



**Australian Government**

**Australian Transport Safety Bureau**

**ATSB TRANSPORT SAFETY REPORT**

Aviation Occurrence Investigation AO-2008-070

Interim Factual

**In-flight upset  
154 km west of Learmonth, WA  
7 October 2008  
VH-QPA  
Airbus A330-303**





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Figure 4, Figure 9, Figure 10 and diagrams included in Appendix A by permission of Airbus.

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### Abstract

At 0932 local time (0132 UTC) on 7 October 2008, an Airbus A330-303 aircraft, registered VH-QPA, departed Singapore on a scheduled passenger transport service to Perth, Australia. On board the aircraft (operating as flight number QF72) were 303 passengers, nine cabin crew and three flight crew. At 1240:28, while the aircraft was cruising at 37,000 ft, the autopilot disconnected. From about the same time there were various aircraft system failure indications. At 1242:27, while the crew was evaluating the situation, the aircraft abruptly pitched nose-down. The aircraft reached a maximum pitch angle of about 8.4 degrees nose-down, and descended 650 ft during the event. After returning the aircraft to 37,000 ft, the crew commenced actions to deal with multiple failure messages. At 1245:08, the aircraft commenced a second uncommanded pitch-down event. The aircraft reached a maximum pitch angle of about 3.5 degrees nose-down, and descended about 400 ft during this second event.

At 1249, the crew made a PAN urgency broadcast to air traffic control, and requested a clearance to divert to and track direct to Learmonth. At 1254, after receiving advice from the cabin of several serious injuries, the crew declared a MAYDAY. The aircraft subsequently landed at Learmonth at 1350.

One flight attendant and 11 passengers were seriously injured and many others experienced less serious injuries. Most of the injuries involved passengers who were seated without their seatbelts fastened or were standing. As there were serious injuries, the occurrence constituted an accident.

The investigation to date has identified two significant safety factors related to the pitch-down movements. Firstly, immediately prior to the autopilot disconnect, one of the air data inertial reference units (ADIRUs) started providing erroneous data (spikes) on many parameters to other aircraft systems. The other two ADIRUs continued to function correctly. Secondly, some of the spikes in angle of attack data were not filtered by the flight control computers, and the computers subsequently commanded the pitch-down movements.

Two other occurrences have been identified involving similar anomalous ADIRU behaviour, but in neither case was there an in-flight upset.

The investigation is continuing.

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# THE AUSTRALIAN TRANSPORT SAFETY BUREAU

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The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal bureau within the Australian Government Department of Infrastructure, Transport, Regional Development and Local Government. ATSB investigations are independent of regulatory, operator or other external organisations.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to fare-paying passenger operations.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and Regulations and, where applicable, relevant international agreements.

## **Purpose of safety investigations**

The object of a safety investigation is to enhance safety. To reduce safety-related risk, ATSB investigations determine and communicate the safety factors related to the transport safety matter being investigated.

It is not the object of an investigation to determine blame or liability. However, an investigation report must include factual material of sufficient weight to support the analysis and findings. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

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Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to proactively initiate safety action rather than release formal recommendations. However, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation, a recommendation may be issued either during or at the end of an investigation.

The ATSB has decided that when safety recommendations are issued, they will focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on the method of corrective action. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations. It is a matter for the body to which an ATSB recommendation is directed (for example the relevant regulator in consultation with industry) to assess the costs and benefits of any particular means of addressing a safety issue.

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## ABBREVIATIONS

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ACARS	Aircraft communications, addressing and reporting system
ADIRS	Air data and inertial reference system
ADIRU	Air data inertial reference unit
ADR	Air data reference
AIRMAN	AIRcraft Maintenance ANalysis database
AOA	Angle of attack
AP	Autopilot
ATSB	Australian Transport Safety Bureau
BEA	Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (France, Bureau of Investigations and Analysis for the Safety of Civil Aviation)
BITE	Built-in test equipment
CASA	Civil Aviation Safety Authority
CMC	Central maintenance computer
CMS	Central maintenance system
CVR	Cockpit voice recorder
EASA	European Aviation Safety Agency
ECAM	Electronic centralized aircraft monitor
EMI	Electromagnetic interference
FAA	Federal Aviation Administration (US)
FCPC	Flight control primary computer (also known as PRIM)
FCSC	Flight control secondary computer (also known as SEC)
FDR	Flight data recorder
FL	Flight level
FMGEC	Flight management guidance envelope computer
GPS	Global positioning system
HF	High frequency
IR	Inertial reference
ICAO	International Civil Aviation Organization
NTSB	National Transportation Safety Board (US)
OEB	Operations engineering bulletin

PED	Personal electronic device
PFD	Primary flight display
PFR	Post flight report
PRIM	Common name for flight control primary computer (FCPC)
QAR	Quick access recorder
SEC	Common name for flight control secondary computer (FCSC)
UTC	Universal time, coordinated
VLF	Very low frequency



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## FACTUAL INFORMATION

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*This interim report provides a summary of factual information that has been derived from the continuing investigation of the subject occurrence – building upon the information presented in the preliminary report (ISBN 978-1-921490-84-2). As the investigation is ongoing, readers are cautioned that there is the possibility that new evidence may become available that alters the circumstances as depicted in the report.*

### History of the flight

At 0932 local time (0132 UTC<sup>1</sup>) on 7 October 2008, an Airbus A330-303 aircraft, registered VH-QPA, departed Singapore on a scheduled passenger transport service to Perth, Australia. On board the aircraft (operating as flight number QF72) were 303 passengers, nine cabin crew and three flight crew<sup>2</sup> (captain, first officer and second officer). The captain was the handling pilot for the flight.

The flight crew reported that the departure and climb-out from Singapore proceeded normally. By 1001, the aircraft was cruising at 37,000 ft (flight level 370) in automatic flight mode with the autopilot number 1 and autothrust systems engaged.

The flight crew reported that the weather was fine and clear and there had been no turbulence during the flight. At about 1239, the first officer left the flight deck for a scheduled rest break. The second officer then occupied the right control seat.

At 1240:28, the autopilot disengaged. The crew reported that there was an associated ECAM<sup>3</sup> warning message (AUTO FLT AP OFF) and that they also started receiving master caution chimes. The captain took manual control of the aircraft using the sidestick. He reported that he attempted to engage autopilot 2 and then autopilot 1, but neither action was successful.<sup>4</sup> The flight data recorder (FDR) showed that, during this period, the aircraft's altitude increased to 37,200 ft before returning to the assigned level.

The crew reported that they cleared the AUTO FLT message from the ECAM. They then received a NAV IR1 FAULT message on the ECAM.<sup>5</sup> The crew were also receiving aural stall warning indications at this time, and the airspeed and altitude

- 
- 1 UTC: Universal time, coordinated (previously Greenwich Mean Time or GMT). Local time in both Singapore and Western Australia was UTC plus 8 hours.
  - 2 The A330 was designed to be operated by two pilots (captain and first officer). Depending on the length of the sectors on a trip, second officers were carried to relieve the captain and first officer during long sectors. On this day, the flight crew were rostered to operate the Singapore-Perth flight and then a Perth-Singapore flight. Second officers do not normally occupy either of the control seats during landing or takeoff.
  - 3 ECAM: Electronic centralized aircraft monitor (see Appendix A).
  - 4 The flight data recorder shows that autopilot 2 did engage for 16 seconds. The recorder also indicated that the disconnection was initiated by the crew. The captain could not recall receiving any indication that autopilot 2 had engaged.
  - 5 NAV: navigation systems. IR: inertial reference part of the air data inertial reference unit (ADIRU) (see *Aircraft information*).

indications on the captain's primary flight display (PFD) were also fluctuating. Given the situation, the captain asked the second officer to call the first officer back to the flight deck.

At 1242:27, while the second officer was using the cabin interphone to ask a flight attendant to send the first officer back to the flight deck, the aircraft abruptly pitched nose-down. The captain reported that he applied back pressure on his sidestick to arrest the pitch-down movement. He said that initially this action seemed to have no effect, but then the aircraft responded to his control input and he commenced recovery to the assigned altitude. The aircraft reached a maximum pitch angle of about 8.4 degrees nose-down during the event, and a maximum g loading of -0.80 g<sup>6</sup> was recorded. The aircraft descended 650 ft during the event.

The flight crew described the pitch-down movement as very abrupt, but smooth. It did not have the characteristics of a typical turbulence-related event and the aircraft's movement was solely in the pitching plane. They did not detect any movement in the rolling plane.

During the initial upset event, the second officer activated the seatbelt sign to ON and made a public address for passengers and crew to return to their seats and fasten their seatbelts immediately.

The flight crew reported that, after returning the aircraft to 37,000 ft, they commenced actions to deal with multiple ECAM messages. They completed the required action to deal with the first message (NAV IR1 FAULT) by switching the captain's ATT HDG (attitude heading) switch from the NORM position to CAPT ON 3 position, and then cleared that message. The next message was PRIM 3 FAULT.<sup>7</sup> The crew completed the required action by selecting the PRIM 3 off, waiting 5 seconds and then selecting it on again.

At 1245:08, shortly after the crew selected PRIM 3 back on, the aircraft commenced a second uncommanded pitch-down event. The captain reported that he again applied back pressure on his sidestick to arrest the pitch-down movement. He said that, consistent with the first event, that action was initially unsuccessful, but the aircraft then responded normally and he commenced recovery to the assigned altitude. The aircraft reached a maximum pitch angle of about 3.5 degrees nose-down, and descended about 400 ft during the second event. The flight crew described the event as being similar in nature to the first event, though of a lesser magnitude and intensity.

The captain announced to the cabin for passengers and crew to remain seated with seatbelts fastened. The second officer made another call on the cabin interphone to get the first officer back to the flight deck. The first officer returned to the flight deck at 1248 and took over from the second officer in the right control seat. The second officer moved to the third occupant seat.

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<sup>6</sup> Acceleration values used in this report were sensed by a triaxial accelerometer located near the aircraft's centre-of-gravity and were recorded by the aircraft's flight data recorder and quick access recorder. 1 g is the nominal value for vertical acceleration that is recorded when the aircraft is on the ground. In flight, vertical acceleration values represent the combined effects of flight manoeuvring loads and turbulence.

<sup>7</sup> The term PRIM is the common name for a flight control primary computer (FCPC).

After discussing the situation, the crew decided that they needed to land the aircraft as soon as possible. They were not confident that further pitch-down events would not occur. They were also aware that there had been some injuries in the cabin, but at that stage they were not aware of the extent of the injuries. At 1249, the crew made a PAN<sup>8</sup> emergency broadcast to air traffic control, advising that they had experienced ‘flight control computer problems’ and that some people had been injured. They requested a clearance to divert to and track direct to Learmonth, WA.<sup>9</sup> Clearance to divert and commence descent was received from air traffic control. Figure 1 shows the track of the aircraft and time of key events.

**Figure 1: Aircraft track and key events**



Following the second upset event, the crew continued to review the ECAM messages and other flight deck indications. The IR1 FAULT light and the PRIM 3 FAULT light on the overhead panel were illuminated. There were no other fault lights illuminated. Messages associated with these faults were again displayed on the ECAM, along with several other messages. The crew reported that the messages were constantly scrolling, and they could not effectively interact with the ECAM to action and/or clear the messages. The crew reported that master caution chimes associated with the messages were regularly occurring, and they continued to receive aural stall warnings.

The captain reported that, following the first upset event, he was using the standby flight instruments and the first officer's primary flight display (PFD, see Appendix A) because the speed and altitude indications on his PFD were fluctuating and he

<sup>8</sup> A PAN transmission is made in the case of an urgency condition which concerns the safety of an aircraft or its occupants, but where the flight crew does not require immediate assistance.

<sup>9</sup> The first upset event occurred when the aircraft was 154 km (83 NM) west of Learmonth. Learmonth was the closest aerodrome suitable for an A330 landing.

was unsure of the veracity of the other displayed information. After the second upset event, he had observed that the automatic elevator trim was not functioning and he had begun trimming the aircraft manually. He later disconnected the autothrust and flew the aircraft manually for the remainder of the flight.

The flight crew spoke to a flight attendant by interphone to get further information on the extent of the injuries. The flight crew advised the cabin crew that, due to the nature of the situation, they did not want them to get out of their seats, but to use the cabin interphones to gather the information. At 1254, after receiving advice from the cabin of several serious injuries, the crew declared a MAYDAY<sup>10</sup> and advised air traffic control they had multiple injuries on board, including a broken leg and some cases of severe lacerations.

The crew continued attempts to further evaluate their situation and, at 1256, contacted the operator's maintenance watch unit<sup>11</sup>, located in Sydney, by SATPHONE to seek assistance. There were several subsequent communications during the flight between the flight crew and maintenance watch, who advised that the various faults reported by the crew were confirmed by data link, but that they were not able to diagnose reasons for the faults. During one of the conversations, maintenance watch suggested that the crew could consider switching PRIM 3 off, and this action was carried out. This action did not appear to have any effect on the scrolling ECAM messages, or the erratic airspeed and altitude information.

The crew conducted a visual descent via a series of wide left orbits, maintaining aircraft speed below 330 kts (maximum operating speed). They completed the approach checklist and conducted a flight control check above 10,000 ft. They were unable to enter an RNAV (GNSS)<sup>12</sup> approach into the flight management computer; however, the aircraft was positioned at about 15 NM for a straight-in visual approach to runway 36. The precision approach path indicator (PAPI) was acquired at about 16 km (10 NM) and the aircraft landed without further incident at Learmonth at 1350.

## Injuries to persons

Table 1 presents a summary of known information on the extent of passenger injuries. As some of the people on board received serious injuries, the occurrence was classified as an accident.<sup>13</sup>

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<sup>10</sup> A MAYDAY transmission is made in the case of a distress condition and where the flight crew requires immediate assistance.

<sup>11</sup> Maintenance watch provides 24-hour assistance to enroute flight crews regarding technical issues.

<sup>12</sup> RNAV (GNSS) approach: area navigation global navigation satellite system non-precision approach. Previously termed a 'GPS approach'.

<sup>13</sup> Consistent with the ICAO definition outlined in Annex 13 to the Chicago Convention, an accident is defined in the *Transport Safety Investigation Act 2003* as an investigable matter involving an aircraft where a person dies or suffers a serious injury, or the aircraft is destroyed or seriously damaged.



**Table 1: Number and level of injuries**

Injuries	Crew	Passengers	Other	Total
Fatal	-	-	-	-
Serious	1	11	-	12
Minor	8	95	-	103
None	3	197	-	200
Total	12	303	-	315

The Western Australia Department of Health reported that 53 people from the flight received medical treatment at a hospital, and that 12 of those people were admitted to hospital. Under the *Transport Safety Investigation Regulations* (2003), a serious injury is defined as ‘an injury that requires, or would usually require, admission to hospital within 7 days after the day when the injury is suffered’.<sup>14</sup>

Given that information about injuries was not able to be obtained from all passengers, the number of minor injuries would be higher than shown in Table 1. Further information on injuries and cabin safety matters is presented in *Cabin safety*.

## Damage to the aircraft

No structural damage to the aircraft was found during an inspection at Learmonth (see *Aircraft examination*).

Inspection of the aircraft interior revealed damage mainly in the centre and rear sections of the passenger cabin. The level of damage varied significantly. Much of the damage was in the area of the personal service units (located above each passenger seat) and adjacent panels. The damage was typically consistent with that resulting from an impact by a person or object. There was evidence of damage above approximately 10 per cent of the seats in the centre section of the cabin, and above approximately 20 per cent of the seats in the rear section of the cabin. In addition, some ceiling panels above the cabin aisle-ways had evidence of impact damage, and many had been dislodged from their fixed position.

