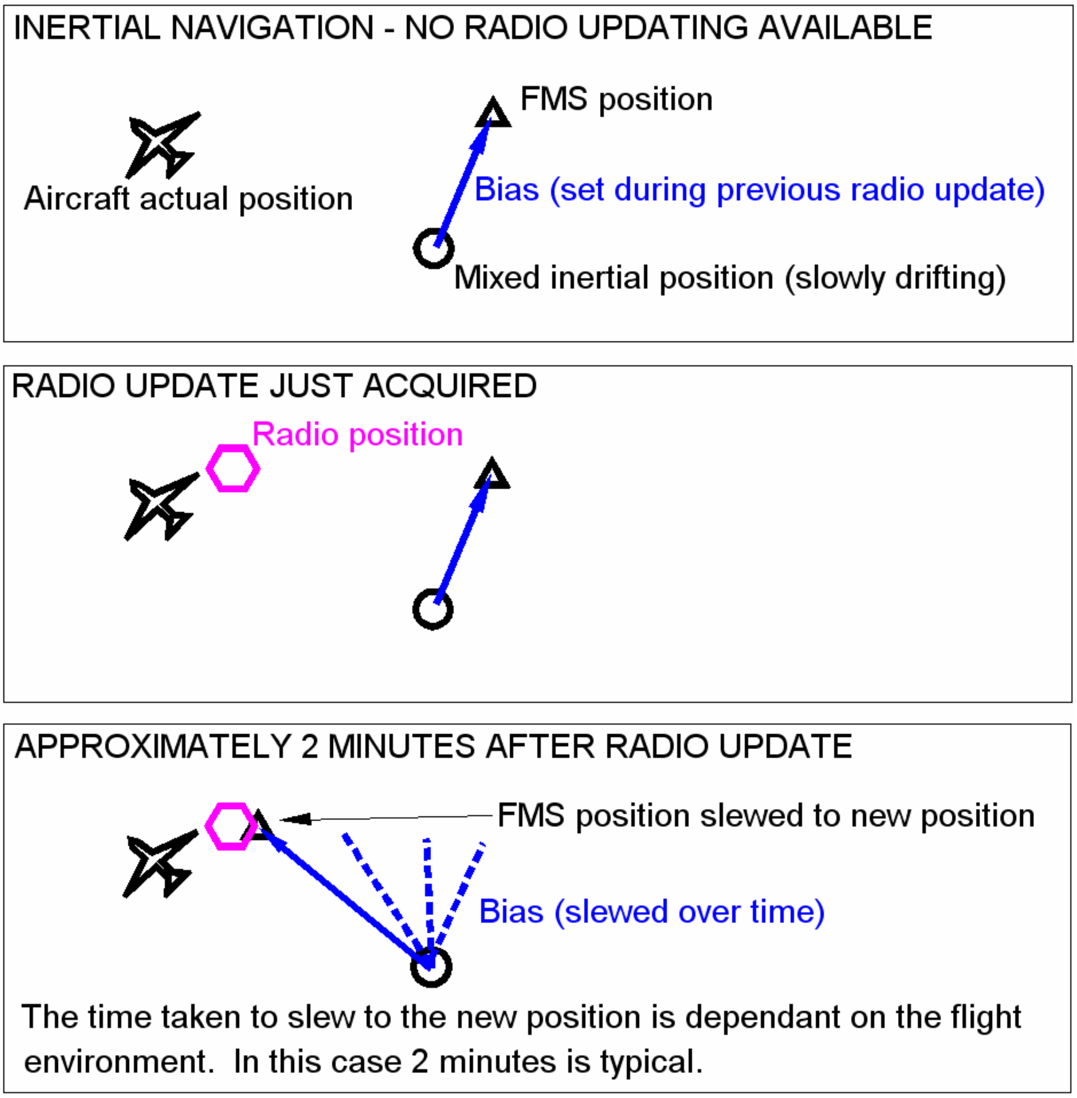


Figure 11
FMS navigation

Before any source is incorporated into the solution of the current position, reasonableness checks are carried out. Each type of source has an estimated position error (EPE) model associated with it. The EPEs of inertial positions increase with time. The EPE models for VOR and DME data are both dependant on distance to the source, though to different degrees. In order to update the inertial bias, once a source of data is assessed as being the best source, it is used to the exclusion of other sources, having already been subject to reasonableness checks against these other sources. Thus, the navigation solution is dependent upon the inertial performance and the bias updating source.

The FMS calculated EPE is not displayed to the crew but it is compared with the position accuracy requirements as defined by airworthiness authorities for the applicable flight area and displays the results on the MCDU as 'HIGH' or 'LOW' navigation accuracy. The Flight Crew Operating Manual (FCOM) includes the following note of caution;

> *''HIGH' or 'LOW' indicates the FM position accuracy based upon estimated error. This is why the flight crew must check the position"*

The procedure provided for the crew to cross check their position is the navigation accuracy check:

> *'In descent and terminal approach areas validate the estimated accuracy, whether it is 'HIGH' or 'LOW', by comparing the FM data with raw data from the VOR/DME at the destination airfield'*

and further

> *'This check verifies and quantifies the FM accuracy.'*

There is a zone of confusion (ZOC) around and close in to navigation aid ground stations in which the FMS cannot use the navigation aid; this avoids poor slant range geometries.

There are many different FMS types in use today and these are installed with a wide variety of radio tuning capabilities and limitations. There are minimum standards for FMS navigation performance with different radio aid sources available. The systems are designed to navigate an aircraft between a procedural departure and arrival, and this has historically been a relatively benign environment; however, the system is now being used increasingly outside of this design intent. In this instance it has been used as the source of positional information for the TAWS, which is guarding against threats at low altitude where the FMS has the least number of radio aids in sight. The FMS is also not designed to provide an alerting function to crew of detected problems with radio aids.

1.8.7 Publications

Relevant, up to date, commercial en-route charts and terminal approach plates were available on the aircraft. The approach chart in use for ADS VOR/DME 25L (see figure1) included a table of advisory altitude/range comparisons from the FAF at 7 DME to a final check at 3 DME, which equated to a 2.9º angle of descent. The published minima for the approach were 8,020 ft MDA (420 ft aal) and 1,600m RVR.

Under Article 37 of ICAO each State is responsible for the publication of Aeronautical Information through its own Aeronautical Information Service (AIS) in compliance with adopted Standards And Recommended Practices (SARPS). Requirements for Notice to Airmen (NOTAM) are published in ICAO Annex 15 as follows:

> *'5.1.1.1 A NOTAM shall be originated and issued concerning the following information:*
>
> *c) establishment or withdrawal of electronic and other aids to air navigation and aerodromes/heliports. This includes: interruption or return to operation, change of frequencies, change in notified hours of service, change of identification, change of orientation (directional aids), change of location, power increase or decrease amounting to 50 per cent or more, change in broadcast schedules or contents, or irregularity or unreliability of operation of any electronic aid to air navigation, and air-ground communication services'*

There was no NOTAM published regarding the serviceability of the ADS VOR either before the incident or subsequent to the incident.

1.9 Communications

Recordings of the communications between Addis ATC and the aircraft were available for the investigation, although the quality was poor and some words were unintelligible. A transcript of the communications during the two approaches is at Appendix 1.

1.10 Aerodrome information

The city of Addis Abeba is located on the central Ethiopian plateau. The airfield is located some 4 km to the south-south-east of the city and is situated at an elevation of 7,625 ft (2,325 m). There is high ground rising all around the airport, the sector safe altitude within 25 nm is 13,300 ft in each quadrant. There are two parallel runways: R25L/07R, which was 3,800 m long and 45 m wide; and R25R/07Lwhich was 3,700 m long and 45 m wide. Runway 25L/07R was recently constructed and first opened for use in October 2002. At the time of the incident there were several areas where construction work was in progress around the airfield.

A copy of the airfield (D1) chart is reproduced at Figures 12. The position of the ADS VOR relative to the runways is depicted incorrectly on chart D1; the ADS VOR was in fact located to the south of both runways.

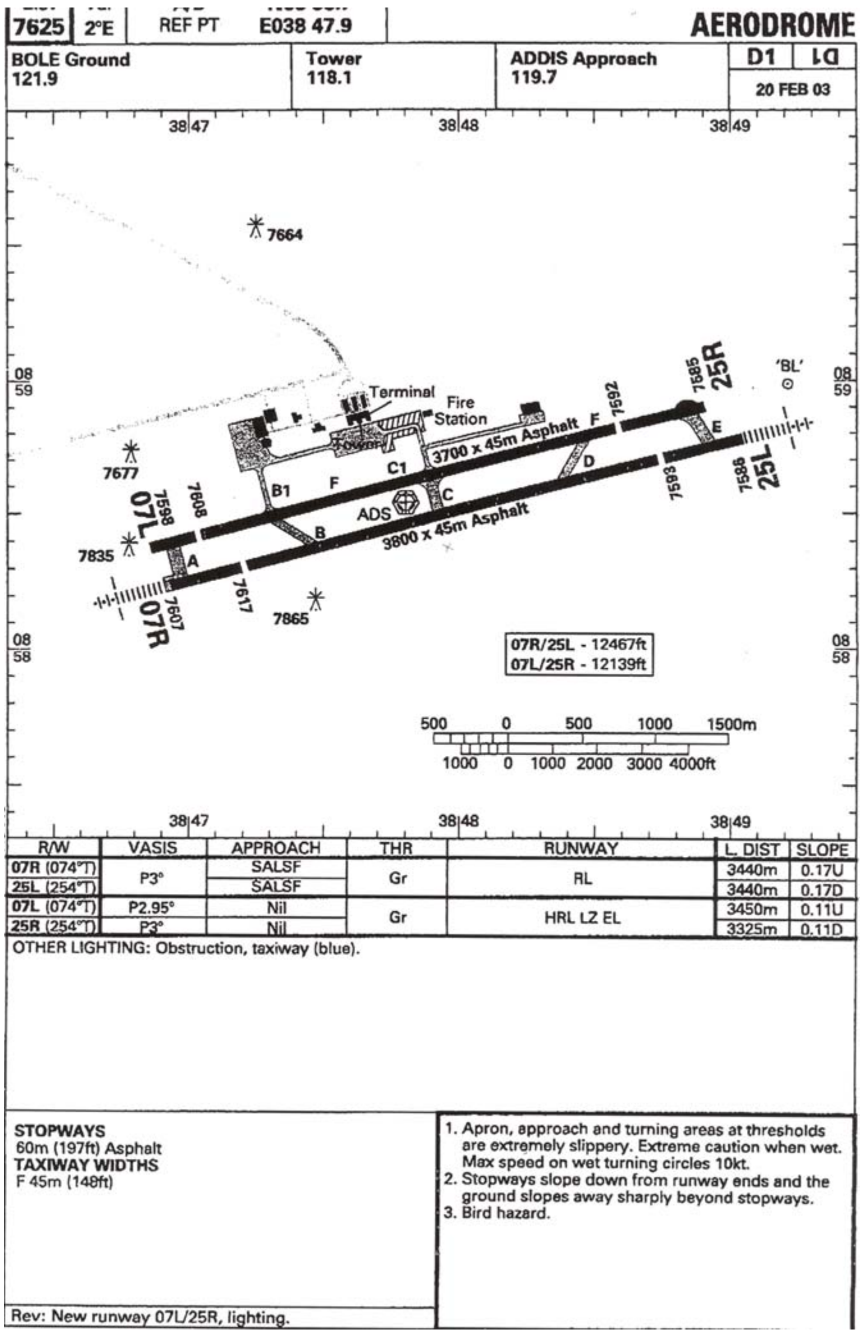


Figure 12
Addis Abeba aerodrome chart D1

1.11 Flight recorders

1.11.1 Sources of data

The aircraft was equipped with a Cockpit Voice Recorder (CVR) and a Flight Data Recorder (FDR). However, because the seriousness of the incident was not realised at the time both CVR and FDR data for the incident flight were overwritten before the investigation was initiated.

