SERIOUS INCIDENT

Aircraft Type and Registration:	Boeing 737-8AS, EI-GJT
No & Type of Engines:	2 CFM56-7B26E turbofan engines
Year of Manufacture:	2018 (Serial no: 44837)
Date & Time (UTC):	9 October 2018 at 2205 hrs
Location:	En route from Porto Airport, Portugal to Edinburgh Airport
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 6 Passengers - 177
Injuries:	Crew - None Passengers - None
Nature of Damage:	None reported
Commander's Licence:	Air Transport Pilot's Licence
Commander's Age:	61 years
Commander's Flying Experience:	19,500 hours (of which 350 were on type) Last 90 days - 170 hours Last 28 days - 60 hours
Information Source:	AAIB Field Investigation

Synopsis

Shortly after reaching cruise at FL360 the commander's attitude indicator malfunctioned affecting numerous aircraft systems, and the aircraft climbed 600 ft. After a significant time delay an IRS caution was displayed. The Quick Reference Handbook (QRH) was followed by the crew and the left Air Data Inertial Reference Unit (ADIRU) was put into ATT mode. The left Primary Flight Display (PFD) continued to display erroneous attitude information to the pilot, and other systems were also affected. The aircraft was flown manually to Edinburgh where it landed safely.

The left Inertial Reference System (IRS) suffered a transient fault in one of its accelerometers which led to an erroneous calculation of position. False position information led to the incorrect attitude information on the commander's PFD, and the autopilot (AP) responded by initiating a slow climb.

One Safety Recommendation is made concerning the Boeing 737 QRH.

History of the flight

The flight was scheduled from Porto, Portugal, to Edinburgh with 6 crew and 177 passengers. The crew had operated the sector into Porto and there had been no technical issues with the aircraft prior to departure for Edinburgh. The crew conducted turnaround procedures for the IRS in accordance with the operator's procedures. The

aircraft left the stand at 1953 hrs and took off at 2000 hrs. The departure and climb were uneventful and the aircraft established in cruise flight at FL360.

Shortly after crossing into the Brest Flight Information Region (FIR), the aircraft began a slow and un-commanded pitch up. The aircraft left its planned cruise altitude and climbed to approximately FL366. As the speed decayed below the minimum manoeuvring speed, the autothrottle minimum speed protection activated increasing the N_1 (thrust) to approximately 95% (although the co-pilot also recalled increasing power). The commander's PFD initially indicated a pitch attitude of around 10° nose-up, though the crew's perception was that the actual aircraft attitude was lower than this. The altitude warning sounded indicating a deviation from the selected flight level. The commander deselected the AP and autothrottle (AT), and the aircraft was recovered to level flight manually using standby instruments.

The initial pitch indication on the commander's PFD was followed by a slow 'topple' in roll with the attitude indicator (AI) showing around 60° left angle of bank. The yellow pitch, roll and flight path vector (FPV) comparator annunciations appeared on both crew PFDs[1]. It appeared that the co-pilot's flight instruments were serviceable, however.

During the recovery, the aircraft descended to FL357 and then returned to its assigned cruise altitude of FL360. The crew discussed the failed attitude indication and the comparator annunciations. They consulted the QRH for a checklist related to these indications but found no guidance. They also consulted the Flight Crew Operating Manual (FCOM) but again found nothing of value to assist in resolving the issue. They then engaged the AP on the co-pilot's side.

There are checklists in the QRH for '*Display Failure*', but the symptoms covered by these are significantly different from those encountered by the crew. They tried to select the AP lateral navigation mode (LNAV) but while the AP would engage in this mode it did not operate correctly, so the crew engaged the heading select mode (HDG SEL). Due to the thrust changes made by the AT during the event, the cause of which the crew felt was unresolved, the crew elected to continue using manual thrust.

After approximately 10 minutes, AP B disconnected and the Master Caution System illuminated with an IRS caution. This drew the crew's attention to a left IRS FAULT indication on the IRS Mode Select Unit (MSU). The MSU is in the overhead avionics panel and, as it is out of direct crew view, caution lights in the system trigger the Master Caution System. The commander took control of the aircraft and directed the co-pilot to action the QRH checklist. The crew then completed the '*IRS Fault'* checklist as directed by the QRH. The checklist has several steps and decision points which the crew discussed and completed. The IRS had been correctly set to NAV for the flight, but the checklist now called for the crew to select ATT on the MSU, which they did.

Footnote

[1] Pitch and Roll comparator annunciations appear on the pilots' PFDs when the associated parameter differs between their instruments by more than 5º. The indications flash for 10 seconds then remain steady.