Oxygen masks had deployed from above nine of the seats where there had been damage to overhead personal service units or adjacent panels. Some of the cabin portable oxygen cylinders and some of the aircraft first aid kits had been deployed.

Examples of the more significant damage are shown in Figure 2 and Figure 3.

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<sup>14</sup> The definition of serious injury in the ICAO Annex 13 to the Chicago Convention includes several conditions, such as hospitalisation for more than 48 hours, fracture of any bone (except simple fractures of fingers, toes and nose), and lacerations which cause severe haemorrhage. Using the ICAO definition, there were also 12 serious injuries. However, four of those people were different to the 12 who were admitted to hospital.

**Figure 2: Example of damage to ceiling panels above passenger seats**



**Figure 3: Example of damage to ceiling panels in aisle**



## Personnel information

Table 2 summarises the operational experience of the flight crew at the time of the occurrence. All the flight crew reported that they were well rested prior to the flight.

**Table 2: Flight crew experience**

	<b>Captain</b>	<b>First Officer</b>	<b>Second Officer</b>
Licence category	ATPL <sup>15</sup>	ATPL	CPL
Total flying hours	13,592	11,650	2,070
Total command	7,505	2,020	1,400
Total A330	2,453	1,870	480
Total last 90 days	165	198	188
Total last 30 days	64	78	62

## Aircraft information

### General information

Aircraft type:	Airbus A330-303
Serial number:	0553
Year of manufacture:	2003
Registration:	VH-QPA
Certificate of Registration:	31 October 2003
Certificate of Airworthiness:	26 November 2003 <sup>16</sup>
Total airframe hours:	20,040
Total airframe cycles:	3,740
Last 'C' maintenance check:	1-13 March 2008

The take-off weight of the aircraft was 207,065 kg. The weight of the aircraft and centre of gravity were within the prescribed limits.

Preliminary analysis of maintenance records for the aircraft and pertinent systems has been conducted. Initial indications are that the aircraft met all relevant airworthiness requirements.

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<sup>15</sup> Air Transport Pilot License.

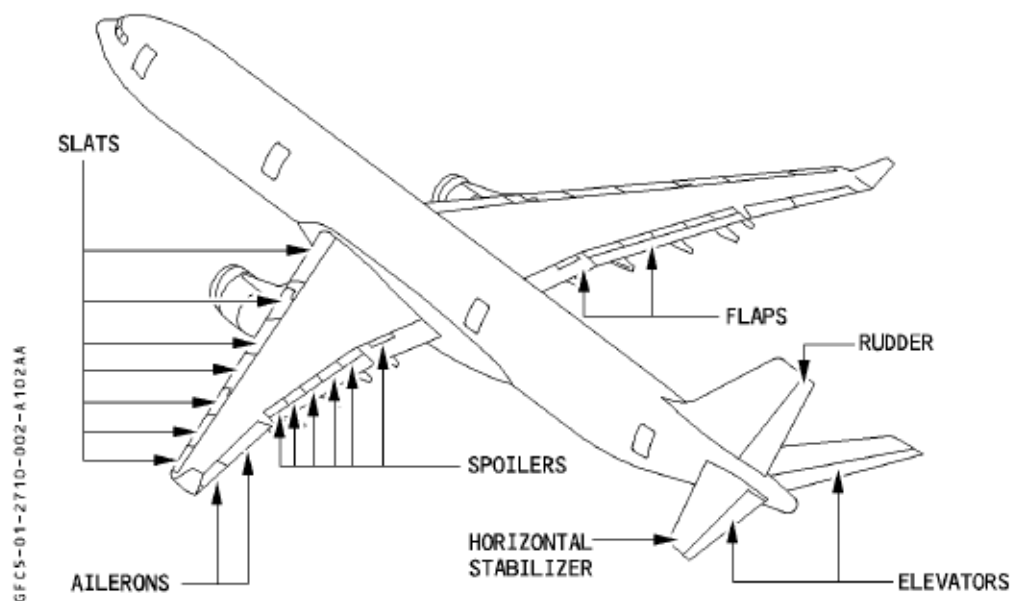
<sup>16</sup> The aircraft was delivered to the operator as an A330-301 model in November 2003. The original Certificate of Airworthiness was dated 26 November 2003. The aircraft was modified in December 2004 which changed the model from a -301 to a -303. A new Certificate of Airworthiness was issued on 10 December 2004 to reflect the correct model number.

## Flight control system

### General description

Figure 4 shows the flight control surfaces on the A330. All of the surfaces were electronically controlled and hydraulically activated. The horizontal stabiliser could also be mechanically controlled.

**Figure 4: Overview of flight control surfaces**



The aircraft's flight control surfaces could be operated using the autopilot<sup>17</sup> or through pilot controls. When the autopilot was not engaged, pilots used sidesticks to manoeuvre the aircraft in pitch and roll. Computers interpreted the pilot inputs and moved the flight control surfaces, as necessary, to follow their orders within the limitations of a set of flight control laws.

The aircraft's flight control system included three flight control primary computers (FCPCs, commonly known as PRIMs) and two flight control secondary computers (FCSCs, commonly known as SECs). In normal operation, one PRIM functioned as the master. It processed and sent orders to other computers, which executed them using servo-controls (see also *Review of PRIM monitoring functions*).

The flight control computers received data from a variety of sources, including from the air data inertial reference units (ADIRUs).

### Pitch control

Pitch control was achieved by two elevators and the trimmable horizontal stabiliser (THS). Maximum elevator deflection was 30 degrees nose up and 15 degrees nose

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<sup>17</sup> The A330 had two autopilots. The flight crew could engage either autopilot 1 or autopilot 2 by pressing the corresponding pushbutton. The autopilot could be disconnected intentionally by the crew or it could automatically disconnect as a result of a number of different conditions.

down. The maximum THS deflection was 14 degrees nose up, and 2 degrees nose down.

The elevators and THS were normally controlled from PRIM 1. If a failure occurred with PRIM 1 or an associated hydraulic system, the pitch control was automatically transferred to PRIM 2. Mechanical trim control of the THS was available to the flight crew using the pitch trim wheels on the centre pedestal in the flight deck.

### ***Control laws***

The electronic flight control system operated according to a set of control laws. In 'normal law', regardless of the flight crew's input, computers prevented exceedance of a predefined safe flight envelope. The flight control system could detect when the aircraft was past or approaching the limits of certain flight parameters, and was capable of commanding control surface movement in order to prevent the aircraft from exceeding those limits. Automatic flight envelope protections included load factor limitation, pitch and roll attitude protection, high angle-of-attack protection (alpha prot), and high speed protection.

If there were certain types or combinations of failures within the flight control system or its components, the control law automatically changed to a different configuration level: alternate law or direct law. Under alternate law, the different types of protection were either not provided or were provided using alternate logic. Under direct law, no protections were provided and control surface deflection was proportional to sidestick and rudder pedal movement.

## **Air data and inertial reference system**

### ***General description***

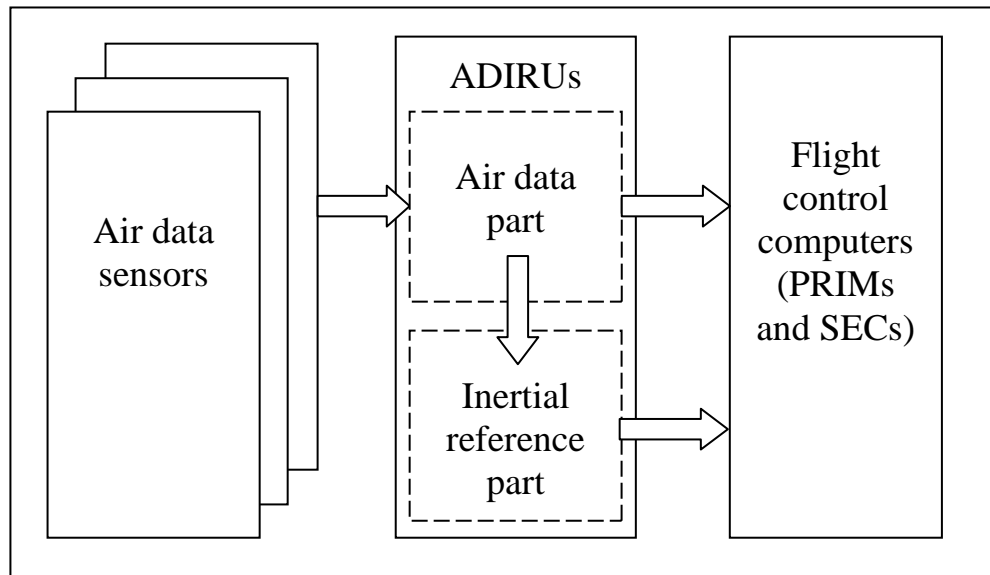
The air data and inertial reference system (ADIRS) included three identical air data inertial reference units (ADIRUs), known as ADIRU 1, ADIRU 2 and ADIRU 3.<sup>18</sup> The ADIRUs provided data for multiple aircraft systems, including the flight control system.

Figure 5 provides a simplified representation of the relationship between the ADIRS and the flight control system. In simple terms, various air data sensors provided data to the ADIRUs, which then provided data to the flight control computers.

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18 Details for the units on VH-QPA were as follows. Model name: LTN-101 Global Navigation Air Data Inertial Reference Unit (GNADIRU). Part Number: 465020-0303-0316. ADIRU 1 Serial Number 4167, ADIRU 2 Serial Number 4687, ADIRU 3 Serial Number 4663.

**Figure 5: Simplified air and inertial data path**



***Air data inertial reference unit (ADIRU)***

Each ADIRU was divided in two parts: the air data reference (ADR) part and the inertial reference (IR) part. Each part could operate separately in the case of the failure of the other part. Figure 6 shows ADIRU 1 from VH-QPA.

**Figure 6: ADIRU 1 from VH-QPA**

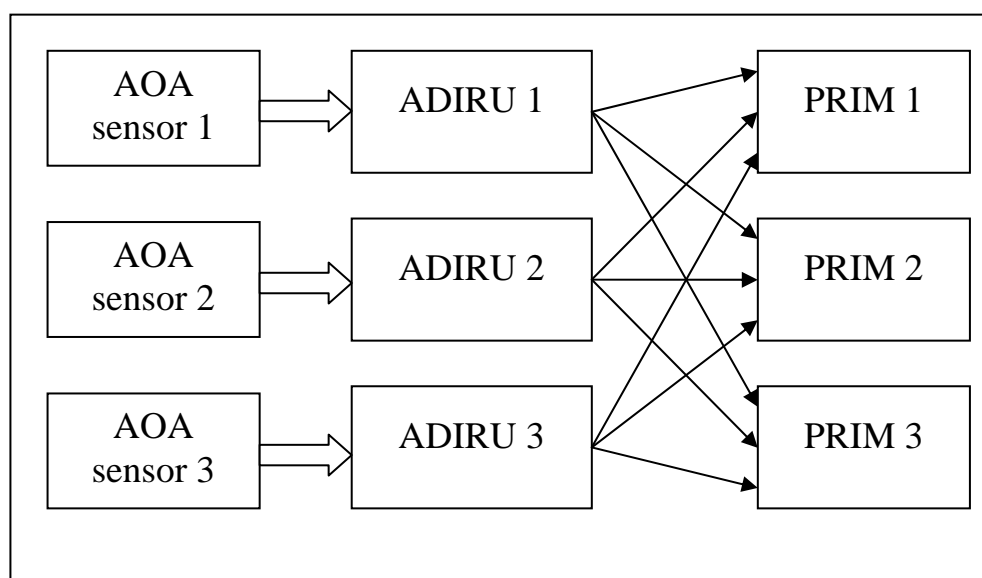


The ADR part of the ADIRU supplied barometric altitude, speed, Mach, angle of attack (AOA) and temperature information to other aircraft systems. It received air data from the aircraft's pitot probes, static pressure ports, AOA sensors, and total air temperature probes. Air data modules converted pneumatic data from pitot and static sources into electrical signals for the ADIRUs.

The IR part supplied attitude, flight path vector, track, heading, accelerations, angular rates, ground speed, vertical speed and aircraft position information to other systems. Two GPS receivers were connected to the IR part of the ADIRUs.

For most types of data, each ADIRU obtained its data from a different sensor. For example, ADIRU 1, ADIRU 2 and ADIRU 3 each obtained AOA data from a different AOA sensor. Each of the PRIMs monitored the outputs from each of the ADIRUs. Figure 7 provides a simplistic representation of the relationship between the sensors, ADIRUs and PRIMs using the AOA sensors as an example.

**Figure 7: Angle of attack inputs to ADIRUs and PRIMs**



### ***Angle of attack sensors***

Angle of attack<sup>19</sup> (AOA) data was sourced from three AOA sensors (AOA 1, AOA 2, and AOA 3), installed on the forward fuselage. AOA 1 and 2 were installed on the left and right sides of the fuselage respectively. AOA 3 was installed below AOA 2. Figure 8 shows the AOA 2 and AOA 3 sensors of VH-QPA.

Each AOA sensor utilised two identical outputs (A and B for each sensor) for redundancy. The relevant ADIRU checked the A and B signals to ensure that they agreed. If they agreed, the data was passed on to other systems.

<sup>19</sup> Angle of attack: the angle between the wing chord (centreline) and the airflow direction.

**Figure 8: Right side AOA sensors (AOA 2 and AOA 3)**



### ***ADIRS control panel***

An ADIRS control panel was located on the overhead panel in the flight deck (Figure 9). The panel provided local fault indications for the parts of the system. If there was a fault with the ADR part of an ADIRU (see item 1 in the figure), an amber fault light illuminated. The relevant part could be deactivated by pressing the push-button switch below the fault indication light. The IR part of the ADIRU operated in the same manner (see item 2).

The IR rotary mode selector (see item 3 in Figure 9) allowed the flight crew to select either the NAV position (supplied full inertial data to aircraft systems for normal operation), ATT (supplied only attitude and heading information) or OFF (ADIRU was not energised and ADR and IR information was not available).

### ***Attitude heading and air data selectors***

ADIRU 1 was connected to the captain's displays and ADIRU 2 was connected to the first officer's displays. ADIRU 3 could be manually switched to either the captain's or first officer's position in the event of a failure of ADIRU 1 or ADIRU 2. This was achieved using either the ATT HDG switch (for IR parameters) and/or the AIR DATA switch (for ADR parameters). The switches were located on the pedestal panel in the flight deck (see item 1 in Figure 10).



