Turbulence and hail damage in-flight, Airbus A321-231, G-MIDJ

Micro-summary: This Airbus A321 experienced turbulence and significant hail damage in flight.

Event Date: 2003-05-26 at 1543 UTC

Investigative Body: Aircraft Accident Investigation Board (AAIB), United Kingdom

Investigative Body's Web Site: http://www.aaib.dft.gov/uk/

Note: Reprinted by kind permission of the AAIB.

Cautions:

1. Accident reports can be and sometimes are revised. Be sure to consult the investigative agency for the latest version before basing anything significant on content (e.g., thesis, research, etc).

2. Readers are advised that each report is a glimpse of events at specific points in time. While broad themes permeate the causal events leading up to crashes, and we can learn from those, the specific regulatory and technological environments can and do change. ***Your company's flight operations manual is the final authority as to the safe operation of your aircraft!***

3. Reports may or may not represent reality. Many many non-scientific factors go into an investigation, including the magnitude of the event, the experience of the investigator, the political climate, relationship with the regulatory authority, technological and recovery capabilities, etc. It is recommended that the reader review all reports analytically. Even a "bad" report can be a very useful launching point for learning.

4. Contact us before reproducing or redistributing a report from this anthology. Individual countries have very differing views on copyright! We can advise you on the steps to follow.

Airbus A321-231, G-MIDJ

Contents

Report Information

AAIB Bulletin No: 6/2004	**Ref: EW/C2003/05/03**	**Category: 1.1**
INCIDENT		
Aircraft Type and Registration:	Airbus A321-231, G-MIDJ	
No & Type of Engines:	2 V2533-A5 International Aero turbofan engines	
Year of Manufacture:	1999	
Date & Time (UTC):	26 May 2003 at 1543 hrs	
Location:	In the cruise at FL340, 70 nm south-east of Vienna	
Type of Flight:	Public Transport	
Persons on Board:	Crew - 8	Passengers - 213
Injuries:	Crew - None	Passengers - None
Nature of Damage:	Significant damage to radome, flight deck windows, stabiliser leading edges and engine nacelles	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	42 years	
Commander's Flying Experience:	11,457 hours (of which 262 were on type)	
	Last 90 days - 184 hours	
	Last 28 days - 49 hours	
Information Source:	AAIB Field Investigation	

Synopsis

The aircraft was in the cruise at FL340 approximately 70 nm south-east of Vienna when it encountered an area of severe turbulence and hail. Some of the flight deck windows became crazed and other areas of the airframe suffered extensive damage although this was not apparent to the crew. The aircraft made a precautionary descent to FL230, in accordance with the required abnormal procedures, and continued the flight to its destination of Manchester. The crew had no indication or warning that the aircraft was about to enter an area of severe turbulence, associated with the upper levels of a Cumulo-nimbus cloud. When they had been using the weather radar to check the route ahead of the aircraft, sometime before the encounter, the radar returns appeared benign.

History of the flight

The crew reported for duty at Manchester at 0555 hrs to operate a return flight to Larnaca in Cyprus. The only weather of note on the 'Sigmet' chart for the outbound sector was Cumulo-nimbus (Cb) cloud activity over the Italian Alps. During the outbound flight no turbulence was experienced and the only Cb activity observed by the crew was over Turkey, to the north of their route. Towering Cumulus (Cu), however, was seen to be building over the northern part of Cyprus. This activity and the Cbs were monitored by the crew on the aircraft's weather radar display. The radar appeared to be functioning correctly and displayed the type of returns the crew would have expected from such weather. The aircraft landed at Larnaca at 1135 hrs after an uneventful flight.

The aircraft was refuelled to full tanks and, after a one hour 'turn-round', departed Cyprus for Manchester with the First Officer (FO) as the Pilot Flying (PF). The commander's duties, as the Pilot Not Flying (PNF), were the management of the navigation and RT communications. The Standard Instrument Departure (SID) and climb to cruising altitude routed the aircraft to the west of the cloud building up on the north side of the island. The intensity and extent of this cloud was monitored by the crew on the weather radar.

The aircraft was initially cleared to 8,000 feet but before reaching that altitude, a further clearance to a cruising level of FL340 was issued and the climb continued. The cabin crew were cleared to commence the cabin service and the aircraft levelled at FL340. The pilots had been monitoring Cb activity, on the weather radar, to the east of their track and approximately two hours into the flight they noted some isolated Cb activity ahead of the aircraft to the right and left of their track. The Cb activity to the right of track was minor and isolated. Cb activity to the left of track was less intense.

The radar was set to a scale of 160 nm and with no significant returns ahead and no thunderstorm activity forecast the radar was switched OFF. The aircraft had been in clear skies above towering Cu for most of the flight and, in accordance with normal procedures, the radar had only been turned on when required.

As the flight progressed the aircraft entered some high Cirrus cloud. The FO, anticipating the possibility of turbulence, switched on the 'seat belt' signs and made a short public address (PA) informing the passengers and cabin crew that this was a precautionary measure. Shortly after the announcement the aircraft entered what the crew described as an area of 'light innocuous turbulence'.

Approximately 20 seconds later however, the turbulence increased through moderate to become severe. The autopilot (AP), which was selected ON in the 'Navigation Mode' at a speed of Mach 0.78 (M0.78), disconnected and the aircraft climbed rapidly above its assigned level. Intense hail then began to impact the aircraft. Both flight crew noted the master warning light illuminate as the autopilot disconnected but neither pilot heard the associated audio warning due to the noise of the hail. The FO flew the aircraft manually, selected engine ignition ON, set the speed to M.076 for the turbulence and turned on the cockpit dome light. The commander changed the range selector on Navigation Display (ND) to 40 nm to check for conflicting traffic on the Traffic Collision Avoidance System (TCAS), monitored the aircraft's speed on his Primary Flight Display (PFD), monitored the first officer's side stick inputs and cancelled the master caution light. Throughout, the PF attempted to regain FL340 and maintain track. The aircraft however, deviated 1,300 feet above to 300 feet below its assigned cruising level, rolling to angles of bank not exceeding 18°. Indications on the Vertical Speed Indicator (VSI) confirmed that on at least one occasion the rates of climb or descent exceeded 5,900 feet per minute.