Other sources of data were available on the aircraft. A Quick Access Recorder (QAR) was installed which provided a record of more than 200 parameters recorded over a period of approximately 20 hours. A subset of these was decoded for the purpose of this investigation. Parameters not recorded that would have been of interest include VOR bearing and autopilot modes.

Another important source of data was the EGPWS, which records a number of parameters surrounding an EGPWS alert. The parameters recorded include data sources as well as internally calculated parameters. The record covered the period between 20 seconds prior to the initial alert and 10 seconds after the event ceased, with each parameter being recorded once per second.

Given that the incident involved navigation errors, the recorded aircraft position was not reliable. A flight path was derived using recorded heading and speed parameters and incorporating inertial drift models. This was adjusted such that the terrain under the derived flight path correlated with the recorded radio altitudes.

1.11.2 Recorded data

The following description of events was derived from the QAR and EGPWS parameters. Times are recorded times in UTC.

The flight departed Bourg-el-Arab Airport, Egypt, at 1940 hrs. The aircraft climbed to a cruise altitude of FL370 heading initially south and then south-east. At 2305 hrs the aircraft commenced the descent to Addis Abeba.

The aircraft overflew the ADS VOR/DME, for the first time during the flight, at 2315 hrs. At this point the aircraft was at FL135 and was decelerating through a CAS of 280 kt. The autopilot was engaged. Figure 13 shows the derived flight path of the aircraft and the recorded FMS position for the arrival at Addis Abeba and the first approach and go-around. This is overlaid on the local terrain and the procedural vectors for the outbound and inbound segments of the approach. This shows that on the outbound segment of the procedure the FMS computed path departed significantly from the actual aircraft path. The difference between the two increased until a point on the outbound leg after which it remained relatively stable. During the outbound leg the aircraft's CAS stabilised at approximately 200 kt and the aircraft steadily descended, levelling at 11,200 ft amsl (approximately 3,600 ft aal) during the inbound turn. During the turn the CAS reduced to between 180 and 190 kt and flaps 1 was selected. As the aircraft completed the turn, a further descent was initiated at 1,000 fpm and the gear was selected down at 10,200 ft amsl. The autopilot was disengaged at 9,200 ft amsl and the rate of descent was reduced. Meanwhile, the terrain stated rising below the aircraft; 10 seconds after the autopilot was deselected the radio altitude was recorded at 688 ft. Flap 2 and then flap 3 were selected and the rate of descent was further reduced to approximately 200 fpm as the CAS dropped to 150 kt. 20 seconds after the point of minimum terrain clearance the thrust levers were advanced, followed a further 10 seconds later by the gear up selection as a positive rate of climb was achieved. Subsequently the autopilot was re-engaged and flaps 2 was selected.

When the aircraft was in the latter stages of the approach the difference between the derived path and the FMS path rapidly reduced.

The go-around was initiated at 2323 hrs with the lowest recorded terrain clearance of 688 ft. The relationship between the FMS and actual flight paths fluctuated to a lesser extend during the go around.

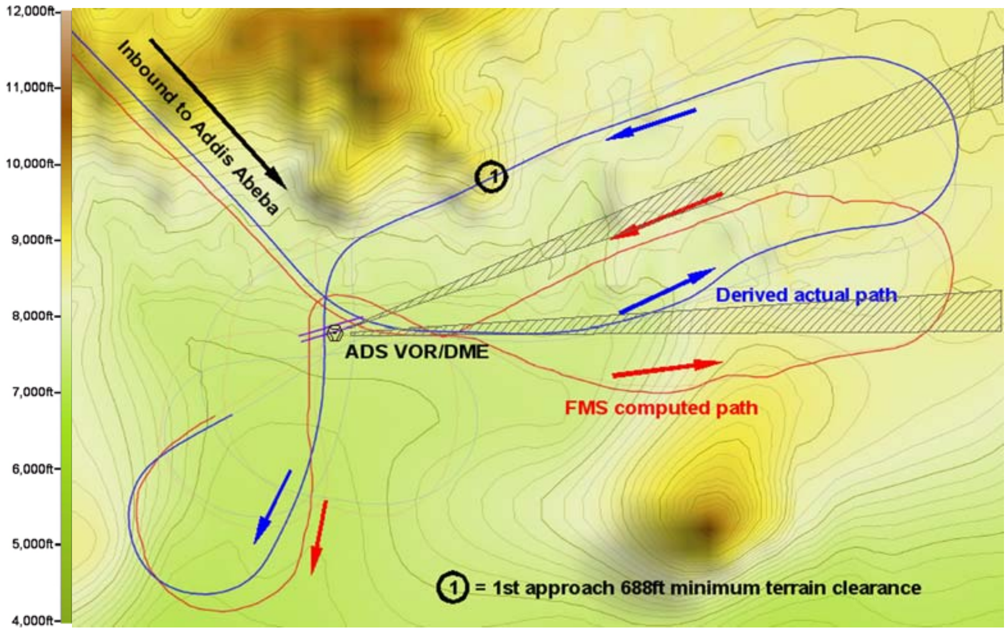


Figure 13

First ADS VOR/DME procedural approach and go-around showing the FMS computed path and derived actual path (Hatched area = procedural ADS VOR bearings)

The second approach had similar lateral position characteristics as depicted in Figure 14. The aircraft completed the turn onto the inbound track and commenced the descent. The aircraft was then configured with the gear down and full flap. The rate of descent varied between 700 and 950 fpm, the indicated airspeed was maintained at about 135 kt, and the heading drifted from 240ºM to 245ºM. The autopilot was engaged throughout the second approach.

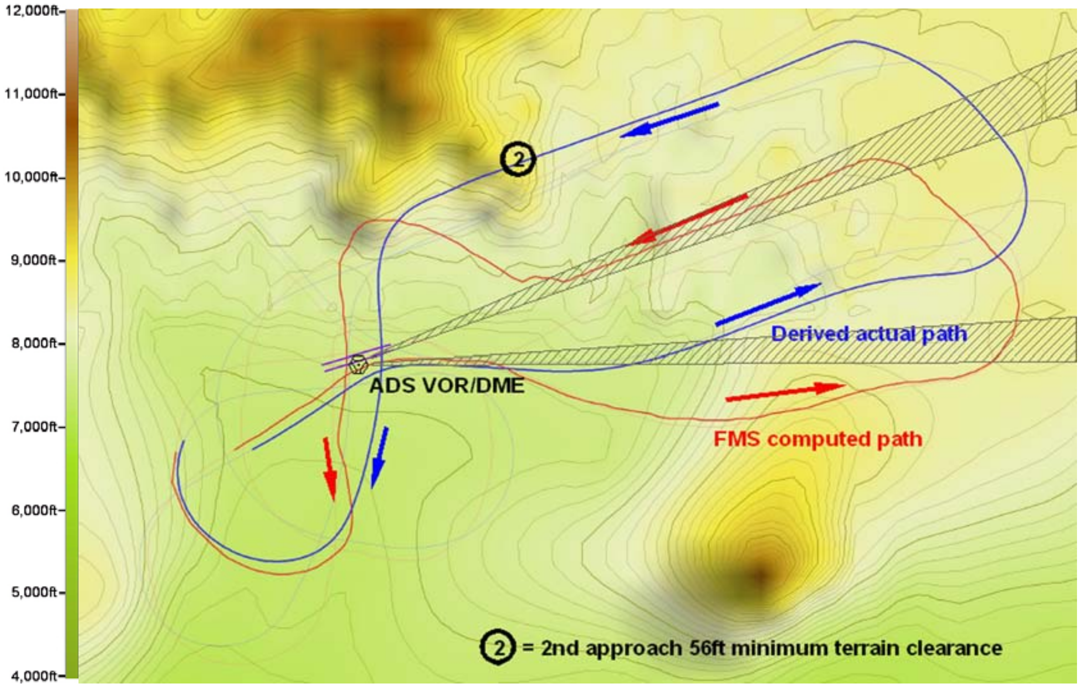


Figure 14

Second ADS VOR/DME procedural approach and go-around showing the FMS computed path and derived actual path (Hatched area = procedural ADS VOR bearings)

Figure 15 shows the final part of the second approach through to the go-around. The descent was stable until between 146 ft and 76 ft above terrain when the autopilot was disconnected, the EGPWS triggered a "TOO LOW TERRAIN" TCF alert and a pitch up command was initiated through the captain's side stick. At some point in this one second period the throttle lever arms moved forward. Sample rate limitations prevent establishing the order in which these occurred. Two to three seconds after the start of the above changes the aircraft had stopped descending and the smallest terrain clearance of 56 ft was recorded. The aircraft subsequently climbed away.

The EGPWS data shows that only the TCF alert was triggered; there were no mode 2 or look ahead alerts.

The EGPWS also recorded the expected terrain elevation from its database for the given FMS aircraft position. This is also shown in Figure 15. When the aircraft was closest to the ground, the difference between the EGPWS database expected terrain elevation and the measured terrain elevation was more than 1,000 ft.