Figure 9: ADIRS control panel schematic

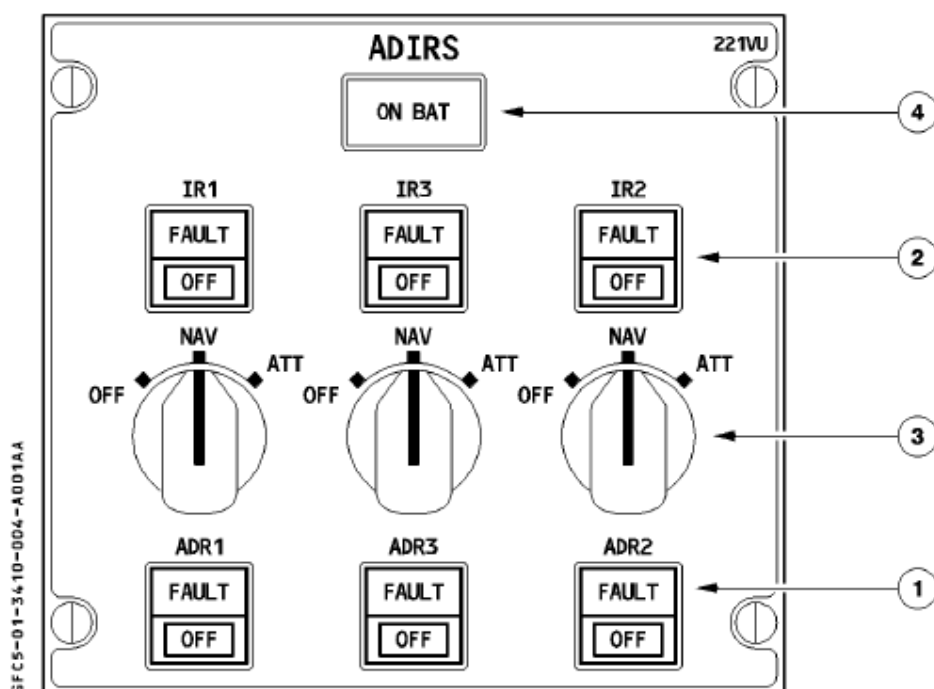
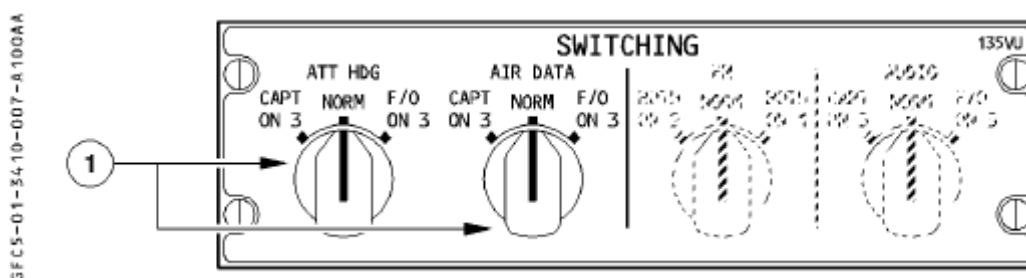


Figure 10: ATT HDG and AIR DATA switches



## Meteorological information

The Bureau of Meteorology provided the following information regarding the weather conditions prevailing at the location and time of the occurrence:

- A ridge extended over southern Western Australia with a surface trough developing along the north and west coasts during the day.
- A sharpening upper level trough extended from the Great Australian Bight through Perth and into the Indian Ocean.
- Some thunderstorm activity was recorded from about Karratha to just north of Learmonth, with cloud tops to about flight level (FL) 330 (33,000 ft).
- The axis of a 120 kt sub-tropical jet stream lay north-west to south-east between Learmonth and Carnarvon at FL 400 (40,000 ft). A shear line was developing south of the jet-stream as the upper trough developed.

- Data obtained at 0600 UTC (1400 local time) on 7 October 2008 showed a shear line associated with the upper level trough well south of the jet stream. There was no evidence of any penetration of cold air under the jet stream that could have lead to increased vertical wind shear.
- Three model-generated forecasts predicted an area of moderate turbulence associated with the jet stream.
- At the time of the occurrence, the aircraft appeared to be in the vicinity of the sub-tropical jet stream, to the near north of a shear line and well south of any significant convection activity.
- Turbulence at a moderate or greater level was unlikely to have influenced the aircraft at the time of the occurrence.

## **Flight recorders**

### **Overview**

The aircraft was fitted with three flight recorders:

- a cockpit voice recorder (CVR)
- a flight data recorder (FDR)
- a quick access recorder (QAR).

The CVR and FDR are the so-called ‘black-boxes’ and are required by regulation to be installed on certain types of aircraft. Information recorded by the CVR and FDR is stored in crash-protected modules.

The QAR is an optional recorder that the operator had chosen to fit to all their A330 aircraft. Information recorded by the QAR is not crash-protected. As the name suggests, QARs allow quick access to flight data whereas FDRs require specialist downloading equipment. The parameters that are recorded by an FDR are defined by regulatory requirements. However, QAR systems can be configured by an operator to record different parameters. Operators routinely use QAR data for engineering system monitoring and fault-finding, incident investigation and flight operations quality assurance programs.

### **Recording system operation**

#### ***CVR system***

The CVR recorded the total audio environment in the cockpit area, which may include crew conversation, radio transmissions, aural alarms, control movements, switch activations, engine noise and airflow noise. The CVR installed in VH-QPA retained the last 2 hours of information in solid-state memory, operating on an endless-loop principle.

#### ***FDR system***

The FDR recorded aircraft flight data and, like the CVR, operated on an endless-loop principle. The recording duration was required to be at least 25 hours and the

FDR typically recorded when at least one engine was operating and stopped recording 5 minutes after the last engine was shutdown. The FDR installed in VH-QPA recorded approximately 1,100 parameters and used solid-state memory as the recording medium.

### ***QAR system***

Like the FDR, the QAR<sup>20</sup> recorded aircraft flight data. The QAR installed in VH-QPA stored data on a removable magneto-optical disk with a capacity of 230 Mbytes and recorded approximately 250 parameters. Operators balance the logistics of handling large quantities of QAR disks with the benefits of obtaining the data as soon as possible after a flight has occurred. Typically most operators would leave a disk inserted in the QAR for several days until the aircraft returned to a suitable maintenance base.

### **Recorder recovery**

The Australian Transport Safety Bureau (ATSB) supervised the removal of the CVR, FDR and QAR disk from the aircraft in Learmonth and their dispatch to the ATSB's technical facilities in Canberra.<sup>21</sup> They were received in Canberra on 8 October 2008 and were replayed immediately. Preliminary FDR data was provided to the investigation team on 9 October 2008.

## **Results**

### ***CVR download***

The entire 2 hours of recorded audio was successfully downloaded by ATSB investigators in Canberra. Analysis of the audio showed that power had been removed from the CVR soon after the aircraft arrived at the terminal in Learmonth. As a consequence, the CVR had retained the audio recorded during the accident sequence from prior to the initial autopilot disconnection and including both pitch-down events.

### ***FDR download***

The FDR was downloaded by ATSB investigators in Canberra. The FDR had recorded over 217 hours of aircraft operation, comprising the accident flight and 24 previous flights. The oldest flight recorded was QF51 on 23 September 2008.

For the accident flight, continuous data from engine start on the ground in Singapore until after engine shutdown at Learmonth was successfully recovered. FDR data was used to produce a sequence of events (see below) and plots (refer to Appendix B). Figure B1 provides summary data for the whole flight, and Figures

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<sup>20</sup> As the parameters recorded by the QAR were configurable by the airline, it is described as a Digital ACMS Recorder (DAR) in Airbus terminology. To avoid confusion, the generic term QAR is used in this report. ACMS is an abbreviation for Aircraft Condition Monitoring System.

<sup>21</sup> CVR details: Part Number 2100-1020-02, Serial Number 000252164. FDR details: Part Number 2100-4043-02, Serial Number 000428627.

B2 and B3 provide more detailed data for the period covering the two in-flight upsets. Figures B4 and B5 provide specific information for each of the upsets.

### **QAR download**

Files stored on the QAR disk were recovered by the ATSB. Flight data from seven flights was successfully recovered. The flights recorded were:

- 4 October 2008: Sydney – Adelaide, Adelaide – Singapore
- 5 October 2008: Singapore – Perth, Perth – Singapore
- 6 October 2008: Singapore – Perth, Perth – Singapore
- 7 October 2008: Singapore – Learmonth

For the accident flight, continuous data from engine start on the ground in Singapore until after engine shutdown at Learmonth was successfully recovered.

### **Sequence of events**

Table 3 provides a sequence of events prepared from data obtained from the aircraft's FDR. Times use UTC; local time was UTC plus 8 hours. Shaded areas indicate events within the two in-flight upsets.

**Table 3: Occurrence flight sequence of events**

<b>Time (UTC) (hh:mm:ss)</b>	<b>Time relative to event (hh:mm:ss)</b>	<b>Event:</b>
01:32:02	-03:10:23	Takeoff at Singapore
02:01:16	-02:41:09	Aircraft reached top of climb (37,000 ft or FL370)
04:40:28	-00:01:57	Autopilot 1 disconnect (involuntary)
04:40:28	-00:01:57	First master warning was recorded. Warnings occurred during the remainder of the flight.
04:40:29	-00:01:56	First master caution was recorded. Cautions occurred during the remainder of the flight.
04:40:31	-00:01:54	IR 1 Fail indication commenced (duration: remainder of the flight)
04:40:34	-00:01:51	First angle-of-attack (AOA) spike for the captain's (or Left) AOA parameter – the spike value was +50.6 degrees. AOA spikes continued for the remainder of the flight.
04:40:41	-00:01:44	First ADR 1 Fail indication (duration: less than 4 seconds)
04:40:50	-00:01:35	First stall warning (duration: less than one second)
04:40:54	-00:01:31	First overspeed warning (duration: less than one second)
04:41:12	-00:01:13	Autopilot 2 engaged
04:41:14	-00:01:11	Aircraft reached 37,180 ft and began to descend to 37,000 ft

04:41:28	-00:00:57	Autopilot 2 disconnected
<b>04:42:27</b>	<b>0:00:00</b>	<b>First pitch-down event commenced</b>
04:42:28	0:00:01	Captain applied back pressure to the sidestick
04:42:28	0:00:01	A maximum nose-down elevator position of +10.3 degrees was recorded
04:42:29	0:00:01	A minimum vertical acceleration of -0.80 g was recorded
04:42:29	0:00:04	A minimum pitch angle of -8.4 degrees was recorded
04:42:30	0:00:05	PRIM master changed from PRIM 1 to PRIM 2
04:42:31	0:00:05	A maximum vertical acceleration of +1.56 g was recorded
04:42:31	0:00:06	PRIM 3 Fault (duration: 120 seconds)
04:43:45	0:01:20	Captain switched his IR source from IR 1 to IR 3
<b>04:45:08</b>	<b>0:02:43</b>	<b>Second pitch-down event commenced</b>
04:45:09	0:02:44	Captain applied back pressure to the sidestick
04:45:10	0:02:45	PRIM master changed from PRIM 2 to PRIM 1
04:45:11	0:02:46	A maximum nose-down elevator position of +5.4 degrees was recorded
04:45:11	0:02:46	PRIM 3 Fault (duration: remainder of the flight)
04:45:11	0:02:46	Flight controls' 'normal law' changed to 'alternate law' (duration: remainder of the flight)
04:45:12	0:02:47	A minimum vertical acceleration of +0.20 g was recorded
04:45:12	0:02:47	A minimum pitch angle of -3.5 degrees was recorded
04:45:13	0:02:48	A maximum vertical acceleration of +1.54 g was recorded
04:47:25	0:05:00	Autothrust disengaged
04:49:05	0:06:40	A radio transmission commenced. Correlation with the CVR showed that this was the PAN transmission.
04:54:24	0:11:59	A radio transmission commenced. Correlation with the CVR showed that this was the Mayday transmission.
05:32:08	0:49:43	Aircraft touched down at Learmonth
05:42:12	1:02:47	Aircraft stopped at terminal
05:50:32	1:08:07	Power removed from FDR

## FDR information related to ADIRUs

### *Recorded ADIRU parameters*

Air data reference parameters that were recorded by the FDR included:

- pressure altitude
- computed airspeed
- mach number

- static air temperature
- angle of attack (AOA) from both the captain's (AOA 1) and first officer's (AOA 2) sensors

Inertial reference parameters that were recorded by the FDR included:

- pitch angle
- roll angle
- groundspeed
- inertial vertical speed
- drift angle
- heading
- latitude and longitude.

Some parameters required inputs from both the ADR and IR functions. They included wind speed and wind direction.

### ***IR 1 and ADR 1 Fail indications***

At 0440:28 UTC (1240:28 local time), autopilot 1 disconnected involuntarily<sup>22</sup> and the inertial reference system (IR) function of ADIRU 1 began to indicate 'Fail' (04:40:31). The IR 1 Fail indication continuously indicated 'Fail' until after landing at Learmonth.

As the IR 1 Fail indication was only sampled once every 4 seconds, it may have preceded the autopilot disconnection. A review of the recorded data and system functionality determined that the autopilot probably disconnected due to a discrepancy between the values of an ADIRU parameter received by the Flight Management Guidance Envelope Computer (FMGEC<sup>23</sup> 1). The specific parameter associated with the disconnection could not be determined.

The first ADR 1 'Fail' indication began at 0440:41 UTC. This indication lasted for less than 4 seconds. Unlike the IR Fail indication, the ADR Fail indication did not continuously indicate 'Fail'. In total, 20 ADR 1 'Fail' indications were recorded before the aircraft touched down at Learmonth. As the ADR 1 'Fail' parameter was sampled once every 4 seconds, a brief ADR 1 fail indication may not necessarily be sampled and recorded. As a result, the number of actual ADR 1 'Fail' indications may have been larger than the number recorded by the FDR.

There were no Fail indications associated with ADIRU 2 or ADIRU 3 throughout the flight.

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<sup>22</sup> An involuntary autopilot disconnection occurs automatically without any action by the crew.

<sup>23</sup> The FMGECs were part of the autoflight system and provided output commands to the control surfaces via the PRIMs and to the engines via the engine electronic control units.

### ***Spikes in FDR and QAR data***

Spikes<sup>24</sup> from ADIRU 1 were evident in the following parameters:

- angle of attack
- pressure altitude
- computed airspeed
- mach number
- static air temperature
- pitch angle
- roll angle
- wind speed
- wind direction.

The spikes appeared to be random in nature and occurred for different parameters at different times.

### ***Angle of attack spikes***

For an A330, during all phases of flight, the typical operational range of AOA is +1 degree to +10 degrees. In cruise, a typical AOA is +2 degrees.

The first AOA 1 spike occurred at 0440:34 UTC. AOA 1 values changed from +2.1 degrees to +50.6 degrees and back to +2.1 degrees over three successive samples. In total, 42 AOA 1 spikes were recorded before the aircraft touched down at Learmonth. As AOA 1 was sampled by the FDR once per second, a spike may not necessarily be sampled and recorded. As a result, the number of actual AOA 1 spikes may have been larger than the number recorded.

One of the recorded AOA spikes occurred at 04:42:26 UTC, immediately prior to the first pitch-down (04:42:27). Another of the recorded spikes occurred at 04:45:08 UTC, immediately prior to the second pitch-down (04:45:09). Both of those spikes had a magnitude of +50.6 degrees.

### ***Effects of the spikes on failure indications***

A stall warning parameter was recorded by the FDR. The first stall warning occurred at 0440:50 UTC and numerous stall warnings were recorded from this time until 0512:00 UTC when the aircraft was descending through an altitude of 12,400 ft. As the stall warning parameter was sampled once per second, a brief warning may not necessarily be sampled and recorded. As a result, the number of actual stall warnings received by the crew may have been larger than the number recorded. Examination of other recorded parameters indicated that the stall warnings were spurious.

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<sup>24</sup> A spike is a short duration transient which exceeds the normal value by a large amount.

An overspeed parameter was recorded by the FDR. The first overspeed warning occurred at 0440:54 UTC and numerous warnings were recorded from this time until 0502:01 UTC when the aircraft was descending through an altitude of 25,400 ft. As the overspeed warning parameter was sampled once per second, a brief warning may not necessarily be sampled and recorded. As a result, the number of actual overspeed warnings received by the crew may have been larger than the number recorded. Examination of other recorded parameters indicated that the overspeed warnings were spurious.

