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Australian Transport Safety Bureau

# MH370 – First Principles Review

2 – 4 November 2016



Investigation

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#### **Addendum**

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# Executive summary

This report documents the proceedings and outcomes of the *First Principles Review* meeting on the search for missing Malaysia Airlines flight MH370 held in Canberra from 2 to 4 November 2016. Participants consisted of experts in data processing, satellite communications, accident investigation, aircraft performance, flight operations, sonar data, acoustic data and oceanography. The purpose of the meeting was to reassess and validate existing evidence and to identify any new analysis that may assist in identifying the location of the missing aircraft.

Throughout the search, the ATSB has issued several reports updating the definition of the search area based on analysis progressively refined, or when new information has come to light. This document complements those reports and provides a summary of the detailed analysis of the satellite data combined with new evidence derived from the modelling of the drift of debris from the aircraft.

The experts attending the meeting considered:

- The results of the search to date.
- Satellite communication metadata and its analysis including methodology, assumptions, limitations, the probability distributions of possible flight paths, and validation results.
- Results from simulations and the aircraft manufacturer's analysis of aircraft performance.
- The width of the search area based on what is known about the end of the flight.
- Hydro-acoustic analysis potentially relevant to the search.
- Failure analysis of recovered debris.
- Drift analysis of aircraft debris.

For background information, please refer to the previous ATSB publications available online at [www.atsb.gov.au/mh370](http://www.atsb.gov.au/mh370)

The updated independent analysis of the satellite data and the drift analysis consistently identified the most likely impact location of MH370 as being close to the 7<sup>th</sup> arc<sup>1</sup> (within ~25 NM) and bounded by latitudes of approximately 33°S to 36°S.

There is a high degree of confidence that the previously identified underwater area searched to date does not contain the missing aircraft. Given the elimination of this area, the experts identified an area of approximately 25,000 km<sup>2</sup> as the area with the highest probability of containing the wreckage of the aircraft. The experts concluded that, if this area were to be searched, prospective areas for locating the aircraft wreckage, based on all the analysis to date, would be exhausted.

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<sup>1</sup> The 7<sup>th</sup> arc is an arc of possible aircraft positions, equidistant from Inmarsat's Indian Ocean Region satellite, where the accident aircraft made the final series of satellite communications transmissions. It is the key datum in the search for MH370 and its derivation is described in previous ATSB search area definition reports.



# Contents

<b>The First Principles Review .....</b>	<b>6</b>
<b>Abbreviated minutes</b>	6
<b>Underwater search .....</b>	<b>7</b>
<b>Background</b>	7
<b>Defining the search method</b>	8
Side scan sonar	8
Synthetic Aperture Sonar	9
Remotely Operated Vehicle	10
Validating the search systems	10
<b>Analysing the sonar data</b>	11
<b>Sonar contacts</b>	11
Sonar coverage	12
<b>Area searched</b>	14
<b>Satellite data .....</b>	<b>15</b>
Search results and likely aircraft autopilot mode	15
Flight crew advice	16
<b>Width of the search area .....</b>	<b>17</b>
<b>Drift analysis .....</b>	<b>18</b>
<b>Residual Probability Map .....</b>	<b>20</b>
<b>Conclusions .....</b>	<b>23</b>
<b>Acknowledgements.....</b>	<b>24</b>

# The First Principles Review

In May 2014 the Governments of Australia, Malaysia, and People's Republic of China agreed that the Australian Transport Safety Bureau (ATSB) would coordinate the underwater search for MH370. The primary objective was to assist the ICAO Annex 13 investigation by locating and positively identifying the aircraft wreckage. It was also essential that any searched area assessed as not containing the aircraft could be discounted with a high degree of certainty.

In November 2016, the high priority underwater search area defined in the ATSB's previous reports was in its final stages of being searched. As such, the ATSB determined that a review of all available information relating to the search area definition was required. Participants at the three-day meeting held from 2-4 November 2016 at the ATSB office in Canberra included experts from each field of expertise where information was available to assist in the search area determination.

Accordingly, there were representatives at the meeting from all of the organisations participating in the Search Strategy Working Group including Australia's Defence Science and Technology Group (DST Group), Boeing, Thales, Inmarsat, the National Transportation Safety Board of the US, the Air Accidents Investigation Branch of the UK and the Department of Civil Aviation, Malaysia. In addition, there were representatives from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Geoscience Australia, Curtin University, Malaysia Airlines and the People's Republic of China.