A Boeing 757 was approximately 25 nm behind G-MIDJ on the same track. The commander of the 757 had his radar selected ON and he could not only see the weather radar returns on his ND but also G-MIDJ displayed by his TCAS. He thought that G-MIDJ had been heading for the gap between two lines of thunderstorms displayed on his radar but realised the gap was closing as the storms were building. He continued using his radar and noted the rapid increase in altitude of G-MIDJ on TCAS as it entered the storm. Initially, in the absence of any radio traffic he initially assumed that G-MIDJ was attempting to climb over the storm. He requested a turn to the right to avoid the weather, which was approved and passed safely clear of the storm activity.

Moments later the commander of G-MIDJ transmitted to Budapest ATC informing them that they were unable to maintain FL340 due to severe turbulence. He was unable to hear the reply because of the hail. This also prevented the pilots from hearing each other for, although they were wearing headsets, it is normal practice for the intercom to be selected OFF and cross-cockpit conversation to be conducted without the use of intercom.

After the aircraft cleared the area of turbulence and hail associated with the storm cell the pilots noticed that the left front (commander's) windscreen and the right (first officer's) Direct Vision (DV) window had sustained severe hail damage. The commander felt his windscreen and noted that, although there were visible signs of damage to the outer layers and an increase in airflow noise, the inside layer was undamaged but the heating had failed. The only caption displayed on the Electronic Central Aircraft Monitoring (ECAM) system indicated that the aircraft's ILS status had been downgraded to Category (CAT) III single only. The commander therefore referred to the Quick Reference Handbook (QRH) for the procedure to deal with a '*cracked windshield*'. This required a descent to FL230 or below and a maximum cabin differential pressure of 5 psi. Budapest ATC instructed the crew to contact Austrian Radar for their descent clearance and although only 'even' levels (FL240, FL220) are normally available for westbound flights on this route, the aircraft was cleared to the requested level of FL230. The aircraft descended gently at 1,500 feet per minute and, in accordance with the QRH procedure, the pressurisation was controlled manually. During the descent the Cabin Service Director (CSD) reported to the commander that everyone in the cabin was secure and that there were no injuries. The commander explained that the situation was still being assessed and an appropriate course of action considered.

The flight crew interrogated the system pages of the ECAM and noted that the engines appeared undamaged as individual engine vibration levels had not been affected as a result of the incident. The aircraft's fuel state had been checked approximately 20 minutes prior to the incident and at that time there had been an excess of 900 kg over the flight requirements. The aircraft appeared to have suffered only windscreen damage and the crew confirmed that at the lower cruising level of FL230 there was still sufficient fuel available to complete the flight. With sufficient fuel and no indication of the aircraft being unsafe the crew elected to continue to Manchester and informed ATC that they had damaged windscreens and would maintain FL230. Frequent monitoring of the fuel available against that required by the flight plan and the Flight Management Guidance System (FMGS) confirmed that sufficient fuel was available to land at Manchester with more than the minimum fuel required.

When the crew contacted London ATCC they re-confirmed that the aircraft had damaged windscreens. They were radar vectored for a CAT I ILS approach to Runway 24R at Manchester where the PF was able to carry out a normal manual landing, having disconnected the AP at approximately 800 feet on finals. The commander was able to monitor the approach even though his windscreen was significantly crazed. The FO taxied the aircraft to the stand where, as was normal procedure for that stand, the commander was able to park the aircraft under the guidance of a marshaller. The passengers exited the aircraft normally using steps positioned at doors L2 and L4.

It was not until the crew vacated the aircraft that they were aware of the extent and severity of the damage to other areas of the airframe. Even though the manufacturer later confirmed that the aircraft was in a safe condition to continue to its destination the commander stated that had he known the full extent of the damage he would have diverted after the incident to the nearest suitable airfield.