The objective of selecting ATT is to recover limited ADIRU operation following an inflight power loss or certain ADIRU fault conditions. Selecting ATT mode resets the local vertical reference. Navigation data (position, groundspeed, track and wind information) is not available in ATT and is removed from the ARINC 429 data bus. The decision point which follows this action in the checklist is based solely on whether the fault light clears: if it does, the QRH checklist ends with the advice to not select either AP. In this case, on selecting ATT the fault light cleared but the IRS continued to provide erroneous attitude data to the pilot's PFD due to a faulty accelerometer. The crew continued in manual flight, sharing the flying task. They considered diverting to an alternate airport but, given the aircraft was controllable, elected to continue to the planned destination of Edinburgh. During the later stages of the cruise, the co-pilot noticed some unexpected handling characteristics in roll.

For the arrival into Edinburgh the weather was a moderate south-westerly wind, gusting to 30 kt, with good visibility and no cloud below 3,000 ft. As the aircraft neared Edinburgh, the crew declared a PAN to Scottish ATC and informed them that there were issues with the aircraft's APs. During their preparations for the approach, the crew considered that the failed IRS would influence other systems and they prepared for this during their approach brief. There was a failure of a single channel of the speed trim system, and the possibility of stick shaker activation was of particular concern. During the approach, they encountered erroneous airspeed and windshear warnings, and the autobrake system would not arm. The roll issues noted by the co-pilot were more evident, but the crew were able to control them satisfactorily and made an ILS approach in good weather conditions. The landing was uneventful, using manual braking, after which the aircraft taxied to the stand where the passengers disembarked.

Recorded information

The aircraft's flight data recorder (FDR) and cockpit voice recorder (CVR) were removed from the aircraft and downloaded at the AAIB where their recorded information was analysed. The duration of the CVR was two hours and included the event. The FDR recorded just over 107 hours of data.

Figure 1 is a plot of the aircraft's latitude and longitude, recorded from the Flight Management Computer (FMC) and the left IRS, together with the groundspeed indicated on the commander's PFD. The figure shows that at 2039 hrs the latitude and longitude in the left IRS began to drift with a corresponding 250 kt jump in the indicated groundspeed.