The aim of the *First Principles Review* meeting was to consider the results of the underwater search to date, examine the data and analysis associated with the accident flight, and the definition of the search area. The meeting also focussed on new analysis relating to recovered aircraft debris.

## Abbreviated minutes

The first day of the meeting focused on a comprehensive review of the satellite communications (SATCOM) data, and the analysis methods used to estimate the aircraft's final location. The meeting included presentations from all organisations with subject matter expertise related to the SATCOM system. The review re-examined the detailed assumptions, calculation methods, and validations that led to the definition of the search area. The analyses had been verified using data from previous flights. The meeting participants determined that techniques used were acceptable and the results for the analysis of the accident flight were valid.

The second day of the meeting focused on the debris that was recovered from the islands to the east of Africa and the African coast from Tanzania to South Africa. CSIRO presented the analysis which examined the rate of movement (drift) of the flaperon (found on La Réunion Island in 2015) and other items, and its correlation to drift models. The results of this analysis identified an area of likely origin of the recovered debris (i.e. the aircraft's impact location). ATSB experts presented conclusions from the examination of the recovered flap section with respect to the likely configuration of the aircraft at the end of flight. The meeting participants determined that the analysis presented on the debris and subsequent results were valid.

The results of the underwater search were also presented including the search methods, completed coverage, sonar data interpretation, quality assurance and confidence in the results. A presentation on the hydro-acoustic data at the time of the accident allowed meeting participants to determine that hydro-acoustic analysis did not contribute any useful new information to the search.

On the third day, the meeting examined how the results of the search to date, the flight path modelling based on the satellite data, the drift modelling and the debris analysis may assist in the definition of any future search activities and the priorities for such activities.



# Underwater search

## Background

In May 2014, the ATSB developed the technical specifications for the search systems to be used in the underwater search for MH370. These specifications were based on consideration and consultation with experts in deep water search and recovery operations. The search for Air France 447 (AF447) in the Atlantic ocean from 2009 to 2011 was the most recent analogous deep water search operation for an aircraft. The ATSB's operational search team consulted extensively with the French Bureau d'Enquêtes et d'Analyses (BEA), the organisation responsible for the AF447 search and recovery and the technical experts involved in that search. A conservative requirement was developed for the search for MH370 that the search equipment must have the ability to detect an object of dimensions 1 m x 1 m x 2 m, the approximate size of the B777 engines, without cowlings.

Planning focused on selecting an effective, efficient method to search a very large area of the seafloor (at that time up to 60,000 km<sup>2</sup>) in ultra-deep water in often poor weather conditions and therefore 6000 m rated deep tow vehicles were selected as the primary search system.

The underwater search required a phased approach given the unknown composition and topography of the seafloor in the search area. Before the high resolution sonar search commenced, a bathymetric survey was conducted to ensure that the deep tow vehicles to be used in the search could be navigated safely and efficiently close to the sea floor. The bathymetric survey work commenced in June 2014 using hull-mounted multibeam sonar systems on the vessels *Fugro Equator* and *Zhu Kezhen*.

Once sufficient area had been surveyed, deep tow operations commenced using two vessels: the Malaysian directly funded vessel *Go Phoenix*, and the ATSB contracted vessel *Fugro Discovery*. A deep tow search system was also mobilised on *Fugro Equator* when that vessel had completed the initial bathymetric survey work.

From late 2014 through 2015, deep tow search operations focused on searching the areas adjacent to the 7<sup>th</sup> arc between latitudes 32.8°S and 39°S. *Go Phoenix* was tasked to search from 32.8°S to 34.5°S in the northern section of the search area while the two *Fugro* vessels were tasked to search from 34.5°S to 39°S in the south.

In April 2015, *GO Phoenix* completed the contract with the Malaysian Government and departed the search area. At this time, the tripartite Governments of Australia, Malaysia, and the People's Republic of China agreed to expand the search area to 120,000 km<sup>2</sup>. Deep tow search operations continued throughout the winter months with the two *Fugro* vessels.

In November 2015, additional analysis of the SATCOM data and flight path modelling was completed by DST Group. This work resulted in the search area being prioritised between 36°S and 39.3°S, and up to 40 NM either side of the 7<sup>th</sup> arc. Search activities have been largely focused in this area since that time.

