BEA
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pour la sécurité de l'aviation civile

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INVESTIGATION REPORT

Serious incident to Airbus A330 registered **F-GRSQ** on 26 December 2014 in cruise, over the Mediterranean Sea

Time	Around 13:45[1]
Operator	XL Airways France
Type of flight	Commercial Air Transport - Passenger
Persons on board	Captain, 2 FOs[2], 10 cabin crew, 304 passengers
Consequences and damage	None

This is a courtesy translation by the BEA of the Final Report on the Safety Investigation published in July 2018. As accurate as the translation may be, the original text in French is the work of reference.

[1] Except where otherwise indicated, the times in this report are in Coordinated Universal Time (UTC).

[2] First Officer.

Unavailability of the three IRSs[3], loss of attitude and navigation data in cruise

[3] Inertial Reference System, see section 2.1.1.

1 - HISTORY OF THE FLIGHT

The history of the flight is based on the recorded flight parameters, statements by members of the flight crew and ATC transcripts. The CVR[4] was not preserved after landing.

The crew was to undertake a flight from Saint-Denis de la Réunion bound for Marseilles (Bouches-du-Rhône). It was an augmented flight crew, consisting of a captain and two FOs, one of whom was to replace the captain during his rest, in accordance with the operator's procedures. This FO is designated in this report as the FO-L[5].

During the preparation of the aeroplane, the crew learned that the previous crew had reported a drift of IRS 2[6]. The captain was the PM[7]. The FO-L was the PF[8] and performed a complete alignment of the three systems, in accordance with the specified procedures. For the departure, the three crew members were present in the cockpit. The aeroplane took off at 05:38.

From the outset of the flight, the crew saw the message "*Check IR 2/FM position*"[9] on the MCDU[10] and observed a drift of IRS 2. Throughout the rest of the flight, the crew regularly monitored the drift of IRS 2. They said that they read values between around 6 and 15 NM. The GPS primary mode was active throughout the first part of the flight.

The captain took his first rest about an hour after take-off. He was replaced by the FO-L. When the captain returned around 09:40[11], the FO left the cockpit for his turn to rest.

[4] Cockpit Voice Recorder.

[5] First Officer, seated in the left seat.

[6] This information was only given orally by a ground technician.

[7] Pilot Monitoring.

[8] Pilot Flying.

[9] This message is generated when there is a significant drift of IRS 2 with respect to the Flight Management (FM) position.

[10] Multipurpose Control and Display Unit.

[11] The handover times given in this report are estimated using the crew statements and the handover practices in the company.

At 10:34, IRS 3 passed from NAV mode to ATT mode[12]. In this mode, the IRS provides attitude data but no longer provides other data such as position and ground speed. The automated flight systems (the FG part of the FMGEC[13], see section 2.1.3) rejected IRS 3 and only used data from IRS 1 and IRS 2 for the rest of the flight. This loss of redundancy does not have an impact on the navigation data displayed and does not require a crew action in the short or medium term. In accordance with the manufacturer's policy, the crew was thus not immediately notified[14].

At around 13:00, the FO relieved the FO-L who left the cockpit. He sat in the right-hand seat and took over the functions of PF.

Shortly afterwards, wanting to monitor the drift of IRS 2 on the MCDU, he noted that IRS 3 was in ATT mode. No alert was displayed on the ADIRU[15] panel. The three mode selectors were set to NAV. He explained that he saw the fields prompting the input of a heading for IRS 3 on the IRS MONITOR page of the MCDU.

The crew consulted the hard-copy of the IR FAULT procedure, which led them to perform the IR ALIGNMENT IN ATT MODE procedure for IRS 3. This procedure requires the mode selector to be set to ATT and the heading to be entered on the MCDU. The captain remembered seeing an ECAM[16] message asking for this IRS to be put in ATT mode. The crew switched IRS 3 to ATT mode. The three crew members said that there had been no action on the IRS mode selectors during the flight before this time.

At 13:36, the FD[17], the AP[18] and the A/THR[19] automatically disconnected. The position and flight plan data on the NDs[20] disappeared. The ECAM messages displayed in decreasing order of priority (via the following colour code: red for warning, amber for caution) were: **AUTO FLT AP OFF**, **AUTO FLT A/THR OFF** and **AUTO FLT REAC W/S DET FAULT**. The GPS primary mode was lost. The FO took back the controls. Then the FO and the captain activated the BACK-UP NAV mode[21] on their respective MCDUs and got back the position and flight plan data.

The captain said that he unsuccessfully tried to check the IRS data in BACK-UP NAV mode. He said that he exited the mode in order to access the POSITION MONITOR and IRS MONITOR pages. He was not able to access valid position data or return to the BACK-UP NAV mode. These actions cannot be given a precise time.

At 13:44, the internal data of each IRS recorded the message "*IN FLIGHT ALIGNMENT*"[22]. The flight control law changed to direct control. The attitude data disappeared from the PFDs up to the end of the flight. The position and flight plan data was no longer available on the NDs. The crew had to use electromechanical standby instruments for the remainder of the flight without AP or A/THR. The ECAM messages still displayed in decreasing order of priority included: **F/CTL DIRECT LAW, NAV IR 1 FAULT, NAV IR 1+2 FAULT, NAV IR 2+3 FAULT, NAV IR 1+3 FAULT, NAV IR NOT ALIGNED**.

[12] The hypotheses that could explain this transition from NAV to ATT are discussed in section 3.1.1.

[13] Flight Management Guidance and Envelope Computer see section 2.1.2.

[14] The operational impact of this failure is presented on the ECAM STATUS page which must be consulted when preparing the arrival.

[15] Air Data Inertial Reference Unit.

[16] Electronic Centralized Aircraft Monitoring.

[17] Flight Director.

[18] AutoPilot.

[19] AutoThrust.

[20] Navigation Display.

[21] The BACK-UP NAV mode is a MCDU standby function which supplies IRS navigation data in the event of a double failure of the function (FM). It allows the flight plan (saved in the MCDU) and the aeroplane position (provided by an IRS) to be displayed on the NDs.

[22] The cause of this triple alignment is discussed in section 3.1.3

Figure 1: Photo taken by crew during descent to Athens

A few minutes later, the captain decided to become PF because reading the standby instruments was easier from the left-hand seat. He requested that the FO-L return to the cockpit. The latter said in his statement that on his return, the three IRS mode selectors were on NAV and the "*IR Fault*" indicator lights were flashing.

The aeroplane was approaching Greek airspace. The FO told the Greek air traffic control that they had lost their RVSM[(23)] capability and declared an emergency. The crew examined the options for diverting to Heraklion or Athens. They retained Athens due to favourable weather conditions and the support they could expect from air traffic control. The crew were given radar vectoring to reach the final approach of runway 21L. During the descent, the crew declared a distress situation. The FO and FO-L checked the performance characteristics for landing.

[(23)]Reduced Vertical Separation Minimum.

