Published: October 2012

Sea Search Operations

Accident on **1st June 2009**
to the **Airbus A330-203**
registered **F-GZCP**
operated by **Air France**
flight AF 447 Rio de Janeiro – Paris

BEA
Bureau d'Enquêtes et d'Analyses
pour la sécurité de l'aviation civile
Ministère de l'Ecologie, du Développement durable et de l'Energie

Table of Contents

GLOSSARY 5

INTRODUCTION 7

A – SEARCH FOR AND EXPLOITATION OF FLOATING DEBRIS 8

A.1 Search and Rescue (SAR) Operations 8

A.1.1 Organisation 8
A.1.2 Resources 8
A.1.3 Role of the E-3F 8
A.1.4 Problems with Emergency Locator Transmitters (ELT) 9

A.2 Collection and Analysis of the Positions of the Floating Debris 10

A.2.1 Problems with identification of the debris 10
A.2.2 Setting up a floating debris database 10
A.2.3 Recovery of remains and aeroplane parts 11
A.2.4 Use of satellite images 11

A.3 Setting up of a Drift committee 13

A.3.1 Methodology 13
A.3.2 Calculation results and limits 13

A.4 Initial Lessons Learned 14

A.4.1 Sea pollution 14
A.4.2 Deployment of buoys by maritime patrol aircraft 15
A.4.3 Linguistic constraints during SAR searches 15

B – PHASE 1 SEARCHES (10 JUNE - 10 JULY 2009) 16

B.1 Search for the signals transmistted by the ULBS 16

B.1.1 Initial Objectives 16
B.1.2 Acoustic detection means deployed 16
B.1.3 Intervention resources deployed 22
B.1.4 Organisation of searches onsite 25

B.2 Results 27

B.2.1 Raw results 27
B.2.2 Weighted results 27

B.3 Feedback 28

B.3.1 Enhanced battery life 28
B.3.2 Additional ULB 28
B.3.3 Recording of raw data 29
B.3.4 Use of unproven resources 29
B.3.5 Use of a submarine 29

C – PHASE 2 SEARCHES (27 JULY - 17 AUGUST 2009) 30

C.1 Preparation 30

C.2 The Towed Acoustic Sonar (TAS) 30

C.3 Coverage of the search zone 31

C.4 Performing zone bathymetry 31

C.5 Development of a methodology 32

C.5.1 Data used 32

C.5.2 Combination of TAS and MBS data (imaging and bathymetry) 32

C.6 Results 33

D – PHASE 3 SEARCHES (2 APRIL - 24 MAY 2010) 34

D.1 Preparation 34

D.1.1 Determination of the search zone 34

D.1.2 Selection and deployment of the resources 35

D.2 Resources deployed 36

D.2.1 Ships and search resources 36

D.2.2 REMUS 6000 autonomous underwater vehicles 38

D.2.3 The US Navy deep towed sonar ORION 39

D.3 Searches conducted 40

D.3.1 Search period from 2 to 25 April 2010 40

D.3.2 Search period from 3 to 24 May 2010 41

D.4 Results 42

D.5 Analysis of the detections made by the Emeraude Submarine 42

E – PHASE 4 SEARCHES (25 MARCH – 9 APRIL 2011) 43

E.1 Preparation 43

E.1.1 Release of drift buoys 43

E.1.2 Metron study 44

E.2 Description of AUV operations 44

E.2.1 Installation of the AUVs on the Alucia 44

E.2.2 Discovery of the accident site 45

E.2.3 Site mapping by merging the ESC images 47

E.2.4 Summary 49

F – PHASE 5 SEARCHES (26 APRIL - 3 JUNE 2011) 52

F.1 Preparation 52

F.2 Resources deployed 52

F.2.1 REMORA III ROV 53

F.2.2 Ile de Sein cable ship 53

F.2.3 USBL positioning system 54

F.2.4 Underwater navigation performance 54

F.3 Organisation of operations 54
F.3.1 Search for and recovery of the flight recorders 54
F.3.2 Study of the accident site 56
F.3.3 Recovery of human remains and psychological aspects 59

G – ADDITIONAL STUDY ON THE NON-DETECTION OF ULBs 61

G.1 Context for the acoustic searches using passive devices 61

G.2 Analysis of the TPL routes in the wreckage area 62

G.3 Examination of the recovered beacon 63

G.4 Predicted range of the ULB signal - Acoustic Dispersion of a ULB 63

H – FINANCIAL SUMMARY 64

I – LESSONS LEARNED AND RECOMMENDATIONS 65

LIST OF APPENDICES 67

Glossary

AAIB	Air Accident Investigation Branch (UK)
ACARS	Aircraft Communication Addressing and Reporting System
ADCP	Acoustic Doppler Current Profiler
EASA	European Aviation Safety Agency
AOML	Atlantic Oceanographic and Meteorological Laboratory
APU	Auxiliary Power Unit
ARCC	Aeronautical Rescue Coordination Centre
ARGO	Array for Real-time Geostropic Oceanography
AUV	Autonomous Underwater Vehicle
AWACS	Airborne Warning And Control System
BFU	Bundesstelle für Flugunfalluntersuchung (German Federal Bureau of Aircraft Accident Investigation)
CCD	Charge-Coupled Device
CECLANT	Commandement en chef de l'Atlantique (French Atlantic Command)
CENIPA	Centro de Investigação e Prevenção de Acidentes aeronáuticos (Brazilian Aviation Accident Investigation and Prevention Centre)
CEPHISMER	CEllule de Plongée Humaine et Intervention Sous la MER (French Navy Diving and Underwater Intervention Group)
CNRS	Centre National de la Recherche Scientifique (French National Centre for Scientific Research)
CF3I	Centre de Formation and d'Interprétation Interarmées de l'Imagerie (French joint forces imaging analysis centre)
CLS	Collecte Localisation Satellites (French satellite services agency)
CROSS	Centre Régional Opérationnel de Surveillance and de Sauvetage (Regional operational search and rescue centre)
CSMU	Crash Survivable Module Unit
CVR	Cockpit Voice Recorder
DLR	Deutsches zentrum für Luft und Raumfahrt (German Space Agency)
DP	Dynamic Positioning
DSL	Deep Scattering Layer
DVL	Doppler Velocity Log/loch
EDCA	Escadron de Détection et de Contrôle Aéroportés (French Air Force Detection and Control Squadron)
ELT	Emergency Locator Transmitter
EMM	Etat Major de la Marine (French Naval Headquarters)
ESC	Electronic Still Camer
FDR	Flight Data Recorder
FIR	Flight Information Region
FTM	France Télécom Marine
GEOMAR	Helmotz Center for Ocean Research Kiel
GPS	Global Positioning System
IAC /MAK	Interstate Aviation Committee (CIS)

IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer (French Research Institute for Sea Exploration)
IMT	Institut de Mathématique de Toulouse (Toulouse Mathematics Institute)
kt	Knot
LARS	Launch And Recovery System
LDA	Louis-Dreyfus Armateurs
LHD	Landing Helicopter Dock
LKP	Last Known Position
MRCC	Maritime Rescue Coordination Centre
MPV	Multi Purpose Vessel
NM	Nautical Miles
NOC	National Oceanographic Centre
NTSB	National Transportation Safety Board (USA)
ICAO	International Civil Aviation Organisation
IMO	International Maritime Organization
Psi	Pressure per Square Inch
ROV	Remotely Operated Vehicle
SAR	Search And Rescue
TAS	Towed Acoustic Sonar
SAROPS	Search And Rescue Optimal Planning System
SIG	Système d'Information Géographique (Geographic Information System)
SHOM	Service Hydrographique et Océanographique de la Marine (French Naval Hydrographic and Oceanographic Department)
SRR	Search and Rescue Region
THS	Trimmable Horizontal Stabiliser
TPL	Towed Pinger Locator
ULB	Underwater Locator Beacon
USBL	Ultra Short Base Line
USCG	US Coast Guard
UTC	Universal Time Coordinated
WGS	World Geodesic System
WID	Waitt Institute for Discovery
WHOI	Woods Hole Oceanographic Institution

INTRODUCTION

This document presents a review of all of the sea search operations carried out by France following the accident that occurred on 1st June 2009 off the Brazilian coast to the Airbus 330-203 registered F-GZCP and operated by Air France.

Flight AF447 disappeared on 1st June 2009 above the mid-Atlantic ridge more than 500 NM from the nearest coast in airspace where radar coverage was not provided and where radio communications were difficult. The only indication of the aeroplane's position available was the last reporting point transmitted automatically at about 2 h 10 min(1) (last known position). The search for the aeroplane was carried out in an unfavourable environment due in particular to the depth and topography of the sea bed.

The search area was initially defined based on the last known position, the aeroplane's planned route and analysis of ACARS messages. This area was within a 40 NM radius(2) circle, centred on the last known position. It represented an area of more than 17,000 km^2. The first floating debris was discovered on 6 June 2009, 5 days after the aeroplane's disappearance, a fact which considerably complicated the search for the submerged wreckage.

This report reviews the sea search operations and presents the solutions chosen during the various search phases. These searches led to the identification of the wreckage on 3 April 2011. It describes the specific resources selected and the strategy adopted for the search and recovery of the flight recorders. Lastly, it details the mapping and recovery operations undertaken by the crews on the *Ile de Sein* during the final phase.

These operations were carried out between 1st June 2009 and 16 June 2011, the latter being the day when the containers were unloaded from the *Ile de Sein* at Bayonne (France). The searches mobilised a number of teams and a wide range of resources.

(1)Unless otherwise specified, the times in this report are expressed in Universal Time Coordinated (UTC).

(2)This figure was determined on the basis of Mach 0.82 (cruise Mach) and a flight duration of 5 minutes (based on the analysis of the ACARS messages).

A – SEARCH FOR AND EXPLOITATION OF FLOATING DEBRIS

A.1 Search and Rescue (SAR) Operations

A.1.1 Organisation

The purpose of an SAR service is to search with maximum efficacy for aircraft or vessels in distress in peacetime and to save lives on land and at sea.

The Air Navigation Charts issued by ICAO indicate, for every region in the world, the boundaries of the various search and rescue regions (SRR). These regions are generally the same as the ICAO Contracting States FIRs. For every SRR there is an air rescue coordination centre (ARCC).

The International Maritime Organisation (IMO) SAR plan shows the world-wide arrangement of maritime SRRs. Every SRR has at least one Maritime search and Rescue Coordination Centre (MRCC). It should be noted that the boundaries of maritime SRRs may be different from those of aeronautical SRRs, although harmonization efforts have been undertaken.

From 1st June 2009, the Natal MRCC (Brazil) was in charge of coordinating the searches for the floating debris of AF447 as the aeroplane had disappeared in Natal's SAR zone of responsibility.

A.1.2 Resources

The chronology of the searches presented in appendix 1 gives details on the conduct of the searches until 6 June 2009, the day when floating debris belonging to the aeroplane was formally identified for the first time.

These search operations involved Brazilian, French, American and Spanish aircraft, as well as the French and Brazilian navies. Civilian ships were diverted to join the operations. The list presented in appendix 2 shows the extent of the resources deployed, including those from the Brazilian and French armed forces.

SAR operations were stopped on 26 June 2009, no further bodies or items from the aircraft having been found for nine days. The aircraft then stopped their patrols and vessels of the Brazilian Navy left the area. French Navy vessels remained a few days longer to support the acoustic search operation for the flight data recorders.

A.1.3 Role of the E-3F

On 3 June 2009, the 36th EDCA squadron in charge of operating the E-3F's (AWACS) was mobilized to join the search for the wreckage of flight AF447. From 3 June 2009 onwards, an E-3F worked over the presumed accident zone. Dakar Airport (Senegal) was its rear base. It undertook daily missions lasting approximately 10 hours from 3 to 7 June 2009.

As part of the efforts to locate the wreckage of flight AF447, the 36th EDCA analysed the radar recordings of the missions it carried out from 3 to 7 June in order to assess the reverse drift from radar returns that could be floating debris from flight AF447.

Based on the position of the vertical stabiliser of the aircraft that was found on 7 June around 13 h 30 min, the squadron operators sought to identify radar returns with a similar recurrence in this area, "replaying" the radar images of the previous days (3 to 6 June inclusive). The details of the methodology are presented in appendix 3.

The subsequent analysis of data showed that radar returns could be associated with floating debris belonging to F-GZCP. However, in the absence of any means of cross-checking (visual identification by an aircraft or boat), it was not possible to confirm the origin of these radar returns. This would have required having, at these precise locations, some means of visual identification working in cooperation with the AWACS. The problem is the same for the analysis of satellite images that require means for visual identification on site.

A.1.4 Problems with Emergency Locator Transmitters (ELT)

The surface searches were intended to rescue any survivors, detect transmissions from the emergency locator transmitters (ELT), and finally locate and recover bodies and floating debris. These searches led to the recovery of human remains and parts of the aeroplane from 6 June 2009 onwards.

ELTs are satellite radio transmitters to assist the detection and location of aeroplanes in emergency or distress situations. They are radio transmitters communicating worldwide with the international Cospas-Sarsat Satellite System for Search and Rescue (SAR). When activated, these transmitters send out a distress signal, which, if detected by satellites, can be located by trilateration(3) in combination with triangulation. These transmitters do not work when submerged.

(3)Sphere intersection method for positioning.

The aeroplane was equipped with an automatically triggered ELT and two others that are manually activated. One manually activated beacon was recovered. Its switch was found in the "OFF" position. The automatic transmitter was found on the wreckage site during the last search phase.

The Cospas-Sarsat system is used to search for and rescue crews in a large number of aeroplane accidents throughout the world. Despite these successes, the detection of ELT signals after an aircraft accident remains problematic. Several reports have identified malfunctions of the transmission triggering system, disconnection of the transmitter from its antenna or destruction of the transmitter as a result of accidents. Even when the transmitter and its antenna are functioning properly, signals may not be adequately transmitted to the Cospas-Sarsat satellites because of physical blockage from aircraft debris obstructing the signal transmission.

Finally, the current delay of 50 seconds between the order to activate an ELT and the first transmission of the distress signal is incompatible in case of an accident at sea (immediate disappearance of the wreckage after impact). These findings reinforce interest in ensuring advance triggering and immediate transmission of the distress signal before impact. Today, such an activation is available to the crew through a manual control, but experience shows that this option is almost never used by flight crews.

An international working group(4) with representatives from official services and industry, led by the BEA as part of the safety investigation into the flight AF447 accident, has since studied the feasibility of triggered transmission of flight data and ELT activation in flight. The concept is to analyze the flight parameters from aircraft in real time to detect emergency situations. In such cases, flight data transmission is automatically triggered to facilitate the location of an aeroplane. The findings(5) of the working group show that it is technically feasible to define reliable criteria based on flight parameters to detect emergency situations, while minimizing the false alarm rate (distress situation not established).

(4)This group included, among others, representatives of investigation authorities, the DGAC, ICAO, Airbus, Boeing, Air France, Iridium, Inmarsat and Cospas-Sarsat.

(5)The results of the working group are available on the BEA website at: http://www.bea.aero/en/enquetes/flight.af.447/triggered.transmission.of.flight.data.pdf.

The synthesis of the work carried out by the international group has found that an aeroplane equipped with devices for automatically triggered transmission of flight data and advance triggering of a distress signal could be located after an accident at sea with an accuracy better than 5 km.

Safety recommendations were published in Interim Report No. 3 so that aeroplanes performing public transport over maritime or hostile areas can benefit from the activation of the ELT, whenever an emergency situation is detected onboard.

A.2 Collection and Analysis of the Positions of the Floating Debris

A.2.1 Problems with identification of the debris

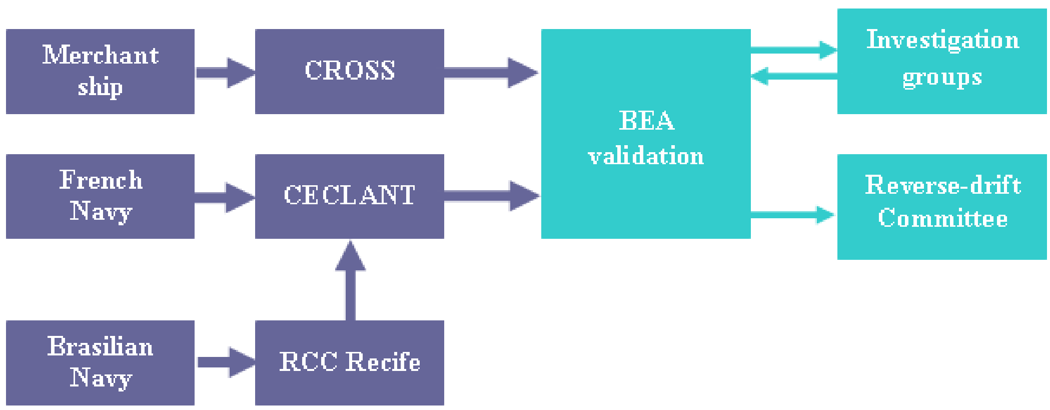
During the first over-flights a lot of debris was identified. Positions were recorded and referenced although the nature of these floating elements could not initially be identified. It is difficult in the absence of vessels in the vicinity to distinguish between debris relating to marine pollution and small debris that may belong to an aeroplane, with the exception of course of large parts such as for example the vertical stabilizer and galleys, which can easily be identified.

The Brazilian Ministry of Defence also made a premature announcement on 2 June 2009 based on aerial observations of drifting elements on the ocean surface which then proved not to be debris from F-GZCP.

The discovery of floating debris from F-GZCP was facilitated by the arrival of the first Brazilian and French vessels on site, guided by the French Air Force E-3F.

A.2.2 Setting up a floating debris database

The French and Brazilian navies found debris belonging to the aeroplane from 6 June 2009 onwards. All the debris made known to the BEA was referenced in a database. The information relating to the size and nature of the objects, as well as the date and location of their discovery, was then used by the "Drift committee" (see A3). The figure below summarizes the main data flow between the various participants



Main data flows during the search for floating debris

Over a thousand items were listed.

A.2.3 Recovery of remains and aeroplane parts

A.2.3.1 Recovery of the first bodies

About thirty bodies were recovered by the frigate *Ventôse* and the *LHD Mistral* between 6 and 17 June 2009 and about twenty by Brazilian ships. All of the bodies were taken to Recife (Brazil) to be autopsied.

A.2.3.2 Recovery of floating debris from the aeroplane

Debris from the aeroplane was found between 6 and 20 June 2009. Parts recovered by the Brazilian Navy were collected in Recife. They were accounted for by the BEA, which recorded them before sending them back to France on the *Ville de Bordeaux* to undergo detailed examinations in Toulouse. The BEA carried out the initial visual inspections on site. The debris recovered by the French Navy was placed on the LHD *Mistral* and brought back to Toulon (France). The debris was then transported to Toulouse (France) to be examined.

The crew of the merchant vessel *MV Gammagas* also recovered some floating debris which was then delivered to British investigators from the AAIB during a port call at Southampton. The latter then shipped it to the BEA.

A.2.4 Use of satellite images

The BEA worked with experts in satellite images in order to search for and analyse images from military and civilian satellites flying over the accident zone from 1st June 2009 onwards.

The DLR provided the following image, acquired by the TERRASAR civilian satellite on 2 June 2009. The photographed area is east of the last reported position of the aeroplane. Its analysis shows dark spots that might be related to pollution or the shadow of waves. Interpretation of the results of these analyses was limited due to adverse weather conditions (degradation of the quality of the image).

TERRASAR image of 2 June 2009

Images from a German military satellite (STARLUPPE) were recovered by the Creil CF3i (France). Analysis of these images made it possible to detect 23 radar returns on 3 June 2009 at 22 h 38 min, approximately 50 NM southeast of the last known position of the aeroplane. A North-South swell (between 350° and 025°) was also observed. According to military experts, these radar returns corresponded to objects on the surface. Air patrols failed however to identify debris belonging to the aeroplane in this area.

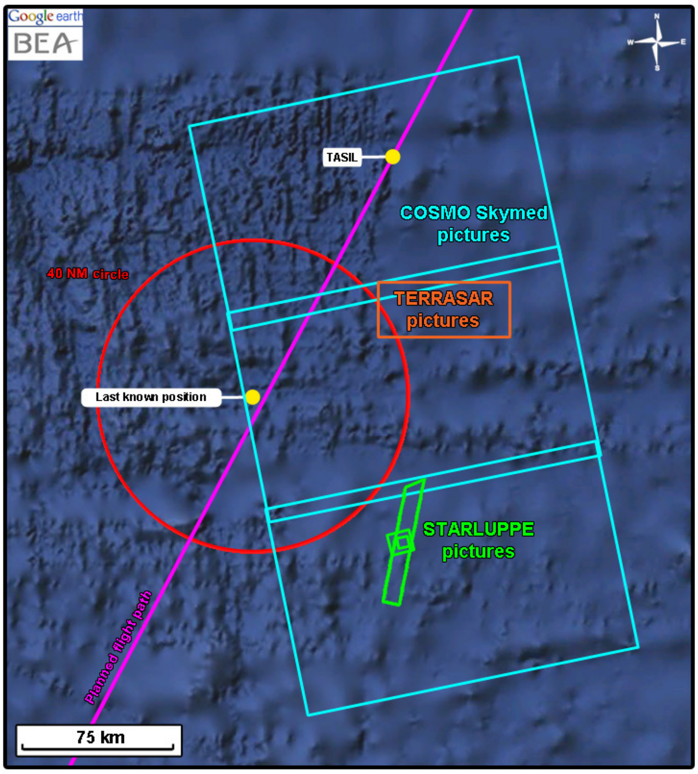
Providers of publicly available pictures were also contacted.

Between 1 and 5 June 2009, in the area of interest, the satellites available for civilian applications were the following:

- ENVISAT: no images,
- Radarsat 1 and 2: no images (filming on 8 June 2009)
- TerraSAR-X (Germany): no images (one image on 6 June 2009)
- COSMO SkyMed (Italy): 5 images taken on 2 June 2009

COSMO SkyMed images and their analyses are in appendix 4. There are a number of pollution spots whose precise origin could not be determined by the analysts.

Note: The indeterminate pollution observed by the Cosmo-Skymed satellite on 2 June at 8 h 15 min 55 (see appendix 4, Scene 2, "pollution probably not linked to a shift") was investigated in phase 2. Its position and distance in time and space from the place where the wreckage was discovered subsequently confirmed that it was not related to the accident.



Summary of satellite information available

A.3 Setting up of a Drift Committee

A.3.1 Methodology

In June 2009, scientists met in the context of a "Drift Committee" working group.

The objective was to estimate a search zone based on calculations of the drift of the bodies and some of the recovered aeroplane parts.

Knowledge of the surface currents and of the winds in the accident zone makes it possible to estimate the previous positions of each referenced body and piece of debris by reverse calculation of a trajectory. By stopping this trajectory at the moment of the accident (1st June 2009 at about 2 h 15 UTC), we can estimate a possible impact zone. This is called the reverse drift or retro-drift calculation.

A team of experts from Météo-France, SHOM, IFREMER, Mercator Ocean and CROSS Gris-Nez[6] worked on the drift calculations. The US Navy, Brazilian Navy and US Coast Guards (USGC) also provided the results of their calculations.

A.3.2 Calculation results and limits

The following table summarizes the numerical models and the associated tools that were used in June 2009 to assess the possible impact area:

Models (tools)	Météo France (MOTHY)	USCG (SAROPS)	US Navy	Brazil (SARMAP)	SHOM*
Oceanic model	MERCATOR	NCOM	G-NCOM	NCOM	(HYCOM + Stokes drift)*
Atmospheric model	ECMWF	NOGAPS	NOGAPS	GFS-10	(ECMWF)*

(*)The SHOM conducted preliminary tests with the HYCOM/ECMWF models, which were not used by the committee.

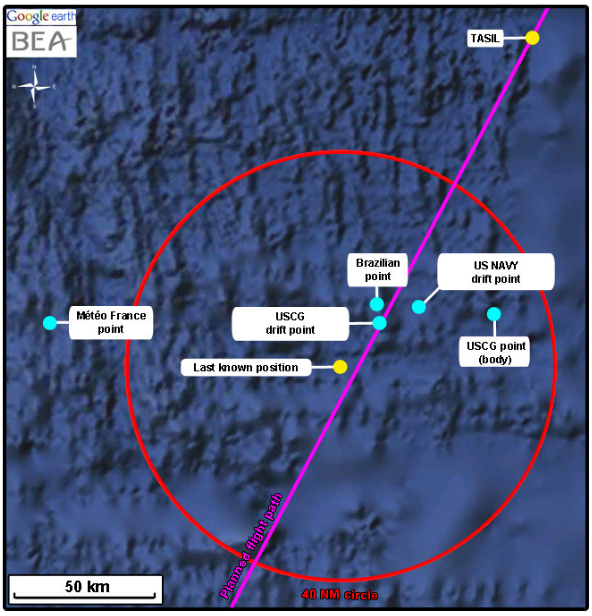
Different reverse drift calculations were carried out either from the position of the vertical stabiliser on 7 June, or from the position of the bodies at the time of recovery. The vertical stabilizer was selected because the wind effect on it could be evaluated and considered negligible (immersion rate close to 100%).

To evaluate the results of reverse drift calculations, data from buoys (ARGO[7] and AOML) drifting in the area at the time of the accident was collected. On 4 June 2009, the French Navy also dropped a buoy that drifted for several hours in the search zone. The Drift committee used the paths of these buoys with different models to compare and try to validate the results of the reverse drift calculations.

The following diagram shows the various organizations' estimated impact positions:

(6)Gris-Nez is the French correspondent for foreign search and rescue centres. It centralizes and handles alerts issued by French ships sailing on all seas around the world. It cooperates with its MRCC counterparts in the framework of the world sea distress and safety system.

(7)ARGO buoys: These buoys come to the surface every 10 days and drift on the surface for 12 hours. ARGO buoys drift at 1,000 m depth (generally) for 10 days then come to the surface where they are positioned for around 12 hours. On the surface they follow the current about 1 m down and are 95% immersed.



Results of reverse drift calculations

The calculations performed by the Brazilian Weather Forecasting Service and by the US Navy gave results close to the USCG calculated point. These various simulations used the same current model: the NCOM model[8]. Météo France used a different model.

In conclusion, the use of the operational tools then available did not lead to a restricted search zone. The first results based on different oceanic and atmospheric models were consistent with each other and presented discrepancies of the order of 100 km after 5 days. These differences can be explained by: the location of the accident in an area difficult to model due to the lack of observations then available, the poor representativeness of the operational oceanic models on small scales, and the delay of more than 5 days between the last message from the aircraft and the first debris found. In addition, the accident occurred during the period of the seasonal start of the North-Equatorial counter-current, which complicated modelling of the sea currents.

For the preparation of phase 3 of the sea searches, the BEA set up a new working group involving international organizations to identify opportunities to improve reverse drift calculations (see chapter D.1).

A.4 Initial Lessons Learned

A.4.1 Sea pollution

It was difficult to identify the origin of the first floating debris recorded by the SAR resources. The presence of many objects, sometimes subsequently attributed to marine pollution, contributed to the confusion in the early days of the searches.

It is estimated that marine pollution mostly comes from land, either from clearly defined, unique and recurrent areas (case of pollution from rich industrialized countries) or from more uncertain areas (in the case of pollution from agricultural waste or debris pushed by winds) which it is difficult to check. Human marine activities are also actively involved in offshore pollution; oil spills and discharges of waste of all kinds by ships in transit are among the significant sources of marine pollution (estimated at around 20%).

[8]The Navy Coastal Ocean Model (NCOM) is based on a 1/8° grid (thus with a resolution of about 15 km). It is fed by the NOGAPS atmospheric model (resolution 50 km) and receives daily, from the US Navy, data from observations and data from forecasts at hourly intervals. This data is regularly integrated and compared with the other sources and with the data sent by the drift buoys.

A.4.2 Deployment of buoys by maritime patrol aircraft

Three sonar buoys[9] were dropped during the search phases. These devices are not dedicated to current measurement. However, the following information was recorded :

- ❒ 4 June 2009 11 h 12 min - time period 6 hours - drift observed: 070°/0.6 kt
- ❒ 5 June 2009 16 h 07 min - time period 6 hours - drift observed: 110°/0.4 kt
- ❒ 15 June 2009 10 h 34 min - time period 6 hours - drift observed: 300°/1 kt.

These data were reviewed by the drift committee.

The deployment of buoys dedicated to the measurement of surface drift by the first aircraft arriving on site would have helped to improve the knowledge of this crucial data for this type of search. This action has been the subject of a recommendation by the BEA.

A.4.3 Linguistic constraints during SAR searches

Coordination between the different participants involved in onsite searches was made more complicated by linguistic factors. Communications between participants of different nationalities mainly took place in English, which sometimes posed some difficulties depending on the level of English of the people involved in the operations.

This communication problem was partially solved by liaison officers rapidly made available by the French Navy at Recife RCC and Natal MRCC.

[9] Equipment comprising a buoy and an acoustic sensor (sonar), equipped with a floating anchor deployed at a depth that depends on that selected for the sensor.

