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INVESTIGATION REPORT

Serious incident to the Boeing 737- 800 registered CN-ROJ operated by Royal Air Maroc

on 30 December 2016
at Lyon-Saint Exupéry (Rhône)

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BEA2017-0003/January 2022

Safety investigations

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SPECIAL FOREWORD TO ENGLISH EDITION

This is a courtesy translation by the BEA of the Final Report on the Safety Investigation published in November 2021. As accurate as the translation may be, the original text in French is the work of reference.

Contents

Glossary

Abbreviation	English version
A/P	Autopilot
A/T	Auto Throttle
ADIRS	Air Data Inertial Reference System
ADIRU	Air Data Inertial Reference Unit
ADR	Air Data Reference
AMM	Aircraft Maintenance Manual
AMP	Aircraft Maintenance Program
APP	Approach
ATC	Air Traffic Control
ATP	Acceptance Test Protocol
ATPL	Airline Transport Pilot Licence
BITE	Built-In Test Equipment
CDU	Control Display Unit
CRM	Crew Resource Management
CRS	Certificate of Release to Service
DA	Decision Altitude
DEU	Display Electronics Unit
DFCS	Digital Flight Control System
EASA	European Aviation Safety Agency
EGPWS	Enhanced Ground Proximity Warning system
F/D	Flight Director
FAA	Federal Aviation Administration
FCC	Flight Control Computer
FCOM	Flight Crew Operating Manual
FIM	Fault Isolation Manual
FMA	Flight Mode Annunciator
FMC	Flight Management Computer
GLIDE	Glide slope

Abbreviation	English version
IAF	Initial Approach Fix
ILS	Instrument Landing System
IR	Inertial reference
IRS	Inertial Reference System
LOC	Localizer
LRU	Line-Replaceable Unit
LVP	Low Visibility Procedures
MCC	Maintenance Control Centre
MCP	Mode Control Panel
MDA	Minimum Descent Altitude
MMR	Multi-Mode Receiver
MOE	Maintenance Organization Exposition
MSAW	Minimum Safe Altitude Warning
MSU	IRS Mode Selector Unit
ND	Navigation Display
NTSB	National Transportation Safety Board
NVM	Non-Volatile Memory
PF	Pilot Flying
PFD	Primary Flight Display
PM	Pilot Monitoring
QAR	Quick Access Recorder
QRH	Quick Reference Handbook
RA	Radio Altimeter
RAM	Royal Air Maroc
RG	Ring laser Gyro
RVR	Runway Visual Range
SB	Service Bulletin
SIGWX	Significant weather
TLB	Technical Log Book
VOR	Very high frequency Omnidirectional Range
WINTEM	WINd TEMperature

Synopsis

Diversion, ADIRU IRS malfunction, go-around, non-stabilized approach in manual control and IMC conditions, descent below the nominal slope, off-centre exit from cloud layer, side-step, MSAW, EGPWS warnings

Time	11:09[1]
Operator	Royal Air Maroc
Type of flight	Passenger commercial air transport
Persons on board	Captain (PF); co-pilot (PF); 4 cabin crew; 149 passengers
Consequences and damage	None

[1]Except where otherwise indicated, the times in this report are in Coordinated Universal Time (UTC). One hour should be added to obtain the legal time applicable in Metropolitan France on the day of the event.

On 30 December 2016, the Boeing 737- 800 was being vectored to the ILS of runway 06 at Paris-Orly (Val-de-Marne). The meteorological conditions required a category 3 instrument approach (CAT III ILS).

After receiving the approach clearance, the crew twice tried to engage the second autopilot (A/P B). The non-reception of radio-altimeter (RA) 2 data by the flight control computer (FCC B) prevented the engagement of A/P B and caused the disengagement of A/P A.

The crew re-engaged A/P A, informed the controller that they could not perform a CAT III ILS approach, and requested to fly a missed approach and divert to Lyon-Saint Exupéry airport. Conditions at Lyon permitted a CAT I ILS approach, which could be carried out with only one A/P functioning.

On intercepting ILS 35R at Lyon-Saint Exupéry, with the A/P in intercept mode and the Localizer radio signal captured (green VOR/ LOC mode), the aeroplane suddenly veered to the right with a bank angle of 30°, crossed the Localizer path and then departed from it on a clearly divergent heading (heading 70°) without any onboard warning being activated. This untimely right turn was commanded by the A/P due to the erroneous data from the IRS module of the left Air Data Inertial Reference Unit (ADIRU).

The invalidity of the data supplied by the left ADIRU then led to the disengagement of A/P A. The captain then flew manually with the Flight Directors (F/D) displayed on the Primary Flight Display (PFD).

The crew first tried to return to the path. As the deviation from the path compromised continuing the approach, they flew a missed approach and then engaged A/P B.

The aeroplane had just been transferred to the Approach again when the L IRS FAULT warning was activated causing the disengagement of A/P B, and the disappearance of the pitch, roll and heading data along with the F/D bars from the left PFD. The captain again flew manually while carrying out from memory, one of the actions of the IRS FAULT check-list, namely, IRS Transfer Switch - BOTH ON R. The two FCC thus used the data supplied by the right ADIRU. The pitch, roll and heading were displayed again on the left PFD and the F/D bars reappeared.

During the second approach and the interception with the localizer, and after re-engaging A/P B and transferring the controls to the co-pilot, the captain informed the controller that he had positioning problems. The controller continued the radar vectoring.

On capturing the Glide, A/P B automatically disengaged due to FCC B not receiving data from RA 2. The F/D disappeared from both sides. The co-pilot then transferred the controls to the captain. The latter informed the Approach controller that he was continuing in manual flight. The flight was transferred to the Tower controller.

The approach, in manual and without F/D, was not stabilized with respect to the approach path or the aeroplane's speed and configuration. Several EGPWS "*SINK RATE*", "*GLIDE SLOPE*" and "*TOO LOW TERRAIN*" warnings were activated on final. The aeroplane came out of cloud cover between runways 35L and 35R, made a side-step and landed on runway 35R.

The following factors contributed to this serious incident:

- The concomitance of two independent failures within two separate systems where the cause of the failures, the absence of any link and the consequences were difficult for the crew to determine, without appropriate information in the operational documentation or sufficiently salient warnings emitted by the aircraft systems.
- The crew's progressive loss of confidence in the plane's systems as the flight continued, causing substantial stress and the crew to focus their attention on the level of remaining fuel.
- The deterioration in CRM by the crew when the workload became very high due, in particular, to having to manage the IRS FAULT during the missed approach phase.
- The operating logic of the FCC which does not monitor the inertial data provided by the ADIRU, except for approaches with the two A/P engaged. The FCC was not designed to, nor was it required for certification, to monitor the AIDRU inputs.
- The ADIRU internal monitoring logic with respect to the validity of the inertial data transmitted to other systems. The activation criteria of the "Drift Angle" fault, which in turn activates the IRS FAULT warning, can cause the latter to appear at a late stage with respect to the start of the ADIRU IR module malfunction.
- The crews' non-systematic reporting of technical malfunctions in the Technical Log Book (TLB) such as the disappearance of the F/D, the ADIRU malfunctions and the A/P automatically disconnecting.
- The persistence of intermittent faults.

The BEA has issued five safety recommendations concerning:

- A re-assessment of the safety study relating to the consequences of the FCC using undetected erroneous data from the ADIRU.
- The ADIRU's built-in monitoring system and the activation of the IRS FAULT warning.
- The flight crew fault reporting procedures.
- The processing of intermittent faults within Royal Air Maroc.
- The company's practices when intercepting the ILS.

Four safety lessons have also been drawn from this incident. These lessons concern:

- The crew's compliance with the fault isolation procedures.
- Pilot training in manual piloting without F/D on an ILS approach with the sudden disconnection of the A/P.
- The importance of line maintenance.
- The update of operational documentation.

ORGANIZATION OF THE INVESTIGATION

On 2 January 2017, at around 11:00, the Lyon Air Navigation Services (SNA-CE) notified the BEA of a near-collision with the ground involving flight RAM780S on approach to Lyon-Saint Exupéry.

In the afternoon, the BEA initiated exchanges with the Moroccan safety investigation authority and the operator, Royal Air Maroc about the circumstances of the occurrence.

On 5 January 2017, the BEA classified the occurrence as a serious incident and opened a safety investigation. The Moroccan safety investigation organization (State of the Operator) and the American safety investigation organization (as State of Design & Manufacture) were notified and each appointed an accredited representative.

The data from the QAR (identical to that from the Flight Data Recorder (FDR)) and the ATC data was collected. The Cockpit Voice Recorder (CVR) data was not preserved by the flight crew after the occurrence.

An investigation team was formed and travelled to Lyon and then Rabat to carry out the first investigation actions.

This report contains five safety recommendations.

1- FACTUAL INFORMATION

1.1 History of the flight

Note: the following information is based on statements, QAR data and ATC recordings (exchanges and radar). The key moments of the event are indicated with a colour letter. These letters are shown on the flight paths in this chapter.

On 30 December 2016, the Boeing 737-800, registered CN-ROJ, took off from Rabat-Salé airport (Morocco) at 07:46 to carry out passenger commercial air transport flight RAM 780S bound for Paris-Orly (Val-de-Marne). The captain was the PF and the co-pilot[2] was the PM. A/P A was engaged after take-off.

The crew indicated in their statement that around one hour after take-off, the "*IRS-L DRIFT*"[3] alert message appeared on the Control Display Unit (CDU). They searched for the for the meaning of this message[4] in the onboard documents, without success. They checked the consistency of the speed and position information on the CDU several times and observed that the problem seemed to be resolving itself.

Around two hours after take-off, the crew observed that the message, "*VERIFY POS: IRS-IRS*"[5] was displayed on the CDU. At Paris-Orly, the meteorological conditions required a category 3 instrument approach (CAT III ILS). The crew indicated that being in descent towards Orly and knowing this message, they did not refer to the documents. Believing that the ground speed information from the two IRS seemed to be converging, the crew decided to continue the approach and selected Lyon-Saint Exupéry airport in case of a diversion.

1.1.1 Approach to Paris-Orly

At 10:01, flight RAM780S, in descent to FL 110, was transferred from the Paris En-route control centre to Paris-Orly Approach.

At 10:07, the aeroplane was radar vectored for an ILS approach to runway 06 at Paris Orly. The control unit informed the crew that the Runway Visual Range (RVR) was 400 m.

At 10:09, the Approach controller cleared the aeroplane to descend to an altitude of 5,000 ft and to intercept the Localizer of runway 06.

At 10:10:53, the crew armed the VOR/LOC mode which engaged 40 s later. The aeroplane started turning to intercept the path of Localizer 06, deviating from it to the right and then to the left before intercepting it. The controller questioned RAM 780S, "*You are not in the Localizer confirm*?" The crew did not reply[6] (see Figure 1 point **A**).

At 10:12:56, the crew engaged A/P B, A/P A disengaged. Then nine seconds later, the crew engaged A/P A and A/P B disengaged.[7]

At 10:13:38, the Approach controller asked, "*Maroc 780S confirm you are established ?*" The crew confirmed (point **B**). The Approach controller transferred the flight to the Tower controller.

[2] The co-pilot is also designated by the term First Officer.

[3] The "*IRS-L DRIFT*" message is issued by the FMC when the speed and/or position information supplied by the left ADIRU is not consistent with that supplied by the right ADIRU and that generated from the GNSS positions.

[4] The *"IRS-L DRIFT"* (or *"IRS-R DRIFT"*) is a new message which appeared with version U11 of the FMC installed on the aeroplane in March 2016. The operational documents which the crew consulted during the flight were not up to date.

[5] The "*VERIFY POS: IRS-IRS*" message is emitted by the FMC when the difference between the positions supplied by the two ADIRU is more than 10 NM for 40 s.

[6] The crew did not indicate whether they had identified this deviation.

[7] The two A/P cannot be simultaneously engaged all the while the Approach mode is not armed by pressing the MCP APP button. CAT III ILS approaches require both A/P to be engaged.

At 10:14:03, the Tower controller asked the crew to call back at 5 NM on final and gave them an RVR of 375 m. The crew read back and then asked if they were cleared for an ILS approach. The Tower controller replied in the negative and repeated his request to the crew to call back at 5 NM. The crew replied that they were descending to 4,000 ft. The controller cleared them for a CAT III ILS approach. At this point, the crew armed the Approach mode (APP[8]) and the aeroplane started its final descent (point **C**).

At 10:15:36, the crew selected the go-around altitude of 2,000 ft with the Mode Control Panel (MCP).

The crew twice tried to engage A/P B. The latter would not engage and caused A/P A to disengage. The crew successfully engaged A/P A each time[9].

At 10:16:37, the crew informed the Orly Tower controller that they could not carry out a CAT III ILS approach and asked for a go-around. The aeroplane was at this time at around 9 NM from the threshold of runway 06, at an altitude of around 3,250 ft (point **D**).

At 10:17:02, the Tower controller then asked the crew to stop the descent at 2,000 ft and to maintain this altitude. The crew read back and then asked for clearance to Lyon-Saint Exupéry, the alternate aerodrome specified in the flight plan (point **E**). The approach was then aborted with A/P A engaged.

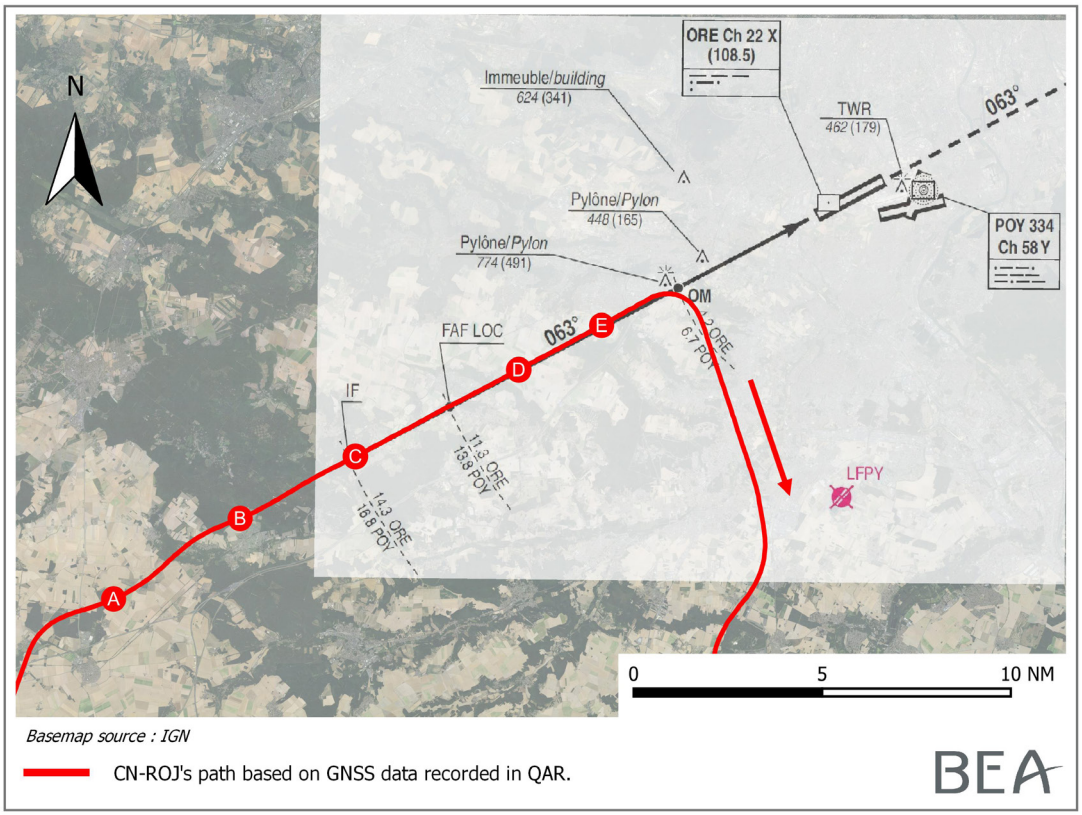


Figure 1: Approach path to Paris-Orly

[8] Guide mode which activates the automatic capture of the LOC and Glide during an ILS approach.

[9] The examinations of the two FCC brought to light that at this point, the disengagement of A/P B was due to the FCC B not receiving RA 2 data.

1.1.2 En route flight between Paris-Orly and Lyon-Saint Exupéry

At 10:31, the crew selected frequency 114.75 MHz, corresponding to the Lyon St Exupéry LSE VOR on the co-pilot's VOR receiver. The VOR remained inactive. The captain then entered "*LSE*" on the FIX INFO page of the CDU in order to check the VOR frequency. The system indicated to him that the "*LSE*" VOR was more than 3,000 NM away[10]

During the descent and the preparation for the ILS 35R approach to Lyon-Saint Exupéry, the crew tried to arm the automatic braking system and observed that the amber *AUTOBRAKE DISARM* light came on. They set the system to OFF as specified by the procedure.

At 10:40:21, the aeroplane was transferred from the Paris En-route control centre to the Marseilles En-route control centre. During the coordination, the Paris controller informed his colleague at Marseilles that flight RAM 780S had had difficulties with landing at Orly and had to carry out a go-around due to fog.

1.1.3 First approach to Lyon-Saint Exupéry

At 10:44:43, the crew were transferred to the Lyon-Saint Exupéry Approach.

At 10:45:40, the Lyon Approach asked flight RAM 780S to descend to FL 90 and then a few minutes later to 3,000 ft and radar vectored the plane to the ILS of runway 35 R.

At 10:58:23, the controller asked flight RAM 780S to turn left heading 020° and cleared the ILS approach to runway 35 R (point **F**).

At 10:58:55, the crew armed the VOR/LOC mode.

At 10:59:20, the VOR/LOC mode engaged (point **G**). Although the crew were expecting a left turn to intercept the Localizer of runway 35R, the aeroplane made a clear right turn, crossed the Localizer path of runway 35 R and then departed to the east. The crew did not carry out any particular action to correct the path following this deviation.

At 10:59:27, the Approach controller asked the crew to reduce their speed to 180 kt and to contact the Lyon-Saint Exupéry Tower controller.

At 10:59:45, the aeroplane entered a left turn, controlled by the A/P. At this point, the aircraft was around 9 NM from threshold 35 R, more than 2.5 dots to the right of the Localizer path, and outbound. At the same time, the crew made contact with the Tower controller.

At 10:59:51, the Approach controller, observing that the aircraft was deviating from the approach path, twice tried to contact flight RAM 780S. The latter was in contact with the Tower controller. The Approach controller asked his assistant to propose to the Tower controller that they take back the aeroplane.

[10] A NOTAM advised that up to 27 April 2017, the Lyon Saint-Exupéry LSE VOR frequency 114.75 MHz was replaced with a temporary VOR named VMP associated with the frequency 117.2 MHz. This NOTAM was present in the "Area En route – Destination – Destination Alternate" part at the end of the flight file and not in the "Destination Alternate" part. This last part comprising NOTAM had not been consulted by the crew before departure.

At 10:59:52, the crew reported that they were on final for runway 35 R. At the same time, A/P A automatically disengaged[11] and the Auto Throttle (A/T) was manually disengaged (point **H**). The aircraft was at 3,000 ft. Six seconds later, the crew informed the controller that they were carrying out a go-around. The Tower controller replied that, "*for me you are not at all on LOC RWY 35R*" but were "*like 1 NM East of the axis*."[12].

A few minutes later, he told the crew that they were now going in the right direction. He specified that the crew could maybe report "*in sight of the field but the weather is not very good. You got overcast 500 ft, report if any visual on the field otherwise we have to make another approach*." The crew asked to make another approach. At 11:00:42, the controller asked them to climb to 5,000 ft and to take heading 360 (point **I**). The crew selected an altitude of 5,000 ft on the MCP as the aeroplane climbed through 4,600 ft.

[11] The examinations of the two FCC found that the disengagement of A/P A at this moment was due to the invalidity of the data supplied by the left ADIRU to FCC A.

[12] The QAR data shows that in reality the aeroplane was 1.6 NM east of the path.

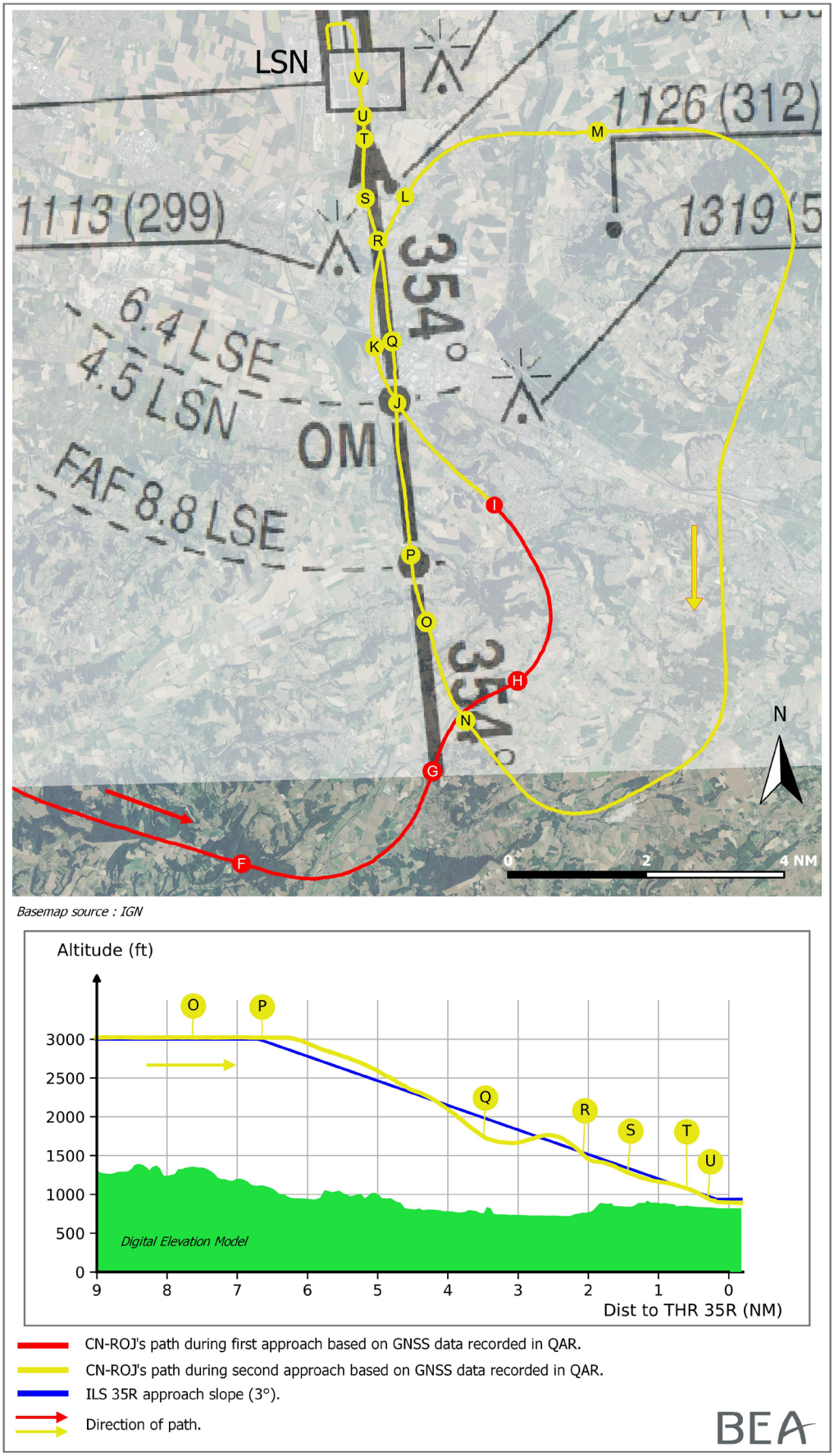


Figure 2: Approach path to Lyon-Saint Exupéry

1.1.4 Second approach to Lyon-Saint Exupéry

At 11:01:17, the aeroplane was transferred to the Approach controller again.

At 11:01:19, the crew engaged A/P B (point **J**). The aeroplane was at this point at an altitude of about 5,650 ft. It stopped climbing and started to redescend to 5,000 ft.

At 11:01:35, the crew contacted the Approach again. At the same moment, the L IRS FAULT warning was activated[13] which caused A/P B to disengage (point **K**), and the disappearance of the F/D bars along with the pitch, roll and heading data from the left PFD. The controller asked the crew to turn right heading 090 for a new vector to ILS 35R. The crew read back.

At 11:01:44, the captain set the IRS Transfer Switch to "*BOTH ON R*"[14]. The L IRS FAULT warning extinguished[15]. The F/D bars reappeared on the left side along with the pitch, roll and heading displays. The aeroplane, in VMC and being manually piloted, started climbing again.

At 11:02:06, the A/T was engaged.

At 11:02:11, A/P B was engaged. The aircraft was at an altitude of around 6,500 ft. The active modes were HDG and MCP SPD. The selected heading was 090°, and the aeroplane redescended to the selected altitude of 5,000 ft (point **L**).

At 11:03:01, the co-pilot asked for an inbound heading, "*Air Maroc 780S, we need an…on demande un cap de rapprochement*" (point **M**). The aircraft was at this point on heading 090° at an altitude of 5,000 ft. The controller asked the crew to turn right heading 180°, and whether they wished to have the shortest approach. The crew did not reply to this question. The controller then gave them the heading 200°.

At 11:03:12, the yaw damper disengaged[16].

At 11:04:20, the control cleared the crew to descend to 3,000 ft, and then asked them to turn left heading 180° "*to intercept correctly*".

The captain indicated that at this point he had transferred control of the aircraft to the co-pilot.

At 11:05:42, the control asked the crew to turn right heading 240°. The captain read back the message.

At 11:06:32, the control asked the crew to turn right heading 320° and cleared the ILS approach to runway 35 R.

At 11:07:30, the crew requested a radar vector. The controller told the crew that they were on the heading to intercept the ILS. The crew indicated that they had positioning problems (point N). The controller replied that they should take heading 355°.

At 11:07:36, at 8 NM from the runway threshold, the crew armed the VOR/LOC mode. Thirty seconds later, the VOR/LOC mode was activated (point **O**). The crew engaged the APP mode three seconds later.

At 11:08:15, the controller asked if the aeroplane had intercepted the Glide signal. The captain replied that they had caught the Localizer signal but had not yet caught the Glide signal.

[13] The amber L IRS FAULT light lit up on the overhead panel along with the Master Caution pushbutton lights and the IRS key on the System Annunciator Panel on the captain's side..

[14] When the switch is set to BOTH ON R, only the data supplied by the right ADIRU is used by the FCC.

[15] The emergency check-list, to be complied with when there is an L IRS FAULT warning, tells the crew that if they want to use the A/P, they must set the IRS Transfer Switch to the remaining ADIRU on the overhead panel and disengage the A/P before the approach phase (see paragraph 1.6.2.2.4).

[16] When only one ADIRU is valid, the yaw damper can only be engaged if the A/P has not been engaged for at least one minute. The yaw damper is automatically disengaged by the plane one minute after the engagement of the A/P (see paragraph 1.6.2.2.2)

At 11:08:28, the G/S mode was engaged. At the same instant, A/P B automatically disengaged[17] (point **P**). At this moment, the pitch and roll F/D bars disappeared from the left and right PFD. On his initiative, the co-pilot transferred aircraft control to the captain.

At 11:08:30, the captain informed the Approach controller that they were continuing the approach in manual control. The controller asked if that meant that they had visual contact; the crew replied in the negative. The captain added that they were continuing in manual and asked in French for the controller to confirm that they were on the correct Glide and LOC. The subsequent exchanges with the Approach controller were in French. The controller replied that he was not able to confirm if the signal captured by the plane was indeed the ILS 35R signal but that given the position of the aircraft on the radar, they should be on the Glide.

At 11:08:36, the crew selected landing gear down.

At 11:08:58, the controller asked the crew if they had sight of the ground, the crew replied in the negative. The controller then asked the crew what were their intentions. The captain replied that they were continuing manually on the Localizer and Glide. At 11:09:09, the Approach controller transferred the flight to the Lyon Tower. The aircraft descended through 2,350 ft.

At 11:09:28, the EGPWS "*Glideslope*" alert was activated in the cockpit when the aeroplane was at an altitude of 1,750 ft (radioaltimeter height of 950 ft) and two dots below the glideslope. One second later, a Minimum Safe Altitude Warning (MSAW) was activated on the Approach controller's radar screen and lasted for about ten seconds (point **Q**). On the activation of this warning, seen by the Approach and Tower controllers, the crew were no longer on the approach frequency and had not yet contacted the Tower.

At 11:09:33, the crew disengaged the A/T.

At 11:09:48, a few seconds after the end of the MSAW, the co-pilot contacted the Tower. The subsequent exchanges were in English up to landing. The Tower controller asked the crew if they had the runway in sight.

At 11:09:56, the crew replied that this was not yet the case. Four seconds later, the EGPWS "*Sink rate*" alert was activated. At this moment, the aeroplane was at an altitude of 1,480 ft (radioaltimeter height of around 710 ft), with an increasing indicated airspeed of 162 kt and a rate of descent of around 2,250 ft/min. It was on heading 345°, at around 2.1 NM from the threshold (point **R**).

At 11:10:02, the co-pilot reported "*We are….we are…..Go around Air Maroc*"[18]. Two seconds later, the EGPWS "*Glideslope*" alert was activated when the aeroplane was at a radioaltimeter height of 560 ft with a deviation of 1.3 dots below the glideslope. The Tower controller told the crew that the runway lights were at their maximum brightness, that they were 2 NM from the threshold of runway 35 R and asked them to call back when they had the runway or runway lights in sight. The aeroplane continued its descent.

[17] The examinations of the two FCC brought to light that at this point, the disengagement of A/P B was due to the FCC B not receiving the RA 2 data.

[18] The playback of the ATC radio recording reveals that from this moment and until landing, there was hesitation and anxiety in the tone of the crew exchanges. The messages themselves were difficult to understand. In particular, the go-around message was not understood by the control.

At 11:10:14, the EGPWS "*Glideslope*" alert was activated again. The aeroplane was at a height of 400 ft and 1.4 dots below the glideslope with an indicated airspeed of 178 kt, between the centrelines of the two runways and at a distance of around 1.4 NM from the threshold of runway 35 R (point **S**). At the same instant, the crew announced that they were continuing the landing and then that they were continuing the manoeuvre. They made a right side-step to align with runway 35 R. They indicated again to the control that they were continuing their manoeuvre (without other information).

At 11:10:20, the EGPWS "*Too low terrain*" alert was activated. The aeroplane was at this point at a height of 240 ft.

At 11:10:29, the controller asked if they had the approach lights in sight. The crew replied in the affirmative. At this moment, the aircraft had just aligned with the centreline of runway 35 R, at around 1,000 m from the threshold and at a height of around 180 ft. The indicated airspeed was 180 kt. Three seconds later, the EGPWS "*Too low terrain*" alert was activated (point **T**).

At 11:10:34, the controller cleared the aeroplane to land. One second later, the EGPWS "*Too low terrain*" alert was activated again. The aeroplane was at this point at a height of about 150 ft.

At 11:10:38, the crew set the flaps to position 40. One second later, the EGPWS "*Sink rate*" alert was activated. The aeroplane was at this point at a height of about 80 ft with a rate of descent of around 1,050 ft/min (point **U**).

At 11:10:40, the aeroplane flew over the runway threshold at a height of around 60 ft. Eight seconds later, it touched down on the runway, around 160 metres after the touchdown zone of runway 35 R at an indicated airspeed of 159 kt (point **V**). The aeroplane vacated the runway at around 900 m from its end.

1.2 Injuries to persons

CN-ROJ	Injuries		
	Fatal	**Serious**	**Minor/None**
Crew	-	-	**6**
Passengers	-	-	**149**
Others	-	-	-

1.3 Damage to aircraft

Not applicable.