The FO-L remembered having performed the NAV-OFF-NAV sequence on IRS 1 at the request of the captain who wanted to try and retrieve at least the attitude data. The witness statements did not indicate whether other actions were carried out on other selectors.

On first contact with the Athens approach and given the slight wind from 140°, the crew accepted the proposal for a visual landing on runway 03R after radar vectoring which would take them to the final approach 10 NM from the threshold.

A short video sequence taken by the FO-L during the final approach shows that the three mode selectors were on NAV and that the "*IR fault*" indicator lights were flashing. The aeroplane landed at 14:37. After the arrival of the aeroplane, a mechanic learnt of the anomalies reported by the crew. The aeroplane electrical systems were de-energized and then energized again. The three IRSs were successfully aligned. Checks were made on the AP and flight control computers. The crew took off again at 17:47 for Marseilles and then Paris Charles de Gaulle where they landed at 22:29. No anomalies were reported on these flights. The ADIRUs were removed shortly after.

2 - ADDITIONAL INFORMATION

2.1 Aircraft information

2.1.1 Overview of IRSs

An IRS independently generates acceleration, linear speed, angular speed, position and orientation parameters based on inertial measurements (accelerometers and gyrometers). The continuous real-time calculation of these parameters, in particular of those calculated by integration, requires that the initial references are determined beforehand.

Thus, the alignment of an IRS refers to all the operations carried out by the equipment to automatically determine the initial horizon, orientation and latitude references. Latitude and longitude values are initialized by an external source (such as manual input or GPS). These operations take between several seconds and several minutes depending on the technologies used, as well as the latitude and level of precision required.

In flight, if the calculation is interrupted (due to a change in mode for example), new initial conditions must be determined in order for it to resume. On the IRS model equipping F-GRSQ, this is possible for the attitude and heading references but requires the crew to comply with a procedure (IR ALIGNMENT IN ATT MODE). However, this is not possible for the references required to generate navigation parameters that can only be determined when the aeroplane is stationary on the ground.

2.1.2 Airbus A330 ADIRS system

The Air Data Inertial Reference System (ADIRS) for the Airbus A330 provides, in particular, the attitude (trim and bank), heading, position, ground speed, acceleration and air parameters. On an Airbus, a complete ADIRS system consists of:

- three identical ADIRUs;
- a MSU[24] or a CDU.

[24] Mode Selector Unit.

The GPS data comes from two Global Navigation Sensor System Units (GNSSU) or two Multi-Mode Receivers (MMR).

Each ADIRU includes an Air Data Reference (ADR) and an IRS. The Airbus F-GRSQ is equipped with a MSU located on the cockpit overhead panel. The MSU controls the mode discretes to select the operational state of each ADIRU: OFF, NAV or ATT. Only crew actions on the MSU can change an ADIRU mode. The selector must first be pulled before being rotated to avoid an involuntary action with irreversible consequences.

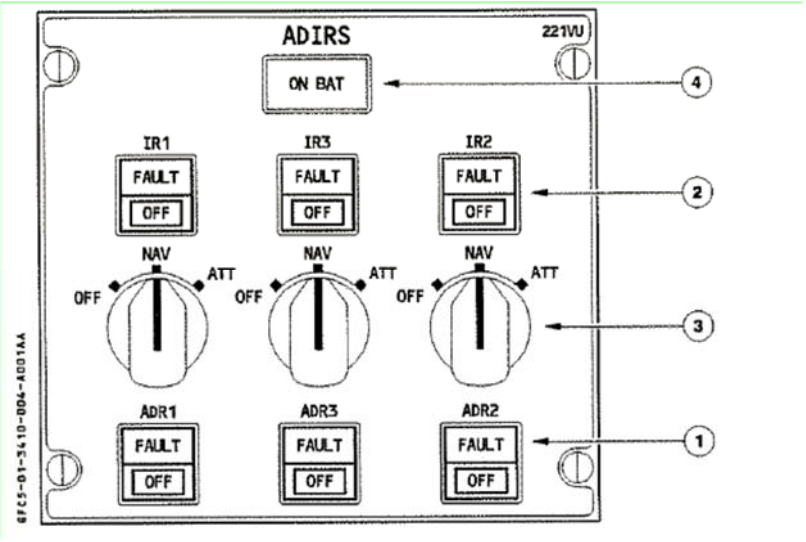


Figure 2: MSU

Moving the selector from OFF to NAV will trigger the alignment of the IRS[25]. The NAV mode is the standard mode used during all the flight. If NAV mode is exited in flight, it is impossible to completely realign an IRS and thus to retrieve the position and ground speed data. In this case, the IRS keeps the total navigation time and the last position and ground speed that were calculated in the non-volatile memory.

In ATT mode, the IRS no longer calculates the position and ground speed. The IRS can still provide the acceleration, angular rate and attitude data. The ATT mode is normally used by a crew when the IRS self-detects a critical fault that may cause excessive errors in navigation.

When one of these faults occurs, the information provided to the crew consists of:

- an "*IR Fault*" flashing light on the ADIRS part of the overhead panel;
- an "*IR FAULT*" message displayed on the ECAM;
- messages specific to the failure may be displayed on the IRS MONITOR page of the MCDU.

In addition, the "*ATT*" and "*HDG*" captions are respectively displayed on the PFD and the ND corresponding to the failed IRS (*see figure 1*). If the "*ATT HDG*" rotary selector (*see figure 3*) is set to "*NORM*", as in the flight of the event:

- the left-hand PFD and ND is for IRS 1 and the right-hand PFD and ND for IRS 2;
- an IRS 3 fault results in no change to the PFDs or NDs.

If there is a failure of IRS 1 or 2, the crew can use the "*ATT HDG*" rotary selector to use IRS 3 data on the left side ("*CAPT ON 3*") or on the right side ("*F/O ON 3*"). In this case, an IRS 3 fault is indicated on the side selected.

The same logic exists for the ADR part (see "*AIR DATA*" rotary switch in *figure 3*).

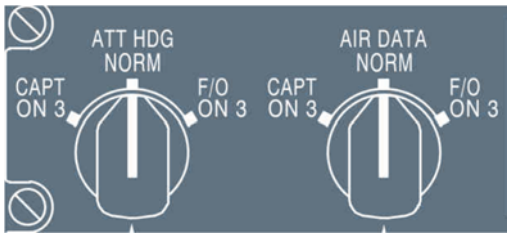


Figure 3: "*ATT HDG*" *and* "*AIR DATA*" *rotary switches*

[25] The complete alignment procedure is carried out on the ground, with the aeroplane at a standstill. It requires the selector to be moved from NAV to OFF for more than 5 seconds and then back to NAV (PRO-SUP-34 P 15/16). Later, when preparing the MCDU, the aeroplane departure position is checked by the crew and transmitted to the IRSs.

On the controlled selection of the ATT mode:

- the crew must keep the aeroplane in stabilized level flight, wings horizontal, so that the IRS can determine new references. In addition, the magnetic heading must be entered on the MCDU in order to retrieve the heading data (IR ALIGNMENT IN ATT MODE procedure);
- if the IR FAULT light was flashing before the switch to ATT, it goes off.