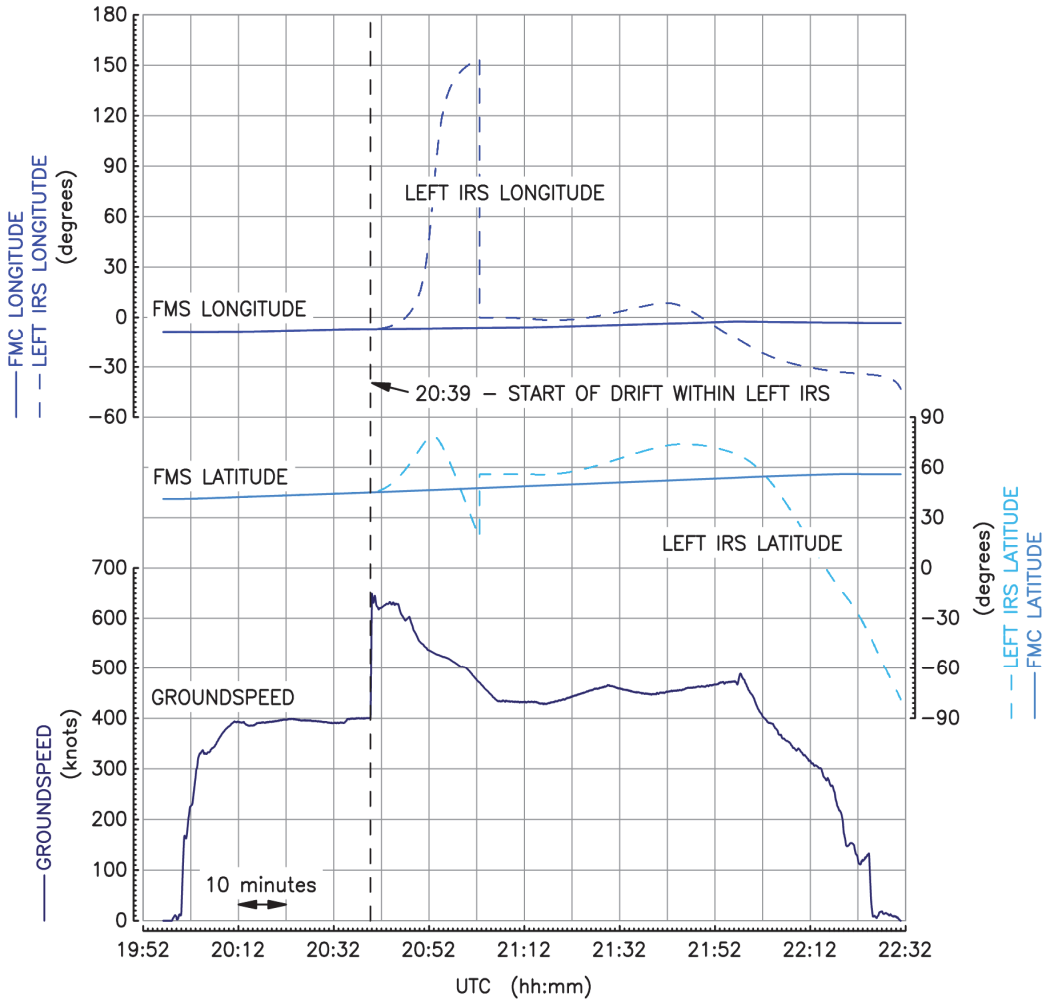

Figure 1

Left IRS latitude and longitude drift during the flight

Figure 2 is a closeup of salient parameters recorded on the FDR from when the left IRS started to drift until just after the failed attitude indication was given. Highlighted in the figure shortly after the drift started are the climb to FL367 from FL360, the increase in N_1 to 95%, the pitch up, and the decrease in airspeed from about 250 kt to below 232 kt when a minimum airspeed warning was triggered. The erroneous attitude, heading and groundspeed information presented to the commander are also plotted and show the pitch attitude increasing to 90° and the heading changing by nearly 180° over a period of about 20 minutes, after which the aircraft issued an indication of invalid attitude information.