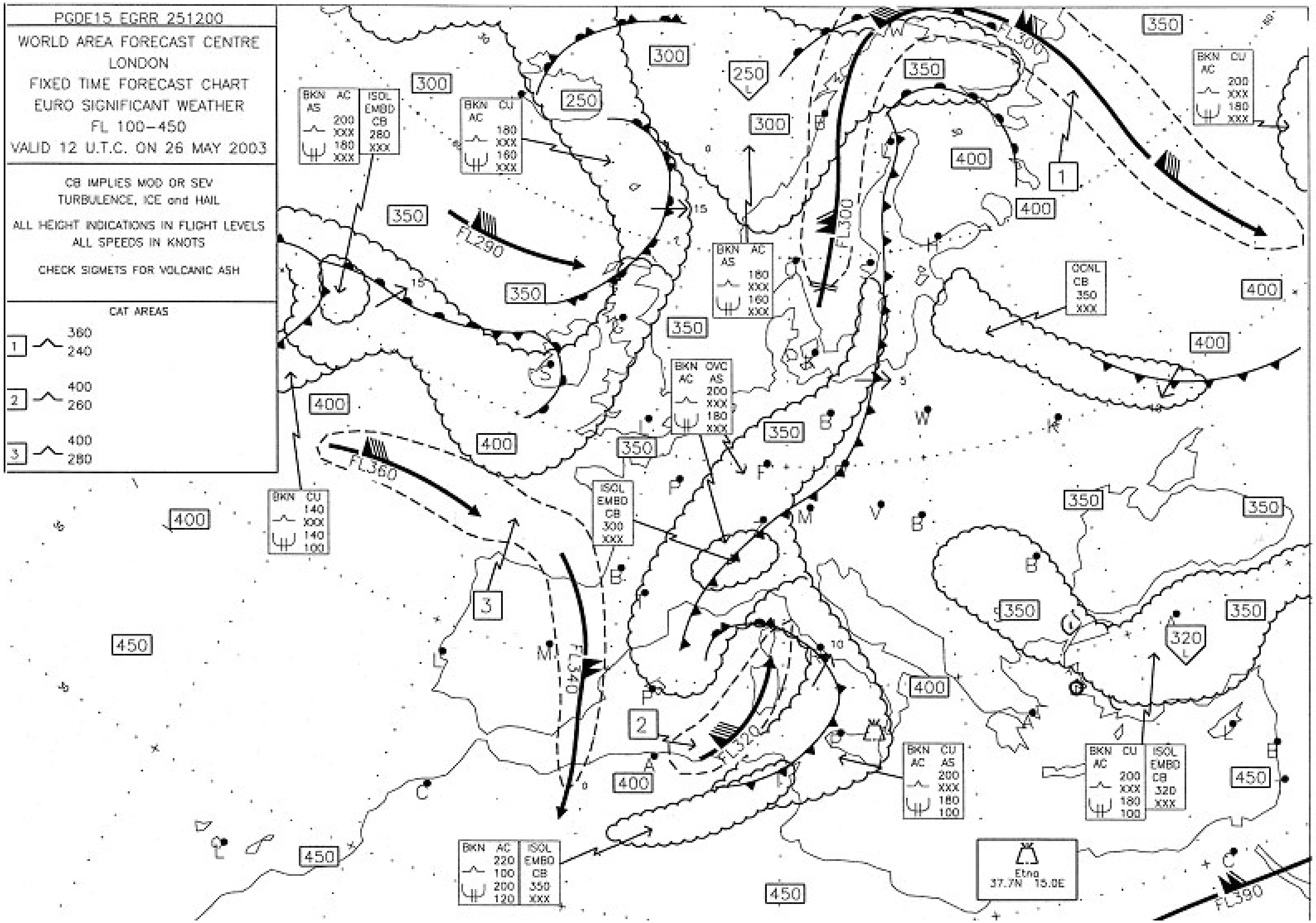
Meteorology

The synoptic situation at 1500 hrs on 26 May 2003 showed a frontal system lying from Poland to Switzerland with a potentially very unstable airmass to the east of the frontal boundary. Isolated Cumulo-nimbus clouds, with tops up to approximately FL400**,** were over the area around eastern Austria, Hungary, Czech Republic and Slovakia with associated hail, icing and turbulence. A ridge of high pressure was situated over the southern half of the British Isles with a weak warm front approaching England and Wales from the west.

The original written weather forecast, obtained by the crew prior to the flight, was not required to be retained after landing and was not available for scrutiny. A copy of the relevant Significant Weather chart, obtained from the Meteorological Office, however, is shown at Figure 1. This indicates isolated (ISOL) embedded (EMBD) Cb cloud with tops up to approximately FL300 over the Alps. It should be noted that the International Civil Aviation Organisation (ICAO) standard specifies that only EMBD Cb and occasional (OCNL) Cb or more, but not isolated ISOL Cb, should be depicted on the chart.

Figure 1: Significant Weather Chart

Satellite information

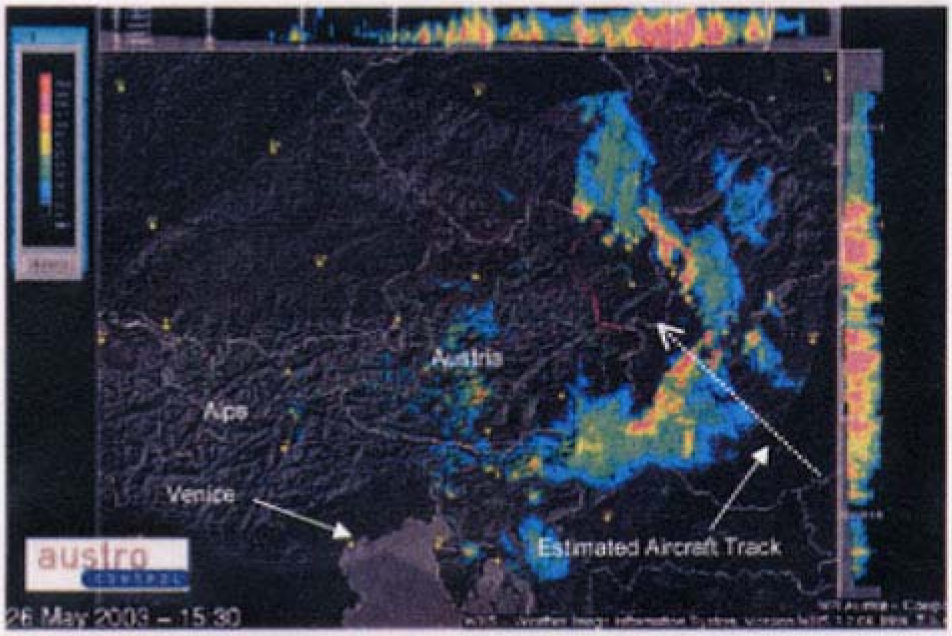


Significant Weather Chart

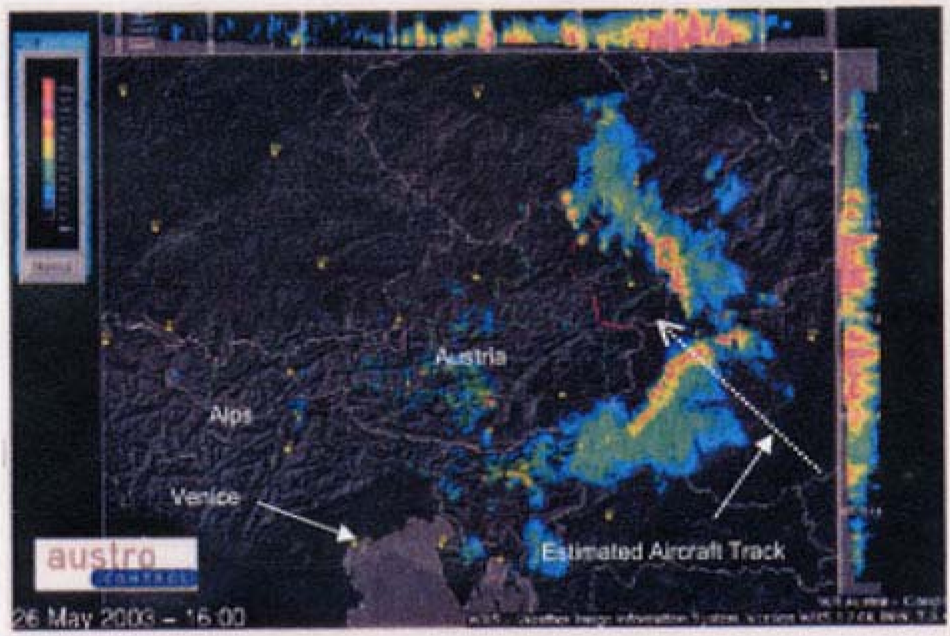
Figure 1

Satellite images of the cold front showing the weather and Cb activity are shown at Figure 2 with the approximate aircraft track indicated.