When the IRS is in ATT mode, if the selector is moved from ATT to NAV, the operational mode remains ATT.

The FCOM (DSC-34-10-20 P 1/6) states that if the crew watch the IR FAULT light, they can determine whether the IRS is retrievable in ATT Mode (light flashing) or is completely unavailable (light continuously lit).

The mode of each IRS is shown on the IRS Monitor and Position Monitor pages of the MCDU, as shown in the following illustrations.

Figure 4: Example of POSITION MONITOR page. Photo taken in simulator. Note the IRS modes

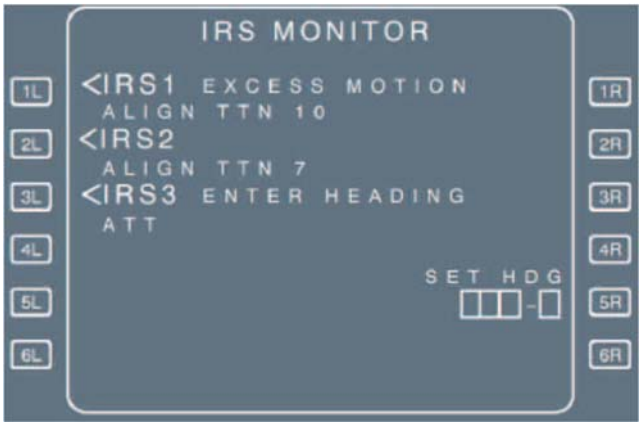


Figure 5: IRS MONITOR page of MCDU taken from FCOM. Note the IRS modes and the possibility of entering a heading (SET HDG) for IRS 3.

2.1.3 Monitoring of IRSs by FG part of FMGEC

The Flight Guidance (FG) part includes the AP/FD and A/THR functions. It rejects an IRS if:

- a datum received is invalid;
- the value of a datum received is not consistent with the values of the other two sources. In this case, the rejection of this value is locked until the AP is disconnected.

When the FG part rejects an IRS, it continues to use data from the other two IRSs and to monitor the validity and consistency of the data received. If a discrepancy between the values of the same datum received from the remaining two IRSs is too great, the two IRSs are rejected and the automated flight systems are no longer available.

2.1.4 Loss of FM positions in case of rejection of three IRSs by FG part of FMGEC

When the remaining two IRSs are rejected by the automated flight systems (FG part of the FMGEC), the behaviour of the Flight Management (FM) part of the FMGEC is different, depending on the FMS standards[26]. The FM positions displayed on the NDs can be lost if the aeroplane is not equipped with the latest FMS standards.

[26] Flight Management System.

Rejection of 3 IRSs by FG part of FMGEC		
FMS standards	**Loss of FM positions**	**Date of introduction**
Honeywell P3 or earlier	yes	-
Honeywell P4	no	2012
Thales	no	2005

F-GRSQ was equipped with the Honeywell P3 FMS standard, which explains the loss of the FM positions at 13:36. Airbus said that 40 to 45 % of their long-haul fleet is equipped with this standard.

The new Honeywell P4 standard includes a modification which enables better availability of the FM position in this type of situation. This improvement is mentioned in the information document on FMS standards sent to operators[27].

[27] Airbus Reference ISI 22-83-34 "*Flight management guidance and envelope computer (FMGEC) evolution*".

2.1.5 Monitoring of IRSs by EFCS[28]

[28] Electronic Flight Control System.

The EFCS receives data from the three IRSs and may reject an IRS if:

- a datum received is invalid;
- the value of a datum received is not consistent with the values of the other two IRSs. In this case, the rejection of this value is locked until the computer is reinitialized.

The flight control system uses and monitors what are known as primary inertial parameters (attitudes, roll, pitch and yaw angles, etc.) but not position and speed.

The NAV IR DISAGREE message did not appear on the ECAM during the flight. This message, generated by the monitoring function of the flight control system, is displayed when:

- an IRS has failed or has been rejected by the flight control system;

and

- the flight control system detects a difference in the primary inertial parameters of the two remaining IRSs.

2.1.6 Unavailability of GPS data

The aeroplane has two independent GPS receivers. The GPS data is transferred to the IRSs which calculate a hybrid GPS/IRS position called GPIRS. The pure GPS data and the hybrid position are transmitted by the IRS to the FMGEC by the same bus. The FMGEC uses the IRS or hybrid GPIRS positions but never the pure GPS positions on their own. These are, however, available for the crew on the GPS MONITOR page of the MCDU.

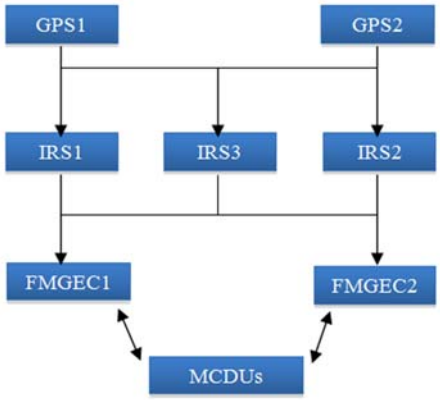


Figure 6: Schematic diagram of transmission of GPS data. The GPS function is provided by the MMRs and the IRS function by the ADIRUs

The FMGEC uses the "*hybrid GPIRS latitude*" parameter as a reference datum to determine the validity of the GPS data (i.e. the pure GPS data and the hybrid GPIRS data).

If this reference data is no longer valid ("*Failure Warning*" status for example), the GPIRS and GPS positions are considered invalid by the FMS part. A parameter must be valid to be used by the FMGEC or displayed on the MCDU.

When an IRS is in ATT mode, the status of the reference data is set to "*Non Computed Data (NCD)*". In this case, the pure GPS data is not declared invalid and is displayed on the MCDU GPS MONITOR page.

During the event, at 13:45, the three IRSs in IN FLIGHT ALIGNMENT failure mode positioned the status of the reference datum at "*Failure Warning*" which explains why the crew did not have access to the pure GPS positions on the MCDU GPS MONITOR pages. If one of the IRSs had been set to ATT mode, this would have modified the status of the reference datum and allowed the crew to view the pure GPS positions on the MCDU. This logic was confirmed by the manufacturer in tests on the aeroplane.

As part of the certification of the aeroplane, Airbus had deemed the failure of 3 IRSs[29] highly improbable and had studied the consequences of a failure of one or two IRSs only. This corresponds to "*NAV IR [X+Y] FAULT*[30]" type ECAM messages. Consequently, the unavailability of the GPS positions due to the failure of the three IRSs without the ATT mode being available, is not a degraded mode foreseen by the manufacturer in the framework of certification.

The BEA informed EASA of the event and, in particular, of the fact that the crew had not managed to retrieve the GPS position data.