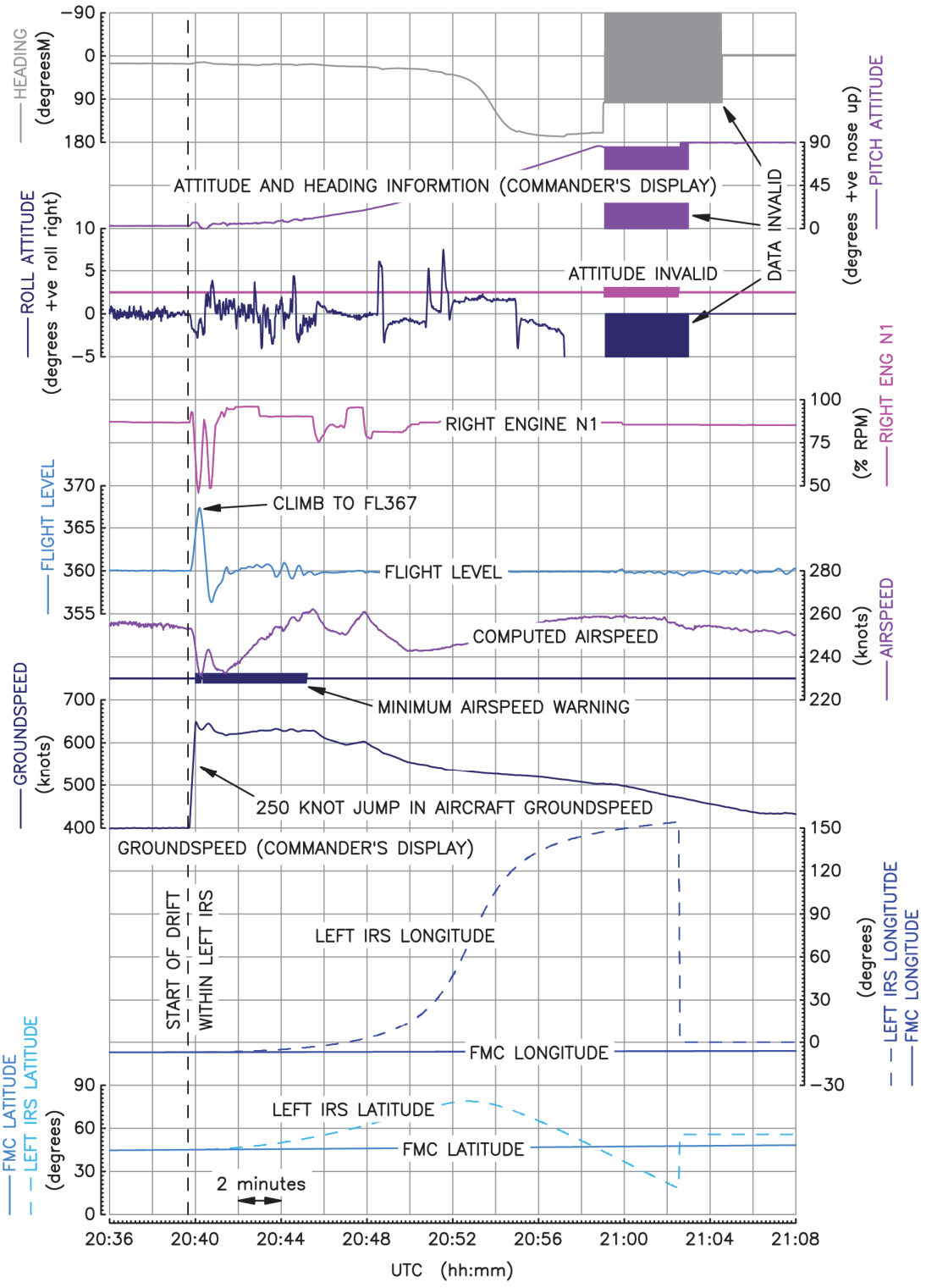

Figure 2

Salient FDR data during left IRS drift event

Although only the latitude and longitude from the left IRS were recorded, it was possible to derive the track and groundspeed it would have been generating, as well as an estimate of the aircraft's heading and, hence, the drift the left IRS was experiencing. These derived

parameters are reproduced in Figure 3 and show that the drift in latitude and longitude was initially driven by an along-track acceleration of about 1.6 g. The figure also shows that when the aircraft issued an indication that the attitude information was invalid, the left IRS drift had just reached 60°.

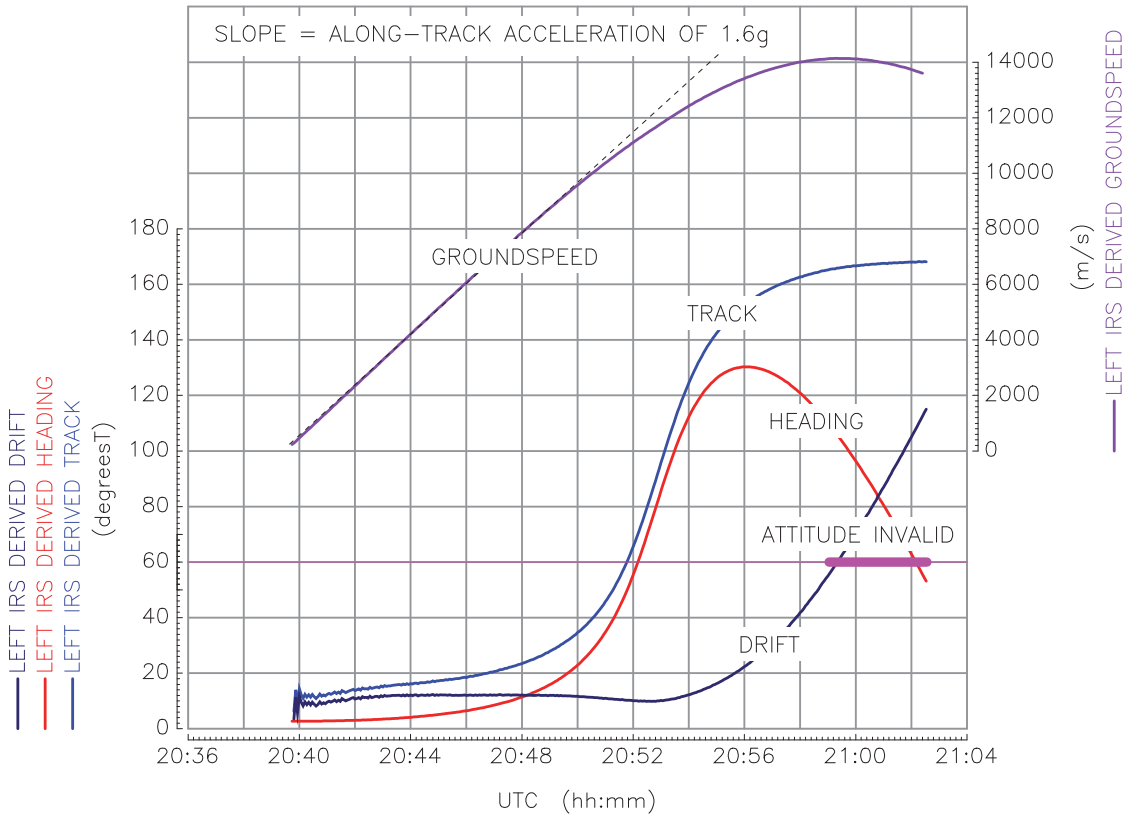

Figure 3

Left IRS derived data based on its recorded latitude and longitude

Aircraft description

EI-GJT is a Boeing 737-800 which was manufactured and entered service with its current operator in 2018, and which had accrued 1,705 flight hours and 890 cycles. Flight information is presented to the crew on the pilot's flight and navigation displays and the engine indication caution advisory system (EICAS) multifunction displays (MFDs).