Figure 2: Satellite images



Satellite image at 1530 hrs



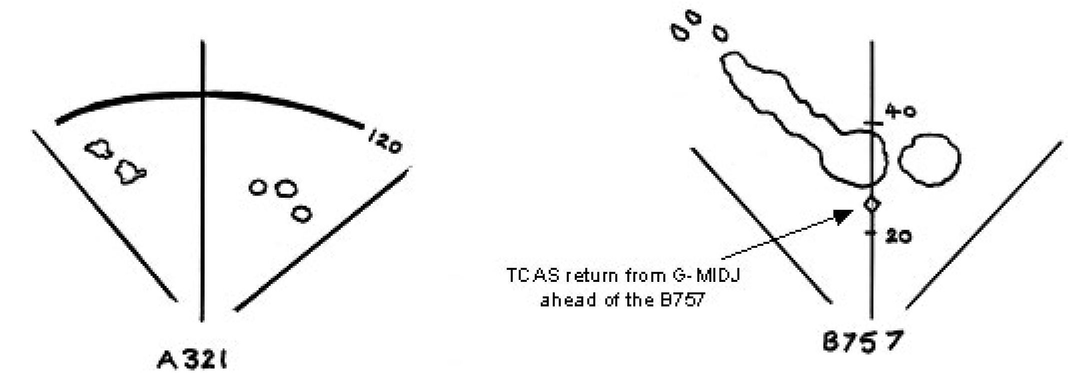
Satellite image at 1600 hrs

Figure 2

The radar picture

The actual weather radar picture seen by the crew is not recorded and therefore cannot be reproduced. A representative drawing from the crew of G-MIDJ, illustrating the radar returns they remembered seeing on their display some time before the incident, is shown on the left below. (Note: the crew reported that they thought the tilt was set between 2º and 3º down at this time).

Figure 3: Representative drawing from the crew of G-MIDJ



Note: The 120 range ring was drawn by the crew to provide a scale and is not present on the radar display.

Note: The drawings above depict the weather situation at different times. The left depicts the A321 approximately 80 nm from the weather returns; the right depicts the A321 5 nm from the returns.

The commander of the 757, who had his weather radar and TCAS selected ON and was using the tilt function of the scanner, saw on his display the TCAS return from the aircraft ahead and the weather radar returns. He was able to recollect the display at the time and an illustration of that display is shown on the right above.

Flight Recorders

The Digital Flight Data Recorder (DFDR) and Cockpit Voice Recorder (CVR) were removed from the aircraft and replayed at the AAIB.

Cockpit voice recorder

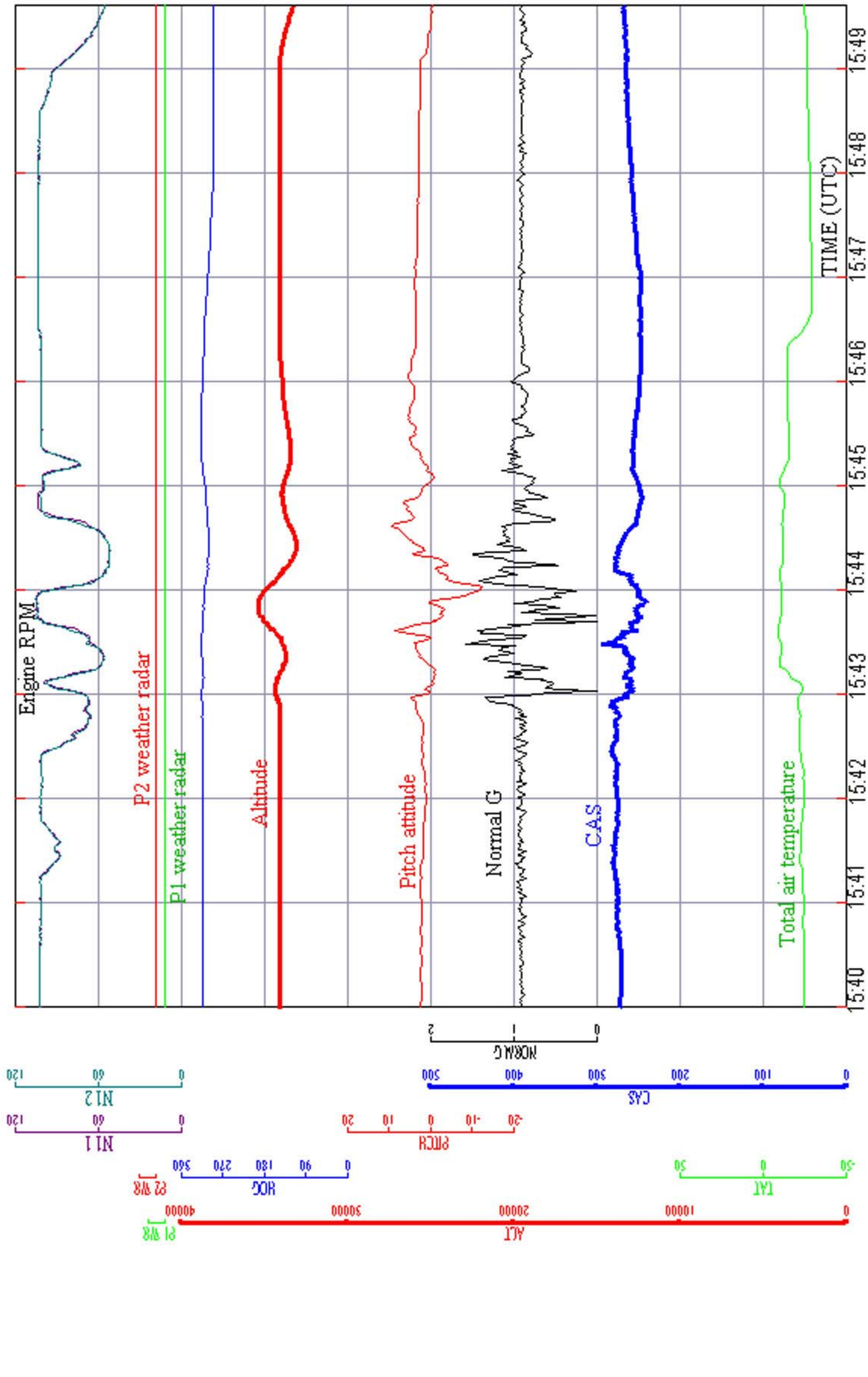
The CVR (2 hour duration) contained only a 30 minute recording of the incident flight as electrical ground power continued to be supplied to the unit after landing, over-writing some of the pertinent recording. The CVR however, confirmed that the first officer was the PF and that the hail damage had rendered the commander's windscreen crazed. The only other matter of note on the recording was an increase in cockpit ambient noise level after the hail encounter.