EASA said that:

- the A330 meets the certification requirements for the installation of navigation equipment available in the JAR-25/CS-25 and the specific guides (JAA TGL-10, EASA AMCs 20-4, 20-5, 20-26, 20-27, FAA ACs);
- the A330 goes well beyond the requirements of CS25.1309 AMC 25-11, which estimates the probability per flight hour ($<10^{-5}$) for the loss of all navigation data from displays.

For this reason, EASA does not plan to issue a requirement that would challenge the current architecture.

2.1.7 Technical monitoring of aeroplane

The engineering department of XL Airways France had decided, as a precaution[31], to replace ADIRU 2 on 24 December during a stopover in Marseilles, because of the drifts recorded by crews in the logbook during previous flights. Due to the Functional Identification Number label 1FP1 (supposed to designate the position of ADIRU 1) and 1FP2 (supposed to designate the position of ADIRU 2) being reversed in the avionics compartment, ADIRU 1 was changed instead of ADIRU 2. The reason why the labels were reversed has not been established. The engineering department indicated that the maintenance history since 2007 did not mention any removal of the frame holding the ADIRUs and on which the labels are glued. No maintenance action requiring the replacement of the labels has been identified since this date. XL Airways France has been operating this aeroplane since its delivery by Airbus in November 2002. The history of this equipment between 2002 and 2007 has not been retraced. The labels of the other two Airbus A330 operated by the company were checked after the incident. They had not been reversed.

The history of the aeroplane does not show up any other events associated with ADIRUs before the incident. XL Airways France stated that no similar malfunction (change in mode) was observed on F-GRSQ after the event (i.e. more than 7,000 flight hours and 930 cycles in May 2016). The ADIRU control panel and the associated connections have not been subject to maintenance. This observation tends to rule out an intermittent failure related to this equipment.

2.2 Analysis of recorded data

The position of the IRS mode selectors was not recorded in the FDR. However, some mode changes can be deduced from the messages recorded in the internal memory of the IRSs and in the PFR.

[29] Data from an IRS is, for example, not available in the following cases:
- when an ADIRU is off (controlled or not)
- in-flight realignment of an ADIRU
- IRS part fault
- fault on the IRS / FMGEC transmission bus.

[30] The ECAM messages and the associated procedures provide for the fault of one or two IRSs only. The ECAM message "*NAV IR 1+2+3 FAULT*" does not exist. Possible ECAM messages are therefore "*NAV IR 1 FAULT*", "*NAV IR 2 FAULT*", "*NAV IR 3 FAULT*", "*NAV IR 1+2 FAULT*", "*NAV IR 2+3 FAULT*", "*NAV IR 1+3 FAULT*".

[31] The AMM requires the replacement of an ADIRU if two consecutive flights result in drifts exceeding defined thresholds. The engineering department prefers to anticipate changing an ADIRU when non-consecutive drifts are reported, to avoid being forced into making a mandatory change when the aeroplane is in a remote stopover.

No IRS 3 fault was recorded in the PFR or in the internal memory of the IRS. The latter contained the following end of navigation data:

- the last position (N12°25.0', E36°45.8') near the border between Ethiopia and Sudan;
- last ground speed: 477.9 kts;
- total navigation time: 5 hours 2 minutes.

The navigation time can be used to determine that IRS 3 exited the NAV mode at 10:34. The end of navigation position and ground speed are consistent with the values recorded in the FDR at this time.

Tests carried out at Honeywell confirmed that the only technical scenario possible was a switchover from NAV mode to ATT mode. On the switchover from NAV mode to OFF, the inertial data is no longer transmitted by the IRS, which would have led to an IR FAULT message on the ECAM, with the message being recorded in the PFR.

This means IRS 3 was thus switched from NAV mode to ATT mode at 10:34 during cruise flight. It was then temporarily rejected[32] by the flight control computers and until the end of the flight by the AP. The loss of the navigation function of a single IRS does not affect flight operations. According to the logic used by the manufacturer, Airbus, this information does not therefore result in an ECAM message appearing. In addition, since the PFDs and NDs use the data from IRS 1 and 2, the loss of the navigation function of IRS 3 had no effect on these screens. The fact that the IRS was in ATT mode was shown on the MCDU (POSITION MONITOR or IRS MONITOR pages) and the crew was requested to enter the heading (see Figures 4 and 5).

At 13:36, i.e. about three hours later, the automatic disconnection of the AP and the A/THR, and the loss of FM position data on the NDs were caused by the rejection by the FG part of the FMGEC of the two remaining IRSs (see sections 2.1.3 and 2.1.4). It is likely that at this point the inertial navigation data of IRS 1 and IRS 2 was no longer consistent[33] because of the drift of IRS 2. The ECAM messages associated with this situation were: **AUTO FLT AP OFF**, **AUTO FLT A/THR OFF, AUTO FLT REA W/S DET FAULT**. The absence of the NAV IR DISAGREE message is explained by the fact that the flight controls (EFCS) still had at least two consistent sources for the primary inertial parameters (see section 2.1.5).

The witness statements indicate that the crew found valid positions again by activating the BACK-UP NAV mode. The entering and exiting of this mode are not recorded but can be timed from the position parameters recorded on the captain and FO sides which became valid and then invalid again:

[32] During the transition from NAV mode to ATT mode, the attitude and acceleration data used by the flight control computers is temporarily unavailable. According to the design principles, this data could be used anew by the flight controls when it became available again.

[33] It is not possible to directly compare the inertial data of ADIRU1 and ADIRU2 because the FDR records only one source. However, there is a significant difference between the speed calculated by ADIRU1 (434 kt) recorded on the FDR and the speed recorded in the memory of ADIRU2 (411 kt) about 8 minutes later, at 13:44.

<table>
<tr><th></th><th>Captain</th><th>FO</th></tr>
<tr><td>13:36
Loss of FM positions on captain's and FO's side simultaneous with disconnection of AP</td><td colspan="2">Unavailable positions</td></tr>
<tr><td>13:38:36
Position on captain's side becomes valid again</td><td rowspan="2">BACK-UP NAV mode
Available positions</td><td>Unavailable positions</td></tr>
<tr><td>13:38:53
Position on FO's side becomes valid again</td><td rowspan="2">BACK-UP NAV mode
Available positions</td></tr>
<tr><td>13:43:58
Position on captain's side becomes invalid</td><td rowspan="2">Unavailable positions</td></tr>
<tr><td>13:44:55
Position on FO's side becomes invalid. In the same minute an in-flight alignment of the three ADIRUs was recorded</td><td>Unavailable positions</td></tr>
</table>

The captain got back valid positions for around five minutes. The positions on the captain's side became invalid again at 13:43:58 which allows the time at which the BACK-UP NAV mode was exited on the captain's side to be found. Exiting this mode should give access to the IRS data on the MCDU "*POSITION MONITOR*" and *"IRS MONITOR"* pages. The ADIRUs were aligned in flight around one minute later. The FO lost the position data at 13:44:55 which was very probably the consequence of the in-flight alignment of the ADIRUs.