The aircraft is fitted with two (left and right) ADIRUs which are powered from the AC electrical busses. Each ADIRU includes an IRS and an air data computer which receives information from separate pitot static sources. The air data part of the ADIRU provides airspeed, Mach number, angle of attack (AOA), barometric altitude and temperature data. The IRS part of the ADIRU uses solid state ring laser gyros and X, Y and Z axis accelerometers to provide information to attitude, FPV and positional data systems. Data is fed by the ADIRUs to the AP, AT, engine control, yaw damper and stall protection systems. Primary flight and navigation data from the ADIRUs are displayed on the PFDs, and the IRS status is shown on the IRS MSU.

The ADIRU NAV mode uses position data entered during the align mode as its initial present position. It then updates the present position based only on inertial data while it remains in the NAV mode, which is the normal operational mode. This inertially-generated positional data in relation to the Earth is used to generate the attitude indication on the PFD.

Data from the IRS and GPS and radio navigational information is integrated within the FMC. The FMC uses GPS position as its priority for position updates. If GPS is not available, FMC position is biased in a ratio of approximately 80:20 toward radio position and IRS position. The FMC also contains a software comparison logic designed to dismiss erroneous data. In this case, the FDR recorded that the FMC position data remained valid throughout the flight.

Engineering investigation

During the flight the crew were presented with several unusual aircraft reactions, display information and configuration data. These included a slow topple of the commander's attitude indication on his PFD with unreliability thereafter, and a slow pitch up with the AP engaged along with a gradual speed loss. As the incident developed the crew also came to distrust the standby instruments and AT. During the approach the crew had to correct an aircraft roll caused by a secondary flying control effect from the rudder due to the yaw damper reacting to spurious inputs from the ADIRU.

Once on stand, the crew debriefed the operator's engineering staff and recorded the symptoms of the failure in the aircraft Technical Log. The engineers downloaded the Quick Access Recorder (QAR) and Built-in Test Equipment (BITE) data and diagnosed a failure of the left ADIRU. The left ADIRU is a line replaceable unit (LRU) and a replacement was fitted. System functional tests were then satisfactorily carried out in accordance with the Aircraft Maintenance Manual (AMM) and the aircraft was released to service. The manufacturer carried out a review of the QAR data and the BITE fault codes and concurred with the fault diagnosis and rectification action[2]. The right ADIRU produced no faults codes and was working normally throughout the incident. There were no previous events in this aircraft with the left or right ADIRU.

The data downloaded from the left ADIRU showed the unit experienced a drift angle test fault whilst in inertial reference navigation mode. The QAR data showed that this was caused by a longitudinal acceleration offset, which manifested itself as a 1.6 g acceleration in the along-track sense. This, and the resultant groundspeed error, induced an ADIRU positional error along the aircraft track, which led to a left IRS position that passed east of the north pole (Figure 4). As the flight progressed, the positional error increased leading to the spurious attitude indication on the PFD experienced by the crew.

Footnote

[2] The operator's engineering staff based at Edinburgh carried out fault rectification without delay as expected and required by the operator. Thus, the diagnosis and rectification work was completed prior to the AAIB deployment. In some circumstances this may not have been ideal. However, in this case there was a detailed audit trial in the aircraft Technical Log of the actions taken and the results, and of the aircraft manufacture's support advice.