B – PHASE 1 SEARCHES (10 JUNE - 10 JULY 2009)

B.1 Search for the signals transmistted by the ULBs

B.1.1 Initial Objectives

Both of the flight recorders of the aeroplane were equipped with a ULB designed to locate it when immersed. The duration of ULB transmission is at least thirty days from immersion[10]. This limitation imposed strict time constraints on the deployment of search resources in the middle of the Atlantic Ocean. The characteristics of these ULBs are detailed in appendix 5. As a rule, acoustic searches should always be preferred during the transmission time of the beacons. They are more effective than searches using sonar, magnetometers or video cameras.

The maximum range[11] of these beacons is of the order of 2,000 to 3,000 m. However, in the search area the average depth was 3,000 m. It was therefore necessary to bring the hydrophones[12] closer to the source of transmission, by towing specialized equipment nearer to the seabed.

If the wreckage had been localised by identifying the ULB signals, the underwater resources selected would have needed to operate in very deep waters to recover the recorders under difficult conditions.

B.1.2 Acoustic detection means deployed

B.1.2.1 Towed Hydrophones

Ships of opportunity

Two ships of opportunity, the *Fairmount Expedition* and *Fairmount Glacier*, were urgently chartered by the BEA to take on board two Towed Pinger Locator (TPL[13]) acoustic detection and location devices.

Both vessels are owned by FAIRMOUNT, a Dutch subsidiary of LDA. They are two identical tugs assigned to towing tasks in offshore activities. Each of them can carry a payload of 500 tonnes on a platform of 380 m^2 and host a team of 24 operators in addition to the 12 crew members. One was located in the Gulf of Guinea and the other off Rio de Janeiro (Brazil) at the time of mobilization. They soon reached the port of Natal (Brazil) to be equipped with the US Navy equipment , which was transported on a special flight from the United States.

Acoustic equipment

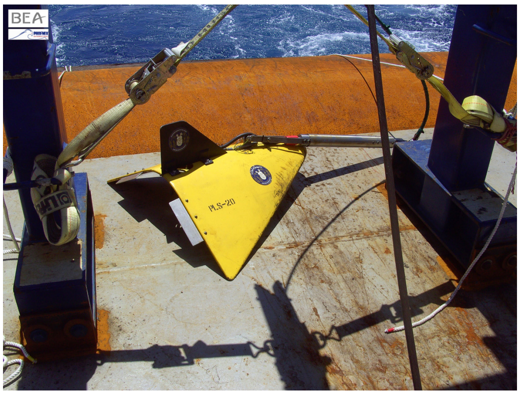
The TPL20 and TPL40 systems are deep-towed devices belonging to the family of the "Towed Pinger Locators" manufactured by Phoenix International for the US Navy. The United States government made both the equipment and the associated operators freely available to the French government (17 people distributed on the two ships). In June 2009 the TPLs were the only systems capable of carrying out passive acoustic searches over large areas at significant depths.

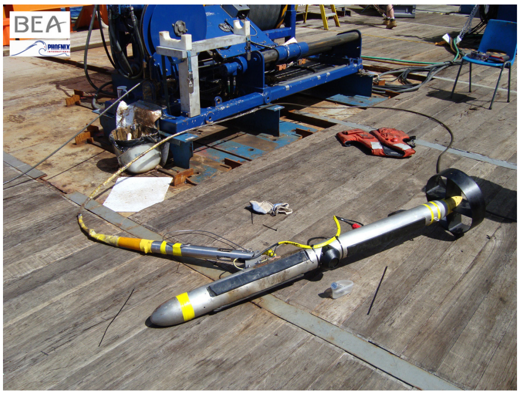
[10]The regulatory minimum is 30 days, but the ULB manufacturer stated that the transmission duration was in reality of the order of forty days. This figure is determined by the capacity of the internal battery.

[11]It may be necessary to take into account the propagation of acoustic waves in a liquid medium, which depends on numerous interconnected parameters, such as the salinity and temperature of the water. When an acoustic wave is propagated in the sea, it is subject to refractions, which generate multiple trajectories. It can also happen that the acoustic waves are deflected in such a way that there is an area of shadow that is never reached by these waves.

[12]Undersea microphone.

[13]The two US Navy TPL's were then the only two towed hydrophones in the world that could operate down to a depth of 6,000 metres.





TPL20 deployed by the *Fairmount Expedition* TPL40 deployed by the *Fairmount Glacier*

The two TPLs are towed devices each equipped with an omni-directional hydrophone which can operate down to depths of six thousand metres with towing speeds ranging from 1.5 to 5 knots. They can be installed on all types of appropriate vessels capable of carrying a load weighing around 25 tonnes. A mapping software application uses GPS positioning information to follow the ship's movements and the position of the towed device. The latter is equipped with a pressure sensor that permanently transmits the immersed device's approximate depth of submersion. Management of the deployed cable length and ship towing speed is used to place the acoustic sensor at the required average submersion depth For example, an average submersion depth of 2,300 m for the TPL is achieved by deploying approximately 6,000 m of cable at a towing speed of 3 knots.

General specifications of the TPL20

The TPL20 is equipped with an omni-directional hydrophone capable of receiving acoustic signals from any sources with a transmission frequency ranging between 5 and 60 KHz. A listening and viewing system provides information to an operator. The TPL20 system has no data recording capabilities (raw or audio translated data).

General specifications of the TPL40

The TPL40 is equipped with four hydrophonic sets (one hydrophone and three antennas) capable of receiving acoustic signals from any source with a transmission frequency ranging between 5 and 60 KHz. The omnidirectional hydrophone is dedicated to detection while the 3 mini linear antennas are used for precise location (high precision directivity: directive beams generated on the left and right sides of the ship). This option enables faster operations in the localisation phase. An acquisition, listening and viewing system provides information to an operator. There is no continuous recording of acoustic data.

Detailed specifications common to both systems

❒ Frequency range:	5 to 60 kHz
❒ Operating mode:	passive
❒ Deployment immersion:	max. 6,000 m
❒ Towing speed:	1.5 to 5 kt
❒ Operating team:	3 people

Additional features

Each system (including all the requisite equipment), with an average weight of 20 tonnes for TPL20 and 27 tonnes for TPL40 can be installed in 24 hours on any type of appropriate vessel capable of carrying such a load. A self-contained unit provides electric and hydraulic power to the assembly, and a dedicated software system is used to monitor the vessel's route. No connection is required to the onboard navigation system.

Constraints

The immersion depth of the acoustic sensor induces high mechanical constraints on the self-supporting electro-cable; limiting these constraints restricts the manoeuvring capabilities of the ship. The speed is limited to 4 kt maximum, and bearing changes are restricted to a few degrees

As an indication, under these conditions an area 30 NM long and 10 nm wide was covered in a little less than 5 days. Within this area a longitudinal pass was carried out in 9 hours, followed by a reverse phase lasting approximately 5 hours. One branch was therefore completed in 14 hours. Long passes were preferred to avoid the multiplication of reversal operations.

The acoustic receiver was generally at an average distance of 1,000 m from the bottom; this gap had to be maintained by monitoring the bathymetric profile on the basis of the data provided by the SHOM. The area was therefore scanned along longitudinal lines spaced approximately 2,600 m apart. This configuration helped maintain an average detection distance ranging between 2,000 m and 3,000 m, to maintain a theoretical overlap of about 800 m between each branch.

Under these conditions, the signal could be sensed for an average period of 30 minutes and the time during which it was perceived the strongest lasted about 5 minutes.

Auditory monitoring was performed by listening to the requisite acoustic signal (centred on 37.5 kHz) translated into the audible band. Upon detection, the signal could be analysed by a spectrum analyser

Availability of resources

The TPL equipment enabled very high operational availability. Two technical interventions caused 19 hours of downtime for the TPL20 for the entire operation, while TPL40 suffered a total downtime of just over 30 hours for the entire mission (due to a connection problem and to a collision with the underwater terrain).

B.1.2.2 The Emeraude (nuclear-powered submarine)

On 2 June 2009, the *Emeraude*, on a stopover in Lisbon (Portugal), was ordered to get under way and proceed to the flight AF447 search zone in order to take part in the operations to detect the flight recorder ULBs. It arrived on site on 10 June 2009.

The *Emeraude* is equipped with numerous acoustic sensors including a sonar interceptor which was used during the search operations. This equipment was not originally designed to detect and localise ULB type acoustic beacons, but thanks to the optimisation of its settings and the use of additional computer software from 30 June 2009, its signal detection capabilities were enhanced.

Deployment constraints

Deployment of the nuclear-powered submarine improved the search system and provided an interesting mobile device in terms of the surface areas covered (its average speed in the zone , between 6 and 10 kt, was higher than that of the other resources deployed). However its use proved difficult, given the safety constraints resulting from its integration in the search operations.

The presence of the nuclear-powered submarine meant that a vast safety zone had to be put in place around its patrol area in order to avoid any collision between the various pieces of towed equipment and the submarine. This permanent preoccupation with safety required delicate management of the undersea zones. Coordination with the nuclear-powered submarine was carried out in liaison with the Brest command centre (France), which meant that notice had to be given a long time in advance for the allocation of the search volumes. The submarine had to interrupt its listening operations daily to return to the surface to establish a radio link with Brest.

Performance

During the search operation, the nuclear-powered submarine support base conducted tests in the Mediterranean using a vessel of the same type in order to verify and optimise the performance of the sensor used. The results of these tests made it possible to define new settings to improve the detection capabilities of the *Emeraude*'s interceptor (the detection distance of 2,000 metres from 10 to 30 June was extended to about 3,200 metres from 1 to 10 July).

The nuclear-powered submarine carried out its mission without interruption from 10 June to 10 July 2009.

B.1.2.3 The oceonographic vessel Pourquoi Pas ?

The BEA chartered the oceanographic ship *Pourquoi Pas ?* from IFREMER together with its specialized exploration and intervention resources, the *NAUTILE* submersible and the *VICTOR 6000* remotely operated vehicle (ROV), which are capable of operating at depths of up to 6,000m.

The *Pourquoi pas ?* is a multi-purpose ship, equipped for working whilst moving and optimised for on-site work. Shared by IFREMER and the French Navy, it can conduct hydrographical (deep or costal waters), geo-scientific and physical/chemical/biological oceanographic missions.

It deploys a great variety of scientific equipment, including the following:

- A Reson MBS 7150 12/24 kHz,
- Current measurement sensors (ADCP 38 and 150 kHz) associated with VMDAS software program for data acquisition,
- A SIPPICAN MK21 Win bathythermograph - for accurate velocity measurement,
- An Ixsea Posidonia USBL (ultra-short baseline system),
- A Simrad EA600 12-38/200kHz single beam sounder

The vessel is designed to receive and deploy IFREMER's heavy equipment. It is equipped with a dynamic positioning system (DP II), which allows it to work on a specific position, even under adverse weather conditions. The vessel also has accommodation facilities (meeting rooms, bedrooms, operational response centre). The phase 1 search and intervention operations were coordinated aboard the *Pourquoi pas ?*.

The *Pourquoi pas ?* had the following acoustic detection equipment onboard:

- An acoustic repeater,
- The MBS (multi-beam sonar), modified to operate in passive mode,
- "ROV homer" directional hydrophones, which can be fitted onto the underwater intervention systems.

Detection resources and their limitations

The multi-beam Seabat 7150 MBS seabed sounder

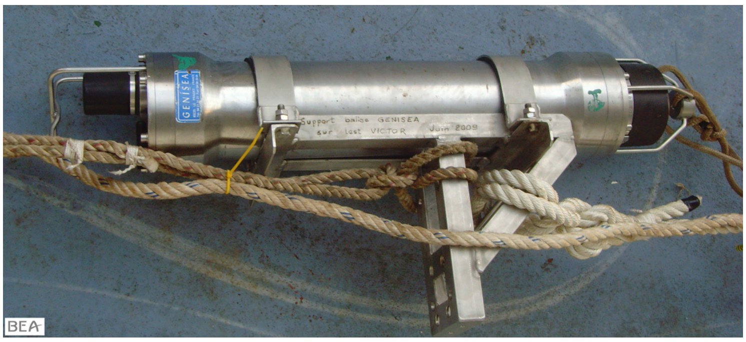
This hull sounder comprises an antenna (8 m long) capable of forming 400 to 800 very narrow beams (1° at 12 kHz, 0.5° at 24 kHz), providing a very fine tracking capability and a significant gain in terms of signal to noise ratio and therefore of detection. This method is commonly used in active mode to perform bathymetry measurements.

In the context of the searches for the flight recorders, it was configured in passive mode and optimized for the 37.5 kHz frequency. However, it was the first time that this equipment had been used in this configuration by the teams on board the *Pourquoi Pas ?*. Its use therefore required an adaptation and validation phase which proved incompatible with the operational and time objectives of the mission.

The 37/12 kHz acoustic repeater

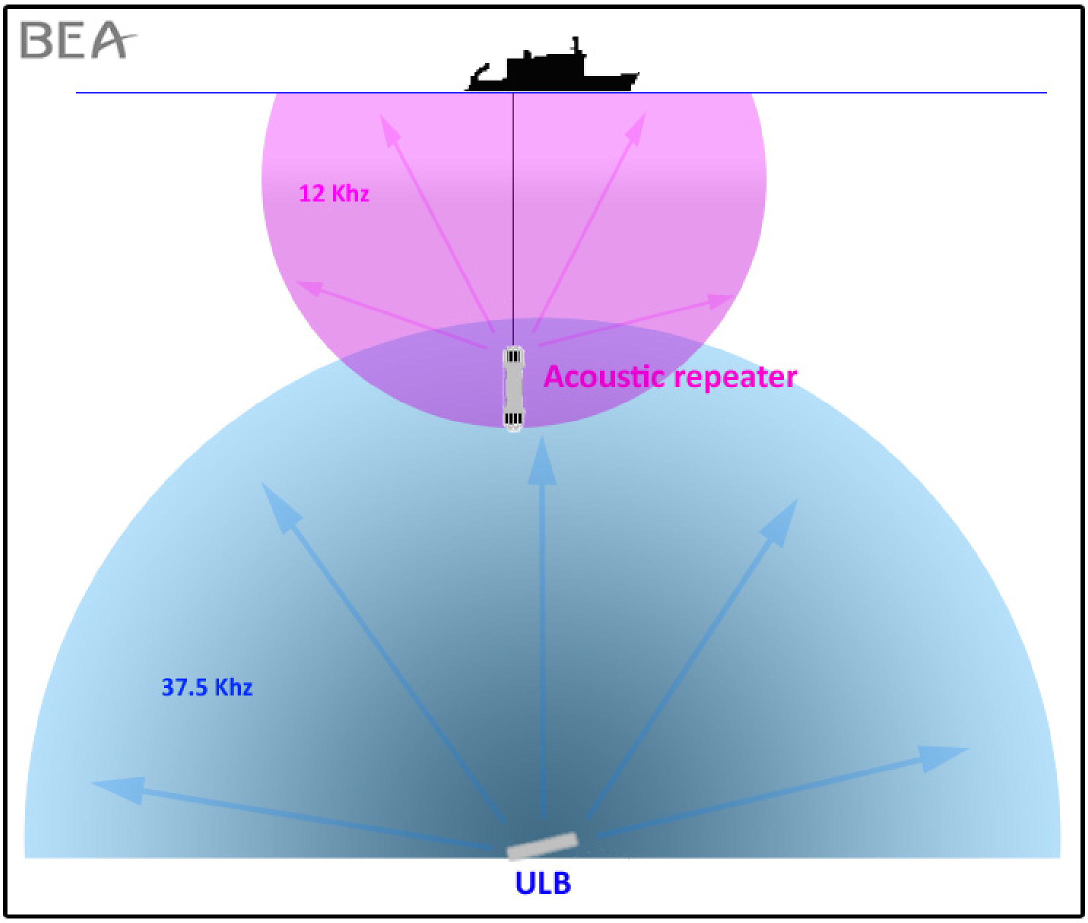
This omni-directional equipment can be towed or suspended by a cable. Its function is to detect and convert a 37 kHz phase acoustic signal into a 12 kHz acoustic signal, which can be detected by various resources available on board the ship, including the EA600 sounder configured in passive mode.

Its upper part is equipped with a transmitting transducer (8 to 16 kHz) and its lower part with a receiving transducer capable of receiving signals between 35 and 40 kHz. Upon receiving a signal between 35 and 40 kHz with a 5 to 15 ms duration, this equipment retransmits a 12 kHz signal of a duration equal to 1 ms for ranges between 500 and 1700 m and 4 ms for ranges less than 500 meters.



37/12 kHz acoustic repeater

It was originally intended to tow the acoustic repeater using a tow cable, but this was not validated by the tests conducted onsite. At a fixed point, i.e. directly beneath the vessel and at standstill, the cable/repeater arrangement (see diagram below), however, was validated as a detection tool. It was used to cross-check the detections recorded by the other systems in the zone. The effective range was limited to 400 m to ensure better detection.



Operating principle of the acoustic repeater

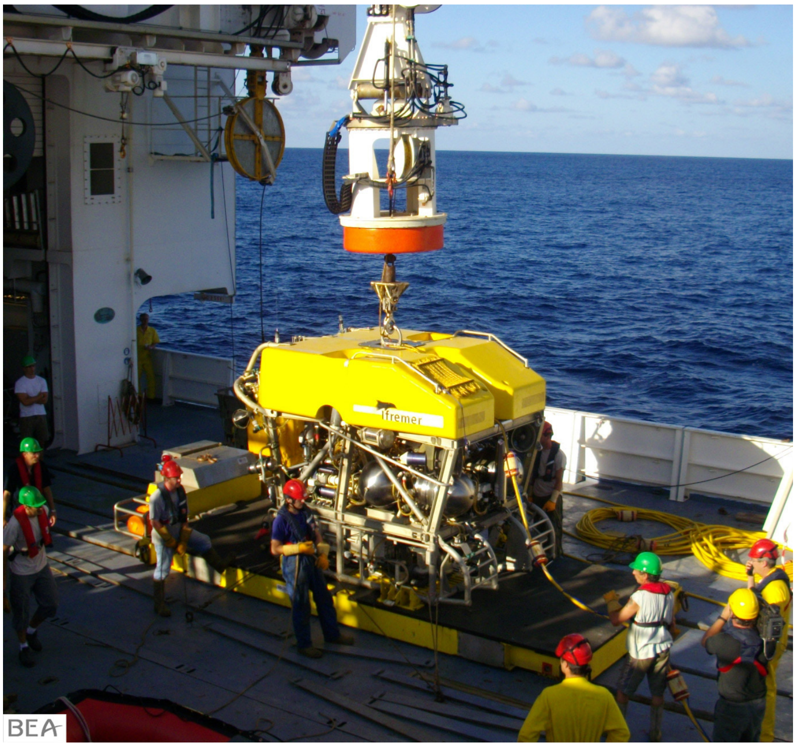
The acoustic repeater did not enable characterization of the received signal. As a result, it was possible that noise pollution in the frequency range between 35 kHz and 40 kHz could have been confused with the signal from the beacons. Similarly, direct noise pollution on reception of the 12 kHz signal from the EA600 On board the ship was possible. Interferences of biological origin were reported by operators during this search phase.

B.1.3 Intervention resources deployed

ROV VICTOR 6000

Dedicated to scientific ocean searches, the *ROV VICTOR 6000* is a remote-controlled system capable of operating at a depth of up to 6,000 m. It is instrumented and modular and can perform high-quality optical imaging, and long-term zone recognition whilst moving or on-site, as well as fine bathymetry and physical measurements, and can carry and operate various types of scientific equipment and tools.

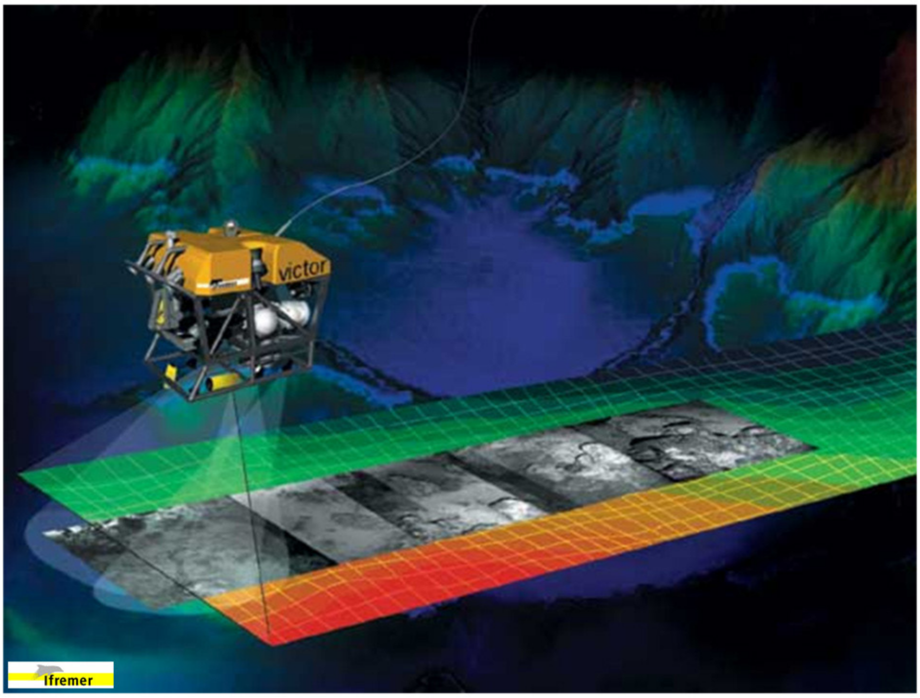
The lower part of the vehicle consists of an instrumented scientific module which can be changed according to the type of assignment. It contains most of the instrumentation as well as the sample basket.



The main *VICTOR 6000* equipment used during this mission was:

- Detection of objects: panoramic sonar and ROV homer for ULB beacons;
- Shooting: 3CCD camera with zoom and direction-finder, control and additional cameras, digital still camera, associated with 8 floodlights and flash units;
- Interventions and handling: a 7-function manipulator arm (100 kg) and a 5-function grasping arm (100 kg);
- Navigation: by the POSIDONIA ultra-short baseline system, making it possible to position several mobiles, combined with the real-time trajectory-plotting and navigation aid provided by the VEMO+ software.

The *VICTOR 6000* also has an optional "En Route" Measurement Module (MMR).



This module is designed to perform high-resolution multi-modal, bathymetric, optical and acoustic mapping of a site by the systematic capture of data on a scale of a few hundred square meters to several square kilometres.

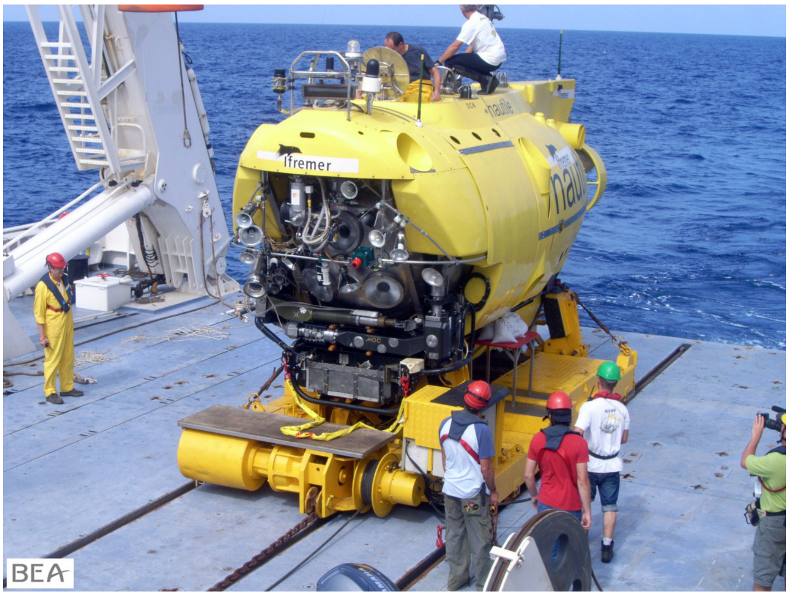
For this particular feature, in addition to other scientific sensors not used for the mission, it includes the following:

- A RESON 7125 multibeam sounder (aperture 1 x 0.5°) able to provide Digital Terrain Models (DTM) with high resolution up to 5 cm using the mapping software programs available onboard the ship;
- A long-range photo camera with light and flash (OTUS), for optical imaging with image geo-referencing and positioning using the GIS software (ADELIE®);
- A conventional vertical colour camera for image mosaics.

Manned submersible "NAUTILE"

The *NAUTILE* is a manned submersible designed for observing and operating at depths down to 6,000 metres. Since it was commissioned in 1984, 1,500 dives have been performed from IFREMER's oceanographic vessels *Nadir, Atalante* and *Pourquoi Pas ?*.

Its fields of operation include exploration of specific zones, collecting samples and manipulating special tools. Thanks to its observation and detection systems, it is a particularly powerful tool for searching for, locating, investigating and providing assistance in raising wrecks.



The submersible can travel at 1.7 knots on the seafloor, with 5-hour autonomy at 6,000 m. It has a payload of 200 kg.

The interesting functional features for the mission were the following:

- Direct viewing, via three portholes with a wide field of vision and six floodlights providing both colour range and restitution;
- Video and still camera shots;
- Object detection on panoramic sonar: the *NAUTILE* is equipped with a high-resolution, long-range sonar, the Straza 1551 (frequency 72-87 kHz). This sonar can be set in 37 kHz beacon detection mode, which ensures a detection range estimated between 3,000 and 4,000 m. In this mode, it is supported by a dual

frequency (RDI) sonar (375/600 kHz) which remains in active mode for safety and the detection of debris;

- ❐ Manipulation and sampling using two arms and a retractable basket;
- ❐ Carrying additional equipment, special tools or to increase sampling capacity;
- ❐ Positioning of the *NAUTILE* ensured by the ship using either a long baseline system (beacons on the sea bed) or an ultra-short baseline system (sensor on board the support ship);
- ❐ Self-positioning: the pilot of the *NAUTILE* checks and compares measurements of distance to beacons with his estimate of position made using the measurements of the submersible speed and attitude;
- ❐ Acquisition and recording on board the vehicle of navigational data and measurements taken by its sensors: altitude, pressure, temperature, heading, speed and time;
- ❐ Preparing, monitoring and archiving data with VEMO+; Analysis of data using ADELIE software program.

Positioning the equipment on the seabed

Positioning mobiles on the seabed has always been a technological challenge because of the complex propagation of acoustic waves in the underwater environment.

The resources of the *Pourquoi Pas ?* were positioned using the POSIDONIA ultra-short baseline system (USBL) (to a maximum of 6,000 m with equipment working under the vessel within a maximum cone of +/- 45°) which nevertheless offers some flexibility when monitoring long exploration profiles.

DGPS is highly recommended for vessel surface positioning. When it is performed without DGPS, the greatest error on positioning comes from the GPS. The accuracy observed is 0.5 to 1% of the water depth, i.e. between 15 and 40 m in the mission zones.

B.1.4 Organisation of searches onsite

B.1.4.1 Tactical coordination of searches

Before the ships and the submarine arrived at the estimated site of the accident, a grid network was made for the search area at the CECLANT centre in Brest by the French Navy and the BEA. The area was thus divided into blocks with sides measuring ten arc-minute lengths (that is to say squares with sides measuring approximately 10 NM at these latitudes). In most of these blocks, depths could exceed 3,500 m. The working areas were distributed between the surface ships and the underwater resources so that the search was carried out rapidly under good safety conditions.

Note: For simplicity, the grid network was established from a north-south axis, corresponding to the orientation of most of the deep sea valleys. It could equally as well have been set using an axis related to the planned route of the aircraft.

The tactical coordination of the searches took place onboard the *Pourquoi Pas ?*. Coordination was undertaken by the BEA with CEPHISMER personnel (French Navy).

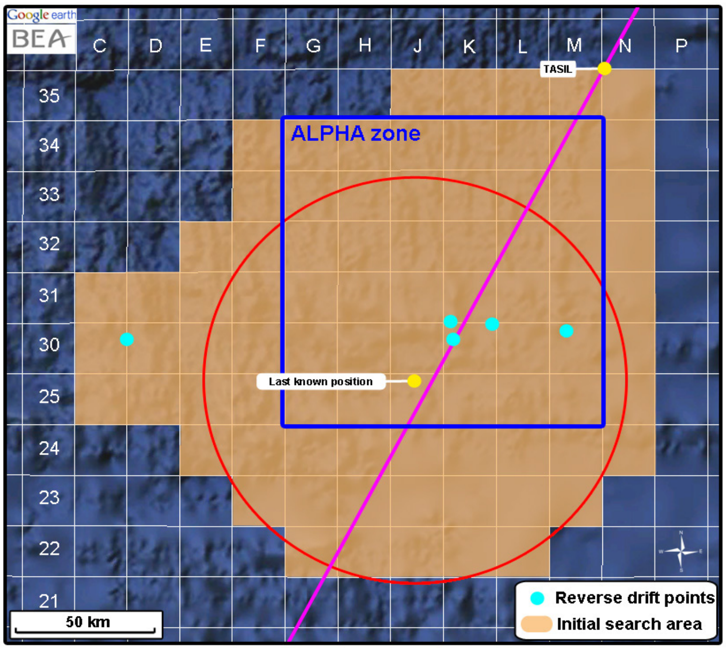
The SHOM detachment on board the *Pourquoi pas ?* worked, among other things, to improve the knowledge of the topography of the area. The deep-sea multi-beam sounder was used to collect depth data within a zone that had remained unknown up to then. Current measurement data and data related to the measurement of the speed of sound in the water were collected and processed.