At 13:44, the attitude data, which was still being taken into account by the flight control computers, became unavailable due to an in-flight alignment in the same minute for each of the three IRSs. In the absence of this data, the active flight control law becomes the direct law. The ECAM messages displayed in order of priority include: **F/CTL DIRECT LAW, NAV IR 1 FAULT, NAV IR 1+2 FAULT, NAV IR 2+3 FAULT, NAV IR 1+3 FAULT, NAV IR NOT ALIGNED**, supplemented by messages considered as the consequences on the other aeroplane systems. The position and flight plan data was no longer available on the NDs.

At 13:46, the recorded position of the "*AIR DATA*" rotary switch changed from "*NORM*" to "*CAPT ON 3"* until the end of the flight. The ADR source used on the left (captain's) side changed from ADR 1 to ADR 3.

The "*ATT HDG"* rotary switch stayed in the "*NORM"* position for all of the flight. This means that the IRS data source on the left (captain's) side was IRS 1 and that the IRS data source on the right (FO's) side was IRS 2.

2.3 Examinations of ADIRUs and study of failure modes envisaged by manufacturer

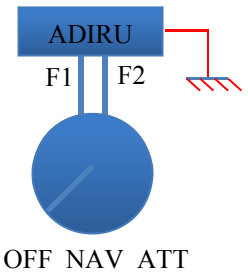
The three ADIRUs were examined at the Honeywell plant. First, conventional validation tests (ATP: Acceptance Test Protocol) were carried out without highlighting any anomaly. Navigation tests gave satisfactory results.

ADIRUs 1 and 2 were returned to operational service by Honeywell and sent back to Air France Industries, their owner. It was thought that their in-flight alignment, simultaneous with that of the ADIRU 3, was controlled by a source outside the three computers, given the extremely low probability of having three simultaneous internal faults.

A visual inspection of the electronic components of ADIRU 3 was carried out to try to explain the possible untimely change in mode at 10:34. This additional examination brought to light no element confirming this hypothesis. ADIRU 3 was returned to service in October 2015 on a different aeroplane and monitored by Air France Industries, owner of the unit, who stated that the equipment then logged more than 8,000 hours of operation up until October 2017, at which date it was removed because of a fail stop unrelated to an untimely change in mode.

Research was carried out to see if a fault in the mode change control could have occurred. The changes in mode of each IRS are exclusively controlled by the MSU. The IRS receives discrete input signals "*Mode Select #1*" and "*Mode Select #2*" from the MSU. Honeywell has forwarded the following correspondence between the input signals and the controlled mode:

ADIRU pin	Signal	Off	Nav	Att
F1	Mode Select #1	Open	Ground	Open
F2	Mode Select #2	Open	Open	Ground



Using an inductive approach as comprehensive as possible, the FMEAs[34] identify for each component of an equipment item:

- the functions of this component;
- the various fault modes of each component;
- the causes of these failures (type of fault of each component or function of the equipment);
- the effects of each failure on the equipment or system;
- the probability of occurrence of each failure.

[34] Failure Mode and Effects Analysis.

The development of FMEAs, widely used in the industry to determine the failure modes of equipment, is partly based on the knowledge and experience of fault modes and mechanisms that the equipment manufacturer's staff may have.

The FMEA document for the ADIRU indicates that an inversion of the signal "*Mode Select #1*" or "*Mode Select #2*" had been evaluated by Honeywell to be 0.034 per million flight hours.

Switchover to ATT Mode (10:34)

Only an inversion of the "*Mode Select #1*" signal and the "*Mode Select #2*" signal can explain a non-controlled switchover to ATT mode. In addition, the two faults must occur simultaneously otherwise the OFF mode is controlled. The likelihood of this non-controlled change is therefore extremely low.

In-flight alignment (13:44)

A temporary inversion of the "*Mode Select #1*" signal can explain the in-flight realignment of an IRS (NAV- >OFF->NAV). Since the ground signals from the ADIRUs are independent, a common fault on the control is almost impossible. The likelihood of the temporary inversion of the "*Mode Select #1*" signal in the same minute for the three ADIRUs is therefore extremely low.

As indicated in section 2.1.8, no malfunction of the connections or control panel was reported before or has been reported since the incident on F-GRSQ.

2.4 Document review and pilot training

2.4.1 Estimation of general knowledge of IRS operating modes

In order to document the knowledge that is usually imparted to pilots during their training on the operation of inertial navigation systems, the BEA reviewed several documents[35] and interviewed a number of working pilots.

It was found that knowledge seemed homogeneous on the following aspects:

- alignment is possible only when the aeroplane is stationary on the ground;
- in flight on Airbus aeroplanes, actions on IRS mode selectors by a crew member (the PM, according to conventional task-sharing) must be subject to confirmation by the other crew member (PF) as is the case for guarded switches, engine master switches, and computer resets, because of their irreversible nature. This is taught in the type rating training and revised based on failures studied during continued proficiency training;
- it is not usually explicitly written that the switch from NAV to ATT is irreversible for navigation data[36]. This is deduced from the various documents and the pilots interviewed felt that this was known to the population of pilots.

[35] Examples include ATPL theoretical courses, Airbus documents (FCOMs, FCTM, PDP, computerized training materials for type rating) and Boeing documents (FCOM 737, 777 and 747).

[36] The Boeing 737 FCOM consulted for this review explicitly mentioned the irreversible nature of switching from NAV to ATT.

2.4.2 Recent continuous training at XL Airways France

In accordance with regulations, XL Airways France organizes recurrent training and checks for all of its flight crews. The programme of each annual campaign must comply with the required content set by the regulations and also contains topics specific to the operator, defined in terms of its activity and its incidents. The recurrent training and checks include:

- theoretical revision with an e-learning system that must be carried out before the two days of ground training. All of the aeroplane systems are reviewed over a 3-year cycle;
- two days of ground training including various courses and QCM validating the revisions;
- four simulator sessions (two checks and two training sessions);
- a line check.

[37] XL Airways France said that the practice of systematically aligning the ADIRUs on the ground in the order 1 (left) and 2 (right) then 3 (centre) helps consolidate assimilation of the architecture. This unwritten practice is taught.

For the 2014/2015 season, the programme contained, in particular, theoretical revision of the ATA 34 Navigation systems with Airbus training materials, including ADIRUs and the BACK-UP NAV mode. In it, the 1-3-2 sequence of the equipment was recalled[37]. The need for the PM to obtain confirmation from the PF before any irreversible action on IRS selectors or switches was not recalled. This revision studied a few failures including NAV ATT discrepancy, ADR1 fault and FMGEC double failure. The NAV IR 1(2)(3) Fault or NAV IR ALIGNMENT IN ATT MODE failures were not included. The QCM included questions on the BACK-UP NAV mode but did not include questions about the ADIRUs and their controls.

The simulator sessions included "*Unreliable Airspeed*" and FMGEC double failure situations.