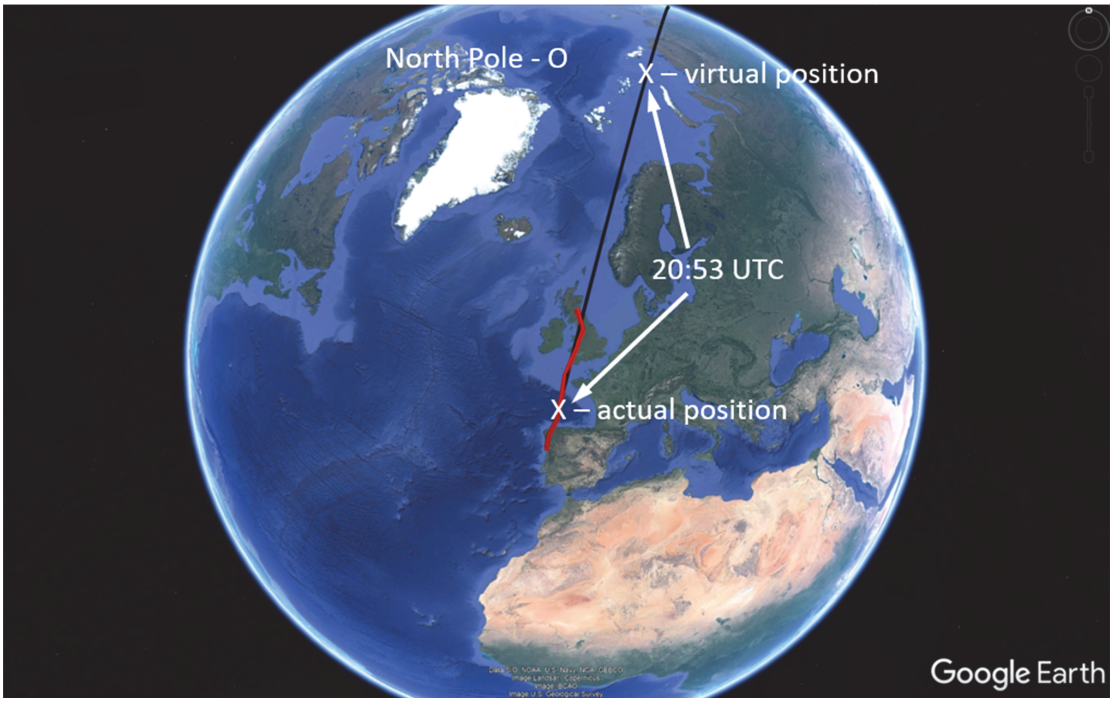

Figure 4

FMC ground track (red) and left IRS ground track (black)

Left ADIRU testing by the manufacturer

Component testing

The left ADIRU was returned to the Original Equipment Manufacturer (OEM) for further investigation. An examination revealed no visual indication of wiring defects, water ingress or physical damage. It was bench-tested and passed the navigation, acceleration, electrical and calibration test in accordance with the acceptance test schedule.

As there were no obvious indications of fault or failure, the manufacturer carried out a programme of follow-on testing. The unit was subjected to thermal testing between -40°C and +75°C over a period of more than 240 hours during 880 power cycles. Throughout this process, no failures were recorded.

Testing was carried out to simulate 1.6 g on the longitudinal axis by injecting an input to the Y axis accelerometer. After approximately 23 minutes this produced a drift angle test fault and created similar conditions to those which resulted in the positional error.

Disassembly, testing and examination of sub-components was also carried out, but no significant faults or defects were found. The simulation results suggested there was an anomaly with the Y axis accelerometer, which was removed for further testing. However, it was found to perform to acceptable test limits and close to the production testing carried out when the component was produced in March 2018.

Manufacturer's findings

Testing by the ADIRU manufacturer validated the QAR data analysis regarding the 1.6 g longitudinal offset. However, the manufacturer was not able to reproduce the drift angle test fault other than by a simulated input to the Y axis accelerometer. It was therefore concluded, based on the available data and testing, that a transient anomaly in the Y axis accelerometer was the most probable source of the longitudinal offset, although no specific fault or failure could be identified or confirmed.

Crew response to the situation

In the initial stages of the event, the crew were presented with several unusual indications and warnings. The attitude information displayed on the commander's PFD was erroneous and faulty data was supplied to AP A which was engaged. The AP responded to the faulty data and the aircraft's flightpath was disturbed. After the crew disengaged the AP and recovered the aircraft to manual flight at the allocated flight level, yellow comparator annunciations appeared on each pilot's PFD. Aware there were no QRH memory items for PFD comparator annunciations, the crew consulted the aircraft QRH for related checklists; there were none. The crew considered the possibility of using other checklists but discounted this because their training discouraged the use of QRH checklists except in response to relevant associated warnings. The QRH states in CI.2.2:

> *'While every attempt is made to supply needed non-normal checklists, it is not possible to develop checklists for all conceivable situations. … In some multiple failure situations, the flight crew may need to combine the elements of more than one checklist. In all situations the captain must assess the situation and use good judgement to determine the safest course of action. It should be noted that, in determining the safest course of action, troubleshooting ie, taking steps beyond published non-normal checklist steps, may cause further loss of system function or system failure. Troubleshooting should only be considered when completion of the published non-normal checklist results in an unacceptable situation.'*

When the crew completed the '*IRS Fault'* checklist, they were aware that they had not recovered the system. However, they had the aircraft under control and were able to maintain its flight path adequately using the co-pilot's PFD and the commander's Integrated Standby Flight Display (ISFD). If the IRS FAULT light clears, the QRH checklist reaches an endpoint. They felt that the QRH discouraged any other actions and that this philosophy was also emphasised by the operator's training department.