Digital flight data recorder

The DFDR contained a time history of the entire flight and showed that the aircraft took off at 1300 hrs and climbed steadily towards its cruising altitude. Two hours and twelve minutes into the cruise the DFDR recorded a severe turbulence encounter (see Figure 3) that lasted in excess of 3 minutes causing disturbances in all aircraft axes. The most severe disturbances were in the 'pitch' and in the 'normal' axes. Recordings during the encounter showed a maximum nose down pitch attitude of -15^{o} and a normal acceleration ranging between +1.5 g and -0.3 g. The aircraft descended to FL230 six minutes after the encounter and remained at this flight level until its descent into Manchester. The aircraft landed normally, with the first officer at the controls, at 1803 hrs.

Figure 4: DFDR Trace for G-MIDJ

DFDR Trace for G-MIDJ

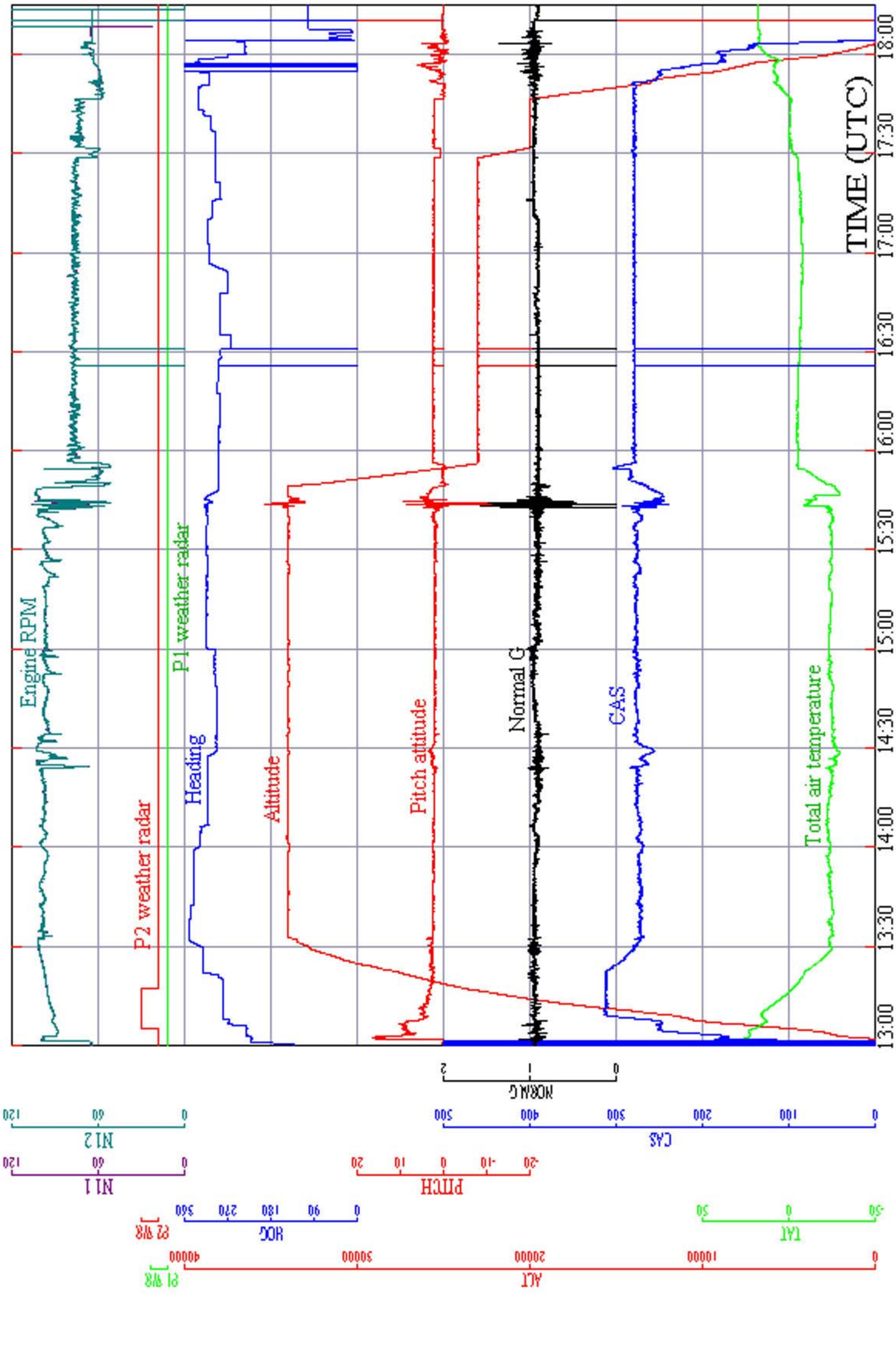


Weather radar data

Recorded data concerning the use of the weather radar (see Figure 4) showed that it was switched on and displayed to the first officer for approximately 12 minutes as the aircraft climbed from 4,700 feet through 23,600 feet. The DFDR did not record any use of the weather radar during the remainder of the flight.