B.1.4.2 Definition of the search zone

Based on the projected path of flight AF447, the analysis of ACARS messages, the debris found on 6 June and the first reverse drift estimates, a large area representing 60x60 NM (Zone Alpha, squares formed by rows 25 to 34 and columns G to M) was initially considered as the area with the highest probability of finding the wreckage.

Reverse drift calculations conducted by Météo France also resulted in a point west of the Alpha zone. Finally, in the event of an attempted turn back by flight AF447, the area south of the ACARS point and outside the 40 NM circle was also taken into account.

Taking into account all these data helped determine the initial search zone (shown in brown on the figure below). This zone represented a surface area of about 29,000 km²



Search area

B.1.4.3 Allocation of zones

Search zone allocation tactics were established according to the constraints imposed by the various resources available, the goal being to cover the search zone as efficiently as possible, with the priority being placed on the Alpha zone:

- The US Navy's TPL were considered to be the most efficient means and were deployed in the Alpha zone;
- When the nuclear-powered submarine was searching in a zone, it automatically excluded all other resources from this zone because of the large safety band it required;
- When the TPLs arrived on site, the zones assigned to the nuclear-powered submarine were shifted to around the reverse drift point calculated by Météo France and in the southern part of the search zone;
- The acoustic detection resources on board the *Pourquoi Pas ?* essentially served to cross-check the detections recorded by the other systems in the zone. The *Pourquoi Pas ?* completed the set-up without covering large search areas. Its intervention resources could still explore the places where signals had been received and therefore cross-check them.

B.1.4.4 Chronology of acoustic search operations

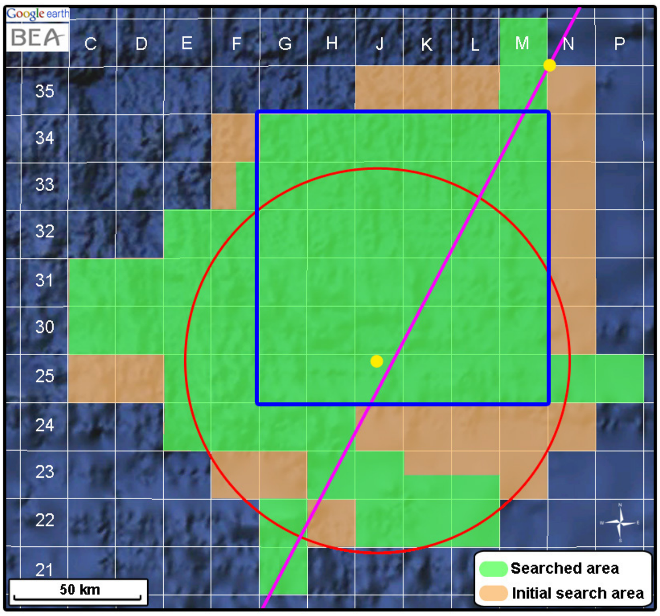
The acoustic searches for the ULBs during phase 1 of the undersea searches began on 10 June 2009 with the arrival of the *Emeraude* in the search zone and ended on 10 July 2009 with the last ships leaving the zone.

The date of 10 July, which corresponds to the end of phase 1, was established on the basis of the information provided by the ULB beacon manufacturer, which had stated that their transmission time was about forty days.

B.2 Results

B.2.1 Raw results

At the end of thirty-one days of acoustic searches on site, about 22,000 km^2 had been explored by the means deployed in the zone, which represents proportionately about 76% of the initial target (see following illustration).



Areas covered by acoustic search means

This result was mainly obtained thanks to the means employed by the US Navy and the nuclear-powered submarine; the *Pourquoi Pas ?* completed the detection mechanism.

No signals were detected from the flight recorders' ULBs.

The underwater observations failed to locate parts of the wreckage of F-GZCP.

The *VICTOR 6000* and *NAUTILE* resources covered a total distance of 245 km on the seabed with about 220 hours of dives, including 200 hours spent exploring the seabed (the site depth imposed relatively long ascent and descent times).

B.2.2 Weighted results

A qualitative analysis of the areas covered by the resources deployed during phase 1 was conducted to prepare for the deployment of the resources required in phase 2.

This analysis consisted in weighting the raw results with reliability indices associated with each piece of equipment deployed in the zone.

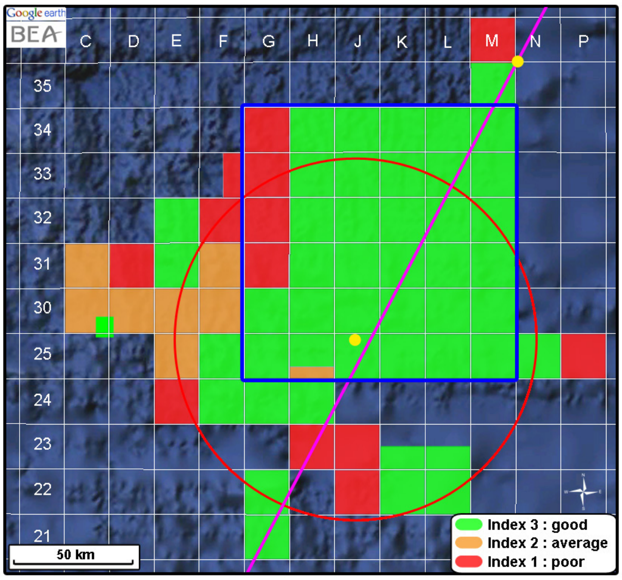
The calculation of this index was established for each piece of equipment on the following basis:

- Their intrinsic detection capabilities, assuming that the ULBs would work;
- The depth of the search area;
- The feedback.

Overall it should nevertheless be noted that:

- The US Navy's TPL equipment obtained a very good reliability index in all the zones because they are designed to operate as close as possible to the seabed;
- The reliability indices obtained by the nuclear-powered submarine were inversely proportional to the depth of the search zone.

The result of this work led to the definition of three reliability indices shown with a colour code for each square in the search area (see figure below).



Weighted results of phase 1 search operations

B.3 Feedback

B.3.1 Enhanced battery life

The use of ULB beacons with 90 days(14) autonomy would have made it possible to extend the search for the ULB beacons in this vast area. The BEA recommended that EASA and ICAO extend the regulatory transmission time of ULBs (from 30 to 90 days)

(14)Technology available in June 2009.

B.3.2 Additional ULB

Using beacons capable of transmitting on lower frequencies (for example between 8.5 kHz and 9.5 kHz) would have facilitated the detection of the wreckage. Indeed, military resources, typically deployed in the early days to take part in SAR operations, are equipped with sonar suited to the detection of low frequency signals, and in addition the use of lower frequencies increases the detection distance. The BEA has recommended that EASA and ICAO make it mandatory for aeroplanes performing public transport flights over maritime areas to be equipped with a low-frequency beacon.

B.3.3 Recording of raw data

The raw acoustic signal received by the TPL sensors was not recorded. If it had been, the provision of these data would have enabled their analysis using dedicated software programs, the objective being to detect a weak signal potentially lost in the background noise.

The nuclear-powered submarine meanwhile proceeded to record acoustic signals as from 30 June 2009. These signals were the subject of further analytical work (see Section D.5)

In the future, it will be necessary to select search resources capable of recording raw acoustic data to allow for further acoustic analyses. This feedback has already been taken into account by some manufacturers.

B.3.4 Use of unproven resources

The use of unproven resources is not desirable. For example, the acoustic resources of the nuclear-powered submarine and the *Pourquoi pas ?* had not been tested on ULB signals before being deployed on site. Tuning systems on-site is hardly compatible with the accomplishment of the mission.

B.3.5 Use of a submarine

The use of a submarine generates significant operational constraints and difficulties in coordinating the surface resource ships. The limited diving depth of submarines is not a decisive advantage over surface ships and even less compared with a submerged hydrophone. A submarine may be useful to explore areas of limited depth provided they are equipped with appropriate sensors.

C – PHASE 2 SEARCHES (27 JULY - 17 AUGUST 2009)

C.1 Preparation

The *Pourquoi Pas ?* was already mobilized for the previous phase. It was decided to send the IFREMER's Towed Acoustic Sonar (TAS) during its port call in Dakar. This sonar imaging equipment was installed on board the *Pourquoi Pas ?* to complement the resources already present for phase 1.

Squaring line (J-M 24) had not been explored for lack of time in phase 1. Phase 2 consisted of covering this zone and then completing the bathymetric data within the 40 NM circle.

Note: The bathymetry of the zone, made up of a plain and slight slopes, was compatible with the use of a towed sonar.

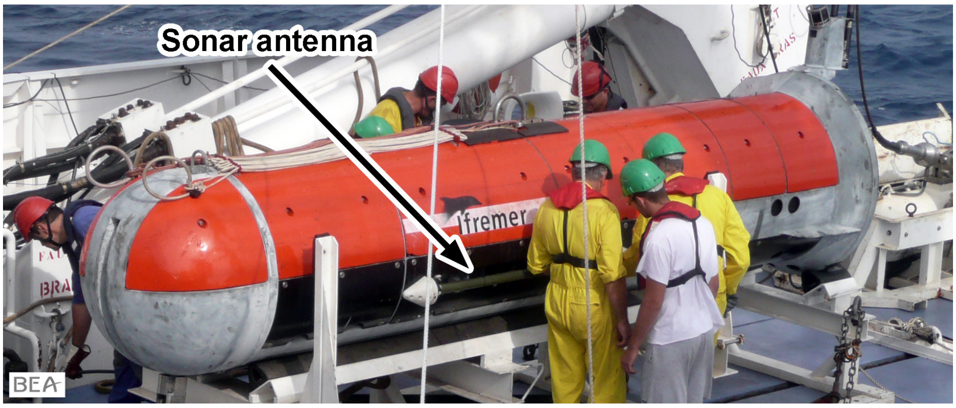
The *VICTOR 6000 ROV* and the *NAUTILE* submersible were in charge of cross-check detections by the TAS.

C.2 The Towed Acoustic Sonar (TAS)

The TAS was designed by IFREMER to study the geological nature and structure of the seabed at great depths (200 to 6,000 metres). It has also been used to search for wrecks.

This side-scan sonar operating at a frequency of 180 kHz can be used, thanks to its imaging resolution (1 pixel for 25 cm), to carry out detailed studies of the seabed to complement other onboard systems designed for larger scale surveys.

The TAS consists of a torpedo-shaped vehicle weighing about 2.4 tonnes that supports two rectangular antennas, about one metre long, installed on either side of the towed vehicle.



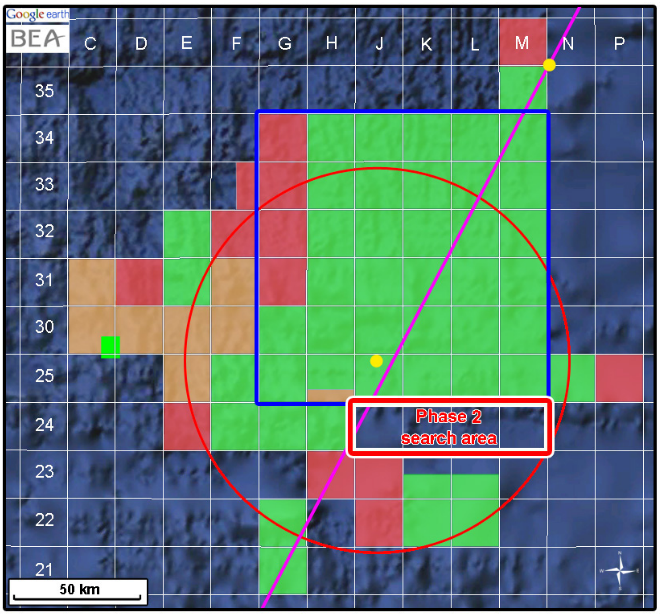
Towed Acoustic Sonar (IFREMER)

The towed acoustic system can cover relatively large surface areas thanks to its operating speed of about two knots, and its scanning range which can cover a strip about 1,500 metres wide (scan swath). The document in appendix 7 gives details of its operating principle.

The TAS has neutral buoyancy in the water regardless of the depth of immersion. It is designed to be very stable during its travel. The TAS is connected via a 30 m lead to a 2 ton ballast ensuring its continuous immersion. The assembly is linked to the towing vessel by an 8,000 m long self-supporting electro-cable. A set of embedded sensors (three-axis attitude unit and pressure sensor) on the immersed device helps control the winch to ensure depth control of the TAS. The overall device helps control the immersion and mechanically dissociate the TAS from the cable and tug movements.

C.3 Coverage of the search zone

The profiles were set 1,200 metres apart to obtain a theoretical coverage of about three hundred metres between two profiles. The profiles were organised in such a way as to facilitate the ship's manoeuvres and take into account the bathymetry (see figure below).



Phase 2 search zone

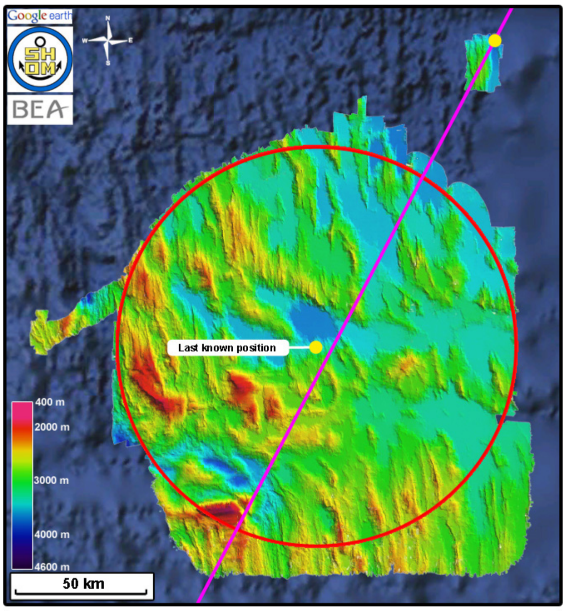
The TAS was operated on line 24, squares J, K, L and M of the grid network.

1,230 square kilometres were thus covered and dives with the aid of the *VICTOR 6000 ROV* were used to cross-check some detections. The surfaces covered by the TAS and the ROV were respectively about 100 km2/day and 5 km2/day.

C.4 Performing zone bathymetry

At the time of this second phase, a detachment from the French Navy hydrographical and oceanographic service (SHOM) on board the *Pourquoi pas ?* completed topographical data on zone (bathymetry) using the multi-beam seabed sounder (MBS).

Carrying out this bathymetry was crucial to the success of the following search phases.



Bathymetry of the search zone

The steeply sloping areas of higher terrain represent about 27% of the surface area. The seabed is more irregular in the western part of the zone which is very close to the mid-Atlantic ridge.

C.5 Development of a methodology

C.5.1 Data used

All the data used to detect the wreckage during the second search phase was information backscatter from the seabed. Backscatter can be defined as the property of a target to reflect a portion of the incident wave in the direction where it comes from (see appendix 7). The backscatter of a wave is related to the composition of the target object and the frequency of the incident wave. In this report, the term "imaging" refers to backscatter data.

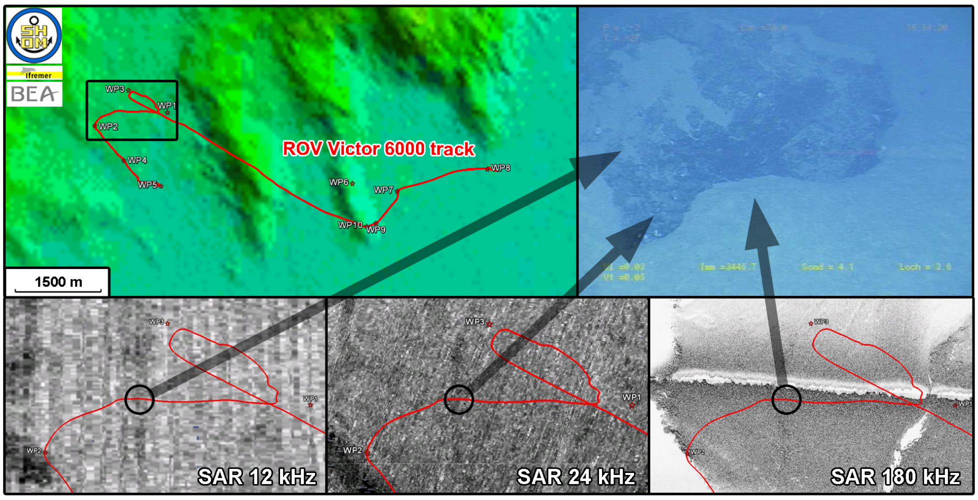
The data used to isolate points of interest was as follows:

- The raw data from the side-scan sonar, displayed in real time on a screen, was continuously printed and replayed later;
- Imaging data from the MBS, used at frequencies of 12 kHz for the first phase and 24 kHz in the second, where available;
- Bathymetric data.

C.5.2 Combination of TAS and MBS data (imaging and bathymetry)

With its high operating frequency (180 kHz), the TAS is a tool that can provide fairly accurate images of an object on the seabed. The lower the frequency of the acoustic waves, the deeper they can penetrate the sediment, and thus provide information on buried back-scattering elements. Thanks to its lower operating frequencies (12 or 24 kHz), the MBS penetrates the sediment and provides additional information. The accuracy of its images, however, is lower than the TAS (about 10 m at 12 kHz and 5 m at 24 kHz).

The inter-operability of the resources made it possible to eliminate some TAS detections that proved to be large rock masses buried in the sediment. Some detections however required the use of the ROV to visually cross-check them.



This methodology developed by IFREMER in phase 2 and the data collected during phases 1 and 2 was used in subsequent phases with the WHOI institute.

C.6 Results

No parts of the wreckage were located during this phase.

The bathymetry of the total surface area the search zone (a 40 NM circle) was nevertheless completed.

D – PHASE 3 SEARCHES (2 APRIL - 24 MAY 2010)

D.1 Preparation

D.1.1 Determination of the search zone

To prepare phase 3 of the sea searches, the BEA formed a new working group, enlarged with international partners, in order to identify the possibility of improving the reverse drift calculations. It was made up of representatives from the following scientific organisations: CNRS/Brest, University of Massachusetts/Dartmouth, INMRAS/Moscow, Mercator Océan/Toulouse, CLS/Toulouse, WHOI/Woods Hole, IMT/Toulouse, SHOM/Brest, NOC/Southampton, IFREMER/Brest and Météo-France/Toulouse.

The work of the group resulted in the definition of a limited search zone. The report[15], prepared by the scientific committee and published on 30 June 2010, presents the work undertaken by the whole group.

The first part of this report is devoted to presenting the data used. The members of the working group were able to collect other observations, including the trajectories of several buoys on a zone near the last known position of the aeroplane, in the days that followed the accident. The second and third parts of the report were devoted to the methods used and their validation in the zone under study.

The first method, called "objective analysis" consisted of calculating the surface current field by linear combination of the observed velocities of the drifting buoys. With the surface current field estimated several times a day, the reverse drift calculations for various bodies and aeroplane parts were undertaken. Imperfect knowledge of the field current required an estimate of the induced error.

The second method consisted of using different numerical ocean models with or without assimilation of the observations (such as temperature, salinity and currents). Similarly, various calculations of reverse drift were performed and the error for each model, in the zone studied, was estimated. The influence of the wind on the surface drifting elements from the aeroplane was preponderant in the reproduction of their movements.

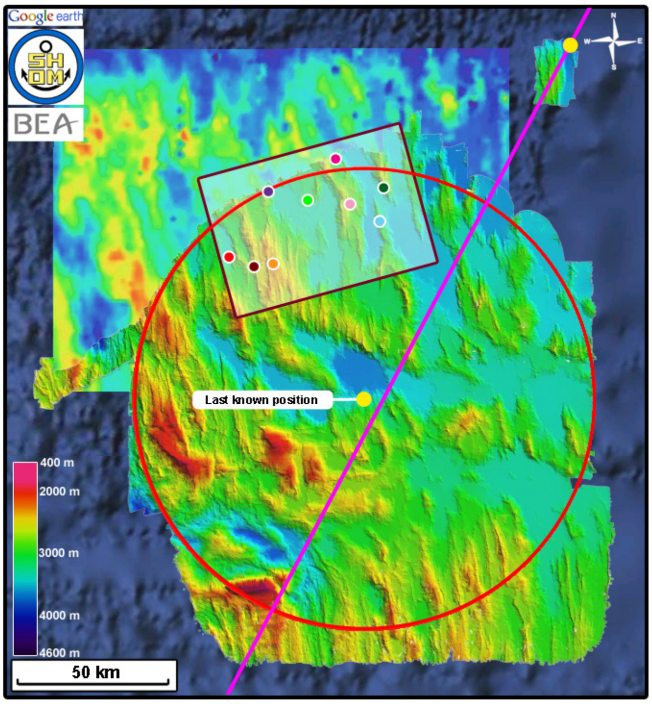
The fourth part of the report defined the search zone (see chart below).

In the light of the results obtained and using the weighting given to each of the approaches selected, a search zone was defined based on the statistics. To do this, six particles judged as being the most representative[16] were used for the reverse drift calculations. For each model or analysis, the mean of the estimated positions of these particles, on 1st June at 2 h 10 UTC, was kept. Subsequently, by using the estimated error of each method after five days, the drift committee was able to determine an area in which the wreckage would be found with a probability of 95%. This zone was used by the BEA as the initial search zone for phase 3. The points shown give the estimated mean positions on 1st June at 2 h 15 UTC of the six selected particles, for each model.

[15] http://www.bea.aero/en/enquetes/flight.af.447/phase3.search.zone.determination.working.group.report.pdf

[16] The representativeness of the particles is based on knowledge of the coefficient of exposure to the wind of the bodies and the aeroplane parts as well as their recovery or observation date.

[17] This zone corresponds to a region determined statistically and based on the reverse drift calculations from the selected models.



Proposed search zone

- In red, the PSY2AVG model, with an adjustment to the buoys' trajectories;
- In brown, the FVCOM model that assimilates the speeds of the drift buoys;
- In orange, the FVCOMW model that includes the interactions with the waves;
- In violet, the ZOOM2 model with no assimilation but with improved physics;
- In magenta, the same model, to which the drift due to waves was added;
- In green, the objective analysis OI50;
- In dark green the objective analysis OI85;
- In pink, the objective analysis OI75 (illustrating consistency, but not used here);
- In sky blue, the INMOM model (not used here, but also consistent).

D.1.2 Selection and deployment of the resources

To select the search and recovery resources, the BEA made a review of the equipment allowing work to be carried out down to a depth of 6,000 metres, with the support of an international working group involving the following organizations:

- Air Accident Investigation Branch (AAIB, United Kingdom);
- Bundesstelle für Flugunfalluntersuchung (BFU, Germany);
- Centro of Investigação e Prevenção de Acidentes aeronãuticos (CENIPA, Brazil);
- Interstate Aviation Committee (IAC/MAK, CIS);
- National Transportation Safety Board (NTSB, USA);
- Secrétariat Général à la Mer (SG Mer, France);
- US Navy (USA).

The table below summarizes the various types of resources that exist for underwater exploration. They all have advantages and disadvantages depending on the nature of the underwater terrain, their installation on board support vessels, the need for real-time or delayed data transmission, etc. The figures provided in the table are indicative only.

Equipment	Speed	Turn (time)	Seabed type	Autonomy	Vessel (requi-rements)	Area coverage
Deep towed sonar	2 kt	3 hrs	Low slopes	10 days	Manoeuvring at slow speeds	100 km^2 per day
AUV	3 to 5 kt	¼ hr	Medium slopes Room for improvement	1 day	Escort	Approx. 100 km^2 per day per AUV
ROV	0.5 to 1 kt	¼ hr	All	3 days	Dynamic positioning	5 km^2 per day

Indicative table of the different resources for underwater searches

Following this preliminary work, the BEA published in January 2010 an international call for tenders which helped group applications and offers from international operators. This required a sophisticated legal mechanism including the following:

- A charter contract under US law between the BEA and the two companies selected, Seabed AS and Phoenix International Inc., in accordance with maritime practices;
- Two service contracts, respectively under Norwegian and US law, with these two companies;
- An amendment to an intergovernmental agreement in order to be able to pay for services provided through the US Navy.

In February 2010, the BEA chartered two ships with the most high-technology equipment on board that could operate down to depths of 6,000 metres:

- The American ship *Anne Candies* from Phoenix International Inc. equipped with an ORION deep towed sonar and a CURV 21 remotely operated vehicle (ROV) belonging to the US Navy;
- The Norwegian ship *Seabed Worker* from the Seabed AS company equipped with one TRITON - XLX 4000 remotely operated vehicle (ROV) and three REMUS 6000 autonomous underwater vehicles (AUV) operated by the American Woods Hole Oceanographic Institution (WHOI), of which two belonged to the Waitt Institute for Discovery (WID) and one to GEOMAR, the German oceanographic institute, as well as equipment to raise substantial elements of the wreckage.

The resources chosen were complementary and considered to be among the best. Their deployment was carried out by experienced operators assisted by specialists in marine geology from the WHOI and IFREMER institutes. Support from scientists in marine geology was instrumental in analysing the data from this area featuring rough underwater terrain (Mid-Atlantic Ridge)

D.2 Resources deployed

D.2.1 Ships and search resources

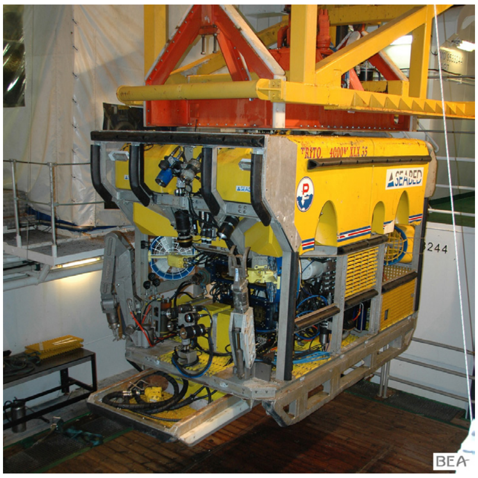
The objective of the third search operation was to explore the smaller search zone defined by the drift committee drift with side scan sonars. The resources selected also allowed, in case of discovery, to raise parts of the wreckage.

The *Seabed Worker* is a 98 m long Multi Purpose Support Vessel (MPV) of the latest generation, that can accommodate any type of specialized equipment on its 650 m² deck area. It has a class 2 advanced dynamic positioning system (DP II) and roll stabilization system.

MPV *Seabed Worker*

Anne Candies

The *Seabed Worker* has an active heave-compensated 100-Ton offshore crane. For phase 3, in addition to the three REMUS autonomous underwater vehicles, the *Seabed Worker* had on board the Triton XLX ROV, which can operate down to a depth of 4,000 m.



TRITON XLX ROV

CURV 21 ROV

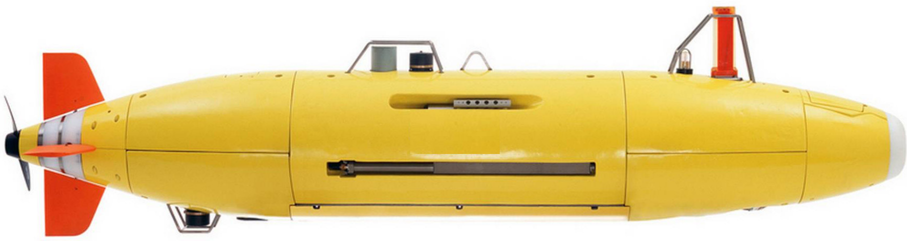
The *Anne Candies* support vessel also has an advanced dynamic positioning (DP II) system. She was the support vessel for the ORION towed sonar and the CURV 21 ROV

The ORION towed sonar and the CURV 21 ROV are designed to be integrated into a single search and recovery system that can be easily transported and deployed on support vessels meeting the specifications of the US Navy. They actually share the same self-supporting electro cable, which represents a significant gain in terms of logistics. As for the CURV 21 ROV, it can operate down to a depth of 6,000 m. Its maximum speed is 2.5 kt.

The CURV 21 ROV was little used during phase 3.

D.2.2 REMUS 6000 autonomous underwater vehicles

The *Seabed Worker* carried three REMUS 6000 autonomous underwater vehicles (AUV) which were deployed by WHOI.



REMUS 6000 autonomous underwater vehicle (AUV)

The REMUS 6000 AUV is approximately 4 m long and weighs around 880 kg. It can carry out missions down to a depth of 6,000 m. The AUV is fitted with a rechargeable lithium-ion battery with a capacity of 11 kilowatt-hours, enabling it to carry out scheduled missions of a maximum duration of 20 hours. An electric motor drives a fixed-pitch propeller, ensuring a standard speed of 3.5 kt in search mode. At this speed, the vehicle can travel about 125 km during a dive. The main search sensor is an EDGETECH 120/410 kHz dual frequency non-simultaneous side-scan sonar. During a wide area search the low frequency was operated at range settings of up to 700 meters. In areas of rough terrain the range was often reduced to 400 to 500 meters in order to improve resolution.

AUV Navigation

The AUV is fitted with a positioning and inertial navigation system. Before each dive, the different phases are programmed into its integrated mission management system. Once launched, it operates automatically and follows the predetermined paths. The natural drift of its inertial navigation system requires regular recalibrations. It uses a long baseline system consisting of a series of acoustic transponders with a frequency range of 8 to 12 kHz immersed in the search area assigned to the AUV. Thanks to the use of coded signals, several AUVs can navigate at the same time with a single pair of transponders.