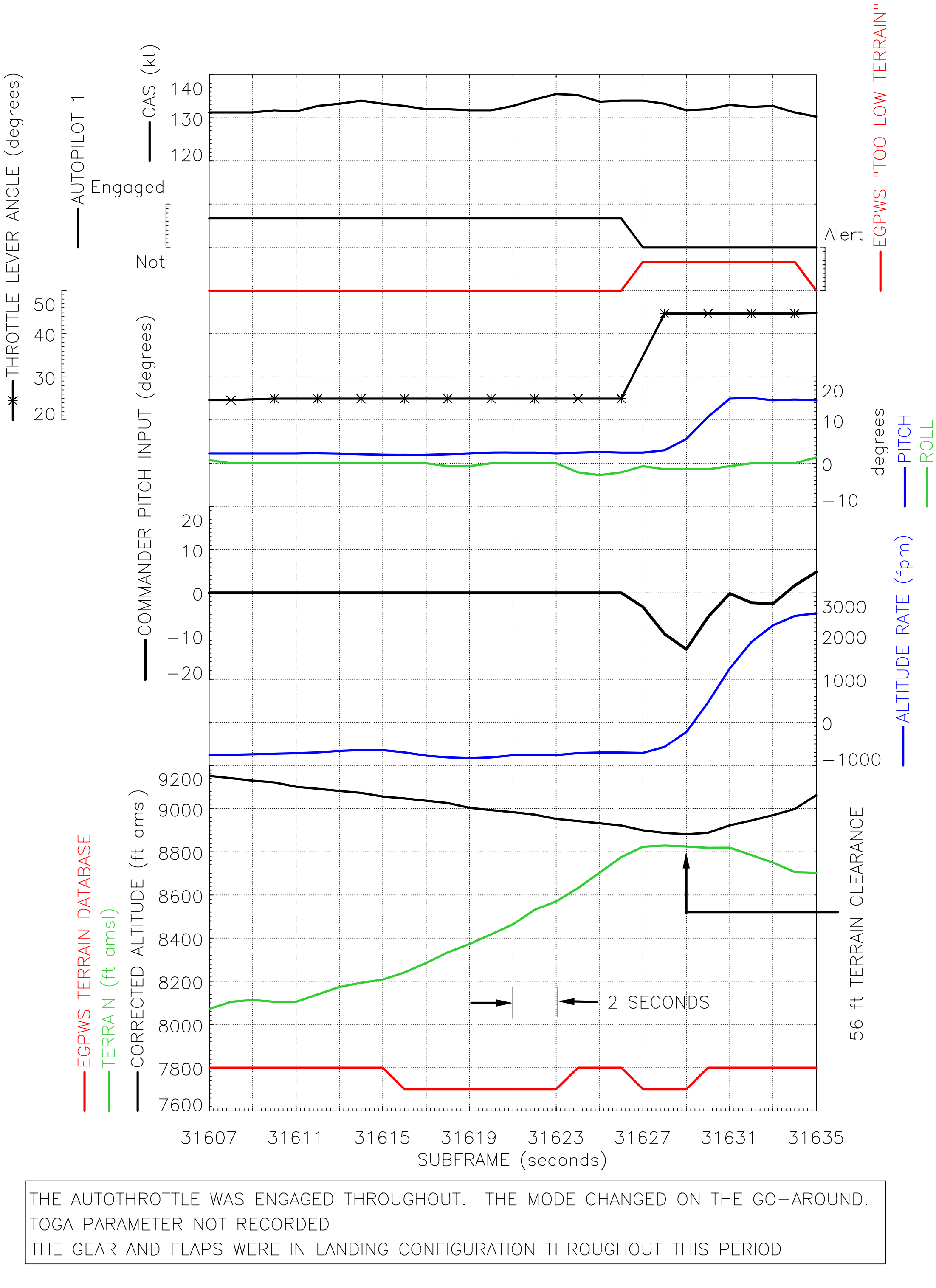
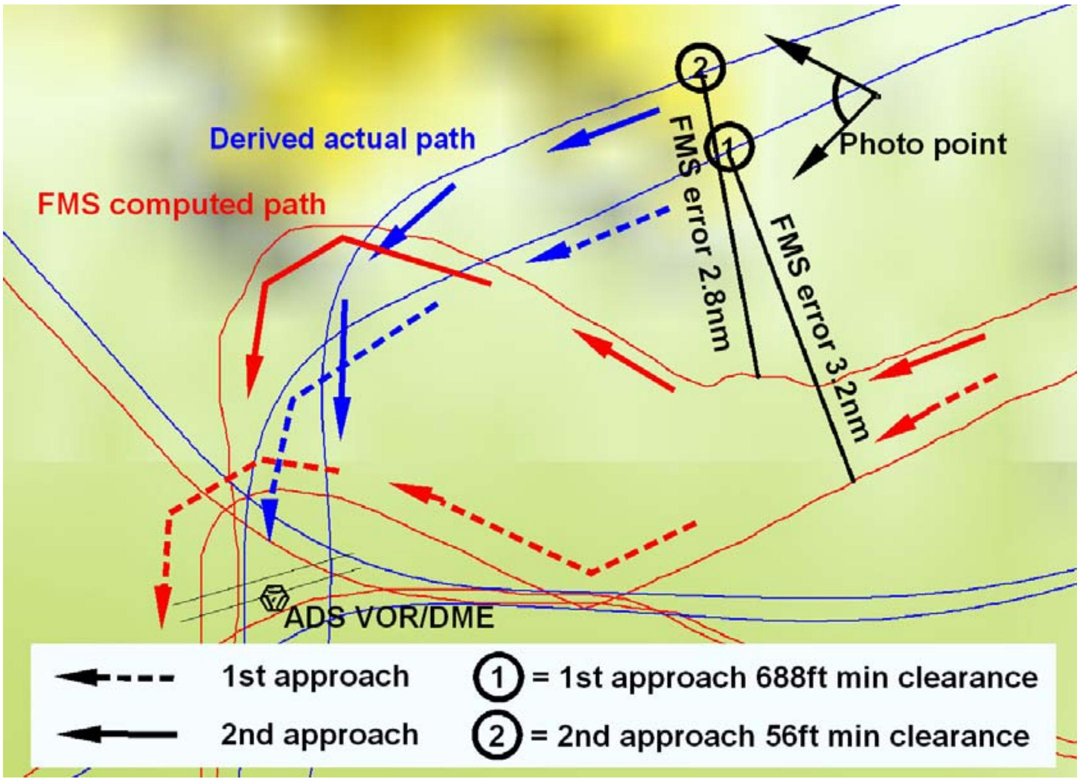


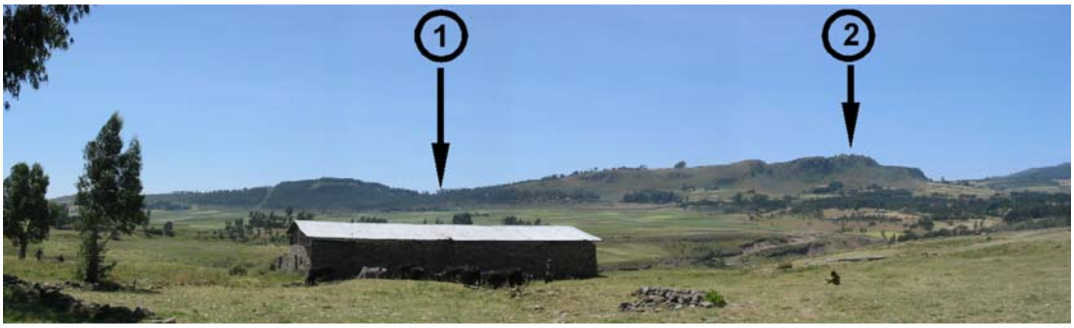
Figure 15

EGPWS alert on the second approach

Figure 16a shows a comparison of the sections of both approaches where the terrain clearance was at a minimum. The data shows that the FMS was approximately 3 nm in error on each approach, with the aircraft over much higher terrain than the FMS position would indicate. The picture at Figure 16b shows the physical locations of the points of closest approach to terrain during each approach.



(a)



(b)

Figure 16

Points of minimum terrain clearance.

a) FMS computed path v derived actual path.

b) Picture showing the points of closest approach to terrain during the 1st and 2nd approaches.

Figure 17 shows the subsequent departure from Addis Abeba, approximately 35 minutes after arriving. The aircraft landed at Ambouli airport, Djibouti at 0042 hrs.

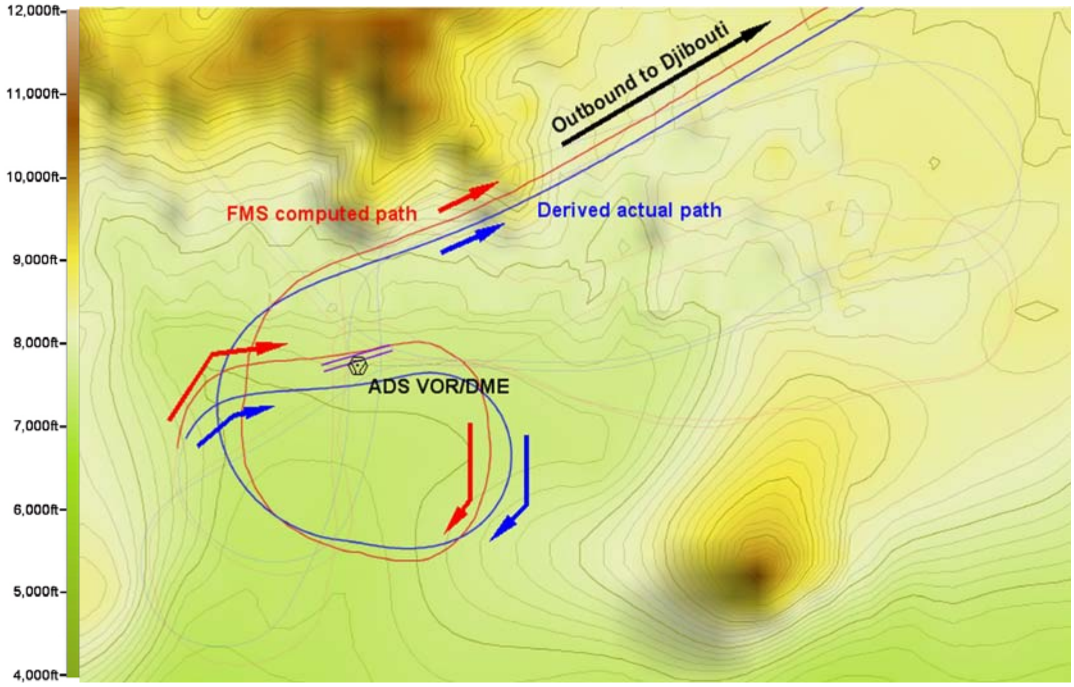


Figure 17

FMS computed path v derived actual path - hold and diversion to Djibouti

Additional EGPWS recordings

The EGPWS records a snapshots of a limited set of parameters on every landing. A review of the data downloaded from the aircraft revealed following key points:

- 1683 landings recorded.
- 78 of these landings were with EGPWS manually inhibited.
- There was one other occurrence of look ahead / TCF alerting recorded, just before landing safely on a flight into Armenia. The navigational error was over 1.5nm. There were a large number of accurate landings on this runway recorded.
- There was one landing with a navigational error in excess of 1nm and this was at Baku. In this instance the look ahead/TCF functions were manually inhibited by the crew.

1.12 Wreckage and impact information

None

1.13 Medical and pathological information

There were no relevant medical factors

1.14 Fire

None

1.15 Survival aspects

None

1.16 Tests and research

None

1.17 Organisational and management information

1.17.1 Operator and procedures

British Mediterranean Airways had operated scheduled service flights from the United Kingdom to Addis Abeba for a number of years. At the time of the incident the safety regulation and oversight of the company was carried out by the UK CAA.

The Operations Manual (OM) was produced in accordance with the requirements of JAR-OPS 1. Included in the manual are prescribed Standard Operating Procedures (SOPs) for flight crews. Procedures are provided for conducting a VOR/DME approach. Where possible, approaches are conducted using a constant descent angle technique. A VOR used for an approach is required to be manually tuned and must be identified by both crew members. One pilot will normally have the VOR displayed on his ND and the other will have the MAP mode displayed. The aircraft should be in the landing configuration and at the final approach speed by the final approach fix. Descent from the final approach fix is carried out using TRK/FPA and published DME crossing altitudes should be called out by the PNF in order to cross check the vertical profile and allow corrections to the flight path angle.

The procedure in the Quick Reference Handbook (QRH) associated with a "TERRAIN TERRAIN" or "TOO LOW TERRAIN" EGPWS alert was for the flight crew to *'Adjust the flight path or carry out a go-around'.*

1.17.2 Airport and Air Traffic Services

The Ethiopian Civil Aviation Authority was responsible for the management of Addis Abeba Airport and provided the Air Traffic Services. The Ethiopian Airports Enterprise have now assumed these responsibilities.

1.18 Additional information

1.18.1 ADS VOR performance

There were no formal reports of problems encountered with the ADS VOR by other operators. There were however anecdotal reports from local operators that the ADS VOR was known to be unreliable/inaccurate.

On 11 April 2003 following notification of the incident and on receipt of information regarding probable erroneous ADS VOR indications the United Kingdom AAIB sent a message to the Ethiopian CAA containing the following information:

> *'Initial investigations have shown that the VOR was transmitting erroneous signals that are a hazard to navigation. A more recently flown approach confirms that the transmissions are still erroneous. We request that the ADS VOR is checked immediately to confirm its serviceability.'*

1.18.2 Unacceptable failure modes

The Airbus A320 is a JAR certified aircraft. JAR 25.1309 sets failure probability standards of onboard systems, relative to the effect that the failure will have on the aircraft. This has more recently been superseded in Europe by EASA CS 25.1309 which for the purpose of this review is identical to JAR 25.1309. ACJ 25.1309 provides additional information regarding JAR 25.1309 processes. Other global safety standards use the same values for the relationship between failure probability and failure effect.