1.4 Other damage

Not applicable.

1.5 Personnel information

1.5.1 Flight crew

1.5.1.1 Captain

Age: 47 years

- Class 1 medical certificate dated 25 May 2016 and valid until 31 May 2017.
- Level 5 English language endorsement obtained on 15 December 2011 and valid until 31 December 2017.

ATPL (A)

- Issued on 5 November 2010 by the Moroccan civil aviation authority.

Ratings

- Instrument flight valid until 30 September 2017.
- LVP (CAT II and III approaches) valid until 31 March 2017.
- Type B73C valid until 30 September 2017.

Training courses

- CRM on 29 March 2016 and valid until 31 March 2017.

Checks

- Last base check on 5 September 2016.
- Last line check on 11 October 2016.

Experience

- Total: 14,885 flight hours, including 4,535 hours as captain.
- On B737: 6,641 flight hours, including 4,003 hours as captain.
- In the previous 28 days: 62 hours, 20 landings, 20 take-offs.
- In the previous 7 days: 18 hours, 7 landings, 7 take-offs.

1.5.1.2 Co-pilot

Age: 30 years

- Class 1 medical certificate dated 6 May 2016 and valid until 31 May 2017.
- Level 4 English language endorsement obtained on 16 June 2016 and valid until 30 June 2019.

CPL (A)

- Issued on 28 May 2010 by the Moroccan civil aviation authority.

Ratings

- Instrument flight valid until 30 April 2017.
- LVP (CAT II and III approaches) valid until 30 April 2017.
- B73C valid until 30 April 2017.

Training courses

- CRM on 12 January 2016 and valid until 31 January 2017.

Checks

- Last base check on 5 October 2016.
- Last line check on 8 March 2016.

Experience as co-pilot

- Total: 2,219 flight hours, of which 2,207 flight hours on type and 12 hours on the BBJ.
- In the previous 28 days: 65 hours, 24 landings, 24 take-offs.
- In the previous 7 days: 14 hours, 6 landings, 6 take-offs.

1.5.2 Information on personnel of Lyon-Saint Exupéry air traffic control services

1.5.2.1 LOC controller (Tower controller)

Ratings

- Air traffic controller.
- Senior controller at Lyon control tower since October 2013.

Experience

- Nine years as senior controller at Paris-Charles de Gaulle between 2002 and 2012.
- One year temporary posting with Paris-Charles de Gaulle service quality.

1.5.2.2 LOC assistant

Ratings

- Air traffic controller since 2009.
- Senior controller at Lyon control tower since July 2013.

1.5.2.3 INI controller (Approach controller)

Rating

- Air traffic controller since 1997.
- Senior controller at Lyon control tower since 7 February 2014.

Experience

- Senior controller at Strasbourg Entzheim control tower between 1997 and 2008.
- Air traffic instructor at the French *École Nationale de l'Aviation Civile* between 2008 and 2012.

1.6 Aircraft information

The Boeing 737 is a twin-engine, narrow-body, short to medium-haul airliner designed and built by The Boeing Company since 1967. The 600, 700, 800 and 900 versions are generally called 737-NG (*Next Generation*).

1.6.1 Airframe

Manufacturer	Boeing
Type	737-800-85P
Serial number[19]	SN: 33,979 LN: 1,963
Registration	CN-ROJ
First fight	31 May 2006
Entry into service by operator	31 March 2007
Certificate of Airworthiness	No. 0173 dated 12 June 2006 issued by the *Direction de l'Aéronautique Civile Marocaine*
Airworthiness review certificate	No. 35/16 valid until 8 February 2017
Operation since major inspection	9,308 flight hours and 3,994 flight cycles
Hours logged as on 30 December 2016	35,628 flight hours and 15,223 flight cycles

[19] Each aeroplane built by Boeing has a unique SN while the LN (Line Number) is a SN per type of Boeing plane.

1.6.2 Descriptions of systems

1.6.2.1 Flight Management Computer (FMC)

1.6.2.1.1 General description

CN-ROJ is equipped with a Flight Management Computer (FMC[20]) which uses the flight plan information entered by the crew, the data supplied by the other systems and the information contained in its navigation database to calculate the position of the aeroplane and the pitch, roll and thrust commands required to follow an optimized path. The FMC sends these commands to the Flight Control Computers (FCC).

[20] A system architecture composed of two FMC is proposed as an option on Boeing 737NG.

The crew use the two CDU to interact with the FMC and enter the flight plan data:

Figure 3: Control Display Unit (CDU)

The FMC determines the position of the aeroplane based on the position information sent by the Air Data Inertial Reference Unit (ADIRU), the GNSS receivers and the radio-navigation systems (VOR, DME).

1.6.2.1.2 FMC "IRS-L DRIFT" and "VERIFY POS: IRS-IRS" alert messages

The "*IRS-L DRIFT*" message received by the crew en route to Paris-Orly, indicated that the speed and/or position data supplied by the left ADIRU was not consistent with that supplied by the right ADIRU and that generated from the GNSS positions, the latter two being consistent with each other. In this case, the FMC only uses the data supplied by the right ADIRU.

The "*VERIFY POS: IRS-IRS*" message appeared when the difference between the position supplied by the two ADIRU was more than 10 NM for 40 seconds.

The Flight Crew Operating Manual (FCOM) paragraph 11.60.2 indicates that these messages concern conditions significantly affecting operation of the FMC.

When the activation conditions are encountered:

- the associated alert messages are displayed on each CDU,
- the amber FMC alert light on each side of the instrument panel lights up (see Figure 4), and
- the (white) MSG lights light up on each CDU.

The messages disappear when the crew press the CDU CLR key or the conditions giving rise to the messages are no longer present.

Furthermore, the crew can, at any moment, consult the active messages, i.e. those where the activation conditions are still present, by calling up the MESSAGE RECALL page via the INIT/REF INDEX page.

1.6.2.1.3 FMC/CDU alerting message check-list

This check-list appears in the crew Quick Reference Handbook (QRH) and concerns the FMC "*IRS-L DRIFT*" and "*VERIFY POS: IRS-IRS*" messages.

These two messages refer the crew to the FMC Navigation Check procedure of the FCOM Supplementary Procedure.

It requests that the actual position of the aeroplane is determined and compared with that calculated by the FMC. To determine the actual position of the plane, the procedure recommends using radio-navigation aids such as the VOR/ADF, ground reference points and radar data available to air traffic controllers. The procedure also provides instructions to compare the FMC position with the IRS positions and shift the FMC position to one of the IRS positions for cases where radio navaids are unavailable.

The "*IRS-L DRIFT*" alert message did not exist in the operational documents available to the crew. This message was entered in the FMC version U11 installed on the plane in March 2016.

The updates of the operational documents supplied by Boeing are published every six months. When a company complies with a Service Bulletin (SB) which involves modifications in the operational documents (as is the case with version U11 of the FMC), it must notify Boeing of this via the MyBoeingFleet website. Boeing can then prepare the update of the company's operational documents which are supplied at the next scheduled publication date.

Boeing was informed on the MyBoeingFleet website of the completion of the installation of version U11 of the FMC on RAM's B 737 fleet in October 2017. It did not find any other notification from the operator. This is why RAM's operational documents were not updated or supplied and why those available to the crew on the day of the serious incident did not contain any reference to the "*IRS-L DRIFT*" alert message.

Only the "*VERIFY POS: IRS-IRS*" alert message (entered in version U10.7 of the FMC) was present in the FCOM list, in the "*Systems Description*" section (paragraph 11.60.13).

See Appendix 5: FMC Navigation Check procedure.

Figure 4: “FMC Push to Reset" light linked to FMC messages

1.6.2.2 Air Data Inertial Reference Units (ADIRU)

1.6.2.2.1 General description

The Boeing 737-800 is equipped with two ADIRU (left and right). The ADIRU supply other aeroplane systems with inertial data and air data.

Each ADIRU is comprised of two sub-assemblies:

- ❒ a sub-assembly which generates the inertial reference data: IR (Inertial Reference);
- ❒ a sub-assembly which generates the air data: ADR (Air Data Reference).

1.6.2.2.2 IR sub-assembly

The IR sub-assembly is composed of three Ring laser Gyros (RG) and three linear accelerometers oriented along the three axes of the aeroplane’s reference frame.

The data supplied by the IR sub-assembly of an ADIRU unit, to the other aircraft systems, includes:

- ❒ pitch, roll and yaw angles;
- ❒ latitude and longitude;
- ❒ magnetic heading and true heading;
- ❒ linear accelerations;
- ❒ angular velocities;
- ❒ ground speed;
- ❒ vertical speed;
- ❒ path angle.

This data is notably used by:

- ❒ the two Display Electronics Units (DEU) to display the flight data on the EFIS screens, in particular the attitudes and heading;
- ❒ the two FCC to calculate the A/P and F/D commands;
- ❒ the FMC to calculate the position;
- ❒ the automatic braking system.

1.6.2.2.3 IRS FAULT warning

An ADIRU inertial critical fault is a fault which affects the primary inertial functions such as the attitudes, heading, angular velocities or accelerations.

When such a fault is detected by the ADIRU built-in test, the IRS FAULT light associated with the faulty ADIRU, situated on the overhead panel, lights up along with the Master Caution lights on the instrument panel and the IRS light on the annunciator, on the left side (see Figure 5 and Figure 6). The Master Caution lights remain lit until a pilot presses one of them or until the conditions for their extinction are met. Furthermore, all the data supplied by an IR sub-assembly with a critical fault is declared invalid and will therefore no longer be used by the other systems.

During the occurrence flight, the IRS FAULT warning was triggered by the left ADIRU "Drift Angle" monitoring function which is activated when the difference between the true track and the true heading is more than 60° and the ground speed is more than 200 kt.

1.6.2.2.4 IRS FAULT check-list

The QRH on board the aeroplane included the *IRS FAULT* emergency check-list.

The check-list provides for two cases:

- If the use of the A/P is desired for the rest of the flight:

  The procedure consists of, notably, setting the IRS TRANSFER SWITCH to BOTH ON R (in case of a fault on the left IRS) which permits recovery of the full display of the two PFD, by using the functional IRS unit (right IRS) as a shared altitude source.

  The check-list indicates that the A/P will be operational on the side of the functional IRS (A/P B, right side) except during the approach when the use of the A/P is not authorized.

- If the use of the A/P is not desired for the rest of the flight:

  The procedure proposes when straight, level and stable flight is possible for a least 30 seconds, restoring the *"Attitude"* part of the ADIRU concerned (ADIRU L) by setting the IRS MODE (L) selector to ATT.

  If the FAULT light extinguishes on the IRS in question, the "*Attitude*" function of the ADIRU is recoverable by selecting HDG/STS on the overhead panel and by periodically entering the plane's magnetic heading via this function. Source redundancy is maintained, each PFD using the attitude source from the corresponding IRS unit.

  In this case, neither of the two A/P can be engaged for the rest of the flight (item 12 of check-list).

  On completion of the check-list, the differed items are displayed and are to be carried out later during the corresponding flight phases.

  In particular, a list of deferred items is to be carried out prior to the start of the approach. In addition to the normal actions, the crew must disengage the A/P and A/T (if it is engaged) before the approach and set the "*Yaw Damper*" switch to ON.

See Appendix 3: "*IRS FAULT*" check-list.

Figure 5: “Master Caution Push to Reset” light and annunciator with IRS light on left instrument panel

Figure 6: IRS FAULT light on IRS Mode Selector Unit on overhead panel

1.6.2.3 Flight Control Computers (FCC)

1.6.2.3.1 General description

The Boeing 737-800 is equipped with two flight control computers: FCC A and FCC B. They carry out the A/P functions (A/P A and A/P B respectively) and the flight director (F/D) functions, displayed on the left PFD and right PFD respectively.

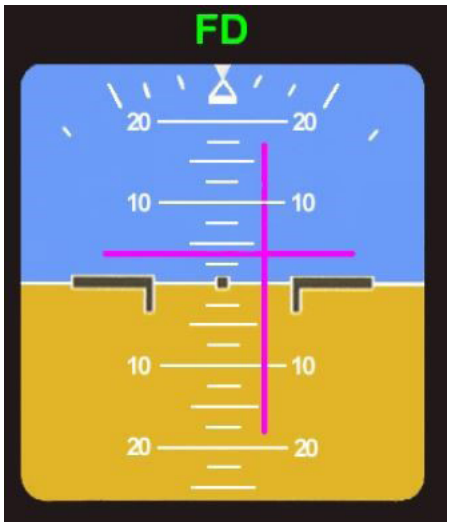


Figure 7: Magenta flight director command bars

For the A/P functions, each FCC sends the commands which it has generated to its hydraulic actuators on the pitch and roll axes which move the control surfaces by means of two hydraulic systems.

In order to carry out the A/P and F/D functions, the FCC acquire the necessary data from the various computers, in particular the ADIRU, the VHF NAV (VOR and ILS) receivers and the radio-altimeters.

1.6.2.3.2 FCC – ADIRU interface

To generate the A/P and F/D commands, each FCC uses amongst other data, data supplied by the ADIRU. This data is used notably for vectoring during an ILS approach.

This data is declared valid or invalid by the ADIRU. In accordance with its specifications, the FCC does not check the validity of the data from an ADIRU except for approaches with the two A/P engaged.

The position of the "*IRS Transfer Switch*" (on the overhead panel) determines the source of the inertial data (left or right ADIRU) used by the FCC. The following table illustrates the different configurations which can exist:

"IRS Transfer Switch" position	A/P A (pitch and yaw command)	A/P A (roll command)	A/P B (pitch and yaw command)	A/P B (roll command)	F/D A	F/D B
NORMAL	left	right	right	left	left	right
BOTH ON L	left	left	left	left	left	left
BOTH ON R	right	right	right	right	right	right

As can be seen in the table above, in normal operation, the FCC use, to generate the A/P commands, inertial data from the ADIRU on both the same side and the opposite side. In the lateral plane, this is notably the roll angle and the roll rate. For the other lateral navigation data, such as the ground track and heading for example, the FCC use data from the ADIRU on the same side.

An ADIRU malfunction with only one A/P engaged gives rise to two cases (the second can evolve into the first):

- Either the ADIRU detects the malfunction and transmits information about the erroneous parameter(s) to the FCC. These parameters will then no longer be used by the FCC. This is the case for example, when the IRS FAULT warning is activated.
- Or the ADIRU does not detect the malfunction and the FCC continue to use all the parameters transmitted, with the possibility that some of these are erroneous.

1.6.2.3.3 FCC – VHF NAV (VOR and ILS) receiver interface

The operating logic of the FCC-VHF NAV receiver link is described in the FCOM (in VOR/LOC mode or in APP mode):

- A/P A and the F/D on the left side use the radio-navigation signals supplied by the VOR 1 receiver, and the LOC and GLIDE signals provided by Multi-Mode Receiver (MMR) 1.
- A/P B and the F/D on the right side use the radio-navigation signals supplied by the VOR 2 receiver, and the LOC and GLIDE signals provided by MMR 2.

Only one VOR or ILS frequency, selected using one of the VHF/NAV control panels, is required to arm and engage the VOR/LOC mode or the APP mode. However, to engage the two A/P in APP mode, the same ILS frequency must be selected on both VHF/NAV control panels.

Different frequencies displayed on the two VHF/NAV control panels may lead to a difference in the left and right F/D display and affect the operations of the engaged A/P.

Displaying a VOR frequency on one of the VHF/NAV control panels prevents the engagement of the two A/P which is necessary for CAT III approaches.

1.6.2.3.4 FCC – radio altimeter interface

The Boeing 737-800 is equipped with two independent radio altimeters (RA 1 and RA 2) which supply the radio altitude to their associated FCC. The data from RA 1 is supplied to FCC A and the data from RA 2 is supplied to FCC B. This data is used notably for vectoring during an ILS approach.

If an FCC does not receive radio-altitude data due to a RA malfunction or a communication problem between the FCC and the radio altimeter, the associated A/P will disengage after the capture of the LOC and Glide. This malfunction will also result in the loss of the F/D associated with the faulty radio altimeter.

1.6.2.4 Automatic braking system

1.6.2.4.1 General description

On landing, the automatic braking system is used to automatically reach a deceleration value preselected by the crew. Braking starts immediately after touchdown.

1.6.2.4.2 AUTOBRAKE DISARM warning

When the crew select an automatic braking level for landing, the system carries out a self-test. This consists in checking the validity of a certain number of aeroplane parameters, including the following inertial parameters supplied by the left ADIRU: attitude, longitudinal acceleration and ground speed.

If the self-test detects invalid parameters, then the automatic braking system does not arm and the amber AUTO BRAKE DISARM light situated above the braking level selector illuminates.

The right ADIRU data is only used to carry out two functions on the inner wheel of the right landing gear and its validity is not necessary to arm and activate the automatic braking system.

1.6.2.4.3 AUTOBRAKE DISARM check-list

If the warning occurs in flight, the QRH indicates that the crew must set the AUTOBRAKE selector to OFF and then select the desired braking level again. If the warning light extinguishes, the problem is resolved. In the opposite case, the check-list indicates that the AUTOBRAKE selector must be set to OFF and to use manual braking for landing.

Figure 8: Amber *AUTOBRAKE DISARM* light

1.6.2.5 Enhanced Ground Proximity Warning System (EGPWS)

1.6.2.5.1 General description

The EGPWS is a system which provides visual and voice alerts in potentially dangerous flight conditions which could result in a collision with the ground.

Two types of alert are generated by the EGPWS:

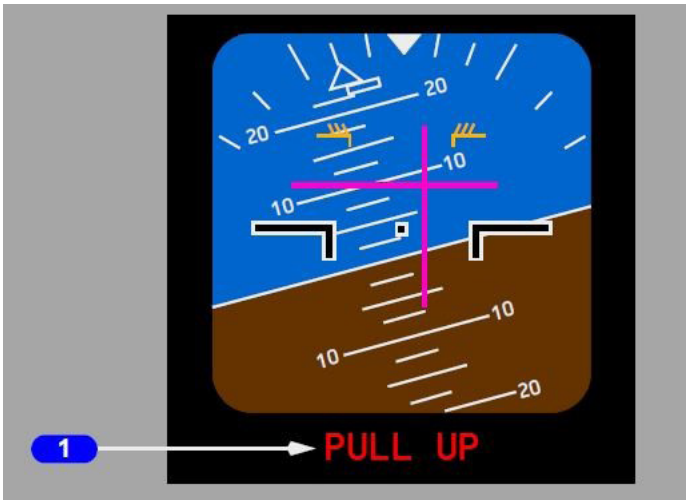
- Reactive alerts based on the value or the evolution of the radio altitude according to other parameters such as altitude, airspeed, deviations from the glideslope or the configuration of the aeroplane.
- Predictive alerts based on the knowledge of the terrain in the vicinity of the aeroplane's position. The terrain data is entered in a worldwide terrain database.

1.6.2.5.2 EGPWS GLIDESLOPE, SINK RATE and TOO LOW TERRAIN alert messages

The "*GLIDESLOPE*" aural alert is a reactive alert generated when the aeroplane is below the ILS glideslope by a certain threshold. It is accompanied by the illumination of two BELOW GLIDESLOPE P-INHIBIT lights situated on the left and right instrument panels (above the PFD and above the ND respectively).

The "*SINK RATE*" aural alert is a reactive alert generated when the plane's rate of descent becomes excessive. It is accompanied by the display of the PULL UP message in the centre (attitude indicator) of the two PFD.

The "*TOO LOW TERRAIN*" aural alert emitted during this occurrence was a predictive alert generated when the height of the aeroplane was too low with respect to the remaining distance to an aerodrome. It is accompanied by the display of the PULL UP message in the centre (attitude indicator) of the two PFD.



Source: operator's FCOM 737-800. Copyright © Boeing. Used with permission.

Figure 9: Display of PULL UP message on PFD on activation of the SINK RATE and TOO LOW TERRAIN alerts

1.6.2.5.3 EGPWS GLIDESLOPE/SINK RATE/TOO LOW TERRAIN check-list

For these alerts, the procedure in the Policy Manual, paragraph 8.3.5.2 as well as in the QRH, Maneuvers-Non Normal Maneuvers - MAN 1.5, asks the crew to correct the aeroplane's path, configuration or speed.

1.6.3 Maintenance operations

1.6.3.1 Preventive maintenance operations

Daily and weekly checks permit preventive maintenance tasks to be carried out and problems reported by crews after a flight to be corrected.

Type-A checks, divided into 8 sub-checks (A01 to A08) take place every 650 flight hours. Type-C checks, divided into 21 sub-checks (C01 to C21) take place every 5,000 flight hours or no later than every 18 months.

The type of tasks to be carried out for each check is determined by the Royal Air Maroc fleet management department in accordance with the fixed intervals in the AMP[21].

1.6.3.2 Last preventive maintenance operations

The last type-C check was C09. It took place on 10 June 2016 at Casablanca Mohammed V airport (Morocco), at 33,590 flight hours. The previous type-C check (C08) was carried out on 18 May 2015 at Bacau Georges-Enesco airport (Romania) at 30,182 flight hours.

The last type-A check was carried out on 14 December 2016 (A05) at Casablanca Mohammed V airport at 35,427 flight hours.

1.6.3.3 Maintenance actions carried out on plane before departure

The investigation team's examination of the aeroplane's maintenance and maintenance program documents found that:

- The right ADIRU was installed during C09 in June 2016, the previous one having been removed during this maintenance operation to repair another aeroplane.
- The left ADIRU was installed on 14 December 2016 following a "*Left IRS INOP*" message reported by the crew the same day in the Technical Log Book.
- FCC A was the original one, installed since May 2006.
- FCC B was installed during C09 in June 2016.

Between 1 December 2016 and the day of the occurrence, the crews and the maintenance personnel had indicated items linked to the automated systems and the Air Data Inertial Reference System (ADIRS) in the TLB[22]:

- On 10 December 2016, during a CAT III approach, the two A/P disconnected at 30 ft from the ground at the beginning of the flare. Maintenance personnel carried out the DFCS[23] Built-In Test Equipment (BITE) procedure and replaced RA 2 following a crew report in the TLB indicating that the RA amber flag[24] had appeared on the right PFD when the A/P disengaged.
- On 12 December 2016, A/P B disengaged on capturing the Glide Slope and the crew were unable to re-engage it. The DFCS BITE was carried out and no fault was reported by maintenance. A DFCS self-test was successfully carried out.

[21] AMP: The Aircraft Maintenance Program was drawn up to give a coordinated view of all the maintenance tasks to be regularly carried out on the systems, structure or engines in order to detect or forestall any fault which might affect the airworthiness of the plane.

[22] The Technical Log Book is used by the crew to report events/anomalies and by maintenance to record the corresponding actions carried out.

[23] Digital Flight Control System: this system principally encompasses the autopilot and flight director functions. The DFCS BITE is the entry point in case of problems linked to the automated systems. It is used to display the faults concerning this system, encountered during flights or currently detectable on the ground.

[24] The RA amber flag is displayed in place of the radio altitude values when a problem prevents them from being displayed.

- On 14 December 2016, the left ADIRU was declared inoperative and was replaced by maintenance; the replacement ADIRU had previously been installed on CN-ROZ from 20 June 2016 to 1 September 2016. It had been removed following a fault and two gyrometers had been replaced.
- On 25 December 2016, A/P B and the right F/D disengaged in approach mode (APP). The DFCS BITE was carried out and no fault was reported by maintenance.
- On 26 December 2016, the *AUTOBRAKE DISARM* light illuminated just after take-off. Later, during the approach with A/P A engaged, the left F/D gave erroneous indications after the approach mode (APP) had been engaged. The aeroplane of its own accord, banked right by 20°.
  FIM 32- 42 task 828 *AUTOBRAKE DISARM* Lights is ON was complied with and no fault was detected. The DFCS BITE was also carried out and no fault was reported. The F/D and MMR/ILS tests were successfully carried out. MMR 1 and 2 were swapped over by maintenance[25].

[25] As part of the search for an intermittent fault.

The left ADIRU, removed on 14 December 2016, was examined by KLM Engineering & Maintenance. The examination found traces of an unknown liquid on the computer electronic boards.

No other report was made until the day of the occurrence.

On 30 December 2016, the aeroplane took off from Rabat-Salé without any deferred maintenance actions.

1.6.3.4 Line maintenance à LYS

1.6.3.4.1 Role of Maintenance Control Centre (MCC)

The role of the RAM Maintenance Control Centre (MCC) is described in the RAM documents and in particular, in the line maintenance manual. The subcontractor, a Part 145 approved organization, was responsible for returning the aeroplane to service in accordance with the Part 145 regulations.

The MCC transmitted the technical documents beforehand to the various subcontractors. A copy of these documents, on a CD, was on board all the RAM aeroplanes. An excerpt could be provided by email at the subcontractor's request.

The MCC also provided document and logistic support if required. If a technician had difficulty accessing a given maintenance procedure, the MCC could send it to him or, if spare parts were required, the MCC could coordinate these being sent to the line station in question. The MCC also had knowledge of the history of the faults on the aeroplane; it could thus direct the line maintenance technician towards suitable maintenance actions.

1.6.3.4.2 Role and actions of line maintenance technician

Following the occurrence flight, line maintenance was carried out by a maintenance technician employed by Aviacare, situated on LYS airport. Aviacare held Part 145 approval and was under contract with RAM.

The technician held a Part 66 B1 licence for turbine-powered planes and various ratings including the B1.1 type rating for the *Boeing 737-600/700/800/900 (CFM56 engines)* dated 12 November 2009.

A Part 66 licence allows the holder to issue an Approval for Release to Service (APRS) after the maintenance work according to the scope of his licence. Holding a B1 licence, the technician was authorized to carry out maintenance work on the structure, engines and mechanical and electrical systems of the aircraft, along with work on the avionics systems only requiring simple tests to demonstrate their correct operation and not requiring troubleshooting.

In the event of a technical incident and it being necessary to troubleshoot at the line station, the line technician must isolate the fault in compliance with the technical documents and approved maintenance procedures provided by the company.

Information about the operations carried out was collected by means of the TLB and interviews with the captain and technician who had been responsible for CN-ROJ and signed the APRS.

In the section of the TLB dedicated to crew reports, the captain had recorded the IRS problem encountered in flight: "*L IRS FAULT*". In the associated section dedicated to the maintenance actions, the technician had recorded that the operational test had been carried out according to the manufacturer's maintenance documentation (reference AMM 34- 21-00/501 ISS 61) and had revealed no fault. The status was indicated as "*F*" (fixed) and the APRS was signed.

1.6.3.5 Boeing ADIRS fault isolation procedure

The applicable Boeing documents for troubleshooting is the Fault Isolation Manual (FIM). Section 34- 21 is dedicated to the ADIRS.

Following a crew report, maintenance personnel must search in the Observed Fault List for the fault isolation procedure to be carried out.

Task 836 must be carried out for the FMC "*VERIFY POS: IRS-IRS*" alert message.

Task 803 must be carried out for an *L IRS FAULT*.

1.6.3.5.1 Fault Isolation FIM 34-21 task 836 - VERIFY POSITION shows on the CDU, and POS SHIFT page shows large ADIRU drift[26].

This task requires two tasks from the Aircraft Maintenance Manual (AMM) to be carried out, the first being the check for IR radial positioning errors and the second being the check for residual ground speed errors.

If the radial positioning or residual ground speed errors are greater than the thresholds defined in the procedure, the ADIRU has to be replaced. This is the case for example, if the residual ground speed error is more than 21 kt at the end of a flight.

Thus, a pilot reporting the FMC "*VERIFY POS: IRS-IRS*" message could lead to the incriminated ADIRU being replaced.

1.6.3.5.2 Fault Isolation FIM 34-21 task 803 - IR Failure procedure

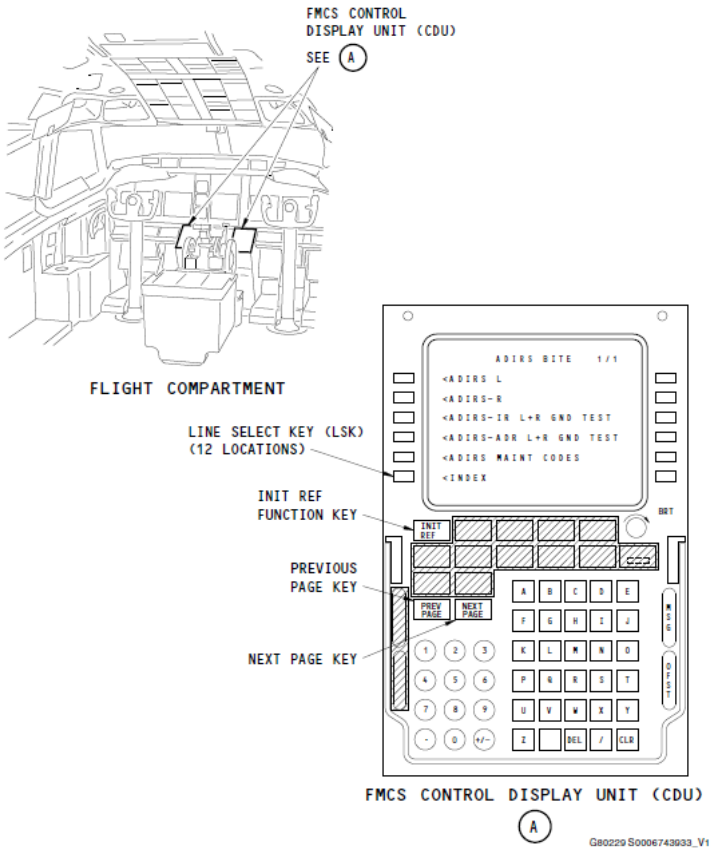
This procedure starts with the initial evaluation of the fault and the possible resolution of the problem without replacing the ADIRU. The maintenance technician must first check that the fault is still current by complying with the ADIRS BITE procedure corresponding to FIM 34-21 task 801 described in paragraph 1.6.3.5.3:

[26] Title of procedure linked to "*VERIFY POS: IRS-IRS*" messages.

- If the *IR Failure* message is not displayed on the CDU, then the fault is not current. The FIM indicates that in this case it is an intermittent fault and the task is finished.
- If the *IR Failure* message is displayed on the CDU, then the fault is current. The procedure indicates that the maintenance technician must first check if there are other current ADIRS faults and resolve them, as applicable, by complying with the associated FIM tasks. On completion, if the IR Failure message is no longer displayed on the CDU, then the fault has been corrected. Otherwise, the ADIRU must be replaced.

1.6.3.5.3 FIM 34-21 task 801 ADIRS BITE procedure

This procedure is used to display the recorded fault messages and their identification code on the CDU, for each ADIRU. To obtain the left ADIRU fault messages, the ADIRS-L sub-menu must be called up from the ADIRS BITE menu.



ADIRS BITE Main Menu
Figure 201/34-21-00-990-803

Figure 10: Main menu of ADIRS BITE test - excerpt from Boeing documentation

The faults are recorded in two different sections, the current faults at the time of the maintenance task are in the *CURRENT STATUS* section and the faults detected during previous flights are in the *INFLIGHT FAULTS* section.

The procedure tells the maintenance technician to first look in the CURRENT STATUS section in order to identify possible current faults and to comply with the associated fault isolation procedures. If no fault is found, the technician must then refer to the second section, INFLIGHT FAULTS, in order to obtain the fault message recorded during the flight in which the fault occurred. The procedure tells the technician to comply with the FIM task associated with the fault message.

When the IR Fault is current, the *IR Failure* message will appear both in the CURRENT STATUS section and in the INFLIGHT FAULTS section.