The '*IRS Fault'* checklist directs selection of ATT mode on the failed system. Once this has been done the QRH directs that neither AP should be engaged, so the crew flew the aircraft manually. Due to the lack of an AP the aircraft was no longer compliant with Reduced Vertical Separation Minima (RVSM) regulations and the crew was required to declare this to ATC. Given the unusual nature of the failure and their confusion over the QRH checklist outcome, the crew did not do so. Nevertheless, after the initial upset the aircraft remained within the RVSM performance limits for the remainder of the flight.

Organisational information

The operator's expectation was that crews would only conduct QRH checklist actions as memory items or in response to non-memory items specifically covered in the QRH. This philosophy was strongly emphasised throughout initial and recurrent training, although the operator incorporated some of their own amendments to the Boeing QRH under the terms of No Technical Objection[3] from Boeing. The objective of the amendments was to provide as much clear guidance as realistically possible while still discouraging actions that could lead to further system failures.

Tests and research

A Boeing 737 simulator was provided by the operator to examine this event, but the simulator was unable to replicate the fault that occurred in the aircraft. If the IRS FAULT light is triggered in the simulator, QRH actions cause the IRS to enter the reversionary mode and recover the PFD. Should the IRS FAULT light remain illuminated after selection of ATT mode (not what happened in this event), the QRH directs use of the IRS Transfer Switch to switch relevant systems to the operative IRS. This action (in the simulator) gave both pilots an operative PFD with only minor capability degradation. The QRH still requires there to be no AP use in this configuration.

The aircraft is fitted with a display source selector which is routinely left in AUTO but which can be used to supply both pilot's displays from either the left or right Display Electronics Unit (DEU). Using this switch following an IRS failure restores PFD indications with only minor degradations.

Other information G-FDZF

The day following the EI-GJT incident, another Boeing 737-800 encountered a similar problem while operating a ferry flight from Manchester to Palma, Mallorca. In this event, the co-pilot was the pilot flying (PF). Shortly after reaching the cruise flight level, AP B disconnected, attitude comparator annunciations appeared on the PFDs, both Electronic Engine Controls (EEC) changed to alternate mode, TCAS FAIL appeared on the Navigation Display (ND) and a HDG fail flag appeared on the standby compass. Neither AP could be re-engaged, so the crew continued in manual flight. On checking the Master Caution recall a MACH TRIM caption was present indicating a single lane failure in the Mach Trim system.

The crew completed the QRH actions for the EEC ALTN caution. Their interpretation was that there was a technical issue with the right IRS, but they did not conduct any IRS or Flight Instrument non-normal checklist (NNC) as the QRH contained no relevant information. They decided to return to Manchester, and during preparations for the approach it became apparent that the autobrake would not arm, further evidence of an IRS issue.

Footnote

[3] A letter of No Technical Objection from Boeing indicates acceptance of the amendment proposed by the operator for inclusion in the QRH used by the operator. This information is not promulgated to other Boeing customers.

During the ILS approach to Manchester, the Master Caution System activated an IRS caution, and the IRS FAULT light appeared on the MSU in the overhead panel. The aircraft was close to touch down and rather than initiate a go-around to complete the '*IRS Fault'* QRH checklist the commander elected to land. The aircraft landed safely and the ADIRU was removed for technical examination and found to have been contaminated by water ingress.

Analysis

EI-GJT

Analysis of the flight data showed that a longitudinal acceleration offset was induced in the left IRS. The resultant velocity error induced an IRS position error, initially along the track of the aircraft. As the flight progressed, the computed track remained constant, passing east of the north pole, while the computed heading changed. The angular difference between track and computed heading (ie the drift) increased until, after a period of approximately 20 minutes, it reached a value of 60° and triggered an IRS FAULT caution.

As the position error increased, the commander's flight instruments began to react in relation to a false position over the surface of the Earth, and he was presented with incorrect attitude information on his PFD. The erroneous attitude information caused the AP to climb the aircraft away from its assigned flight level. Pitch and roll comparator annunciations appeared on both PFDs. By comparing the information on the co-pilot's PFD and the ISFD the crew were able to satisfy themselves that the faulty information was being displayed on the commander's PFD. The AP and AT were disconnected, and the aircraft was recovered to level flight using standby instruments, cross-referenced against the co-pilot's PFD.

During the event the crew believed that the AT may have malfunctioned because they observed the N_1 reaching 95%. However, the flight data indicated that during the uncommanded climb the airspeed fell below minimum manoeuvre speed and the AT minimum speed protection activated.