ADIRU 1 normally supplies the captain's PFD with IR and ADR parameters. The spikes in many of these parameters would have led to fluctuations and loss of data on the captain's PFD. At 0443:45 UTC, the source of IR parameters for the captain's PFD was switched from IR 1 (ADIRU 1) to IR 3 (ADIRU 3).<sup>25</sup> This action provided valid IR parameters to the PFD; however ADR parameters were still being sourced from ADR 1 (ADIRU 1).

A master caution aural alert (a single chime) occurs when certain types of failure messages appear on the ECAM. Separate master caution parameters for the captain and first officer were recorded by the FDR. The first master caution occurred at 0440:29 UTC and repetitive master cautions were recorded from this time until the FDR was powered down on the ground at Learmonth.

The PRIM faults are discussed in *Review of PRIM monitoring functions*.

## **Aircraft examination**

### **Structural examination**

Visual inspection of the aircraft found no missing or loose fasteners, no creases or folds in the fuselage skin and no signs of distress to any of the fuselage, wing or empennage skin, fairing panels or flight controls.

The FDR data showed that the peak g loadings during the flight were +1.56 g and - 0.80 g, with almost no lateral g loading. The conditional inspection section of the *Aircraft Maintenance Manual* (AMM) (Section 05-51-17, *Inspections after flight in excessive turbulence or in excess of VMO*) defined the normal flight operating range as -1.0 g to +2.5 g. Aircraft operation within this environment did not require additional inspections. Based on the review of the FDR data, the aircraft manufacturer asked for a visual inspection of the elevator servo-control attachment fittings. The inspection found no problems.

### **Cargo hold inspection**

Inspection of the cargo area found all cargo was loaded in the correct position as recorded on the load manifest for the flight and no load shift was evident. All of the cargo containers and palletised cargo remained properly secured by the integral cargo restraint systems built into the floor of the cargo holds. Each individual freight container and pallet was also examined for load shift or break out of

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<sup>25</sup> This change was consistent with the crew selecting the ATT HDG switch to the CAPT ON 3 position at about this time in response to an ECAM message.



individual items from within each unit. None was evident. After removal of the cargo, the aircraft hold's structure and restraint systems were inspected for damage which might be attributed to the event. No anomalies were found.

Once removed from the aircraft, and under the supervision of Australian Quarantine and Customs officers, the cargo was inspected for items which might be possible sources of electronic or electromagnetic interference. None were identified.

## **Wiring examinations**

Due to the level of damage to ceiling panels in the cabin, all the ceiling panels were removed and wiring looms were visually inspected. No defects were observed.

After the aircraft had been ferried to a maintenance base, the operator conducted precautionary checks of the aircraft's ADIRU interface wiring. The checks involved continuity, short circuit, electrical bonding and shielding tests. No problems were found.

## **Central maintenance system**

The central maintenance system (CMS) enabled trouble-shooting and return-to-service testing to be carried out rapidly from the flight deck. The hub of the CMS was the central maintenance computer which assisted in the diagnosis of faulty systems.

### ***Central maintenance computer (CMC)***

Each aircraft system has built-in test equipment (BITE) which is used to test system components and detect faults and to confirm system operation following any maintenance. Each of the aircraft's systems communicates with the CMC and sends it information on detected faults and any warnings indicated to the flight crew.

When the aircraft was on the ground, maintenance engineers could access the CMC using a multi-purpose control and display unit (MCDU) from the flight deck and obtain information from the most recent flight or earlier flights. Through using the MCDU, BITE information from aircraft systems could be interrogated and the systems tested.

Aircraft systems could detect faults in two ways: internally, by monitoring its own operation, or externally, by another aircraft system which received and monitored information from the 'faulty' system. For example, a fault with an ADIRU could be detected by the ADIRU itself or by another ADIRU or system.

### ***Post flight report (PFR)***

The CMC produced various reports that were accessible through the MCDU when the aircraft was on the ground. Those reports included the post flight report (PFR), which was produced and printed at the end of a flight. The PFR contained fault information received from other aircraft systems' BITE and which was sent to the CMC during flight.

When the CMC produced the PFR at the end of a flight, it carried out some correlation between the warnings provided by the flight warning computer (FWC) and the fault data provided by aircraft system BITE.

The PFR had some limitations:

- fault information was only recorded to the nearest minute
- it only showed the first occurrence of a fault, so an intermittent occurrence of the same fault message would not be shown
- the correlation performed by the CMC, at the time that the first fault was detected, was designed to group all the same ATA<sup>26</sup> chapter faults together and would only show the first fault that was detected along with a list of systems that detected the fault.

The PFR recorded that, between 0440 and 0442, a fault was detected with ADIRU 1 by several aircraft systems. At about the same time, several related fault messages were provided to the ECAM, including:

- NAV IR 1 FAULT
- NAV GPWS FAULT
- FLAG ON CAPT ND MAP NOT AVAIL
- NAV GPS 1 FAULT
- NAV GPS 2 FAULT
- NAV IR NOT ALIGN

Starting at 0440, there were also a series of related messages which were associated with the anti-icing aspect of the ADIRS sensors, including A.ICE L CAPT STAT HEAT, A.ICE R CAPT STAT HEAT, A.ICE CAPT PROBES HEAT, A.ICE CAPT PITOT HEAT and A.ICE CAPT AOA HEAT.

The PFR recorded that a fault was detected with PRIM 1 and PRIM 3 at 0442. Related fault messages provided to the ECAM included:

- F/CTL PRIM 1 PITCH FAULT
- F/CTL PRIM 3 FAULT

The PFR also recorded that a fault was detected with PRIM 2 at 0445. Related fault messages provided to the ECAM included:

- F/CTL PRIM 2 PITCH FAULT
- F/CTL ALTN LAW (see also *Review of PRIM monitoring functions*).

## **Data downloads from aircraft systems**

As the PFR only shows a summary of the warnings and faults, to obtain complete information, further interrogation of the BITE information from individual systems could be performed. When the aircraft was on the ground, reports generated from system BITE memory could be printed using the MCDU.

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<sup>26</sup> The Air Transport Association (ATA) categorises aircraft systems based on a chapter numbering system. This categorisation is widely used in aircraft documentation.

Based on an examination of the FDR data, the aircraft manufacturer recommended removing ADIRU 1 and the number-1 PHC before conducting any data downloads or testing of the aircraft's systems. Replacement units were then installed and BITE data downloaded from the following aircraft equipment and systems while the aircraft was at Learmonth:

- electronic flight control system (including the PRIMs, flight control secondary computers and flight control data concentrators)
- autoflight system including the flight management guidance envelope computers (FMGECs)
- air data and inertial reference system
- landing gear control interface units (LGCIUs)
- enhanced ground proximity warning system (EGPWS)
- probe heat computers
- multi-mode receivers
- electrical power generation system.

Pertinent results were as follows:

- FMGEC 1 and 2 were each connected to ADIRUs 1, 2 and 3. Both FMGECs 1 and 2 detected anomalous behaviour of ADIRU 1 but did not detect any problems with ADIRUs 2 and 3.
- LGCIUs 1 and 2 were connected to ADIRUs 1 and 3 (ADR part only). Both LGCIUs 1 and 2 detected anomalous behaviour of ADIRU 1 but did not detect any problems with ADIRU 3.
- EGPWS was connected to ADIRU 1 only. EGPWS detected anomalous behaviour of ADIRU 1.

In summary, the BITE data for several systems indicated a problem with ADIRU 1 but no data indicated a problem with ADIRU 2 or ADIRU 3 (see also *ADIRU test results*).

## **System testing**

After PFR and BITE data were downloaded, operational tests were performed on the following aircraft systems at Learmonth in accordance with the aircraft manufacturer's recommended maintenance procedures:

- electronic flight control system
- inertial reference systems
- air data reference systems
- probe heat computers
- multi-mode receivers
- flight guidance computers
- electrical power generation system
- elevator hydraulic actuation and pitch control.

A fault was identified with the elevator hydraulic control, but this was considered by the aircraft manufacturer to be unrelated to the circumstances of the occurrence. The fault had a known cause that was only triggered under a very specific set of circumstances, different to those seen during the occurrence. The aircraft systems passed all other tests.

### **Flight control primary computers (PRIMs)**

The three PRIMs were removed from the aircraft and examined by an authorised agency. It was confirmed that each PRIM was loaded with identical operational software (version P7/M16). The PRIMs were tested and the BITE data was downloaded from each unit. The results were:

- FCPC 1 (serial number 7270): During testing, no fault was found. No faults were stored in BITE data.
- FCPC 2 (serial number 6165): During testing, no fault was found. The BITE data did not contain any faults relevant to the pitch-down events.
- FCPC 3 (serial number 6170): During testing, the unit failed a lightning protection test. The aircraft manufacturer advised that this result was unrelated to the pitch-down events. The BITE data did not contain any faults relevant to the pitch-down event.

Based on a review of the recorded data and system functionality, the PRIM faults recorded by the FDR and PFR were found to be consequences of the pitch-down events (see *Review of PRIM monitoring functions*).

### **Probe heat computer**

Some of the PFR messages indicated a potential fault with the number-1 probe heat computer (PHC). Those messages could be generated by either a PHC fault or by an ADIRU fault. The PHC (serial number 2083) was tested by an authorised agency and no fault was found. Based on a review of available information, the messages related to the PHC were considered to be spurious.

### **Angle of attack sensor**

The AOA 1 sensor (serial number 0861ED-972) was tested by an authorised agency. No fault was found with the sensor and all test parameters were within limits.

### **ADIRU testing**

The ATSB took custody of ADIRU 1 (serial number 4167) in Learmonth on 10 October 2008 while ADIRUs 2 and 3 (serial numbers 4687 and 4663 respectively) remained installed in the aircraft. On 15 October 2008, after the aircraft had been ferried back to Sydney, ADIRUs 2 and 3 were removed from the aircraft and quarantined by the operator. Also on 15 October 2008, custody of ADIRU 1 was transferred from the ATSB to the operator.

The three ADIRUs were despatched to the ADIRU manufacturer's facility in Los Angeles. ADIRU 1 was received on 17 November 2008 while ADIRUs 2 and 3

were received on 18 November 2008. All three ADIRUs were quarantined on arrival and locked in a secure storage room awaiting the arrival of the investigation team.

## **ADIRU test plan**

To make the testing process efficient, it was necessary to have an agreed test plan in place before the investigation teams arrived at the manufacturer's facility. The testing priorities were to:

- minimise the chance of losing perishable data
- use standard test procedures before testing the ADIRUs with novel procedures
- review current test results before proceeding with the next test
- order the testing so that 'whole box' testing was completed before an ADIRU was disassembled

To minimise the chance of losing perishable data or the chance that test equipment/procedures might damage an ADIRU, an exemplar ADIRU was included in the testing. The exemplar unit was provided by the ADIRU manufacturer and was functionally identical to ADIRU 1, and had the same hardware/software modification status. ADIRU testing was performed on the exemplar unit before being performed on ADIRU 1.

## **Participants**

The following organisations attended the ADIRU testing at the manufacturer's facilities in the US: the ATSB; the French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA); the US National Transportation Safety Board (NTSB); the aircraft manufacturer; the ADIRU manufacturer; the operator; and the US Federal Aviation Administration (FAA).

## **ADIRU test schedule**

Testing commenced on 17 November 2008 with all the participating organisations present. Daily reviews and discussions of the test results were held. Once it was realised that an obvious fault with ADIRU 1 was not going to be found, an ongoing test program was developed and agreed. The witnessed testing period concluded on 25 November 2008 and the test program is continuing at the manufacturer's facility. Protocols are in place for the oversight of the testing, regular reporting of the results to investigation team members and analysis of the results.

## **Completed ADIRU tests**

The tests completed at the time of publication of this report were:

- Physical inspection: the three ADIRUs were inspected visually for damage with particular emphasis on the connector pins.
- Ground integrity test: various connector pins on ADIRU 1 were electrically tested for ground integrity.

- Program verification: the three ADIRUs were connected to a test bench and the operational flight program (OFP) software was downloaded from the units to check that it was the correct version and was not corrupted.
- Recorded data download: BITE data from the three ADIRUs was downloaded and analysed.
- Built-in test and manufacturing test procedure: the three ADIRUs were connected to a test bench and the units' internal test equipment was run. Additional functional tests were also performed on the bench.
- Bus tests: ADIRU 1 was connected to a test bench and the bus traffic was recorded while different bus load impedances were simulated. The bus output waveforms were also recorded and analysed for comparison with the specification.
- Internal visual inspection: the case of ADIRU 1 was opened and an internal visual inspection was completed without removing any internal equipment.
- Environmental tests: ADIRU 1 was subjected to a range of environmental tests including vibration and temperature. One environmental stress screening test used a temperature range of -40 °C to +70 °C. ADIRU 1 was also subjected to electromagnetic interference (EMI) tests in accordance with the frequencies and field strengths specified in DO-160C.<sup>27</sup> In addition to the frequencies specified in the standard, ADIRU 1 was also subjected to specific conducted susceptibility tests at the Harold E. Holt Naval Communication Station frequency of 19.8 kHz and a field strength of 100 Volts/metre (see *Electromagnetic interference*).

## ADIRU test results

The BITE data from ADIRUs 2 and 3 was successfully recovered and showed that there were anomalies in the way that ADIRU 1 had been transmitting data to other aircraft systems. The BITE data did not show any problems with the performance of ADIRUs 2 and 3.

BITE data from ADIRU 1 was recovered and showed:

- No data had been stored for the time periods relating to the pitch-down events.
- Several routine BITE messages that were expected to have been stored were not recorded.
- There were anomalies in the BITE elapsed time interval parameter.

Following the BITE downloads and successful completion of the standard manufacturing test procedures, the investigation team agreed that no further testing of ADIRUs 2 and 3 was required.

None of the testing that has been completed to date on ADIRU 1 has produced any faults that were related to the pitch-down events. While some faults have been detected during the extensive testing, they have been confirmed as being due to the artificial nature of the testing or problems with the test equipment.

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<sup>27</sup> DO-160C, *Environmental Conditions and Test Procedures for Airborne Equipment*, produced by the Radio Technical Commission for Aeronautics (RTCA). Issued 12 April 1989.

Further testing of ADIRU 1 is in progress (see *ONGOING INVESTIGATION ACTIVITIES*).

## Review of PRIM monitoring functions

The aircraft's flight control system included three flight control primary computers (FCPCs, commonly known as PRIMs) and two flight control secondary computers (FCSCs, commonly known as SECs). One PRIM functioned as the master while the other two PRIMs could take over as master if a fault in the current master was detected. The master PRIM processed and sent control surface deflection orders to other computers, which executed them using servo-controls. The two other PRIMs continuously computed control orders and monitored control surface deflections but those orders were not actioned.

Each PRIM consisted of two independent parts, a Command (COM) part and a Monitor (MON) part. The MON part monitored the performance of the COM part and the position of the control surfaces. If there was a discrepancy between COM and MON, then the PRIM would 'fault' itself. The fault could be for only a part of the PRIM (for example, pitch channel) or for the whole PRIM. A PRIM could not generate a fault for the whole PRIM unless it was the master. The PRIM Fault parameter recorded by the FDR was active only for a fault of the whole PRIM and not for a partial fault (for example, a pitch channel fault). However, partial faults were recorded by the PFR.

For elevator control, the active servo-controller in normal operation was PRIM 1. The servo-controller priority order was PRIM 1, PRIM 2, SEC 1 and SEC2. If PRIM 1 could not perform this function, then the servo-control function reverted to PRIM 2 and so on.