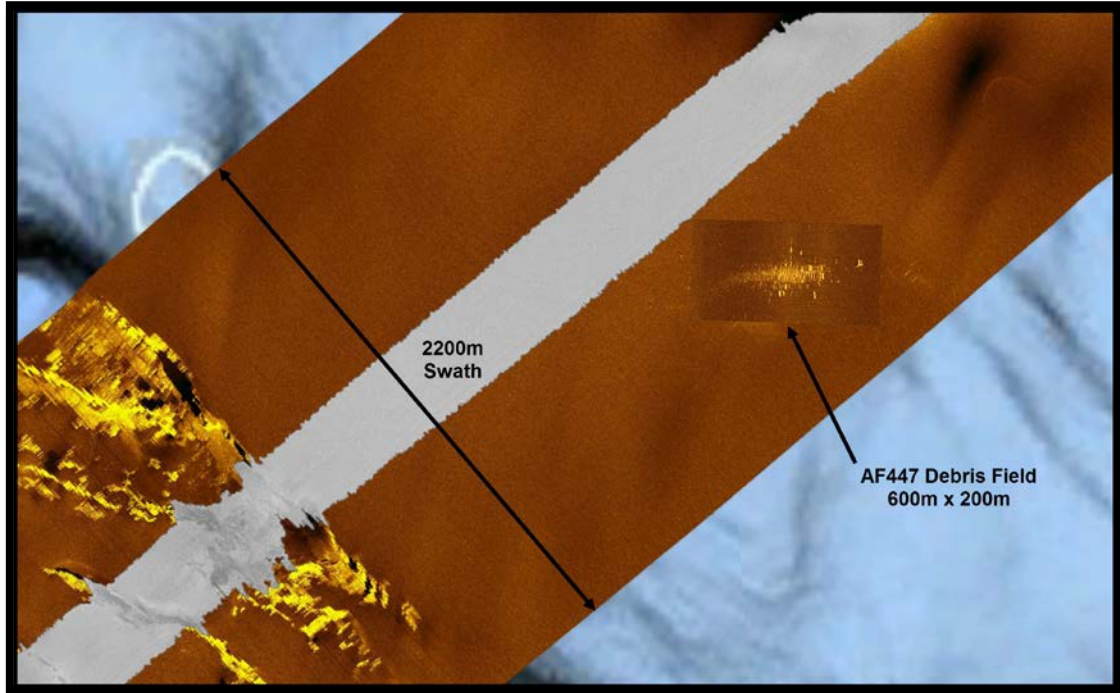
Deep tow search operations were supplemented each summer by autonomous underwater vehicle (AUV) campaigns. Better weather in the summer months allowed for efficient AUV operations in the search area. The AUV was used to search areas where the seafloor terrain was difficult for the deep tow systems to safely navigate and effectively search. The AUV was initially mobilised on *Fugro Supporter* during the summer of 2014/15, then on *Havila Harmony* in the summer of 2015/16 and is currently mobilised on *Fugro Equator*.

In February 2016, the Chinese vessel *Dong Hai Jiu 101* joined the search, initially equipped with the same deep tow system which was mobilised on *Go Phoenix*. A remotely operated vehicle (ROV) was also mobilised on the vessel some months later and was used in the latter part of 2016 to investigate and discount a number of sonar contacts detected during deep tow and AUV search operations.

## Defining the search method

When defining the search method, debris fields from previous air crashes into deep water were reviewed. The most relevant accident, Air France flight 447, was a similar sized aircraft and the wreckage was recovered from a depth of water similar to depths in the MH370 search area. The AF447 debris field was approximately 600 m x 200 m in size and at a depth of 3,980 m.

Figure 1. Air France 447 debris field overlaid to scale on a swath of MH370 deep tow sonar data.



Source: Fugro / BEA / ATSB

Figure 2. Air France 447 engines on the seafloor.



Source: BEA

## Side scan sonar

The feature detection capability of a conventional side scan sonar system is a function of several factors and operational parameters. The frequency of the sonar signal, the transmit/receive cycle (range scale), acoustic energy levels and system noise levels are some of the main factors.

Sonar coverage rates are a function of the sonar's effective range (swath) and the speed of the sonar system over the sea floor. Lower frequency systems typically have greater range capability however longer range scales also have longer transmit cycles between "pings" and therefore fewer "pings" reflect off an individual target than would occur with using shorter range scales for a given speed through the water. This essentially lowers the detection capability. Using slower tow



speeds can increase the number of "pings" on a target however this directly impacts sea floor coverage rates.