The transponders are dropped from the ship over specific geographical positions chosen according to the bathymetry of the area. Once installed on the seabed each transponder is geo-referenced from the surface through two antennas placed at the end of a pole on board the support vessel. This geo-referencing is performed after a triangulation process. Precise navigation of AUV, achieved through a combination of long baseline/inertial navigation is further improved by the ADCP/DVL[18].

During dives, the AUV can be acoustically tracked from the support vessel using an acoustic telemetry/communication system. Through this channel, the mobile provides messages about its situation and the operator can, if necessary, redirect the mission in real time.

The recorded data was downloaded and analysed after hoisting the AUV onto the deck.

In addition, the AUV is equipped with an electronic still camera (ESC).

[18] Device designed to measure the underwater currents and the relative speed of the vehicle in relation to the sea floor.

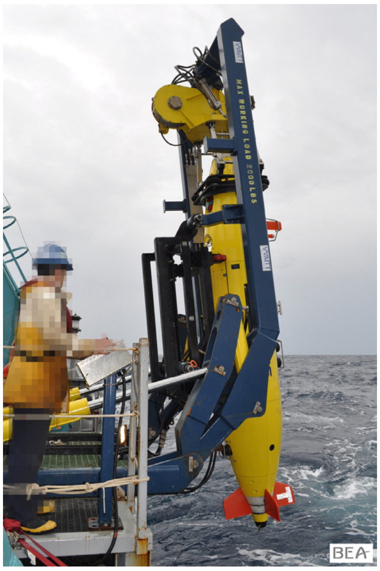
Three-step search mission

- **Location**: The EDGETECH 120/410 kHz side-scan sonar allowed any anomalies to be detected on the seabed. The AUV moved about 60 m above the underwater terrain. It recorded the acoustic imaging of the seabed, including anomalies related to the presence of potential targets. The AUV was programmed to follow parallel "lanes", spaced about 700 m apart in order to achieve full coverage.
- **Identification**: After the mission, if an anomaly was detected and validated by a sonar imaging expert, the AUV could be programmed to "overfly" the potential target at an altitude of about ten meters. The digital camera (ESC), synchronized with a powerful flash, photographed the area systematically. Up to 18,000 photographs could be taken during a dive. These were then subject to later analysis.
- **High-resolution identification**: The high-resolution side-scan sonar (using the frequency 410 kHz) and the digital camera were used to carry out detailed mapping of the site.

Note: The presence of a ROV on board made cross-checking possible, with the advantage of having images in real time.

AUV launch and recovery system

The launch and recovery of an AUV was a delicate operation. WHOI developed a dedicated hydraulic launch and recovery system (LARS). This articulated structure helped deploy the cradle hosting the AUV, and launch or recover the AUV while limiting the risk of collision with the ship. It required precise coordination between the team in charge of the AUV and the gateway in charge of manoeuvring the ship.



LARS system

D.2.3 The US Navy deep towed sonar ORION

ORION is a deep towed sonar which can operate down to depths of 6,000 m. Its operating principle is similar to that of IFREMER's TAS, except that the ORION sonar is a dual frequency side-scan sonar (57/240 kHz). The antennas are mounted on a neutral-buoyancy body, with ballast to dissociate the movements of the towed sonar from those of the surface vessel.

Picture of the ORION towed sonar

The ORION deep towed sonar could cover relatively large surface areas thanks to its operating speed, usually 1 to 3 kt depending on the required depth, and its 1,500 m scanning range that meant it could cover a swath about 3,000 m wide (scan swath) at 57 kHz and 900 m at 240 kHz. Sonar signals were displayed in real time for detection. Data was digitised and stored for identification of the targets.

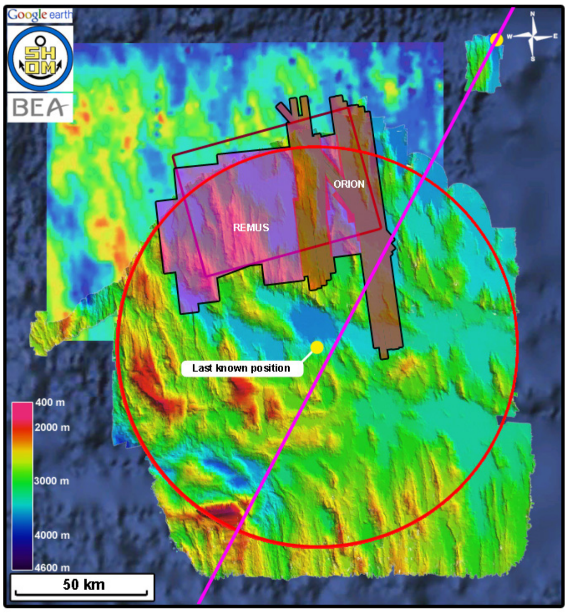
D.3 Searches conducted

The third search phase was conducted over two periods of approximately one month each in order to relieve the crews.

D.3.1 Search period from 2 to 25 April 2010

The ships left the port of Recife on 29 March 2010 and the sea searches took place at the site from 2 to 25 April 2010.

During this period, the ORION towed sonar, which was better suited to exploring sedimentary plains, was deployed to the East while the REMUS AUVs were deployed to the West in the areas where the seabed was the most uneven.



Overview of areas covered by 25 April 2010

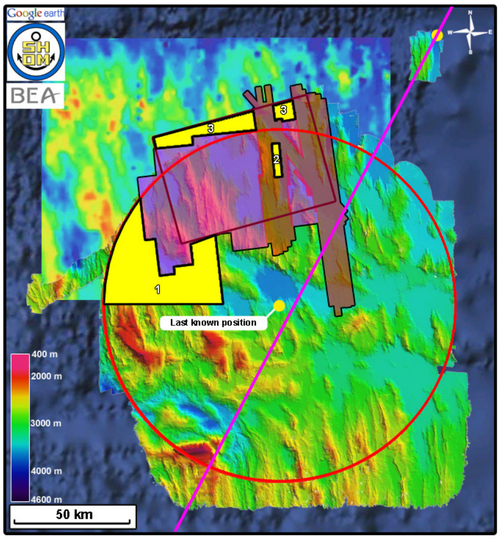
After exploring an area of around 4,500 km², the ships left the area on 25 April for a port visit at Recife on 28 April 2010.

D.3.2 Search period from 3 to 24 May 2010

The *Anne Candies*, equipped with US Navy ROV CURV 21 and towed sonar ORION, and the GEOMAR AUV, left the search operations due to other planned operational activities. The operations continued with the *Seabed Worker* and the two AUVs launched by WHOI.

The *Seabed Worker* left Recife on 30 April 2010. The searches in the area started again on 3 May and were scheduled to take place in the following order:

- An area adjacent to the initial area and located to the north-west of the last known aeroplane position (zone 1);
- An area already covered, located in the initial area whose re-exploration appeared to be necessary due to very uneven seabed (zone 2);
- Finally, the northern part of the rectangle defined by the scientific work (zone 3).

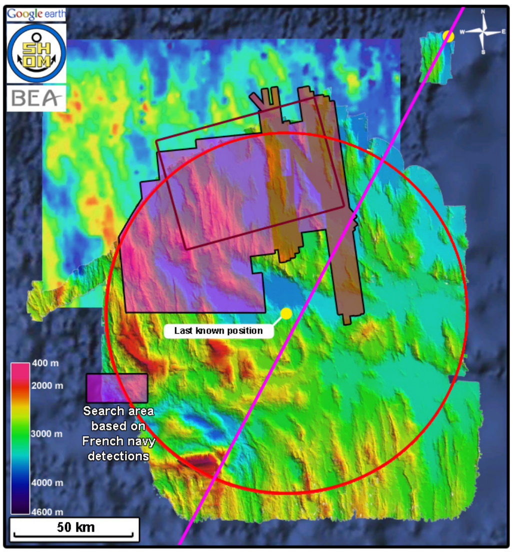


Search areas scheduled for the second period of phase 3

On 6 May, the French Ministry of Defence announced positive results from the post analytical work carried out on the data recorded on 30 June and 1 July 2009 (phase 1) by the *Emeraude* nuclear submarine. The French Navy staff headquarters first reported the detection of two acoustic sources comprising signals with similar characteristics to those transmitted by an Underwater Locator Beacon (ULB). While searches were being conducted in zone 1, the BEA decided to move its resources to the positions in which both sources were identified and reported by the French Navy (see figure below).

The *Seabed Worker* thus sailed to an area located south-west of the last known aeroplane position. It was explored from 7 to 12 May 2010 without any results. After ensuring optimal coverage of the whole area, the BEA decided to go back to the searches originally planned.

The *Seabed Worker* continued its searches in zones 1 and 2 from 13 to 24 May 2010, which was when the ship left the area to sail to the port of Praia (Cape Verde).



Areas covered during phase 3

During the second period, an area of almost 1,800 km^2 was explored, including the area of around 300 km^2 whose definition was based on the data provided by the French Navy.

D.4 Results

In all, an area of nearly 6,300 km^2 was thus explored during this search phase, but without succeeding in finding the aeroplane wreckage. The resources deployed meant that a high level of confidence could be attributed to the searches carried out during this phase.

D.5 Analysis of the detections made by the *Emeraude* Submarine

Following the analytical work carried out on the data recorded by the nuclear-powered submarine *Emeraude* from 30 June to 10 July 2009, the French Navy found two detections of a signal coming from a ULB. These two detections led the BEA to define a new search area during phase 3.

The continuation of the work conducted by the French Navy in order to validate the detections served to identify other signals of interest (ULB transmissions) in the previously analysed data, as well as to disprove the detections initially reported. However, it quickly became apparent that there was a high risk that the recordings made on board the *Emeraude* could have been polluted by noise.

A closing meeting for the analytical work was held on 21 May 2010 in Toulon. The BEA did not have access to the raw data recorded by the *Emeraude*, only to the results of the analytical work. All the detections found were disproved, with the exception of a long set of sounds considered as a potential acoustic source by the French Navy. However, based on the information provided to the BEA and to the acoustic propagation experts, it was established that the characteristics of this set of sounds (duration, amplitude, geographical distribution) made it impossible to have great confidence in them.

The discovery of the wreckage site at a distance of 40 NM from the area explored from 7 to 12 May 2010 confirmed that these detections were not related to the ULBs from flight AF447.

E – PHASE 4 SEARCHES (25 MARCH – 9 APRIL 2011)

E.1 Preparation

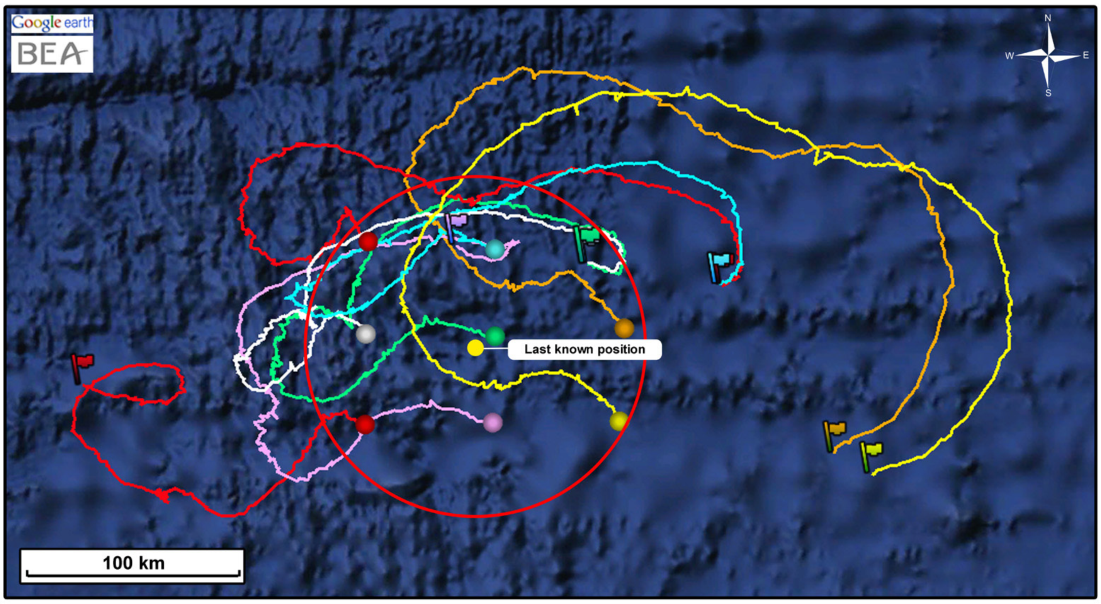
The failure of the first three search phases led the BEA to improve its knowledge of environmental conditions (currents) and re-evaluate the levels of confidence initially given to the resources deployed in order to determine a new search strategy. The hypothesis of non-functioning ULBs was also taken into account.

E.1.1 Release of drift buoys

The BEA asked the French Navy to drop drift buoys on the wreckage search area at the beginning of June 2010. The purpose of the operation was to improve knowledge of surface currents occurring in this part of the Atlantic in the seasonal period corresponding to that of the accident, and to evaluate the predictive ability of reverse drift calculations.

The Centre of Practical Expertise in Pollution Response (CEPPOL) thus provided 9 SLDMB buoys(19), which are normally used for monitoring surface currents in maritime pollution response operations. The buoys were released on 3 June 2010 over the estimated area of the accident by a French Navy Falcon 50.

The trajectories of 8 satellite-tracked buoys(20) highlighted the turbulent nature of the currents in the area, thus the great difficulty in predicting their drift.



Trajectories of the drifting buoys from 3 to 17 June 2010

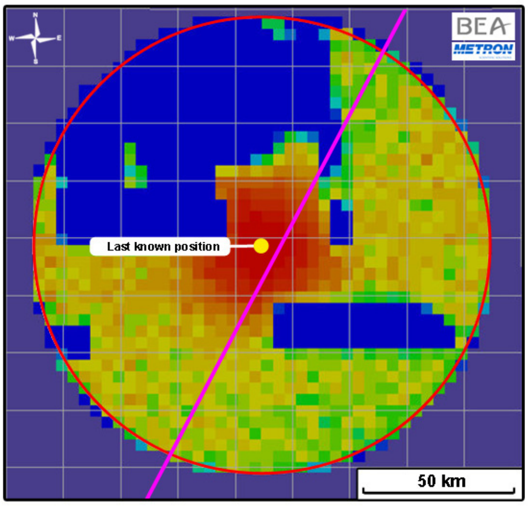
(19)The Self Locating Data Marking Buoy (SLDMB) designed by METOCEAN (Canada) is equipped with lateral cloth panels that serve as a floating anchor. The associated electronics provide satellite positioning (GPS) and the temperature of the water. The SLDMB is designed to deploy automatically after impact with the water. When it is completely deployed, it transmits its GPS position via the ARGOS system which transfers the data by satellite.

(20)The ninth buoy did not work.

E.1.2 Metron study

The BEA asked METRON to analyse the results of previous searches in order to produce a probability map for the location of the wreckage. METRON used the SAROPS[21] tool and a distribution based on studies by the BEA and its Russian counterpart (MAK) focusing on nine aircraft accidents that had occurred in cruise.

An updated distribution of probabilities of the presence of the wreckage was produced taking into account the efficiency of the sonar searches during phases 2 and 3, and the unsuccessful searches in phase 1. The lack of results from the air and sea searches conducted from 1 to 6 June 2009 was also taken into account.



Mapping of the probability of presence of the wreckage, assuming the ULB beacons did not work (in red: strong; in yellow: medium; in green: low; in blue: very low)

On 20 January 2011, the BEA published the results of the METRON[22] study on its website. It mentioned an area where there was a high probability of the wreckage being present near the centre of the circle.

The summary of the analysis of the results from the previous phases, reinforced by the findings of the METRON study, helped define the search strategy for phase 4. This involved a systematic search starting from the centre of the circle, with the exception of areas already explored using sonars during phases 2 and 3, for which a re-exploration with the same type of resources was deemed unnecessary.

E.2 Description of AUV operations

Phase 4 took place on the site from 25 March to 9 April 2011.

The three REMUS 6000 AUVs were once again selected for this phase. They were operated by WHOI from the support vessel *Alucia*, property of Deep Ocean Expeditions. This company makes its ship and equipment available for the organisation of underwater observation.

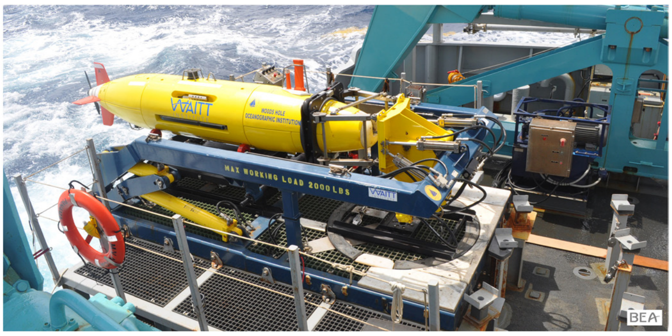
E.2.1 Installation of the AUVs on the *Alucia*

Taking into account the experience gained during phase 3, the AUVs were perfected to improve their seabed monitoring capacity. A new version of the software allowed for ascent/descent angles of up to 40 degrees (35 in phase 3). A new 300 kHz DVL increased altitude monitoring by 60 to 170 m above seabed.

[21] The SAROPS system has been in use operationally since January 2007 by the US Coast Guard (USCG) to plan and conduct SAR searches around the US coast and in the Caribbean. It is based on the NCOM oceanic current model and integrates the surface wind component to calculate the drift of objects. Its calculations are based on the Markov/Monte-Carlo techniques. The simulator then modelled the bodies and the debris with the aid of particles. It can simulate up to ten thousand particles for each scenario with an interval of twenty minutes. For each particle a probability level is applied related to its manner of drifting, according to the parameters like its composition, size and immersion. This makes it possible to establish a amp of the density of probabilities according to the length of the drift. The zone with the greatest density of particles is then considered to be the probable impact zone.

[22] http://www.bea.aero/fr/enquetes/vol.af.447/metron.search.analysis.pdf

MV Alucia

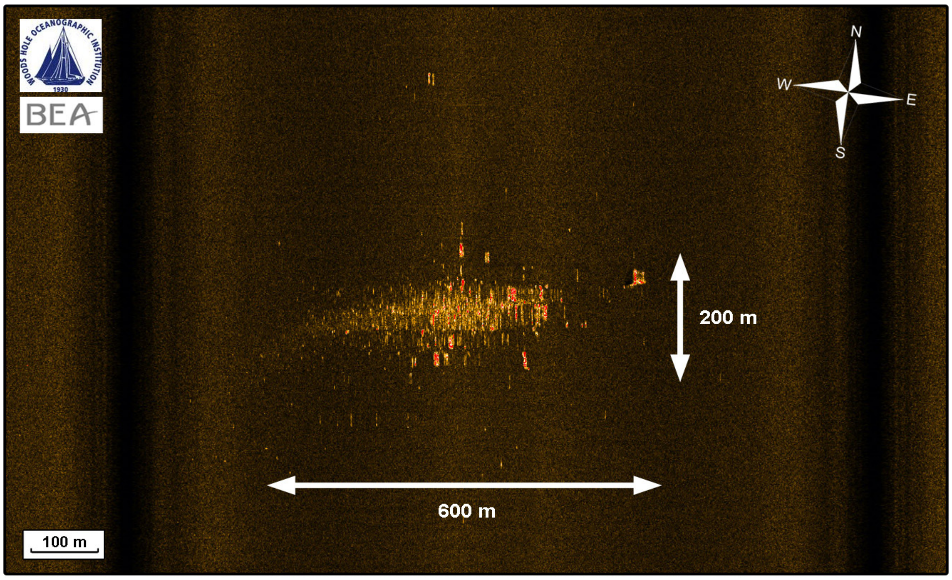


Aft deck with a REMUS on the LARS

Due to the size of the ship, the deck could only accommodate two AUVs simultaneously, whereas the operational requirement imposed the utilization of all three AUVs. In order to meet this requirement, shifts for the three vehicles were organised so that at least one AUV would always be exploring. Missions were thus conducted day and night, without interruption. Maintenance operations took place before every launch, while data unloading operations were performed at the end of each mission.

E.2.2 Discovery of the accident site

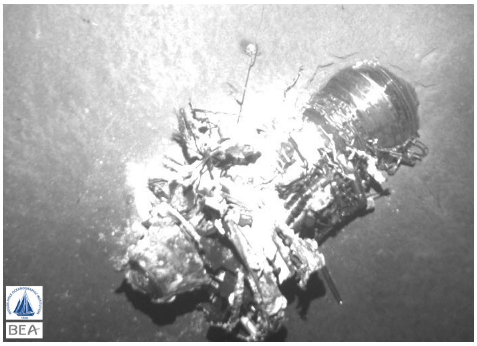
On 2 April 2011, the analysis of the data from the 18th mission showed a concentration of sonar returns over an area of about 600 by 200 m (see below).



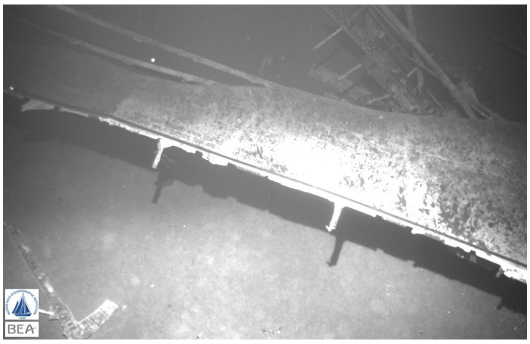
General view using sonar imaging: 120 kHz, range of 700 m

In order to cross-check these returns, a mission was scheduled in order to obtain high frequency sonar images and ESC photos in bursts. The flatness of the terrain and excellent visibility facilitated the use of the ESC camera. The first pictures were mainly taken at an average distance of 10 m, with an image resolution of 1024 by 1024 pixels.

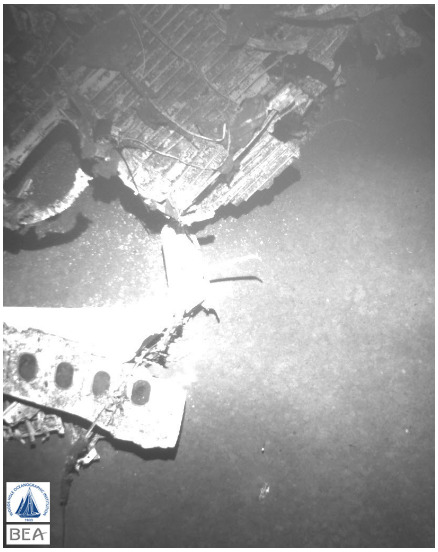
On 3 April 2011, the wreckage of the aeroplane was formally identified. The news was publicly released on the following day and some photographs were presented on the BEA website (see below photos taken by the AUV on 3 April 2011).



Engine



Wing

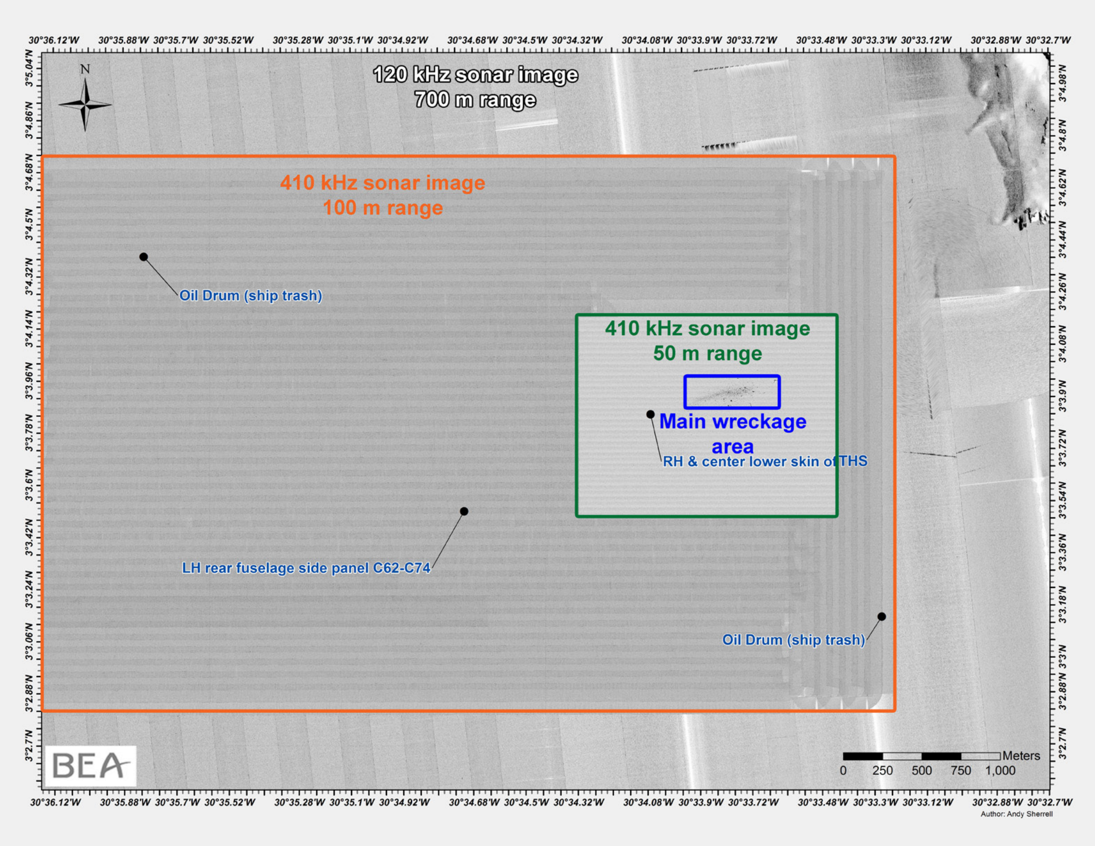


Fuselage panel

Landing gear

The wreckage was discovered on a line NNE of the last known position and at a distance of about 6.5 NM. During the following six days, additional missions were conducted to determine the spread of the wreckage debris field, and to make a full photographic survey of the site.

This work made it possible to locate a part of the fuselage about 2 km from the main zone (see figure below). High resolution sonar images (410 kHz) made it possible to map the wreckage site with great accuracy.