Table 4 provides a sequence of events for the PRIMs and is based on a review of the FDR and PFR data by the aircraft manufacturer and investigation team.

**Table 4: PRIM sequence of events**

Time (UTC): (hh:mm:ss)	Master PRIM:	Active Law:	Pitch servo- controller:	Event:
Prior to 04:42:30	PRIM 1	Normal	PRIM 1	Uneventful flight (takeoff, climb and initial cruise)
04:42:30	PRIM 3	Normal	PRIM 2	F/CTL PRIM 1 Pitch Fault (during first pitch-down event). PRIM 3 became master PRIM.
04:42:31	PRIM 2	Normal	PRIM 2	PRIM 3 Fault (duration: 120 seconds). PRIM 2 became master PRIM.
04:43:31	PRIM 2	Normal	PRIM 2	PRIM 3 status changed from Fault to No Fault. This was consistent with it having been reset by the crew.
04:45:10	PRIM 3	Normal	SEC 1	F/CTL PRIM 2 Pitch Fault (during second pitch-down event). PRIM 3 became master PRIM.
From 04:45:10 until the end of flight	PRIM 1	Alternate	SEC 1	PRIM 3 Fault. PRIM 1 became master PRIM, but because it already had a Pitch Fault it could not operate in

In summary, the PRIM PITCH FAULTs and PRIM 3 FAULTs that occurred during the flight were consistent with the system design. They were consequences of the pitch-down events and not the initiators of those events.

## **Review of PRIM angle of attack processing**

In addition to identifying the nature of the ADIRU failure which led to erroneous data outputs, a key aspect of the investigation was to determine why the erroneous data outputs had an undesirable and abrupt effect on the aircraft's elevator positions. As part of the investigation, the manufacturer conducted a detailed review of how AOA data was processed by the PRIMs on the A330.

### ***General ADIRU data processing algorithms***

As with other modern airline aircraft, the A330 used a variety of redundancy and error-checking mechanisms to minimise the probability of erroneous ADIRU data having a detrimental effect on the aircraft's flight controls.

For most of the ADIRU parameters, the PRIMs obtained three different values of the same parameter. Each value came from a different sensor and was processed by a different ADIRU. The PRIMs compared the value of the parameter coming from each ADIRU. If the value of any of the parameters differed from the median (middle) value by more than a threshold amount for more than a set period of time, then the relevant part (that is, ADR or IR) of the associated ADIRU would no longer be used by the PRIMs.

In addition, for ADIRU parameters except for AOA, when all three values were valid, the median value was used for calculating the flight control commands. The use of the median values was robust to any error from one data source.

### ***Angle of attack data processing algorithms***

There was a potential for the AOA sensors on the right side of the aircraft (AOA 2 and AOA 3) to provide different values to the AOA sensor on the left side of the aircraft (AOA 1) in some situations due to aircraft sideslip.<sup>28</sup> In order to minimise the potential effect of this difference, the PRIMs used different processes for AOA compared with other parameters when determining the value to use for calculating flight control commands. More specifically, the processing of AOA data involved the following:

- As with the other parameters, the PRIMs would continuously monitor the AOA values from the three ADIRUs. AOA data was sampled about 20 times per second.
- To confirm the validity of the AOA data, the PRIMs would compare the median value from all three ADIRUs with the value from each ADIRU. If the difference was greater than a set value for more than 1 second continuously, then the PRIM

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<sup>28</sup> Sideslip: a condition in which the oncoming airflow is at a sideways angle to the aircraft's centreline.



would flag the ADR part of the associated ADIRU as faulty and ignore its data for the remainder of the flight.

- To calculate a value of AOA to use for calculating flight control commands, the PRIMs would use the average value of AOA 1 and AOA 2. In other words,  $(AOA\ 1 + AOA\ 2)/2$ . This value was passed through a rate limiter to prevent rapid changes in the value of the data due to short-duration anomalies (for example, as a result of turbulence).
- If the difference between AOA 1 (or AOA 2) and the median value from all three ADIRUs was higher than a set value, the PRIMs memorised the last valid average value and used that value for a period of 1.2 seconds. After 1.2 seconds, the current average value would be used.

In summary, in contrast to other parameters, only two values of AOA were used by the PRIMs when determining flight control commands. However, several risk controls were in place to minimise the potential for data inaccuracies to affect the flight control system.

### ***Scenario where AOA spikes could influence flight controls***

The aircraft manufacturer advised that the AOA processing algorithms would prevent most types of erroneous AOA inputs provided by the ADIRUs having an influence on flight control commands. This included situations such as an AOA 'runaway' (or a continuous divergence from the correct value), single AOA spikes and most situations where there were multiple AOA spikes. However, the manufacturer identified that, in a very specific situation, the PRIMs could generate an undesired nose-down elevator command. This specific situation involved multiple AOA data spikes with the following properties:

- there were at least two short duration, high amplitude spikes
- the first spike was shorter than 1 second
- the second spike occurred and was still present 1.2 seconds after the detection of the first spike.

Recorded flight data from the accident flight showed that there were 42 recorded spikes in AOA 1 data. Due to recorder sampling rate limitations, it is likely that there were additional AOA 1 spikes that were not evident in the recorded data and it is not possible to reconstruct the exact duration and timing of any of the spikes.

Although a large number of AOA 1 spikes occurred on the accident flight, on all but two of those occasions, the processing algorithm filtered them out and they had no influence on the flight controls.

The aircraft manufacturer advised that AOA spikes may occur on many flights, but in its experience, there were usually only a very small number of spikes on any particular flight. It was not aware of any previous event where AOA spikes had met the above conditions and resulted in an in-flight upset.

### ***Simulation studies***

As part of the investigation, the manufacturer reported that it had performed simulation studies concerning the filtering of AOA spikes by a PRIM. The simulation studies confirmed that the input of two AOA spikes which met the

conditions listed above, were not effectively filtered by the PRIM, and could lead to undesired nose-down elevator commands.

### ***Flight envelope mechanisms influenced by AOA spikes***

The aircraft manufacturer reported that, based on its analysis of the available data and its review of system design, two of the flight envelope mechanisms were influenced by the AOA spikes during the accident flight: high angle of attack protection (alpha prot) and anti pitch-up compensation.

Alpha prot was designed to protect the aircraft from high AOAs which could lead to a stall and loss of control. If the PRIMs detected that the aircraft's AOA exceeded a predefined threshold, the computers would command a nose-down elevator movement to reduce the AOA. Alpha prot was only available when the aircraft was in normal law. When the aircraft was above 500 ft above ground level, alpha prot was effective immediately, while below 500 ft it was only active after the AOA exceeded the threshold for 2 seconds or more.

Anti pitch-up was a pre-command included in the control laws to compensate for a pitch-up at high Mach due to aerodynamic effect.<sup>29</sup> The compensation was available above Mach 0.65 and when the aircraft was in a 'clean' configuration (that is, with the landing gear and flaps retracted). The maximum authority of the anti pitch-up compensation was 6 degrees of elevator movement.

The aircraft manufacturer advised that the 10-degree elevator command associated with the first in-flight upset, was the result of 4 degrees of alpha prot and the 6 degree authority of the anti pitch-up compensation. The 10-degree command was close to the worst possible scenario that could arise from the design limitation in the AOA processing algorithm.

For the accident flight, there was only a limited potential for additional upsets to occur. After the second upset, alpha prot was no longer operative as the flight control law had reverted from normal law to alternate law. From approximately 18 minutes after the second upset, the aircraft was below Mach 0.65 and anti pitch-up compensation was no longer active.

The manufacturer advised that a simulation performed with the AOA profile identified during the first pitch-down event, showed that such an AOA profile would not have produced a pitch-down event had the aircraft been below 500 ft.

### ***Relevance to other aircraft types***

The manufacturer advised that the AOA processing algorithms used by A330 aircraft were also used by A340 aircraft. However, different algorithms were in use on other Airbus types, which were reported to be more robust to AOA spikes. The manufacturer advised that AOA spikes matching the above scenario would not have caused a pitch-down event on Airbus aircraft other than an A330 or A340.

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<sup>29</sup> Pitch-up is an aerodynamic anomaly that can occur in aircraft with swept wings at high altitude and at high speed.

## Other ADIRU-related occurrences

### ADIRU reliability

Most components on modern aircraft, including ADIRUs, are highly reliable. Nevertheless, failures do occur. The aircraft manufacturer reported that the average mean time between failure<sup>30</sup> (MTBF) for ADIRUs of the model used on VH-QPA, was about 17,500 flight hours.

### ADIRU failures affecting flight controls

It is extremely rare for any ADIRU failures to have an undesirable effect on an aircraft's flight controls.

The ATSB investigated an in-flight upset occurrence related to an ADIRU failure on a Boeing 777-200 aircraft, which occurred on 1 August 2005, 240 km north-west of Perth. The ADIRU on that aircraft was made by a different manufacturer and of a different type to that on VH-QPA. Further details of that investigation can be found on the ATSB web site.<sup>31</sup>

Airbus has reported that it is unaware of any previous occurrences where an ADIRU failure on one of its aircraft has resulted in undesirable elevator commands. However, there have been two other known occasions where ADIRUs have exhibited similar anomalous behaviour to that which occurred on the 7 October 2008 accident flight, although those problems did not result in any adverse affect on the aircraft's flight controls. Those events occurred on 12 September 2006 and 27 December 2008.

### VH-QPA, 12 September 2006

On 12 September 2006, VH-QPA was on a scheduled passenger transport service (QF68) between Hong Kong and Perth, Australia. At 2052 UTC (0452 local time), while the aircraft was in cruise at 41,000 ft, there was a failure of ADIRU 1. The ADIRU was the same unit (serial number 4167) as on the 7 October 2008 flight. The flight crew entered the problem into the aircraft's technical log, noting that there had been a NAV ADR 1 FAULT and that they had received numerous ECAM messages.

The PFR showed that there was a NAV IR1 FAULT at 2052 and, subsequently, a NAV ADR 1 FAULT at 2122. Maintenance records stated that, in accordance with the manufacturer's maintenance procedures for the relevant PFR fault messages, an ADIRU re-alignment was conducted and a system test of both the IR and ADR was conducted. No faults were found.

Following the 7 October 2008 accident, further information was obtained regarding the 12 September 2006 occurrence. The crew reported that the event occurred at night and that the aircraft was in clear conditions at the time of the event. The first

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<sup>30</sup> In this context, MTBF is the average time between two failures of any type requiring the unit to be repaired.

<sup>31</sup> See [http://www.atsb.gov.au/publications/investigation\\_reports/2005/AAIR/air200503722.aspx](http://www.atsb.gov.au/publications/investigation_reports/2005/AAIR/air200503722.aspx).

officer was the handling pilot and autopilot 2 was engaged. The crew reported that they received numerous ECAM warning and caution messages. The messages changed rapidly and consequently they could not be read properly or actioned. There were also overspeed and stall warnings present.

The crew reported that they contacted maintenance watch, but subsequent discussions could not resolve the issue. A scan of the overhead panel identified a very weak and intermittent ADR 1 fault light. The crew decided to turn off the ADR 1. Following that action, the warning and caution messages ceased and the flight continued without further incident. The crew reported that at no stage was there any effect on the aircraft's flight controls. The autopilot and autothrust remained engaged throughout the event.

No FDR or QAR data was available for the 12 September 2006 flight. The location of the aircraft at the time of the NAV IR 1 FAULT was estimated using positions reported by ACARS<sup>32</sup> messages transmitted before and after the fault occurred. That technique gave a position 980 km (530 NM) north of Learmonth (Figure 11).

**Figure 11: Locations for each occurrence (the point shown is where the anomalous ADIRU behaviour commenced)**



The PFR for the flight contained a series of messages associated with ADIRU 1 which were similar to the PFR for the 7 October 2008 flight. Consistent with there being no in-flight upset, there were no PRIM FAULTS or PRIM PITCH FAULTS on the 12 September 2006 PFR. The NAV ADR 1 FAULT, which was recorded 30 minutes after the NAV IR 1 FAULT, may have been associated with the crew action of turning ADR 1 off.

32 ACARS: Aircraft communications, addressing and reporting system. ACARS transmits maintenance and operational messages at intervals throughout a flight.

## VH-QPG, 27 December 2008

### Sequence of events

On 27 December 2008, an Airbus A330-303 aircraft, registered VH-QPG, was on a scheduled passenger transport service (QF71) from Perth to Singapore. At about 0829 UTC (1729 local time), while the aircraft was in cruise at 36,000 ft, the autopilot (autopilot 1) disconnected and the crew received an ECAM message (NAV IR 1 FAULT). ADIRU 1 was the same model but a different unit (serial number 4122) to that involved in the 12 September 2006 and 7 October 2008 events. Table 5 presents a summary of the sequence of events based on FDR and QAR data.

**Table 5. VH-QPG sequence of events**

Time (UTC) (hh:mm:ss)	Time relative to event (hh:mm:ss)	Event:
07:49:55	-00:39:01	Takeoff at Perth
08:14:01	-00:14:55	Aircraft reached top of climb (36,000 ft or FL360)
08:28:55	-00:00:01	IR 1 Fault indication commenced. Sampled once every four seconds.
<b>08:28:56</b>	<b>00:00:00</b>	<b>Autopilot 1 disconnect (involuntary)</b>
08:29:20	00:00:24	ADR 1 Fault indication commenced. Sampled once every four seconds.
08:30:21	00:01:25	Autopilot 1 re-engaged
08:32:25	00:03:29	Captain's PFD source switched to IR 3
09:25:45	00:56:49	Touchdown at Perth (aircraft gross weight was 195.3 tonnes)

The crew reported that they actioned the relevant operational procedure<sup>33</sup> by selecting the IR 1 push-button to OFF and the ADR 1 push-button to OFF. Both OFF lights illuminated.

The crew also reported that, even though the procedure had been completed, they continued to receive multiple ECAM messages. Those messages were constantly scrolling on the display. The ECAM procedure for the NAV IR 1 FAULT was displayed and it recommended switching the IR rotary mode selector to the ATT position. The crew reported that they completed this action (see Table 5, 0832:25), but it was unsuccessful in preventing further ECAM messages. The crew elected to return to Perth and an uneventful overweight landing was conducted. The crew reported that at no stage was there any effect on the aircraft's flight controls.

Examination of the FDR/QAR data showed that at 0829:20, there was an ADR 1 Fault indication recorded on the FDR, which was consistent with the crew turning off ADR 1. Recorded data confirmed that the ADR 1 was selected OFF and was not providing further data to the aircraft's systems from that time. However, even

<sup>33</sup> This procedure was different to that which applied at the time of the 7 October 2008 occurrence. The relevant procedure at the time of the 27 December 2008 occurrence was based on Airbus Operations Engineering Bulletin (OEB) 74-3 issued in December 2008 (see *SAFETY ACTION*).

though the IR 1 push-button had also been selected OFF, the IR 1 continued to supply erroneous data to the aircraft's systems.

At the time that the autopilot disconnected, the aircraft was approximately 260 NM north-west of Perth Airport and approximately 650 km (350 NM) south of Learmonth Airport (Figure 11).

The PFR for the 27 December 2008 flight contained a series of messages associated with ADIRU 1 which were similar to the PFR for the 7 October 2008 flight. Consistent with there being no in-flight upset, there were no PRIM FAULTS or PRIM PITCH FAULTS. There was a NAV ADR 1 FAULT recorded 1 minute after the NAV IR 1 FAULT, and this was associated with the crew action of turning ADR 1 off.