The main items of this requirement and associated documentation (ACJ) that affect this investigation are as follows:

- JAR 25.1309 (b) (1) (i) requires that "*Any catastrophic failure condition ...(i) is extremely improbable...*". This means that the probability of a system failure that results in the loss of the aircraft and multiple fatalities should be less than 1×10^{-9} per flight hour (pfh).

- JAR 25.1309 (b) (1) (ii) requires that "*Any catastrophic failure condition ...(ii) does not result from a single failure...*".

- JAR 25.1309 (c) requires that "*Information concerning safe system operation condition must be provided to the crew to enable them to take appropriate corrective action...*".

1.18.3 Other limitations of FMS installations

There are several other features of FMS installations which may have an impact on their suitability as a navigation source for TAWS.

Historically approach procedures around the world were based on a variety of co-ordinate systems. The FMS was designed to accommodate these variations and can successfully navigate an aircraft relative to the local environment as defined by the local AIP. TAWS data however, is derived using a single global standard of co-ordinates, the WGS 84 system, the same system used by GPS. Thereby the accommodations made by the FMS in the local environment degrade the effectives of TAWS. Even where an aircraft has GPS fitted, many FMS installations disregard GPS when localiser data is available.

Scenarios, not all applicable to the FMS or aircraft type used during the Addis Abeba incident, whereby the FMS derived information could be corrupted by a single source include the following:

- DME error in the VOR/DME solution when there are no viable DME/DME geometries or localizer updating facilities available.

- Poor localizer data, either in the signal or navigation database. Many FMS installations disregard GPS and DME/DME data when localiser data is available.

- DME/DME updating when other DME pairs have lower priority or the algorithms/tuners are not sophisticated enough to compare all DME solutions available to them.

- Inertial drift when the destination is served by a fully functional VOR/DME but the particular FMS installation does not accept VOR/DME updates and there are no viable DME pairs in line-of-sight.

- Inertial drift in a DME/DME and VOR/DME rich area because the procedural tuning of a navaid effectively locks out radio updates on that particular installation type.

- There have been examples on other air transport aircraft types with different architectures whereby DME/DME updating does not occur due to navigation database, memory capacity or algorithm limitations even when in a DME rich environment.

- A GPS corruption which is not made evident in the GPS's own quality indicators.

Susceptibility to these types of problems can only be precisely known by reviewing each combination of airfield, navaid infrastructure (including geometries), FMS type and navigation database contents.

1.18.4 Airbus policy on sources of navigational data

On 5 February 2004 Airbus sent a TELEX to operators regarding a change in policy with respect to the use of GPS for TAWS. The content of the TELEX was as follows:

'OUR REF.: SE 999.0015/04/VHR DATED 05 FEB 2004

OIT CLASSIFICATION: AIRWORTHINESS, RECOMMENDATION

1. PURPOSE

THE PURPOSE OF THIS TELEX IS TO INFORM ALL AIRBUS OPERATORS OF THE NEW AIRBUS POLICY CONCERNING THE USE OF GPS POSITION FOR TAWS OPERATIONS. PLEASE NOTE THAT TAWS IS ALSO KNOWN AS EGPWS (ENHANCED GROUND PROXIMITY WARNING SYSTEM) OR T2CAS (TRAFFIC AND TERRAIN COLLISION AVOIDANCE SYSTEM).

2. DESCRIPTION OF THE USE OF GPS POSITION FOR TAWS OPERATIONS.

REMINDER: TAWS WILL BE RENDERED MANDATORY BY JAA AND FAA EARLY 2005. FOR MORE INFORMATION ON THESE MANDATORY REQUIREMENTS AND ASSOCIATED DATES, PLEASE CONSULT OIT REF. SE 999.0013/04/VHR DATED 05 FEB 2004.

THE TAWS IS AN IMPROVED SYSTEM OVER THE EXISTING GPWS (GROUND PROXIMITY WARNING SYSTEM). TAWS IMPROVES ON EXISTING SYSTEMS BY PROVIDING THE FLIGHT CREW AUTOMATIC ADVANCED AURAL AND VISUAL DISPLAY OF IMPENDING TERRAIN, MUCH EARLIER WARNING, FORWARD LOOKING CAPABILITY, AND OPERABILITY IN LANDING

CONFIGURATION. THESE IMPROVEMENTS PROVIDE MORE TIME FOR THE FLIGHT CREW TO MAKE SMOOTHER AND GRADUAL CORRECTIVE ACTION. TO ACHIEVE THE NEW TERRAIN FUNCTIONS, THE TAWS COMPUTER USES THE AIRCRAFT POSITION TO LOCATE THE AIRCRAFT ON ITS INTERNALLY LOADED TERRAIN DATABASE. THIS AIRCRAFT POSITION IS CURRENTLY PROVIDED BY THE FLIGHT MANAGEMENT SYSTEM (FMS) THAT COMPUTES IT:

1) FROM THE ADIRUS AND GPS POSITION SOURCE FOR AIRCRAFT EQUIPPED WITH GPS SENSOR UNIT (GPSSU) OR MULTIMODE RECEIVER (MMR), WHEN GPS PRIMARY IS AVAILABLE, OR

2) FROM THE ADIRUS AND RADIO POSITION UPDATE, FOR AIRCRAFT NOT EQUIPPED WITH GPS, WHEN GROUND RADIO NAVAIDS ARE AVAILABLE, OR

3) FROM THE ADIRUS ONLY, FOR AIRCRAFT NOT EQUIPPED WITH GPS RECEIVER WHEN RADIO POSITION UPDATE IS NOT AVAILABLE

3. NEW AIRBUS POLICY

IN THE FRAME OF THE AIRBUS POLICY FOR IMPROVEMENT OF TAWS OPERATIONS, AIRBUS WOULD STRONGLY ENCOURAGE THE USE OF A GPS SOURCE IN THE GLOBAL ARCHITECTURE OF THE TAWS SYSTEM.

AS A CONSEQUENCE, AIRBUS HIGHLY RECOMMENDS TO ASSOCIATE TAWS OPERATIONS WITH THE USE OF GPS RECEIVERS, THROUGH THE INSTALLATION OF MULTIMODE RECEIVERS.'

1.18.5 Safety action by the operator

Once the significance of the event and an understanding of the underlying causes had been established the operator suspended all of its flights to Addis Abeba in aircraft that were not equipped with GPS.

1.18.6 Safety action by the UK CAA

The UK CAA in response to this incident issued a Flight Operations Department Communication 16/2003 (issued May 2003) which, together with information about the incident, contained the following two safety recommendations to operators:

> *'1.4.1 Operators should ensure that the details of this incident, and the advice contained above, are brought to the attention of their flight crews.*
>
> *1.4.2 Operators should endeavour to use aircraft with GPS on routes that involve long sectors both over water and terrain that terminate in remote areas served with few navigation aids. This will ensure that both FMS position update computations and EGPWS are provided with a choice of information sources from ground-based and satellite navigation systems.'*

2 Analysis

2.1 General overview

The aircraft is of a modern design and was equipped with up to date standards of navigation displays and presentation of information to the crew. It was equipped with the latest standard of TAWS equipment, meeting existing and future requirements. In spite of this the aircraft came very close to impacting the terrain, and had the terrain continued to rise ahead of the flight path on the second approach it would indeed have done so. In order to understand the issues surrounding this serious incident, not only is it important to understand the failure that led to the aircraft nearly hitting the terrain, but it is also vital to determine why alerting systems put in place to prevent this failed to provide an adequate warning.

The second approach was the occasion when the aircraft came closest to ground contact, within 56 ft whilst 5 nm from the airport, and the safety of the aircraft was most seriously compromised. On this approach the crew had no visual indication of the proximity of the ground and, even after the event, no perception of how close the aircraft had been to the terrain. The go-around action however was positive. In this event, and considering the ground profile ahead, the aircraft might have just cleared the ridge without crew intervention.

Safe terrain clearance was also compromised on the first approach but is perhaps less significant because the crew had some visual ground contact. On the first approach a minimum RA of 688 ft was reached about 25 seconds before the go-around commenced. The RA then increased to 1,080 ft agl, at which point the go-around was initiated. The aircraft had descended across the ridge of high ground in a slightly different location, thus providing more terrain clearance.

The reason for the vulnerability of the aircraft in this incident was that a single navigational source, the ADS VOR, was being used by the crew to fly the approach as well as by the FMS to update its position and to supply positional information to the TAWS. The ADS VOR was operating but was radiating a corrupted signal which caused the aircraft to be in a different position from where the crew thought it to be. The navigation and safety of the aircraft relied upon this single navigation aid, which was in error. The safety net was therefore rendered ineffective and there was nothing to alert the crew to the real situation of the aircraft.

2.2 Flight operation

2.2.1 Conduct of the flight

The flight crew operated the aircraft in accordance with their company's procedures. They used the available on board and ground based aids to enhance their situational awareness.

All the indications presented to the crew, with the exception of the ADF bearing which they discounted due to the thunderstorm activity, showed the aircraft to have been in the correct place. Altitude and range cross checks were made against the published approach parameters, where possible, to monitor the vertical profile. The required vertical profile was flown accurately on both approaches.

The airfield elevation of 7,625 ft (2,325 m) is unusually high. This means the True Airspeed (TAS) is some 20% to 25% higher than the Indicated Airspeed (IAS) during the approach phase. Thus groundspeeds and required rates of descent are correspondingly higher and to make a stabilised approach the final landing configuration needs to be achieved in good time.

The crew, on the first approach, noticed some unsteadiness of the ADS VOR signal but were satisfied they had sufficient information to continue. They achieved visual ground contact but carried out a go-around when they could not positively identify the airfield environment and had lost the VOR indications. This approach was discontinued in good time from a height of 1,200 ft aal. The reason they could not locate the airfield is probably that the aircraft was not lined up with the runway as expected but was several miles to the north of the extended centreline.

The crew were disconcerted by the failure of their first approach and questioned ATC as to whether the ADS VOR was functioning correctly. As the aircraft crossed over the ADS VOR its indications were seen to be working again and, reassured by this they decided to attempt a second approach.

On the second approach the crew were careful to ensure that the aircraft was fully configured for landing at an early stage to allow for good monitoring and cross checking of their vertical profile. The commander was first alerted to the fact that all was not well by the 'FOUR HUNDRED' automatic callout, and although there was a slight delay while he recognised that 400 ft was wrong for that stage of the approach he had started to increase power for the go-around as the EGPWS alert "TOO LOW TERRAIN" caution was received. The audio caution reinforced his actions and resulted in a more aggressive go-around during which 1.5g and 15º nose up pitch attitude was achieved. Although he did not make a full aft stick input a high rate of climb was attained.

In view of the reported cloudbase of 2,300 ft aal the crew should have had sight of the surface at around 8 nm from the airport. This appears to have been the case on the first approach where they did report having seen ground lights. On the second approach though; which was further to the north and closer to the high terrain, they did not see anything. This may have been as a result of lower cloud in the vicinity of the high ground, or because of a lack of ground lighting and habitation in the immediate area.

2.2.2 Human factors

The flight crew were approaching the end of their duty day but neither lack of vigilance nor fatigue were considered to be a factor in this incident.

As the number of aircraft equipped with moving map displays has increased pilots have become more reliant upon this aid to situational awareness. The crew in this case had positional and navigational information which was reinforced from several apparently different sources to build up their situational model. The time that elapsed between the commander hearing the "FOUR HUNDRED" auto callout and his recognising that something was wrong was some four to five seconds. This was how long it took him realise that a routine call, heard on every flight, was inappropriate for that stage of the approach and he immediately started the go-around. There was not time for the crew to question the validity of their situational model and the commander's action in going around was the necessary response to the uncertainty generated by the RA callout.