1.6.3.6 Boeing automated systems fault isolation procedure

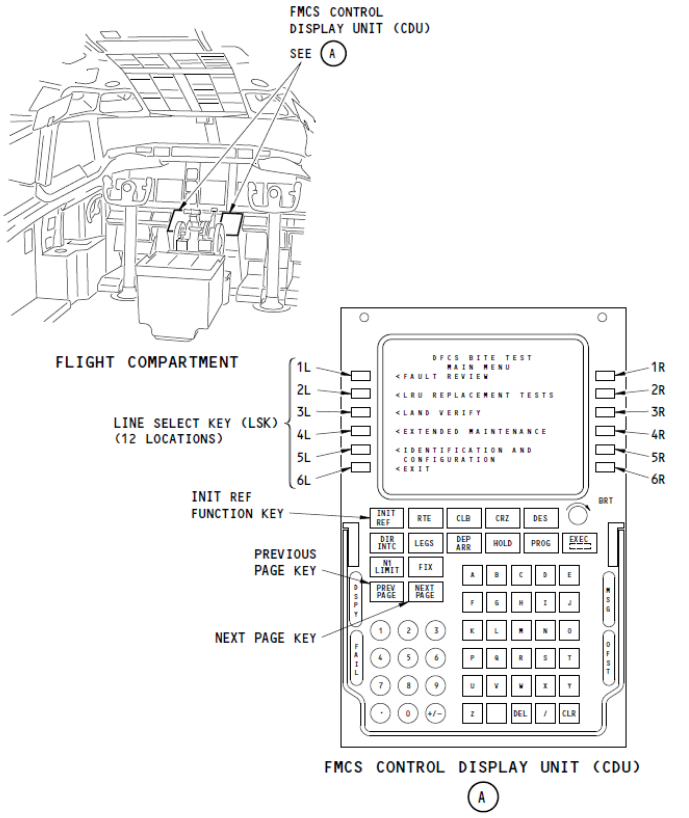
In the month prior to the occurrence and after the occurrence, there were several reports in the TLB of problems crews had encountered with the use of the automated systems (in particular the A/P and F/D). To resolve these problems, the maintenance personnel indicated that they carried out the DFCS BITE procedure each time. This operation corresponds to task 801 of FIM 22-11. It permits the maintenance technician to access the history of the recorded faults and current faults in connection with the automated systems, at the time of the task.

The current faults are displayed in the *CURRENT STATUS* section. The history of the recorded faults are in the *FAULT HISTORY SORTED BY FLIGHT LEG* section and the *FAULT HISTORY SORTED BY FLIGHT DECK EFFECT* section[(27)].

[(27)] Faults recorded in fault history sorted by flight or by flight deck effect.

The normal sequence of this procedure starts with a review of these latter.

- If faults are recorded, the maintenance technician must identify the incriminated Line Replaceable Unit (LRU) (e.g. FCC, MMR, RA). The technician is then invited to carry out the associated LRU test.
  - If the *TEST PASSED* message is displayed on the CDU, the Boeing procedure indicates that the DFCS BITE has not found any problem with the incriminated LRU. This fault may be either an intermittent fault or a fault which only appears in flight conditions. The procedure indicates that it is possible to carry out the BITE procedure of other systems (such as the FMC or A/T for example) or to carry out a self-test of an LRU which has a fault in the fault history.
  - If the *TEST FAILED* message is displayed on the CDU, then the maintenance technician must comply with the tasks associated with the fault message which appeared during the test in order to correct it. The procedure includes the exhaustive list of fault messages potentially recorded and their associated task.
- If no fault is recorded in the history, the technician must then query the system about current faults. In the CURRENT STATUS menu, the DFCS self-test (*Current Status Quick Test*) is automatically carried out first. Then applicable additional tests must be carried out, selected from the five proposed (Current Status Additional Test): AUTOPILOT, FLIGHT DIRECTOR, MACH TRIM SYSTEM, SPEED TRIM SYSTEM and ALT ALERT. The additional tests are tests which are not automatically carried out.



DFCS BITE Test Main Menu
Figure 202/22-11-00-990-804

Figure 11: Main menu of DFCS BITE test - excerpt from Boeing documentation

1.7 Meteorological information

1.7.1 General situation

Anticyclonic conditions covered all of the French territory. These conditions led to the formation of low stratus cloud, mist and fog in several French regions, notably Paris and Lyon. The blankets of mist and fog had difficulty in dissipating due to the high pressures and the average wind which remained light. The low level SIGWX chart, valid at 09:00, showed for the area extending from Paris to Lyon, a stratus cloud layer of 5 to 8 octas with a base situated between the ground and an altitude of 300 ft and the top at 1,000 ft, horizontal visibility between 0 and 5 km, and mist or fog, probably freezing (iso 0°C on ground).

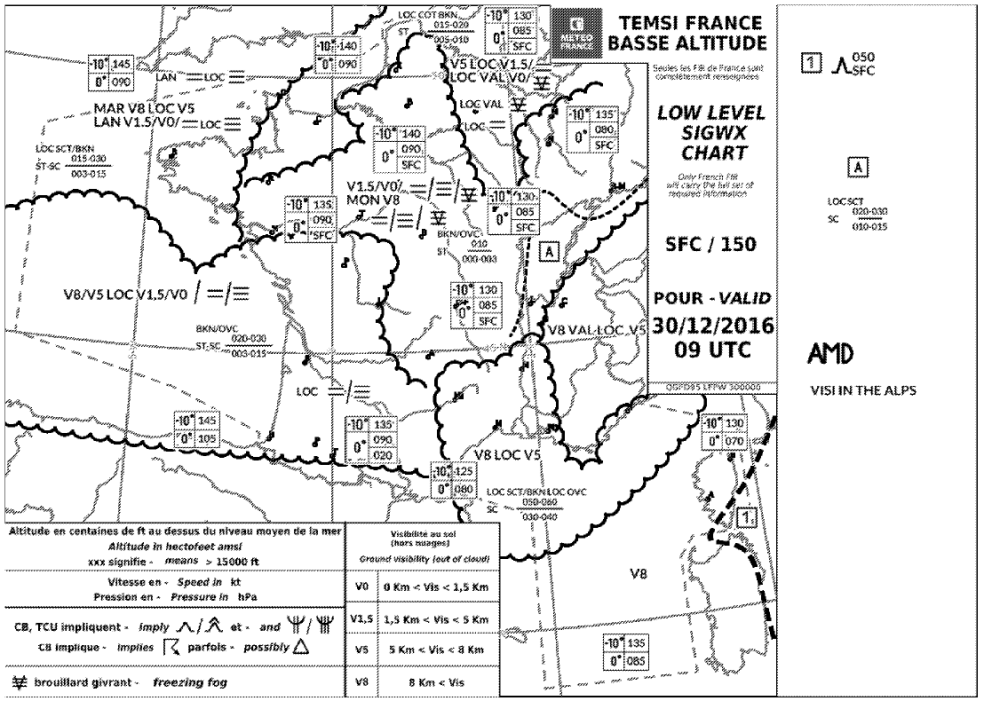


Figure 12: Low level SIGWX chart valid at 09:00 on 30 December 2016

1.7.2 Information received by crew

1.7.2.1 Flight file

The flight file containing the meteorological information received by the crew was prepared on 29 December, around 22:00. The weather part of this file contained:

- ❒ All the meteorological reports and forecasts available when the flight was prepared for the destination and alternate airports. In particular, the forecasts indicated:
  - ■ At Paris-Orly: horizontal visibility of 300 m with freezing fog and sky obscured up to 09:00; an improvement was forecast from 11:00 with visibility reaching 8 km and the sky clearing.
  - ■ At Lyon: horizontal visibility of 600 m with freezing fog and sky obscured up to 10:00; an improvement in visibility to 6 km was forecast from 11:00 with a ceiling at 600 ft.
  - ■ At Nantes: horizontal visibility of 1,400 m with mist, and cloud of 5 to 7 octas at 600 ft up to 06:00, an improvement in visibility to 6 km was forecast from 10:00.
- ❒ WINTEM and SIGWX charts (Europe and world) concerning the levels above FL 100, available when the flight was prepared and valid for the duration of the flight.
- ❒ Cross section of wind profile on the route.
- ❒ Two infra-red satellite photos dated 29 December at 21:30 indicating the cloud top temperature.

1.7.2.2 Information received during flight

The crew indicated that during the flight they had obtained information about the meteorological conditions at the alternate airports along the route and at the destination alternate airport (refer to paragraph 1.18).

1.7.3 Meteorological conditions at destination and alternate airports

1.7.3.1 Meteorological situation at Paris-Orly (destination)

Fog had formed the previous evening (29 December) due to an area of very high pressure at the surface (around 1038 hPa), light wind and high humidity on the ground and became freezing fog from 01:30 due to negative temperatures.

In particular, the TAF issued at 05:00, and valid from 06:00 on 30 December to 12:00 on 31 December, forecast horizontal visibility of 600 m with fog and an overcast cloud layer at 100 ft and temporarily between 06:00 and 10:00, visibility of 100 m with freezing fog and sky obscured, evolving between 10:00 and 13:00 to visibility of 4,000 m with mist. However, this forecast had been amended at 10:03 due to the persistence of the freezing fog and sky obscured with horizontal visibility of 100 m, the favourable evolution in visibility being forecast from 12:00.

Aerodrome routine meteorological reports (METAR) issued between 09:00 and 10:30 indicated variable wind between 2 and 3 kt, freezing fog with sky obscured, horizontal visibility fluctuating between 150 m and 200 m, RVR at the threshold of runway 06 fluctuating between 400 and 450 m without any significant evolution and temporarily, visibility of 100 m.

During the approach, the air temperature was -2°C, close to the dew point temperature which was -3°C, the wind was calm and the sky obscured. Horizontal visibility was 200 m at 10:00 and 250 m at 10:30.

1.7.3.2 Meteorological situation at Lyon-Saint Exupéry (Paris-Orly alternate airport)

The TAF issued at 05:00, and valid from 06:00 on 30 December to 12:00 on 31 December, indicated visibility of 3 km, with mist and an overcast cloud layer at 100 ft, with a 40% probability of having temporarily, between 06:00 and 09:00 on 30 December, visibility decreasing to 600 m with freezing fog and sky obscured, then improving between 09:00 and 12:00, with horizontal visibility increasing up to 6 km and a cloud ceiling of 5 to 7 octas at 600 ft.

The METAR issued between 07:00 and 10:00 indicated visibility between 2 and 3 km, 800 m to the south with fog banks and an overcast cloud ceiling between 100 and 400 ft. The reported RVR for runway 35R were 900 m at 06:30, gradually evolving up to 2,000 m at 08:30.

The ATIS information (information Kilo recorded at 10:16, obtained by the crew before their first radio contact with Lyon Approach) indicated wind calm, visibility 3,000 m, mist, OVC 400 ft, temperature 0°C, dew point -1°C, QNH 1038 hPa.

The 11:00 METAR (at the time of the second approach) indicated: wind variable at 2 kt, mist, visibility 4,000 m, OVC 500 ft, temperature 0°C, dew point -1°C, QNH 1038 hPa.

1.7.3.3 Meteorological situation at airports accessible from Lyon (Grenoble, Marseilles)

1.7.3.3.1 Meteorological situation at Grenoble Isère

10:30 automated METAR: wind 120°/05 kt CAVOK temperature 4°C QNH 1037 NOSIG.

11:00 automated METAR: wind variable/03 kt visibility 9,000 m temperature 02°C QNH 1036 NOSIG.

11:30 automated METAR: wind 070°/04 kt CAVOK temperature 02°C QNH 1036 NOSIG.

1.7.3.3.2 Meteorological situation at Marseille Provence

The METAR issued between 10:30 and 12:00 indicated wind 340°/6 kt, CAVOK, QNH 1037 hPa.

1.8 Aids to navigation

- "OL" (Orly) VOR/DME:

A NOTAM in the flight file specified that the "OL" VOR/DME, frequency 111.200 Mhz, was being tested and should not be used because of possible false indications.

This VOR was not selected by the crew during the approach.

- "LSE" (Lyon St-Exupéry) VOR/DME:

The day of the occurrence, as part of the renewal of the "LSE" (Lyon-Saint Exupéry) VOR/DME, the latter had been replaced by the temporary "VMP" VOR/DME.

The crew set the VOR receivers to the LSE VOR/DME (114.75) frequency, instead of the temporary "VMP" VOR/DME frequency, at 10:31 and kept this frequency up until the end of the flight.

The LSE VOR had the following characteristics:

- Frequency: 114.75 Mhz / 094 Y
- Coordinates: 45°44'43.90"N 005°05'26.10"E

The temporary mobile VMP VOR which replaced LSE emitted on frequency 117.2 and was placed close to the deactivated LSE VOR/DME.

In this context, the paths of the various instrument flight procedures remained the same.

This information and the changes relating to the aeronautical information were available in the supplement AIP 219/16.

In addition, the period in which the LSE VOR/DME was not available and the entry into service of the VMP VOR/DME were indicated by NOTAM. This NOTAM was in the crew's flight file, in the "destination alternate(s)" en-route part and was not consulted (see paragraph 1.18).

No malfunction of the other radio-navigation ground systems associated with the approach procedures (see paragraph 1.10) was reported the day of the occurrence.

1.9 Communications

From the request to abort the approach to Paris-Orly, up to the landing at Lyon, the crew were successively in contact with the following control units:

- Orly Tower;
- Orly Approach;
- Paris En route control centre;
- Marseilles En route control centre;
- Lyon Approach;
- Lyon Tower.

See transcript of the radiotelephone exchanges in appendix 1.

1.10 Aerodrome information

1.10.1 Paris-Orly airport

Paris-Orly airport is a civil, controlled aerodrome open to public air traffic. It has three runways.

The day of the occurrence, runway 06 was in use for landings. This runway permits CAT I, II and III ILS approaches to be carried out.

The initial segment for an approach to 06 starts at ODILO, where the approach procedures and the holding racetrack terminate. At this point, except if the aeroplane has been vectored beforehand, the aircraft starts its approach at FL 100 and then descends to 4,000 ft on heading 035° for 24.3 NM before intercepting the final approach path.

The ILS procedure approach path is at 063°. In the event of a missed approach, the published instructions are to continue straight ahead climbing to 2,000 ft and to anticipate radar vectors from the ATC services.

For these procedures, the published minima for a Boeing 737 (category C) are the following:

Approach	Altitude (Height) of DA or MDA (ft)	RVR (m)
CAT I ILS	490 (200)	550
LOC	700 (440)	1,300

1.10.2 Lyon-Saint Exupéry airport

Lyon-Saint Exupéry airport is a civil, controlled aerodrome open to public air traffic. It has two parallel runways whose centrelines are at a distance of 350 m.

The day of the occurrence, runway 35R was in use for landings. This runway permits CAT I, II and III ILS approaches to be carried out.

The initial segment for an approach to 35L or 35R starts at TALAR. At this point, except if the aeroplane has been vectored beforehand, the aircraft starts its approach on heading 153° up to the VNE VOR where it turns to 101° to intercept the final approach path.

The ILS procedure approach path to runway 35R is on 354°. The published missed approach path is to continue straight head climbing to 5000 ft and to anticipate radar vectors from the ATC services.

The published minima for a Boeing 737 type aircraft are the following:

Approach	Altitude (Height) of DA or MDA (ft)	RVR (m)
ILS	1,020 (200)	550
LOC	1,250 (430)	1,300
VOR	1,260 (440)	1,300

1.11 Flight recorders

1.11.1 Flight recorders

When the BEA was notified of this occurrence, the crew and aeroplane had already left for Morocco. It was therefore not possible to remove the flight recorders. The CVR recording of the occurrence was not preserved.

However, on the BEA's request, the operator provided the data from the QAR for the occurrence flight. Around 1,000 parameters were recorded. Graphs of the parameters are presented in Appendix 2.

Subsequently, the operator provided the QAR data from flights carried out in the days before and after the occurrence. The BEA obtained data for all the flights carried out between 25 December 2016 and 3 January 2017.

1.11.2 Sequence of events

The data from the incident flight, downloaded from the aeroplane's QAR, brought to light the following significant events:

Approach to Orly CAT III ILS RWY 06 A/P A engaged (MCP SPD/HDG, ALT SEL 5,000 ft, SPD SEL 230 kt), F/D A & B engaged, A/T engaged			
UTC	**QNH altitude 1,038 (ft) (QNH identical at Orly and Lyon)**	**Calibrated airspeed (kt)**	**Occurrences**
10:10:53	7,444	230	VOR/LOC mode is armed.
10:11:10	7,104	231	Selected airspeed is 180 kt.
10:11:33	6,838	222	VOR/LOC mode engages. *"F/D ROLL R"* parameter starts fluctuating (BOV).
10:11:44	6,742	219	Activation of ILS frequency on right MMR receiver.
10:11:55	6,666	210	Selection of flaps position 1.
10:12:15	6,522	197	Selection of flaps position 5.
10:12:17	6,501	196	Selected airspeed is 165 kt.
10:12:56	6,151	174	A/P B engaged.
10:12:58	6,134	173	A/P A disengaged.
10:13:05	6,059	170	A/P A engaged.
10:13:07	6,032	170	A/P B disengaged.
10:14:08	5,086	165	ALT ACQUIRE mode engages.
10:14:15	5,018	165	ALT HOLD mode engages.
10:14:53	5,023	165	G/S mode engages. *"F/D PITCH R"* parameter starts fluctuating (BOV).
10:15:17	4,577	177	Selected airspeed is 155 kt.
10:15:18	4,543	177	Selection of flaps position 15.
10:15:26	4,281	177	Landing gears are locked down.
10:15:37	4,017	170	Selected altitude is 2,000 ft.
10:15:47	3,940	161	A/P A disengaged for 1 second.
10:15:58	3,881	157	A/P B engaged for 1 second.
10:15:59	3,875	157	A/P A disengaged for 1 second.
10:16:47	3,150	156	Landing gears retract.
10:16:53	3,073	158	Selected airspeed is 169 kt. Selection of flaps position 5.
10:17:09	2,829 (RA = 2,280)	169	VOR/LOC and G/S modes are disengaged. MCP SPD mode is engaged. CWS Roll mode engages. *"F/D PITCH R"* parameter stops fluctuating.
10:17:18	2,687 (RA = 2,151)	170	HDG mode is engaged. *"F/D ROLL R"* parameter stops fluctuating.
10:17:18	2,158 (RA = 1,594)	169	Selected altitude is 4,000 ft.

First approach to Lyon CAT III ILS RWY 35R A/P A engaged (MCP SPD/HDG, ALT SEL 3,000 ft, SPD SEL 210 kt), F/D A & B engaged, A/T engaged			
UTC	**QNH altitude 1,038 (ft) (QNH identical at Orly and Lyon)**	**Calibrated airspeed (kt)**	**Occurrences**
10:58:52	3,008	213	ALT HOLD mode engages.
10:58:55	3,000	212	VOR/LOC mode is armed.
10:59:06	3,000	210	Selection of flaps position 1.
10:59:19	3,027	210	Selected airspeed is 185 kt.
10:59:20	3,027	210	VOR/LOC mode engages. *"F/D ROLL R"* parameter starts fluctuating (BOV).
10:59:22	3,024	210	Plane enters a right turn up to a maximum bank of 30.4° reached at 10:59:33.
10:59:31	3,025	200	Selection of flaps position 5.
10:59:33	3,028	198	Selected airspeed is 171 kt.
10:59:45			After reaching a maximum heading of 070°, the plane enters a left turn up to a maximum bank of 27.1° reached at 10:59:50.
10:59:52	3,048	180	A/P A disengaged.
10:59:56	3,036	179	A/T is disengaged.
11:00:49	4,624	189	Selected altitude is 5,000 ft.
11:00:50	4,657	189	VOR/LOC mode is disengaged. HDG mode is engaged. *"F/D ROLL R"* parameter stops fluctuating.
11:00:53	4,770	188	Selected airspeed is 188 kt. ALT ACQUIRE mode engages.
11:01:03	5,200	182	Heading 0° is selected.
11:01:19	5,674	187	A/P B engaged.
11:01:27	5,850	189	Selection of flaps position 1.
11:01:35	5,836	203	A/P B disengaged.
11:01:36	5,821	205	The *"IR FAULT"* parameter is triggered for 11 seconds. The *"F/D ROLL L"* and *"F/D PITCH L"* parameters start fluctuating (BOV). The *"CAPTAIN DISPLAY PITCH ATT"*, *"CAPTAIN DISPLAY ROLL"* and *"CAPTAIN DISPLAY HEADING"* parameters start fluctuating (NCD – FW).
11:01:47	5,770	223	The *"IRS Transfer Switch"* parameter is recorded as *"BOTH ON R"*.
11:01:50	5,821	225	Heading 90° is selected.
11:01:57	6,054	223	V/S mode is engaged.

11:02:00	6,178	221	Selected airspeed is 222 kt. MCP SPD mode is engaged (LVL CHG activated on board).
11:02:00	6,399	216	A/T engaged.
11:02:11	6,476	208	A/P B engaged.
11:02:15	6,410	207	Selected altitude is 4,000 ft.
11:02:31	5,760	218	Selection of flaps position 0.
11:02:35	5,647	218	The selected airspeed is 210 kt.
11:03:12	4,884	216	Yaw damper disengaged.
11:03:20	4,781	214	Heading 180° is selected.
11:03:47	4,418	210	The selected altitude is 5,000 ft.
11:03:49	4,401	210	Heading 200° is selected.
11:04:17	4,634	210	Selected altitude is 4,000 ft.
11:04:29	4,825	210	Selected altitude is 3,000 ft.
11:04:53	4,419	211	Heading 180° is selected.
11:05:53	3,517	210	Heading 240° is selected.

Second approach to Lyon CAT I ILS RWY 35R A/P B engaged (MCP SPD/HDG, ALT SEL 3,000 ft, SPD SEL 210 kt), F/D A & B engaged, A/T engaged			
UTC	**QNH altitude 1,038 (ft) (QNH identical at Orly and Lyon)**	**Calibrated airspeed (kt)**	**Occurrences**
11:06:08	3,239	210	Selection of flaps position 1.
11:06:12	3,172	211	Selected airspeed is 186 kt.
11:06:25	3,037	203	ALT ACQUIRE mode engages.
11:06:27	3,021	202	Selection of flaps position 5.
11:06:28	3,016	201	ALT HOLD mode engages.
11:06:30	3,016	199	Selected airspeed is 170 kt.
11:07:36	3,021	171	VOR/LOC mode is armed.
11:08:09	3,022	171	VOR/LOC mode engages. *"F/D ROLL R"* parameter starts fluctuating (BOV).
11:08:12	3,024	171	G/S mode is armed.
11:08:28	3,023	170	G/S mode engages. The *"F/D PITCH R"*, *"F/D PITCH L"* and *"F/D ROLL L"* parameters start fluctuating (BOV). A/P B disengaged.
11:08:39	2,956	172	Landing gears are locked down.
11:09:04	2,447	177	Selection of flaps position 15.
11:09:08	2,348	178	Selected airspeed is 156 kt.
11:09:20	2,031	180	Selection of flaps position 30.
11:09:26	1,811	183	Speed brakes extended until 11:09:46.
11:09:28	1,745 (RA = 949)	184	EGPWS GLIDESLOPE alert for 1 to 2 s.
11:10:00	1,478 (RA = 710)	162	GPWS SINK RATE warning for 2 to 4 s.
11:10:04	1,420 (RA = 560)	167	GPWS GLIDESLOPE alert for 1 to 2 s.
11:10:14	1,263 (RA = 403)	178	GPWS GLIDESLOPE alert for 1 to 2 s.
11:10:20	1,182 (RA = 242)	178	GPWS TOO LOW TERRAIN warning for 3 to 5 s.
11:10:32	1,062 (RA = 180)	180	GPWS TOO LOW TERRAIN warning for 1 to 3 s.
11:10:35	1,011 (RA = 147)	178	GPWS TOO LOW TERRAIN warning for 3 to 5 s.
11:10:38	949 (RA = 116)	177	Selection of flaps position 40.
11:10:39	930 (RA = 82)	175	GPWS SINK RATE warning for 2 to 4 s.
11:10:51	825	159	Touchdown.

1.12 Wreckage and impact information

Not applicable.

1.13 Medical and pathological information

Not applicable.

1.14 Fire

Not applicable.

1.15 Survival aspects

Not applicable.

1.16 Tests and research

The factual elements gathered during the analysis of the flight data recorded in the QAR (see paragraph 1.11.2) led the BEA to ask for an examination of the two ADIRU and the two FCC installed on CN-ROJ during the occurrence flight. The type and history of these computers are summarized in the table below:

	ADIRU #1 (Left ADIRU)	ADIRU #2 (right ADIRU)	FCC #1 (FCC A)	FCC #2 (FCC B)
Manufacturer	Honeywell	Honeywell	Rockwell Collins	Rockwell Collins
Part number	HG2050AC07	HG2050AC07	822-1604-101	822-1604-101
Serial number	56002660	56019441	16D1XL	17F969
Installed on CN-ROJ	14 Dec 2016	10 June 2016	22 May 2006	10 June 2016
Removed from CN-ROJ	06 Jan 2017	23 January 2017	04 May 2017	03 January 2017
History after removal from CN-ROJ	Isolated for examination.	Installed on CN-ROR 23 January 2017, then removed 4 April 2017 for examination.	Isolated for examination.	Installed on CN-ROZ 3 January 2017, then removed 27 January 2017 for examination.

1.16.1 Examination of ADIRU

The operator sent the two ADIRU to the Honeywell centre at Coon Rapids, Minnesota, in the United States. The examinations took place on 8 and 9 May 2017 in the presence of the BEA.

The Non-Volatile Memories (NVM) containing the BITE data of the two ADIRU were read out. Their content was then analysed:

- No fault message was recorded in the BITE of the right ADIRU and the Acceptance Test Protocol (ATP) did not reveal errors or malfunctions.
- The content of the NVM of the left ADIRU included several fault messages including one on the day of the occurrence: "Drift Angle". This fault message was also recorded by the BITE of the left ADIRU during a flight on 1 January 2017. It resulted in the illumination of the L IRS FAULT light on the overhead panel, the Master Caution lights on the instrument panel and the IRS light on the left annunciator (see paragraph 1.6.2.2.3).
- The residual ground speed recorded in the left ADIRU at the end of the occurrence flight was 187 kt.
- The position of the plane recorded in the left ADIRU on the tarmac at Lyon airport was around 64 NM from its actual position.

Honeywell carried out additional examinations on the left ADIRU for several weeks, between June and August 2017, in order to reproduce the "Drift Angle" fault and to identify what caused it.

The totality of the tests carried out on this unit did not permit the identification of defective components which could explain this fault message.

Nevertheless, Honeywell specified that the fault could have been caused by the failure of either a gyrometer or an accelerometer.

The QAR data showed that the attitudes and heading supplied by the left ADIRU were consistent. It therefore seemed that a gyrometer fault could be excluded.

Consequently, it is probable that the "Drift Angle" fault message is linked to a failure of an accelerometer which could explain the ground speed and position residual values recorded at the end of the flight at Lyon.

1.16.2 Examination of FCC

The operator sent the two FCC to the Rockwell Collins centre at Cedar Rapids, Iowa, in the United States. The examinations took place on 10 and 11 May 2017 in the presence of the BEA.

The electrical continuity tests did not indicate any problem. The BITE content of the two FCC was read. No fault message linked to a failure of the FCC was recorded. ATP were carried out and did not reveal a fault relating to the FCC.

However, the content of the BITE NVM of each FCC revealed numerous fault messages dated the day of the occurrence and also in all the BITE recording period (20 April 2015 to 4 May 2017 for FCC A and 1 January 2015 to 27 January 2017 for FCC B).

These fault messages mainly concerned the following equipment (in ascending order of number of messages):

- Left ADIRU;
- RA 2;
- VHF/NAV Control Panel 1;
- VHF/NAV Control Panel 2;
- Multi Mode Receiver 1;
- Multi Mode Receiver 2.

These fault messages were associated with, in the majority of cases, the following effects on the functions ensured by the FCC (effects observed particularly during the occurrence flight):

- Disconnection of A/P;
- Deletion of display of one or several F/D command bars.

The following table groups the information gathered by the BEA in order to explain the cause of these fault messages:

System	FCC	Date of messages	Causes of messages
Left ADIRU	A & B	30 December 2016 01 January 2017	These messages are linked to the "Drift Angle" fault message recorded on the same dates by the left ADIRU BITE (see paragraph 1.16.1). For the occurrence flight, the fault messages indicated the invalidity of the heading or path at the time of the right turn and disconnection of the A/P during the first approach to Lyon. The heading from the left ADIRU was recorded in the QAR and was correct which allows us to conclude that the path was invalid (not recorded in the QAR). Furthermore, Boeing and Rockwell Collins managed to reproduce this situation by means of a simulation with deliberately false path values.
RA 2	B	Several occurrences between 26 June 2016 and 2 January 2017 and in particular during the occurrence flight (FCC B removed from CN-ROJ on 3 January 2017).	RA 2 present on CN-ROJ at the time of the occurrence had been installed on 10 December 2016. However, the first fault messages with respect to RA 2 were recorded on CN-ROJ from 26 June 2016. It therefore seemed that these messages were not due to a radio altimeter failure. Furthermore, the RA 2 antennas had been checked by the operator's maintenance staff on 16 January 2017 without finding any fault. Based on these elements, it appeared probable that these fault messages were caused by a communication problem between RA 2 and FCC B.

VHF/NAV Control Panel 1	A & B	FCC A: very numerous occurrences between 20 April 2015 and 4 May 2017, in particular during the occurrence flight. FCC B: very numerous occurrences between 1 January 2015 and 23 June 2015 and one occurrence during the occurrence flight.	The investigation found that these fault messages were the consequence of the company's operational procedure asking the PM to select the destination airport VOR/DME during the ILS approaches in order to check that the correct glide signal is captured. Details about the cause of these messages are given in the following paragraph.
VHF/NAV Control Panel 2	B	Very numerous occurrences between 23 June 2015 and 26 January 2017, in particular during the occurrence flight.	
Multi Mode Receiver 1	A & B	FCC A: very numerous occurrences between 20 April 2015 and 4 May 2017. FCC B: very numerous occurrences between 1 January 2015 and 23 June 2015.	
Multi Mode Receiver 2	B	Very numerous occurrences between 23 June 2015 and 26 January 2017, in particular during the occurrence flight.	

1.16.3 Disappearances of F/D and disengagements of A/P observed in QAR data: causes

On analysing the QAR data, it was observed that there were multiple instances of the F/D disappearing and of the A/P disengaging during the occurrence flight and also during several other flights before and after the occurrence flight.

The examinations of the two FCC permitted us to understand the causes for this, four in number, during the occurrence flight:

- Cause 1: The crew's compliance with the operator's standard practice which consisted in delaying the display of the Localizer frequency and in keeping the display of a VOR frequency on the PM's navigation system. This method kept a VOR displayed in the plane so that the pilot had a better picture of his position with respect to the airport, could check the anticipation of the turn required to correctly align on the Localizer and as applicable, capture the correct Glide signal using the DME associated with the VOR, when the ILS did not include a DME. The selection, on the PM's control panel, of an active frequency other than the frequency of the ILS being intercepted results in the F/D roll command disappearing when the VOR/LOC mode is engaged and the F/D pitch command disappearing when the G/S mode is engaged, on this side. This work method corresponds to a former practice also used in other companies, notably French companies, in the past. The current procedure set out in the FCOM (see paragraph 1.17.1.3.1.1) requires that the Localizer frequencies are displayed on both navigation systems before intercepting the Localizer[28].
- Cause 2: The non-arming of the APP mode which prevented the engagement of the two A/P.
- Cause 3: FCC B not receiving data from RA 2 which led to the F/D disappearing from the right PFD, the disengagement of A/P B and the disengagement of both A/P when they were both engaged.
- Cause 4: The transmission of erroneous inertial data from the left ADIRU to FCC A and B which caused the F/D on the left PFD to disappear, A/P A to disengage and A/P B to disengage.