### ***Examination of ADIRU 1 from VH-QPG***

Following the incident on 27 December 2008, the ADIRU initially remained on the aircraft but was unpowered. The unit was later removed from the aircraft and sent to the manufacturer's facility in Los Angeles. It was received on 8 January 2009 and was locked in a secure storage room while a test plan was developed.

The investigation team agreed that the ADIRU should undergo a standard manufacturer's test procedure and BITE download and the results analysed.

Examination of the BITE data showed anomalous results that were similar to those obtained from the BITE download of ADIRU 1 from VH-QPA. More specifically:

- BITE data was recovered but it did not contain information from the time period relating to the anomalous ADIRU behaviour
- several routine BITE messages that were expected to have been stored were not recorded
- there were anomalies in the BITE elapsed time interval parameter.

At the time of publication, the source of the fault with ADIRU 1 from VH-QPG had not been identified and the unit has been securely stored until testing on ADIRU 1 from VH-QPA had been progressed.

### **Search for similar events**

Following the 7 October 2008 occurrence and based on information available at the time, the aircraft manufacturer and ADIRU manufacturer advised that they were not aware of any other occurrence involving similar anomalous ADIRU behaviour. They also advised that, if such a problem had occurred and no fault was found in a subsequent ground test of the unit, then the event would probably not be reported to them.

Following the 27 December 2008 event, Airbus conducted a review of PFRs using the AIRcraft Maintenance ANalysis (AIRMAN) database. AIRMAN is a ground-based software tool that assists operators of Airbus aircraft to identify and manage unscheduled maintenance. Fault data is downloaded in real time, and PFRs are stored and available for subsequent analysis. The use of AIRMAN is an operator-based decision, with most Airbus operators electing to use the tool. AIRMAN is currently used to monitor over 2,000 aircraft worldwide.

Airbus searched the AIRMAN database for PFRs which contained a similar pattern of fault messages as occurred on the 12 September 2006, 7 October 2008 and 27 December 2008 flights. For the period January 2005 to December 2008 for A330/A340 aircraft with ADIRUs of the same model, four matching PFRs were identified: three for the events already identified and another event from a related operator (see *VH-EBC, 7 February 2008*). No matching PFRs were identified for single-aisle Airbus aircraft (A318, A319, A320, A321) or A330/340 aircraft with different model ADIRUs.

Airbus advised that there were about 900 A330/A340 aircraft in operation, and 397 had the same model of ADIRU as fitted to VH-QPA and VH-QPG. AIRMAN data was available for 248 of those aircraft in the 2005 to 2008 period. The sample of 248 aircraft included 48 operators, and those included several airlines that operated flights to and from Australia.

### **VH-EBC, 7 February 2008**

On 7 February 2008, an Airbus A330-200 aircraft, registered VH-EBC, was on a scheduled passenger transport service (JQ07) from Sydney to Saigon, Vietnam. At 0604 UTC, while the aircraft was in cruise, there was a failure of ADIRU 1. The ADIRU was the same model but a different unit (serial number 5155) to those involved in the other three events.

The crew reported in the aircraft's technical log that they received a NAV IR 1 FAULT message. After consulting the ECAM and operations manual, they switched the IR rotary mode selector to the ATT position and the ATT HDG switch to the CAPT ON 3 position. Following the identification of this event via the AIRMAN search, the crew of EBC on 7 February 2008 were interviewed about the event. Their recollection was consistent with the technical log entry. After following the specified procedure, they received no additional ECAM messages and the flight continued without further incident.

No FDR/QAR data was available for the 7 February 2008 flight. The PFR showed that there were many similar fault messages associated with ADIRU 1 as occurred for the other three events. Consistent with there being no in-flight upset, there were no PRIM FAULTS or PRIM PITCH FAULTS.

The location of the aircraft at the time of the NAV IR 1 FAULT was estimated using positions reported by ACARS messages transmitted before and after the fault occurred. That technique gave a position 700 km (380 NM) north-west of Sydney and 3,250 km (1,760 NM) east of Learmonth.

At the time of publication, the investigation team had not confirmed whether or not this event was related to the other occurrences.

## **Electromagnetic interference**

### **General information**

All electrical systems generate some electromagnetic emissions, commonly called radio waves, either as an intended function of the system or as an unintended consequence of the physical properties of its electrical circuits. All systems can also

be disturbed, to varying levels, by emissions from another source. Electromagnetic interference (EMI) is an undesired disturbance in the function of an electrical system as a result of electromagnetic emissions from another source.

Electrical systems, particularly aircraft avionics, are designed to be resilient to undesirable disturbances as a result of emissions from other systems, and also to minimise emissions that may cause disturbances in other systems. For example, the signal strengths within a system are designed to be far greater than the amount of currents and voltages that are expected to be induced by other systems, so that the magnitude of any unintentionally induced signal is too low to have an undesirable effect on the system.

Emissions can be divided into two types: conducted and radiated. Conducted emissions travel along wire interconnects between systems or parts of a system. Radiated emissions travel through free space and are generated by time-varying electrical signals in a conductor. However, radiated emissions can induce currents in electrical wiring, and currents in wiring can emit electromagnetic radiation.

A system may produce both conducted and radiated emissions over a range of frequencies and varying magnitudes. Conversely, a system may also be susceptible to conducted or radiated interference over a range of frequencies and magnitudes. Those characteristics of a system's emissions and susceptibilities are a consequence of the physical properties of the system, mostly by design. For example, a piece of electrical equipment may be enclosed in a metal housing that prevents internal radiated emissions from emanating outside the unit and also shields the unit from external radiated emissions. However, the system's physical properties may change over time as a result of environmental effects and ageing, or if there is a hardware fault. For example, an electrical connection may degrade and result in undesired emissions.

In an aircraft, emissions may originate from a number of sources:

- from aircraft systems
- from personal electronic devices (PEDs) carried by passengers or crew, or active electronic devices in the aircraft's cargo
- from external artificial sources such as radar sites and communications facilities
- from natural sources such as electrical storms, rain particles, electrostatic discharge, and solar and cosmic radiation.

## **Electromagnetic compatibility standards**

The A330 aircraft type was certified to meet European and US airworthiness requirements. As such, the aircraft and equipment were required to be resistant to EMI, demonstrated through aircraft and equipment design and testing.

US Federal Aviation Regulations required the systems to be resistant to electromagnetic field strengths of 50 to 3,000 volts per metre (V/m), depending on frequency. At very low frequencies (VLF), the limit was 50 V/m.

Equipment may be vulnerable to conducted and radiated emissions, and special test methods can be used to determine the susceptibility to both types. Conducted susceptibility tests induce interference on the wiring interfaces of the equipment,



while radiated susceptibility tests subject the equipment to high strength radio waves.

Conducted susceptibility tests covered the 10 kHz to 400 MHz range (such as audio and VLF frequencies), and radiated susceptibility tests covered the 30 MHz to 18 GHz range (such as high frequency radio and radar frequencies).

As part of the certification of the ADIRU design, a sample ADIRU was tested to limits specified by the DO-160C standard. The limits for that standard were 100 V/m field strength for radiated susceptibility and 150 milliamperes (mA) induced current for conducted susceptibility.

### **Potential sources of EMI in the geographical area**

As shown in Figure 11, the three known related events occurred within 1,000 km of Learmonth. The operator reported that its A330 aircraft conducted 9,149 sectors in 2008. Approximately 19 per cent of those sectors were flights between Perth and Singapore or Hong Kong and passed in relatively close proximity to Learmonth. Approximately 29 per cent of its A330 flights passed within 1,500 km of Learmonth. In addition, other A330/A340 operators conducted regular flights between Asian locations and Perth.

Given that the events all occurred in a broadly similar geographical area, the investigation reviewed information concerning potential sources of EMI in the area.

#### ***Harold E. Holt Naval Communication Station***

The 7 October 2008 occurrence occurred within 170 km of the Harold E. Holt Naval Communication Station near Learmonth, Western Australia. The station transmitted at a frequency of 19.8 kHz which is within the VLF band. The transmission power was about 1 megawatt using an omni-directional antenna.

The station transmitted almost continuously with the exception of weekly maintenance periods, and was transmitting at the time of the three A330 ADIRU-related occurrences under investigation (12 September 2006, 7 October 2008, and 27 December 2008).

The Australian Department of Defence advised that:

- no equipment malfunctioned near to or during the time of the events
- the frequency of 19.8 kHz had been in use for over 10 years
- there had been no changes in the nature of the transmissions in recent years.

The Harold E. Holt station has been in operation since 1967. VLF transmitters are also located in other countries including the USA, UK, China, France, India, Japan and Russia.

Estimated field strengths as a result of transmissions from the station, at the three locations where the ADIRU-related events occurred, are provided in Table 6. Those field strength values were significantly below the levels at which the ADIRU design was tested during certification.

**Table 6: Estimated field strengths as a result of transmissions from the Harold E. Hold Naval Communication Station**

Event	Aircraft	Approximate distance to station (km)	Approximate electromagnetic field strength (V/m)
12 Sep 2006	VH-QPA	950	0.011
7 Oct 2008	VH-QPA	170	0.059
27 Dec 2008	VH-QPG	700	0.014

As noted in *ADIRU testing*, the test plan for the ADIRU 1 from QPA included testing the unit at the frequency used by the VLF transmitter. No problems were found with the performance of ADIRU 1. This testing only involved conducted susceptibility.<sup>34</sup>

### ***High Frequency (HF) radio communications site***

A high frequency (HF) radio communications site is also located on North West Cape near Learmonth. The site can transmit signals in the HF frequency band (3 to 30 MHz) at a signal power of 10 kilowatts or less. Records indicate that the site was transmitting at the time of the 12 September 2006 and 27 December 2008 events. It was not transmitting at the time of the 7 October 2008 event.

## **Cabin safety**

### **Passenger seating disposition**

There were 297 passenger seats on the aircraft: 30 located in business class (rows 1 to 5, between doors 1 and 2), 148 in the centre of the aircraft (rows 23 to 41, between doors 2 and 3), and 119 in the rear of the aircraft (rows 45 to 60, between doors 3 and 4).

The 303 passengers included three infants who were seated with a parent for the takeoff. Three of the passengers on staff travel arrangements were located on non-passenger seats for takeoff; one in the fourth occupant seat on the flight deck and two in the cabin crew rest area (four seats located in rows 40 and 41). During the flight, the two passengers seated in the cabin crew rest area moved to the cabin crew jump seats located at the front of the aircraft.

At the time of the in-flight upsets, the meal service had been completed and the service carts were secured in the galleys. Many passengers reported that they had recently returned from or were in the process of going to the toilets.

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<sup>34</sup> Low-frequency radiated susceptibility tests require very specialised transmitting equipment that was not available to the investigation. In practice, low frequency susceptibility is usually evaluated using conducted emissions as that method is both practical and representative of actual low-frequency electromagnetic coupling.

## **Passenger questionnaire**

A passenger questionnaire was developed to obtain information from passengers about their experience and observations during the upset events. It also included questions on safety information, use of seatbelts, injuries and use of personal electronic devices. The questionnaire could be completed electronically or on a hard copy form, or by interview if requested by the passenger.

Distribution of the questionnaire commenced on 28 October 2008. It was not able to be sent to all passengers as contact details were incomplete.

As of 26 January 2009, 95 surveys had been received. Those surveys also included details for six children. In addition to the surveys, the ATSB obtained some information by interview or email from 29 other adult passengers, which included information for 11 other children. In the survey responses and additional information received, some passengers provided information about other passengers.

Multiple attempts were made to contact passengers who were seriously injured or attended hospital and did not respond to the survey. However, information from a small number of those passengers was not able to be obtained.

## **Passenger description of first in-flight upset**

Passengers reported that they noticed nothing unusual about the flight prior to the upset. Some passengers and cabin crew reported that, a few minutes prior to the upset, they noticed a reduction in thrust, whereas some other passengers described a slight change in the aircraft's flight similar to the commencement of the descent for landing. Both of those observations were consistent with the aircraft's descent from 37,200 ft back down to 37,000 ft following the autopilot disconnect.

Passengers reported that the upset occurred without any prior warning. They first noticed a sudden movement of the aircraft, generally described as a 'drop' or a 'pitch down'. Many passengers and loose items were thrown upwards, and many of these hit ceiling panels or overhead lockers.

## **General injury information**

In addition to information obtained from passengers, basic information on passenger injuries was obtained from the Western Australia Department of Health and the operator. A review of the available data identified the following:

- Almost all of the injuries occurred at the time of the first in-flight upset.
- Of the 106 passengers known to be injured, seven were located in the front section of the aircraft, 55 located in the centre section, and 44 were located in the rear section.
- Of the 51 passengers who attended hospital, 32 were located in the centre section and 19 were located in the rear section.
- Of the 11 passengers who were seriously injured, seven were located in the centre section and four were located in the rear section. The severity of injuries of both those who attended hospital and those who did not attend hospital, varied considerably.

## **Seated passengers**

Based on the information provided by passengers, 82 passengers were seated with seatbelts fastened and 61 were seated without seatbelts fastened. Although most of the remaining passengers would have been seated, there was no information available regarding whether they had their seatbelts fastened. Therefore, the overall compliance rate for wearing seatbelts could not be reliably estimated. However, information obtained from many of the passengers suggested that there were more than 61 passengers who did not have their seatbelts on at the time of the first in-flight upset.

For the passengers reported to have their seatbelts fastened:

- 35 per cent of those passengers were reported to be injured and 13 per cent attended hospital.
- The most common type of injury was a strain / sprain of the neck or back. Some passengers reported injuries due to being hit by another person or by an object, or bruises due to hitting arm rests.
- Two of the passengers received serious injuries. One of those passengers was a child who received abdominal contusions from a seatbelt. The other passenger experienced a stroke three days after the flight.

For the passengers reported to not have their seatbelts fastened:

- 91 per cent of the passengers were reported to be injured and 38 per cent attended hospital.
- The most common type of injuries were head or neck injuries from hitting the ceiling or overhead lockers, and bruising or other injuries of the back, legs or other parts of the body when landing on a seat or the floor.
- Three of the passengers received serious injuries. Two received spinal injuries and an infant received minor head injuries.

Four passengers reported that, even though they were wearing seatbelts, they were not restrained in their seats and they subsequently hit the ceiling or were thrown from their seat. Three of those passengers advised that they had their seatbelts loosely fastened and one advised they had their seatbelt firmly fastened.

## **Non-seated passengers**

Eighteen passengers were reported to have been standing or walking in the cabin at the time of the first upset. Most of them were reported to be on their way to or from a toilet and some were attending to children. All of those passengers were injured, and 67 per cent attended hospital. Four of the standing / walking passengers received serious injuries. All of the seriously injured received multiple injuries, including spinal injuries.

Two passengers were reported to be in toilets at the time of the first upset. One passenger received serious injuries and the other attended hospital. Both passengers experienced multiple injuries, including spinal injuries.

## **Crew member injury details**

At the time of the first in-flight upset event, three flight attendants and the first officer were standing in the forward galley and one flight attendant had just left that galley. The first officer and two of the attendants received minor injuries and the other was uninjured.

Four of the flight attendants were in the cabin crew rest area at the time of the first in-flight upset. They were all preparing to leave the crew rest area either because their break was about to end or because they reported feeling something similar to the ‘top of decent’ prior to the first in-flight upset. As a result, none had their seatbelts fastened at the time.

Another flight attendant was standing in the rear galley at the time of the first in-flight upset and received serious injuries.

## **Passenger seatbelts**

### ***Seatbelt description***

The passenger seatbelts on the aircraft were a common type of lap belt with a lift-latch release mechanism (Figure 12). The buckle was on the passenger’s left side and the tongue on the right side. Passengers could adjust the tightness of the belt by adjusting the distance of the buckle from its anchor point. In general, when the seatbelt was firmly fastened, the buckle was centred across the passenger’s hips.