2.3 Air Traffic Control

ATC cleared the aircraft for the ADS VOR/DME approach procedure. After the first go-around the flight crew notified them they were having difficulty in receiving a signal. There was some discussion then between ATC and the flight crew regarding the ADS VOR. After the second go-around the crew again notified ATC that the ADS VOR was not operating correctly for the latter stages of the approach. ATC were thus made aware that there was a possible problem with the ADS VOR.

With the ADS VOR monitor inoperative ATC would not have had any means of verifying the operation of the ADS VOR other than through the reports from aircraft. Other aircraft had landed on the same runway and apparently had not reported any problems with the ADS VOR. It should be noted though that it is possible that the other aircraft may have had access to and been using approach aids other than ADS VOR (for example GPS or Localiser 25R).

2.4 Airfield navigational equipment

2.4.1 AD NDB

The AD NDB was probably giving accurate indications but to discount its information was understandable given that the crew could see thunderstorm activity on the weather radar in the vicinity of the airfield.

2.4.2 R25R Localiser

The R25R Localiser was not available for this flight operation because it was not promulgated in the current AIRAC cycle, therefore, no charts relating to the approach were available on the aircraft. It is believed however, that some other flights by other operators were conducted using the R25R Localiser, either as a primary or supplementary means of navigation.

2.4.3 ADS VOR

The ADS VOR was reported as unserviceable to ATC after the incident by the operating crew. It was still in error when the aircraft returned to the airport the next day. On 11 April 2003 further information was sent from the UK by telex to the Ethiopian CAA advising that the ADS VOR was transmitting erroneous signals that constituted a hazard to aviation. A NOTAM to promulgate this information was never issued.

The erroneous transmissions may only have occurred when there had been recent rain. Because the monitor was not operating to shut down the ADS VOR when in error any reoccurrence of the errors may not have been detected.

2.4.3.1 ADS VOR maintenance

The cause of the ADS VOR error was found to be water ingress into the antenna feeds due to poor maintenance practices; a faulty transistor was also identified. Following the incident, the rectification and subsequent testing that was carried out created the impression that the ADS VOR was now operating correctly and it was returned to service. The checks utilising the hand-held VOR receiver were not conducted from a surveyed position and could not validate the accuracy of the radiated pattern. Aircraft in flight were asked for serviceability reports but since these were not dedicated flight check aircraft they could only have provided limited information on the functionality of the ADS VOR. The only manner in which correct operation of the ADS VOR facility could have been ensured was through a calibration flight conducted by a suitably equipped aircraft, and none was available. The reports of ADS VOR bearing problems some days after the rectification indicated that errors were still present.

2.4.3.2 ADS VOR monitoring

It is clear, from the observations made by the crew and the effect that the ADS VOR failure had on the flight path of the aircraft, that the ADS VOR was in error by more than 1 degree. This should have triggered the ADS VOR monitor systems to react, as required by ICAO Annex 10, VOLUME I, PART I, section 3.3.7. The monitor failed to activate, either to remove the identification and navigation components from the carrier, or to cause the radiation to cease. The monitor should also have sent a signal to ATC, across the other side of the runways, that it was inoperative or that the ADS VOR was not transmitting correctly. It was reported though that the cable across the runway from the monitor to ATC had been disrupted during construction work.

2.4.3.3 ADS VOR bearing error

The crew were attempting to remain on a steady VOR bearing during both approaches and yet the flight path achieved by the aircraft would not normally result from a steady VOR bearing. Subsequent observations of the VOR and the evidence of the FMS behaviour indicate that the water ingression caused a change in the power and/or phase of at least one of the varying signals used to generate the rotating ADS VOR radiation pattern. This would result in a non-uniform error in the ADS VOR bearing around the ground station. It is therefore possible that whilst the aircraft bearing relative to the ADS VOR ground station was reducing during the approach, the error was increasing, giving the impression of a steady VOR bearing.

A non-uniform bearing error means that instead of placing an aircraft within a narrow arc relative to the VOR ground station, the bearing range could put the aircraft within a much wider geographical arc, one that may not even be centred on the desired bearing. This is supported by the crew observations the next day that on the inbound leg the error was nearly 8º larger than that seen on the outbound leg despite the actual paths being only 23º apart relative to the ADS VOR ground station.

No single simplistic model of VOR error matched all the observed ADS VOR deviations, however, observations were made at different times and it is likely that the effect of the water ingression on the radiated ADS VOR signal varied over time.

2.5 Aircraft navigation performance

2.5.1 FMS general

It is known that FMS navigation is susceptible to errors and this is recognised in the Airbus FCOM. There is a required procedure for the flight crew to use to verify the position accuracy before descent and this check was carried out. However, the technique suggested does not safeguard against a ground station failure being the source of the error. Thus, a statement in the FCOM regarding the navigation accuracy check to be performed by flight crew:

> *'This check verifies and quantifies the FM accuracy'*

cannot be said to be true because, as in this case where the ADS VOR itself was in error, it led to an equivalent error in the FMS position.

2.5.2 FMS performance

There is no evidence to suggest that the FMS did not operate in accordance with the design and certification requirements. During the flight in the vicinity of Addis Abeba the FMS was navigating using triple mix inertial navigation and radio navigation using the ADS VOR/DME only.

When inbound to the airfield the aircraft flew approximately along the northwest / southeast (NW/SE) ADS VOR antenna axis. The FMS did not deviate from the derived position and so the VOR/DME radio position at this time/location was either accurate, unavailable or invalidated by the FMS. At this bearing, the suspect NE/SW signal had no impact and so any error in this signal would not have resulted in a bearing error, assuming that the NW/SE signal did not have a phase error as well.

The aircraft then flew through the ADS VOR ZOC. On emerging from the ZOC the bearing errors would have resulted in only small geographical errors because of the small distance from the ADS VOR. Thus, the ADS VOR/DME position would have appeared reasonable and been adopted by the FMS as a radio update. During the procedure, when the aircraft was on the ADS VOR 092 radial outbound leg, the distance from the ADS VOR/DME increased and the geographical error correspondingly increased also, causing the FMS position to start drifting south of where the aircraft actually was.

At about 11nm DME outbound the ADS VOR/DME was rejected and the FMS path paralleled the derived actual path. At the point of rejecting the ADS VOR/DME the FMS would have switched to using inertial position offset by the bias.

However, the bias would have been set using the last ADS VOR/DME position that appeared valid, just before the source was rejected. Therefore, the bias was likely to have been generated using a source just below the rejection threshold. The FMS appears then to have continued onto the inbound 069 ADS VOR radial on inertial navigation with the same bias applied.

At about 3nm DME inbound, the FMS position rapidly moved off in a different direction from the aircraft track indicating that radio updating had been resumed. Then the ADS VOR/DME ZOC was flown through again.

The second outbound/inbound leg was much the same as the first but with a longer period of radio updating at the end of the turn to the inbound leg. The use of the ADS VOR/DME was reinitiated at about 5nm.

When reviewing the FMS path for the outbound legs it was estimated that the VOR error required to generate the observed deviations would be in the order of 20 degrees. During the periods of radio updating on the inbound legs, the VOR error required to generate the observed deviations would have been in excess of 20 degrees.

From the above analysis, the following points have been drawn:

- The FMS did detect a VOR problem a number of times and switched from radio updating accordingly. If the FMS could have alerted the crew that the FMS had rejected the navigation aid that the crew were depending on for their procedural approach, the near CFIT may have been averted.

- The FMS, after rejecting the navaid, used the bias based on its last 'valid' output (that is, built on a foundation created from a source identified as unreasonable).

- The FMS can adopt a bad VOR before reaching the zone of confusion if the approach is made along a VOR antenna pair axis which is functioning properly even if a fault on the other axis is causing considerable VOR bearing errors elsewhere around the VOR.

- The FMS does not permanently reject a source that has been identified several times as unreasonable (at least not within the time scales associated with this event – which is a pertinent time scale).

- The FMS will accept new radio updates even though this would indicate that the inertial performance is jumping sporadically which is uncharacteristic of a triple mix inertial installation such as this.

In summary, the FMS had sufficient information to identify that the ADS VOR/DME was unreliable. Had the crew been aware it was unreliable different decisions regarding the flight could have been made.

The scenario by which a failure of a single source leads the FMS to provide an inaccurate navigation position would not be limited to a VOR error. All that is required is dependence on a source that the FMS error modelling deems the most appropriate. This can occur in areas which would be considered rich in navigation aids. Other key factors are the type, age and capability of the various FMS systems fitted to various air transport types.

2.6 TAWS effectiveness

TAWS should have provided some protection against this type of threat in a number of ways as stipulated in section 1.6.2.2, these are reviewed below.

2.6.1 Mode *2B*

The DO-161A and Honeywell product specification nominal mode 2B alerting envelope was penetrated by the aircraft 12 seconds before the point of least terrain clearance (if no data smoothing is carried out). No alert was issued. Applying a simplistic 10 second smoothing filter against the recorded parameters results in the alert envelope not being penetrated.

Honeywell reviewed the data and were satisfied that mode 2B was operating as intended; ie, the necessary rate filtering prevented an alert in this case. This filtering was justified in this design because of the significant historical problem of nuisance mode 2B alerts, a high level of which could cause pilots to ignore the system completely. This illustrates the ineffectiveness of the present mode 2B alert mode and calls into question the validity of maintaining it as a required function. The TAWS manufacturers appear to desensitize or switch the mode off completely whenever possible.

The limitations of mode 2B are drivers for the FLTA and PDA alerting functions, however, from a certification point of view, mode 2B is seen as protection in the event of failure of the FLTA and PDA functions. This incident does not support this view.

2.6.2 Premature Descent Alerting / Terrain Clearance Floor

The TCF alert was the only one triggered by the EGPWS during this event. It was triggered at about the same time that the commander was initiating the go-around anyway, so was not the go-around trigger although it reinforced his action.

The TCF allowed clearance height is a function of distance to runway, therefore the effect of the FMS error on the TCF function should be reviewed. The effect on TCF distance is shown in Figure 18 below.

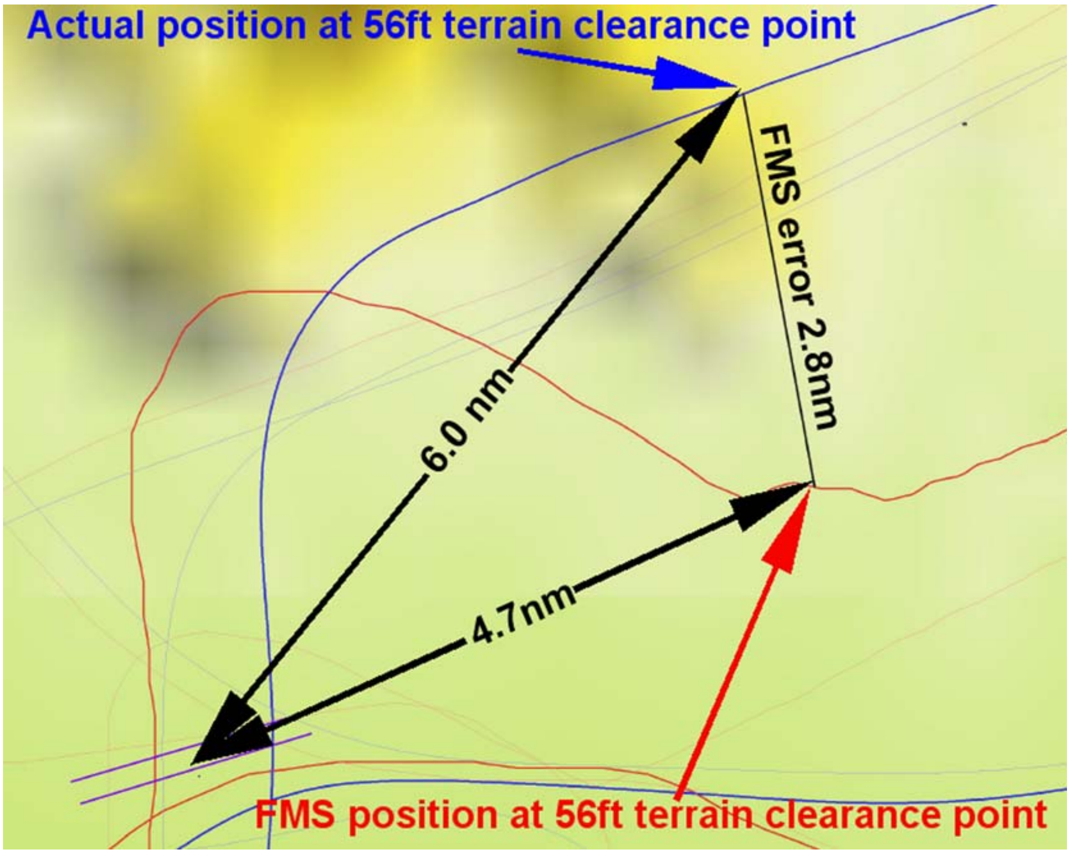


Figure 18
Effect of the FMS error on the distance to runway centre calculation of the TCF function, at the point of minimum terrain clearance

Applying these distances along with a simplistic model of the aircraft's flight path gives a less sensitive TCF alert envelope with the FMC error than if the navigation had been accurate. This is illustrated in Figure 19.