[28] Note: the display of a VOR frequency on one of the VHF/NAV control panels prevents the engagement of the two A/P which is necessary for CAT III approaches.

The sequence of disruptions to the automated systems during the occurrence flight is the following:

Approach to Paris-Orly

At 10:10:53, the crew armed the VOR/LOC mode. The active frequency on the left VHF/NAV control panel was the ILS 06 frequency while the active frequency on the right was the Orly DME (POY) frequency.

At 10:11:33, the VOR/LOC mode was engaged and the aeroplane turned right. At that moment, the F/D roll command bar (vertical command bar) disappeared from the right PFD (cause 1).

Then 11 seconds later, the ILS 06 frequency was activated on the right side but the F/D roll command bar did not reappear (cause 3).

At 10:12:58, on engaging A/P B, A/PA disengaged. Likewise, nine seconds later, the successive attempts to engage both A/P led to the disengagement of A/P B (cause 2).

At 10:14:53, the crew were cleared for the CAT III ILS approach. At that moment, the crew selected the Approach mode which had the effect of arming the G/S mode. The G/S mode was engaged, the F/D pitch command bar (horizontal command bar) disappeared from the right PFD (cause 3).

At 10:15:47, A/P A disengaged (cause 3).

At 10:15:58, A/P B then A/P A disengaged (cause 3).

Approaches to Lyon

At 10:58:26, the crew were cleared for ILS 35R at Lyon. They displayed the ILS frequency of runway 35R (instead of the LSE VOR-DME frequency) on the left and right VHF/NAV control panels. The aeroplane intercepted the altitude of 3,000 ft, then the crew armed the VOR/LOC mode.

At 10:59:19, the VOR/LOC mode engaged. At that moment, the F/D roll command bar disappeared from the right PFD (cause 3).

At 10:59:52, A/P A disengaged (cause 4).

At 11:01:35, the L IRS FAULT warning caused the disengagement of A/P B (cause 4).

At 11:08:09, the VOR/LOC mode was engaged. At that moment, the F/D roll command bar disappeared from the right PFD (cause 3). The crew activated the APP mode three seconds later which had the effect of arming the G/S mode.

At 11:08:28, the G/S mode was engaged. At that moment, A/P B was automatically disengaged and the F/D pitch command bar disappeared from the right PFD (cause 3). At that moment, the F/D roll and pitch command bars also disappeared from the left PFD for a reason which could not be explained during the investigation.

Summary

It appeared that the majority of the disappearances of the F/D bars was due to FCC B not receiving RA 2 data (cause 3).

This fault mode also explained the majority of the A/P disengagements.

1.16.4 Analysis of QAR data from other flights

Royal Air Maroc provided the BEA with the data from an additional 43 flights carried out the same plane between 25 December 2016 and 3 January 2017. The analysis of this data brought to light the following elements:

- The characteristic signature of the "*F/D Roll*" and "*F/D Pitch*" parameters indicating the disappearance of the F/D was observed a very large number of times on both the left and right side. This phenomenon occurred during 29 of the 43 flights.
- Difficulties with intercepting the LOC path during ILS approaches with the A/P engaged were observed on seven flights between 26 December 2016 and 2 January 2017. These difficulties were characterized by the plane's path fluctuating around the LOC path, as observed in this incident during the approach to Paris Orly or diverging with respect to the LOC path requiring the disconnection of the A/P, as observed during the first approach to Lyon.
- The L IRS FAULT warning was activated during a flight on 1 January 2017.
- The EGPWS "*SINK RATE*" warning was activated during the final approach of the flight following the incident flight, between Lyon and Paris-Orly performed by the same crew.

1.16.5 Analysis of crew reports in TLB

The data read out from the FCC BITE and QAR was put side by side with the TLB to assess the consistency between the TLB reports concerning technical problems encountered by the crews and the faults recorded. This comparison was carried out for the CN-ROJ flights between 25 December 2016 and 3 January 2017, i.e. 43 flights.

During this period, the QAR data and the data contained in the FCC BITE showed that there were 29 flights during which the F/D display disappeared.

Of these 29 cases, 17 were due to compliance with the operator's operational procedure which consisted of checking that the correct Glide signal had been captured during the ILS approach by selecting a VOR-DME on the PM's side. For the operator, this was not a system failure which needed to be reported in the TLB.

The 12 other cases were caused by technical problems. According to the results of the FCC examinations (see paragraph 1.16.2), 11 of these 12 cases were due to FCC B not receiving data from RA 2. The last case was due to the divergence between the left and right F/D commands with the VOR/LOC and G/S modes engaged.

There were two crew reports in the TLB with respect to F/D problems.

Likewise, the QAR data and the data contained in the FCC BITE showed that there were 18 cases of the A/P automatically disengaging due to communication problems between FCC B and RA 2, or left ADIRU problems.

There were six crew reports in the TLB concerning A/P problems.

Lastly, on 1 January 2017, the left ADIRU recorded a "Drift Angle" fault message which was also visible in both the QAR data and FCC A BITE data. No crew report was made in the TLB at the end of this flight.

This analysis brought to light the non-systematic reporting of technical problems, encountered by the flight crews, in the TLB.

The occurrence flight was not an exception. Only the "*L IRS FAULT*" information was actually mentioned in the TLB. The appearance of the FMC fault messages, "*IRS-L DRIFT*" and "*VERIFY POS: IRS-IRS*", the multiple times that the A/P disengaged and the F/D disappeared, as well as the activation of the *AUTOBRAKE DISARM* light were not mentioned.

1.16.6 Analysis of Boeing safety study relating to an undetected ADIRU malfunction

During the first approach to Lyon with A/P A engaged, the left ADIRU which had experienced internal problems during this flight, supplied erroneous data marked as valid to FCC A. FCC A which directly takes into account this data without any additional checks, sent an erroneous command signal.

It was possible to observe similar problems during the seven flights between 26 December 2016 and 2 January 2017.

Boeing presented a summary of the safety study carried out to assess the risk relating to entering an uncommanded turn with the A/P engaged, caused by erroneous inertial data not being detected.

1.16.6.1 Risk assessment

Boeing defined the hazard effects of the FCC using undetected erroneous inertial data as being:

- Erroneous F/D guidance;
- A/P controlling a sudden deflection possibly of large amplitude (hardover) of a pitch or roll control surface (one or the other axis but not both at the same time);
- Oscillatory commands;
- Degraded control.

Boeing ranks these effects as "*minor*" or "*major*"[29] depending on the flight phase. They are ranked as "*major*" in the approach phase. In this case, the FCC's use of undetected erroneous inertial data must not occur more frequently than on the order of 10-5 times per flight hour.

[29] This ranking is defined in the American *Federal Aviation Regulations Part 25 § 1309*.

This classification is based on the following design considerations:

- Single channel autopilot operation is authorized above 400 ft after take-off and down to 158 ft during approach.
- Undetected erroneous inertial data transmitted by an ADIRU to a FCC can only cause a hardover on one axis (pitch or roll). To generate its pitch and roll commands, FCC A (B) uses the inertial data transmitted respectively by the left (right) ADIRU and the right (left) ADIRU.
- The yaw damper monitors and compares the data provided by the two ADIRU. When only one ADIRU is valid, it is not possible to keep both the A/P and the yaw damper engaged. This design choice guarantees that erroneous inertial data will not interfere with the plane's path on the three axes simultaneously.

These design choices reduce the seriousness of the hazard effects by limiting the number of aeroplane axes simultaneously affected by an undetected malfunction of an ADIRU. However, they do not provide any means of detection and thus do not limit the hazard exposure time.

The only means of detecting this hazard identified in the safety study is monitoring by the crew:

- *"Pilots are trained to monitor the airplane's flight path, airspeed, and altitude, and to correct for any deviations from those which were intended."*

Boeing identified the following additional risk mitigations during an approach:

- *"Display of inertial data on second, independent, ADIRU source, and on standby instrument display*
- *Display of ILS deviations on primary, navigation and standby displays*
- *Display of airplane position on navigation displays*
- *Traffic Alert and Collision Avoidance System (TCAS) monitoring*
- *Ground Proximity Warning System (GPWS) monitoring*
- *Air Traffic Control (ATC) Monitoring."*

1.16.6.2 Estimation of probability of occurrence

Honeywell estimated that the probability of an ADIRU sending undetected erroneous inertial data was 1.22×10^{-5} per flight hour. This was an estimation made during the design phase of the ADIRU and was not checked or subsequently updated by feedback due to the "undetected" nature of the hazard.

Boeing also calculated the probability of this same hazard occurring during an approach phase based on the assumption that this phase would last for 12 minutes. This gave a probability of occurrence of 2.44×10^{-6}.

1.16.6.3 Effectiveness of crew monitoring as detection means

The only detection means identified in the safety study presented by Boeing is solely based on the crew's capacity to detect and correct any deviation from those which were intended. The effectiveness of this means is chiefly based on the crew's detection time and reaction time. The presupposition in the safety study is that the detection time and reaction time will be sufficiently short to prevent this hazard from evolving into a dangerous or indeed catastrophic situation.

More generally, this is a presupposition of the safety model developed and used in the scope of the certification of the Boeing 737. Its validity is discussed in the Joint Authorities Technical Review (JATR) presenting the work jointly carried out by ten civil aviation authorities, NASA and NTSB following the accidents to the Boeing 737 Max in Indonesia and Ethiopia[30]. In their report, these authorities[31] indicate that it is common practice for the candidates for a type certificate issued by the American Federal Aviation Administration (FAA) to use the detection and reaction times defined in the FAA guide AC 25-7D developed to carry out flight tests. This guide recommends using a detection time of one second and a reaction time of three seconds.

The Joint Authorities underlined the fact that these times are used during aeroplane design and particularly in safety studies, although the AC 25-7D was drawn up for the performance of flight tests.

[30] Although there is a difference in the nature of the system faults in the two accidents to the Boeing 737 Max and the serious incident to CN-ROJ, some of the analyses and recommendations made by the JATR are also applicable to Boeing 737-NG.

[31] These authorities will be referred to as the "Joint Authorities" in the rest of the report.

Furthermore, the Joint Authorities did not find any study to substantiate these reaction and detection times. A study by the NASA[32] and the analysis of several accidents found that crews could take a significantly longer time than that defined in the AC 25-7D to detect and react to a malfunction.

Lastly, the Joint Authorities emphasized that the presupposition that the crew continuously monitor the operation of the automated systems and particularly, that they are capable of reacting in less than four seconds, dates back several decades when the reliability of the systems required their correct operation to be constantly monitored. This presupposition is perhaps no longer valid today.

The Joint Authorities therefore made several recommendations to the FAA with respect to this:

- "*The FAA should establish appropriate pilot recognition times and reaction times, based on substantive scientific studies which take into account the operational environment, the circumstances under which malfunctions may occur, and the effect of surprise.*" (Recommendation R2.8).
- "*As part of the certification process for transport category airplanes, the FAA should examine all "major hazards" where a key mitigation is flight crew action to see if they are potentially catastrophic. The FAA should evaluate the impact of the hazard and its mitigations at the aircraft level, including the impact on the crew and cockpit environment, to determine if additional mitigating design features are required.*" (Recommendation R6.2)

1.16.7 Technical situation of aeroplane after occurrence

1.16.7.1 Maintenance actions carried out on 30 December 2016

Following the occurrence flight, CN-ROJ flew back to Paris-Orly and then carried out a Paris-Orly-Marrakech flight the same day. On this last leg, the crew reported in the TLB that A/P B disconnected during the final approach.

The Royal Air Maroc maintenance personnel wrote in the TLB that the fault message, *22-11052 Radio Alt-2 (J1B-B04, A04)* was read on carrying out the DFCS BITE procedure. This fault refers the technician to FIM 22-11 task 805: *Radio Altimeter Output Problem – Fault Isolation*.

In this new task, it is indicated that the message, *Radio Alt-2 (J1B-B04, A04)* is recorded when FCC-B receives invalid data or no data from RA 2.

Before starting the fault isolation procedure, the fault has to be confirmed on the ground first. It is possible to run an LRU test associated with the fault displayed on the CDU. The LRU test was successfully passed. This meant that the fault was either intermittent or was triggered in different conditions to those of the maintenance operation.

It was also indicated in the TLB that a message concerning the F/D appeared on the CDU, that the associated test was an interactive test[33] and that it had been successfully passed.

[32] Casner, S.M., R.W. Geven, and K.T. Williams (2013). The Effectiveness of Airline Pilot Training for Abnormal Events, *Human Factors*, 55, 477-485[-33].

[33] Additional F/D test requiring the maintenance technician to carry out the actions requested by the system.

1.16.7.2 Maintenance actions carried out at beginning of 2017

After the day of the occurrence, the flight crews operating CN-ROJ were confronted with the A/P automatically disengaging several times. The technician then carried out the maintenance actions given in the table below:

Date	Description	Maintenance actions
2 January 2017	*- ILS APP MODE UNAVAILABLE IN BOTH A/P A AND B* *- IRS-L DRIFT MSG VERIFY-POS: IRS L* *- A/P B DISCONNECTED AT G/S CAPTURE* *- A/P DISCONNECTED AT G/S CAPTURE*	Replacement of FCC B.
6 January 2017	*- REF MORE COMPLAINTS A/P B DISCONNECTED AT FINAL* *- IRS L DRIFT MSG FMC VERIFY POS IRS LH*	- Replacement of Multi Mode Receiver 1; - Replacement of VHF/NAV Control Panel 1; - Replacement of left ADIRU.
16 January 2017	*A/P B DISENGAGE AFTER G/S CAPTURE*	- Check of wiring between RA 2 and FCC A & B; - Removal/reinstallation of two antennas associated with RA 2 for inspection and cleaning; - RA 1 and 2 temporarily swapped over for the DFCS BITE test. No fault found.
23 January 2017	*LEFT IRS DRIFTED ON GROUND BY MORE THAN 6 WITH MSG IRS POS ORIGIN DISAGREE*	- Removal of right ADIRU (for investigation) and replacement; - Replacement of left ADIRU.
6 February 2017	*ON APP A/P RIGHT SIDE DISENGAGE STP*	- Check of wiring between Multi Mode Receiver 2 and FCC B; - Check of wiring between VHF/NAV Control Panel 1 and 2 and FCC B; - Replacement of Multi Mode Receiver 2; - Replacement of VHF/NAV Control Panel 2.
11 February 2017	*DUE TO RECURRENT MSG SHOWED ON RH DFCS FAULT HISTORY AT DESCENT PHASES*	- Detailed inspection of antennas associated with RA 2; - Replacement of antennas associated with RA 2; - Check of wiring between RA 2 and FCC A and B.
22 February 2017	*AUTO PILOT B DISENGAGED ON MODE APP AND NO FD BARS*	- Replacement of RA 2.

These different maintenance actions did not bring to light any failure on the inspected systems which could explain the problems encountered during the occurrence flight. Nevertheless, Royal Air Maroc advised the BEA that the problems with the A/P automatically disengaging encountered on CN-ROJ disappeared after 22 February 2017, the date at which RA 2 was replaced.

1.17 Organizational and management information

1.17.1 Operator

1.17.1.1 General description

Royal Air Maroc, RAM, the Moroccan national airline was created on 29 June 1957 and is based at Mohammed V - Nouasser airport at Casablanca.

The day of the serious incident, it held a Technical Operating Certificate[34] (No. CN-XC01/96) issued by the Moroccan Ministry of Equipment, Transport and Logistics on 24 June 2015 and valid until 26 June 2017. It was authorized to carry out passenger and freight commercial air transport on both domestic and international flights. An annex to this certificate specifies that CN-ROJ held an authorization for category I to IIIA instrument approaches.

At the time of the occurrence, the company operated 48 Boeing and Embraer planes, of which 36 were Boeing 737-700s (6) and 737-800s (30).

The company held the IOSA certification since 2005.

1.17.1.2 Operational procedures in case of an incident

The RAM Policy Manual specifies in chapter 1.4.2.7 that the captain must comply with the following provisions after the flight:

- Lodge an ASR in case of an accident or incident.
- Preserve the data recorded on the Flight Data Recorder (DFDR) and the Cockpit Voice Recorder (CVR) in case of an accident or incident which may be subject to a compulsory declaration or an investigation.

The document specifies in chapter 2.4.5 that the mission of the company's flight crew duty manager is to handle events, incidents and accidents. His mobile phone number is given in the document.

Chapter 11 gives information about handling incidents and accidents.

Chapter 11.1.2 defines an incident as an occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation and a serious incident as an incident involving circumstances indicating that an accident nearly occurred. The manual specifies that the difference between an accident and a serious incident lies only in the result.

Examples of serious incidents are given including near collisions requiring an avoidance manoeuvre to avert a collision or an unsafe situation or when an avoidance action would have been appropriate, system malfunctions, weather phenomena, manoeuvres outside the approved flight envelope or other occurrences which may have made it difficult to control the aircraft.

Chapter 11.5 indicates the measures to be taken in the event of a serious incident:

[34] The Technical Operating Certificate is the licence authorizing a Moroccan operator to carry out commercial air transport (passengers, cargo and mail), air taxi and aerial work services. The same document is called the Air Operator Certificate (AOC) by Annex 6 to the Convention on International Civil Aviation.

11.5 MESURES EN CAS D 'INCIDENT GRAVE

Rôle du CDB responsable du vol :

• Protection du CVR

• Compte tenu de la nature de l'incident, le CDB peut estimer que la préservation des enregistrements du CVR est nécessaire pour l'analyse de l'événement. Dans ca cas, à l'arrivée au bloc, le CDB doit confirmer l'arrêt de l'enregistreur en tirant le disjoncteur du CVR et le mentionner au TLB.

Note – En vol et au sol avant l'arrivée au bloc,l'arrêt volontaire du CVR est interdit.

• Renseigner le TLB
• Si l'événement a pour origine une défaillance technique ou est de nature à avoir une conséquence technique, le CDB doit s'assurer que l'événement est reporté sur le TLB.
• Rédiger un ASR
• Le CDB relate l'événement sur l'imprimé de l'ASR, et le fait transmettre immédiatement à CMNOW et CASEX (télécopie). C'est le support de référence "vol" pour informer les services officiels.
• Préservation des indices matériels.
• Le CDB s'assure que toutes les pièces du dossier de vol sont présentes dans l'enveloppe de navigation. Si nécessaire il fait préserver localement tout document qu'il juge utile pour l'analyse de l'événement et fait effectuer des photos des indices volatils (état cabine, situation, traces sur la piste, etc...).
• Information du siège.
• L'information des mouvements CMNOW est faite sous la responsabilité du CDB.
• Informer D.A.C et inspecteur sécurité aéronautique (tel:00 212 22 902726 fax:902190)

Rôle de l'escale

• Préservation des indices matériels
L'escale préserve tout document jugé utile pour l'analyse de l'événement et fait effectuer des photos des indices volatils (état cabine, situation, traces sur la piste, etc...).
• Information du siège
L'escale informe CMNOW par un message signé par le CDB, commençant par la mention "INCIDENT GRAVE". Dans le cas où la gravité de l'incident résulte de son caractère spectaculaire ou de la qualité des passagers, le message doit faire mention très explicite et très
complète des données concernant ces aspects.
Il appartient à CMNOW d'effectuer la diffusion de l'information auprès de tous les services concernés.
Après un incident grave, l'escale assure la maîtrise de l'interface entre l'équipage et les divers organismes en présence : autorités, média notamment en liaison étroite avec le service communication externe.
En dehors du Maroc, toute déclaration aux autorités officielles doit être effectuée en conformité avec la réglementation locale et sous la responsabilité du Chef d'escale.

1.17.1.3 Flight procedures

1.17.1.3.1 Normal procedures

1.17.1.3.1.1 Configuration and preparation for a category I ILS procedure approach

The FCOM descent procedure indicates on page NP 21.40 that for the descent:

- ❒ The PF and the PM recall (Recall key) and review the system annunciator lights together.
- ❒ The PF and the PM display and check the radio navigation systems as well as the courses displayed for the approach.

The APP procedure (FCOM NP.21.42) indicates that for an ILS approach, the crew must display the Localizer frequencies[35] before the Initial Approach Fix (IAF) or well before the start of the vectoring to the final approach path if being radar vectored.

The FCOM indicates[36] on page NP.21.44, the configurations and speeds for a CAT I ILS approach:

- ❒ Select flaps 1 and speed "*1*" (Vref40 + 50) then flaps 5 and speed "*5*" (Vref40 + 30) before intercepting the LOC.
- ❒ Control landing gear down and select flaps 15 and speed "*15*" (Vref40 + 20) when the Glide is active, set Engine start switch to CONT.
- ❒ Arm the speed brakes.
- ❒ On capturing the Glide, select the planned flap configuration for landing and VAPP = Vref+ wind factor.
- ❒ Display the go-around altitude on the MCP.
- ❒ Carry out the landing check-list.
- ❒ At the final approach fix (FAF or FAP), check the crossing altitude.
- ❒ Disengage the A/P and A/T no later than the DA.

During the 2nd CAT I ILS approach to runway 35R at Lyon-Saint Exupéry, the following parameters were observed (Vref40 = 135 kt):

- ❒ Flaps 1 and selected speed 186 kt then flaps 5 and selected speed 170 kt.
- ❒ Landing gears commanded down just after the engagement of the G/S mode. Around 30 s later, selection of flaps 15 and selected speed 156 kt.
- ❒ Speed brakes not armed.
- ❒ Flaps 30 and selected speed not modified 52 s after the engagement of the G/S mode. Flaps 40 are selected at a height of around 115 ft.
- ❒ Display of altitude 2,700 ft on MCP (missed approach altitude 5,000 ft).
- ❒ Not known (no CVR).
- ❒ Altitude of 2,270 ft at D4.5 LSN (according to the approach chart, at this fix, the altitude must be 2,260 ft).
- ❒ A/P / A/T disconnected for all the final approach.

[35] The display of the Localizer frequencies on the two navigation systems thereby replaces the VOR frequencies which may have been selected.

[36] The company specified that this canvas is to be used as a guide which can be left to the captain's judgement, to comply with the stabilization criteria at 1,000 ft AAL in IMC or 500 ft AAL in VMC, both of which are compulsory.

1.17.1.3.1.2 Stabilization of approach

The company's Policy Manual indicates in paragraph 8.1.3.6.2 that an approach is considered stabilized when all the following conditions are acquired by 1,000 ft AGL if the plane is in IMC flight conditions or by 500 ft AGL in VMC conditions[37].

[37] Due to the weather conditions, the final approach to Lyon was carried out in IMC.

The manual indicates that if just one of the stabilization criteria is not acquired by 1,000 ft AGL in IMC conditions or if an approach becomes non-stabilized below 1,000 ft AGL, a missed approach and go-around must be carried out and that all go-arounds that have been started must be continued.

During the second final approach to Lyon, at 1,000 ft AGL, the speed was more than 41 kt above the Vref, the vertical speed indicator was 2,000 ft/min for a maximum authorized value of 1,000 ft/min and the Glide was 1.8 dot for a maximum of 1 dot.

1.17.1.3.2 Division of crew tasks

The company's Policy Manual describes the method which all crews must adhere to in performing their duties, notably with respect to the division of tasks between the crew members.

Paragraphs 1.5.2 and 1.5.3 indicate that the PF is responsible for piloting and navigation, and that the PM is in charge of telecommunications (or the PF if necessary). It is specified that in all circumstances, both on the ground and in flight, the PF's management of the flight path must be monitored by the PM. It is also indicated that the captain remains solely responsible for the whole execution of the flight and that he must intervene each time he considers this necessary.

Paragraph 13.1.1.2 specifies that when manually piloting, the PF manages the power levers, the engagement of the A/P and the trims (except setting the rudder trim to neutral on final) and that the PM is responsible for all the other controls and switches under the captain's responsibility and in compliance with the operational procedures.

When using the A/P, the PF is in charge of the power levers, the MCP selections and the speed brakes while the PM is in charge of all the actions on the overhead panel.

1.17.1.3.3 Abnormal and emergency procedures

The operator's abnormal and emergency operational procedures relating to the incident can be found in Appendix 4. They adopt, in full, the procedures in RAM's Policy Manual concerning general aspects for dealing with an abnormal situation and those in the aeroplane's FCOM and QRH for the related faults.

The Policy Manual indicates in chapter 0.1.2 that nothing must prevent a person from acting according to his own judgement in case of an emergency and according to the circumstances.

In case of an emergency and according to the circumstances, the captain must take all the measures that he considers necessary in the interest of safety, can deviate from operating rules, procedures and methods and shall, as quickly as possible, notify the local authorities concerned and complete an ASR in accordance with the procedure described in chapter 11 of the manual (see paragraph 1.17.1.2).

1.17.1.3.3.1 General case: reaction to an abnormal situation

RAM's Policy Manual, chapter 13.1.1.6, deals with general aspects concerning the desired reaction of a crew to a warning or abnormal situation and the associated manner of dealing with it.

This framework notably applies on the occurrence of a L IRS FAULT warning, like the one which appeared at 11:01:36 during the first approach to Lyon.

This framework recommends that the crew:

- ❒ Call out and identify the L IRS FAULT warning on the overhead panel and clear the MASTER CAUTION warning.
- ❒ Confirm or redefine the tasks of the PF and the PM (captain): the PF normally follows the path, pilots and navigates and the PM carries out the communications.
- ❒ Refer to the "*IRS FAULT*" check-list in the QRH (PF).
- ❒ Read and carry out the QRH "*IRS FAULT*" check-list with appropriate cross-checking (PM).
- ❒ Check that the left IRS circuit-breakers are closed.
- ❒ Assess the technical, economical, commercial and human aspects.
- ❒ Take into account operational considerations:
  - ■ Limitations
  - ■ Fuel
  - ■ Weather (destination and alternate airports)
  - ■ Passenger transport and accommodation.
- ❒ Consult the company's CCO if possible.
- ❒ Take a decision.
- ❒ Inform the company, ATC and passengers.

This general philosophy also applies in case of FMC "*IRS-L DRIFT*" and "*VERIFY POS: IRS-IRS*" messages.

1.17.1.4 Recurrent training and checking

1.17.1.4.1 General provisions

In Royal Air Maroc, each member of the flight crew must follow the operator's recurrent training and checking programme, in accordance with the ministerial order of the Moroccan authorities No 3163-12 of 21 September 2012 with respect to the licences and ratings of flight crew members.

The training programme for the operator's crews is based on 3-year recurrent training and checking cycles, broken down into semesters. At the time of the occurrence, the crews were in a training and checking cycle which had started in 2015 and was to finish in 2017.

1.17.1.4.2 Recurrent training

Each year the recurrent training includes:

- A ground refresher course covering theoretical knowledge, including the aircraft systems, the study of the operator's normal, abnormal and emergency procedures, and dangerous goods and safety training. (The latter two are part of a two-year cycle).
- Two flight simulator training sessions. This programme is drawn up so that all the aeroplane's major system failures along with the associated procedures are covered over the three years. This training also includes Low Visibility Procedures (LVP) and CAT II and III procedures. Chapter 2.4.1.2 of the Operations Manual Part D indicates that simulator training should include a reversion to manual flight and approaches with an A/P equipment fault at low altitude.
- Safety, lifesaving and security training.
- Crew Resource Management (CRM) training; it is specified that radio telephony must be carried out in English.

1.17.1.4.3 Recurrent checking

The recurrent checking includes, each year:

- Two simulator base checks. One of these sessions includes the proficiency check exercises for the type rating, with an ILS approach to the minima, in manual, without F/D, and at least three exercises in the normal and abnormal use of the aeroplane's systems and three normal and emergency procedures.
- A safety, lifesaving and security check.
- A line check including the check for CRM skills.

1.17.1.4.4 Combining training session with base check

The operator's documentation specifies that simulator training can be combined with the base check. In practice, the operator indicated that the training sessions were always combined with the simulator base checks carried out every six months.

1.17.1.4.5 Recurrent training and checking cycles followed by crew

All of the crew training file was examined during the investigation. The table below indicates in which semestral sessions the items concerning the A/P and the faults on the navigation systems were studied.

ATA		2015		2016		2017	
		Session A	Session B	Session C	Session D	Session E	Session F
Automatic flight	Autopilot disengage					X	
Automatic flight	Auto throttle disengage					X	
	FMC Disagree - FMC Disagree vertical					X	
	FMC fail					X	
	GPS						X
Flight management navigation	FMC/CDU alerting message					X	
	IRS DC fail, IRS fault, IRS on DC			X			
	Unable REQ NAV Perf-RNP			X			
	Go around 1 or 2 engines operative	X	X	X	X	X	X

X: session completed at time of event.
X: session not yet completed at time of event.

1.17.1.4.6 IRS fault training carried out

The operator's recurrent training and checking cycle scheduled a refresher course about the IRS for 2016 comprising a summary of the system, abnormal situations and a questionnaire. The IRS FAULT was studied during the annual ground refresher session. Only the IRS DC FAIL was seen in the simulator, during the take-off run when the captain was PF.

1.17.1.4.7 Training carried out for ILS approaches in manual and sudden disconnections of A/P

The recurrent training and checking programme scheduled training corresponding to A/P faults and its sudden disconnection in 2017, in session E (table above).

1.17.1.5 Fuel load and management

1.17.1.5.1 Regulatory aspects

The company's Operations Manual specifies in chapter 8.1.7.1 of the Policy Manual that the fuel quantities to be taken into account for the flight plan are the following:

a) **Taxiing**

b) **Trip fuel**: quantity of fuel required from brakes off at the departure airport to touchdown at the destination airport, taking into account all the foreseeable conditions on the route.

c) **Route factor fuel**: quantity corresponding to 5% of the trip fuel, to allow for unforeseeable events likely to have an impact on the quantity of fuel actually used up to the destination airport (deviation of actual consumption from forecast consumption, changes in route or flight level, weather conditions, etc.).

d) **Alternate fuel**: quantity of fuel required to carry out a missed approach at the destination airport, and the climb, en route, descent, instrument approach and landing phases at the furthest alternate airport specified in the flight plan (Lyon-Saint Exupéry).

e) **Final fuel**: quantity of fuel corresponding to 30 minutes of flight at a height of 1,500 ft overhead the alternate airport.

f) **Additional fuel**: if required by type of operation: not applicable for this flight.

g) **Supplementary fuel**: quantity of fuel required to cover the specificities of the destination airport (systematic holding, long approach, etc.).

This quantity is determined by the captain.

1.17.1.5.2 Fuel load for this flight

Given the items a) to e) above, the minimum regulatory fuel quantity to be carried for a departure from Rabat and shown on the operational flight plan was 9.7 t.

This quantity included the 0.2 t for taxiing + 6 t for the trip fuel + 0.3 t for the route factor + 2.1 t for the alternate fuel + 1.1 t for the final fuel.

As the adverse weather conditions prevailing at Paris-Orly (fog) might have led to the plane holding on arrival, the captain chose to add an additional one tonne of fuel. The actual quantity of fuel on board when leaving the parking at Rabat was therefore 10.7 tonnes.

1.17.1.5.3 Fuel management in flight

RAM's Operations Manual gives instructions to the crew about the management of fuel in flight (Policy Manual paragraphs 8.1.7.5 and 8.3.7).

The captain must regularly compare the actual quantity of fuel with the planned consumption, check that the remaining fuel is sufficient for completing the flight and plan to land at the destination or alternate airport with at least a quantity of fuel corresponding to the final fuel (1,100 kg).

If the quantity of fuel on board is such that the plane risks crossing the landing runway threshold with less fuel than the final fuel quantity, the crew must declare an emergency (MAYDAY).

The manual specifies that to carry out a diversion, the fuel quantity on board must be at least equal to the final fuel plus the alternate fuel (paragraph 8.1.7.5.3), i.e. for this flight a minimum quantity of 3,200 kg at Paris-Orly when taking the decision to divert to Lyon.