The crew consulted the Boeing QRH for information and actions related to the pitch and roll comparator annunciations, but it includes no such actions. They also searched the FCOM, which explains the purpose of the comparator annunciations but offers no advice on restoring instrument capability. This caused some confusion in the crew, but they were reluctant to take any other action because their training discouraged them from doing so. As a result, although a solution to restore attitude information on the PFD was available – selecting a different data source for the PFD – the actions required were not taken because they were not directed to be taken by the QRH. Consequently, the commander's PFD displayed erroneous information for the rest of the flight, and the comparator annunciator indications remained on both PFDs. These displays are the pilots' primary attitude reference and the information on them is crucial for safe flight. Both pilots were faced with significant distractions on these primary instruments for the remainder of the flight.

When the IRS FAULT light illuminated, the crew selected ATT mode as directed by the QRH. The fault light cleared but the commander's PFD continued to provide erroneous information. This was because the ATT mode uses the same ring laser gyros and accelerometers as the NAV mode and so the system remained affected by accelerometer anomalies.

Following this incident, Boeing decided to amend the QRH checklist for IRS FAULT. The reference to ATT mode would be removed and the checklist would direct crews to use the IRS Transfer Switch to supply relevant systems from the serviceable side.

The crew's consideration of the fault allowed them to predict and prepare for the influence of the faulty attitude information on other systems. Accordingly, they were prepared for a number of erroneous indications which arose during the rest of the flight. The crew felt that there was some degradation of the aircraft's handling in manual flight, particularly in roll. The failed left ADIRU continued to supply information to the yaw damper computer for the remainder of the flight. As the yaw damper was periodically deflecting the rudder to the maximum extent allowed by the system, the roll issue felt by the crew was a secondary effect of the erroneous yaw damper action.

G-FDZF

The crew of G-FDZF faced similar problems to those experienced by the crew of EI-EGT: erroneous attitude information and failure of several systems. They recognised that the problem lay with the IRS but, like the crew of EI-EGT, they did not carry out any corrective action as there was no relevant guidance in the QRH.

QRH guidance

In both cases discussed in this report there was a significant period between the first symptoms of faulty attitude information and the appearance of the IRS FAULT indication. Shortly after the attitude information failed, pitch and roll comparator annunciations appeared on both PFDs. While these flags indicate a failure, they do not decisively indicate where it lies. Pilots must use standby instruments to determine where the failure is and, if necessary, recover to the correct attitude through manual flight. Selecting a different source for the faulty PFD would remove the flags and restore valid attitude information on both pilots' PFDs, although it would lead to a reduction in redundancy because all PFD attitude information would be from a single source. Information is available in the FCOM to aid crew understanding, but because of the expressed philosophy in the QRH discouraging troubleshooting, and the training discouraging the use of QRH checklists except in response to relevant associated warnings, it is unlikely crews will act unless specifically directed to do so by the QRH checklist.

In these events, the failure occurred in VMC and straight and level flight and the outcome was benign. However, the PFD is a primary instrument which dominates a pilot's display panel, and a failed attitude display presents a powerful disorientating stimulus to the relevant pilot. The comparator annunciation appears simultaneously in both PFDs and, if no action is taken, can remain as a significant distraction for the remainder of the flight. In

manoeuvring flight it could be unclear where the failure lay, and the presence of the failed display would continue to constitute a disorientating factor.

Boeing decided to amend the QRH checklist for IRS FAULT but this would not address the situation where there was faulty attitude information but no IRS caution message. Therefore, the following Safety Recommendation is made:

Safety Recommendation 2019-012:

It is recommended that Boeing Commercial Aircraft amend the Boeing 737 Quick Reference Handbook to include a non-normal checklist for situations when pitch and roll comparator annunciations appear on the attitude display.

Conclusion

On EI-GJT, the IRS of the left ADIRU suffered a fault which led to an erroneous calculation of position. On G-FDZF, the ADIRU was contaminated by fluid ingress. In both cases, this resulted in the display of faulty attitude information on the commander's PFD, and the supply of erroneous information to several aircraft systems. The problems were contained through manual flight and the use of standby instrumentation. Although action could have been taken to restore reliable attitude information to the commander's PFD, such action was not directed from within the QRH. The training given to the crews discouraged them from acting unless directed by the QRH, so this lack of relevant information in the QRH contributed to the situation.

Safety action

Following this incident, Boeing decided to amend the QRH checklist for IRS FAULT. The reference to ATT mode would be removed and the checklist would direct crews to use the IRS Transfer Switch to supply relevant aircraft systems from the serviceable side.

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