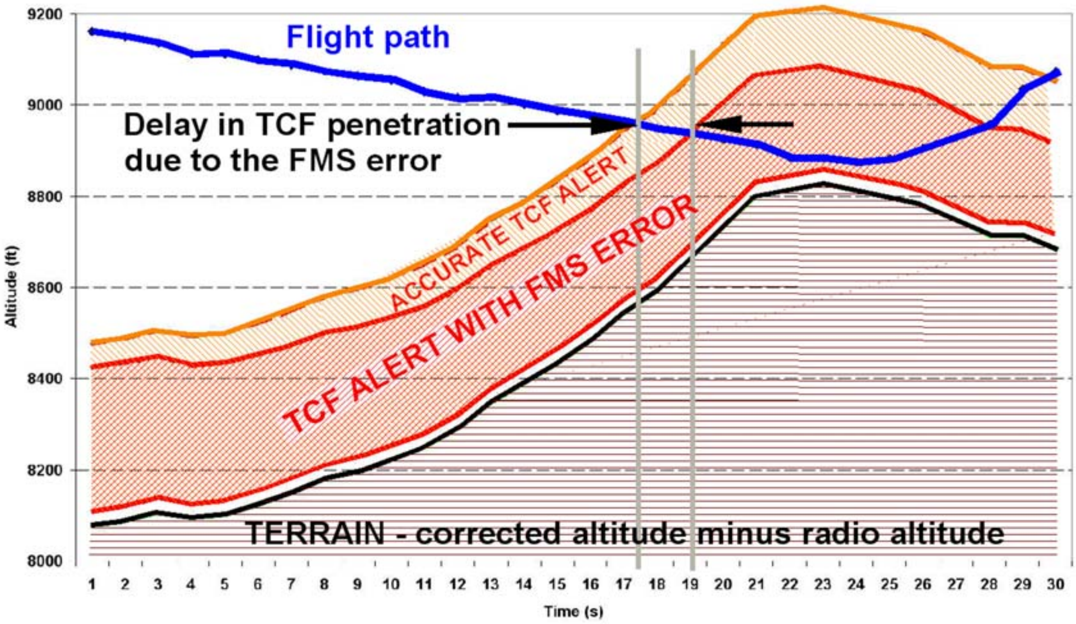


Figure 19

TCF alert envelope with and without the FMS error

The FMS error effectively only delayed the alert by approximately 1.5 seconds. In this case, using the latest, tightest TCF envelopes would not have significantly increased the time to alert.

The time between TCF alert and projected terrain impact is a function of aircraft speed and the inclination of the terrain. This is a fundamental limitation of look down alerting functions such as this. It is clear that in this case, even with accurate navigation, the steep nature of the terrain rendered the TCF function ineffective. TCF is designed to mitigate the mode 2B problem of allowing an aircraft land anywhere as long as it is suitably configured. TCF is not designed to protect against excessive closure rate with terrain, other alert modes are relied upon to detect this type of terrain threat.

2.6.3 Forward Looking Terrain Avoidance

This is the primary alerting mode to protect against terrain rising ahead of the aircraft. No look ahead alerts were triggered during the incident. According to the TSO standards an alert ought to have been generated between 22 and 46 seconds prior to the point of minimum terrain clearance. Honeywell's analysis of the EGPWS design indicated that a caution and warning would have been generated at 32 seconds and 25 seconds respectively before reaching the point of minimum terrain clearance, had an accurate source of navigation data been used.

In this case the cross track navigation error was about 2.8nm so the alert algorithm 'passed' by the side of the hazard. Figure 20 illustrates this using terrain data that is not from the EGPWS but is of a resolution that is representative of typical terrain cell sizes used by the EGPWS in terminal areas. The representation of blocks of interest to the look ahead alert algorithms are only an illustration of the nature of the interaction of the terrain data with the algorithms are not definitive indications of actual terrain cells used in the terrain database.

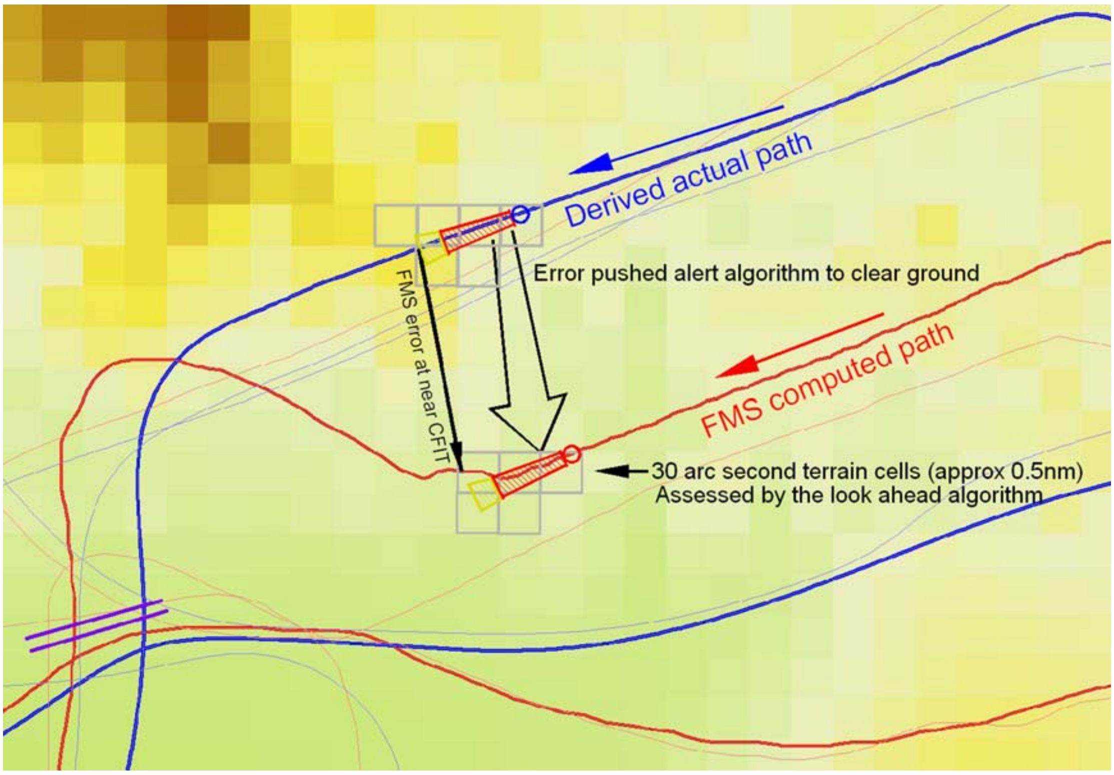


Figure 20

FLTA - Honeywell alert envelopes in relation to the navigation error

At the point of minimum terrain clearance the detected terrain was over 1,000 ft higher than the expected terrain from the database with the given location. The lack of an alert was due to the large FMS navigation error. However, it is likely that a navigational error smaller than that experienced would have offset the look ahead algorithms sufficiently to prevent an alert.

Extrapolating the circumstances further, if the hazard terrain had been equally steep to the side as it was head on to the aircraft, then a navigation error in the order of 0.5nm would have been all that was needed for the look ahead algorithm to miss the hazard.

The TAWS certification allows the use of navigation sources which allows errors greater than 0.5nm for 5% of the time. So, in theory, TAWS could be bypassing the terrain hazard cells in front of the aircraft 5% of the time. This is without allowing for degradation of performance due to failures.

Had the ADS VOR been switched off, as was appropriate given the failures at the ground station, the FMS position would have been based on the drifting inertial mix position. Inertial referencing systems, especially at the end of a flight, are not accurate enough to support effective TAWS operations.

In these circumstances FLTA would only be effective if other means of updating were available to the FMS or alternatively if GPS was available as a direct source for the EGPWS. It is of further interest to note that TAWS certification allows the use of an FMS source that is incapable of VOR/DME updating. Such a system renders TAWS ineffective in all such approaches where line of sight restrictions due to terrain mean that VOR/DME is the only radio navigation solution available.

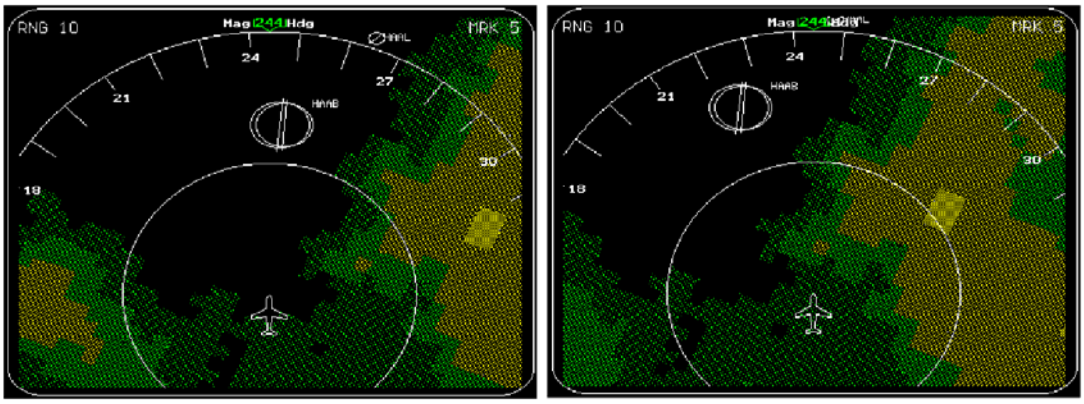
When EGPWS / TAWS was first developed, FMS was being used as an effective tool to aid efficient navigation between departure and approach procedures. As such it was seen as a good source of navigational data. Operational experience has shown that the FMS does not perform as well when navigating down to the runway as it is deprived of line-of-sight to the navigation aids it needs to maintain accurate and robust operation. However, this is how it is used by TAWS.

2.7 Terrain display

Figure 21 shows six terrain displays. The displays were simulated by Honeywell so the form of the display is not identical to that seen on the A320 but the type of information and the location of the terrain data and runway symbols are accurate. The three displays on the left illustrate what the terrain display looked like on the aircraft at three points during the second approach. The three displays on the right indicate what the displays would have looked like with accurate data feeding both the EGPWS and the navigation display runway symbols.