Figure 5: DFDR Trace for G-MIDJ

DFDR Trace for G-MIDJ



After the aircraft had been repaired AAIB inspectors, with the assistance of the operator's engineers, carried out a full operational check of the weather radar and its recording on the DFDR. The DFDR data was downloaded after the check and analysis confirmed that the DFDR faithfully recorded the use of the weather radar. It should be noted however that the data recording was not confirmed post incident before major repair work had been undertaken and some radar components had been replaced.

Passenger cabin activity`

In the aircraft cabin, which was in a 'Charter' configuration, were 213 passengers and 6 cabin crew, including a Cabin Service Director (CSD), working with two crew in the forward cabin and three in the aft cabin area. Although the outbound flight had been uneventful the aircraft commander had warned the cabin crew, at their initial briefing, that they could experience some turbulence during the outbound sector of the flight.

The incident

Immediately prior to the incident, the cabin crew were positioned with three in the forward galley, two in the aft galley and one who had just commenced moving forward through the cabin. The meal service had been completed and all the passenger food trolleys had been stowed and secured. All were aware that the seat belt sign had been switched ON and heard the PF's PA announcement warning of possible turbulence. The PF contacted the CSD on the interphone after making the PA announcement to confirm it had been heard and was being responded to.

Several passengers and cabin crew members were not seated and secure when the turbulence rapidly increased from slight, through moderate to severe causing the aircraft to enter a sudden and rapid descent. The cabin crew member and three passengers moving forward along the aisle to return to their seats fell to the floor and remained there. One passenger, seated but not secure, rose out of her seat and struck her head on the overhead Passenger Service Unit (PSU). A cabin crew member, unsuccessfully attempting to stow the crew meals trolley in the rear galley, was lifted from the floor, along with the trolley. A cabin crew colleague, seated and secure in an adjacent cabin crew seat, however, attempted to hold onto her to prevent her from falling. Two cabin crew members, along with the CSD, positioned in the forward galley, had not had time to make themselves secure. They also rose clear of the floor momentarily. The CSD was able to make a short PA for everyone standing to sit down on the floor. Those passengers who ended up on the floor were restrained, as much as was possible, by the crew.

Post incident

When the noise had abated and the turbulence ceased those passengers and crew on the floor got up and the passengers returned to their seats. The CSD contacted the flight deck on the interphone and was instructed by the commander to keep the passengers seated. He also reassured him that the flight crew were in full control of the aircraft and would call back shortly. The CSD used the PA to check if any of the passengers were injured but none were. He then walked to the rear galley to ensure that none of the rear cabin crew was injured. As passengers remained in their seats, two passengers, who had been occupying the front and rear toilets at the time of the incident, emerged shaken but uninjured to return to their seats. The cabin crew cleared up the galley areas and a senior stewardess moved through the cabin talking to each passenger and reassuring those that were distressed. The CSD visited the flight deck to inform the commander that the passenger cabin was safe and that no one had been injured. He was briefed by the commander that the windscreen was damaged but all other aircraft systems were normal and, subject to fuel considerations, the aircraft would continue on to Manchester. This information was relayed to the other cabin crew members. Once order had been restored the commander authorised the commencement of a bar service to enhance an atmosphere of normality and approximately one hour later, at the request of the senior stewardess who had spoken to the passengers, a further PA was made to reassure the passengers.

Aircraft damage

The aircraft sustained damage to most of the leading edge surfaces of the airframe. The outer layer of the radome surface had been damaged by the hail although it was not punctured. Airflow impinging on the damaged outer layer then caused the inner honeycomb layer to implode onto the flat plate antenna of the weather radar, rendering it unusable. Post incident inspection of the radome, by the aircraft manufacturer, showed that it was not at risk of detaching from the aircraft.

The captain's windscreen suffered a cracked outer layer, as had the FO's DV window. The damage to the captain's windscreen was to the extent that the windscreen heater element, which ran through the outer layer, was rendered inoperative. The first officer's main (front) windscreen remained intact. Both were subsequently subjected to a detailed examination by the manufacturer. The windscreen and DV window, which are constructed of several plys, consist of an outer ply of glass that is non-structural, and internal plys, also of glass, providing the structural element. Both the cracked windscreen and DV window showed evidence of several impact damage points from the hail, resulting in the fracture of the glass. This was limited to the outer ply and did not cause a reduction in the structural integrity of either of them. Inspection of the captain's main (front) windscreen showed a single fracture origin in the lower third of the glass and in excess of 85 other impact points. The first officer's DV window showed two fracture origins in the glass and approximately 8 additional impact points.

Other areas of the aircraft structure also sustained extensive damage from the hail. The crown skin above the flight deck suffered several dents some to a depth of approximately 0.05 inches with a diameter of 1 inch. There was also denting to the aircraft skin below the first officer's DV window.

The leading edges of the wings, the engine intake lips, the engine saddle fairings and the horizontal stabiliser all had dents along their leading edges. The horizontal stabiliser tips exhibited the worst damage, with the left tip being holed.

The composite structure of the aircraft, the wing to body fairings, pylon to wing attachment fairings and the leading edge of the vertical fin, were also exposed to hail damage. This damage, however, resulted only in paint erosion.

Engine damage was limited to the engine intake lips. The fan blades were intact and showed no signs of impact with the hail. Furthermore, internal boroscope examination did not show any other damage within the engines.

The Airbus A321 has a system that produces a post flight report on defects recorded by the computer systems during flight. Faults were recorded for the captain's windscreen heater, the standby pitot probe heater and due to autopilot disengagement. All these faults were recorded at 1543 hrs and are directly related to the hail encounter.

Weather radar system

The weather radar system fitted to the aircraft works on the principle of radio echoing. The radar operates in the x-band producing energy at very high frequency in the form of electromagnetic pulses. These pulses are emitted from a flat plate antenna mounted in the radome at the front of the aircraft. The antenna scans left to right over an angle of 180° with the pulses being emitted at regular intervals during the scan. When the electromagnetic pulses come in contact with weather they are reflected back to the scanner. The direction, distance and intensity is then calculated by a transceiver/receiver unit and displayed to the crew.