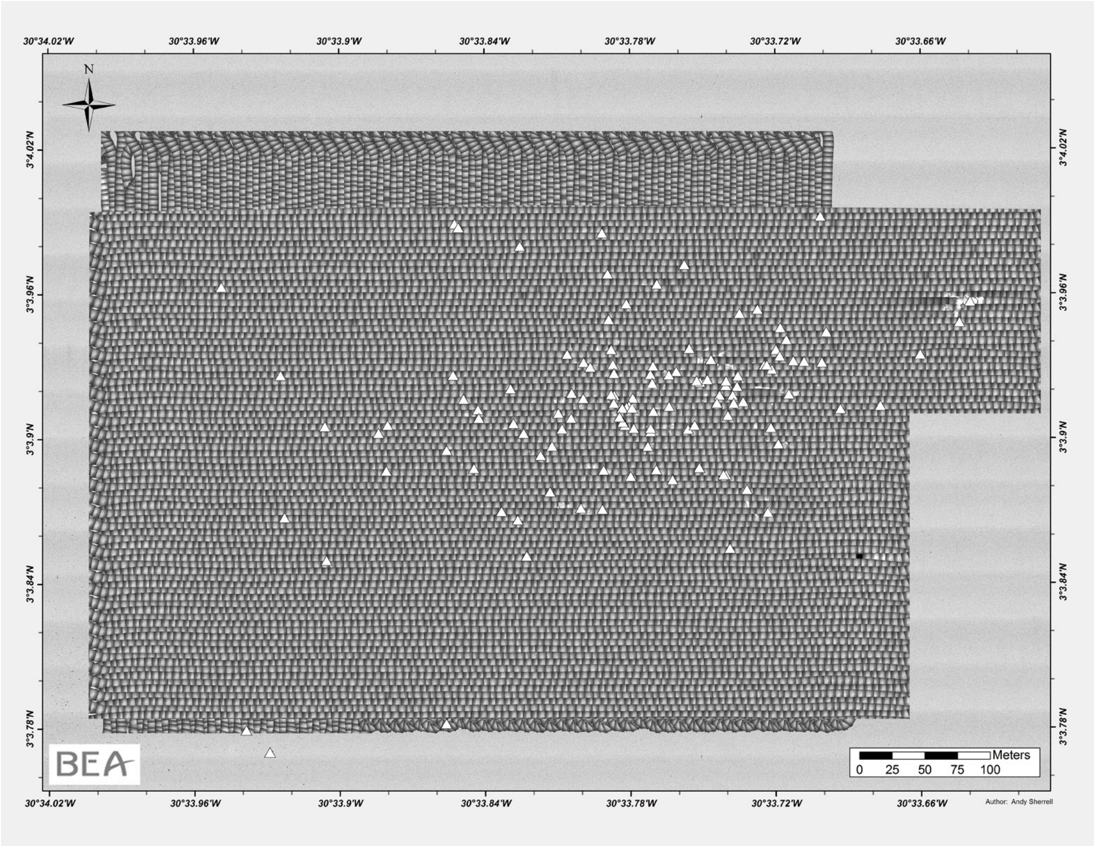


Overlay of sonar images taken with different settings

E.2.3 Site mapping by merging the ESC images

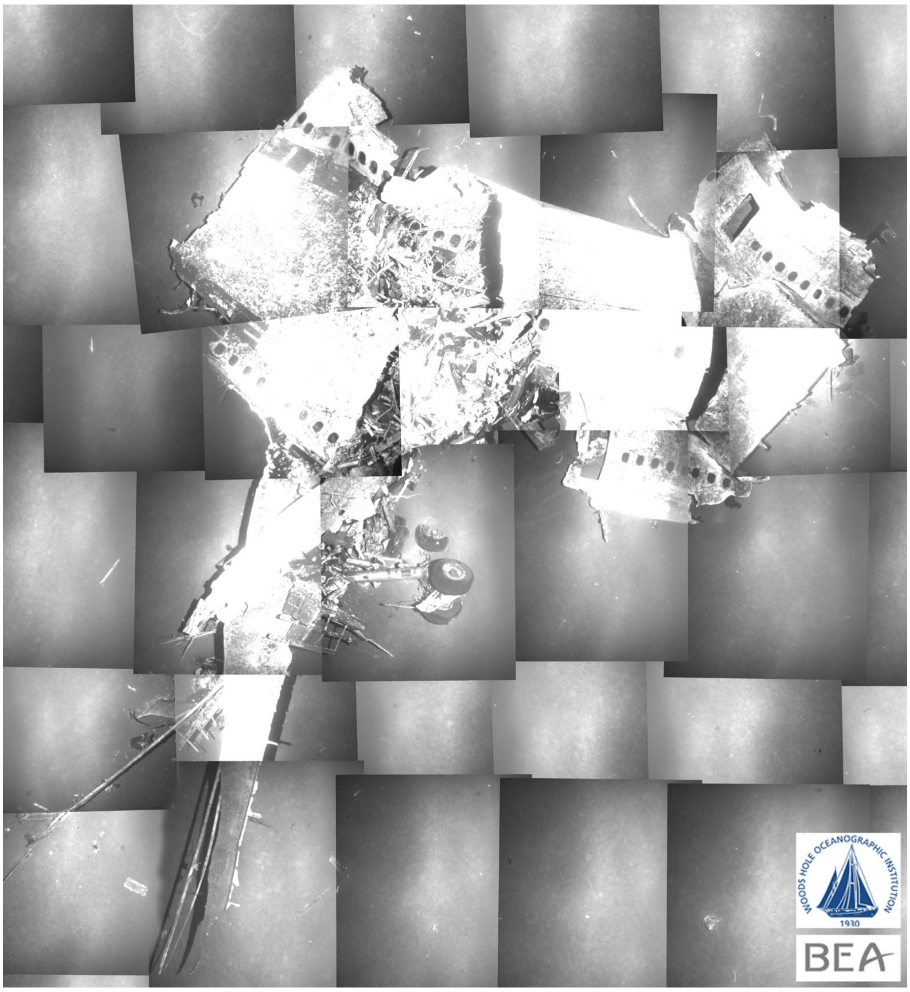
During the following missions, many ESC photos were taken. Given the good lighting conditions, the resolution was enhanced to 2048 by 2048 pixels. For these shots, the vehicle was slowed down to about 3 kt in order to obtain seabed pictures every 4.5 m along the AUV's trajectory.

The debris field was thus photographed several times along the north-south and east-west axes (see figure below).



Visualisation of the photo mosaic taken by the REMUS AUVs and the aeroplane debris identified using the REMORA III ROV (phase 5)

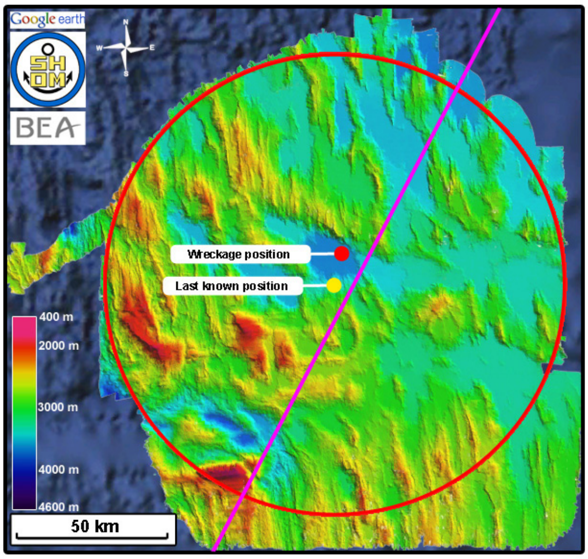
The WHOI and WID institutes used software tools to help the analysts link and merge the mosaic photos semi-automatically. The example below shows the merging process on one of the largest elements of the debris field. This type of image provided the operators and investigators with an accurate overview of the debris field, and facilitated the preparation of on-site ROV response operations.



Example of a merged image

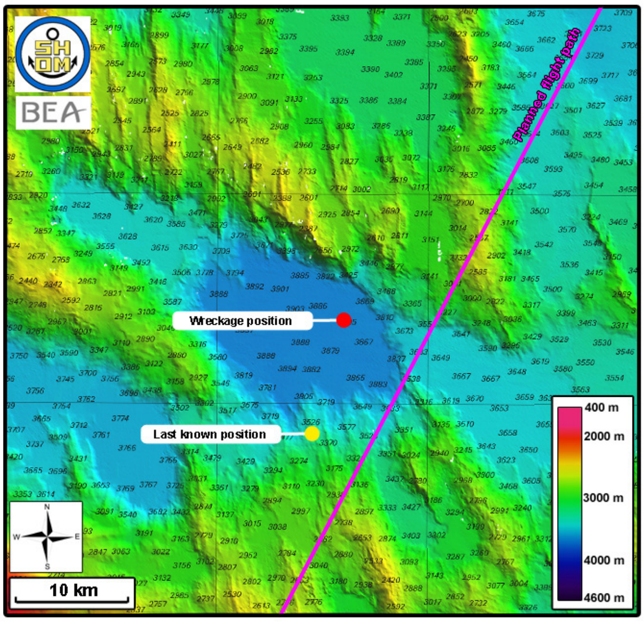
E.2.4 Summary

The wreckage of the aeroplane was found near the centre of the initial search zone, on a line NNE at about 6.5 NM from the last known position recorded at 2 h 10 min.



Position of the wreckage

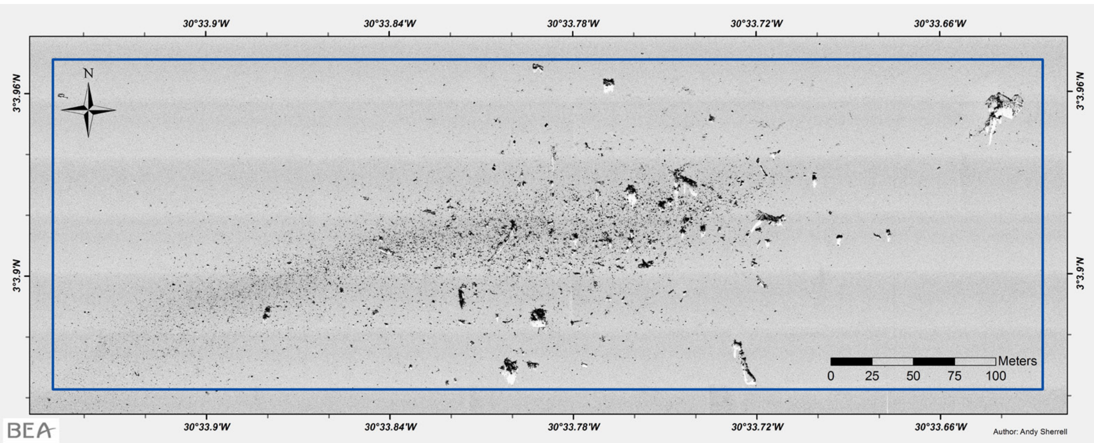
The wreckage site is located west of the trajectory planned by the flight plan, on an abyssal plain at a depth of about 3,900 m, surrounded by uneven terrain (see below).



Visualisation of the search area topography and site of the wreckage

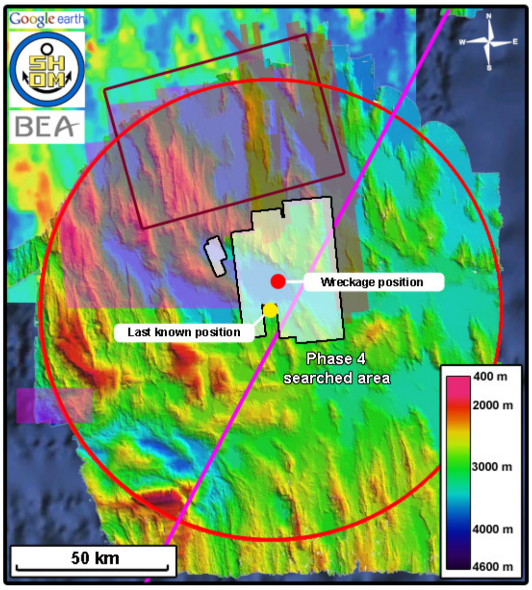
The area was covered by the AUVs with different sonar settings to ensure no debris located beyond the main zone was omitted. The initial visualisation was subsequently enhanced using high resolution 410 kHz sonar images.

The figure below shows the main zone of the wreckage site (600 over 200 m).



Detailed sonar image of the main zone: 410 kHz, range of 50 m

During phase 4, 37 missions were conducted at the site, including 24 to search for the wreckage and its various elements, 8 to take photographs and 5 using the high resolution sonar to comprehensively cover the entire accident site.



Areas covered by the end of phase 4

The surface area covered during phase 4 was around 1,250 km^2. More than 85,000 photos were taken.

The data collected during phase 4, especially the photo mosaic of the accident site, saved a considerable amount of time for the BEA during the following phase. For the first time, investigators had a full two-dimensional representation of the accident location, based on side-scan sonar images and high resolution photos[23], before ROV response operations at the site. The "aerial" photos helped conduct phase 5 efficiently.

[23]However, colour imaging would have facilitated the identification of the orange flight recorders

F – PHASE 5 SEARCHES (26 APRIL - 3 JUNE 2011)

Phase 5 was organised in two stages.

- The first, which took place on-site from 26 April to 13 May 2011, involved the search for and recovery of the flight recorders and aeroplane parts;
- The second took place from 21 May to 3 June 2011, the purpose being to carry out underwater observation of the whole wreckage, map the debris and finally recover the human remains.

F.1 Preparation

Phase 5 was the recovery phase. Phases 4 and 5 were prepared jointly; the initiation and conduct of phase 5 were conditioned by the results of phase 4. During phase 4, the *Alucia* had search equipment on board, but no recovery equipment. After the location of the wreckage, there was an urgent need for a support vessel fitted with recovery equipment.

The BEA issued an international call for tenders in the form of a framework agreement. The Contractor was required to provide the following services:

- Positioning of and search for the wreckage;
- Underwater observation (mapping) of the wreckage site ;
- Logistics support;
- Recovery of the flight recorders;
- Raising parts and equipment essential to the understanding of the accident;
- Recovery of the human remains under the responsibility of the judicial authorities.

The BEA preselected three offers that met its technical criteria. These offers took into consideration the difficult environment and the remoteness of the accident site and were mainly based on:

- Ship storage capacity;
- Ship and ROV lifting capacity;
- ROV maximum operating depth and manoeuvring capabilities.

The BEA took great care to ensure that dedicated procedures were applied and resources deployed to optimise the recovery and conservation of human remains. Preparation and psychological follow-up of operators involved in body recovery completed the arrangements.

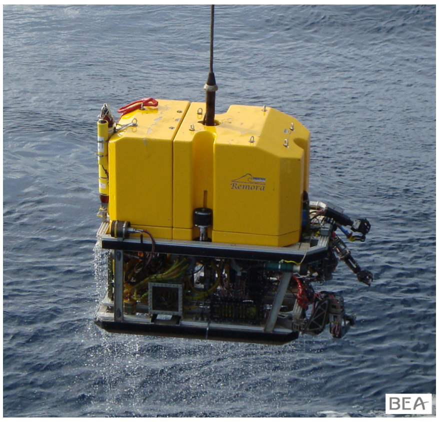
F.2 Resources deployed

When the wreckage was located on 2 April 2011, the BEA quickly selected the vessel that was closest to the site of the accident among the three preselected vessels. This was done after a short consultation period with a deadline of 7 April 2011.

The cable ship *Ile de Sein* from Alcatel-Lucent and Louis Dreyfus Armateurs, equipped with a REMORA III ROV from Phoenix International was selected.

Vessel and equipment used in phase 5

Ile de Sein cable ship



REMORA III ROV

F.2.1 REMORA III ROV

The complete system consists of a vehicle, fibre optic cable and winch, a launch/recovery system, and operations and maintenance vans. The REMORA's design strikes a balance between power and its capacity to meet a wide range of operational requirements. It is sized for air transport and rapid mobilization on vessels of opportunity anywhere in the world. This relatively small and powerful vehicle has axial lateral thruster geometry enabling precisely controlled manoeuvres in the tightest of spaces and minimizes the probability of entanglement or damage with debris. Its maximum operational immersion depth is 6,000 m. The REMORA III was installed on the cable ship *Ile de Sein* at Las Palmas (Canary Islands).

F.2.2 *Ile de Sein* cable ship

The *Ile de Sein* cable ship is the sister ship of the *Ile de Batz* that was used in 2004 to recover the wreckage of the Flash Airlines B737 that crashed off Sharm El-Sheikh (Egypt). The *Ile de Sein* has a length of about 140 m. It is designed to carry a working ROV on its deck with its support equipment. It is equipped with a dynamic positioning system (DP II). This vessel was designed to lay cables on the seabed. It has systems for high precision management of the payout speed to control the tension on the cable. This accuracy turned out to be very useful for the recovery of aeroplane parts of all sizes.

Its accommodation capacities helped make the *Ile de Sein* a particularly well-suited vessel for a long-term mission at a remote site.

The "test room" was equipped to be used as the operations command room. The investigation team guided the work of the ROV team through several video screens and the Phoenix survey centre. The "survey" function of the *Ile de Sein* and coordination with the vessel's bridge team were also relocated to this room.

Thanks to its size, the vessel embarked with two 40-foot containers for parts on the lower deck (near the 50 ton A-frame) and three 20-foot refrigerated containers (one spare) for storing human remains on the upper deck.

The *Ile de Sein* was thus the support ship for the REMORA III ROV.

F.2.3 USBL positioning system

Before the onsite mission, a new Ultra-Short BaseLine (USBL) acoustic positioning system was installed in Las Palmas on the *Ile de Sein*'s through-hull deployment pole. The Sonardyne Ranger 2 USBL system was designed for deep water, long range tracking of underwater targets and position referencing for dynamically positioned (DP) vessels. The system calculates the position of a subsea target by measuring the distance from the vessel-mounted transceiver. In this case, the acoustic transponders were fitted to the ROV, the recovery baskets and the lift lines.

This system was integrated with the positioning device of the Remora III ROV. After a tuning period, it enabled an average system accuracy of 0.3% of slant range and 0.1% under optimal sea conditions.

F.2.4 Underwater navigation performance

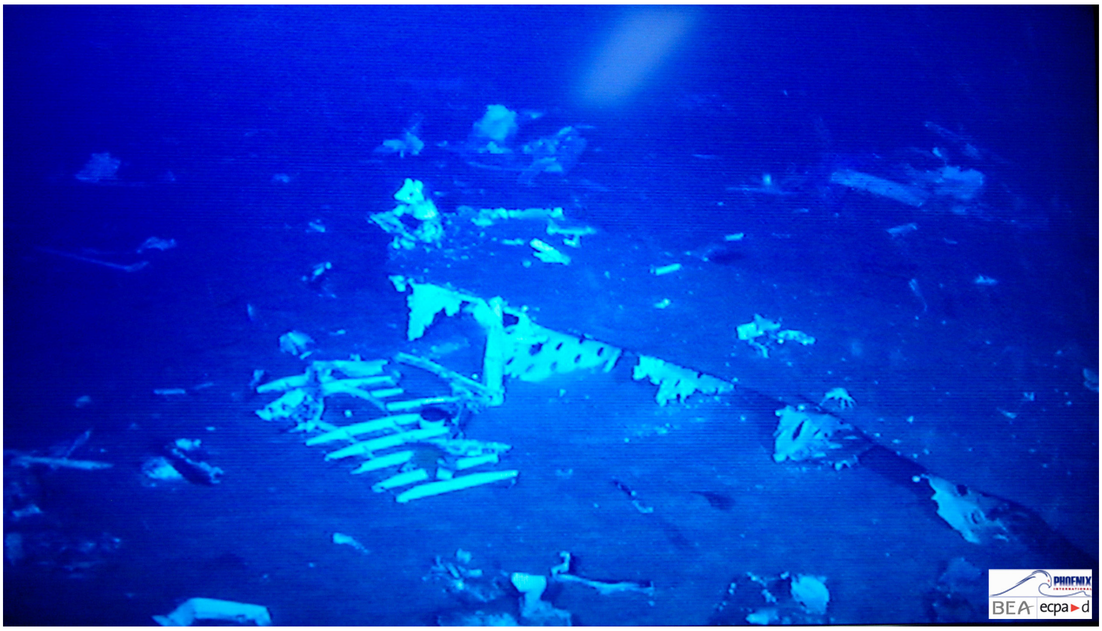
The implementation of this new positioning system combined with the data from phase 4 proved to be very useful. The sonar image maps and the photo mosaic were geo-referenced in the ROV navigation system, which was itself connected to the positioning system of the *Ile de Sein*. When acoustic transmissions were disrupted, the ROV pilots could still continue their navigation with accuracy, with the help of the "aerial" photographs from the REMUS AUVs. The pilots used the leap-frog technique to visually navigate from one debris item to the next, the latter being generally recognizable thanks to the photographs in the mosaic. Range and bearing were given by the coordination centre to the ROV operators so that they could find with a precision of one meter each aeroplane component previously observed and identified on the AUV photographs. The latter were available to the ROV operators for real-time comparison with the images transmitted by the ROV cameras. Large debris from the sonar images was systematically searched for and identified.

F.3 Organisation of operations

F.3.1 Search for and recovery of the flight recorders

The wreckage was highly fragmented and spread over an area of over 10,000 m^2. Few large parts of debris were found.

The search for the flight recorders represented a major challenge, given the number of items of debris scattered on the sea floor, as shown in the following picture.

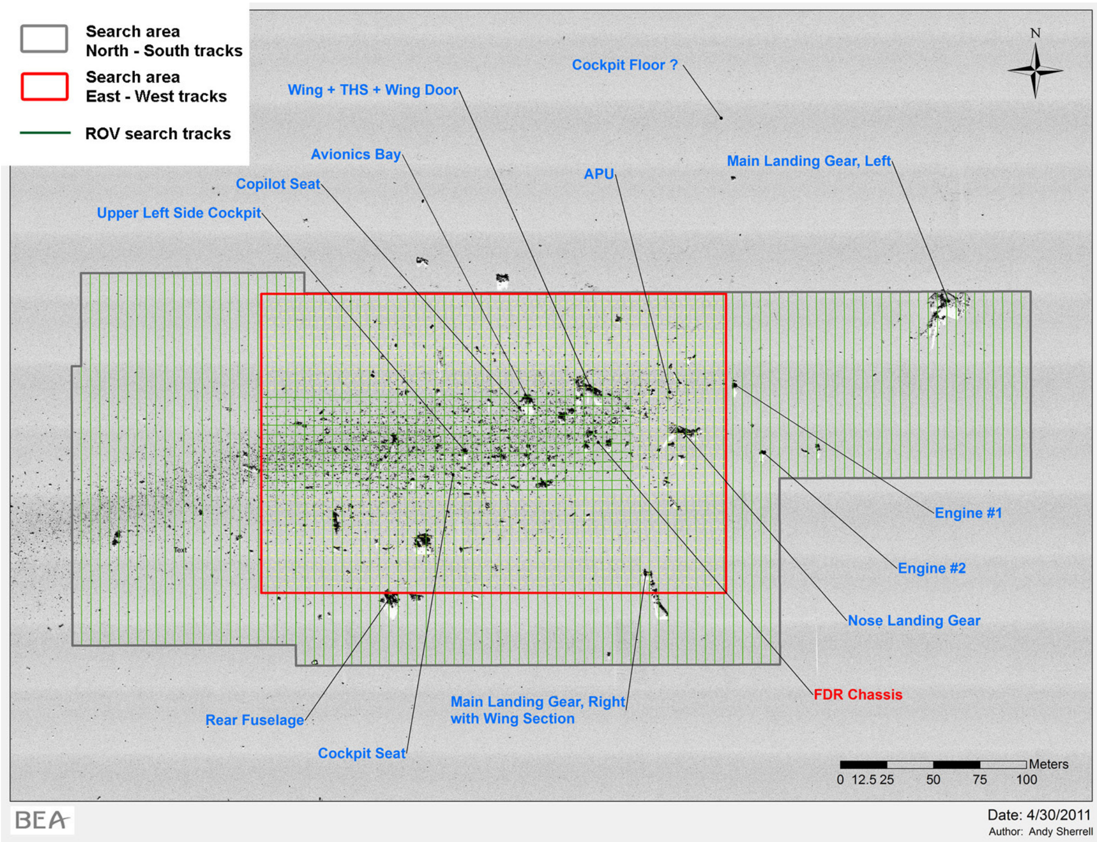


Debris scattered at the bottom of the ocean

The searches for the data recorders took place in two stages:

- The ROV began by exploring the areas of interest that had been predefined from black and white aerial photographs taken by the AUVs;
- Following these unsuccessful initial explorations, a search grid was defined to systematically explore the whole site. The lines were spaced 5 m apart to ensure an overlap between two successive search lanes.

The following image shows the progression of these systematic searches.



Search grid

The chassis of the flight data recorder (FDR) was identified during the first dive by the ROV, but without its protected module (CSMU) that contains the data. This part was surrounded with debris from parts of the aeroplane from either the front or rear sections. The search began from the centre of the area of interest, first along the North-South lines and then along the East-West lines.

On 1st May 2011, the investigation team localised and identified the FDR CSMU. It was raised aboard the cable ship *Ile de Sein* by the ROV on same day. The next day, the cockpit voice recorder (CVR) was located and identified. It was raised aboard the *Ile de Sein* on 3 May 2011. The flight recorders were then transferred to the port of Cayenne by the French Navy patrol boat *La Capricieuse* and finally transported to the BEA by plane on 12 May 2011. The recovery of aeroplane parts continued until 13 May 2011, when the engines and the avionics bay containing the onboard computers were raised.

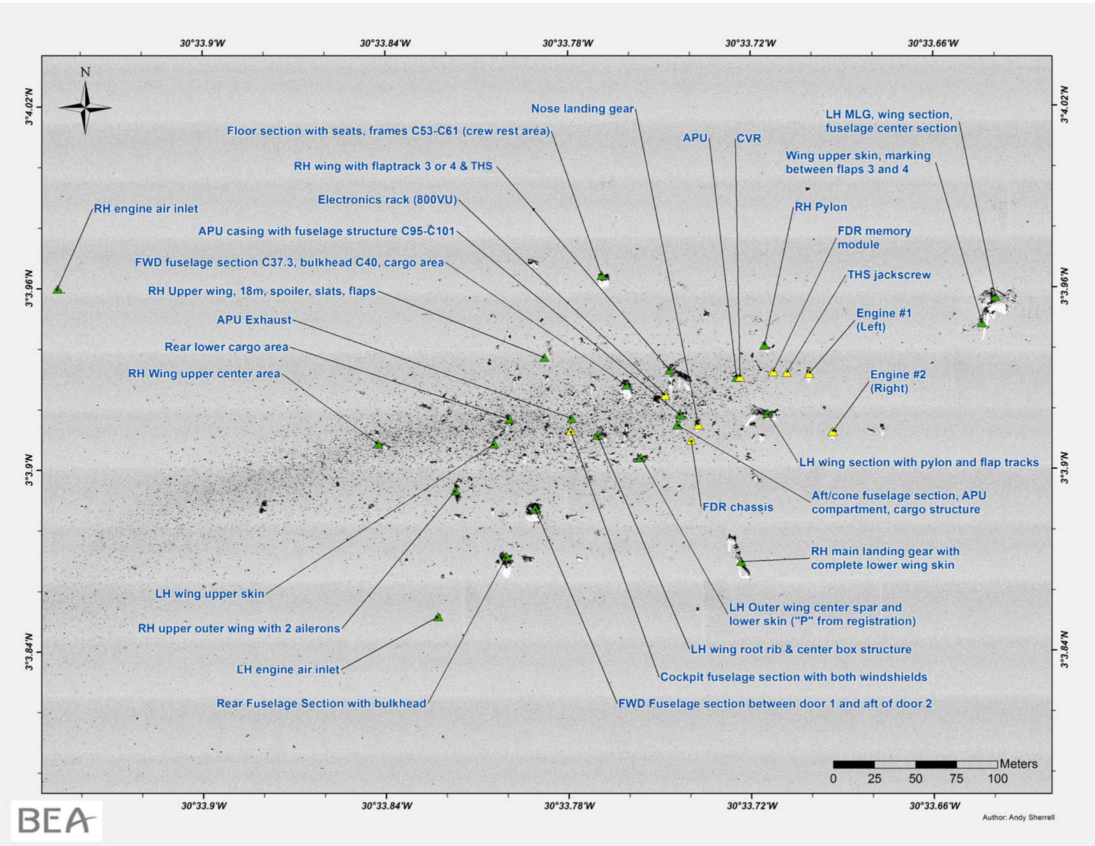
F.3.2 Study of the accident site

F.3.2.1 Identification of the aeroplane debris

The ROV's manipulating capabilities were jointly used with the *Ile de Sein*'s cranes to move and raise aeroplane debris to the surface. The zoom capacity of the ROV "Pan & Tilt" camera enabled investigators to read part number references of the debris scattered over the ocean bed.

A geo-referenced database was created, and a complete map of the main wreckage site was established (see figure below).

Appendix 8 shows some examples of the parts listed.



Mapping of the main elements of the aeroplane

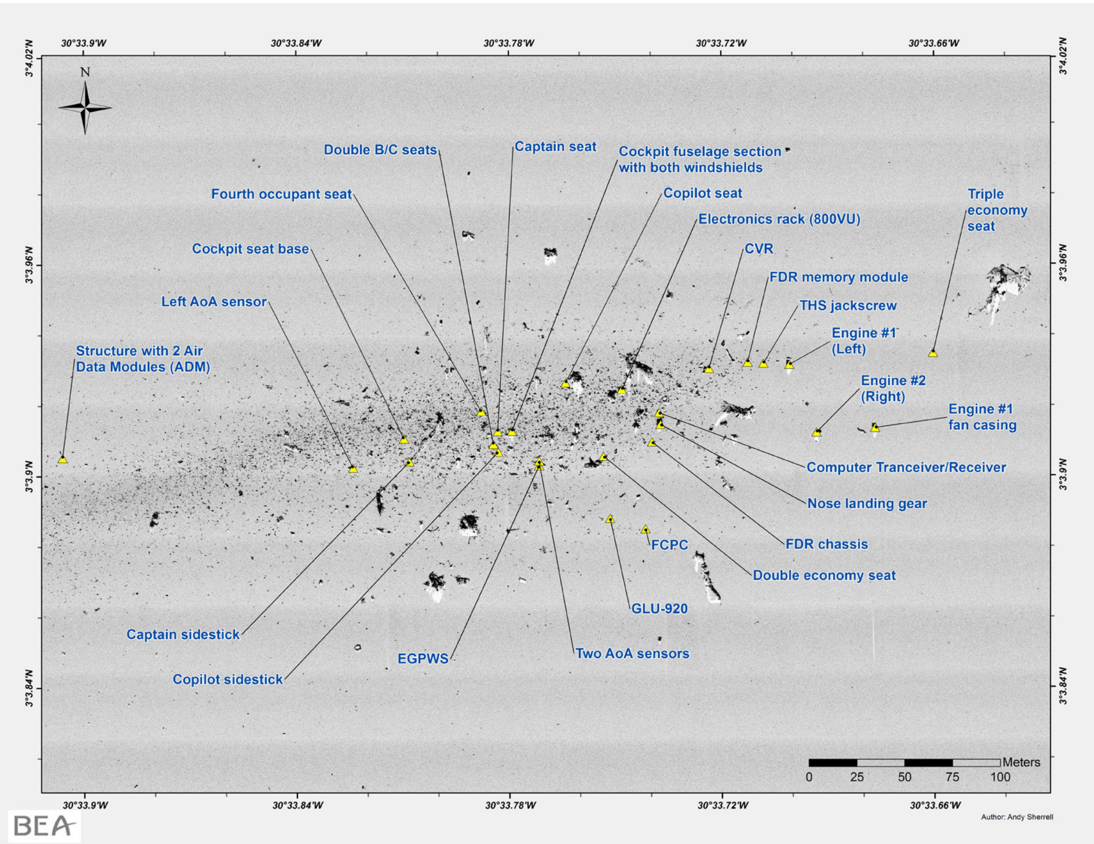
As a reminder, two large elements (part of the rear left fuselage and covering part of the THS) were discovered to the south-west outside the primary wreckage area.