2.5 Personnel information

The captain, aged 53, held an ATPL issued on 27 April 2004. He joined the operator in November 2000 as a FO on the A320 and then the A330 (type rating obtained in 2003). He served as captain on the Boeing 737 (type rating obtained in 2011) and then on the A330 in 2013. He had logged 11,321 flight hours including 6,200 on the A330 (154 in the previous three months).

The FO-L, aged 49, held an ATPL issued on 19 November 2003. He joined the operator in April 2003 as FO on the A320 (type rating obtained in January 2003) and then on the A330 in 2005. He had followed the course allowing him to serve as FO-L in April 2010. He had logged 11,366 flight hours including 5,646 on the A330 (184 in the previous three months).

The FO, aged 40, held an ATPL issued on 4 December 2008. He joined the operator in June 2007 as FO on the A320 (type rating obtained in 2006) and on the A330 about 18 months later (March 2009). He had logged 5,300 flight hours, including more than 3,000 on the A330 (136 in the previous three months).

The three crew members had followed the 2014-2015 recurrent training and checks programme satisfactorily.

2.6 Meteorological information

Valid weather forecasts for 12:00 indicated that southern Greece was under broken to overcast cumulus and stratocumulus based between FL15 and FL40, with tops between FL70 and 110, locally associated with showers and possible isolated cumulonimbus.

The Athens METAR at 13:50 was:

- LGAV 261350Z 18005KT 140V210 9999 SCT030 BKN070 15/08 Q1013 NOSIG QNH1013.6=

These conditions were indicated to the crew at 13:59 by the air traffic controller as well as the meteorological conditions at Heraklion: wind 360° 3 knots, visibility 10 km, few clouds at 2,000 ft, broken at 8,000 feet, temperature 17°C, QNH 1014.

2.7 Search for similar events

Airbus said they had found in their incident database (1999 to 2015) a triple IRS loss.

In March 2002, after take-off, the crew of an A320 noted a jump in the FM position followed by an automatic reset of the FMS on the FO's side. Shortly afterwards, the three IRSs became unavailable with the same consequences as those in the F-GRSQ incident (loss of FMS position data, loss of the flight plan, switchover to direct law). The PFR and the internal memory of the IRSs indicated an in-flight alignment for the three IRSs. The crew reported having attempted an in-flight re-alignment. The information obtained by Airbus at the time did not provide further details on the actions of the crew.

2.8 Articles illustrating automatic performance of actions

The ASRS[38] document "*CALLBACK Issue 434*" dated March 2016 entitled "*Managing Muscle Memory*" illustrates that a usual sequence of actions can sometimes be repeated outside their context when a particularity of the situation creates a link (appropriate or not) to the beginning of the sequence[39], such as untimely engine shutdown on the ground. It also sums up how repeated actions become automatic: "*The more often we perform a given physical action, the more likely we are to do it as needed, when needed without having to think about the specific combination of movements involved. These habits become an unconscious process that occurs when triggered by a given circumstance or set of cues.*"

In addition, in the majority of cases, operators managing industrial processes, vehicles or aeroplanes are trained to adopt automatic reflexes in temporal emergency situations where any activity based on rules and all the more so, on declarative knowledge would be doomed to failure. However, learning can also be incidental: the responses to situations the most frequently encountered become automatic and thereby rigid. This mechanism is particularly economical as often it leads to the adoption of low-demand procedures (in particular with respect to attention resources). But there may be a high price to pay when a new and dangerous situation presents perceived similarities with a familiar situation. There is a risk of the (unsuitable) automatic reflex prevailing. [...] Cognitive economy will first lead to a new situation being assimilated with a known situation, as far as possible, and will initially lead to routines (automatic reflexes) or rules being applied before starting tedious interpretive mechanisms based on declarative knowledge.[40]

[38] Aviation Safety Reporting System.

[39] https://asrs.arc.nasa.gov/publications/callback/cb_434.html

[40] *Régulation des activités cognitives et gestion du risque par l'opérateur humain* by Hoc & Rogalski, P. Dubois & G. De Terssac (Eds.) *Les nouvelles rationalisations de la production* CEPADUES January 1992.

3 - LESSONS LEARNED AND CONCLUSION

3.1 Scenario

3.1.1 IRS 3 switched from NAV mode to ATT mode at 10:34

Two hypotheses may explain this change in mode:

- 1- A non-controlled change in mode.

  The functional and visual technical examinations of the ADIRU did not consolidate this hypothesis. XL Airways France has reported no new similar incident on F-GRSQ, which would seem to exclude a connection fault between the controls and the ADIRU as being the cause of this change in mode. Air France Industries has not reported any similar anomaly on the ADIRU since its return to service. In this hypothesis, it would seem to be the case of a one-off, non-reproducible anomaly.

- 2- A crew member moving the mode selector from NAV to ATT.

  This would be consistent with the recorded data collected. In this hypothesis, the crew, concerned about monitoring the drift of IRS 2, may have wished to switch IRS 2 to ATT mode, but may have moved the IRS 3 selector by mistake (see section 3.2.2.2). It is important to note at this point that the interface does not visually advise of the irreversible nature of this action (see section 2.1.2). Finding that there was no satisfactory result subsequent to this action, the crew may have returned the selector to NAV, the position observed by the FO on his return to the cockpit at around 13:00. However, this sequence is not consistent with the statements made, which indicate that no action on the rotary switches was performed during this phase. Furthermore, it is not part of a planned procedure.

For this reason, the investigation was unable to establish the cause of the change in mode. However, the lack of any report of a new anomaly on the equipment involved, which has been in service since the event, makes the second hypothesis more likely.

3.1.2 Disconnection of AP and A/THR and loss of position data at 13:36

The disconnection of the automated systems is the result of the drift of IRS 2 with respect to IRS 1 detected by the FG part of the FMGEC, IRS 3 having already been completely rejected. A logic specific to the FMS standard installed in this aeroplane, modified in the new standards, also results in the loss of FM positions (see section 2.1.3 and section 2.1.4). The deterioration of the situation at 13:36 is not therefore linked to crew actions performed at that time. From this moment, the FO (PF) flew the aeroplane while the captain (PM) was concerned about the need to retrieve the position and navigation data.

The ECAM messages displayed to the crew did not prompt them to take any action on the aeroplane systems. They did not make the crew aware of either the cause of this automatic disconnection or the cause of the loss of positions (see section 2.2). The crew only had access to the consequences of the problem but not to its origin, although it was known to the systems. Thus, they may have felt they were outside a listed failure situation and were required to perform actions without the support of a procedure. For example, they took the initiative of using the BACK-UP NAV mode.

This mode, although not intended for the situation in which they found themselves, allowed the crew to retrieve position and navigation data. It is important to note here that this mode had been revised during the 2014-2015 recurrent training and checks. It is probable that this refreshment facilitated the recourse to this solution. The exiting of the BACK-UP NAV mode by the captain in order to check information about the IRSs is akin to troubleshooting to find a technical explanation for the situation. It again led to the loss of position data on his side. The FO, however, kept this data until the in-flight alignment of the three IRSs a few minutes later. The loss of position is a rare event that seems to have been a major destabilizing factor for the crew.