Therefore the frequency, feature detection capability, resolution required, and rate of coverage of sonar systems are all related and need to be considered and carefully weighed based on the requirements of the survey (or search). For the search for MH370 with a basic requirement to detect an object two cubic metres in size, an optimal range and associated coverage rate was selected based on the feature detection capability of the sonar system.

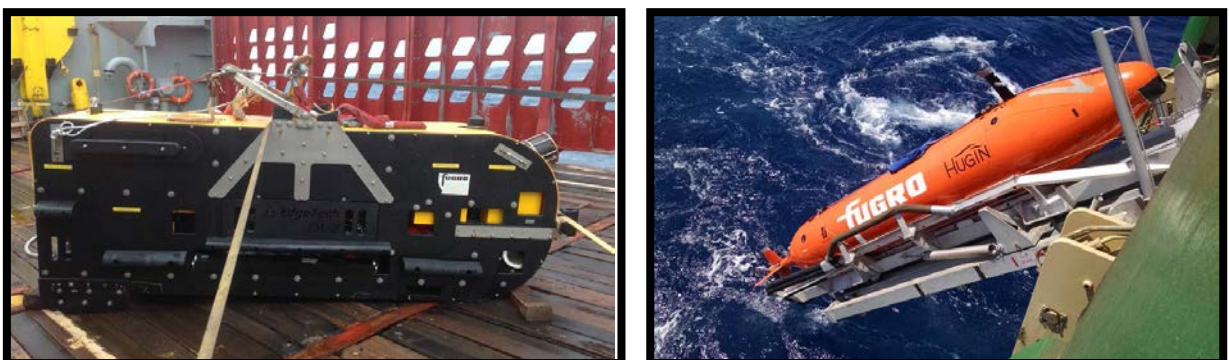
Fugro's Edgetech deep tow vehicle (rated to 6,000 m) and Hugin 1000 AUV (rated to 4,500 m) are both fitted with dual frequency 75/410 kHz side scan sonar transducers with 75 kHz used for primary coverage. The deep tow vehicles are operated at speeds between 2.5 and 3 knots and the AUV at 3.5 knots (generally using a lower range scale than the deep tow vehicles). At these speeds the deep tow vehicles can consistently achieve the required detection capability with a swath width of 2000 m.

Another important coverage consideration for the sonar search systems is the side scan sonar "blind spot" in the nadir area directly beneath the vehicle. This can impact the amount of overlap required between adjacent search lines and therefore the overall seafloor coverage rate. The vehicles used in the search (deep tow and AUV) had an independent sonar instrument to cover the nadir area (a multibeam echo sounder) rather than rely on a very large overlap between adjacent search lines to cover the nadir area.

Similarly, accurate positioning of the sonar vehicle reduces the overlap required at the edge of the swath to ensure complete coverage between search lines. The depth of the water in the search area resulted in the deep tow sonar vehicle being up to 9 km behind the search vessel, which also necessitated an accurate positioning system for the deep tow vehicles. An inertial navigation system in each vehicle was used to provide primary positioning which was corrected to an accuracy of around 50 metres using a very long range ultra-short baseline (USBL) acoustic positioning system.

The Hugin 4500 AUV was also positioned using a USBL system. During AUV operations the support vessel is manoeuvred on the surface to closely track the position of the AUV as it surveys the seafloor below and therefore positional accuracy for the AUV is higher than for the deep tow systems given the shorter range (distance) from the vessel to the vehicle.

**Figure 3. Fugro search vehicles, Edgetech deep tow and Kongsberg Hugin 1000 AUV.**



Source: Fugro

### ***Synthetic Aperture Sonar***

The SL Hydrospheric LLC ProSAS SLH PS-60 (ProSAS) deep tow vehicle, mobilised at different times in the search on both *Go Phoenix* and *Dong Hai Jiu 101*, was the latest generation of deep water (rated to 6,000 m) towed sonar systems. It was equipped with a 60 kHz synthetic aperture sonar (SAS) system which was able to achieve higher resolutions at longer ranges compared to traditional side scan sonar systems. The SAS processing combines data from several individual

sonar “pings” in a sequence with highly accurate inertial navigation data to build a map of the seafloor with a resolution of 10 cm.