Part of the aft left fuselage

Apart from these two parts only a few pieces of light debris from the aeroplane were identified (fragments of honeycomb panels, small alloy parts, air conditioning ducts, various pipes).

F.3.2.2 Raising certain parts of the aeroplane

Only the parts of interest defined before the read-out of the flight recorders in the framework of the safety investigation and the judicial investigation were brought to the surface. They are marked on the figure below.



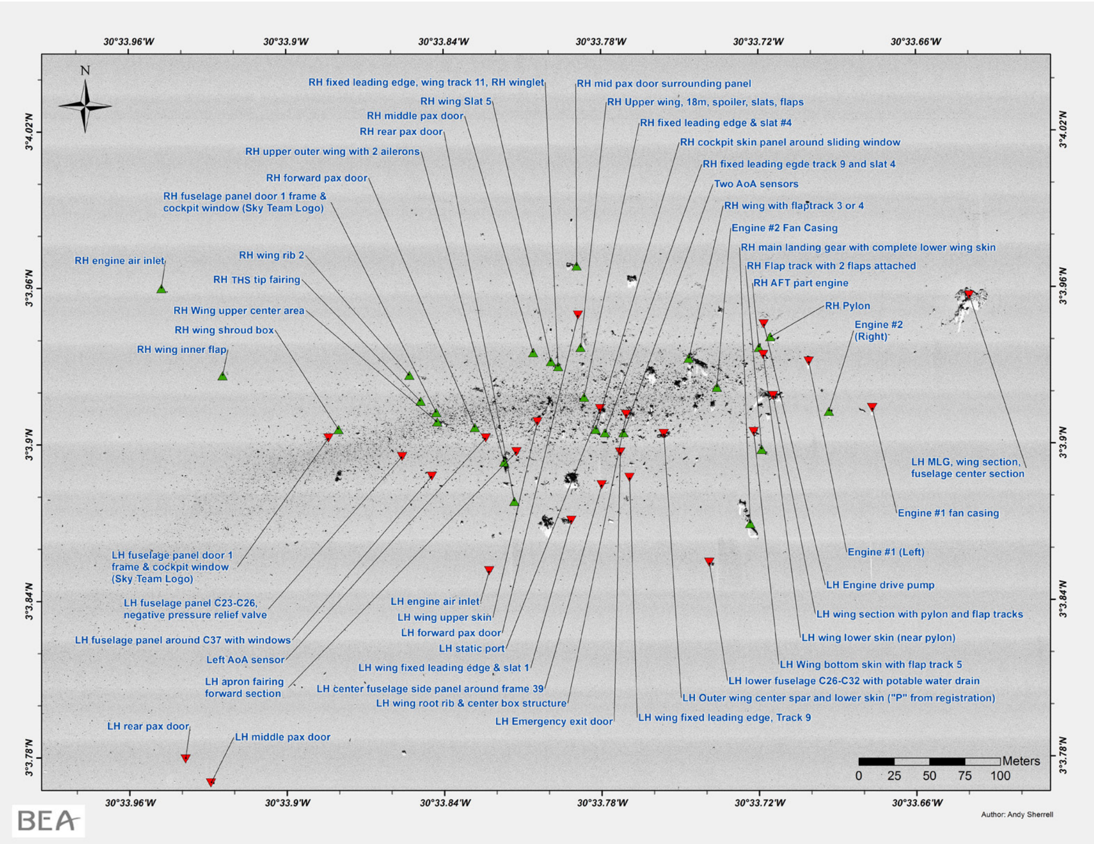
Mapping of the parts brought to the surface

F.3.2.3 Analysis of the distribution of aeroplane debris

The first observation was that the whole wreckage was highly fragmented with some large pieces of debris. The general distribution of the debris was along an East-West axis at 260°.

The densest debris (central section, engines, APU, landing gear) were found to the East of the site. The lighter debris were generally found to the West.

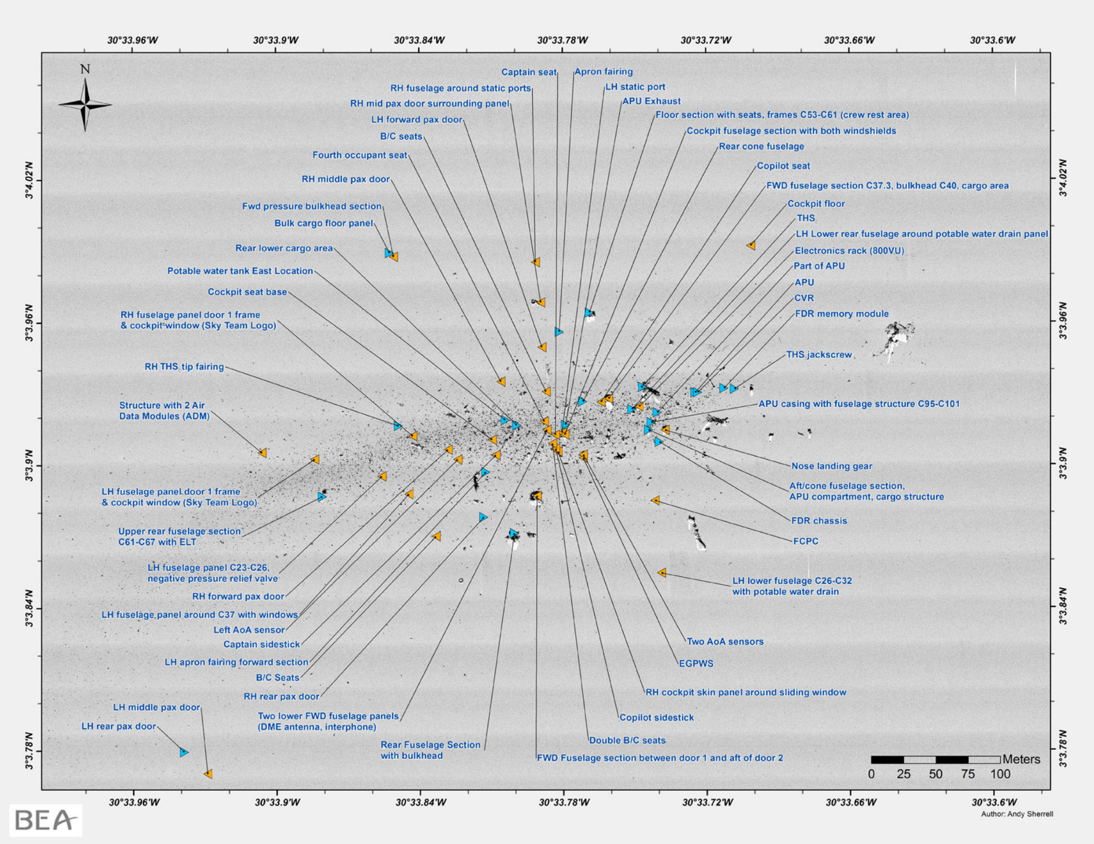
The currents measured during field operations were always low close to the surface and virtually non-existent in the water column.



Distribution of items of debris

depending on whether they came from the right or left of the aeroplane

Using the previous illustration, it can be seen that the items of debris from the right side of the aeroplane were found more to the North of the area, while those from the left side were found to the South. This is consistent with the flight path towards the West indicated by the last parameters recorded on the FDR and an aeroplane flying belly down.



Distribution of items of debris depending on whether they came from forward or aft of the aeroplane

The distribution of items of debris according to whether they came from the forward or aft of the aeroplane did not help define a specific tendency. Items of debris from the aft were mixed with other debris from forward.

F.3.3 Recovery of human remains and psychological aspects

The second part of phase 5 was mainly dedicated to the recovery of human remains. The retrieval of any bodies and personal effects was placed under the responsibility of the representatives of the judicial authorities: A dual sweep of the accident site was undertaken by the BEA team and the judicial team in order to:

- ❒ Map to the fullest extent possible the distribution of parts of the wreckage;
- ❒ Ensure that all the human remains were found.

The recovery of human remains is a delicate operation that requires careful preparation both in terms of equipment and the personnel involved. It is essential to have:

- ❒ Adequate space dedicated to the operations;
- ❒ High-quality logistical support for the forensic team to work with calm, discretion and decency;
- ❒ A medico-psychological unit aboard (consisting of a psychiatrist and a psychologist) for the preparation and support of the teams facing this difficult human experience.

The *Ile de Sein*, its crew and all the experts on board fully complied with these conditions.

The presence of a medical and psychological support unit on board the ship from the beginning of the mission enabled its psychological aspect to be taken into account during each step (whether organisational or operational). It also showed how the particularly difficult nature of the mission was recognised.

Medical and psychological support was adapted to each step of the mission, by taking the three following separate phases into account:

- Preparation of the set-up and the teams assigned prior to the start of operations;
- Monitoring of the teams and set-up during operations;
- Individual and group debriefings at the end of the mission, and preparation of the post-mission phase.

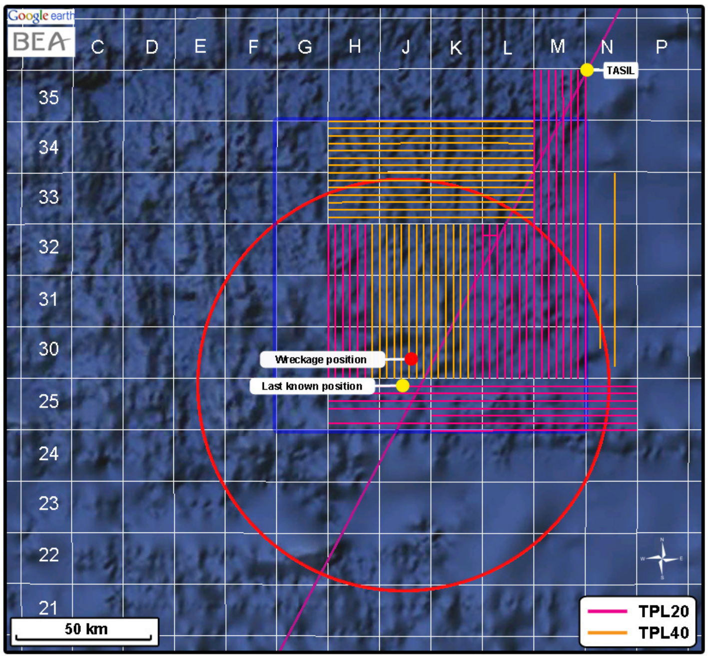
The lessons learned from previous operations were implemented during this sensitive mission. Psychological preparation and support were offered to every person on board the *Ile de Sein*. An initial survey showed that nobody seemed to suffer from post-traumatic stress symptoms after the mission.

Taking the psychological aspect of the mission (cognitive and emotional load) into account from the start enabled the medical and psychological unit to take part in the creation and adaptation of a three-step program (preparation, operations and debriefings), minimising mental health risks for designated staff. Thanks to this advance support initiative, all the professionals on board showed exemplary work and ethics in the performance of the body recovery operations. Post-mortem tasks were carried out professionally and humanely, and the bodies were handled in a dignified manner.

G – ADDITIONAL STUDY ON THE NON-DETECTION OF ULBs

The aim of this study was to put the phase 1 search operations into context in order to try to understand the reasons for the non-detection of the beacons and recommend areas for improvement.

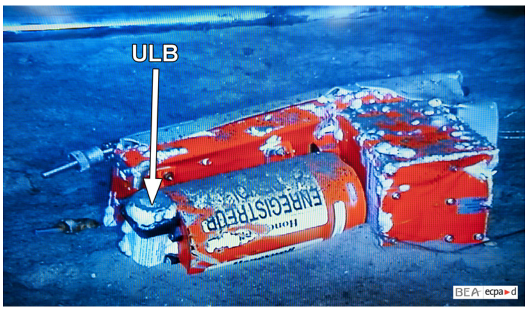
As shown in the figure below, the wreckage was discovered in grid square J30 of the search area covered by the towed hydrophones of the US Navy during phase 1.



Lines made by the towed hydrophones (TPLs)

The FDR and CVR from flight AF447 were recovered on 1 May and 3 May 2011 respectively at a depth of 3,900 meters. The photos below show that the ULB beacon was present on the CVR but was missing from the FDR; it was never found.

Photos taken of the recorders at the time of their discovery

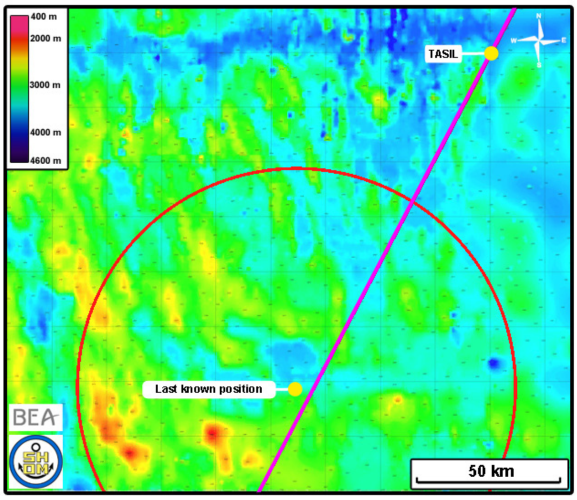


CVR with its ULB beacon

Protected part of the FDR without its ULB beacon

G.1 Context for the acoustic searches using passive devices

The accident area was above the Mid-Atlantic Ridge. The searches took place in a particularly unfavourable environment due to the great variations in depth in the area and the extremely uneven topography of the sea bed. The bathymetric data available to the search teams in June 2009 (see the figure below) was of limited accuracy, since the seabed in the area was little known.



GEBCO bathymetric data available on 1st June 2009

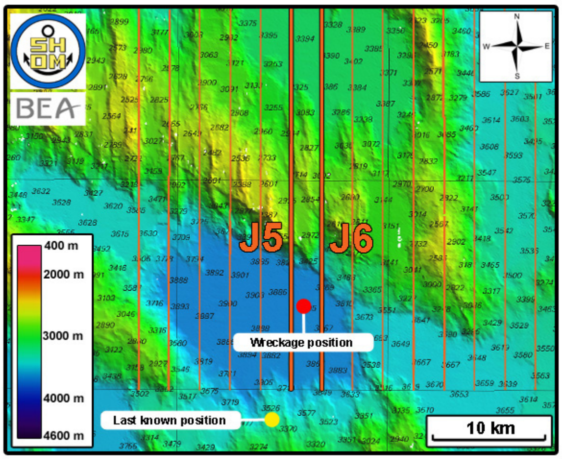
Each flight data recorder was equipped with an underwater locator beacon transmitting on 37.5 kHz (± 1 kHz). In this type of search, priority should be initially given to acoustic searches by passive devices (hydrophones), taking into account an average range of between 2,000 and 3,000 m.

Given their limited range and the average depth in the area (3,000 m), listening from the surface was not possible. It was therefore necessary to bring the hydrophones closer to the source of transmission, by towing specialized TPLs near the seabed.

G.2 Analysis of the TPL routes in the wreckage area

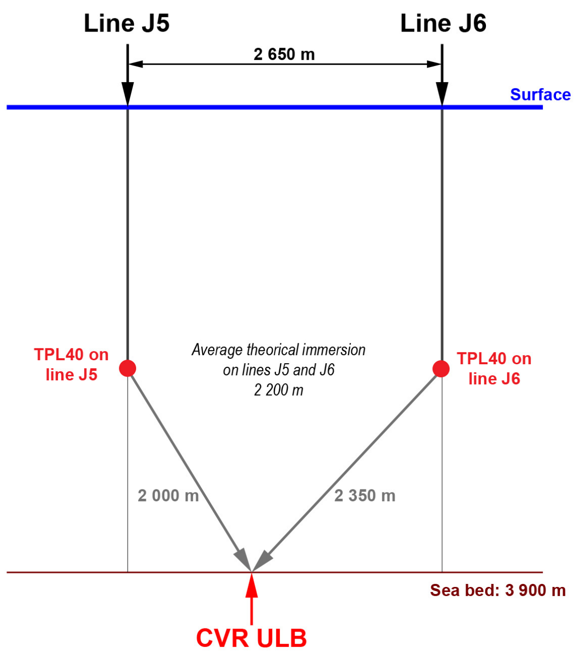
The only TPL data available was the relative position information of the TPL in relation to the ship and the average immersion values on the line.

The accident area was investigated on 22 and 23 June 2009, in other words less than thirty days after the accident (regulatory nominal transmission period). This exploration was carried out by the *Fairmount Glacier* using the TPL40 on the lines named J5 and J6 of square J30. The estimated depth of TPL40 on the overall line was of the order of 2,200 m. The figure below illustrates a top view of the two lines in the horizontal plane.



Lines explored on 22 and 23 June 2009

The following construction shows that in slant range, on 22 and 23 June 2009 the hydrophone was approximately 2,350 m and 2,000 m respectively from the CVR ULB.



Theoretical average slant distances between the TPL and the beacon on the course of lines J5 and J6

The theoretical calculations of the slant distance from the hydrophone and the ULB are based on the recorded values for the ship's position and the average theoretical immersion depth of the TPL.

On 22 June 2009 at 12 h 30 min, on line J6, the TPL40 was at a nominal distance of approximately 2,350 m from the ULB. A second convergence occurred on line J5 around 11 h on 23 June, at an estimated theoretical distance of 2000 m. For thirty minutes, the TPL40 remained within 2,500 m of the ULB in both cases. During these two periods, an operator was theoretically capable of hearing a signal.

G.3 Examination of the recovered beacon

A report[24] details the examination of the CVR ULB. The damage to the body of the ULB was due to the impact. The characterization of the acoustic signal from the ULB made on the day of the examination was not nominal, despite the renewal of the power source (new battery).

This examination more than two years after the accident is not conclusive because it is impossible to decide on the level of damage to the ULBs that equipped the aeroplane and their ability to nominally transmit a signal in the aftermath of the accident.

G.4 Predicted range of the ULB signal - Acoustic Dispersion of a ULB

The range and conditions for the propagation of acoustic signals at the wreckage site were the subject of preliminary work in preparation for phase 1, based on statistical environmental data and generic technical data. The lack of environmental data measured in-situ (sea noise at the beacon frequency) and detailed information about the acoustic sensitivity of the sensors used[25] allowed only average predictive assessment of the expected detection range.

In addition to the study[26] by SHOM in June 2009, a study[27] to characterize the dispersion of the ULB mounted on a recorder was carried out by the DGA in 2011.

(24)http://www.bea.aero/fr/enquetes/vol.af.447/cvr.ulb.examination.report.pdf

(25)The TPL20 and TPL 40 towed hydrophones are military equipment that belong to the US Navy. The acoustic sensitivity information is classified. They are the only tested means of undertaking ULB searches on the high seas at depths greater than 1,500 m.

(26)http://www.bea.aero/fr/enquetes/vol.af.447/shom.050609.pdf

(27)http://www.bea.aero/fr/enquetes/vol.af.447/bea.dga.ulb.measurement.09.2011.pdf

H – FINANCIAL SUMMARY

The search and rescue (SAR) operations were conducted by three countries: France, Brazil and, to a lesser degree, the United States. The cost was covered by the Brazilian and French armed forces. The global cost of the SAR operations can be assessed at about 80 million euro.

All of the undersea search operations were conducted under the control of the BEA, either through direct contracts managed by the BEA (phases 1, 2, 3 and 5) or through contracts managed by the industrial partners, Airbus and Air France (phase 4). Costs were shared between the French government and the industrial partners.

The table below shows a summary of the costs of the search for and recovery of AF447 and the number of days spent on site during each phase.

Surface search	June 2009	26 days	€ 80 million (estimate)
Phase 1	June / July 2009	30 days	€ 9 million
Phase 2	August 2009	22 days	
Phase 3	April / May 2010	52 days	€ 12 million
Phase 4	March / April 2011	15 days	€ 4 million (estimate)
Phase 5	April / May 2011	31 days	€ 6 million
TOTAL phases 1-5 (on site)		**176 days**	**€ 31 million (estimate)**

Cost and duration of sea search operations

I – LESSONS LEARNED AND RECOMMENDATIONS

Some lessons in relation to improving the localisation of wreckage at sea and the conduct of search operations were learned as a result of the failure of the first search phases. The main lessons are presented below.

ULB

In its Interim Report n°2, the BEA recommended that EASA and ICAO:

- extend as rapidly as possible to 90 days the regulatory transmission time for ULBs installed on flight recorders on airplanes performing public transport flights over maritime areas;
- make it mandatory, as rapidly as possible, for airplanes performing public transport flights over maritime areas to be equipped with an additional ULB capable of transmitting on a frequency (for example between 8.5 kHz and 9.5 kHz) and for a duration adapted to the pre-localisation of wreckage.

Raw acoustic data

During the acoustic searches undertaken during the first phase, the raw acoustic data from the towed pinger locators (TPL) was not recorded. Use of post-readout software would have made it possible to check if the ULB signals were present in the background noise. For future passive acoustic search systems, it appears to be essential to record this raw acoustic data.

Data transmission

The aeroplane was transmitting its position every 10 minutes. The last position transmitted made it possible to determine a search area of 17,000 km2. It is obvious that any significant improvement in the transmission frequency of this position information would have made it possible to considerably reduce the area of the search zone. Based on this general principle, the BEA directed an international working group on "Triggered transmission of flight data"[28], and in its Interim Report n°3 issued two additional recommendations requesting:

- that EASA and ICAO make mandatory as quickly as possible, for airplanes making public transport flights with passengers over maritime or remote areas, triggering of data transmission to facilitate localisation as soon as an emergency situation is detected on board;
- that EASA and ICAO study the possibility of making mandatory, for airplanes making public transport flights with passengers over maritime or remote areas, the activation of the emergency locator transmitter (ELT), as soon as an emergency situation is detected on board.

[28] See: http://www.bea.aero/en/enquetes/flight.af.447/triggered.transmission.of.flight.data.pdf

Drift Calculations

The release of drifting measuring buoys, to measure surface currents, by the first aircraft to arrive over the zone, was not undertaken. Knowledge of this data is, however, decisive for the effectiveness of this type of search.

The absence of this current data information for 5 days, associated with the difficulty in modelling the surface currents in this zone at this time of the year, made it impossible to determine a restricted search zone containing the wreckage site.

The search operations themselves showed that any results based on reverse-drift calculations should be considered with caution.

Possessing in-situ data on the surface currents, supplied by the first SAR aircraft deployed in a search zone, must thus be a priority, without which any reverse-drift calculations are very imprecise. On this point, BEA issued a recommendation addressed to ICAO requesting that:

❐ ICAO amend Annex 12 on search and rescue operations so as to encourage Contracting States to equip their search aircraft with buoys to measure drift and to drop them, when these units are involved in the search for persons lost at sea.

Sonar resources and underwater detection

At the end of the period of ULB transmission, only sonar resources are able to detect wreckage. These resources can be towed by a surface ship or installed on an AUV: both of these configurations were employed during search phases 2, 3 and 4.

The REMUS AUVs proved to be a very effective equipment, capable of reaching great depths and useable over very varied topography. Equipped with cameras, they made it possible to confirm sonar detection and to ensure photo coverage of the entire debris field, enabling considerable time to be saved during the following recovery phase.

The use of AUVs, of a type adapted to the depth required for the searches, is thus recommended for detection of wreckage in area with rough terrain after the end of the ULB transmission time period.

Naval resources and recovery strategy

The naval resources employed during phase 3 were multi-purpose ships, equipped with ROVs and sonar as well as cranes, for the *Seabed Worker*. They thus had the capability to detect, confirm and recover. This versatility is expensive in practice.

Separating the detection mission from the recovery mission can be an effective solution where there is great uncertainty on the localisation of the wreckage given that it can lead to the use of more economical ships

List of Appendices

Appendix 1
Chronological Summary of SAR Operations around the Last Known Position

Appendix 2
Summary of the Role of the E-3F between 3 and 7 June 2009

Appendix 3
Resources deployed in June 2009

Appendix 4
Analysis of SAR images from Flight AF 447

Appendix 5
Beacons on Board F-GZCP

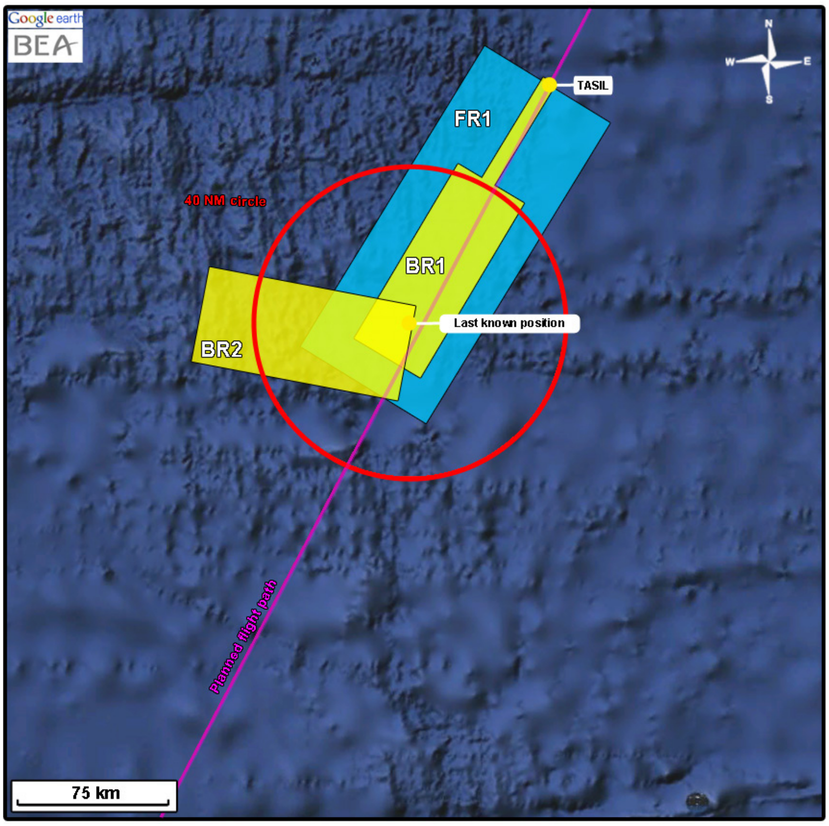
Appendix 6
Signal Pollution from Biological Sources

Appendix 7
Operations of Side-Scan Sonars

Appendix 8
Parts raised (Selected)

Appendix 1
Chronological Summary of SAR Operations around the Last Known Position

1st June 2009



Aerial SAR operations carried out from 1st June around the last known position

Towards midday, a French navy reconnaissance aeroplane (Atlantique 2) took off from Dakar (Senegal) and searched in zone FR1. It reported average visibility of 8 NM (about 15 km), reducing to 3 NM (about 5 km), in the squally areas.

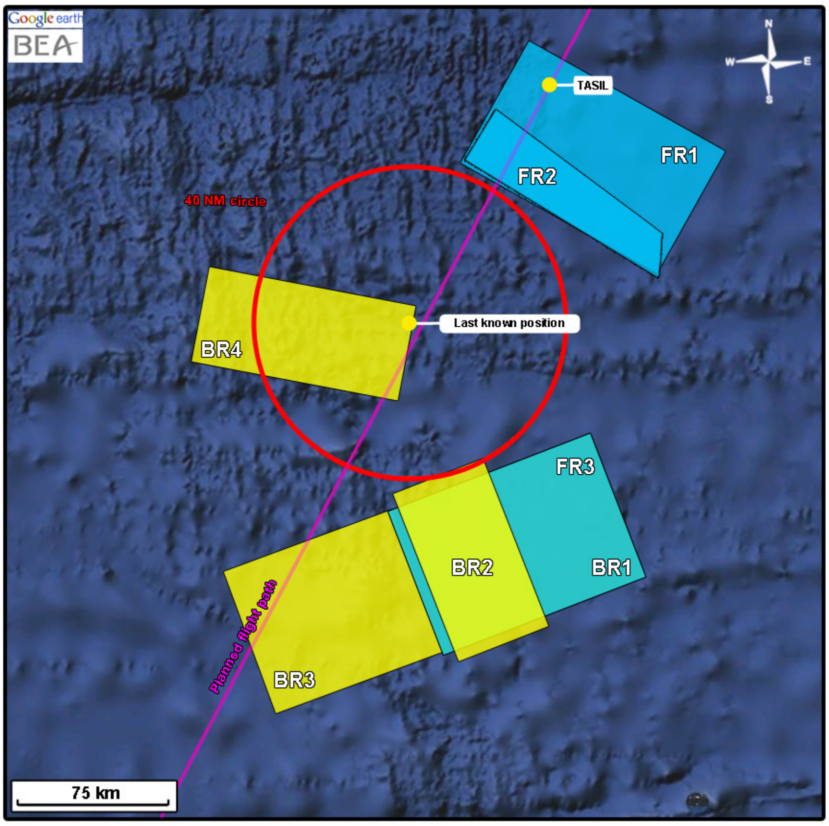
Two Brazilian aeroplanes (Hercules C-130 and Bandeirante) searched in zones BR1 and BR2.

Three ships from the Brazilian navy were mobilised to participate in the searches and headed to the search area which they would reach on 3, 4 and 6 June.

A French container ship that was in transit through the area was rerouted by the MRCC to participate in the first searches.

A US Navy reconnaissance aeroplane (P-3 Orion) would arrive on the days following to back up the aerial search group.