**Figure 12: Seatbelt buckle of type fitted to VH-QPA**



### ***Seatbelt examinations***

A sample of 51 seatbelts was examined in detail. The sample included the seatbelts of the four passengers who reported that they were wearing their seatbelts, but the seatbelts did not restrain them to their seats. It also included other passengers who attended hospital and it was not known whether or not they were wearing seatbelts at the time of the occurrence. No problems were identified with the condition of the webbing, buckle or tongue of any of those seatbelts.

### ***Potential for inadvertent seatbelt release***

During the seatbelt examination, investigators identified a scenario by which a loosely fastened seatbelt could inadvertently release. The scenario involved the following:

- The seatbelt had to be loosely fastened. The buckle of the seatbelt could then slide down off a passenger's right hip.
- The buckle had to be positioned under the passenger's right armrest.
- If a vertical force was then applied, the lift-latch part of the buckle could get caught on a ridge on the underside of the armrest. If the lift-latch got caught on the ridge, the buckle would release.

When the buckle of a loosely fastened belt was placed in a position underneath the armrest, investigators could consistently make the buckle release by positioning the buckle underneath the armrest and then standing up. In general, for the scenario to be fulfilled, the belt had to be adjusted to be near the end of its adjustment range.

Subsequent examination has shown that this potential for inadvertent release is not restricted to seats on the A330 aircraft type or the operator's aircraft. A similar potential has been identified on aircraft from multiple other operators and other manufacturers, though it is not present on all aircraft and more difficult to do on some seats than others. The potential appears to depend on a range of factors, including the design of the seat and armrest.

The seatbelt manufacturer, aircraft manufacturer, aircraft operator, the Civil Aviation Safety Authority, the ATSB and other investigation agencies, were previously unaware of this inadvertent release scenario. Initial research by the ATSB has not identified this scenario to be associated with injuries in previous in-flight upsets.

The seatbelt manufacturer has advised that seatbelts are not designed to be worn improperly adjusted. It also reported that it would not be possible to ensure proper placement of the seatbelt on the body when seatbelts were worn 'extremely loosely fastened'.

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## ONGOING INVESTIGATION ACTIVITIES

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### **Air data inertial reference units**

ADIRU testing is ongoing in accordance with a test program that was developed and agreed by the investigation team. Protocols are in place for the oversight of the testing, regular reporting of the results to investigation team members and analysis of the results.

Further testing of ADIRU 1 from VH-QPA (unit 4167) will include the following activities:

- Further EMI testing. The frequencies to be covered are associated with onboard transmitters and other onboard systems that have been nominated by the investigation team for particular attention. This testing will be conducted before unit disassembly to prevent disturbance to the unit's hardware that could otherwise invalidate the EMI testing.
- The unit will be disassembled and the individual modules tested separately.
- Pending the results of the additional EMI and component testing, the test plan may be expanded to include additional testing.

A test plan for ADIRU 1 from VH-QPG (unit 4122) and ADIRU 1 from VH-EBC (unit 5155), will be developed and further testing conducted.

In addition to the testing of the specific units, the following related activities are being conducted:

- The operator has initiated a detailed review as well as specific ongoing monitoring of ADIRU performance across its A330 fleet. The results will continue to be reported to the investigation team.
- The ADIRU manufacturer is conducting a theoretical analysis of ADIRU software and hardware to identify possible fault origins.
- The aircraft manufacturer is conducting a detailed analysis of differences in aircraft configuration between the operator's A330 aircraft and other operators' A330 aircraft with the same type of ADIRU. The results of these configuration comparisons may lead to additional ADIRU testing requirements.
- A detailed analysis is being conducted of whether there were any commonalities in operational, environmental or maintenance aspects of the flights/aircraft that were involved in the occurrences.

### **Flight control system**

The investigation is examining various aspects of the PRIM software development cycle including design, hazard analysis, testing and certification.

### **Electronic centralized aircraft monitor (ECAM)**

The investigation is examining the performance of the ECAM and its effectiveness in assisting crews to manage aircraft system problems.

## **Cabin safety**

Further work on cabin safety aspects is ongoing, including the following:

- Further analysis of information obtained from passengers to determine patterns related to the occurrence or severity of injuries.
- Further examination of the potential for inadvertent seatbelt release associated with loosely fastened seatbelts. The examination will consider the scope of the problem across different types of aircraft, as well as relevant design requirements for seatbelts and seats.
- Review of relevant aviation industry requirements regarding the use of seatbelts.

## **Flight recorders**

Examination of CVR, FDR and QAR information from VH-QPA is on-going and includes the following:

- analysis of CVR audio regarding aural warnings, crew actions, aircraft handling and crew/cabin communications during the pitch-down events and the subsequent approach and landing at Learmonth
- analysis of QAR data to assist in evaluating the performance of aircraft systems
- analysis of FDR data to produce a detailed sequence of events and assist in evaluating the performance of aircraft systems
- a review of the earlier flights recorded by the FDR and QAR for any evidence of anomalous performance of aircraft systems.

Examination of FDR and QAR information from VH-QPG is on-going and includes the analysis of data to assist in evaluating the performance of aircraft systems and to produce a detailed sequence of events.

The aircraft manufacturer and the operator are examining the feasibility of recording additional parameters from ADIRUs 1 and 2 on the QAR. This would require wiring changes to the operator's A330 aircraft to access an additional ADIRU databus and modifications to the aircraft condition monitoring system (ACMS) software.

## **Other activities**

The ATSB is aware that a post-incident multi-agency debrief has been conducted. The debrief included representatives from all available private, government and non-government organisations involved in the emergency response to the accident and the Westralia Airports Corporation is coordinating actions from that meeting. The ATSB will review those outcomes in relation to information obtained at interviews and from responses to the passenger questionnaire.



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## **SAFETY ACTION**

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### **Aircraft manufacturer**

#### **Operational procedures**

On 14 October 2008, as soon as a preliminary analysis of the occurrence was conducted, Airbus published Operator Information Telex (OIT) / Flight Operations Telex (FOT) SE 999.0083/08/LB ('A330 in-flight incident'). The telex was issued to Airbus operators, who were asked to distribute it to all A330/A340/A340-500/A340-600 flight crews without delay. The telex provided brief details known about the occurrence. It also provided operational recommendations applicable for A330/A340 aircraft fitted with Northrop Grumman air data inertial reference units (ADIRUs). The telex stated that, pending final resolution, Airbus would issue an OEB [Operations Engineering Bulletin] 74-1 that would instruct flight crew to select OFF the whole ADIRU in the case of an inertial reference (IR) failure, instead of switching OFF only the IR part.

On 15 October, OEB-A330-74-1 was dispatched, applicable to all A330 aircraft fitted with Northrop Grumman ADIRUs. The OEB stated that, in the event of a NAV IR FAULT (or an ATT red flag being displayed on either the captain's or first officer's PFD), the required procedure was for the crew to select OFF the relevant ADR and then select OFF the relevant IR. A compatible temporary revision was issued to the Minimum Master Equipment List at the same time. The procedure in the OEB was subsequently issued as an Emergency Airworthiness Directive by the European Aviation Safety Agency (EASA) (No. 2008-0203-E) effective on 19 November 2008 and the Civil Aviation Safety Authority (CASA) (AD/A330/95) effective on 20 November 2008.

The OEB procedure was subsequently amended in December 2008 to cater for a situation where the IR and ADR pushbuttons are selected to OFF and the OFF lights did not illuminate. If the lights did not illuminate, the new OEB (74-3) required crews to select the IR rotary mode selector to the OFF position. This OEB was subsequently issued as an Emergency Airworthiness Directive by EASA (No. 2008-0225-E) effective on 22 December 2008 and CASA (AD/A330/95 Amendment 1) effective on 22 December 2008.

Following the 27 December 2008 event, Airbus issued another OEB (74/4) on 4 January 2009. This OEB provided a different procedure for responding to a similar ADIRU-related event to ensure erroneous data would not be used by other aircraft systems. The procedure required the crew to select OFF the relevant IR, select OFF the relevant ADR, and then turn the IR rotary mode selector to the OFF position. The modified procedure was subsequently issued as an Emergency Airworthiness Directive by EASA (No. 2009-0012-E) effective on 19 January 2009 and CASA (AD/A330/95 Amendment 2) effective on 19 January 2009.

Similar OEBs were issued by Airbus for A340 aircraft, and the EASA Airworthiness Directives also applied to A340 aircraft.

## **Flight control system**

Airbus is in the process of developing a modification to its PRIM software to make it more robust to AOA spikes.

## **Aircraft operator**

On 15 October 2008, in response to the Airbus releases, the operator issued Flight Standing Order 134/08 for its A330 operations. On 24 October 2008, this order was replaced by Flight Standing Order 136/08, which incorporated the material from the Airbus OEB. In addition, a program of focussed training during simulator sessions and route checks was initiated to ensure that flight crew undertaking recurrent or endorsement training were aware of the contents of the Flight Standing Order. Subsequent Flight Standing Orders were issued in response to the modified OEBs in December and January 2009.

## **Seatbelt reminders**

In its media statements providing updates on the investigation on 8 and 10 October 2008, the ATSB noted that this accident served as a reminder to all people who travel by air of the importance of keeping seatbelts fastened at all times when seated in an aircraft.

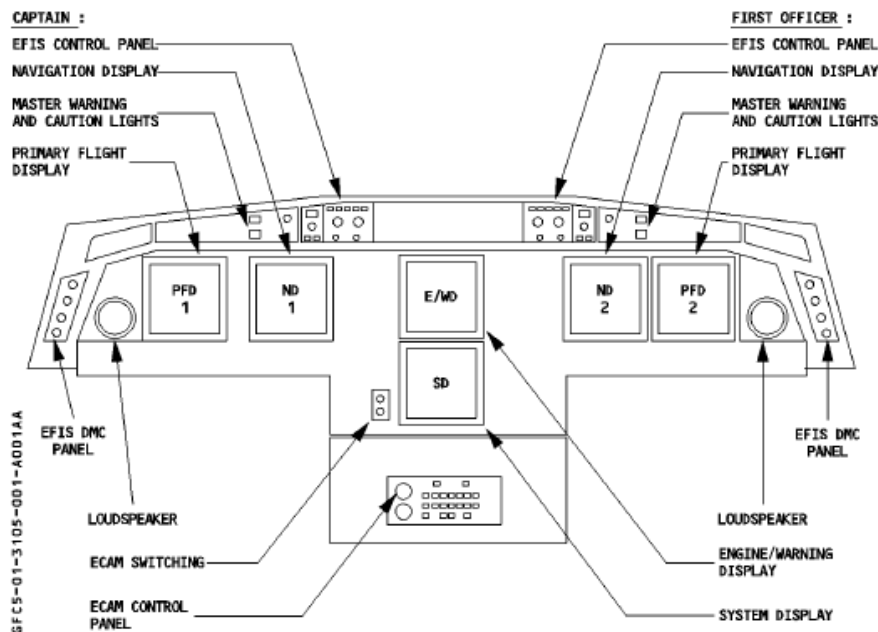
On 27 October 2008, the Australian Civil Aviation Safety Authority issued a media release that stated that the occurrence was as a timely reminder to passengers to 'remain buckled up when seated at all stages of flight'. The media release also highlighted the importance of passengers following safety instructions issued by flight crew and cabin crew, including watching and actively listening to the safety briefing given by the cabin crew at the start of each flight.

## APPENDIX A: ELECTRONIC INSTRUMENT SYSTEM

This appendix provides general background information on the A330 electronic instrument system. It is based on information contained in the operator's *A330 Flight Crew Operating Manual, Volume 1: Systems Description*. The information is not exhaustive.

Figure A1 shows the general layout of the electronic instrument system. Key components of the system are the electronic centralized aircraft monitor (ECAM) and the primary flight display (PFD).

**Figure A1: Overview of electronic instrument system**



### Failure mode classifications

Failures of an aircraft system are classified at three levels:

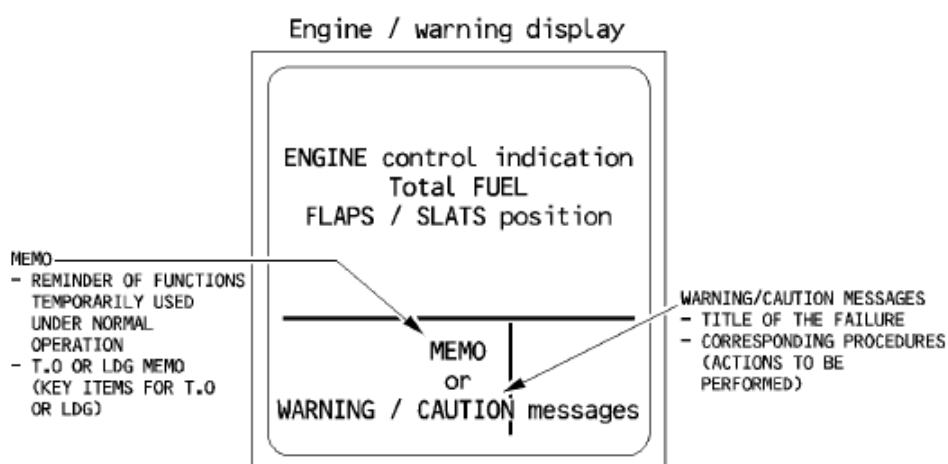
- Level 3 failure or 'warning', associated with the colour red. The configuration or failure requires immediate action by the flight crew.
- Level 2 failure or 'caution', associated with the colour amber. The flight crew should be aware of the configuration or failure, but need not take immediate action.
- Level 1 failure or 'caution', associated with the colour amber. Requires crew monitoring.

For a level 3 warning, the MASTER WARN red light flashes (or specific red light illuminates), and a continuous repetitive chime (or other specific aural signal) sounds in the cockpit. For a level 2 caution, a steady MASTER CAUT amber light illuminates and there is a single chime. The lights and signals cease when the warning/caution situation no longer exists or when the flight crew press the respective 'attention getter' light or press other controls on the electronic centralized aircraft monitor (ECAM).

## Electronic centralized aircraft monitor (ECAM)

ECAM provides information on the status of the aircraft and its systems on two display units. The upper unit or engine/warning display (E/WD) presents information such as engine primary indications, fuel quantity information and slats/flap positions. It also presents warning or caution messages when a failure occurs, and memo messages when there are no failures. The lower or system display (SD) presents aircraft synoptic diagram and status messages. Figure A1 shows the location of the ECAM display units. Figure A2 presents a more detailed overview of the E/WD.

**Figure A2: Engine / warning display of ECAM**



Level 3 warning messages are displayed on the E/WD in red. Level 2 and level 1 caution messages are displayed in amber. In the event of a level 3 or level 2 failure, the E/WD will display the relevant warning or caution message, together with relevant actions the crew should take in response to the failure. The system display also shows the system page for the affected system.

The ECAM system is designed to prioritise error messages, with level 3 failures having priority over level 2 failures, which have priority over level 1 failures.

In addition to the ECAM messages and the 'attention getters', a local warning light directly controlled by the affected system may illuminate (for example, the IR lights on the overhead panel discussed above).

## Primary flight displays

The electronic flight instrument system (EFIS) displays flight parameters and navigational data on the primary flight displays (PFDs) and navigational displays (NDs).

The PFD provides flight information such as aircraft attitude, airspeed, altitude, vertical speed, heading and track, autoflight information, vertical and lateral deviations, and radio navigation information. Various 'flags' and messages pertaining to specific parameters are also displayed on the PFD.