In the present case, the fuel quantities present during the flight, recorded in the QAR, were:

- At Orly on starting the diversion to Lyon: 4,300 kg.
- At Lyon when the IRS FAULT warning was activated: 2,600 kg.
- On landing: 2,180 kg.

1.17.2 Organization responsible for maintenance

RAM was awarded Part 145 approval by the European Aviation Safety Agency (EASA) in 2011 for line maintenance and was approved by the Moroccan civil aviation directorate for line maintenance up to the type A inspection. The type C and D inspections were subcontracted, after a call for tender in Morocco, for the 737-NG. RAM was audited on a yearly basis by EASA and two to four times a year by the civil aviation directorate.

Line maintenance can be subcontracted or not. If it is subcontracted, it can be carried out by:

- An organization approved by the Moroccan civil aviation directorate;
- An organization with EASA part 145 approval;
- An organization with FAR approval or a Canadian organization recognized by EASA;
- Integration of a maintenance technician in the RAM quality system, exclusively for Africa.

The RAM procedure QP 06- 04, management of internal and external audits, indicates in part 5 devoted to the procedure for planning audits that for subcontractors with EASA PART 145 approval, the audit takes the form of a questionnaire (Ref. QP 06-04-07) which is sent to the subcontractor by email for assessment. However, the quality manger can decide to carry out an audit on site.

RAM asks its subcontractors to complete a questionnaire every two years.

The RAM Line Maintenance Manual (amended on 29 April 2015, revision 0) sets out the applicable procedures for line maintenance work. Line maintenance includes the rectification of faults reported in the TLB[38] or observed during the daily or weekly inspections.

Each new maintenance subcontractor receives training from a member of the RAM engineering department; a certificate is awarded at the end of this training.

A CD-ROM containing the technical documents required for maintenance, in pdf format, is permanently available in the cockpit of RAM planes. It contains notably the AMM, IPC, WDM, FIM and SSM.

[38] Designated CRM within the company. To avoid confusion with the term Crew Resource Management designated CRM in this report, this acronym is not used here.

1.17.2.1 Aviacare

Aviacare, the RAM subcontractor at the time of the occurrence, was responsible for the line maintenance at Lyon-Saint Exupéry. It held EASA PART 145 approval. In accordance with the procedure, a questionnaire was sent to the company in May 2015. Before this date, Atis Derichbourg carried out the maintenance at Lyon. Aviacare went into liquidation in March 2017. Only one questionnaire was therefore completed by Aviacare.

1.17.2.2 RAM–line maintenance coordination

The RAM's Maintenance Organization Exposition (MOE) describes the organization, means, methods and procedures of the Engineering Division of the RAM group to ensure the maintenance of the aeroplanes and parts of the aeroplanes operated by RAM and those of third-party organizations. Part 2, Maintenance procedures, describes the procedures for maintaining aeroplanes and aeroplane parts in accordance with the required rules and is supplemented by part L2, Additional line maintenance procedures which specifically covers the work procedures at regular stations.

L2.3 - SUIVI DES DEFAUTS ET DEFAUTS REPETITIFS POUR L'ENTRETIEN EN LIGNE.

Arrêté 1027-00 Article 4 Chapitre 4.1.1 (m)

Les défauts en entretien en ligne peuvent être signalés par l'équipage sur le TLB et/ou CLB ou durant les visites d'entretien.

Le personnel habilité APRS doit s'assurer que tous les défauts sont enregistrés sur le TLB et/ou CLB.

Les mécaniciens d'escale et les mécaniciens convoyeurs assurent l'entretien en ligne préventif et curatif. Ils sont habilités à proposer les reports et les tolérances en courrier.

Le report des travaux doit être effectué conformément au chapitre 2.13.2 du MOE.

La coordination entre le personnel APRS en entretien en ligne et l'opérateur pour la rectification et le report des défauts est assurée par le MCC.

Pour les défauts importants et dépannages complexes, ils font appel à la fonction Maintenance Support qui, par téléphone, fax, télex et moyens HF, les assiste techniquement 24 heures / 24 et 7 jours / 7.

La fonction Maintenance Support dispose des moyens suivants pour le suivi et le traitement des défauts ponctuels et répétitifs :

- Télex ou e-mail "ETAT MACHINE" envoyé par le mécanicien responsable du traitement avion à chaque touchée escale. Ce télex reprend les enregistrements techniques du vol précédent et des travaux d'entretien effectués ou reportés (voir chapitre 3 du Manuel Entretien en Escale (MEE)).
- Feuillets du TLB (Technical Log Book), du CLB (Cabin Log Book), et ELB pour le B787.
- Suivi du DDM.
- Historique des dépannages dans le système informatique AMOS.

Pour les exploitants sous-contrat, les contrats d'assistance peuvent prévoir des procédures traitant le suivi des défauts pour l'entretien en ligne.

La notification des anomalies classées est effectuée suivant le chapitre 2.18 du MOE.

Figure 13: Excerpt from RAM - MOE / L2.3 document

Part L2.3 of the MOE deals with the follow-up of faults and repetitive faults in line maintenance. It is indicated that the coordination between the line maintenance APRS personnel and the operator to rectify and defer faults is ensured by the Maintenance Control Centre (MCC). For major faults and complex repairs, they must contact Maintenance Support who by telephone, fax, telex and radio, will assist them technically 24/7.

It is specified that the RAM Maintenance Support has access to the TLB and the repair history in the AMOS computer system.

It is indicated that for the operators under contract, procedures for dealing with faults in line maintenance can be set up.

1.17.2.3 Technical Log Book

Royal Air Maroc uses a system to record operating faults and anomalies discovered during operation as well as all the maintenance operations carried out on the plane between the scheduled inspections on the maintenance sites. It is composed of:

- ❒ Technical Log Book (TLB);
- ❒ Hold Item List (HIL);
- ❒ Cabin Log Book (CLB).

The TLB is an aircraft document used to record operating information relating to the aeroplane's equipment and systems.

Chapter 8.1.11 of the RAM's Operations Manual indicates that for each flight, the TLB must be completed and signed by the captain. This information includes:

- The captain's name.
- Date, number and leg of flight.
- Flight time (airborne).
- Planned quantity of fuel on board.
- Quantity of fuel taken on board during refuelling.
- Quantity of fuel available in tanks when refuelling started.
- Details concerning any fault likely to affect airworthiness or operating safety, including the safety systems. If no complaints are reported during the leg, then "NTR" or "NIL" is entered in the "REP" section. Any information entered in the TLB must not be deletable, it can be corrected in case of error provided that the correction is identifiable and the error remains legible.

It is specified in the Operator's Maintenance Manual, that all the complaints and the processing of occasional or repetitive faults indicated in the TLB are recorded on AMOS.

1.17.2.4 Management of intermittent faults

Intermittent faults, as opposed to determinate faults, are faults which can appear at random, for a period which can also be random.

Boeing's FIM is organized into tasks. The majority of these tasks have an initial evaluation step before complying with the fault isolation procedure for the fault encountered.

The initial evaluation step of the task is used generally to confirm whether the fault encountered is current.

If the fault is not current, the task being carried out will not isolate the fault as it is an intermittent fault.

The FIM indicates that in case of an intermittent fault, the technician must:

- Follow the company policy in this respect.
- Use his judgement and the aeroplane's maintenance history to decide on the action to be carried out.
- Monitor the aeroplane to see whether the fault occurs on the following flights.
- If the fault reoccurs on subsequent flights, then use his own judgement to determine what maintenance action should be carried out.

In the case of CN-ROJ, the fault linked to FCC B not receiving data from RA 2 (22-11052 Radio Alt-2 (J1B-B04, A04)) was an intermittent fault. It appeared several times without maintenance being able to obtain its confirmation on the ground.

On 10 December, the job card associated with the maintenance actions carried out indicates that the DFCS BITE self-test for channels A and B was successful. Faults linked to FCC A and FCC B were recorded. The crew mentioned that the RA 2 amber light had illuminated during the disconnection of the A/P. The RA 2 was replaced.

On 25 December, the TLB specifies that the DFCS BITE was carried out and that the tests (probably self-tests) were successfully completed although this fault had been recorded on that very day.

On 2 January, crews reported the following messages for different flights in the TLB:

- *"ILS APP MODE UNAVAILABLE IN BOTH A/P A AND B"*
- *"IRS-L DRIFT MSG VERIFY POS: IRS L"*
- *"A/P B DISCONNECTED AT G/S CAPTURE"*
- *"A/P B DISCONNECTED AT G/S CAPTURE"*

The message, "*52 RADIO ALT-2 (J1B-B04,A04) NO RADIO ALT DATA*", responsible for the disconnection of A/P B was recorded several times in the FCC B BITE that day. On the ground, the DFCS BITE were carried out and no mention was made of this message being read by maintenance in the TLB. However, FCC B was replaced.

1.17.3 Air traffic control units

1.17.3.1 Organisation of air traffic control at Lyon-Saint Exupéry

The Lyon-Saint Exupéry air traffic control unit manages the air traffic flying inside the Lyon flight information sector as well as the Lyon TMA and CTR.

For this purpose, the service is organized into the following sectors: PRE-FLIGHT, GND, LOC, DEP, INI, ITM, and INFO.

The sectors concerned by this occurrence are the following:

- INI: The initial approach sector (which is broken down into the sub-sectors east and west) which covers the different IAF and the specific routes described in the operational documents.
- ITM: The ITM sector which manages the aircraft transferred by the INI sector up to the transfer to the destination airport control unit.
- DEP: The departure sector (which is broken down into the sub-sectors east and west) which covers the Lyon SID procedures, the specific routes described in the operational documents and the management of inbound or outbound traffic of certain satellite airfields.
- LOC: The LOC sector which is responsible for the Lyon CTR, the runways, their safety areas and the taxiways.

Note: All of the INI, ITM, and DEP sectors are often designated by the generic term "Approach".

1.17.3.2 Control procedures

1.17.3.2.1 Vectoring to ILS procedures

The French order of 6 July 1992 regarding procedures for units providing air navigation services to general air traffic aircraft (RCA 3) stipulates, notably that:

- An aircraft using a final approach aid where the data is interpreted by the pilot must be instructed to call back when it is correctly established on the final approach path. Radar vectoring ends at this time. (Paragraph 10.7.4.2).
- The approach clearance is given:
  - before the IAF for an aircraft cleared to carry out a complete instrument approach procedure;
  - in case of radar vectoring, the approach clearance can be differed until the last vector clearance (paragraph 4.3.1.5).

1.17.3.2.2 Missed approach procedure

The Lyon-Saint Exupéry operations manual stipulates that the missed approach procedure, regardless of the runway used, is for the aircraft to climb straight ahead to 5,000 ft and to anticipate radar vectoring. It specifies that if necessary, the controller can anticipate a possible modification to the missed approach procedure by amending it at the beginning of the final approach. It is specified that during the initial go-around phase, this procedure can only be amended in case of necessity in order to ensure the required separations.

1.17.3.2.3 MSAW

If the aircraft is not being radar vectored, the controller must, in the event of a MSAW:

- ❒ Immediately inform the pilot that a terrain alert has been generated.
- ❒ Instruct the pilot to immediately check the aircraft's level or altitude.
- ❒ Supply the QNH.

The following phraseology is to be used:

"*xxxxxxx, terrain alert, check your altitude immediately, Q_N_H xxxxxx*"

If the aircraft is being radar vectored, the controller must:

- ❒ Instruct the pilot to immediately climb to a level above or equal to the radar minimum safe altitude.
- ❒ Supply the QNH.
- ❒ if necessary, give the pilot a new radar heading to avoid the terrain.

The following phraseology is to be used:

"*xxxxxx, immediately climb xxxx feet, Q_N_H xxxx, immediately, due terrain*".

1.18 Additional information

1.18.1 Captain's statement

The captain explained that to prepare the flight, he had downloaded the operational flight plan onto his tablet. The flight plan mentioned two alternate airports (Nantes-Atlantique and Lyon-Saint Exupéry). He added that due to the adverse weather conditions at Paris-Orly, he had asked for a discretionary ton of fuel instead of the 500 kg that he usually added. He expected that they would have to carry out a CAT III approach to Paris-Orly.

The captain indicated that during the ground actions, the LNAV[39] lights had directly changed to green when they were armed. He disconnected the LNAV mode, reconnecting it at an altitude of around 400 ft.

He explained that around one hour after take-off, he observed the "*L IRS DRIFT*" message displayed on the CDU. He was not able to find this message in the documents on his tablet. He specified that the position and airspeed indicated by the left IRS varied and that the position of the right IRS was normal. At this point, he thought that the left IRS was in the process of correcting itself and approaching the actual position of the aeroplane. The position of the left IRS rejoined and then exceeded the actual position of the plane. He hoped that the problem would correct itself before the final to Paris-Orly.

Then the "*Check IRS Position*"[40] message appeared. He indicated that it was a message which was not often seen and which disappeared when the positioning systems were reset, generally by selecting radio navigation equipment.

[39] Navigation mode for which the FMS produces a lateral vector.

[40] It was in fact the "*VERIFY POS: IRS-IRS*" message.

He explained that during the arrival briefing, the weather conditions at Nantes airport were adverse, Lyon was in CAT I. He added that the Marseilles and Bordeaux airport meteorological reports indicated CAVOK. He specified that diversions to these two cities were not specified on the flight plan. He explained that the CAT I approach to Lyon was suitable; the high-speed train being a possible means of transporting passengers to Paris. Despite his preference for Bordeaux, he confirmed Lyon as the alternate airport in case of a problem at Paris-Orly in order to stay compliant with the flight plan.

During the CAT III ILS approach to runway 06 at Paris-Orly, A/P B disconnected just after being activated. The crew immediately performed a go-around and asked for clearance to divert to Lyon airport. He cannot remember telling the controller what the problem was. He added that it was during the diversion to Lyon that fuel management had become a concern.

The pilot indicated that during the descent, the Auto-brake selector was set to 3. The "*AUTOBRAKE DISARM"* message appeared and the selector was set to "OFF". Furthermore, when he selected the LSE VOR on the CDU, the system indicated that the radio navigation equipment was at a distance of 3,000 NM. He specified that the NOTAM indicating that the LSE VOR had been replaced by the VMP VOR was in the "En route" part and not the "Terminal" part of the flight plan. These two elements were described as stressful.

He explained that the approach was carried out in IMC with a radar vector to runway 35R. The ILS was captured in VOR/LOC mode with the A/P engaged. The aeroplane turned right instead of turning left. The captain indicated that this event was particularly stressful. He thought that this untimely manoeuvre was linked to the reception of a false LOC signal and informed the Tower of a path problem before carrying out a go-around.

During the missed approach, the L IRS FAULT light illuminated. He set the IRS TRANSFER switch to "*BOTH ON R*" and engaged A/P B. He specified that he did not get out the check-list due to lack of time and because they were under high time pressure.

Shortly afterwards, the co-pilot and the captain changed roles: the co-pilot became the PF. At this point, the captain indicated that he had doubts about the plane's position and questioned the appropriateness of a new approach to Lyon over a diversion to Marseille Provence airport. He specified that the ACARS displayed the message "*ACARS NO COM*"; as a consequence, the crew only had the previous hour's meteorological information for Marseilles. This new event made the captain even more worried about the technical condition of the aeroplane and its systems.

He indicated that the Lyon Tower asked them for their intentions. He decided to carry out a second approach to Lyon. He specified that the crew had received inbound headings with A/P B in operation.

He stated that after the LOC radio signal had been captured, the A/P disconnected on intercepting the GS; the co-pilot then called out that he was transferring control to the captain, and the latter became PF again. The aeroplane was in clouds and "Flaps 5" configuration. He indicated that he had doubts about the position of the plane, that the workload was very high and that the remaining quantity of fuel was an additional cause for concern for him. He added that he then heard numerous warnings including the "*Terrain*" and "*Glide Slope*" warnings; he could not remember hearing the "PULL UP" message but it was possible that it had been activated.

The captain explained that the aeroplane came out of the cloud layer at a height of around 400 ft and to the left of the centreline of runway 35R. He accepted the Tower controller's proposal to carry out a side-step to runway 35R. He specified that he was aware that the aeroplane was not stabilized but that he preferred correcting the path and landing due to the stress level generated by the two missed instrument approaches already made. He added that after landing, he saw the low fuel message in relation to one of the fuel tanks; he had not noticed anything in particular with respect to the F/D. He explained that they had had *to "fight the plane"* and were happy to be on the ground.

Once the aeroplane was in the parking, the crew contacted the company which carried out the air vehicle cross servicing for the operator. A technician came to the plane and restarted the IRS. The captain indicated that he was not satisfied with the work and called the engineering department at the operator's base. The engineering department asked the technician to check the avionics bay for possible signs of water on the IRS (due to previous occurrences).

The technician indicated that there were no signs of water. The captain therefore decided to take-off for Paris-Orly airport taking a fuel uplift of 10 tonnes (in order to be able to divert to any airport if necessary). The improvement in the meteorological conditions (CAT I approach) also contributed to this decision.

The flight between Lyon and Orly was uneventful. However, the captain explained that during the return flight between Orly and Marrakesh, on final, with the co-pilot as PF, and A/P B in operation, the F/D disappeared then the A/P disconnected on intercepting the ILS. He recorded this in the TLB. He specified that the landing was carried out in VMC without any problem.

1.18.2 Co-pilot's statement

The co-pilot explained that during the flight preparation (Rabat – Paris Orly – Marrakech), there was reduced visibility at Paris Orly and a CAT III approach was planned. The alternate airports specified by the dispatch office were Lille and Lyon; he remembered that the forecast ceiling at Lyon was 400 ft and that a CAT III approach was in force at Lille. He specified that he was PM on the flight between Rabat Salé Paris Orly airports and that an additional ton of fuel had been uplifted.

He indicated that around 1 h 30 min after take-off, the "*IRS L DRIFT*" message appeared on the CDU. He specified that both pilots had looked for the meaning of this message in the FCOM and QRH without being able to find it. He added that the pilots checked the position and speed information on the CDU's POS INIT 2 page. They then observed significant inconsistencies concerning the indicated airspeed given by the left IRS; this speed varied between 200 and 600 kt while the indicated airspeed given by the right IRS was 400 kt. They also observed a difference in position between the two IRS.

Around 30 minutes after the appearance of this first message, a new message, "*VERIFY POS – IRS*" was displayed on the CDU. The co-pilot explained that the two pilots did not look for the meaning of the latter message as they knew it and the aeroplane was in descent. He added that on seeing the speed values of the two IRS converge, they decided to wait, and discussed the diversions and the CAT III approach. Given that there was no Master Caution warning and "*IRS FAIL*" message, they considered that the IRS was operating and that the values would become consistent again.

They carried out a CAT III approach to Orly with Lyon as the alternate airport where a CAT I was possible. The co-pilot indicated that after intercepting the ILS, at the FAF, the second A/P had not engaged and the crew carried out a missed approach and then diverted to Lyon airport where a CAT I approach was possible.

The co-pilot explained that during the VOR/LOC approach to Lyon, on intercepting the LOC, with the A/P engaged and the LOC mode activated, the aeroplane turned right although the airport was on the left. He specified that the crew had not understood what had caused the problem and flew a missed approach. During this go-around, the "*IRS FAULT*" warning was activated. The corresponding check-list was not carried out due to the pilots' lack of availability, being worried by the fuel management.

The captain (PF) set the *IRS TRANSFER* switch to "*BOTH ON R*". They then swapped over the PF and PM roles. He indicated that during the second approach, on intercepting the LOC, the A/P disengaged itself again; he specified that the F/D disappeared from both sides. He added that the captain took control of the aircraft again after the flaps were extended to the first detent position and the approach was flown in manual with neither the A/P nor the F/D. He specified that he did not call out the LOC and GLIDE deviations as the PF was in the process of correcting them. He then heard the "*GLIDE SLOPE*" and "*PULL UP*" warnings[41]. Following this latter warning, he called out for a new missed approach; at the same time, the two pilots saw the runway and the PF carried out a side-step before landing. He specified that they preferred to land in order not to continue any longer with a degraded aircraft.

The co-pilot described the occurrence as being very stressful with a lot of systems that were not operating.

He specified that the crew did not transmit a "*PAN PAN*" message for a mere A/P fault. He estimated that there was around 1,900 kg of remaining fuel after landing at Lyon.

He added that after the incident, the captain contacted the company by telephone. They did not discuss the occurrence of the GPWS warnings, or the need to preserve the CVR.

[41] The investigation found that the "*Too Low Terrain*" aural warning had been generated and that it had been accompanied by the display of the PULL UP message on the attitude indicator of the two PFD. There was no "*PULL UP*" aural warning (see paragraph 1.6.2.3).

1.18.3 Lyon-Saint Exupéry line maintenance technician

The technician who carried out the maintenance at Lyon Saint-Exupéry indicated that line maintenance with RAM was mainly carried out by following the telephone instructions given by the MCC. He specified that he did not have the technical documents. He indicated that the MCC asked him to restart the IRS before aligning them. He specified that these steps were carried out without a fault appearing. He did not look for fault messages using the CDU.

1.18.3 Controllers

1.18.4.1 Lyon Saint-Exupéry approach (INI) controller

Note: during the occurrence, the INI E, INI W and ITM sectors were combined under the name INI and the corresponding control position was manned by a controller and an assistant.

The controller indicated that the occurrence took place in the morning, in degraded meteorological but not LVP conditions. There had just been a handover. There was little traffic as the peak of activity was over and there were only two or three aeroplanes on the frequency. The situation was perfectly normal.

The controller could not remember that the pilot reported a particular problem on checking in. Having checked by means of the radar display that the aircraft was on the approach slope, he transferred it to the Tower controller.

The plane seemed to him to be correctly aligned on the Localizer, but just after it had left his frequency, he saw it deviate from the path.

The assistant controller called the Tower controller to ask what the plane was doing.

The INI controller asked his assistant to offer, to the LOC controller, that they take back the plane for the approach.

The controller noted that when the pilot came back onto the INI frequency, he spoke in French.

The latter seemed very stressed to him. The controller deduced from this that he was in a rush, thinking that he did not have a lot of fuel.

Without insisting so as not to increase the onboard workload, the controller indicated that he supplied radar vectors to the plane and gave him an interception heading.

He added that the pilot asked him if he was correctly aligned on the ILS path. The controller replied by giving him the correct ILS frequency. The pilot then told him that he was not capturing the Localizer but that he would continue in manual.

Unsure as to what the pilot meant by this last sentence, the controller asked him if he was talking about a visual approach. He emphasised that he asked the crew if they had visual contact with the installations as he doubted this was the case given the weather conditions, and proposed the option of a missed approach.

He then called the Tower who asked him to transfer the plane.

A MSAW was activated but he no longer had the plane on the frequency.

The controller added that the crew had never clearly explained the problems that they were experiencing which meant that he could not help them more.

1.18.4.2 Tower (LOC) controller

The Tower controller was informed by the supervisor of the Marseilles En route control centre that the RAM flight was diverting from Orly due to meteorological conditions. The LVP conditions at Lyon had just been lifted. The ceiling was at around 300 ft. The approach lights were at maximum brightness.

The controller saw the aeroplane on the approach without being particularly worried. His role was to manage the runways. The crew reported that they were established on the centreline of runway 35R whereas the plane had a northeasterly heading (40-50° right of the centreline). He realised this and informed the crew, asking them if they had visual contact without really believing that this was possible. The aeroplane carried out a go-around. The controller asked them to contact the Approach.

The Approach vectored them again. The LOC controller monitored the path.

During the aeroplane's transfer from the Approach to the Tower, the MSAW was activated. When he had the aeroplane on the frequency again, the warning had stopped and the rate of descent was "*consistent*".

He gave them bearings by indicating distances and heights. There were then a few exchanges which were difficult to understand. The crew finally told him that they had "*contact*" which he understood as the crew having visual contact with the runway and the controller cleared them to land.

The controller indicated that the aeroplane made an "*acrobatic*" landing. The aeroplane vacated the runway. The controller asked the crew if they required assistance. The crew replied that all was well.

2 - ANALYSIS

2.1 Scenario

2.1.1 En route FMC alert messages (left IRS)

Around one hour after take-off, the Flight Management Computer (FMC) detected inconsistent aeroplane speed and position data coming from the left Inertial Reference System (IRS). The "*IRS-L DRIFT*" alert message was displayed on the screen of the Control Display Unit (CDU). Unable to find the procedure associated with this message in the onboard documentation, the crew carried out actions from memory, which consisted of checking the position given by the two IRS. It appeared that the left IRS was indicating erroneous and fluctuating position and speed values. The crew observed that the problem seemed to be resolving itself.

During the descent to Paris-Orly, a second alert message appeared on the CDU ("*VERIFY POS: IRS-IRS*"). Given that there was no *Master Caution* and *IRS FAULT* warnings, the crew considered that the IRS was operating and that the values would become consistent again before arriving at Paris-Orly.

The crew decided to continue to Paris-Orly on a CAT III ILS 06 approach and to divert to Lyon if there was a problem during the approach.

2.1.2 CAT III approach to Paris-Orly and impossibility to engage both A/P

On intercepting the LOC signal, the A/P commanded an S-shaped path around the LOC path which led the Approach controller to ask the crew if they had indeed intercepted the LOC. The crew did not reply.

The flight was transferred to the Tower without being given an approach clearance. The APP mode was thus not armed. As a consequence, the crew's attempt to engage both A/P at this point failed.

After receiving the approach clearance from the Tower and arming the APP mode, the crew twice tried to engage the second A/P (A/P B). This time, it was the Flight Control Computer (FCC B) not receiving RA 2 data which prevented A/P B from being engaged and also caused A/P A to disengage. The CAT III ILS approach could not be carried out with this malfunction.

The crew re-engaged A/P A, informed the controller that they could not perform a CAT III ILS, and requested to fly a missed approach and divert to Lyon-Saint Exupéry airport. Conditions at Lyon permitted a CAT I ILS approach, which could be carried out with only one A/P functioning.

On carrying out the missed approach at Paris-Orly to head to Lyon, the quantity of fuel on board permitted an estimated holding time of 27 minutes at Lyon[42], before carrying out the approach and landing at the alternate airport with a final fuel quantity of 1,100 kg.

[42] Taking into account the trip fuel of 2,100 kg between Orly and Lyon (including approach to Lyon) and a holding fuel consumption of 40 kg/mn.

2.1.3 Diversion to Lyon

During the diversion and the preparation for the ILS 35R approach to Lyon-Saint Exupéry, the crew indicated that they tried to arm, without success, the automatic braking system and observed that the amber *AUTOBRAKE DISARM* light came on.

The non-operation of the automatic braking system was possibly linked to the malfunction of the left IRS.

As the manufacturer's documentation did not indicate the possible consequences of the FMC *"IRS-L DRIFT"* and "*VERIFY POS: IRS-IRS"* messages on the automatic braking system, and as the *IRS FAULT* light was not illuminated, the crew had no way of anticipating the non-arming of the automatic braking system and of being informed of the left IRS malfunction which seemed to be nevertheless present at this moment.

The erroneous selection of the LSE VOR combined with the indication on the CDU that the LSE VOR was situated at an improbable distance then made the crew doubt the position of the plane given by the FMS.

2.1.4 First missed approach at Lyon and IRS FAULT warning

When the A/P changed to intercept mode and the Localizer radio signal was captured (green VOR/ LOC mode), the aeroplane suddenly veered to the right with a bank angle of 30°, crossed the Localizer path and then departed from it on a clearly divergent heading (heading 70°) without any onboard warning being activated. This untimely right turn was commanded by the A/P due to the erroneous data from the IRS module of the left ADIRU.

The captain thought that this untimely manoeuvre was linked to the reception of a false LOC signal.

The invalidity of the data supplied by the left ADIRU next led to the disengagement of A/P A. The captain then manually piloted the plane with the F/D displayed on the PFD.

The crew first tried to return to the path. As the deviation from the path compromised continuing the approach, they flew a missed approach. The Tower controller cleared them to climb to 5,000 ft.

The crew selected the target altitude of 5,000 ft on the MCP on climbing through 4,600 ft. The F/D command bars were not followed by the captain who was flying manually. The captain unintentionally exceeded the altitude of 5,000 ft, and engaged A/P B when the aeroplane flew through 5,650 ft still in climb. The aeroplane temporarily stopped climbing and then made a short descent to the selected altitude of 5,000 ft.

The aeroplane had just been transferred to the Approach again when the *L IRS FAULT* warning was activated causing the disengagement of A/P B, and the disappearance of the pitch, roll and heading data along with the F/D bars from the left PFD. The captain again flew manually while carrying out from memory one of the actions of the check-list, namely *IRS Transfer Switch* - BOTH ON R. The two FCC thus used the data supplied by the right ADIRU. The pitch, roll and heading were displayed again on the left PFD and the F/D bars reappeared.

Twenty seconds after his action on the *IRS Transfer Switch*, the captain engaged the A/T and A/P B. The aeroplane which had climbed to an altitude of around 6,500 ft started descending in order to return to 5,000 ft.

The captain transferred control of the aircraft to the co-pilot and then tried to use the ACARS system in order to obtain the latest weather information for a possible diversion to Marseilles. The system displayed the "*ACARS NO COM*" message.

The captain, who said that he was worried about the fuel during this phase, decided to carry out a second approach to Lyon-Saint Exupéry.

At this point, the alternate fuel of 2,100 kg had been used as provided for and the quantity of fuel on board permitted the plane to hold for 27 minutes before making a new approach to Lyon[43] and landing with at least the final fuel quantity of 1,100 kg.

[43] Taking into account the 400 kg required to make a second approach to Lyon.

During this phase, the crew did not carry out the "*IRS FAULT*" check-list in the QRH, as they considered that they lacked time, which meant that they were not aware of the limitations concerning the use of the A/P in approach imposed by the manufacturer.

2.1.5 Second approach to Lyon and non-stabilization of approach

During the Localizer interception phase, the captain asked for a radar vector, indicating that they were having positioning problems. The controller vectored them to the ILS.

The crew carried out a "*fast*" approach with respect to the (speed, flaps, landing gear) configurations recommended by the ILS approach procedure described in the FCOM. A/P B was kept engaged during the approach.

On capturing the Glide, A/P B automatically disengaged due to FCC B not receiving data from RA 2. The F/D then disappeared from both sides. The co-pilot transferred control of the aircraft to the captain. As the A/P had disconnected before starting the final descent, the captain thus had to manage both taking back control of the aircraft and an immediate initiation of descent in order to intercept the approach slope.

This interception was made all the more difficult by the captain not having had the time to calibrate his inputs on the stick, i.e. to adjust them in terms of the force and amplitude required to correct the path deviations, as is the case when the disconnection of the A/P is anticipated and is made by the pilot beforehand.

The captain continued to manage the radio communications until being transferred to the Tower controller and twice informed the Approach controller that he was continuing the approach in manual.

The approach, in manual and without the F/D, was not stabilized with respect to either the path and slope or the aeroplane's speed and configuration. Several EGPWS "*SINK RATE*", "*GLIDE SLOPE*" and "*TOO LOW TERRAIN*" warnings were activated on final.

The go-around called out by the co-pilot was not followed as according to the captain, it was concomitant with sight of the runway. The co-pilot then announced to the controller, in a voice revealing hesitation and substantial stress, that they were continuing the manoeuvre after all.

The captain would specify later that he was aware that the aeroplane was not stabilized but that he preferred correcting the path and landing due to the stress level generated by the two missed approaches already made.