A control panel for the weather radar is provided on the cockpit centre console. This incorporates the ON/OFF selector of the entire weather radar system. In addition there are controls for gain, tilt, mode and ground clutter suppression. When the weather radar is switched ON the weather information can be displayed on the captain's and first officer's ND. Each pilot has a separate control panel on the glareshield where he can not only control his respective ND but also the range of the weather display up to a maximum distance of 320 nm. Weather is not displayed if the ND selection is to the 'plan' mode. An additional system allows for the display of terrain data on the ND rather than weather. Normal practise is for the PNF to have his ND selected to display terrain data and the PF to have his ND selected to show weather.

The tilt of the weather radar antenna beam, stabilised automatically in pitch and roll to compensate for the aircraft's attitude, can be controlled manually to point above and below the horizon up to ±15°. This allows the antenna beam to be moved upwards to reduce the radar returns from the ground or to scan different levels of the atmosphere ahead. If the tilt is selected to too high or too low an angle however, some weather activity, that might affect the aircraft on the track ahead, may be missed.

Weather radar system tests

Following the accident the weather radar transmitter/receiver, control panel and the scanner pedestal were tested by the manufacturer. During the test of the transmitter/receiver there was a single test failure on the input/output card, however, despite subsequent repeated tests the fault could not be reproduced and it was thus concluded that the single failure was a 'test glitch'. The remaining equipment operated without fault.

Operation and limitations of the weather radar equipment

The operating procedures and limitations of the weather radar are comprehensively covered in the company's Operations Manual (OM). The Supplementary Techniques in the OM, for the operation of the weather radar, have been reproduced from the manufacturer's instructions.

The capabilities and limitations of the equipment, detailed in the beginning of the instructions, are summarised below:

> *GENERAL*
>
> *The radar is nothing more than a precipitation detector. How much weather it detects depends upon the raindrops, their size, composition and number.*
>
> *The radar does not detect:*
>
>> *Clouds, fog or wind (too small droplets or no precipitation at all)*
>>
>> *Clear air turbulence (no precipitation)*
>>
>> *Wind shear (no precipitation except in microburst)*
>>
>> *Lightning.*

The radar does detect:

Rainfall

Wet hail and wet turbulence

Ice crystals, dry hail and dry snow (above 30,000 feet) will only give small reflections.

The technique for operating the weather radar effectively utilises a combination of range and beam depression or elevation referred to as tilt. Guidance on the range setting that should be set on the ND for each pilot for avoiding thunderstorms recommends that the PF selects his ND to 80 nm and the PNF to 160 nm. The ND should be set to a range of 40 nm when in 'Turbulence Mode' and the antenna tilted to avoid ground returns. The importance of readjusting the tilt frequently in order to monitor storm development and to get the best cell echo is emphasised. Failure to tilt the antenna down periodically may cause a target to disappear.

As the 0° tilt angle is slaved to the horizon, a formula is provided for calculating the vertical distance between the top of the weather cell and the aircraft flight level. The tilt angle element of the formula is based on adjusting the tilt until the echo begins to disappear and then noting the tilt angle.

The company provide operating procedures, titled *'Encountering Adverse and Potentially Hazardous Atmospheric Conditions' covering the situation where thunderstorm activity is detected either visually or by using the weather radar. The information includes 'Techniques for Flying Through Areas of Thunderstorm Activity' and the advice given is that above 30,000 feet, 'avoid all echoes by 20 miles'. Advice also states that 'the pilot should not attempt to penetrate a cell or clear its top by less than 5,000 feet vertically, because otherwise the aircraft may encounter severe turbulence. If the top of the cell is at or above 25,000 feet, overflying should be avoided due to the possibility of encountering turbulence stronger than expected'.*

A formula for calculating the vertical distance between the top of the weather cell detected on the radar and the aircraft flight level is provided as:

Vertical distance (feet) = range of cell (nm) x radar depression angle (°) x 100.

Weather radar training

Crew training in the use of the weather radar is carried out during the aircraft type conversion course and initial line training. Procedures, set out in the 'supplementary techniques' for the use of the weather radar mentioned previously, and training videos, covering the use of the weather radar and adverse weather operations, are also provided by the operator.

Recent developments

The latest weather radar equipment, called a 'multi-scan system', incorporates an antenna that not only automatically scans left to right but also up and down. This system also incorporates automatic ground clutter suppression allowing only weather to be displayed. By scanning the whole atmosphere precipitation at the bottom of the thunderstorm cell, that is normally hidden within ground clutter, can be detected. Thus thunderstorms can be displayed more clearly and sooner. The present in-service systems' detection level is poorer in that when set to scan only the top of a thunderstorm cell they will only be targeting levels of the atmosphere where only dry ice is present. This newer equipment thus encourages aircraft track adjustments around thunderstorm cells that may contain areas of severe turbulence present at levels undetected by the present radar equipment.

Flight Management Guidance System (FMGS)

Having checked that the aircraft systems were in a safe condition, the crew used the FMGS to determine whether the aircraft had sufficient fuel remaining to continue the flight to Manchester. They decided that an en-route diversion was not required and by remaining on their planned route the fuel required on the flight plan at each way-point could easily be checked against the fuel available. The FMGS 'fuel page' provided a calculation of the fuel required to continue to Manchester, at the lower level of FL230, as well as any extra fuel that was available. The extra fuel available just before the aircraft entered the hail had been 900 kg. The fuel calculations made by the FMGS, however, are based on aircraft performance data stored in the computer. This data (also available to the crew in hard copy), calculated on the assumption that the aircraft is aerodynamically undamaged, and not on fuel actually being consumed, is used to establish the fuel required. The extra fuel figure is continually re-calculated by the FMGS by subtracting the fuel required from the fuel available.

The radome and aerodynamically significant airframe surfaces of G-MIDJ were damaged by hail and the total drag coefficient of the airframe, and thus its performance were, to some unknown extent, affected. The FMGS fuel calculations did not take account of this change and thus the fuel required to destination, displayed to the crew, was somewhat unrepresentative. In the event the resultant increase in drag was subsequently found to be insignificant and constant monitoring of the fuel state by the crew ensured that the aircraft arrived at its destination with more than the minimum fuel prescribed.

It is interesting to note that, according to the manufacturer, if the radome had become detached from the aircraft, the fuel burn, resulting from the increased drag, could have been increased by as much as 27%. This would clearly have caused a major difference between the computed fuel required and the actual fuel required and would have manifested itself as a rapid reduction in the extra fuel available or the estimated fuel at destination.