In his statement, the captain specified that he was no longer able to return to the BACK-UP NAV mode. This is understandable if the captain tried to activate this mode again after the in-flight alignment of IRS 1[(41)].

[(41)] The BACK-UP NAV mode on the captain's side is not available in this case.

3.1.3 In-flight alignment of the three IRSs at 13:44

The investigation did not bring to light a technical fault explaining the simultaneous triple in-flight alignment. The absence of any CVR recording and the statements from the two crew members in the cockpit made it impossible to identify possible actions made at that time on the three IRS mode selectors. Nevertheless, this simultaneous triple alignment was probably the consequence of crew actions while the captain was in the process, as previously mentioned, of searching for data on the position of the aeroplane. This hypothesis is consistent with the FO-L's statement, who on returning to the cockpit a little later, found that the three selectors, including that of IRS 3 were set to NAV. According to the captain and the FO, this selector had previously been switched to ATT before the disconnection of the automated systems, in order to apply the IR ALIGNMENT IN ATT MODE procedure. The selector would thus have been moved, through the OFF position, before finally being returned to NAV, before the FO-L returned to the cockpit. Other similar actions could have been made on the three selectors at this point, causing the triple alignment.

In this hypothesis, these actions would be of an improvised nature and would not correspond to the application of an expected procedure or to the structured processing of an anomaly. They could be explained by weak knowledge of the systems and/or by the stress created by a major deterioration, the cause of which being misunderstood. It should be noted here that these three improvised alignments were probably carried out in rapid succession. If they had been carried out in slow succession, they would have led to a progressive deterioration with effects visible to the crew, in particular the change to an alternate flight control law with an ECAM message and an audio warning, which does not stand out in the various technical data. This deterioration, observed by a crew monitoring the result of their actions, would have probably led to them stopping their actions. This sequence would seem to show rapid action, symptomatic of high stress and perhaps the repetition of ground alignment procedure actions triggered by unsuitable automatic behaviour (see section 2.8).

Indeed:

- the alignment of the three IRSs is a task frequently performed on the ground by crews and the succession of actions as a consequence, has every chance of being automatic;
- the loss of position on the ND may have created a link with the systems generating the position, namely the IRSs.

3.1.4 Diversion

The crew was now flying the aeroplane in direct law mode with the standby instruments. The radio navigation equipment was still available.

The crew said that they abandoned the technical analysis in order to manage the flight path and diversion. This ensured a safe diversion with the help of the Greek air traffic control. However, an action is noted, carried out two minutes after the in-flight alignment akin to troubleshooting ("*AIR DATA*" rotary switch set to "*CAPT ON 3*"). During the descent, probably once the diversion had been decided on and implemented, the crew returned to the technical issues by trying at least one NAV-OFF-NAV sequence with the IRS 1 selector. This action was undertaken without reference to a planned procedure or to the ECAM (see section 3.2.3).

The FO said that the GPS position data was unavailable. The absence of the GPS position may have increased the crew's lack of understanding in its technical analysis. Indeed, the crew could legitimately expect that the GPS data did not depend on the availability of the IRSs. The investigation has shown that pure GPS data travels on the IRS buses to the FMGECs. By design, each FMGEC is based on the validity of the GPIRS hybrid position received to invalidate all the GPS data sent on the bus (see section 2.1.6). The GPS data therefore became invalid during the triple in-flight alignment. However, the pure GPS data would have been found if the ATT mode of one of the IRSs had been selected, as provided for by the procedures associated with the ECAM messages.

It is important to note at this point that flying in direct law mode with standby instruments worked, although exposure of crews to this situation is rare. The weather conditions were mild, which saved the crew the added difficulty of an instrument approach in deteriorated technical conditions.

3.2 Safety considerations

3.2.1 Preservation of CVR

The absence of CVR data made it impossible to supplement the interviews. The CVR could have clarified in particular, the actions carried out at 13:44 during the triple alignment of the IRSs. However, it could not have explained the first change in mode, which occurred approximately four hours before the aeroplane landed, a period longer than the regulatory CVR recording time. The BEA has already recommended that the CVR recording times be increased to enable the analysis of incidents occurring during a long-haul flight (recommendation FRAN-2012-025). This modification has been taken into account by the ICAO (Annex 6) and the European Union which imposes a recording time of 25 hours for aeroplanes of more than 27 t and produced after 1 January 2021[42].

[42] Commission Regulation (EU) No 2015/2338 of 11 December 2015 amending Regulation (EU) No 965/2012 as regards requirements for flight recorders, underwater locating devices and aircraft tracking systems.

3.2.2 Considerations concerning manual actions on mode selectors

3.2.2.1 Irreversible actions

The irreversibility of actions on IRS mode selectors is not visually recalled on the control unit. The rotary switch must, however, be pulled before being turned, to prevent unintentional action and may serve as an ultimate reminder of the irreversible nature of the action about to be performed. Similarly, the engine master switches must be pulled before being flipped backwards. Other controls in the cockpit are guarded to recall this feature even before the operator's hand touches the control. Computer resets (via unguarded circuit-breakers or pushbuttons) are not "protected" against individual action without confirmation.

Airbus stated that these differences corresponded to the need to graduate the irreversible nature of a control according to the seriousness of the consequences of the action in order to not generalize the guarded controls with the risk of weakening the effectiveness of this barrier. Whatever the ergonomy of these controls, the procedures taught to crews specify that these irreversible actions first require confirmation by the two crew members (see section 2.4.1).

For the less "protected" controls, the fact that the action must be confirmed by both pilots is based solely on the crew's memory. The sensitive nature of these controls and switches is taught during training and recalled during simulator sessions via troubleshooting requiring PF/PM confirmation and seems to be known to pilots.

However, the stress created by a real failure, infrequent exposure to certain actions in training or other factors reducing the cognitive performance of an individual can, in all likelihood, impair the effectiveness in recalling rules or knowledge stored in memory. Training on IRS failures in flight is rare and provides little occasion for crews to carry out this cross-confirmation for these rotary switches. It is thus possible that this confirmation requirement did not provide the expected protection during the triple alignment around 13:44.

The investigation was unable to confirm whether the ergonomy of the selectors, their use and the associated training actually played a role in the event.

3.2.2.2 1-3-2 layout of IRS mode selectors

The layout of the selectors reflects the left, standby, and right assignment of the IRSs. The IRS numbers are clearly marked on the unit and this layout is recalled in training. However, it is different from the numerical order 1, 2, 3.

The presentation of the status of the IRSs on the POSITION MONITOR page of the MCDU is in numerical order 1, 2, 3, and is therefore different from the order used for the selectors.