# APPENDIX B: FLIGHT DATA RECORDER PLOTS

Figure B1: Data plot for complete flight duration

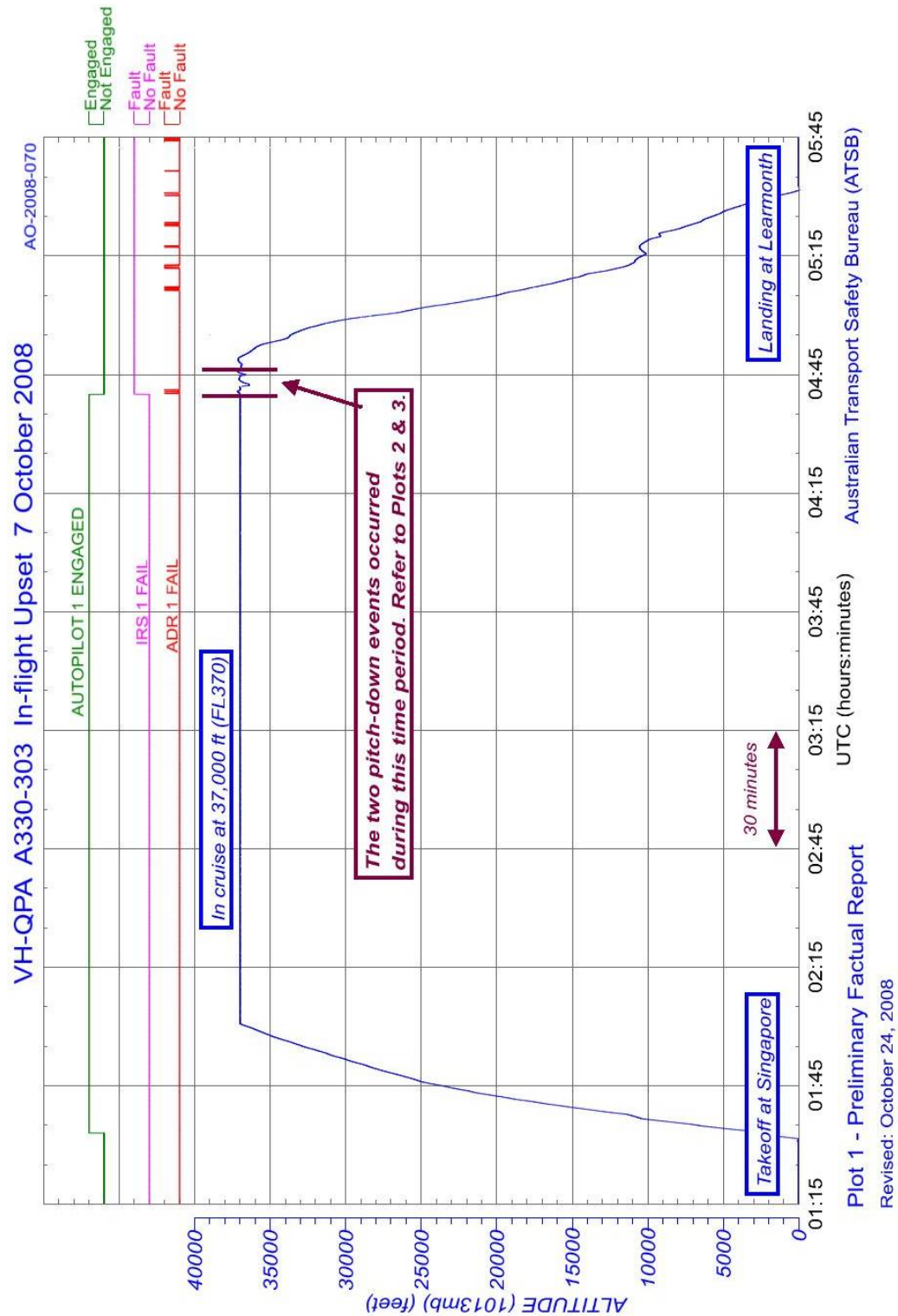


Figure B2: Plot showing selected data during period of both in-flight upset events

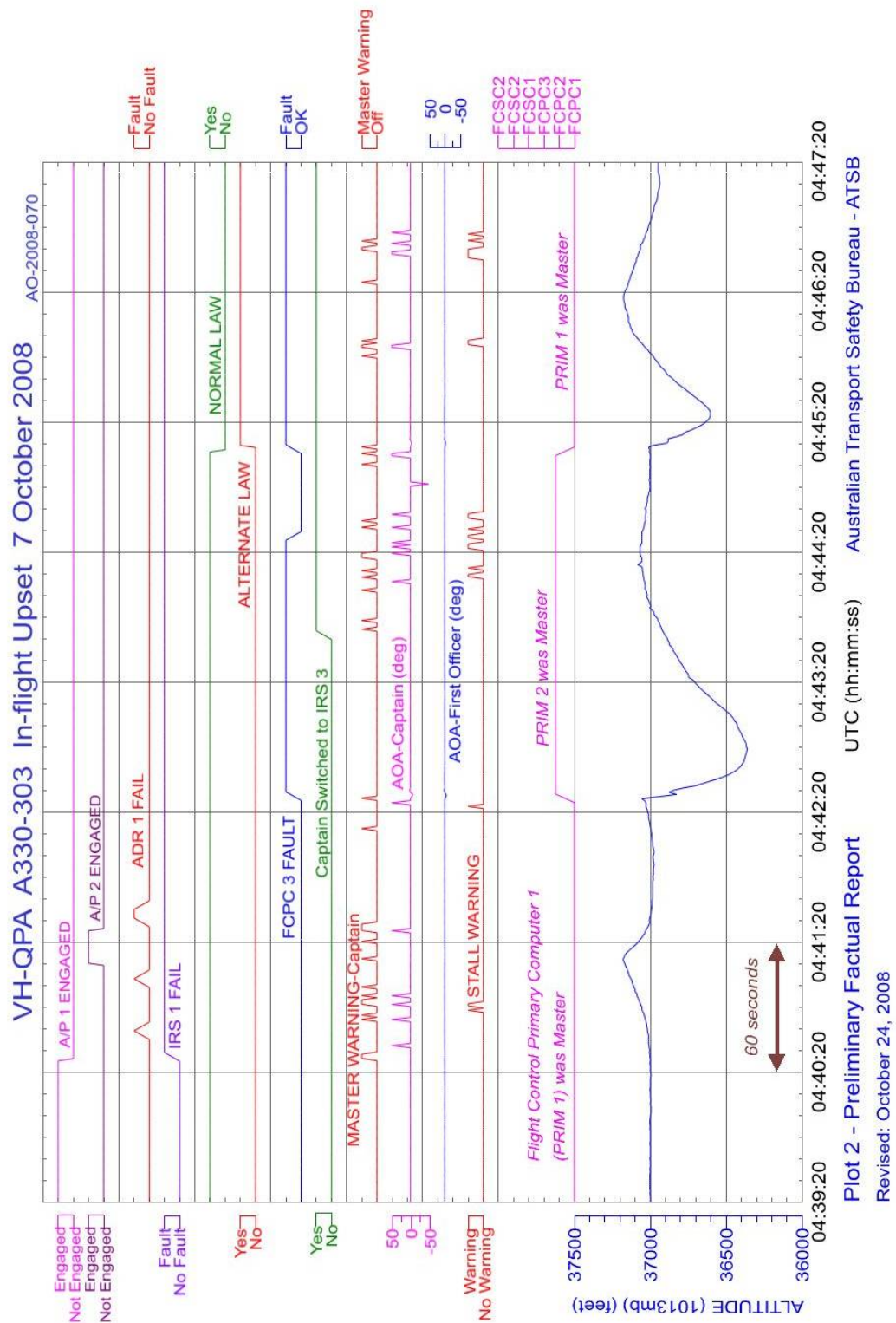


Figure B3: Plot showing selected data during period of both in-flight upset events

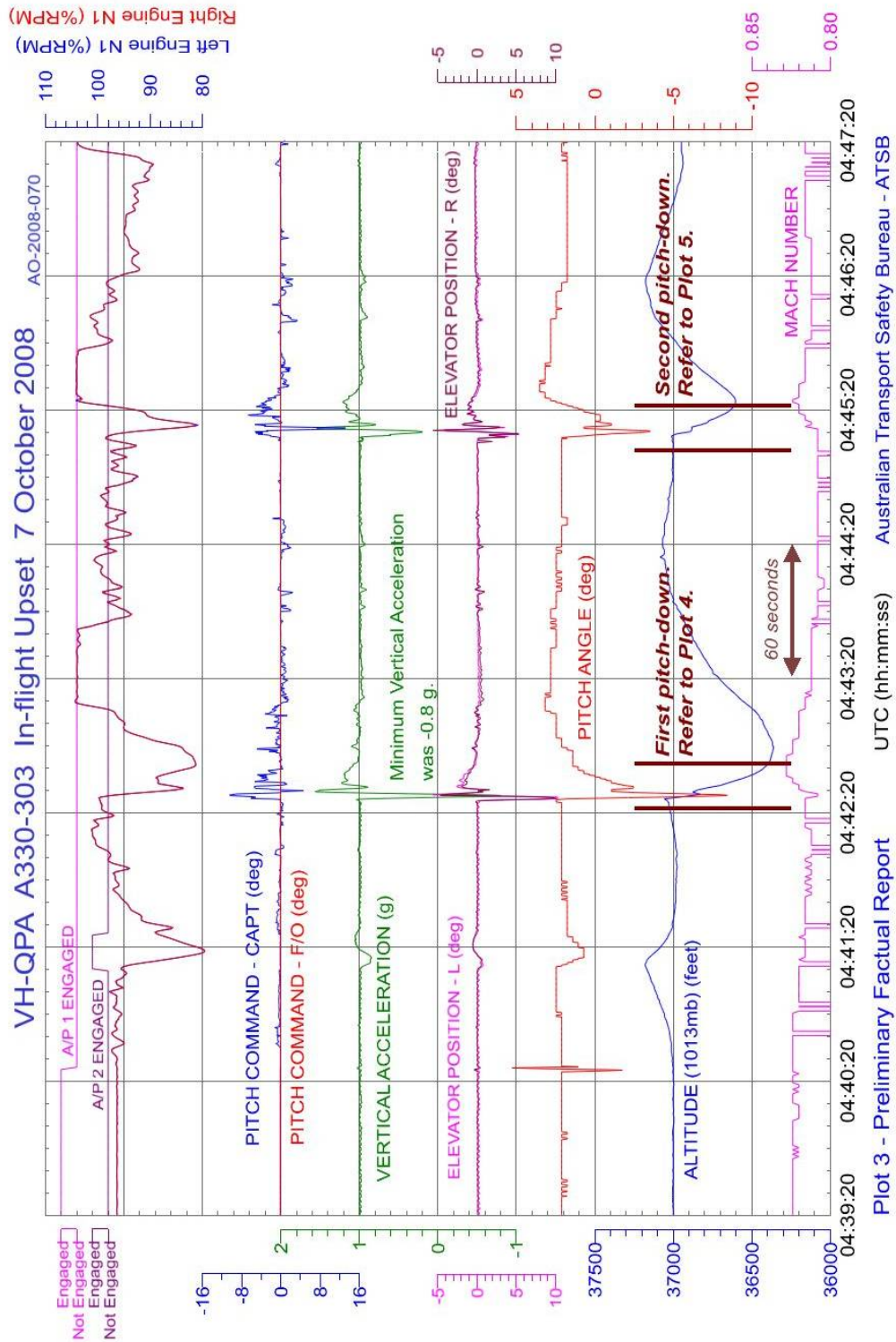




Figure B4: Plot showing selected data for first in-flight upset event

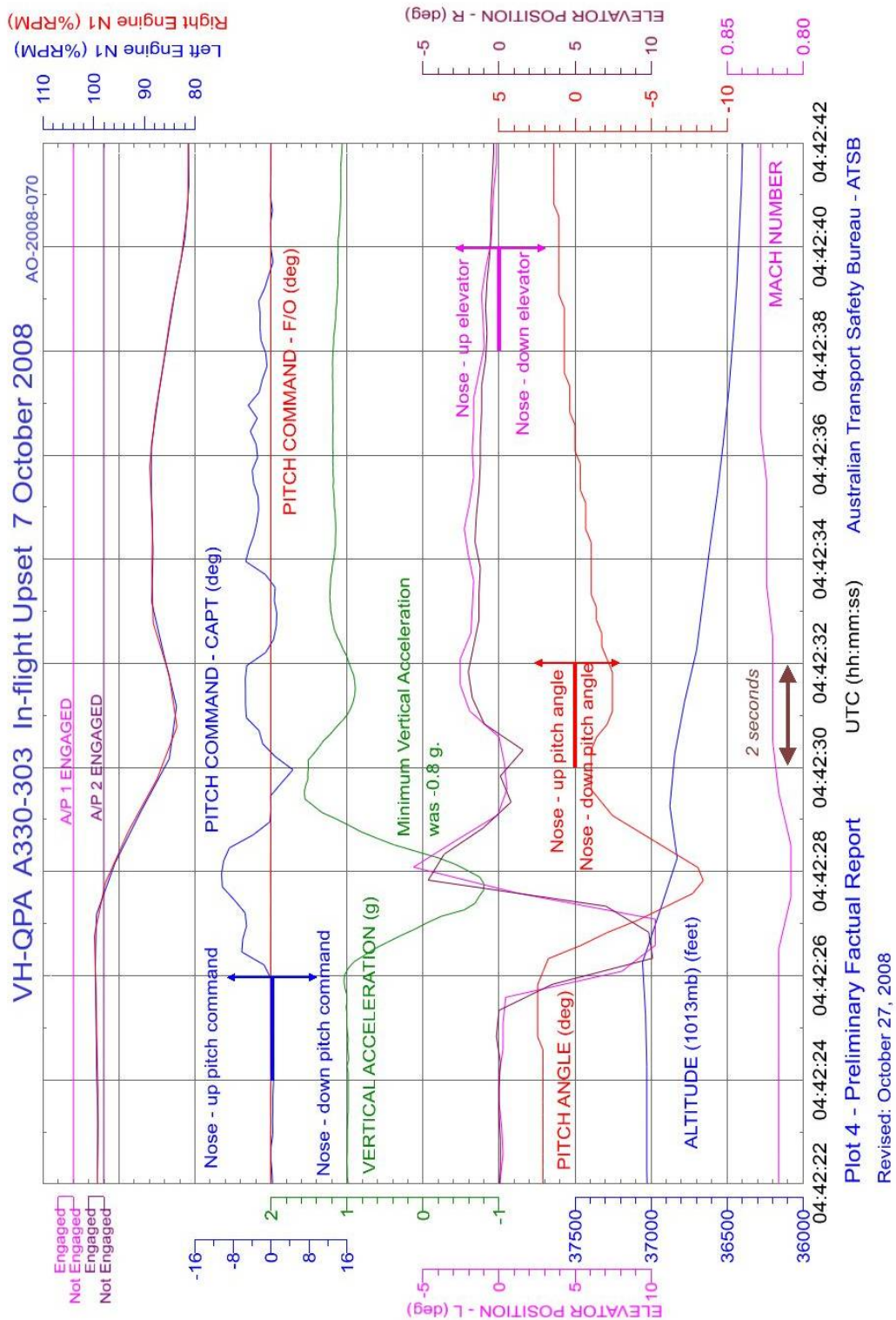




Figure B5: Plot showing selected data for second in-flight upset event