If the terrain display and the navigation display systems had used independent sources of navigation data then the display would have either given correct terrain depiction and incorrect runway depiction or vice versa. Either way, it would have been a possible cue to the crew that things were not right.

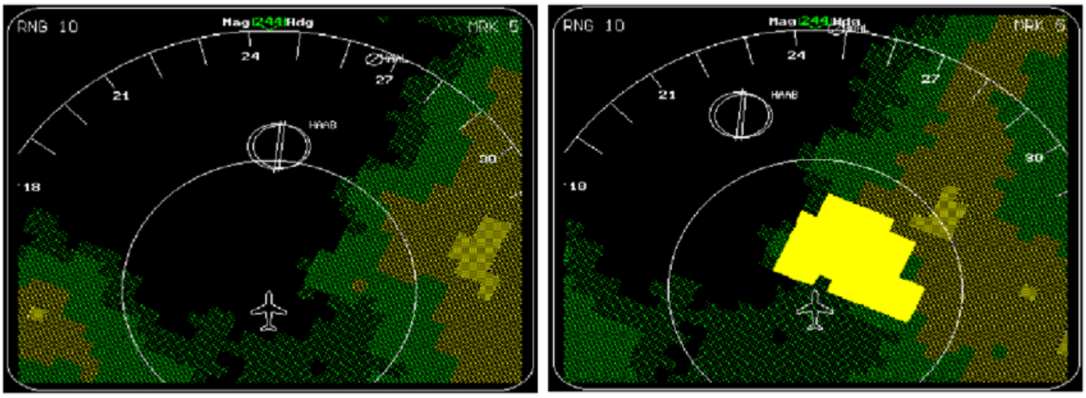
At 9,500 feet



With FMS Position Error
Approximately 2.6 NM cross-track error

Actual Aircraft Location

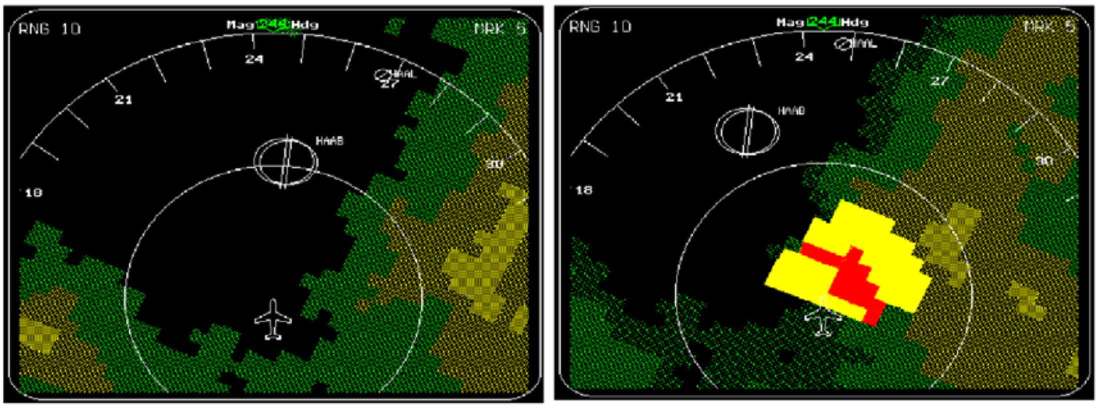
At 9,300 feet
32 seconds to the closest encountered terrain



With FMS Position Error
Approximately 2.6 NM cross-track error

Actual Aircraft Location
"Caution Terrain"

At 9,200 feet
25 seconds to the closest encountered terrain



With FMS Position Error
Approximately 2.6 NM cross-track error

Actual Aircraft Location
"Terrain Ahead Pull-up"

Figure 21

Simulated navigation displays.
The left hand images are what the crew would have seen during the incident and the right hand images are what the crew would have seen had the FMS been accurate.

It is clear that the terrain display at the time could only re-enforce the false impression of no terrain hazards along the flight path and so is hazardously misleading. Since the source of the error was effectively initiated outside of the TAWS, this occurrence of a hazardously misleading display falls outside of the TAWS certification requirements designed to limit such occurrences. Given that the navigation data appears to be one of the more likely sources of errors leading to hazardously misleading displays, it would appear inappropriate that external sources of error are not considered as part of the certification of the system on the aircraft.

2.8 TAWS performance against certification objectives

TGL12 states as a certification objective that the system unavailability rate should be no worse than 1 x 10^{-3} pfh. The EGPWS recorded data shows that the system was manually inhibited for just under 5% of landings. This clearly does not meet the requirements as written.

TGL12 states that the probability of failure of the system to provide the required aural and visual alerting functions without a failure indication shall be shown to be no greater than 1 x 10^{-4} pfh. With an FMS navigation standard allowing errors of greater than 0.5nm for 5% of the time, when on approach, it can be argued that for 5% of the time the look ahead algorithms are not scanning the correct terrain database cells. This figure will vary according to the size of the terrain cells in the database and in practice performance may often be better than this.

TGL12 states a nuisance alert objective of 1x 10^{-4} pfh. The sample of flights from the EGPWS recorded data does not give a statistically meaningful data set. However, 1 of the 1683 recorded landings induced a nuisance alert. Depending on the average length of flight, this equates to a performance that is probably slightly shy of the objective but in the same order of magnitude. The A320 FMS architecture, functionality and performance is not representative of all FMS installations, there are many that are worse with reduced number of inertial platforms and reduced radio updating capability. These other FMS systems are also certified under codes recognised as acceptable for use in the TAWS certification process. It is clear that the nuisance alert rate objective is not compatible with the given acceptable standards for the source of navigation data.

2.9 Common mode failure

Some of the points of the above analysis that are pertinent to the issue of common mode failure are as follows:

- The crew were reliant on instruments for navigation as there were no reliable external visual reference points.

- The procedure being flown was dependent on the ADS VOR which was giving inaccurate indications.

- The navigation display was driven by the FMS that was heavily influenced by the ADS VOR.

- The terrain display was driven by the FMS output and so was also heavily influenced by the ADS VOR.

- The CFIT alerting algorithms designed to combat steep terrain were driven by the FMS output and so was also corrupted by the ADSVOR.

- But for an arbitrary 56ft, this would have been a catastrophic accident.

In summary a single source of data effectively compromised the procedure designed to assure safe flight, the tools designed to improve crews situational awareness of both the flight path and hazardous terrain and the CFIT alerting safety net. Under JAR/CS 25.1309 a catastrophic event cannot be associated with a single failure and therefore in this regard the aircraft does not comply with JAR/CS 25.1309.

There are other sources of data which on some aircraft types and in the wrong environment and circumstances could cause a similar failure. These include, but are not limited to bad, yet valid ILS, altitude, GPS and DME data.

The TAWS certification guidance material, shows no consideration to exposure to common mode failure. At the time of generating the guidance material TAWS was not mandatory and sources of navigational information on aircraft other than FMS were not practical for the world's fleet of aircraft. It is most likely that allowing the certification of TAWS with these inherent common mode failure weaknesses had an overall significantly positive impact on the fight against CFIT. However, time has given the industry affordable alternative sources of navigational data, and a wealth of operational data showing the shortcomings of many different navigation systems. In light of this, it is no longer appropriate that the onboard navigation systems are used as the primary navigation source for TAWS.

2.10 Unsafe operation

JAR 25.1309 (c) requires that '*Information concerning safe system operation condition must be provided to the crew* to enable them to take appropriate corrective action'. This incident demonstrated two means by which one system could indicate the unsafe operation of another.

Before the EGPWS warning occurred, the terrain detected by the radio altitude was at odds with the terrain expected by the EGPWS, initially by a few 100 ft but later by more than 1,000ft. This is an indication of a significant error in the database, aircraft location, aircraft altitude or radio altitude. Whilst it may be difficult to determine where the error lies, it might be feasible to alert the crew to such a significant mismatch.

During the flight in the vicinity of Addis Abeba, the FMS rejected the ADS VOR a number of times on the grounds of estimated position error. Had the information been effectively relayed to the crew, with appropriate procedures, the unsafe reliance on the ADS VOR for the procedural approach could have been questioned earlier.

2.11 Safety action

The operator took action to protect their susceptible aircraft by examining and restricting the routes upon which their non-GPS equipped aircraft could operate.

Airbus has taken action to advise operators of their recommendation to fit GPS to all TAWS but other types of aircraft will also be susceptible.

The UK CAA took action soon after the incident to inform existing UK operators of the possible hazard to navigation caused by these circumstances .

The above actions will have reached some operators of susceptible aircraft but a more global appreciation of the hazards identified has probably not been achieved. For some years to come there will be aircraft operating with equipment that has a similar susceptibility to a single failure. To correct this a revision of the equipment standards will be required.

3 Conclusions

3.1 Findings

1. The flight crew were properly licensed, medically fit and adequately rested to conduct the flight.

2. The flight crew followed their company's standard operational procedures.

3. The aircraft navigation and CFIT protection systems operated as designed.

4. The ADS VOR/DME was the only approach aid available for the aircraft.

5. An incorrect sealant was used to seal the ADS VOR/DME antenna housing during maintenance activity at some time prior to the incident; this allowed rain to penetrate the antenna housing and interfere with the antenna feeds.

6. The ADS VOR suffered a failure due to water ingression that resulted in significant distortion of the radiated pattern. The aircraft VOR sensors thereby provided incorrect bearing information to the navigation displays; the bearing error was non-uniform and included observed errors of up to 30 degrees.

7. As a result of failures in the monitor system the ADS VOR was not shut down and the airport authority was not alerted to the problem; this is contrary to ICAO requirements.

8. Flying with reference to the received ADS VOR bearing put the aircraft significantly to the north of the procedural and intended track.

9. There was significant terrain to the north of the procedural approach track and on each approach the safety of the aircraft was compromised by reduced terrain clearance.

10. The ADS VOR failure was a common mode failure that affected the flight deck instruments, the aircraft navigation systems, the aircraft CFIT alerting system and the terrain awareness display.

11. The FMS accepted the ADS VOR bearing when proximate to the ADS VOR and when flying on a vector along the antenna axis. However, it did detect problems and switch from radio updating when more distant from the ADS VOR. The resultant FMS cross track error on final approach was in the order of 3 nm.

12. The FMS did not alert the crew to the identified problem with the ADS VOR and was not required to do so.

13. The aircraft navigation system is not designed to handle identified problem sources in an effective long-term manner. It continued navigating using a position previously based on a source it had identified as bad and then allowed the same source to be used again.

14. The TAWS installation, in this case a Honeywell EGPWS installation, is designed to reduce the risk of CFIT. This is achieved by providing a terrain display to the crew, providing alerts against terrain closure away from a runway using its TCF alerting function and providing alerts against terrain rising ahead of the aircraft using its FLTA function. The older mode 2 alerting function also provides a warning against terrain closure. The installation complied with the required certification standards.

15. The existing TAWS certification standards were not sufficient to protect against this type of navigation error. The standards allow the use of navigation data sources that are inadequate for effective protection against CFIT. The standards do not account for common mode failures that can induce a CFIT condition, such as lateral and vertical position errors.

16. The TCF alerting function triggered a TOO LOW TERRAIN alert approximately 2 to 4 seconds before the point of closest approach to terrain. The FMS error did not sufficiently affect the TCF alert time to be the controlling factor in the lateness of the TCF alert.

17. The TCF alert is ineffective against steep terrain hazards, a fundamental limitation of look down alerting functions. This is why it is used in combination with the FLTA function of the EGPWS.

18. The FLTA function of the EGPWS ,which is the system's primary means of alerting against rising terrain ahead of the aircraft, did not issue an alert.