2.2 Consequences and means of detecting an ADIRU malfunction

2.2.1 Consequences of an ADIRU malfunction

During this flight, the left ADIRU, whose inertial module was experiencing internal problems, supplied erroneous or invalid data to several other systems and in particular:

- Erroneous ground speed and position data to the FMC during the en route phase. The problem was detected by the FMC and gave rise to the "*IRS-L DRIFT*" and "*VERIFY POS: IRS-IRS*" alert messages being displayed on the CDU and the activation of the amber FMC lights. The crew were thus informed of the drift of the left IR at these moments of the flight. The FMC automatically stopped taking into account the left IR data for its position calculations in order not to downgrade its accuracy and used the right IR data.
- Erroneous route data for FCC A during the first approach to Lyon. FCC A took this data into account without additional checks and sent an inappropriate right turn command when the aeroplane was in the process of turning left to intercept the Localizer of runway 35R. The plane reached a maximum roll angle of 30° and a heading divergence of 70°. A/P A then disengaged when the route data was declared invalid by the left ADIRU. At this point, the aeroplane was at a distance of around 1.6 NM to the right of the Localizer path.
- Invalid roll angle data for FCC B during the missed approach at Lyon. At this moment, the left IR declared an IR fault and the amber *L IRS FAULT* light illuminated. This led to the disengagement of A/P B.

It is also likely that the left ADIRU sent longitudinal acceleration data and/or ground speed data declared invalid by the automatic braking system during its self-test when the crew wanted to arm it during the descent to Lyon. This is shown by the activation of the amber *AUTOBRAKE DISARM* light on the instrument panel which informed the crew of the impossibility of using the automatic braking system for landing.

The consequences of an ADIRU malfunction are therefore multiple, and their seriousness depends on the capacity of the systems and flight crews to detect this malfunction.

If the ADIRU malfunction is not detected in time, the seriousness of the consequences of the malfunction increases according to the criticality of the system affected, as is the case for a FCC. Indeed, no corrective measure can be applied.

This is what happened during the first approach to Lyon with FCC A engaged. The F/D commands were erroneous and the A/P directed the plane on a path that was nearly perpendicular to that which it should have followed. This phenomenon was also observed to a lesser degree during the same flight to Paris-Orly when the plane followed an *S*-shaped path around the Localizer path when it intercepted it. In total, between 26 December 2016 and 2 January 2017, seven flights were identified during which the A/P had similar difficulties in intercepting the Localizer path during an ILS approach. In some cases, the crew had to take control to correct the plane's path. The erratic paths which resulted from this were very probably due to a malfunction of the left IR.

All the while the ADIRU does not declare it has a fault, systems which do not test the data sent to them use potentially erroneous data, which constitutes a hazard. This is the case of the FCC, except when carrying out approaches with both A/P engaged. This can have significant consequences for the management of the flight, particularly when it occurs in the approach phase. For example:

- In the case of simultaneous parallel approaches to an airport with dense traffic, this could lead to a conflict between several planes. Furthermore, if this conflict occurs at low height, the TCAS systems of the aeroplanes concerned will not transmit a resolution advisory.
- In the case of an approach to an airport with surrounding terrain, this could lead to the plane's path being directed towards the terrain requiring an emergency evasive manoeuvre.

The effects and seriousness of this hazard were assessed by Boeing by carrying out a safety analysis during the design of the FCC (see paragraph 1.16.6). The seriousness during the approach phase was considered "*major*". This assessment was based on the design choices to mitigate the consequences of the hazard, but also on the hypothesis that ultimately it will be detected by the crew who are trained to monitor the aeroplane's path, airspeed and altitude and to correct any deviations from those which were intended. The detection thus relies solely on the crew and no monitoring and detection function for this type of hazard was built into the FCC, except in the case of approaches with both A/P engaged. The crew could therefore only know that inertial data was erroneous if it was declared invalid by the ADIRU, unlike other systems such as the FMC or the automatic braking system.

The validity of the presupposition that the flight crew constantly monitor the automated systems and are ready to immediately react in case of a malfunction is questioned in the Joint Authorities Technical Review (JATR) presenting the work jointly carried out by ten civil aviation authorities along with the NASA and NTSB following the accidents to the Boeing 737-Max in Indonesia and Ethiopia (see paragraph 1.16.6.3). This serious incident along with the comments made by the Joint Authorities, show that the crews' detection and reaction times can be significantly longer than the hypotheses adopted during the design of the aeroplane and in the safety studies. This observation can thus call into question the classification of hazards where the only means of detection is crew monitoring.

2.2.2 ADIRU built-in monitoring and activation of IR FAULT warning

The inherent drift in any inertial reference system cannot be detected by the ADIRU itself as it does not have a reference. The FMC is capable of detecting it because it has access to other information sources such as the GNSS position and the position based on the VOR-DME.

However, the ADIRU can check the consistency of some of its parameters, for example the heading and the route. When the difference between these two parameters is greater than 60° and the plane's ground speed more than 200 kt, the "Drift Angle" fault message is sent and the *IRS FAULT* warning is activated.

However, the definition of the criteria which activate the "Drift Angle" fault message is such that the latter can only appear at a late stage with respect to the start of the ADIRU IR module malfunction. A deviation of more than 60° between the heading and the route is in fact a significant difference.

In case of an ADIRU failure similar to that encountered during this flight, this difference will not be systematically reached. This implies that this type of ADIRU malfunction may not be detected by the crew or by certain systems which use the data supplied by the ADIRU, and which will therefore continue to use it. Thus, during this occurrence, FCC A used erroneous data from the left ADIRU until it declared it had a fault, by emitting the "Drift Angle" message, although its malfunction had appeared 2 min 15 s earlier when the plane started a right turn during the interception of the Localizer path, and even several dozen minutes earlier on trying to arm the automatic braking system and on the appearance of the FMC alert messages.

Likewise, when the plane's ground speed is less than 200 kt in the final approach phase, the "Drift Angle" fault message cannot be sent. This was the case during a flight on 26 December 2016, i.e. four days before the occurrence flight, during which the aeroplane turned right with A/P A engaged although it was going to capture the Localizer path. This unexpected plane manoeuvre was probably due to the malfunction of the left IR but as the aeroplane's speed was at around 180 kt at the time, the "Drift Angle" fault message, the trigger factor for the *IRS FAULT* warning could not be activated.

The AAIB also underlined this significant time period between the start of the ADIRU malfunction and the appearance of the "Drift Angle" fault in its investigation report concerning the serious incident to the Boeing 737-800 registered EI-GJT[44] on 9 October 2018 while in cruise.

[44] https://assets.publishing.service.gov.uk/media/5f58dab2d3bf7f7232e7e631/Boeing_737-8AS_EI-GJT_12-19.pdf

It can be seen that the absence of a FCC check of the validity of the inertial data transmitted by the ADIRU, except in the case of approaches with both A/P engaged, along with the ADIRU's built-in monitoring logic with respect to the "Drift Angle" fault, can result in the FCC using erroneous inertial data in case of a malfunction of the IR module, for an extended period, and have a significant disruptive effect on the plane's path, particularly in the final approach phase.

2.3 Progressive loss of confidence in plane and stress generated

Both pilots, during their interviews, expressed the large amount of stress that they had felt. The co-pilot mentioned a very stressful occurrence with a lot of systems that were not operating; the captain explained that they had fought the plane and that they were relieved when they touched down.

During the first part of the flight, the crew were confronted with minor disruptions. The first two FMC messages, "*IRS-L DRIFT*" and "*VERIFY POS: IRS-IRS*", did not initially have an impact on the management of the flight; the pilots observed the inconsistencies of the left IRS speed and the position differences between the two IRS and then saw that the problem seemed to be resolving itself. The first unsettling element was the absence of a description of the "*IRS-L DRIFT*" message in the documentation. The second message was not unusual for the crew, as it occurred from time to time and also led the crew to monitor the consistency of the data from the two IRS.

The first deviation on capturing the LOC at Paris-Orly does not seem to be significant for the crew, they did not reply to the controller when questioned about it and did not mention it when they were interviewed. At this point, it was nearly impossible for the crew to link this deviation with the messages previously received. The crew also did not mention that they were unable to engage the two A/P due to the APP mode not being armed in their statements; it was a minor operational disruption without consequence at the time that it occurred. However, it might have instilled doubts in the crew's mind as to their control of the situation or been assimilated subsequently with the other disengagements of the A/P.

No element allowed the crew to understand that the disengagement of the A/P which subsequently occurred on capturing the LOC at Paris-Orly was due to the RA 2 problem. There was no message in the cockpit to explain the cause of it.

A CAT I missed approach and diversion, although planned for, are nevertheless infrequent events, and are very consuming in crew resources. The captain explained that the crew started to become concerned about fuel levels at this point. Lyon airport was the planned alternate airport and the quantity of fuel required was present on board. However, the alternate fuel was for a single approach to the alternate airport.

It is likely that at this moment the crew were worried about the quantity of remaining fuel on board in case of possible unexpected events.

During the descent, the "*AUTOBRAKE DISARM*" message was displayed. Then when the VOR selected on the CDU was indicated as being at a distance of more than 3,000 NM, the crew, whose confidence in the plane was already degraded, attributed this new malfunction to the aeroplane's positioning systems without being able to explain the cause.

At this point, the crew, starting a new approach to Lyon, may have had in mind the "acceptable" weather conditions, a possible drift of the left IRS, a possible A/P problem, the non-availability of the automatic braking system and possible malfunctions of the navigation systems. However, besides the perception and understanding of elements, one of the fundamental components of situational awareness is the possibility of foreseeing their status in the near future. This projection was not possible for the crew as certain malfunctions could not be easily explained. For other malfunctions, such as the problems with the VOR which are radio-electrical systems with their own frequency and which do not rely on the data supplied by the IRS, a confirmation bias may have led them to interpret any disruption as revealing a new malfunction of the plane's systems.

This difficulty in constructing appropriate situational awareness may explain the stress gradually felt by the crew. Stress results, in general, from the interaction between a person's assessment of a situation, their capacity to deal with it and their perception of the importance of dealing with it. In the context of the flight, the crew could consider the situation as perilous especially since the malfunctions seemed to be unconnected and were thus all the more difficult to foresee; the importance of dealing with the situation was accentuated by the concern about the fuel. This concern created a vicious circle: the apprehension about having insufficient fuel generated time pressure which led the crew to think that it was important to quickly deal with the situation. The time pressure which they felt they were under meant that they did not objectify the problem and overestimated its importance.

The first missed approach at Lyon, following the major path deviation and disengagement of the A/P was the tipping point where the stress felt by the crew reached such a level that it affected the management of the flight. This overwhelming stress level is mentioned in the crew's statements and can also be observed in the exchanges with the control, whether it be in terms of the tone used or the requests made.

It was also shown by the dissociation of the crew, the workload no longer being shared, the check-lists and fault isolation procedures not being carried out due to the perceived time pressure and the captain seeming to act alone, for example after the co-pilot transferred control to him during the second approach to Lyon (see paragraph 2.4). The consequences of the stress on the management of the flight are evident: exceedance of the cleared flight level by more than 1,500 ft, a non-stabilized approach beyond the stabilization minima defined by the operator and multiple deviations giving rise to the EGPWS warnings.

During the flight, the crew were confronted with various malfunctions either linked to technical failures or of an operational nature. Confronted with malfunctions which they could not explain, foresee or interconnect, their confidence in the plane progressively decreased, their attention being particularly focused on the fuel level which they believed insufficient. Each instant delaying the landing risked seeing new faults appear. The crew had thus progressively passed from conventional management in normal mode, at the beginning of the flight, to "*emergency*" mode management with them wanting to land as quickly as possible.

Yet the meteorological conditions at the alternate airport allowed a CAT I approach which could be carried out in manual and the remaining fuel on board permitted holding and continuing the flight without haste.

A gulf was thus created between the actual status of the plane and the crew's perception of it.

2.4 Workload and crew cooperation

In the absence of CVR data, it was not possible to analyse crew cooperation in detail in the scope of the investigation. However, the playback of the exchanges with the control units and the statements brought to light the following points.

No notable event can be singled out during the first part of the flight. In the statements, when the pilots mentioned the first messages on the CDU, they explained that they both looked in the documentation and consulted each other about the choice of Lyon as the alternate airport.

The workload in the cockpit was high at times as was shown, for example, by the lack of response to the Paris- Orly controller's question during the erratic interception of the LOC.

The workload then became so high that at certain moments the crew gave priority to some tasks by voluntarily omitting others. When the *L IRS FAULT* occurred, the captain who was the PF, without the A/P engaged, explained that he set the *IRS Transfer Switch to BOTH ON R*. While carrying out this action, the aeroplane exceeded the cleared flight level by more than 1,500 ft. The captain explained in his statement that the crew did not get out the check-list because of lack of time.

The crew redefined the roles to mange the extra workload. When the A/P was engaged again, the captain became PM and managed the radio communications in order to ask the controller for radar vectoring and help with capturing the LOC. When A/P B disengaged on capturing the Glide, the captain became the PF again on the co-pilot's request, but kept, nevertheless, the radio communications and asked the controller for assistance in helping them confirm the capture of the LOC and glide. The captain who had been using English up until this point, changed to French. The vocabulary used was the same as that used previously in English, thus the change to French cannot be associated with a language problem but was symptomatic of a cognitive overload.

The division of tasks appears to become more standard again thereafter, the captain kept control of the aircraft and the co-pilot took back the radio. However, during the last two minutes of the flight, the crew tasks are dissociated. The captain continued the final approach in manual, the co-pilot was in continuous communication with the controller and made a go-around call. At the same time, the crew made visual contact with the runway and the captain continued the approach.

With the increase in stress level, the CRM became weak at a time when the situation and high workload required an appropriate division and prioritization of tasks.

2.5 Crew/air traffic control interface

2.5.1 Approach-Tower transfer

At Paris-Orly, after receiving confirmation that the aeroplane had indeed intercepted the Localizer, the Approach controller transferred the flight to the Tower controller without giving the approach clearance beforehand. This meant that there was a delay in the crew arming the APP mode. During the first approach to Lyon-Saint Exupéry, the Approach controller transferred the flight to the Tower controller without having first asked the crew to call back when they were established on the Localizer. Immediately after this transfer, the aeroplane entered an unexpected turn in the opposite direction to the turn to intercept the Localizer and took a clearly divergent path to the Localizer path. The Approach controller realised this and tried to call back the crew. The crew had already left the frequency. The Tower controller was contacted a few moments later by the crew who reported first of all, that they were on final for runway 35R before reporting six seconds later that they were performing a go-around, which required a transfer back to the Approach. Keeping the plane on the Approach frequency, which was both necessary and a regulatory requirement as the plane was not established on the Localizer, could have permitted better continuity in the management of the flight and have thus reduced the onboard workload.

2.5.2 Crew-air traffic control exchanges

The exchanges between the crew and the air traffic control were based on a lot of implicit elements and did not permit the latter to have a precise understanding of what was happening on board. During the first approach to Lyon, despite the deviation from the path observed, the Approach controller did not inquire about the problems encountered. He thought, on giving the last radar vector to the ILS, that there was a possible fuel problem and thus proposed a shortened path to the crew. This was not of a nature to contribute to a second approach in the best conditions. As for the crew, they only mentioned the type of problems encountered to the air traffic control during the second approach to Lyon-Saint Exupéry when they reported a positioning problem.

The weakness of these exchanges meant that the air traffic control could not provide suitable assistance.

2.6 RAM practices

2.6.1 ILS interception

A company practice consists of keeping the VOR frequency displayed on the PM's side until the glide has been captured, in contrast with the FCOM Approach procedure which indicates that for an ILS approach, the crew must display the Localizer frequencies before the IAF or well before the start of the vectoring to the final approach path when being radar vectored.

The consequence of this company practice is to cause the F/D to disappear from the PM's side if the VOR is still set when the LOC mode is engaged.

Furthermore, the FCOM specifies in this respect that having different frequencies on the two VHF/NAV receivers may lead to a difference in the left and right F/D display and affect the operation of the engaged A/P.

This practice may also accustom crews to the phenomenon of the F/D disappearing. Thus this may no longer constitute a system failure requiring a systematic report to be made in the TLB. However, as shown by this investigation, these disappearances may be the consequence of technical problems requiring maintenance work.

Lastly, numerous fault messages regarding the MMR and the VHF/NAV control panels were recorded in the FCC BITE because of this practice. This misled the RAM maintenance department which thought that these systems were experiencing technical problems.

2.6.2 Non-systematic reporting of technical dysfunctions, encountered by the flight crews, in the TLB

The analysis of the QAR data and fault messages recorded in the FCC BITE brought to light that the RAM crews did not systematically report the technical malfunctions in the CN-ROJ TLB.

The crews being used to the phenomenon of the F/D disappearing, explained above, may be one of the reasons for this.

However, it is more difficult to explain the absence of reports concerning the automatic disengagements of an A/P or the malfunctions of an ADIRU shown by the appearance of an IR FAULT warning or FMC alert messages.

The RAM's Operations Manual specifies that the captain must make a detailed entry in the TLB about any fault likely to affect airworthiness or operating safety, including the safety systems. This principle was not sufficiently complied with by the RAM pilots over the period analysed by the BEA.

The crew reports play an essential role in the maintenance actions that will be carried out on the aircraft a posteriori. If a fault which occurs in flight is not reported, it will not be the subject of a corrective maintenance action or specific monitoring by the department responsible for monitoring and managing faults.

Systematic reporting of the faults and anomalies encountered by the crew gives the maintenance department the possibility of correcting the problems or in the case of intermittent faults, of monitoring their evolution. It would have permitted the RAM maintenance department to be better prepared for resolving the problems encountered on this plane. In particular, it would have probably been able to identify the communication problem between RA 2 and FCC B sooner and to replace the left ADIRU more quickly.

Furthermore, if the FMC "*VERIFY POS: IRS-IRS*" message which occurred in flight had been recorded in the TLB, after landing at Lyon, it would have permitted the maintenance personnel to observe that the residual ground speed recorded at the end of the occurrence flights was 187 kt, which required the replacement of the ADIRU (residual ground speed error of more than 21 kt).

2.7 RAM maintenance

2.7.1 Management of RA 2 fault

The examination of the FCC carried out after the incident showed that RA 2 of CN-ROJ had been encountering malfunctions since 26 June 2016, i.e. around six months before the occurrence. These malfunctions, shown by the *RADIO ALT-2 (J1B-B04, A04)* fault message in the BITE of FCC B, were due to the FCC B not receiving valid data from RA 2. These fault messages had consequences on the automated systems: disappearance of the F/D display and/or disengagement of the A/P during the approach phase.

In the six months up until the day before the occurrence, this fault linked to RA 2 was recorded 35 times, including 16 times since 9 December. During the occurrence flight, this same fault, *RADIO ALT-2 (J1B-B04, A04)* was recorded seven times in FCC B.

Although not systematically reported by the crews in the TLB, these malfunctions were indicated after flights carried out on 10, 12 and 25 December. In the TLB of these flights, the maintenance operation steps were not all systematically indicated which meant that it was not possible for the BEA to follow the complete sequence of each maintenance action. RAM indicated to the BEA that the reply in the TLB was the final/major maintenance action carried out on entering the engineering shop [(45)]. The reading of the maintenance documents suggests that the fault did not reappear during the ground tests, thereby indicating, in accordance with the FIM, that either it was intermittent or it only appeared in flight conditions.

The Boeing procedure indicates that, in this case, the maintenance technicians must comply with the operator's policy for processing intermittent faults, use their judgement and the operator's maintenance history and specifically monitor the aeroplane in question.

Following the crew's report of a problem linked to RA 2 on 10 December 2016, RAM replaced it. However, the fault occurred again on 12 December 2016. The cause of the fault was therefore not removed. It then reoccurred on 25 December 2016 after 54 problem-free flights. FCC B was replaced three days after the occurrence, on 2 January 2017, without the problem disappearing. It was therefore highly likely that the malfunction was due to neither RA 2 or FCC B, but due to the connection between the two systems.

Although it appeared on several occasions and its consequences were notified by the crews, the base maintenance centre was not able to solve this fault, resulting, on the day of the event, in a degraded aircraft, presenting automated system problems mainly in the approach phase.

[(45)] The company indicated that the base technicians are now equipped with a tablet on which they record the operations and results as the operations are carried out. This was not the case at the time of the incident.

2.7.2 Line maintenance at Lyon

During the maintenance actions carried out at Lyon-Saint Exupéry after the occurrence flight, the technician indicated to the BEA that he just restarted the left IR in accordance with the telephone instructions provided by the RAM MCC, and that he did not use documentation. However, contrary to what the technician indicated, his qualification and the documents provided by the operator meant that he had the means of autonomously managing this fault.

As recommended by the manufacturer's documentation, the crew's report of the L IRS FAULT message in the TLB should have led him to carry out the *IR Failure – Fault isolation* (FIM 34-21 task 803) procedure and to check if the left ADIRU fault was still current. In such a case, a search would have been made for other possible current faults. If these steps did not delete the IR Failure from the CDU, the procedure would have then required the replacement of the left ADIRU.

Although these procedures were not strictly complied with, they probably would not have had an effect in the present case as there was no light indicating an L IRS FAULT on the ground when the maintenance technician restarted the IRS. It is highly likely that this fault was not current on the ground and was therefore an intermittent fault. This assumption is reinforced by the fact that during the flight after the occurrence, the L IRS FAULT was not activated.

Nevertheless, it is interesting to note that a crew report concerning the FMC messages received in flight ("*IRS-L DRIFT*" and "*VERIFY POS: IRS-IRS*") would have resulted in the maintenance personnel carrying out a task which would have led to the replacement of the left ADIRU.

Either way, the analysis of the QAR data and the fault messages recorded in the left ADIRU BITE would show that the left ADIRU would malfunction again two days after the occurrence, on 1 January 2017, with the activation of the L IRS FAULT warning. The next day, 2 January, an *IRS-L DRIFT MSG VERIFY POS: IRS L* message would also be mentioned by the crew in the TLB.

3 - CONCLUSIONS

3.1 Findings

- The flight crew held the necessary licences and ratings to carry out the flight.
- The aeroplane had a valid airworthiness certificate.
- The aeroplane took off from Rabat-Salé airport without any deferred maintenance actions.
- Around one hour after taking off, the FMC *"IRS-L DRIFT"* alert message appeared. The crew looked for the meaning of this message in the onboard documentation, without success. They then observed that the problem seemed to be resolving itself.
- The FMC *"IRS-L DRIFT"* (or *"IRS-R DRIFT")* alert message is a new message introduced with the new version of the Flight Management Computer (FMC) installed on the aeroplane in March 2016. It did not figure in the onboard documentation.
- Royal Air Maroc (RAM) had not informed Boeing of the compliance with a Service Bulletin (SB) regarding the installation of version U11 of the FMC. This notification was required for Boeing to modify the operational documentation.
- During the descent to Paris-Orly, where category 3 (CAT III) approaches were in force, the crew observed the appearance of the FMC *"VERIFY POS: IRS-IRS"* on the Control Display Units (CDU). Knowing this message, they did not refer to the documentation. Observing that the speed information from the two Inertial Reference Systems (IRS) was converging and was going to become consistent before arriving at Paris-Orly, the crew decided to continue the approach and selected Lyon-Saint Exupéry in case of a diversion.
- Once the approach mode (APP) was armed, the crew were not able to engage the two autopilots (A/P), a requirement to carry out a CAT III approach, due to one of the Flight Control Computers (FCC B) not receiving data from Radio Altimeter (RA) 2.
- The crew flew a missed approach and asked for a diversion to Lyon Saint-Exupéry airport. The meteorological conditions at Lyon permitted a category 1 (CAT I) approach which did not require the use of two A/P.
- During the descent to Lyon-Saint Exupéry airport, the crew tried to arm the automatic braking system and observed the illumination of the amber *AUTOBRAKE DISARM* light.
- The Lyon-Saint Exupéry Approach controller transferred the plane to the Tower controller without having made sure that it was established on the Localizer path of runway 35R.
- On intercepting the Localizer, and when the green VOR/LOC mode was engaged, the aeroplane suddenly entered a turn in the opposite direction to the turn to intercept the Localizer, crossed the Localizer path and then departed from it.
- This phenomenon was caused by internal problems in the left ADIRU. The latter had supplied erroneous data to FCC A. FCC A had taken this information into account without additional checks and sent an inappropriate turn command.
- A/P A then disengaged due to the invalidity of the data supplied by the left ADIRU.
- The crew flew a missed approach and asked to make a new approach.

- The crew engaged A/P B and were transferred to the Approach for a new pattern to align with the ILS.
- Shortly after being transferred to the Approach, the *L IRS FAULT* warning was activated, causing the disengagement of A/P B. This warning occurred 2 minutes 15 seconds after the inappropriate turn command on intercepting the ILS.
- The crew did not consult the IRS FAULT check-list as they believed that they lacked time. Furthermore, they were worried about the quantity of remaining fuel on board.
- The captain, from memory, set the IRS Transfer Switch to BOTH ON R. The check-list indicates that it is not possible to use the autopilot system for the approach and requests that it is disconnected beforehand (Deferred item).
- The playback of the ATC recordings reveals exchanges where the tone, content and rhythm were indicative of a high stress level aboard during the second approach to Lyon.
- This stress was the result notably of the two previous missed approaches, a progressive loss of confidence in the aircraft and its systems along with concern about the remaining quantity of fuel.
- The investigation found that the remaining fuel at the time of the *IRS FAULT* warning permitted the plane to hold for more than 20 minutes before starting the second approach and landing, before reaching the final fuel quantity.
- The crew started the final approach to Lyon with a non-standard speed/flap configuration with respect to the provisions in the Flight Crew Operating Manual (FCOM).
- While the crew were following the heading to intercept the Localizer, the captain asked for a radar vector, indicating that they were having positioning problems.
- Just after capturing the Glide, A/P B disengaged. This disengagement was caused by FCC B not receiving RA 2 data.
- The disconnection of A/P B led to the control of the aircraft being transferred from the co-pilot to the captain and the ILS final approach being continued without external visual references, in manual, without Flight Directors (F/D).
- The captain informed the control unit that he was continuing the approach in manual flight.
- Several alerts from the Enhanced Ground Proximity Warning System (EGPWS) ("*GLIDE SLOPE*", "*TOO LOW TERRAIN" and "SINK RATE"*) and Minimum Safe Altitude Warnings (MSAW) were activated during the final approach.
- On the activation of the MSAW, seen by the Approach and Tower controllers, the crew were no longer on the approach frequency and had not yet contacted the Tower.
- The aeroplane was not stabilized according to the company's criteria when flying through 1,000 ft AGL.
- The go-around called for by the co-pilot was not followed by the captain who, on acquiring sight of the runway at the same time as the co-pilot's call, decided to carry out a side-step.
- According to the captain, the aeroplane came out of the cloud layer at approximately 400 ft. He called out that he was continuing the landing.
- The aeroplane came out of the cloud layer between the two runway centrelines and the captain (PF) carried out a right side-step to align with runway 35R.

- The aeroplane landed at around 600 m from the threshold of runway 35R at an indicated speed of 159 kt.
- On landing, the remaining fuel quantity was 2,180 kg, more than the final fuel quantity (1,100 kg). On the ground, a low fuel level message was observed for one of the fuel tanks.
- The stress and the extra workload were shown by the dissociation of the crew, with the breakdown in Cockpit Resource Management (CRM).
- None of the tests carried out on the faulty left ADIRU identified the cause of the fault messages emitted during this flight, the sudden change of heading on intercepting the Localizer during the first approach to Lyon-Saint Exupéry and the two A/P disengagements. The analysis of the QAR data found a probable failure on an accelerometer.
- The investigation was not able to identify the cause of the fault messages relating to FCC B not receiving data from RA 2. It was established that RA 2 was not implicated. It seems probable that these fault messages were caused by a communication problem between RA 2 and FCC B. These malfunctions were behind several cases of the F/D disappearing and two disengagements of the A/P: one at Paris-Orly and the second one at Lyon-Saint Exupéry.
- The absence of a FCC check, in accordance with the specifications, of the validity of the inertial data transmitted by the ADIRU (except in the case of approaches with both A/P engaged) along with the ADIRU's built-in monitoring logic with respect to the "Drift Angle" fault, can result in the FCC using erroneous inertial data in case of a malfunction of the IR module, for an extended period, and have a significant disruptive effect on the plane's path, particularly in the final approach phase.
- A company practice requires the PM to select a VOR/DME during ILS approaches. The consequence of this practice is to cause the F/D to disappear in the ILS interception phase.
- The absence of explicit exchanges between the crew and air traffic control about the nature of the problems encountered on board meant that the air traffic controllers could not provide the crew with suitable assistance.
- The malfunctions and anomalies encountered by the crews were not systematically recorded in the documents provided for this (in particular in the TLB).
- Based on the information found in the maintenance documents during the investigation, it was not possible to check whether RAM had fully complied with the maintenance procedures with respect to the faults reported by the CN-ROJ crews in previous flights.
- The tests carried out indicated that the fault associated with RA 2 was not confirmed on the ground and that as a consequence, it was an intermittent type fault. This fault could be systematically found by the maintenance personnel in the fault history of the Control Display Unit (CDU) (DFCS BITE procedure).

- The fault messages recorded by the non-volatile memories (BITE) of the FCC indicated that the intermittent fault in relation to RA 2 had been present on CN-ROJ for at least six months.
- The technician working for the line maintenance company at Lyon held a Part 66 licence and had the necessary qualification to manage the L IRS FAULT.
  The necessary maintenance documentation, although not consulted by the technician, was available.
- The CN-ROJ crew did not preserve the CVR at the end of the flight, contrary to the operator's recommendations in case of a serious incident.

3.2 Contributing factors

Sequence of events

The Boeing 737-800, registered CN-ROJ, took off from Rabat airport (Morocco) bound for Orly airport. En route, the crew received alert messages on the CDU relating to the drift of the left inertial reference system. The crew observed that the problem was resolving itself and continued the flight to Paris-Orly. During the CAT III ILS approach to runway 06 at Paris-Orly, the aeroplane's path fluctuated while capturing the Localizer of runway 06 probably due to the reception of erroneous data from the left ADIRU. Then the crew were not able to engage the two A/P simultaneously which meant that the CAT III ILS approach could not be carried out, due to one of the Flight Control Computers (FCC B) not receiving data from RA 2. The crew carried out a missed approach and asked for a diversion to Lyon-Saint Exupéry airport where the meteorological conditions permitted a CAT I approach.

On intercepting ILS 35R at Lyon, the aeroplane made an untimely right turn although it was in Localizer capture (green VOR/ LOC mode), due to erroneous data supplied by the left ADIRU. There was no warning on board at this stage. A/P A then disengaged. The crew asked to make a new approach and then engaged A/P B. A few moments later, the L IRS FAULT warning was activated, causing A/P B to disengage. The captain set the IRS Transfer Switch to BOTH ON R, one of the items figuring in the IRS FAULT check-list and then re-engaged A/P B. One of the following items of the check-list specified that the A/P cannot be used during the approach.

On being vectored to the Localizer, the captain indicated to the controller that they were having positioning problems. On capturing the Glide, A/P B disengaged due to FCC B not receiving data from RA 2 again. No warning was triggered on board. The F/D disappeared from both the PF's and PM's side. The co-pilot transferred aircraft control to the captain and the captain decided to continue the approach in manual, without A/P or F/D. During the approach, carried out in IMC, the EGPWS "*SINK RATE*", "*GLIDE SLOPE*" and "*TOO LOW TERRAIN*" alerts followed one after the other on board the plane. The aeroplane, not stabilized at 1,000 ft AGL, came out of the cloud layer, just below 400 ft AGL, between the two runway centrelines.

The crew made a right side-step to align with runway 35R. The EGPWS "*TOO LOW TERRAIN*" and "*SINK RATE*" alerts continued to sound on board until landing. The aeroplane landed at around 600 m from the threshold of runway 35R.