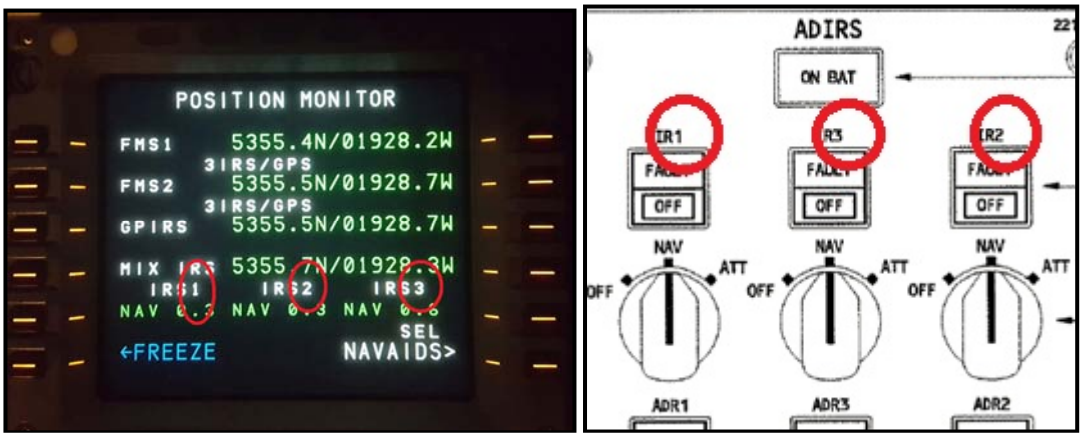


Figure 7: Comparison of orders in which IRSs are numbered

The crew regularly consulted the POSITION MONITOR page during the flight to monitor the drift of IRS 2. They were therefore concentrated on reading the drift value in the centre and may have associated IRS 2 with this central position. For this reason, when acting on the selector, it is possible that the crew operated the middle mode selector (IRS 3) instead of the one on the right (IRS 2), bypassing the step which involves reading the IR number and the cross-check which are the counter-measures for this error.

Again, the investigation was unable to determine whether this set of ergonomic features and training actually played a role in the event.

3.2.3 Improvised actions

It emerges from the recorded data and crew statements that the latter had difficulty in remaining within the conventional operational practices for managing the drift of an IRS (according to the probable hypothesis of IRS 3 being set to ATT in response to the drift of IRS 2) and then troubleshooting based on the ECAM messages. At 13:36, the disconnection of the automated systems and the loss of positions without a technical explanation was in all likelihood not understood by the crew who started looking for why this had happened. The crew also had to ensure the urgent aspects of flying. According to the ECAM messages, no technical action was required: the crew should have reviewed the ECAM STATUS page and then decided on the operational steps to be taken. This lack of technical explanation and guidance in troubleshooting, when the consequences for the flight are important, is probably difficult to accept for a crew. It may leave the impression that an unforeseen failure has occurred, prompting the crew to think that the usual processing framework is no longer fully adapted and thus opens up the possibility of seeking unconventional solutions.

From this point of view, this event echoes a recommendation already made by the BEA about information received by the crew on the activation of monitoring[43]. However, the triple alignment probably from a crew input indicates that the latter suspected the IRSs as being the cause of the deterioration. Information about the reason for the technical deterioration could have perhaps reassured the crew by showing them that they were in a foreseen failure and encourage them to comply with the expected troubleshooting process.

[43] The BEA recommended (FRAN-2012-049) to EASA that "[it] *study the relevance of having a dedicated warning provided to the crew when specific monitoring is triggered, in order to facilitate comprehension of the situation.*" In subsequent discussions with EASA on the consideration of this recommendation, the BEA insisted that it was not limited to the monitoring of speeds at stake in the accident of flight AF447.

The departure from the conventional troubleshooting process seems to have persisted during the diversion. The captain in fact asked the FO-L, without following any procedure, to operate a rotary switch to try to retrieve data. The processing of the ECAM NAV IR [x+(y)] FAULT type messages would have led the crew to check the availability of the ATT mode and thus to their retrieval of the attitude data, an alternate control law and GPS navigation data on the MCDU. This mode was effectively available as indicated by the three flashing IR Fault lights (see section 2.1.2) and the paper procedure had been consulted earlier. The resources allocated to flying, performance calculation and exchanges with the controller were considerable and probably left little opportunity to return to the processing of system issues in the first part of the diversion. As it became clearer that there would be a favourable outcome, the crew could probably have envisaged resuming the processing of these issues. It is possible that the crew, probably tired by the management of the incident and having admitted their incomprehension, decided not to risk additional deterioration in the last minutes of the flight and concentrated on managing the approach.

3.3 Causes

Note: In the absence of the CVR and given the differences between the technical data collected and certain aspects of the crew's statements, the investigation can only infer probable or only possible factors to explain the following sequence.

The incident, the unavailability of the three IRSs, led to deteriorated flight control laws and to the deteriorated autonomous navigation capability of the aeroplane. This unavailability occurred in four main steps:

- at 10:34, the switchover of IRS 3 from NAV mode to ATT mode, probably the result of a manual action by a member of the crew;
- at 13:36:
  - the disconnection of the AP and A/THR, probably further to a navigational discrepancy between IRS 2, which had been drifting since take-off, and IRS 1,
  - the loss of position and navigation data on the NDs as a result of the previous event according to the logic specific to Honeywell P3 and earlier FMS standards. This data was found again two minutes later when the crew activated the BACK-UP NAV mode;
- shortly before 13:44, the loss of position data on the left side following the BACK-UP NAV mode being exited on the left (captain's) side;
- at 13:44, the in-flight alignments of the three IRSs, probably consecutive to improvised actions by the crew possibly without conferring, during attempts to retrieve position data on the captain's ND.

The loss of positions was a major concern for the crew. The new FMS standards would have prevented this loss of data. Greater robustness in maintaining autonomous navigation capabilities is important for flying over the ocean or desert areas, or close to conflict zones[(44)].

The problem of the previously identified drift of an IRS was not resolved because of the mislabelling on the chassis. However, the drift of a single IRS in flight is not a major abnormal situation.

[(44)] For example the Korean Airlines 007 flight shot down on 31 August 1993 when it deviated from the planned route into soviet territory.

The following factors were considered to try to understand the reasons for the probable non-standard actions of the crew on the IRS rotary switches, without it being possible to specify their degree of contribution:

- the ergonomy of the ADIRU control panel not visually recalling the irreversible nature of IRS mode changes;
- the presentation of IRS data on the POSITION MONITOR page of the MCDU in a numerical order (1,2,3) which is different to the layout of the rotary switches (1,3,2), which is representative of the aeroplane's architecture;
- the logic for presenting ECAM data to the crew preventing them from understanding the reason for the disconnection of the AP and the loss of positions which occurred at 13:36;
- the low exposure of crews to IRS failure situations.

Lastly, the influence of other factors cannot be excluded, specific to the crew (e.g. fatigue or individual knowledge) or the flight environment that the investigation was not able to identify.

Following the incident, Airbus carried out a document review to include the generalisation of the use of the BACK-UP NAV mode to all the cases leading to the loss of positions on the NDs, the most probable case identified still being the double loss of FMSs.