Discussion

Thunderstorm activity was only depicted on the forecast Significant Weather charts for the route to Cyprus as 'ISOL EMBD CB' over the Alps. This was noted by the flight crew and at the pre-flight briefing the commander warned the cabin crew of the possibility of turbulence occurring during that part of the flight. The line of CB activity associated with the cold front lying across Hungary was not depicted on the chart as its intensity was forecast as not meeting the 'EMBD' or 'OCNL CB' criteria.

The departure from Cyprus was flown in clear conditions where the weather radar was only used to monitor the cloud building up over the northern part of the island and over the Turkish mainland to the right of the intended track. This weather was clearly depicted on the chart and the commander visually assessed the tops of the clouds to be at approximately FL280. Thereafter the flight was generally conducted in clear conditions above some ISOL CU with the flight crew being able to visually assess the weather ahead of the aircraft. The weather radar, when selected, was displayed on the ND being used by the PF and was visible to the commander.

As the flight progressed neither pilot adjusted the radar tilt leaving it selected 2º to 3º down. They were satisfied that the weather returns to the right and minor returns to the left of track posed no significant threat to the aircraft and thus the radar was selected OFF.

The weather radar has the limitation that ice crystals, dry hail and dry snow above 30,000 feet will only give small reflections. A pilot must therefore rely on vertical scanning of a storm cell, using the tilt facility to direct the radar beam, in order to detect adverse weather. This was not the technique being used when the crew observed what they interpreted as minor returns before they deselected the radar. They thus entered an area of significant turbulence and hail without warning.

As a result the aircraft suffered significant damage to the airframe and some of the flight deck windows. The only damage visible to the crew however was that evident on the flight deck. Neither the commander nor the FO left the flight deck to examine the wings or engine intakes from the passenger cabin windows. Had they done so it is unlikely that they would have been able to appreciate the level of damage to the aircraft as the small but numerous indentations left by the hail stones were not visible from the cabin. Furthermore, the areas where the hail had penetrated the aircraft skin were not visible from within the aircraft.

The manufacturer's opinion was sought regarding whether or not a diversion should have been carried out given the level of damage caused to the aircraft. They believed that the design of the structure, based on certification requirements and design specifications, was such that it absorbed the damage and the aircraft remained in a safe condition.

The FMGS provided information on the fuel estimated to be on board when the aircraft arrived at its' destination and any extra fuel available. When the aircraft descended and levelled at FL230 these amounts were recalculated by the FMGS computer and should have remained constant for the remainder of the flight. Any unexplained reduction of these amounts could have indicated degradation in the aircraft's performance brought about by an increase in airframe drag caused by the damage. This would have been of greater potential significance if the aircraft had been carrying out an Extended Range Twinjet Operation (ETOPs).

The windscreen in front of the commander and the DV window on the FO's side were both damaged. In the event, although the first officer carried out the landing and taxi to the stand, the commander still had enough vision to park the aircraft. It is worthy of note that if the damage had been more significant and the visibility through both front windscreens had been degraded the crew would still have been able to have landed the aircraft using the autoland facility.

Finally, testing of the FDR showed that it correctly recorded when the weather radar was selected ON or OFF. This recorded evidence however, is at variance with the recollection by the crew of when the radar was being operated. It is of note that the FDR discreet, recording the status of the weather radar, was only tested after significant disruption to, and reconnection of the aircraft avionics system.

Therefore because the reliability of the recorded evidence could be questioned the investigation accepted the account of the events provided by the crew.

Conclusions

This serious incident occurred when the aircraft, initially cruising in VMC, entered an area of cirrus cloud and penetrated an area of severe turbulence and hail. The weather radar, when used by the crew, did not show the severity of the weather ahead of the aircraft. This weather however, was observed by the crew of the B757 on their weather radar display. The apparent lack of significant weather returns resulted in the crew of the G-MIGJ turning off their weather radar. Having entered the area of turbulence and hail associated with a storm cell, the PF made measured control inputs, monitored by the commander, which reduced the excursions of the aircraft without imposing large load factors on the airframe or those onboard. The absence of injuries sustained by the passengers and crew was solely attributable to the timely illumination of the fasten seat belt signs and the fact that most passengers were seated with their seat belts secure. The actions by the cabin crew, in not attempting to move about the cabin but remaining on the floor during the worst of the turbulence, probably assisted in avoiding injury. The maintenance of communication between the flight deck and cabin crew throughout the flight meant that all crew were fully aware of the resulting course of action decided upon by the commander. Having made an assessment of the damage to the aircraft caused by the hail and the serviceability of the aircraft systems the flight deck crew continued to the planned destination of Manchester, monitoring the fuel situation to ensure adequate fuel was available to safely complete the flight.

It was not until the crew vacated the aircraft that they were aware of the extent and severity of the damage to other areas of the airframe. Even though the manufacturer later confirmed that the aircraft was in a safe condition to continue to its destination the commander stated that had he known the full extent of the damage he would have diverted after the incident to the nearest suitable airfield.

Follow-up actions

The operator has since issued a Flying Staff Instruction to all flight crews reminding them of the correct use of the weather radar.

Recommendation

Present guidance material not only suggests that, in areas of thunderstorm activity, readjusting the radar tilt frequently is the only way to monitor storm development but also that when the upper limit of the storm cell is determined it should be avoided vertically by at least 5,000 feet. The inability of weather radar to detect certain types of precipitation, associated with storm cells, in the upper levels of the atmosphere above 30,000 feet however make it impossible to determine with any accuracy the upper limit of a cell when its vertical development exceeds 30,000 feet. Calculations to determine the aircraft's clearance above the upper limit of a cell can therefore be inaccurate resulting in an aircraft entering the active element of a storm cell whilst attempting to safety over-fly it. It is therefore recommended that:

Safety Recommendation 2004-47

The Civil Aviation Authority should consider reviewing their guidance material concerning the use and interpretation of airborne weather radar, with a view to highlighting the potential for displayed data to be unreliable when used for calculating the safe vertical clearance for overflight of active storm cells.