Contributing factors

The following factors contributed to this serious incident:

- The concomitance of two independent failures within two separate systems where the cause of the failures, the absence of any link and the consequences were difficult for the crew to determine, without appropriate information in the operational documentation or sufficiently salient warnings emitted by the aircraft systems.
- The crew's progressive loss of confidence in the plane's systems as the flight continued, causing substantial stress and the crew to focus their attention on the level of remaining fuel.
- The deterioration in CRM by the crew when the workload became very high due, in particular, to having to manage the IRS FAULT during the missed approach phase.
- The operating logic of the FCC which does not monitor the inertial data provided by the ADIRU, except for approaches with the two A/P engaged. The FCC was not designed to, nor was it required for certification, to monitor the ADIRU inputs.
- The ADIRU internal monitoring logic with respect to the validity of the inertial data transmitted to other systems. The activation criteria of the "Drift Angle" fault, which in turn activates the IRS FAULT warning, can cause the latter to appear at a late stage with respect to the start of the ADIRU IR module malfunction.
- The crews' non-systematic reporting of technical malfunctions in the TLB such as the disappearance of the F/D, the ADIRU malfunctions and the A/P automatically disconnecting.
- The persistence of intermittent faults.

4 - SAFETY RECOMMENDATIONS

Note: in accordance with the provisions of Article 17.3 of Regulation No. 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation, a safety recommendation in no case creates a presumption of fault or liability in an accident, serious incident or incident. The recipients of safety recommendations report to the issuing authority in charge of safety investigations, on the measures taken or being studied for their implementation, as provided for in Article 18 of the aforementioned regulation.

4.1 Re-assessment of the safety study relating to the consequences of the FCC using undetected erroneous data from the ADIRU.

The investigation found that erroneous data from an ADIRU had resulted in the plane making an unwanted turn commanded by the FCC, with the A/P engaged, without this data being detected as erroneous by the aircraft systems.

In accordance with its specifications, the FCC does not check the validity of the data from an ADIRU except for approaches with the two A/P engaged.

The FCC's use of erroneous inertial data can have significant consequences for the management of the flight, particularly when it occurs in the approach phase.

Boeing ranks these effects as "*minor*" or "*major*" depending on the flight phase. The effect is ranked as "*major*" in the approach phase.

Boeing established this classification based on the hypothesis that "*Pilots are trained to monitor the airplane's flight path, airspeed, and altitude, and to correct for any deviations from those which were intended.*" In final approach, the crew may have to disconnect the A/P to correct a deviation. However, an unanticipated change to manual piloting during the approach presents piloting difficulties liable to affect the flight path being followed and jeopardize flight safety.

Furthermore, the validity of the presupposition that the flight crew constantly monitor the automated systems and are ready to immediately react in case of a malfunction is questioned in the Joint Authorities Technical Review (JATR) presenting the work jointly carried out by ten civil aviation authorities along with the NASA and NTSB following the accidents to the Boeing 737-Max in Indonesia and Ethiopia. This serious incident, along with the comments made by the Joint Authorities, show that the crews' detection and reaction times can be significantly longer than the hypotheses adopted during the design of the aeroplane and in the safety studies. This observation can thus call into question the classification of hazards where the only means of detection is crew monitoring.

A malfunction ranked as having a "major" effect must not occur more frequently than 10^{-5} times per flight hour

The equipment manufacturer estimated the probability of an ADIRU sending undetected erroneous inertial data as 1.22×10^{-5} per flight hour. Boeing's calculation of the probability of this same hazard occurring during an approach phase was 2.44×10^{-6}.

This was an estimation made during the design phase of the ADIRU and was not checked or subsequently updated by feedback due to the "undetected" nature of this hazard.

Consequently, the BEA recommends that:

- **whereas the only means of detecting the hazard of the flight control computers (FCC) using undetected erroneous inertial data is the monitoring and reaction of the crew, and the effects of this hazard are ranked as "*major*";**
- **whereas this incident questions the hypothetical crew reaction time taken into account for the aeroplane's certification to counter such a malfunction;**
- **whereas the Joint Authorities who instigated the JATR published following the accidents to the Boeing 737-Max in Indonesia and Ethiopia, also questioned the presupposition that the flight crew constantly monitor the automated systems and are ready to immediately react in case of malfunction;**

  the FAA in liaison with Boeing, re-assess the safety study relating to the consequences of the FCC using undetected erroneous data from the ADIRU, notably in order to check the associated severity level and to ensure, based on in-service occurrences, that the safety objective is met.
  [Recommendation FRAN 2021- 013]

4.2 ADIRU built-in monitoring and activation of IRS FAULT warning

The definition of the criteria which initiates the "Drift Angle" fault, which in turn activates the IRS FAULT warning, is such that the latter may only appear a long time after the start of the ADIRU IR module malfunction. Indeed, a deviation of more than 60° between the heading and the route constitutes a significant difference.

The AAIB also underlined this significant time period between the start of the ADIRU malfunction and the appearance of the "Drift Angle" fault in its investigation report concerning the serious incident to the Boeing 737-800 registered EI-GJT on 9 October 2018 while in cruise.

In case of an ADIRU failure similar to that encountered during this flight, this difference in angle will not be systematically reached. This implies that this type of ADIRU malfunction may not be detected by certain systems which use the data supplied by the ADIRU, and as a consequence will continue to use it.

Likewise, when the plane's ground speed is less than 200 kt in the final approach phase, the "Drift Angle" fault message cannot be sent.

Consequently, the BEA recommends that:

- **whereas the IRS FAULT warning appears at a late stage with respect to the start of the ADIRU IR module malfunction and certain onboard systems may continue to use the ADIRU erroneous data;**

  Boeing reconsider the activation criteria of the ADIRU "Drift Angle" fault message and the associated IRS FAULT warning in order to both avoid systems using erroneous inertial data and permit flight crews to react in a timely manner.
  [Recommendation FRAN 2021- 014]

4.3 Royal Air Maroc flight crew fault reporting procedures

The investigation brought to light the non-systematic reporting of technical problems, encountered by the flight crews, in the Technical Log Book (TLB). This concerned the problems linked to the F/D bars disappearing, the untimely disconnections of the A/P and the malfunctions of the ADIRU.

The occurrence flight was not an exception. Only the "*L IRS FAULT*" information was actually mentioned in the TLB. The appearance of the FMC fault messages, the multiple times that the A/P disengaged and the F/D disappeared, as well as the activation of the *AUTOBRAKE DISARM* light were not mentioned. The investigation was able to identify that if the FMC "*VERIFY POS: IRS-IRS*" message, which occurred in flight, had been recorded in the TLB, after landing at Lyon, it might have permitted the line maintenance personnel to observe that the residual ground speed recorded at the end of the occurrence flight was 187 kt, which required the replacement of the ADIRU (residual ground speed error of more than 21 kt).

Systematic reporting of the faults and anomalies encountered by the flight crews is necessary for the maintenance personnel to correct the problems or in case of an intermittent fault, to monitor their evolution, as specified by the manufacturer's procedures.

Consequently, the BEA recommends that:

- **whereas the non-systematic reporting of technical malfunctions by the crews does not facilitate the identification and processing of intermittent faults;**

  Royal Air Maroc implement the necessary provisions in order that the technical malfunctions observed in flight are systematically reported in the documents provided for this purpose. [Recommendation - FRAN 2021- 015]

4.4 Processing of intermittent faults within Royal Air Maroc

The investigation showed that the malfunctions linked to RA 2, observed during the incident flight, were intermittent faults and that they had existed on CN-ROJ for at least six months.

Boeing has asked operators to implement a policy for processing intermittent faults, with these faults being specifically monitored on several consecutive flights. It is possible to access the faults recorded by the main computers through the CDU, after a flight, even if they are no longer active on the ground.

Consequently, the BEA recommends that:

- **whereas Boeing lets the operator choose the strategy for resolving intermittent faults;**
- **whereas the persistence of intermittent faults which contributed to this serious incident;**

  Royal Air Maroc reinforce its policy with respect to the processing of intermittent faults. [Recommendation - FRAN 2021- 016]

4.5 Company's practices when intercepting ILS

The FCOM specifies that for an ILS approach, the flight crew must display the Localizer frequencies on the PF's side and the PM's side before the IAF or well before the start of the vectoring to the final approach path if being radar vectored. It indicates that displaying different frequencies on the two VHF/NAV receivers may lead to a difference in the left and right F/D display and affect the operation of the engaged A/P.

In contrast, a company practice, during an ILS approach, consists of keeping the VOR displayed on the PM's side until the GLIDE has been intercepted in order to be able to check the position of the aeroplane with respect to the airport and the turn in progress to align on the LOC and to confirm that the correct Glide signal has been captured if the ILS is not DME. The consequence of this practice is the disappearance of the F/D roll bar on the PM's side when the VOR/LOC mode is engaged and the F/D pitch bar when the Glideslope (G/S) mode is engaged. What's more, displaying a VOR frequency on one of the radionavigation control panels prevents the engagement of the two A/P which is necessary for CAT III approaches.

In addition, this practice may accustom crews to the phenomenon of the F/D bars disappearing and thus no longer give rise to systematic reporting of this in the TLB although, as shown by this investigation, these disappearances may be the consequence of technical problems requiring maintenance work.

Consequently, the BEA recommends that:

- **in order that the ILS interception procedures do not cause the disappearance of the flight director (F/D) bars and do not affect the operation of the engaged autopilot (A/P);**

  Royal Air Maroc clarify its position with respect to the ILS interception procedure and what is practised by certain crews, and if there are deviations from the manufacturer's procedure, that the operational consequences of these deviations are documented and their effects on flight safety studied.
  [Recommendation - FRAN 2021- 017]

5- SAFETY LESSONS

5.1 Crew's compliance with the fault isolation procedures

The investigation found that the flight crew did not call up the appropriate check-list and carried out one of the check-list items from memory. Furthermore, the crew did not carry out a technical and operational assessment as required by the operations manual.

In the event of a fault, except in case of an emergency and according to the circumstances, the exhaustive compliance with the fault isolation procedure remains the most fitting way of safely continuing the flight, while having processed the direct and indirect consequences of the fault.

5.2 Pilot training in manual piloting without F/D on an ILS approach with sudden disconnection of A/P

Safety studies are based on the fact that pilots are trained to monitor the aeroplane's flight path, airspeed and altitude, and to correct for any deviations from those which were intended.

The change to manual piloting for a final approach, if it is unanticipated, is an additional difficulty for a pilot as he does not have the time to calibrate his inputs on the stick, i.e. to adjust them in terms of the force and amplitude required to correct the path deviations Furthermore, the absence of the VOR position information displayed on the PM's side may make positioning more difficult before intercepting the ILS and increase the reaction time in the event of an A/P malfunction on intercepting the Localizer or Glide.

Recurrent simulator training in manual flying without F/D for ILS approaches must permit pilots to prepare for this by including the untimely disconnection of the A/P at different moments of the final approach, including the interception of the Glide.

5.3 Following procedures during line maintenance

Following the crew's report of the "*L IRS FAULT*", the maintenance technician at Lyon-Saint Exupéry did not carry out the fault isolation procedure, even though it was requested in the technical documentation and approved maintenance procedures provided by the company.

Line maintenance, performed by a qualified technician, employed by a Part 145 approved company, permits faults to be isolated in accordance with approved maintenance procedures. Line maintenance is an important link in the aviation safety chain.

5.4 Update of operational documentation

The "*IRS-L DRIFT"* alert message did not exist in the operational documents available to the crew of CN-ROJ. This message had been entered in version U11 of the FMC installed on the plane in March 2016, i.e. nine months before the incident. Royal Air Maroc had not notified Boeing of the start of the installation of the new software on its Boeing 737 fleet and therefore did not benefit from a temporary update of the operational documentation for the aircraft concerned as the new software was being installed.

For this reason, RAM's operational documentation did not contain a reference to the "*IRS-L DRIFT"* alert message at the time of the incident.

The documentation was updated in October 2017 when RAM informed Boeing that the installation of version U11 of the FMC on its B 737 fleet had been completed.

It is important for operators to ensure that internal procedures are in place so that any software changes on board an aircraft are incorporated into the aircraft's operational documentation without delay.

6 - MEASURES TAKEN BY ROYAL AIR MAROC

Following this serious incident on 30 December 2016, RAM's Quality, Safety & Security Committee met on 27 January 2017 to analyse the event and decide on the corrective actions to be implemented.

The crew involved in the occurrence were able to benefit from the following actions:

- A refresher Human Factors Module covering several topics including compliance with procedures.
- Two simulator sessions of four hours each with training in managing the *IRS FAULT* and manual piloting in IMC without F/D, with emphasis on the operation of the IRS and associated procedures.

In addition, *IRS FAULT* training followed by a manual approach in IMC without F/D was added to the three-year training cycle for all company pilots.

APPENDICES

APPENDIX 1

Transcript of radio exchanges

IMPORTANT NOTE

The following transcription represents what it was possible to understand during the playback of the radio exchanges recorded by the air traffic control unit(s) (ATC).

The reader's attention is drawn to the fact that the recording and the transcription of an ATC recording only partially reflects the events. Consequently, extreme prudence must be exercised when interpreting such a document.

GLOSSARY

UTC Time	Source: ATM recording
[xxx]	Controller on frequency used [TWR].
( )	The words or groups of words in brackets could not be confirmed with certitude.
(*)	Incomprehensible words or groups of words

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
10:00:38		Start of transcription	
10:01:05		**[PARIS]**: Air Maroc 780S, maintain FL110, contact Orly 123.875, bye	
10:01:24	Orly, Air Maroc 780S bonjour, descending FL110, Information N		
10:01:33		**[ORLY]**:RAM 780S, good day, descent FL 100, hold at ODILO, expected approach time 15	
10:01:40	Descend 100, hold ODILO, expecting approach time 15, Air Maroc 780 S		
10:07:04		**[ORLY]**: Air Maroc 780 S, fly heading 020, vectoring ILS RWY 06	
10:07:11	(*) Maroc 780S and heading 020, by left Air Maroc 780 S		
10:08:09		**[ORLY]**: Air Maroc 780S, descend FL70	
10:08:14	Descend 70, Maroc 780 S		
10:08:16		**[ORLY]**: RAM 780S, RVR 400 m	
10:08:24	Copied Maroc 780S		
10:09:13		**[ORLY]**: Air Maroc 780S, turn 10° right	
10:09:18	10° by the right, Air Maroc 780S		
10:09:20		**[ORLY]**: Air Maroc 780S, contact Orly Approach, 124.450, bye	
10:09:24	124.450, Air Maroc 780S, bye		
10:09:34	Orly Approach, Air Maroc 780S, bonjour, descending 70		
10:09:38		**[ORLY APP]**: 780S bonjour, descend 5000 ft, 1038 and intercept Localizer 06	
10:09:47		And for your information, I need you to fly 020 for the interception	

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
10:09:56	Descent 5000 ft, QNH 1038, on heading 020 then to intercept Localizer RWY 06, Air Maroc 780S		
10:11:05		**[ORLY APP]**: RAM 780S, speed back 180 kts please	
10:11:09	Speed 180 kts RAM 780S		
10:11:55		**[ORLY APP]**: RAM 780S, please speed back 160 kts	
10:11:59	Speed 160, Maroc 780S		
10:12:01		**[ORLY APP]**: For your information 780S, you took the message of the 640E when you (*)	
10:12:24		**[ORLY APP]**: Maroc 780S, you are not on the Localizer, confirm?	
10:13:13		**[ORLY APP]**: Maroc 780S, 160 kts	
10:13:16	160 kts, Air Maroc 780S		
10:13:38		**[ORLY APP]**: Maroc 780S, confirm you are established	
10:13:41	Affirm Maroc 780S		
10:13:43		**[ORLY APP]**: Maroc 780S, 160 kts Tower 118.7, au revoir	
10:13:46	160 kts, 118.7 Maroc 780S		
10:13:51	Orly Tower, Maroc 780S, bonjour		
10:14:03		**[ORLY TWR]**: Maroc 780S bonjour, report 5 miles final RWY 06, wind calm, RVR 375	
10:14:12	Call you 5 miles RWY 06, Air Maroc 780S		
10:14:37	780S, confirmed we are cleared for ILS		
10:14:40		**[ORLY TWR]**: Maroc 780S, negative report 5 miles final RWY 06	
10:14:46	And we descent to 4000 ft, Air Maroc 780S		
10:14:50		**[ORLY TWR]**: Yes you are cleared to the ILS CAT 3 approach	
10:14:54	Cleared ILS RWY 06 CAT3, Air Maroc 780S		
10:16:37	Air Maroc 780 S, category 3 unable and requesting go around Air Maroc 780 S		

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
10:16:45		**[ORLY TWR]**: Maroc 780S copied, call you back soon	
10:16:48	OK		
10:16:53		**[ORLY TWR]**: Maroc 780S, stop descent 2000 ft	
10:16:58	Confirm we descent to 2000 ft, Air Maroc 780S?		
10:17:02		**[ORLY TWR]**: You stop the descent at 2000 ft, you maintain 2000 ft reaching	
10:17:06	We will maintaining 2000 ft, Air Maroc 780S		
10:17:31	Air Maroc 780S, requesting clearance to Lyon		
10:17:36		**[ORLY TWR]**: You want to divert to Lille?	
10:17:39	To Lyon, Air Maroc 780S		
10:17:42		**[ORLY TWR]**: Ly..?	
10:17:43	(*) Lima Lima		
10:17:45		**[ORLY TWR]**: That is copied, direct climb now altitude 4000 ft	
10:17:50	Climb now 4000 ft Air Maroc 780S		
10:17:53		**[ORLY TWR]**: Maroc 780S turn right heading 160	
10:17:56	Turn right heading 160 Maroc 780S		
10:18:00		**[ORLY TWR]**: RAM780S, confirm you stop the descent at 2000 ft?	
10:18:08	Air Maroc 78...		
10:18:42		**[ORLY TWR]**: Maroc 780S contact 124.450 the Approach	
10:18:47	124.450 Maroc 780S, bye bye		
10:18:59	Orly Approach Air Maroc 780S, rebonjour, climbing 4000 ft, on heading 160		
10:19:06		**[ORLY APP]**: 780S bonjour, confirm you want to divert?	
10:19:11	Affirm Maroc 780S, our destination is LFLL		
10:19:17		**[ORLY APP]**: Oui Lyon, ok copied, I call you back	
10:19:28		**[ORLY APP]**: RAM780S for the moment you turn right direct to UDILO and you climb FL 70	

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
10:19:38	To UDILO by the right, climb 70, Maroc 780S		
10:19:53		**[ORLY APP]**: RAM 780 S, are you sure you want to divert now or do you want the MET report of Lyon before?	
10:20:03	We want to divert to Lyon, Air Maroc 780S		
10:20:05		**[ORLY APP]**: Ah you are sure, you want to divert to Lyon and you know now?	
10:20:10	Affirm Maroc 780S		
10:20:12		**[ORLY APP]**: Copied. In this case, make 360s by the... continue present heading, continue heading 180 and climb FL70	
10:20:24	Confirm heading 180 and climb 70 Maroc 780S		
10:21:32		**[ORLY APP]**: RAM 780S climb FL130, heading South	
10:21:36	Climb 130, heading South, Air Maroc780S		
10:21:45		**[ORLY APP]**: Maroc 780S, direct LESPI	
10:21:49	Direct LESPI, Air Maroc 780S		
10:21:51		**[ORLY APP]**: Négatif, LESPI, Lima Echo Sierra Papa India	
10:21:54	Lima Echo Sierra Papa India, Air Maroc 780S		
10:22:36		**[ORLY APP]**: Maroc 780S, contact Paris 135.405, au revoir	
10:22:41	135.405, Air Maroc 780S, bye bye		
10:22:50	Paris Bonjour, Air Maroc 780S, climbing FL 130 to LESPI		
10:22:56		**[PARIS]**: Marocair 780S bonjour, climb FL 190 to LESPI	
10:23:03	190 to LESPI Air Maroc 780S		
10:25:20		**[PARIS]**: Marocair 780S, say estimated time of arrival to Lyon please	
10:25:27	Call you back Air Maroc 780S		
10:26:10	780S, may we have the runway in use at Lyon?		
10:26:14		**[PARIS]**: I call you back	

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
10:26:15	Merci madame		
10:26:58		**[PARIS]**: Marocair 780S, continue climb FL 250, runway in use RWY 35 in Lyon	
10:27:05	35 in use, continue climb 250 Maroc 780S		
10:29:14		**[PARIS]**: Please Marocair 780S, can you give me the estimated time of arrival Lyon please?	
10:29:26	Call you back Air Maroc 780S		
10:30:48	Air Maroc 780S, we estimating LESPI at 1056		
10:30:54		**[PARIS]**: Roger and arrival please?	
10:31:00	Fifteen minutes later		
10:31:01		**[PARIS]**: Roger	
10:34:45		**[PARIS]**: Marocair 780S direct TALAR	
10:34:49	Direct TALAR, RAM 780S		
10:37:07		**[PARIS]**: Marocair 780S, descent FL200	
10:37:11	Descent 200, Air Maroc 780S		
10:40:09		**[PARIS]**: Marocair 780S, contact Marseille 123.805, bye bye	
10:40:15	123.874, au revoir madame		
10:40:17		**[PARIS]**: Negatif, frequency 123.805	
10:40:21	123.805 Air Maroc 780S, bye bye		
10:40:31	Marseille bonjour, Air Maroc 780 S, descending FL 200 to TALAR		
10:40:36		**[MARSEILLE]**: Bonjour Air Maroc 780 S continue, descend FL 120	
10:40:42	(*) descend 120, Maroc 780 S		
10:42:01		**[MARSEILLE]**: Maroc 780 S, direct to (*) VNE	
10:42:10	Victor November Echo, Air Maroc 780 S		
10:44:43		**[MARSEILLE]**: Maroc 780 S, contact Lyon Approach, 136.075, good bye	
10:44:56		**[MARSEILLE]**: Maroc 780 S?	
10:44:59	Maroc 780 S, go ahead		

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
10:45:00		**[MARSEILLE]**: Maroc 780 S, contact Lyon Approach, 136.075, good bye	
10:45:05	136.075, Air Maroc 780 S, bye		
10:45:33	L'Approche Air Maroc 780S, descending FL 120 to VNE		
10:45:40		**[LYON APP]**: RAM 780S, bonjour descent FL90, vector ILS 35 R, Information Kilo	
10:45:54	Descent 90, expect vectoring ILS 35R, Air Maroc 780S		
10:48:41		**[LYON APP]**: RAM 780S, continue present heading, descent FL 70	
10:48:49	Descent 70 on present heading, Air Maroc 780S		
10:53:10		**[LYON APP]**: RAM 780S, descent FL 60	
10:53:14	Descent 60, Air Maroc 780S		
10:54:12		**[LYON APP]**: RAM 780S, say heading	
10:54:16	Heading 143, Air Maroc 780S		
10:54:19		**[LYON APP]**: Roger, RAM 780S, turn left heading 130, descent 5000 ft, QNH 1038	
10:54:26	At left 130, descent 5000 ft, QNH 1038, Air Maroc 780S		
10:56:11		**[LYON APP]**: RAM 780S, descend 3000 ft, QNH 1038	
10:56:16	Descent 3000 ft, QNH 1038, Air Maroc 780S		
10:57:13		**[LYON APP]**: Air Maroc 780S, turn left heading 100 and reduce speed 210	
10:57:20	Reduce speed 210, by the left heading 110, Air Maroc 780S		
10:58:23		**[LYON APP]**: Royal Air Maroc 780 S, turn left heading 020, cleared ILS 35 R	
10:58:28	Turn left heading 020, cleared ILS 35 R, Air Maroc 780 S		
10:59:27		**[LYON APP]**: Air Maroc 780 S, reduce 180 kts, and Tower 120.450, bye bye	At this point, the aircraft turned right

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
			and left the Localizer path
10:59:33	One... 170 kts, 120.450, Air Maroc 780 S, bye		
10:59:45	TWR, Royal Air Maroc 780 S, bonjour		
10:59:49		**[LYON TWR]**: Bonjour, Maroc 780 S.	
10:59:51		**[LYON APP]**: Royal Air Maroc 780 S?	
10:59:51		**[LYON APP]**: RAM 780 S?	
10:59:52	Maroc 780 S, on final RWY 35 R		"Wail" warning in background (disconnection of AP)
10:59:58	Maroc 780 S, going around		
11:00:01		**[LYON TWR]**: Maroc seven zero..., Maroc 70S, for me you are not at all on LOC RWY 35R. You are on heading...maybe you are turning, but you are like 1 NM East of the axis	
11:00:16	Copied Air Maroc 780 S		
11:00:23		**[LYON TWR]**: Maroc 780S, you are going the good direction, report maybe insight of the field but the weather is not very good. You got overcast 500 ft, report if any visual on the field otherwise we have to make another approach	
11:00:39	We will make another approach Air Maroc 780S		
11:00:42		**[LYON TWR]**: Ok in that case, climb 5000 ft, QNH 1038, 5000 ft on heading 360.	
11:00:50	Confirm (*) on heading 360, Air Maroc 780S		
11:01:17		**[LYON TWR]**: Maroc 780S for another approach, contact Radar on 125.425	
11:01:22	125.45, Maroc 780S		
11:01:35	Lyon, Royal Air Maroc 780 S, bonjour		"Wail" warning in background (disconnection of AP)
11:01:38		**[LYON APP]**: Bonjour RAM 780S, turn right heading 090 for another radar vectoring ILS 35 R	

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
11:01:47	Turn right heading 090, Air Maroc 780S		
11:02:08		**[LYON APP]**: Air Maroc 780S, you can descent 4000 ft now, QNH 1038	
11:02:14	Descent 4000ft, QNH 1038, Air Maroc 780S		
11:02:18		**[LYON APP]**: Affirm, could you confirm your speed please?	
11:02:22	Within 180 kts, Air Maroc 780S		
11:03:01	Air Maroc 780S, we need an...on demande un cap d'approchement		Comment: stress in co-pilot's voice
11:03:07		**[LYON APP]**: Pas de problème RAM 780S, turn right heading 180	
11:03:12	180, Air Maroc 780S		
11:03:17		**[LYON APP]**: RAM 780S, you want the shortest approach you can have, confirm?	
11:03:39		**[LYON APP]**: Air Maroc 780S turn right heading 200	
11:03:42	200, Air Maroc 780S		
11:04:18	Confirm Air Maroc 780S (*) please		
11:04:20		**[LYON APP]**: Affirm RAM 780S, now you can descent 3000 ft, 3000 ft, QNH 1038.	
11:04:29	3000 ft QNH 1038, Air Maroc 780S		
11:04:38		**[LYON APP]**: Air Maroc 780S?	
11:04:41	780 S, go ahead		
11:04:42		**[LYON APP]**: 780 S, turn left heading 180 to be correctly... to intercept correctly, heading 180 by the left please	
11:05:42		**[LYON APP]**: RAM 780S, turn right heading 240	
11:05:49	Heading 240, Air Maroc780S		From this point, the messages between the crew and Lyon APP are transmitted by the captain
11:06:32		**[LYON APP]**: RAM 780S, turn right heading 320,	

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
		cleared ILS 35 R	
11:06:39	Right heading 320, cleared ILS 35R, Air Maroc 780S.		
11:07:30	Air Maroc 780S, request radar vector		
11:07:34		**[LYON APP]**: You intercept now, it's the heading to intercept the ILS. Do you have the frequency?	
11:07:39	We have 111.5 but we have problems of positioning		
11:07:44		**[LYON APP]**: But the heading now normaly, you will have the glide in 2 NM, at heading 355	
11:07:51	We will set heading 355, RAM 780S		
11:08:15		**[LYON APP]**: RAM 780S, did you catch the glide now?	
11:08:20	We catch the LOC and coming for the glide, RAM 780S		
11:08:24		**[LYON APP]**: Exactly 780S	
11:08:30	We continue manually RAM 780 S		"Wail" warning in background (disconnection of AP)
11:08:35		**[LYON APP]**: You mean visual?	
11:08:37	Negative, we continue manually...heu confirmez si on est sur le bon glide et le bon LOC.		
11:08:43		**[LYON APP]**: Moi je ne peux pas vous confirmer ça, si vous recevez l'ILS 35 R, la fréquence c'est 111.5, donc normalement vous devriez êtes sur le glide et en l'occurrence ça a l'air d'être bon là	
11:08:55	Bien reçu on continue RAM 780S		
11:08:58		**[LYON APP]**: Est-ce que vous avez au moins la vue du sol?	
11:09:00	Négatif pour le moment		
11:09:01		**[LYON APP]**: D'accord. Vous voulez poursuivre sur l'ILS, vous avez tout, le LOC, le glide ou on remet les gaz? Qu'est-ce-que vous souhaitez faire?	
11:09:05			
11:09:07	Continuer manuellement et on continue sur le LOC		

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
	et le glide		
11:09:09		**[LYON APP]**: D'accord RAM 780S. Dans ce cas, contactez la Tour 120.450, au revoir Monsieur	
11:09:16	Cent cinquante, au revoir		
	############## Activation of MSAW for 8 to 12 seconds ##############		
11:09:48	Tower Air Maroc 780S bonjour		From this point, the messages between the crew and Lyon TWR are transmitted by the co-pilot
11:09:51		**[LYON TWR]**: Maroc 780S bonjour. Do you have visual on the runway?	
11:09:56	Not yet Air Maroc 780S, confirm we are... we are...		GPWS "Sink rate, Sink rate" warning in background
11:10:02	Go around Air Maroc...		
11:10:04		**[LYON TWR]**: Maroc 780S, the lights are on the strongest possible, you are 2NM from threshold 35 R, report visual on the runway or the approach lights	
11:10:14	(Tower) continue landing Air Maroc 780S		
11:10:22	Poursuit manoeuvering, Maroc 780S		
11:10:24		**[LYON TWR]**: Say again	
11:10:26	(Continue) manoeuvering Air Maroc780S		
11:10:29		**[LYON TWR]**: Ok you have visual on the approach lights on the runway?	
11:10:32	Contact ground three five right		
11:10:34		**[LYON TWR]**: Ok cleared to land 35 R, wind calm	
11:11:31	Now vacate the runway Air Maroc 780S		
11:11:33		**[LYON TWR]**: Maroc 780S, clear to cross runway 35 L via B4	

UTC Time	CN-ROJ (RAM 780 S)	Control unit	Comments, noise
11:11:38	Cross 35L via B4, Air Maroc 780S		
11:12:08		**[LYON TWR]**: 780 S so just for our information, the ... you could not follow the glide and the localizer on automatic, the aircraft was not able to do that anymore?	
11:12:18	Affirm Air Maroc 780S		
11:12:20		**[LYON TWR]**: Ok. Is everything okay for you, do you need something?	
11:12:24	Thank you very much Air Maroc 780S		
11:12:26		**[LYON TWR]**: You welcome Sir, contact ground 121.825	
11:12:29	121.825, Air Maroc 780 S bye bye		
11:11:46		End of transcription	