19. The FLTA was assessing terrain hazards against the incorrect terrain cells in the terrain database due to the error in the navigational data received from the FMS.

20. The FLTA would have been rendered ineffective by navigational errors smaller than those experienced.

21. The terrain display provided hazardously misleading terrain information to the crew that reinforced the other incorrect navigation display information.

22. The requirements that guard against hazardously misleading terrain displays specifically exclude the quality of the external navigation source from being considered.

23. The TAWS certification standards are such that even without a ground station failure such as the ADS VOR failure, the navigation source for TAWS can be in error by more than 0.5nm for 5% of the time. An error of this size near an airfield, where the terrain database cell sizes are small, means that the FLTA may not check the terrain cells that are in the flight path of the aircraft, significantly compromising the benefits of TAWS.

24. The EGPWS functions were inhibited for approximately 5% of landings on this aircraft. This will vary by installation type and route structure.

25. The EGPWS was actively using data that was conflicting, the expected terrain elevation was significantly different from the detected terrain elevation. No indication of this was given, or required to be given, to the crew.

26. The EGPWS mode 2B alerting function operated as per design but did not provide an alert. Under the circumstances of this event, the mode 2B standards do not define an effective alerting function. The ineffectiveness of mode 2B calls into question any credit mode 2B may be given as an effective backup to FLTA or TCF in the event that these functions should be degraded due to navigational issues.

27. Airbus have taken action since this event to advise operators of a change in policy regarding the use of GPS for TAWS operations. The recommendation is to use a GPS source for TAWS.

28. Other types of aircraft and Flight Management Systems are affected by this problem of inadequate navigation source information.

3.2 Causal factors

1. The incident was caused by the ADS VOR/DME providing incorrect bearing information thereby displacing any aircraft following the published ADS VOR/DME procedure to the north of track, amongst high terrain.

2. Quality controls associated with the maintenance and monitoring of the ADS VOR failed to ensure correct parts were used during maintenance and that the monitoring system was fully operational.

3. The aircraft system architecture was such that this single failure affected the flight instruments, the navigation systems, the CFIT alerting system and the terrain awareness display. In effect, a failure that created a CFIT hazard simultaneously affected all the means by which CFIT is guarded against.

4 Safety Recommendations

The systems that were fitted to the aircraft to provide a safety net against a CFIT accident performed as they were designed but were ineffective in preventing this incident. Therefore, the safety of the aircraft during the ADS VOR/DME approach procedure was entirely dependant on the correct operation of the ADS VOR and its monitoring systems. For as long as the ADS VOR continued to radiate incorrect bearing information there was a risk that another aircraft could suffer the same problem. The following recommendations are made:

Safety Recommendation 1: It is recommended that the Ethiopian Civil Aviation Authority review the quality mechanisms that govern maintenance and monitoring of the ground station facilities to ensure that the correct procedures and correct parts are used.

Safety Recommendation 2: It is recommended that the Ethiopian Civil Aviation Authority review their procedures for the issuing of NOTAMs and other safety related information to ensure a more robust process.

Safety Recommendation 3: It is recommended that the International Civil Aviation Organization review the methods by which the effectiveness of radio navigation aid ground station monitors are assured.

Since the original standards for TAWS were set the industry has improved the performance and understanding of the TAWS capabilities significantly beyond the required minimum standard. Due to the significance of these improvements the major aircraft manufacturers have encompassed many of these improvements into their new deliveries. However, there are no retrofit requirements and as long as non-GPS systems are present on aircraft there is a significant potential for a CFIT accident due to a navigation error.

Safety Recommendation 4: It is recommended that the European Aviation Safety Agency and the Federal Aviation Administration review and revise the existing TAWS certification requirements with a view to ensuring that they protect against common mode failures that could induce a CFIT accident. Furthermore the minimum requirements for the navigational accuracy of sources used for TAWS should be tightened to reflect the needs of the system to perform its function. These revised standards should then be applied retrospectively to all aircraft required to be fitted with TAWS.

Both the FMS and TAWS had sufficient information to identify that there was a problem with the ADS VOR and the derived position information but there is no mechanism or requirement to communicate this effectively to the crew.

Safety Recommendation 5: It is recommended that the European Aviation Safety Agency and the Federal Aviation Administration study the issues relating to the use of TAWS so that where data source problems are identified by the system the flight crew can be alerted.

Safety Recommendation 6: It is recommended that the European Aviation Safety Agency and the Federal Aviation Administration consider whether the crew should be alerted when a FMS has identified a recurrent problem with a particular navigation aid and furthermore consider whether the subsequent use of that navigation aid for position information is desirable.

APPENDIX 1

Transcript of R/T Communications

Time (UTC)	Source	
0:06:26	Aircraft 6711	Good morning, Juliet six seven one one descending flight level one six zero
0:06:31	?	Standby
0:06:34	Tower	Alpha Juliet six seven one one good morning, report distance.
0:06:39	Aircraft 6711	Aah, one five miles from Addis.
0:06:42	Tower	Roger, *unintelligible* one zero two nine re-cleared thirteen thousand five hundred, *unintelligible* cleared to commence approach upon arrival, report leaving the VOR outbound for the VOR/DME approach two five Left.
0:06:56	Aircraft 6711	…thirteen thousand five zero zero feet and report leaving the VOR for the the VOR/DME approach two five left Juliet six seven one one . Just confirm the QNH?
0:07:08	Tower	QNH one zero two nine .
0:07:11	Aircraft 6711	zero two nine
0:07:14	Tower	Report souls onboard.
0:07:20	Aircraft 6711?	six seven
0:07:23	Tower	*Unintelligible.*
0:07:27	Aircraft 6711	six seven passengers and seven crew.
0:07:30	Tower	*Unintelligible.*
0:09:18	Aircraft 6711	Lima Alpha Juliet six seven one one commencing VOR, the VOR/DME approach two ...
0:09:24	Break-in	... metres one zero two three …
	Tower	six seven one one report base turn complete inbound.
0:09:29	Aircraft 6711	...report base turn completed inbound BAsix seven one one .
0:13:21	Aircraft 6711	BA six seven one one base turn complete.
0:13:26	Tower	Lima Alpha Juliet six seven one one report final two five left. Wind calm.
0:13:32	Aircraft 6711	Report final two five left six seven one one .
0:16:38	?	*Unintelligible.*
0:17:12	Aircraft 6711	..six seven one one going around.
0:17:19	Tower	Lima Alpha Juliet six seven one one say again.
0:17:23	Aircraft 6711	Going around, standby.
0:18:10	Aircraft 6711	Tower Bmed six seven one one .

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0:18:13	Tower	Go ahead
0:18:16	Aircraft 6711	Yes the Addis VOR is not working on the approach, it dropped on the final part of the approach.
0:18:25	Tower	Alpha Juliet six seven one one, roger, climb…eh…thirteen thousand five hundred, please report entering the hold.
0:18:32	Aircraft 6711	OK, we're climbing out of *unintelligible*.
0:18:51	Tower	Lima Alpha Juliet six seven one one , do you *unintelligible* VOR?
0:18:55	Aircraft 6711	Standby.
0:19:04	Aircraft 6711	And eh we have a DME off the VOR but *unintelligible* VOR indication.
0:19:10	Tower	Confirm *unintelligible* VOR indication?
0:19:16	Aircraft 6711	OK, yeah, it's come back now, VOR indication has come back now.
0:19:21	Tower	Roger *unintelligible* VOR approach.
0:23:17	Aircraft 6711	Juliet six seven one one wind check please.
0:23:22	Tower	Wind calm
0:24:07	Aircraft 6711	Bmed six seven one one has left the hold we're outbound on the procedure.
0:24:15	Tower	Lima Alpha Juliet six seven one one , report leaving the VOR outbound for VOR/DME approach runway two five left.
0:24:24	Aircraft 6711	Affirm we have left the eh VOR for the VOR/DME two five left, six seven one one .
0:24:31	Aircraft 6711	six seven one one for information do you have the localizer still radiating on two five right?
0:24:40	Tower	Say again?
0:24:42	Aircraft 6711	Do you still have the ILS localizer radiating for two five right?
0:24:48	Tower	*Unintelligable* the localizer for eh two five right but now procedure is two five left
0:24:55	Aircraft 6711	Affirm *unintelligible* safety backup *unintelligible*
0:24:59	Tower	*Unintelligable.*
0:25:46	Tower	Alpha Juliet six seven one one eh confirm eh do you take VOR now?
0:25:52	Aircraft 6711	Affirm we receive the VOR now B med six seven one one .
0:25:57	Tower to unknown	*Unintelligable* caution eh the VOR is not reliable.
0:26:06	Aircraft KC	Calling tower Alpha Kilo Charlie.
0:27:07	Aircraft 6711	Tower, B med six seven one one .
0:27:12	Tower	Alpha Juliet six seven one one go ahead.
0:27:15	Aircraft 6711	Can we have the approach lights for the runway at maximum brightness please.

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0:27:21	Tower	Alpha Juliet eh six seven one one report final runway two five left wind is calm.
0:27:28	Aircraft 6711	Will report finals two five left, can you make sure the lights are full brightness please.
0:27:34	Tower	Roger.
0:27:45	Tower internal	*Unintelligable.*
0:29:34	Aircraft 6711	B med six seven one one inbound.
0:29:39	Tower	Lima Alpha Julliet six seven one one roger.
0:30:21	Tower	Alpha Juliet six seven one one have you seen the approach lights?
0:30:27	Aircraft 6711	Negative.
0:30:31	Tower	Report eh, runway in sight.
		Tape change over so timing discontinuity.
0:31:59	Aircraft 6711	B med six seven one one going around.
0:32:03	Tower	*Unintelligable.*
0:33:34	Aircraft 6711	Tower B med six seven one one
0:33:38	Tower	Go ahead
0:33:39	Aircraft 6711	Yeah there is no indication from the VOR in the latter stages of the approach, you completely lose the VOR.
0:33:51	Tower	Confirm you can't eh pick the VOR for your approach.
0:33:55	Aircraft 6711	Negative there is no VOR on the later stages of the approach.
0:34:05	Aircraft 6711	Bmed six seven one one can you confirm that you have a localizer that will transmit on two five right.
0:34:16	Tower	Confirm you like to land on two five right
0:34:19	Aircraft 6711	Negative. I want a localizer, a localizer approach. I cannot get in on the VOR, if I don't have anything else to go on I can't land.
0:34:29	Tower	So you want eh to make your approach eh via using localizer. Instrument landing localizer eh two five right and eh coming to two five left.
0:34:42	Aircraft 6711	I could land two five left from the localizer to two five right provided I can pickup the airfield you-see-if I can't see the airfield because the VOR isn't working there is not much else.
0:34:53	Tower	Yeah the localizer is working, the localizer is working for two five right, confirm you unintelligable establish on the localizer
0:35:06	Aircraft 6711	Eh negative we are not established on the localizer. I've received no information on the localizer signal and I am not getting the tone on the localizer signal. six seven one one ...entering the hold.

0:36:26	Tower	six seven one one roger copied and eh, are you equipped with GPS?
0:35:34	Aircraft 6711	Negative if we had GPS we'd find the airfield.
0:35:37	Tower	Without GPS eh, you pick VOR/DME, VOR/DME approach.
0:35:44	Aircraft 6711	We can't do a VOR/DME without a VOR, your VOR is not working.
0:35:49	Tower	Copied, the VOR is not eh working, you'll eh, you missed the VOR and in addition you missed a localizer.
0:35:57	Aircraft 6711	I missed the VOR because there is no VOR transmitting on final approach, I didn't see a localizer signal on approach either.
0:36:07	Tower	Roger, climb flight level one five zero in the hold, report when there