2 June 2009



Aerial SAR operations carried out on 2 June around the last known position

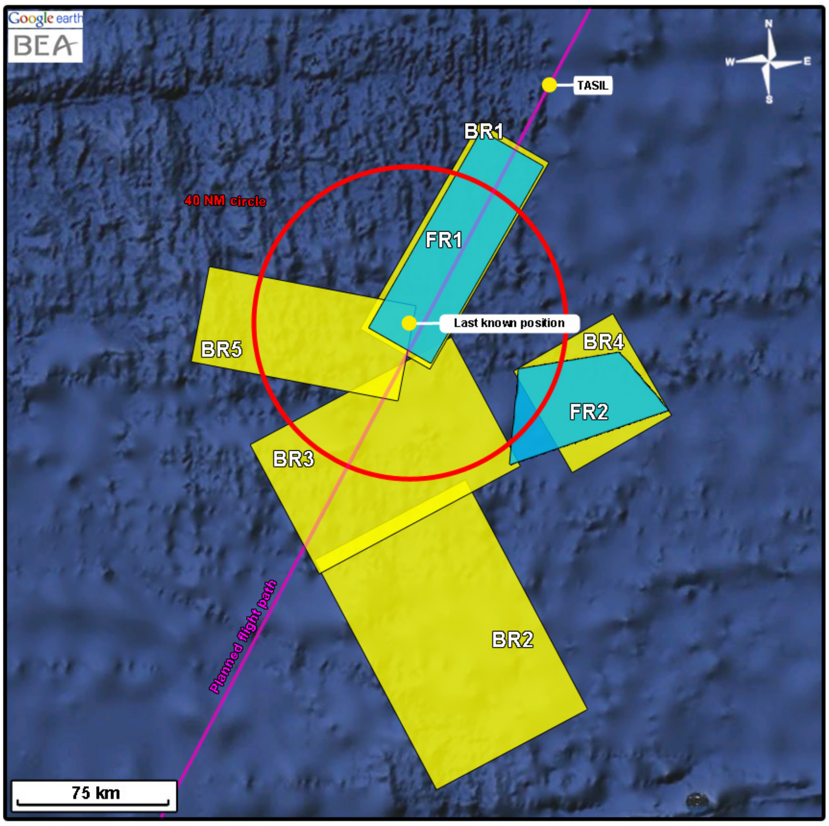
An Atlantique 2 searched in zone FR1, followed by a second French aeroplane (Falcon 50) which searched in zone FR2. It reported worsening visibility, which fell to 2 NM (about 3 km). A third French reconnaissance aeroplane (another Atlantique 2) searched in zone FR3.

Brazilian aircraft searched in zones BR1, BR2, BR3 and BR4.

The Brazilian Minister of Defence announced that debris had been identified (a seat, some small white debris and traces of fuel). It was subsequently shown that, following recovery of these parts, they did not come from the F-GZCP.

Two other merchant ships, in transit through the zone, were invited to join the search group.

3 June 2009



Aerial SAR operations carried out on 3 June around the last known position

Brazil announced that some new debris had been identified, as well as traces of hydrocarbons.

The first ship from the Brazilian navy arrived on the search area and four other ships sailed towards this area, which they reached in the following days.

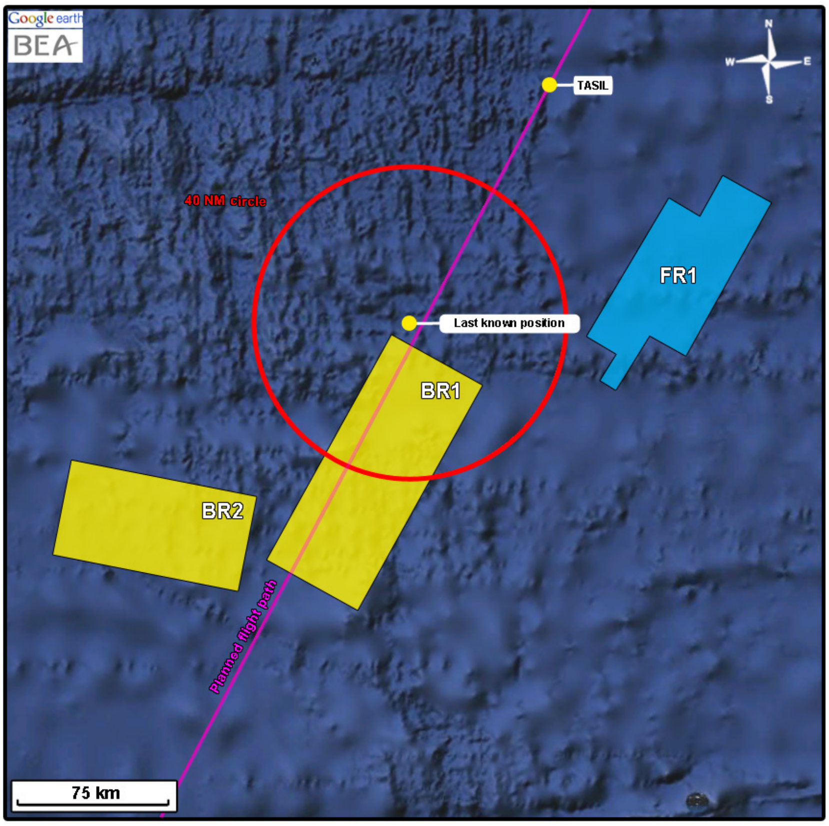
A French navy Falcon 50 searched both zones, FR1 and FR2, during the day.

Brazilian aeroplanes searched zones BR1, BR2, BR3, BR4 and BR5.

An airborne surveillance aircraft, E-3F (AWACS), was mobilised and deployed by France to coordinate the activity of aircraft over the area and to detect possible radar returns from the surface.

Two of the three commercial ships that were backing up the search group returned to their initial routes.

4 June 2009



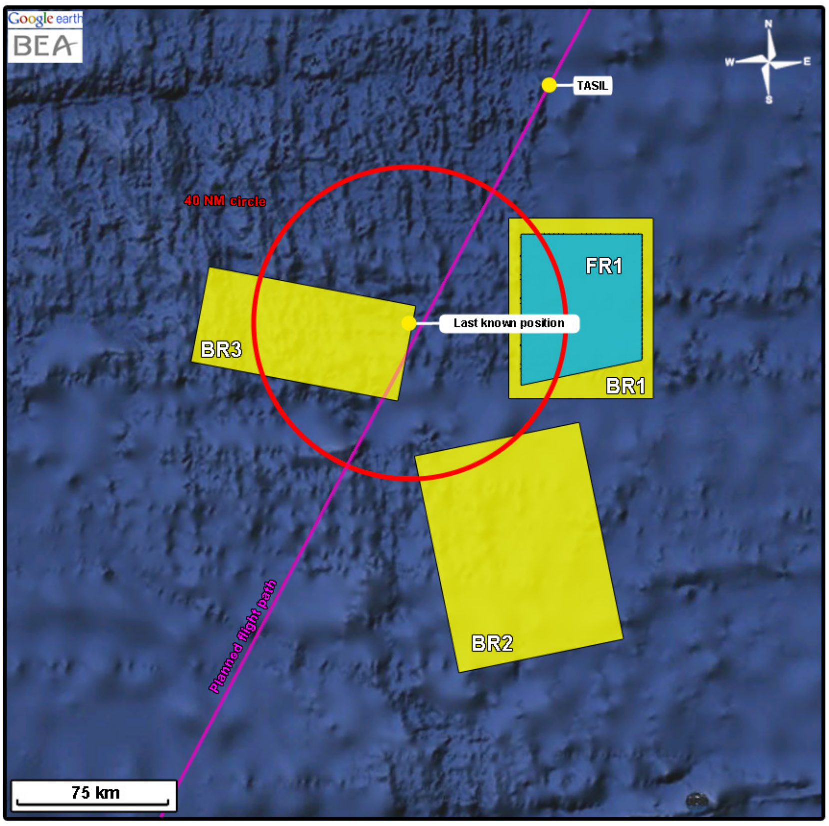
Aerial SAR operations carried out on 4 June around the last known position

A second Brazilian ship arrived in the search area. It was equipped with an onboard helicopter.

A Brazilian reconnaissance aeroplane (Embraer R99) searching in zone BR1 reported some debris. This was recovered by the helicopter. This find was announced by the Brazilian press. The parts proved not to come from the missing aeroplane. Another reconnaissance aircraft searched zone BR2.

Two French aircraft (Atlantique 2 and Flacon 50) searched in zone FR1 during the day.

5 June 2009



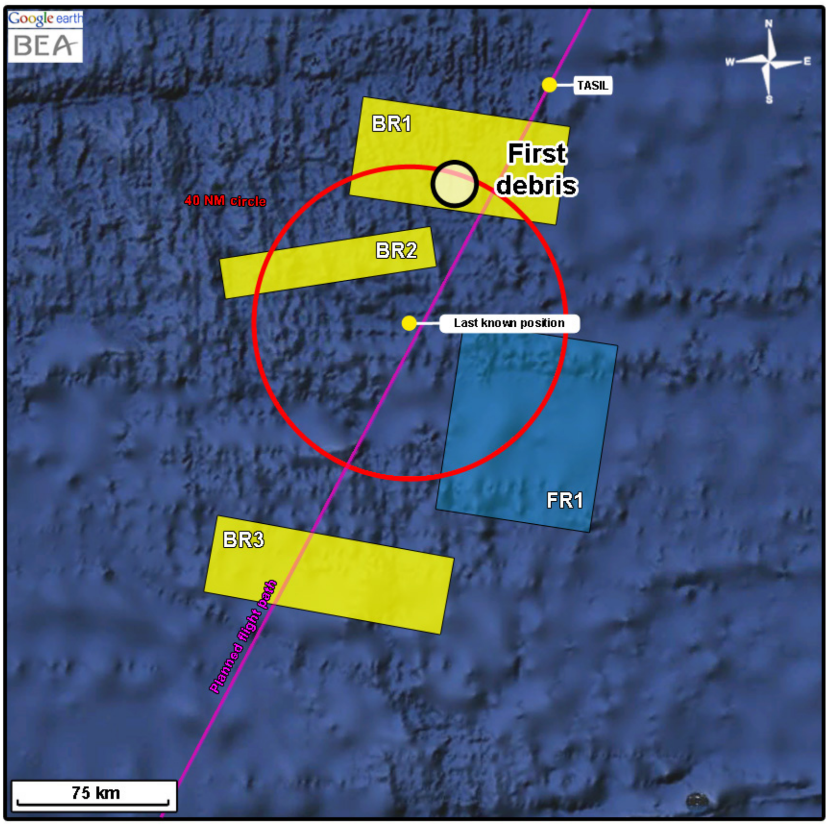
Aerial SAR operations carried out on 5 June around the last known position

The Brazilian authorities indicated that the next announcements on finds would only be made after definite identification of parts from the aeroplane had been made. They confirmed that as of 5 June, no debris belonging to F-GZCP had been found.

Two other Brazilian navy ships were deployed for the searches. They headed for the area, which they reached on 7 June.

Reconnaissance aeroplanes searched in zones FR1, BR1, BR2 and BR3.

6 June 2009



Aerial SAR operations carried out on 6 June around the last known position

A Brazilian Embraer R99 aeroplane detected, at dawn, radar returns 70 km north of the last known position. A Hercules C-130 noticed a collection of debris in the same sector.

The Brazilian corvette Cabloco caught a blue seat in the morning bearing the number 23701103B331-0. It recovered two bodies afterwards, personal belongings including a suitcase containing an Air France boarding card.

Aerial search groups flew over zones BR1, BR2, BR3 and FR1.

Appendix 2
Summary of the role of the E-3F between 3 and 7 June 2009

Description of the E-3F

The E-3F carrier is a Boeing 707-320 with a reinforced structure for a 7.5-tonne rotating dome mounted on the upper section of the fuselage.

The E-3F's primary radar operates in various modes:

- in Doppler mode it can detect low flying targets;
- in pulse mode it can detect distant targets;
- in maritime mode it can detect echoes at water surface level.

During antenna rotation, these modes are combined.

The secondary radar operates on an interrogation-response basis to identify aeroplanes with transponders (or IFF responder[29]) in different modes (from 1 to 4, C and S).

The E-3F also carries on board ESM[30] equipment which enables it to detect and analyse electromagnetic signals from any transmitter. This data is used as an identification aid.

The ESM device has four antennae (see previous photo) which ensure reception of electromagnetic signals (passive detection).

To identify ships, the surveillance system (radars and ESM) also includes AIS data[31] constantly transmitted from ships in accordance with IMO requirements[32].

A ship's AIS automatically provides shore stations, other ships and aircraft equipped with suitable material with data on identity, type, position, heading, speed, navigation conditions as well as other information linked to safety. These elements enabled the position of ships in the area from 31 May to 7 June 2009 to be validated, and these ships were then contacted by the BEA to obtain information relating to observed currents and wind.

The various systems described previously were used during the SAR operations launched in the search for flight AF447.

[29]Identification Friend or Foe.

[30]Electronic Support Measures.

[31]Automatic Identification System.

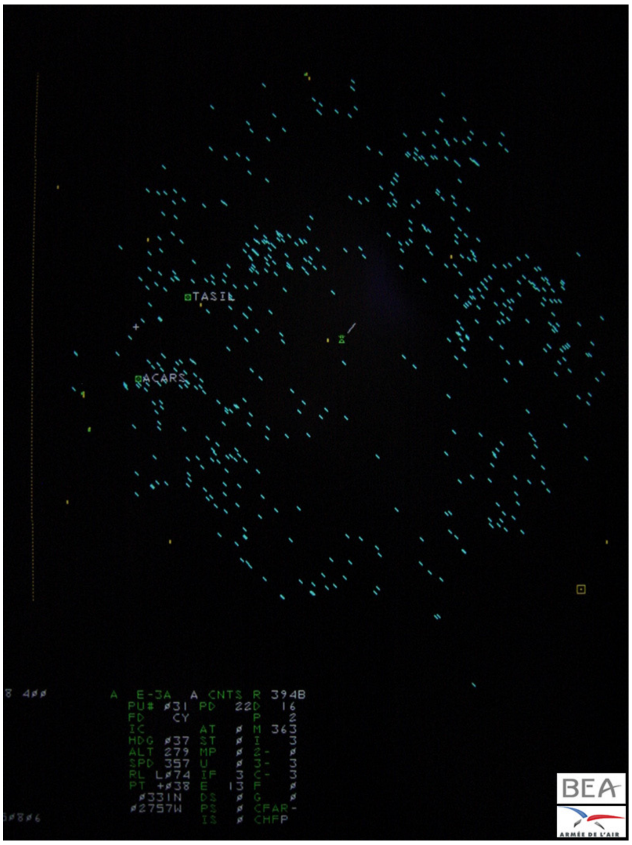
[32]The IMO makes provision in the 1974 International Convention for the Safety of Life at Sea (regulation 19 of chapter IV: requirements relating to ship-borne navigational systems and material) that all cargo ships of 300 gross tonnage and upwards engaged on international voyages, all cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships, irrespective of size, are required to carry an automatic identification system (AIS). The application of this obligation to fishing boats is left to the discretion of the authorities of each State.

Methodology for the search for floating debris

In the context of the AF447 mission, the E-3F was deployed to search for floating debris, to coordinate and ensure collision avoidance of resources within the search area, to carry out radio relays and guide resources suitable for visual reconnaissance. The data were merged and summarised onboard the E-3F and then transmitted to the operation centres.

The radar in maritime mode was the main source of data in the search for floating debris. Specific radar returns detected were quickly correlated with the AIS data transmitted by the ships in the area. Most returns could not be identified by AWACS resources (requiring visual reconnaissance). Some were persistent and others erratic. They were spread over a vast area defined by a circle with a radius of about 220 NM.

A considerable quantity of data was processed in real time inside the E-3F. The flight operators used analogue systems which generated a heavy work load, particularly for correlation which was often manual. The operators consistently followed in real time a great number of returns and selected those that were of interest (potential targets).



Example of a radar image on 6 June 2009 in maritime mode
with 363 echoes listed during an antenna rotation

These radar returns may have been floating objects, for example, schools of cetaceans, or wave breaks on the ocean surface, etc.

The quality and recurrence of a radar return depends on the type of floating object, of the Surface Equivalent Radar (SER) as well as its albedo (quantity of incident radiation energy transmitted or reflected by a body). The operators tried to select returns with frequent recurrence to define targets of interest. Experience showed that in sea conditions exceeding force 3, this task is almost impossible when the objects are small.

The position of the E-3F also influenced the quality of detection as returns seen under grazing incidence (on the periphery of the radar range circle) were very difficult to distinguish.

It is important to note that when returns were not identified by the AWACS' own resources, only cooperation with a means of visual search in the area (aeroplane, helicopter or boat) enabled the E-3F to recognise the returns detected by its radar in maritime mode.

Appendix 3
Resources deployed in June 2009

French SAR resources

❒ Ships:
- Ventôse (F733) Frigate
- Mistral (L9013) Command Ship

❒ Aeroplanes:
- Atlantique 2
- Falcon 50
- AWACS

❒ Helicopter:
- AS565 Panther

US SAR resources

❒ Aeroplane:
- P-3 Orion

Brazilian SAR resources

❒ Ships:
- Triunfo (R23) Patrol Boat
- Jaceguai (V31) Corvette
- Grajau (P47) Patrol Boat
- Goiana (P43) Patrol Boat
- Constitucao (F42) Frigate
- NT Alte Gastao Motta (G23) Tanker
- Cabloclo (V19) Corvette
- Rio De Janeiro (G31) Landing Ship
- Guiba (P41) Patrol Boat
- Bocaina (P62) Patrol Boat
- Bosisio (F48) Frigate

❒ Aeroplanes:
- C-130 Hercules
- C-105 Amazonas
- R-99 Guardiao
- P-95 Bandeirante
- SC-95 Bandeirante
- SC-105 Amazonas

❒ Helicopters:
- H34 Super Puma
- H-60 Blackhawk
- MK-95 Super Lynx

Civil SAR resources

- Ships:
  - Douce France
  - Arneborg
  - UAL Texas
  - Stolt Inspiration
  - Laura Maersk
  - Lexa Maersk
  - Jo Cedar
  - Ursula
  - Gammagas

Undersea search resources deployed by France

- Ships:
  - Pourquoi pas ?
  - Fairmount Glacier (Netherlands)
  - Fairmount Expedition (Netherlands)

- Submarine:
  - Emeraude (S604) Nuclear-powered submarine

Appendix 4
Analysis of SAR images from Flight AF447 accident

ANALYSE IMAGES SAR SUR ACCIDENT VOL AF447

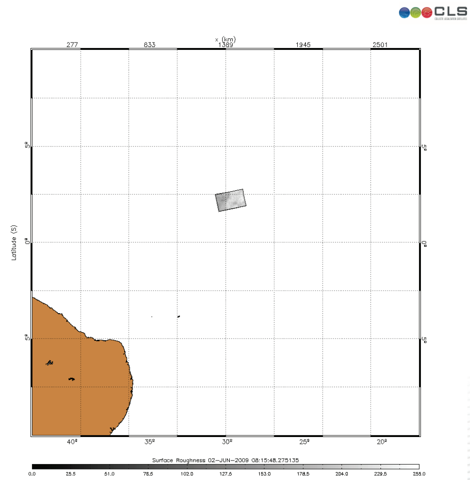
Données techniques

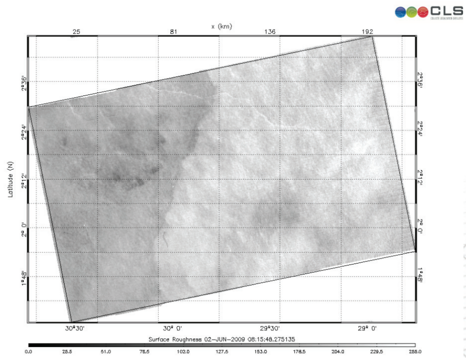
- Dans le cadre de l'étude de faisabilité de recherche des traces et de la localisation de l'accident de l'Airbus A330 du vol AF 447, trois images satellite radar ont été utilisées.

- Ces trois images proviennent du satellite bande X Cosmo-Skymed ;
  - mode de prise de vue était Wide Region produit niveau 1B ascendant
  - incidence moyenne le long de la trace était de 30
  - polarisation HH (horizontale) et l'orientation droite
  - résolution spatiale de 30 mètres (pixel spacing 15 mètres)
  - Date de prise de vue : 2 juin 2009
  - Heures de début de scènes : 081541 Z, 081555Z et 081608Z

Scène 1 : couverture

Page 3



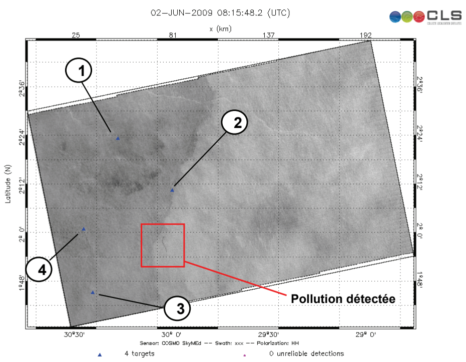


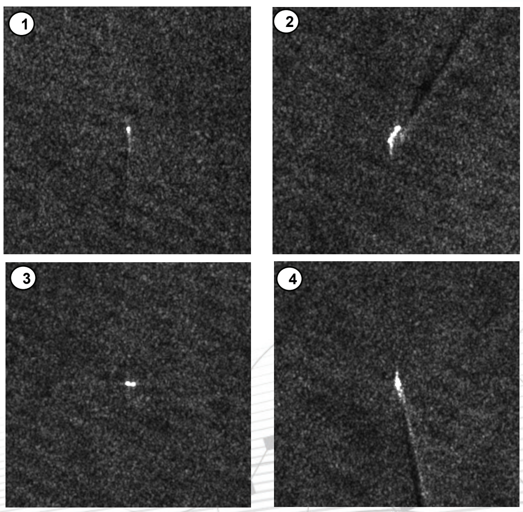
BEA : analyse images AF447

http://www.cls.fr

Scène 1 : détection de navires

Page 4





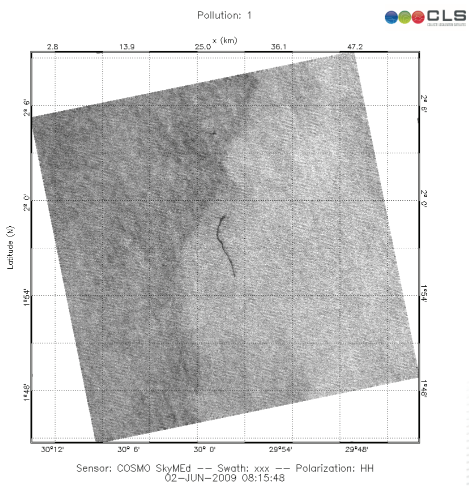
Quatre navires détectés :
1 – longueur env 60 m en route au 352 ;
2 – longueur env 180 m en route au 201 ;
3 – longueur env 110 en route au 090 ou 270 vitesse faible absence de sillage.
4– longueur env 110 en route au 338 ;

BEA : analyse images AF447

http://www.cls.fr

Scène 1 : pollution détectée

Page 5



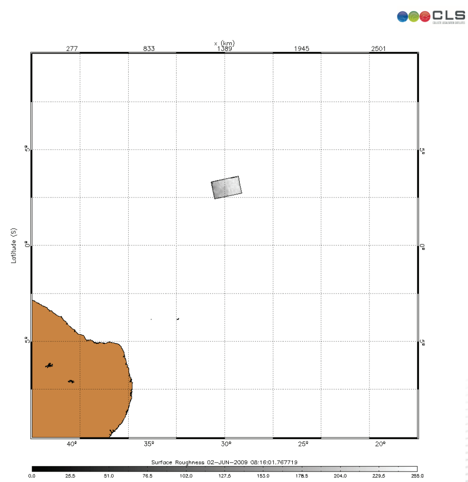
- Une pollution est détectée aux cordonnées :
- 001°59’04’’ N / 029°58’15’’ W
- L’origine de la pollution provient vraisemblablement d’un navire.

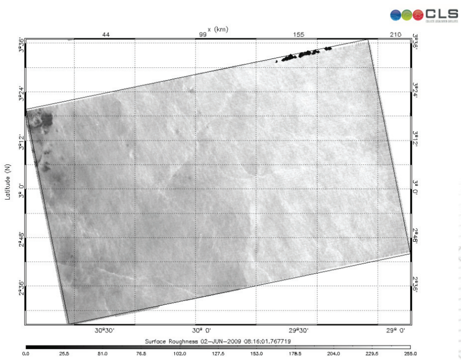
BEA : analyse images AF447

http://www.cls.fr

Scène 2 : couverture

Page 6

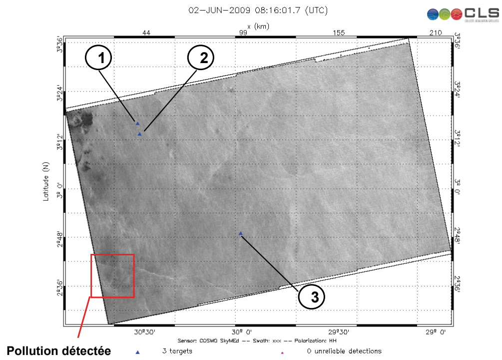


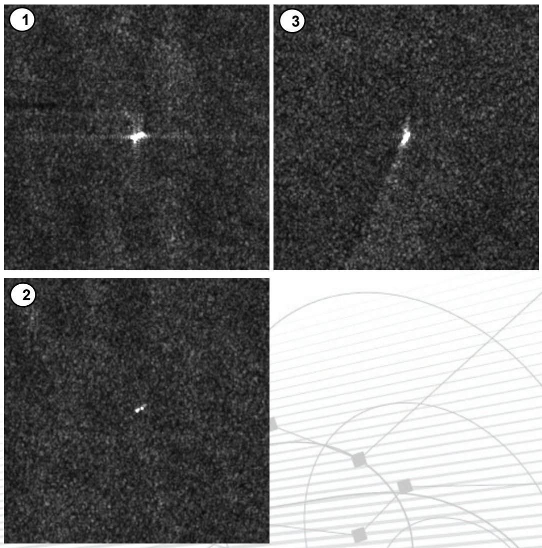


BEA : analyse images AF447

http://www.cls.fr

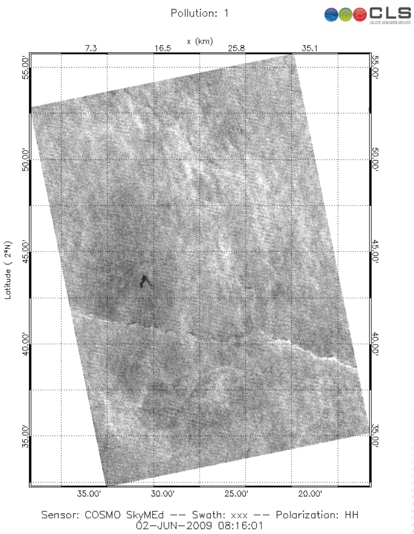
Scène 2 : détection de navires





Trois navires détectés :
1 – longueur env 160 m en route au 081 ;
2 – longueur env 60 m en route au 050 ou 230, possible à l'arrêt ou à vitesse très faible;
3 – longueur env 110 en route au 338 ;

Scène 2 : pollution détectée

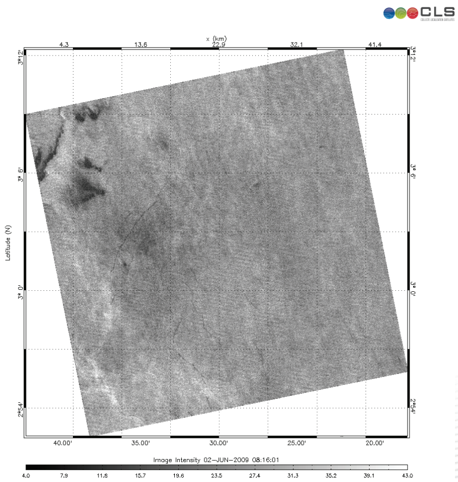


- Une pollution est détectée aux cordonnées :
- 002°43'24'' N / 030°30'29'' W

Pollution probablement non associée à un déplacement

Scène 2 : Zone dernier message ACARS

Page 9



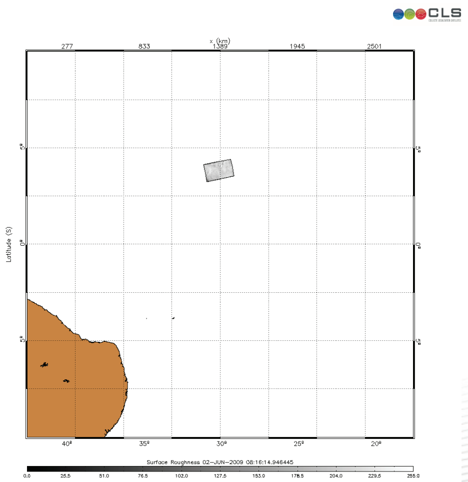
- Présence de filaments qui ne sont pas associés à une pollution.
- Zone de vent faible
- Filaments probablement d'origine organique

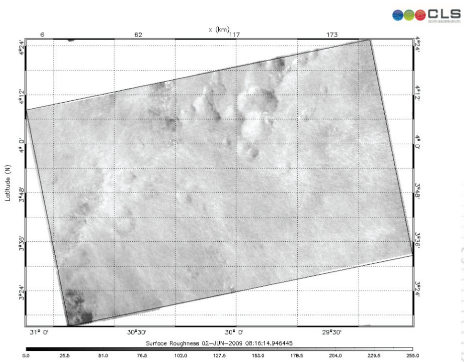
BEA : analyse images AF447

http://www.cls.fr

Scène 3 : couverture

Page 10



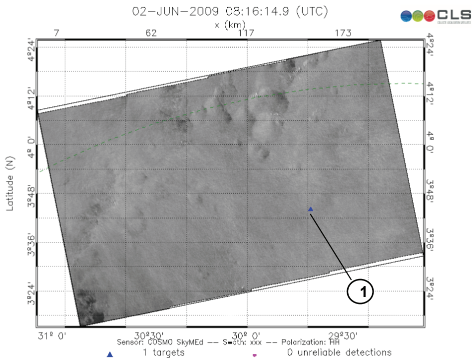


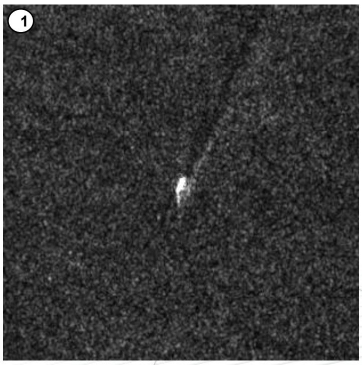
BEA : analyse images AF447

http://www.cls.fr

Scène 3 : Détection de navires

Page 11





Un navire détecté :
1 – longueur env 150 m en route au 192 ;

BEA : analyse images AF447

http://www.cls.fr

- CLS Headquaters

  8-10 rue Hermès
  31526 Ramonville-St Agne
  France

- CLS Brest

  Bâtiment Le Ponant
  Avenue La Pérouse
  29280 Plouzané
  France

BEA : analyse images AF447

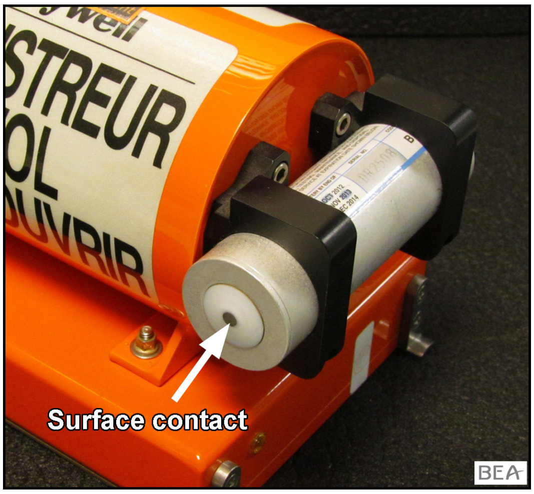
© Connaître aujourd'hui, mieux vivre demain

Appendix 5
Beacons on board F-GZCP

The ULBs[33] installed on the A330 F-GZCP MSN[34] 660 at the time of the accident were Dukane 120 (DK120) transmitters.