APPENDIX 2

QAR parameter graphs

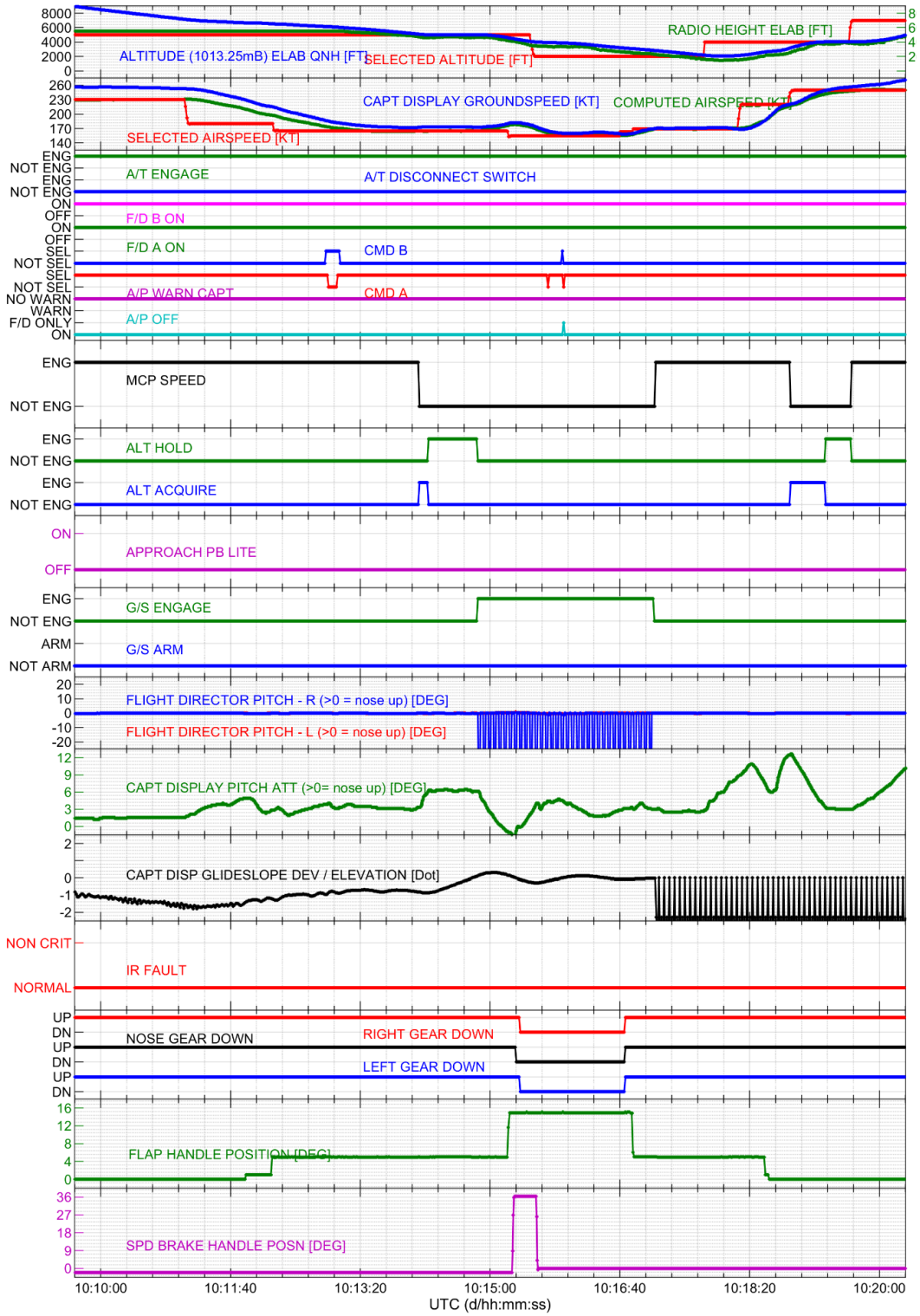


Figure 14: Orly approach - longitudinal parameters

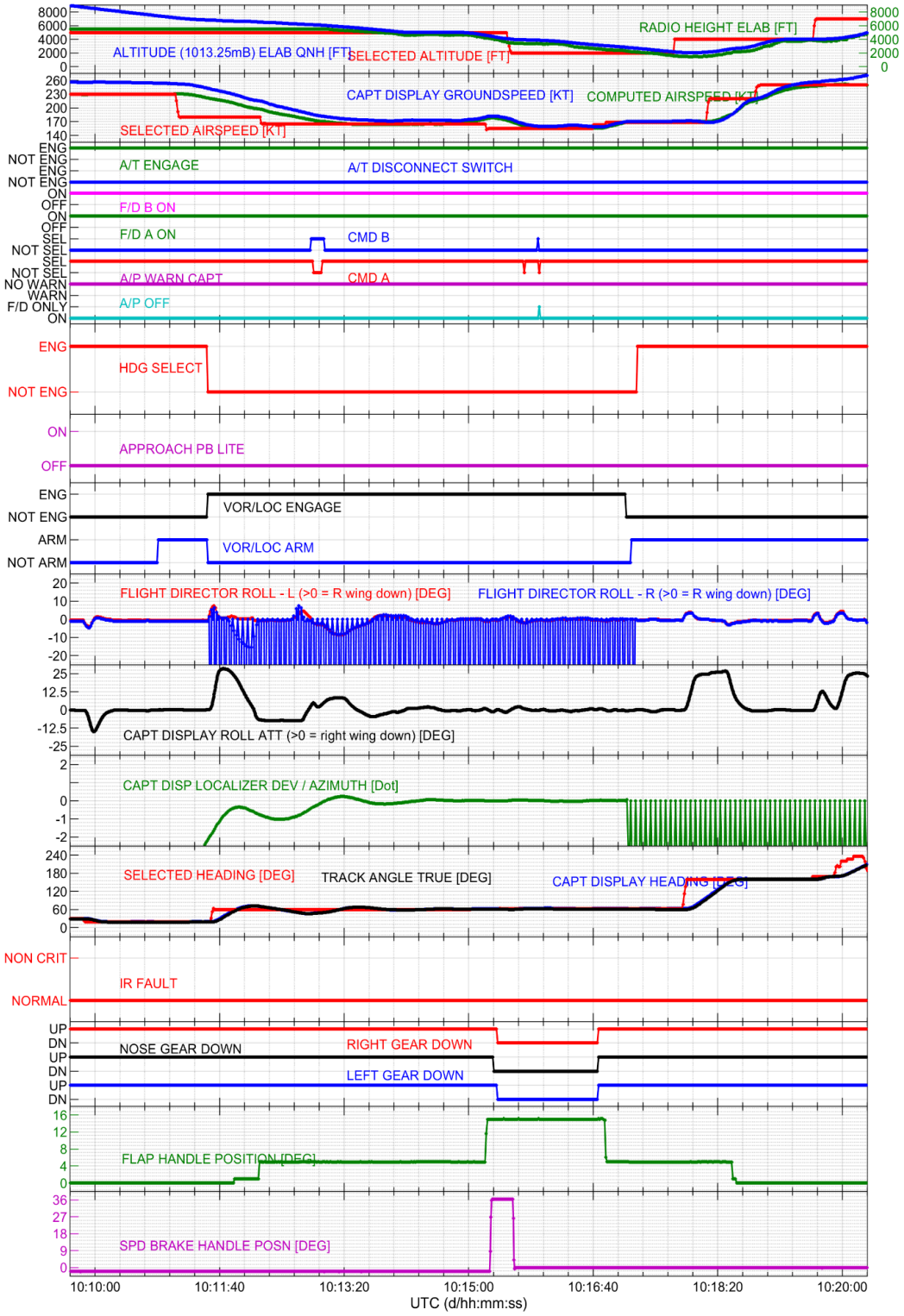


Figure 15: Orly approach - lateral parameters

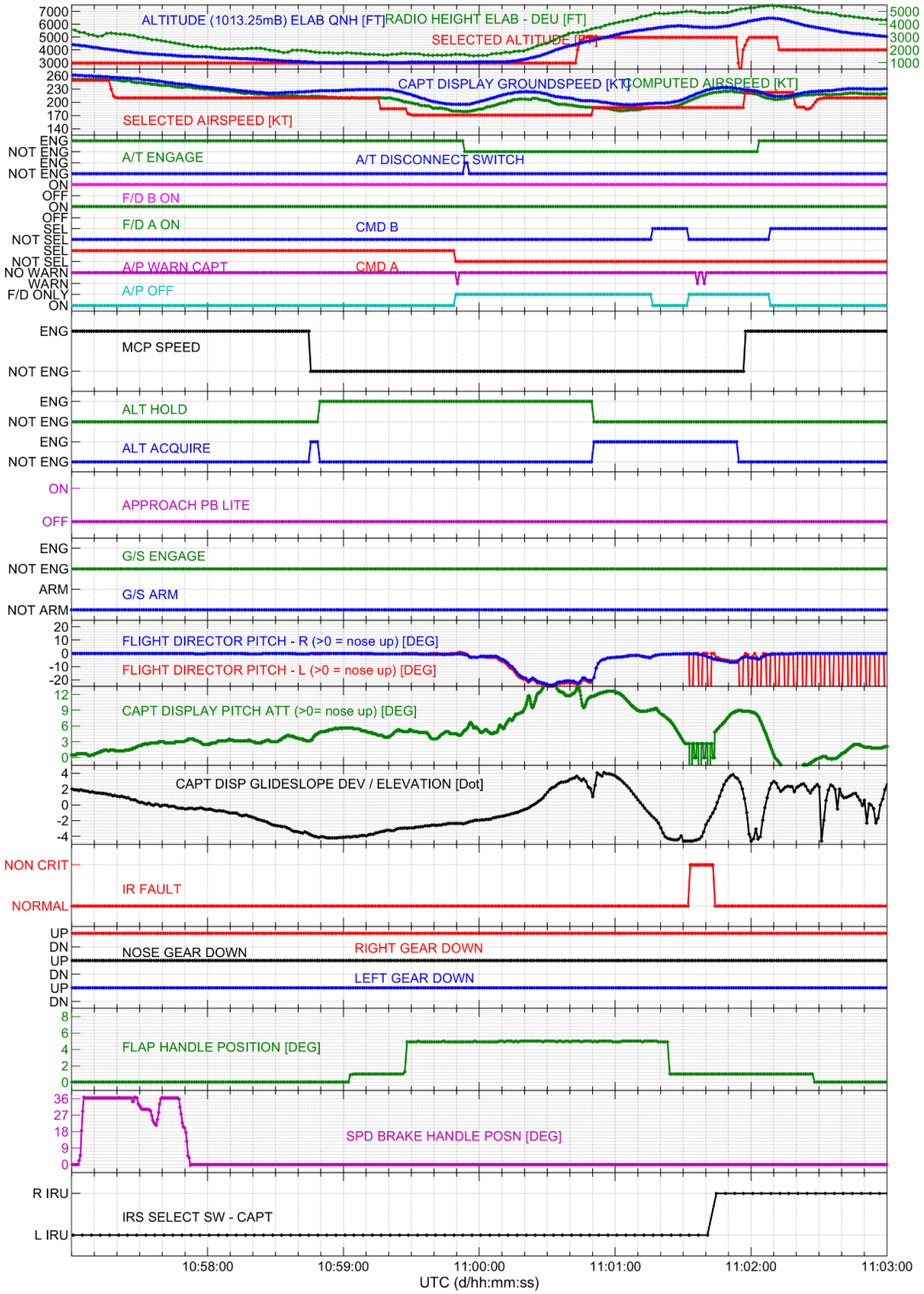


Figure 16: First Lyon approach - longitudinal parameters

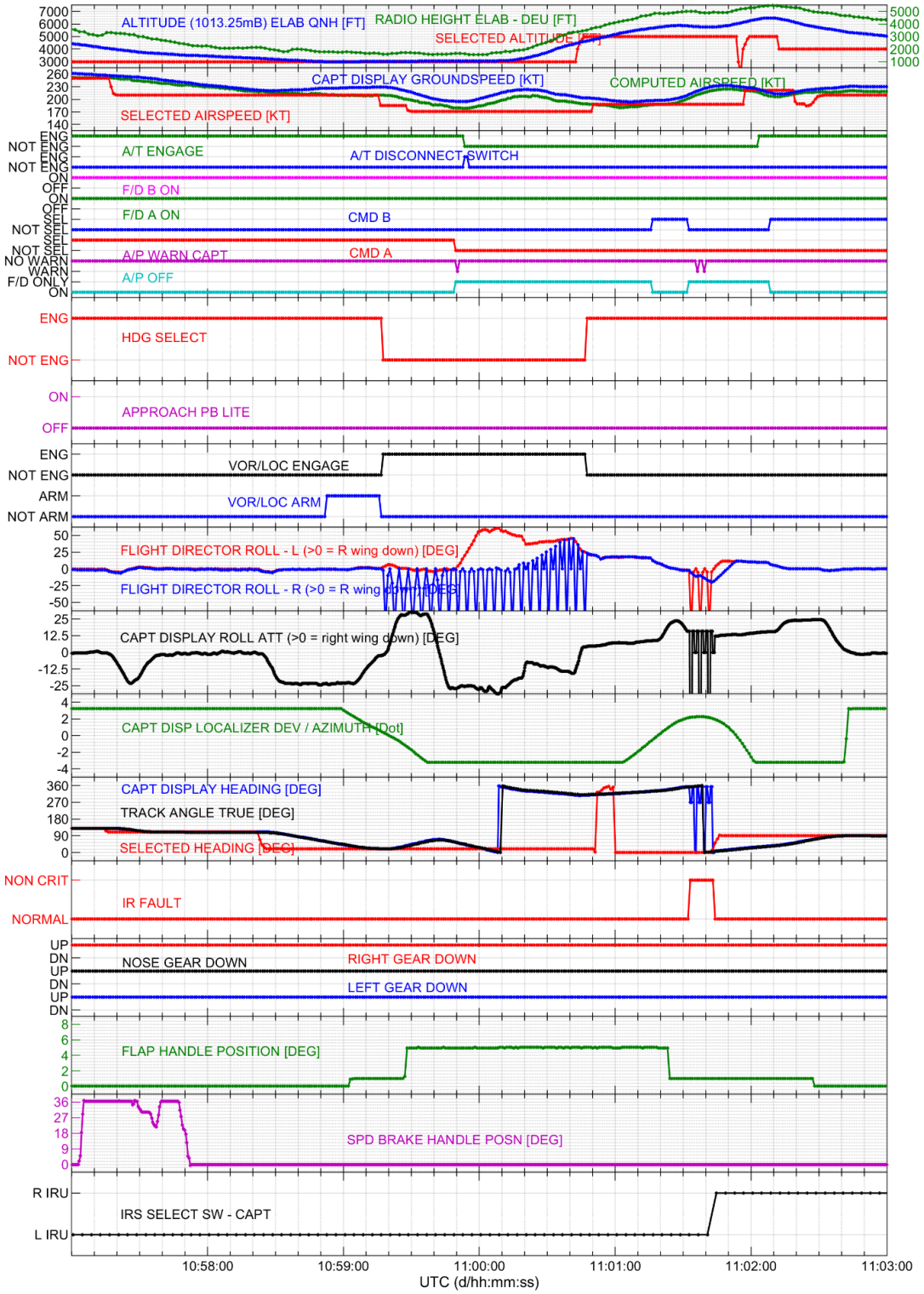


Figure 17: First Lyon approach - lateral parameters

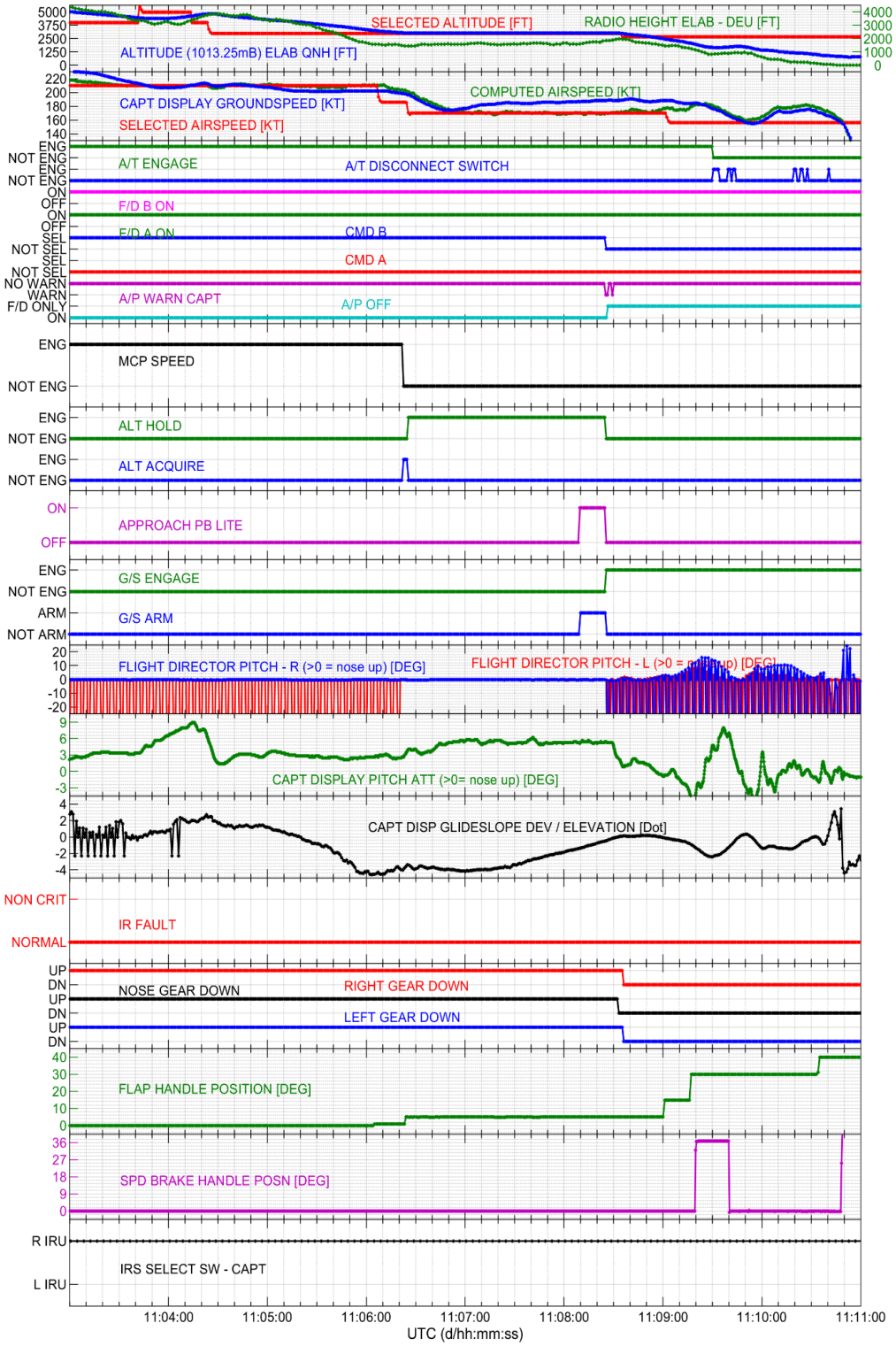


Figure 18: Second Lyon approach - longitudinal parameters

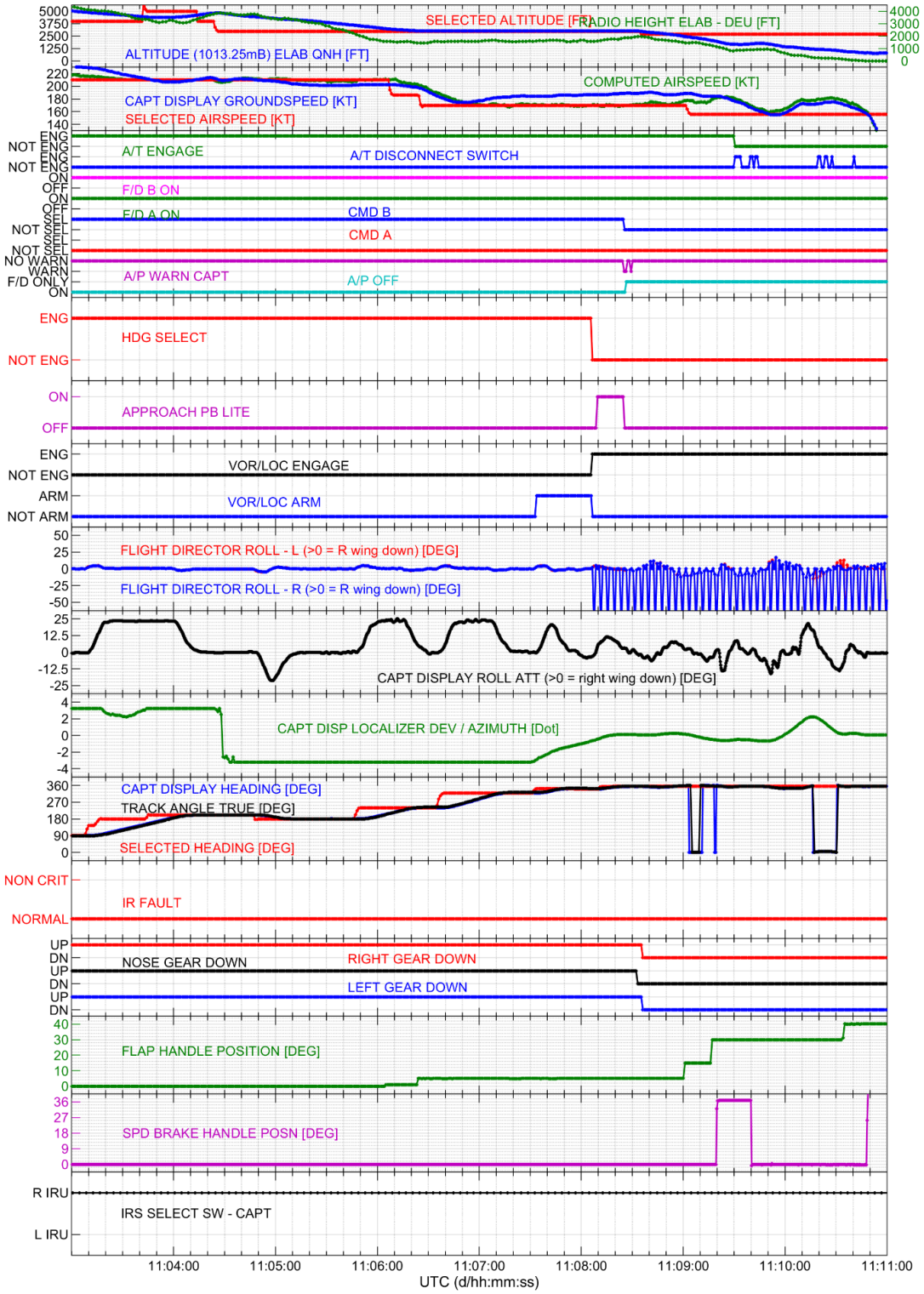


Figure 19: Second Lyon approach - lateral parameters

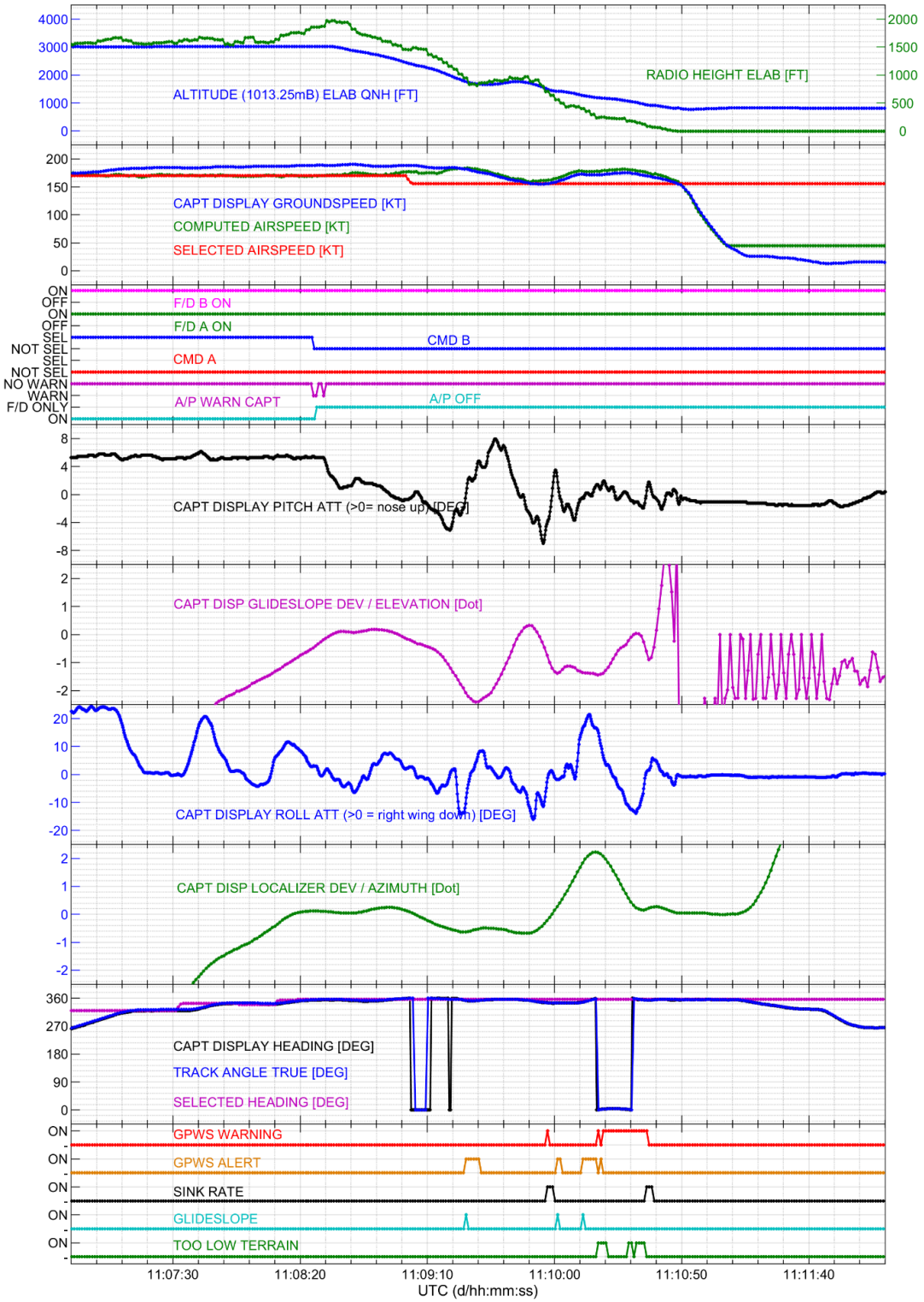


Figure 20: Second Lyon approach - EGPWS warnings

APPENDIX 3

"IRS FAULT" CHECK-LIST - Excerpt from QRH version 4.3.1

BEA note: Items 1 to 5 of the "IRS FAULT" check-list concern the occurrence of the fault on the ground.

In flight

6 The IRS ATT and/or NAV mode(s) can be inoperative.

▼ Continued on next page ▼

11.10

▼IRS FAULT continued▼

7 Choose one:

◆Autopilot use **is** desired:

►►**Go to step 13**

◆Autopilot use is **not** desired:

►►**Go to step 8**

8 Partial capability can be restored by selecting attitude mode on the failed IRS. Straight and level, constant airspeed flight must be maintained for at least 30 seconds.

9 Choose one:

◆Selecting attitude mode on the failed IRS **is** desired:

►►**Go to step 10**

◆Selecting attitude mode on the failed IRS is **not** desired:

►►**Go to step 13**

10 Do the next step **only** if the captain's **or** the first officer's primary attitude display is failed.

Action is irreversible.

11 IRS mode selector (**failed side**) . . . . . Confirm . . . . ATT

Maintain straight and level, constant airspeed flight until the attitude display recovers (approximately 30 seconds).

▼ Continued on next page ▼

11.11

▼IRS FAULT continued▼

The primary attitude display stays failed and the SET IRS HDG prompt on the POS INIT page is blank until the attitude mode alignment is complete.

12 Choose one:

◆FAULT light **extinguishes**:

Enter magnetic heading on the POS INIT page or on the overhead IRS display unit by selecting HDG/STS.

Note: Periodically enter updated heading on the POS INIT page or on the overhead IRS display unit by selecting HDG/STS.

Do **not** engage either autopilot.

■ ■ ■ ■

◆FAULT light **stays illuminated**:

►►**Go to step 13**

13 IRS transfer switch . . . .BOTH ON L or BOTH ON R

14 The autopilot on the side with the operational IRS can be used **except** during approach. Autopilot use during approach is not authorized.

Note: If the autopilot is engaged, the yaw damper disconnects after approximately 1 minute and cannot be reconnected until the autopilot is disengaged.

▼ Continued on next page ▼

▼IRS FAULT continued▼

15 **Checklist Complete Except Deferred Items**

Deferred Items

Descent Checklist

Pressurization . . . . . LAND ALT ___
Recall . . . . . Checked
Autobrake . . . . . ___
Landing data . . . . . VREF ___, Minimums ___
Approach briefing . . . . . Completed

Approach Checklist

Altimeters . . . . . ___

Prior to Start of the Approach

Autopilot . . . . . Disengage
Autothrottle (if engaged) . . . . . Disengage
YAW DAMPER switch . . . . . ON

Landing Checklist

ENGINE START switches. . . . . CONT
Speedbrake . . . . . ARMED
Landing gear . . . . . Down
Flaps . . . . . ___, Green light

■ ■ ■ ■

APPENDIX 4

Excerpt from RAM Policy Manual - Reacting to and dealing with an abnormal situation

الخطوط الملكية المغربية royal air maroc	POLICY MANUAL	25/12/2012
	Chapitre 13	Révision: 20
	Consignes RAM	13.1.3.1

13.1.1.6 REACTION ET TRAITEMENT D'UNE SITUATION ANORMALE:

COMPORTEMENT IMMEDIAT :
ANNONCE " Par le PNT détectant l'anomalie,"
EFFACER l'alarme (sonore ou lumineuse), lorsqu'elle
est clairement identifiée par : PF **et** PM

⇩

CDB confirme ou redéfinit les tâches PF/PM
TRAJECTOIRE - PILOTAGE - NAVIGATION → PF
COMMUNICATIONS ATC → PM

⇩

CHOIX ET APPEL DE LA PROCEDURE ADAPTEE :
Identification de la check list
CHECKLIST ENCADREE
Execution des "memory items" selon "area of responsibility"
REFERENCE A LA DOC
Verification "memory items" et execution "reference items"
CHECKLIST URGENCE, SECOURS,
PROCEDURES SUPPLEMENTAIRES
(Vérification du panneau de disjoncteurs)

⇩

BILAN
Technique, Economique, Commercial et Humain
CONSIDERATIONS OPERATIONNELLES:
Limitations, carburant, météo en route, destination,
déroutement, DDM, transport,
et hébergement passagers

⇩

Si possible, après consultation Compagnie
(CCO : Centre Coordination Opérations)

⇩

DECISION

⇩

INFORMATION (Compagnie, ATC, Passagers)

APPENDIX 5

FMC Navigation Check procedure

FMC Navigation Check

If the VERIFY POSITION message, UNABLE REQD NAV PERF – RNP message, or both GPS-L INVALID and GPS-R INVALID messages are shown in the scratch pad, or course deviation is suspected, do the following as necessary to ensure navigation accuracy:

Actual position ..... Determine and compare with FMC position

Determine actual airplane position using raw data from VHF navigation or ADF radios.

If radio navaids are unavailable:

FMC position.....Compare with the IRS position

Use the POS SHIFT page of the FMC CDU. If the two IRS positions are in agreement and the FMC position is significantly different, the FMC position is probably unreliable. The POS SHIFT page may be used to shift FMC position to one of the IRS positions. This is accomplished by line selecting the IRS or radio position and then pressing the EXEC Key.

Actual position.....Confirm with ATC radar or visual reference points.

Navigate using most accurate information available (continue to monitor FMC position using VOR/ADF raw data displays on non–flying pilot's navigation display).

CAUTION: Navigating in LNAV mode with an unreliable FMC position may result in significant navigation errors.

Navigate by conventional VOR/ADF procedures, radar vectors from ATC, dead reckoning from last known position, and/or use of visual references.

BEA

Bureau d'Enquêtes et d'Analyses
pour la sécurité de l'aviation civile

10 rue de Paris
Zone Sud - Bâtiment 153
Aéroport du Bourget
93352 Le Bourget Cedex - France
T: +33 1 49 92 72 00 - F: +33 1 49 92 72 03
www.bea.aero

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FRANÇAISE
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