This model of ULB comprises a battery, an electronic module and a transducer, protected by a metallic cylinder.

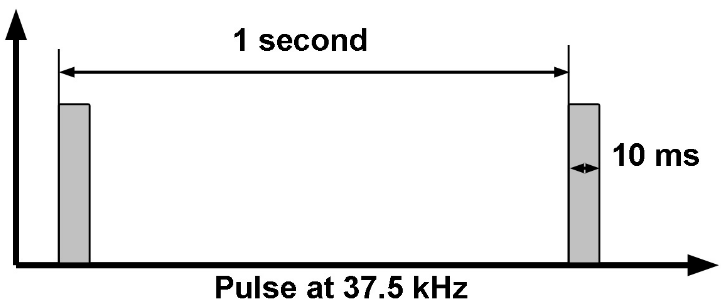
This beacon was mounted on a flight recorder attached with two retaining rings connected to the protected casing containing the recorded data.



Operation

The ULB is an autonomous transmitter which is activated as soon as it is submerged (in fresh or salt water). The water surrounding the beacon ensures an electric liaison between the surface contact and the body of the beacon; this connection authorises the transmitter to operate. The electric pulse produced by the electronic module is transmitted to a ring-shaped piezo-electric transducer which transforms electrical energy into mechanical energy. The body of the beacon acts as an acoustic transmitter by transmitting omni-directionally the pressure variation generated by the transducer.

A 37.5 kHz ultrasonic acoustic signal is transmitted into the underwater environment for 10 ms. This signal is repeated every second, until the internal battery is exhausted.



The ULB transmits for a minimum of 30 days after being submerged in water. It has a useful range in the order of 2,000 to 3,000 m. Environmental conditions (depth, temperature, salinity), ambient noise and seabed topography are the main parameters which influence the distance at which this beacon can be detected.

[33] Underwater Locating Beacon.

[34] Manufacturer Serial Number.

Technical specifications

- ❒ Operating frequency — 37.5 kHz ± 1 kHz
- ❒ Operating depth — surface to 6,096 m
- ❒ Pulse length — 10 ms +/- 10%
- ❒ Pulse repetition rate — not less than 0.9 pulse/s
- ❒ Operating life — 30 days minimum
- ❒ Battery life — 6 years (excl. transmission)
- ❒ Initial acoustic output — 160.5 dBµPa to 1 m
- ❒ Acoustic output after 30 days — 157.0 dBµPa to 1 m
- ❒ Operating temperature — -2.2 °C to +37.8 °C
- ❒ Activation — immersion in fresh or salt water
- ❒ Radiation pattern — rated output over 80% of sphere
- ❒ Size — diameter: 3.30 cm / length: 9.95 cm
- ❒ Weight — 190 g
- ❒ Storage temperature — -54 °C to 71 °C (without the battery)

This operating performance is expected for a beacon subjected to the environmental tests specified in ETSO[35]-C121.

[35] European Technical Standard Order.

Information relating to the F-GZCP ULBs

The Dukane ULB type number DK120 serial number DU44028 was installed on 20 August 2006 on the DFDR (Honeywell type number 980-4700-042 serial number 11469).

The Dukane ULB type number DK120 serial number ST24703 was installed on 13 March 2009 on the CVR (Honeywell type number 980-6022-001 serial number 12768).

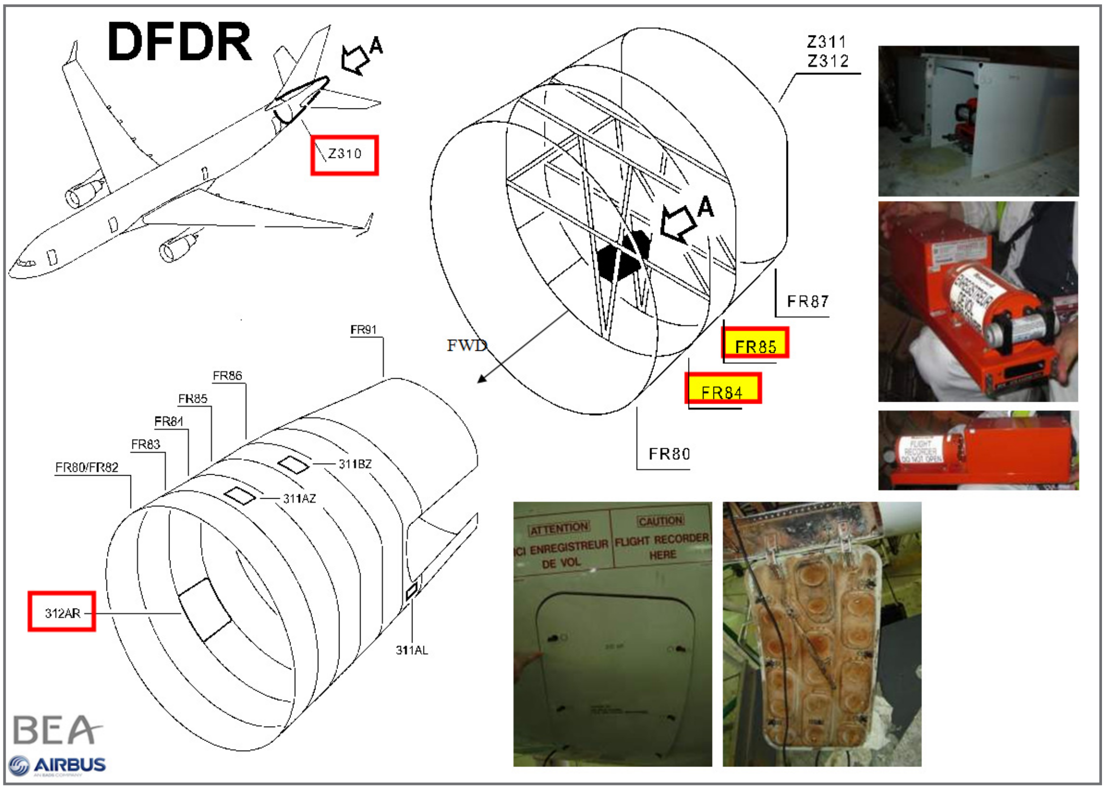
The pulse frequency, repetition and length parameters are systematically measured for each beacon produced. These data are archived by the manufacturer. They were communicated to the BEA shortly after the accident and were completed by information on the operating life.

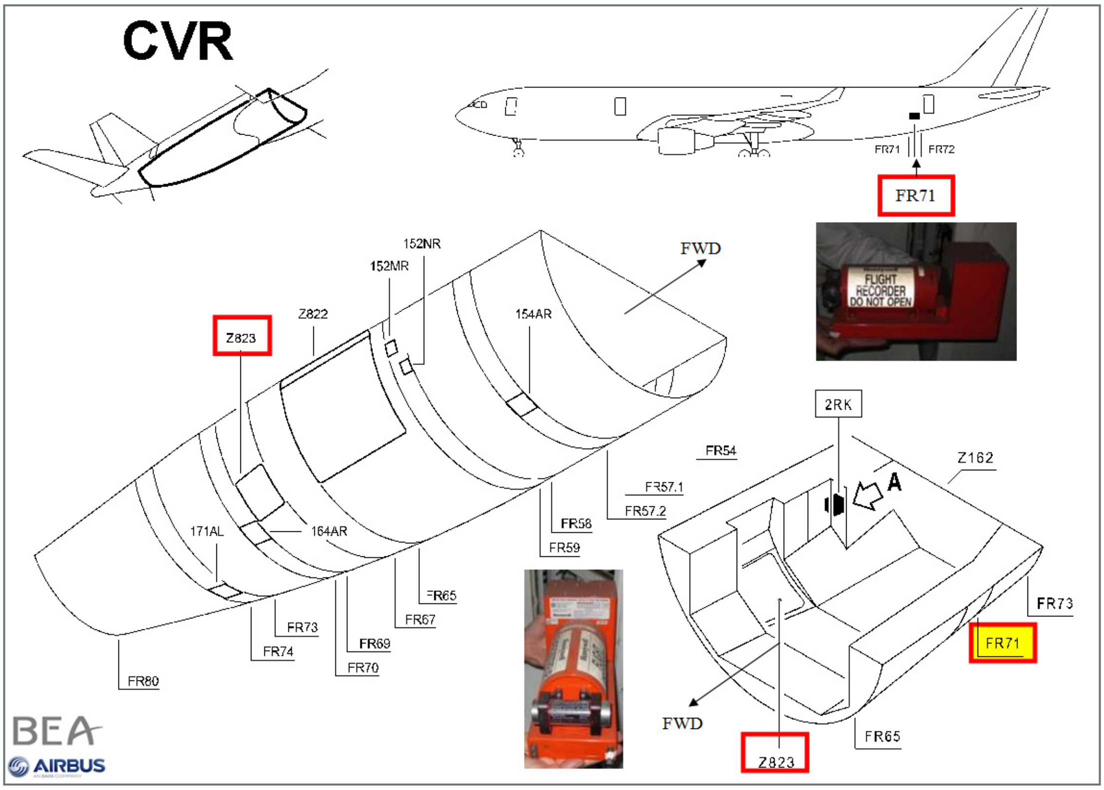
Flight recorder	P/N Beacon	S/N Beacon	End of validity date	Acoustic frequency	Pulse repetition rate	Pulse length	Operating life
DFDR	DK120	DU44028	07/2011	37.7 kHz	1083 ms/ pulse	9.19 ms	42 days
CVR	DK120	ST24703	02/2015	37.6 kHz	1086 ms/ pulse	9.21 ms	31 days

Positions in the aeroplane

The two beacons were found at the rear of the aeroplane:

- ❒ The DFDR was in the non-pressurised section between frames 84 and 85;
- ❒ The CVR was in the pressurised section at frame 71.


DFDR
A
Z310
Z311
Z312
A
FR87
FR85
FR84
FR80
FWD
FR91
FR86
FR85
FR84
FR83
FR80/FR82
311BZ
311AZ
312AR
311AL
ATTENTION
ICI ENREGISTREUR DE VOL
CAUTION
FLIGHT RECORDER HERE
BEA
AIRBUS


CVR
FR71
FR72
FR71
FWD
152NR
152MR
Z822
Z823
154AR
FLIGHT RECORDER DO NOT OPEN
2RK
FR54
Z162
A
FR57.1
FR57.2
FR58
FR59
171AL
164AR
FR65
FR67
FR73
FR74
FR69
FR70
FR80
FR73
FR71
FWD
Z823
FR65
BEA
AIRBUS

Maintenance

The beacons must be tested before and after their installation on the flight recorder as well as at each change of battery. Battery replacement and testing the leakage current must be carried out every six years. In the case of a recorder in service (on an aircraft), cleaning and testing the beacon every 2 years is recommended.

Air France policy on the maintenance of flight recorder ULBs consists of checking the battery expiry date every 2A check (4 months) and replacing the ULBs if this date is reached before the date of the following 2A check.

During C maintenance checks beacons are systematically tested by the Air France maintenance service. F-GZCP's last C maintenance check took place on 17 July 2008.

Appendix 6
Signal pollution from biological sources

Operations to detect signal transmissions at 37.5 kHz from flight recorders' ULBs could sometimes be affected by biological activity. Even if these events remained marginal and were often identified by operators, they could lead to erroneous detection, which was then subject to investigation.

Origin of the interference

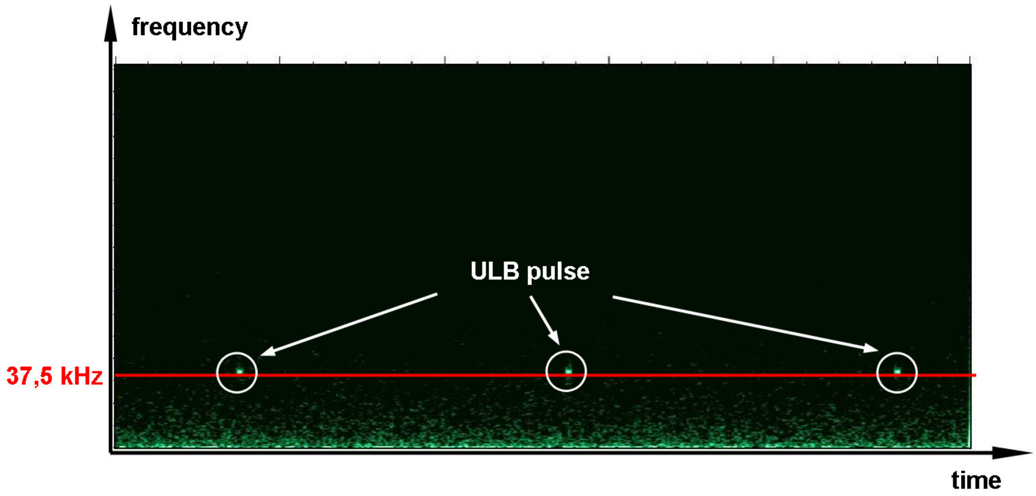
A large number of marine animal species transmit sounds in order to communicate or to detect their prey. These animal transmissions can in some cases deceive automatic detection systems, where the frequency is between 35 and 40 kHz.

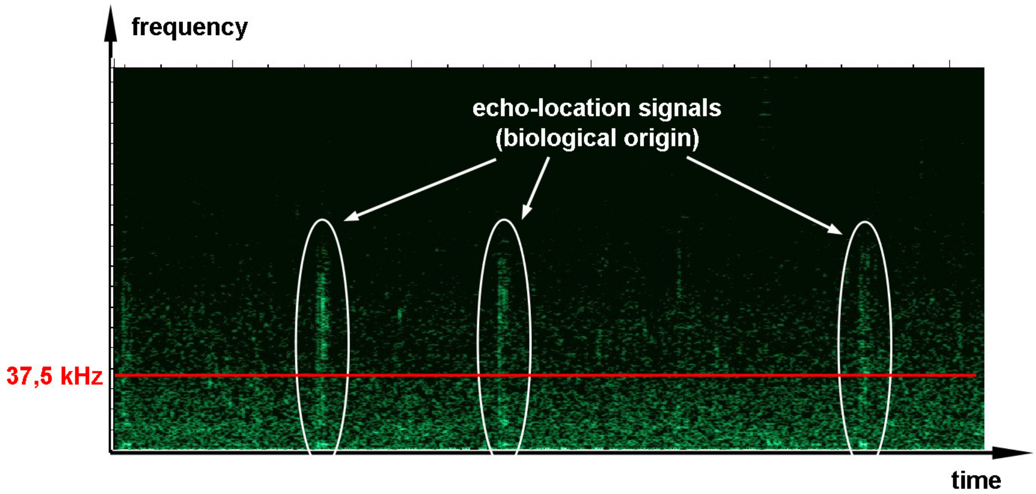
The table below summarizes the main species that present a risk of interference. The values given are examples since they vary according to scientific publications.

Animal species	Frequency range	Observations
Beaked whale (Ziphius)	18 à 80 kHz	Rare species
Stenosis	5 à 32 kHz	Short series of clicks
Sperm whale	100 Hz à 35 kHz	Very strong clicks / very regular clicks / Maximum energy between 2 and 8 kHz
Common Dolphin	30 à 100 kHz	Series of very fast clicks
Great Dolphin	40 HZ à 80 kHz	
Orca	25 à 50 kHz	

Sound discrimination (illustration)

A comparative frequency and temporal analysis of the two types of transmission (ULB and animal) is shown below.





The signal from the ULB is a signal with generally stable frequency pulses at around 37.5 kHz, and with a precise duration of between 9 and 11 ms, repeated regularly every second.

Contrary to ULB transmissions, a signal of animal origin possesses a very wide frequency distribution (several kHz), a very random pulse pattern, and repetition which is often perceived as regular but where precise measurement reveals great instability.

These differences in characteristics are perceived on the raw signals (between 35 and 40 kHz) as translated signals (ultrasound transmissions in the audible band from 20 Hz to 15 kHz).

Tools used to discriminate between sources

A sonogram image is most appropriate in order to clear any doubts quickly. A check through auditory means is also a good way distinguish the origin of signals received (the frequency richness of an animal signal is perceived as a series of shocks).

Appendix 7
Operation of side-scan sonars

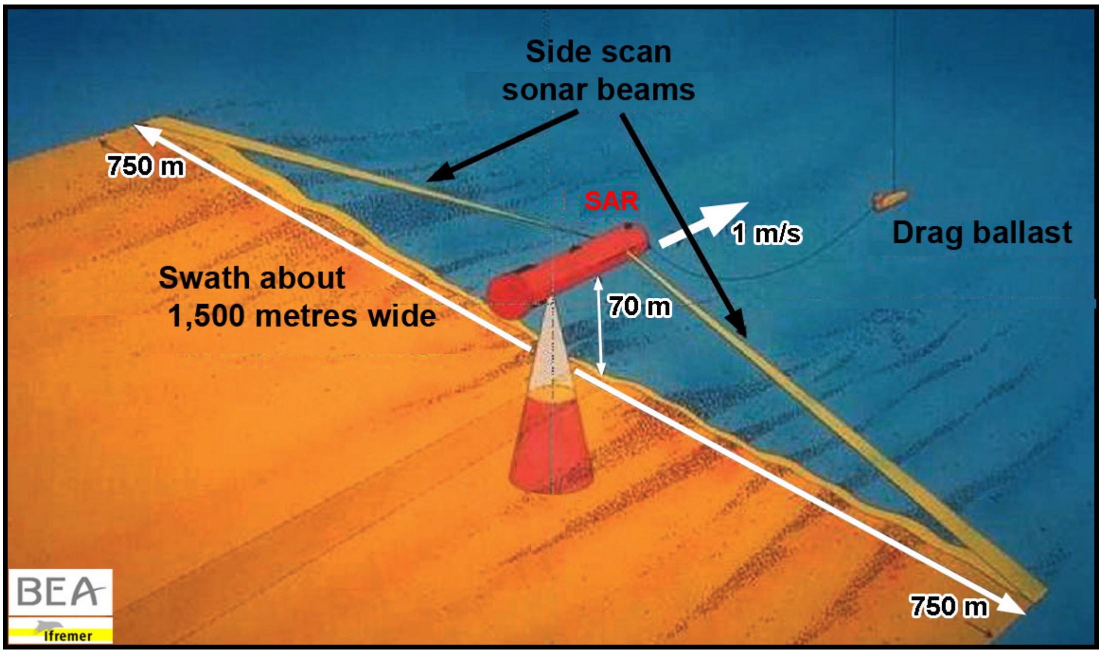
The underwater world is not transparent to light, and most standard imaging resources available in the aviation world cannot be used.

Progress in the fields of hydrography, sedimentology and wreckage search is mainly linked to the developments in the last few decades of acoustic measuring systems like side-scan sonar.

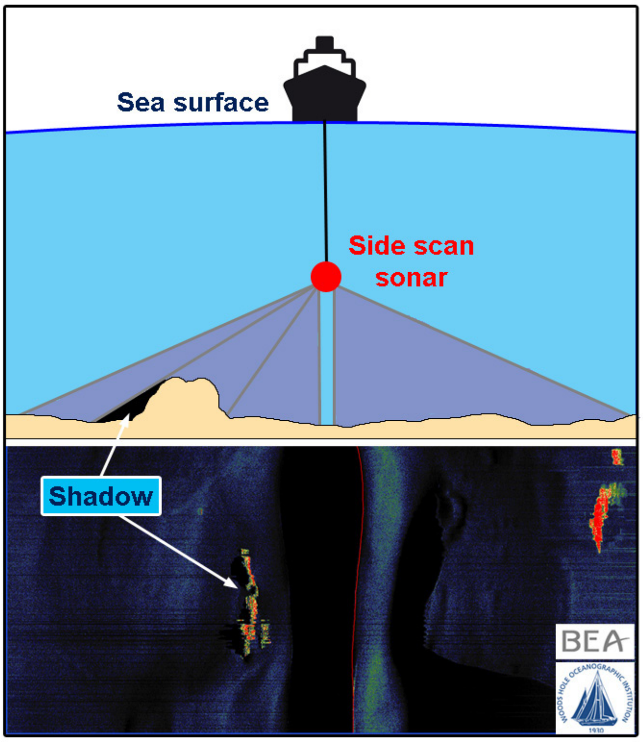
Operating principle

A narrow sound beam is transmitted via antennae with grazing incidence. It intercepts the seabed with a thin band which fans out with distance. Within this zone, the very short signal transmitted will define a very small insonified area which sweeps the whole area covered, called a swath.

The signal transmitted will be reflected according to the nature of the seabed towards the surface. The return received in this way over time is a representation of backscatter from the seabed the length of the swath. Backscattering enables the presence of irregularities or small obstacles to be visualised which are detected by the signal transmitted with high frequency. This feature offers high resolution. This signal, transmitted and received perpendicular to the sonar trajectory, ensures side-scan sonar coverage. This allows an “acoustic image of the seabed” to be obtained, line after line. Rocks, hardened sediments or objects backscatter more than soft sediments.

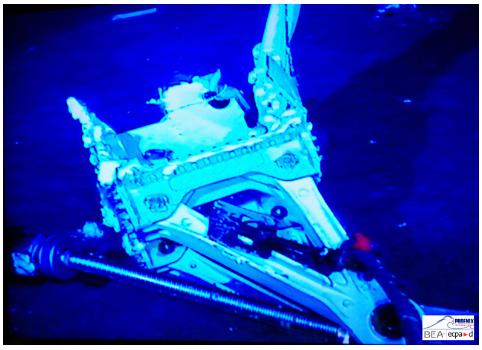


During sonar imaging search, the formation of drop shadows is also exploited. An obstacle of sufficient height will intercept part of the sound beam transmitted, and will prohibit backscatter by the seabed. The level of the echo received will be modulated by wave incidence variations in relation to the masking object. This phenomenon is expressed by the appearance of a shadow on the sonar image (see figure below) with a shape corresponding to that of the object, and whose analysis will enable the size and shape of the latter to be estimated. Analysis of drop shadows is useful for all search and identification applications of objects on the seabed like wreckage.

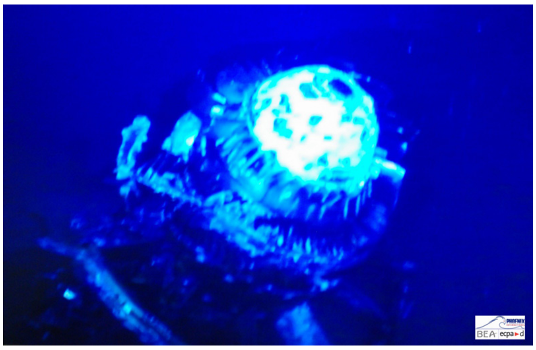


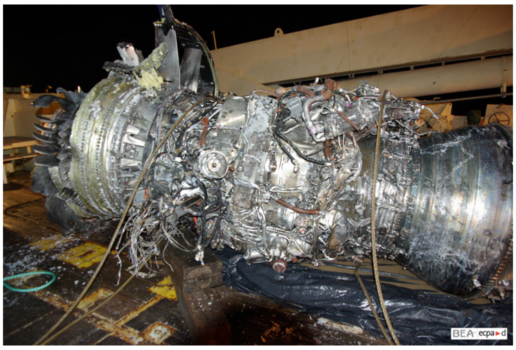
Shadows generated by side-scan sonar

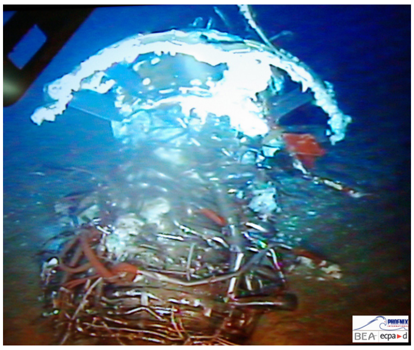
Appendix 8
Parts raised (selected)

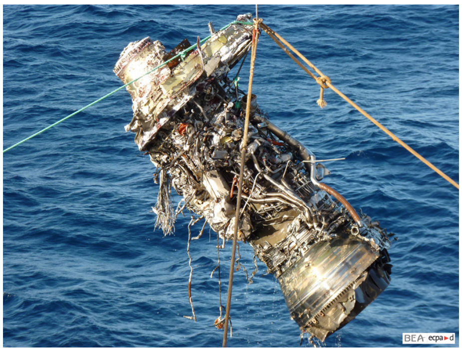

THS screwiack


THS screwiack


Left engine

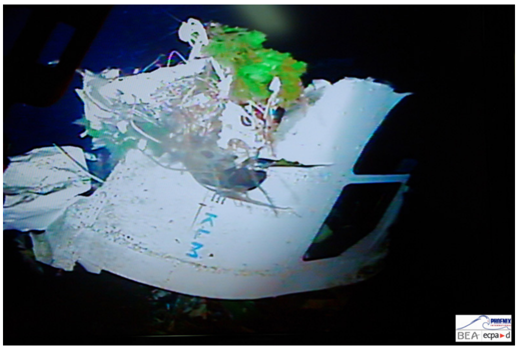

Left engine


Right engine

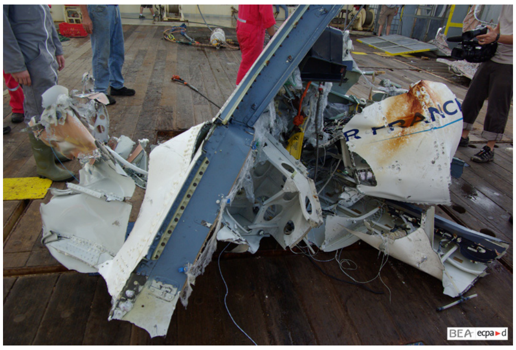

Right engine


Avionics bay


Avionics bay



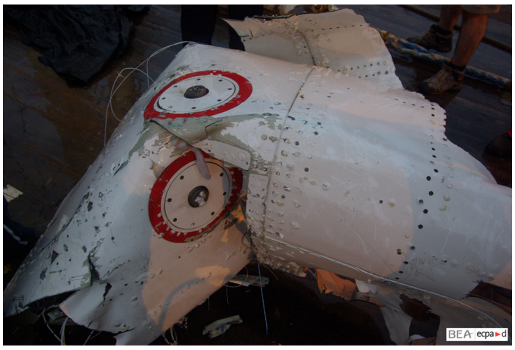
Section of forward fuselage



Section of forward fuselage

FDR chassis

FDR chassis



Angle of attack sensors

Angle of attack sensors

Fan casing

Nose landing gear

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

200 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