The ProSAS vehicle was operated at a speed of around 1.8 knots, achieving a swath of 2,000 m (range and speed are directly related for a SAS system). The ProSAS deep tow system was also equipped with a multibeam echo sounder to cover the nadir region.

**Figure 4. ProSAS SLH PS-60 deep tow vehicle**



Source: SL Hydrospheric LLC

### ***Remotely Operated Vehicle***

Phoenix International Holding's Remora III remotely operated vehicle (ROV) was used late in 2016 to examine sonar contacts of interest. Unlike the AUV, the ROV remained tethered to, and controlled from, the support vessel. The ROV was rated to a depth of 6,000 m and was fitted with a camera system (video and still), scanning sonar, manipulators (to gather samples), and a USBL positioning system. In good weather the ROV was able to be deployed, dive, survey and film the target, return to the surface and be recovered by the vessel in 5 to 6 hours.

**Figure 5. Remora III remotely operated vehicle.**



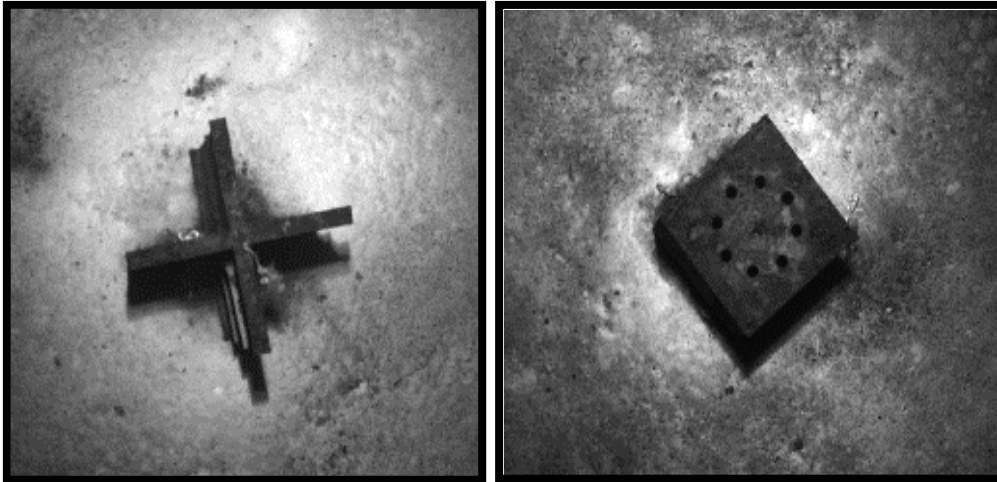
Source: Phoenix International Holdings

### **Validating the search systems**

The capability of every sonar system used in the search for MH370 was tested over a purpose built sonar test range prior to commencing operations and after any significant maintenance. The test range consisted of five purpose built targets spread across 1,150 m on the seafloor in a water depth of 650 m. All vessels were required to demonstrate their sonar vehicle's ability to detect and

accurately depict the test range targets in the sonar data and the satisfactory operation of the complete search system before transiting to the search area.

**Figure 6. Test targets on the test range (images captured by AUV camera).**



Source: Fugro

### **Analysing the sonar data**

Analysis of the sonar data started at the time of acquisition (data was transmitted up the tow cable from the deep tow systems in real time) which was continuously monitored by experienced sonar data analysts on each of the search vessels. The quality of the data, position, speed and altitude of the deep tow vehicle were also monitored continuously by the mission crew and independently by an ATSB client representative on each search vessel. Sonar contacts of preliminary interest were marked at this time.

For the Fugro vessels, the sonar data was then streamed from the vessel, via satellite, to the Fugro data analysis team in Perth. It was then analysed for quality, coverage and contacts by a team of sonar data specialists and geophysicists. The data was then provided to the ATSB.

For the ProSAS sonar data, after preliminary analysis on board the search vessel (*Go Phoenix* or *Dong Hai Jiu 101*), it was stored on board until port calls when it was provided to the ATSB.

All search data was checked again for quality, coverage and contacts by geospatial information systems (GIS) staff in the ATSB's Canberra office before being integrated into coverage maps, including the bathymetry information, and prepared for storage.

Data analysis was also performed by the ATSB's quality assurance manager based in the USA and finally by independent highly experienced sonar data experts also based in the USA.

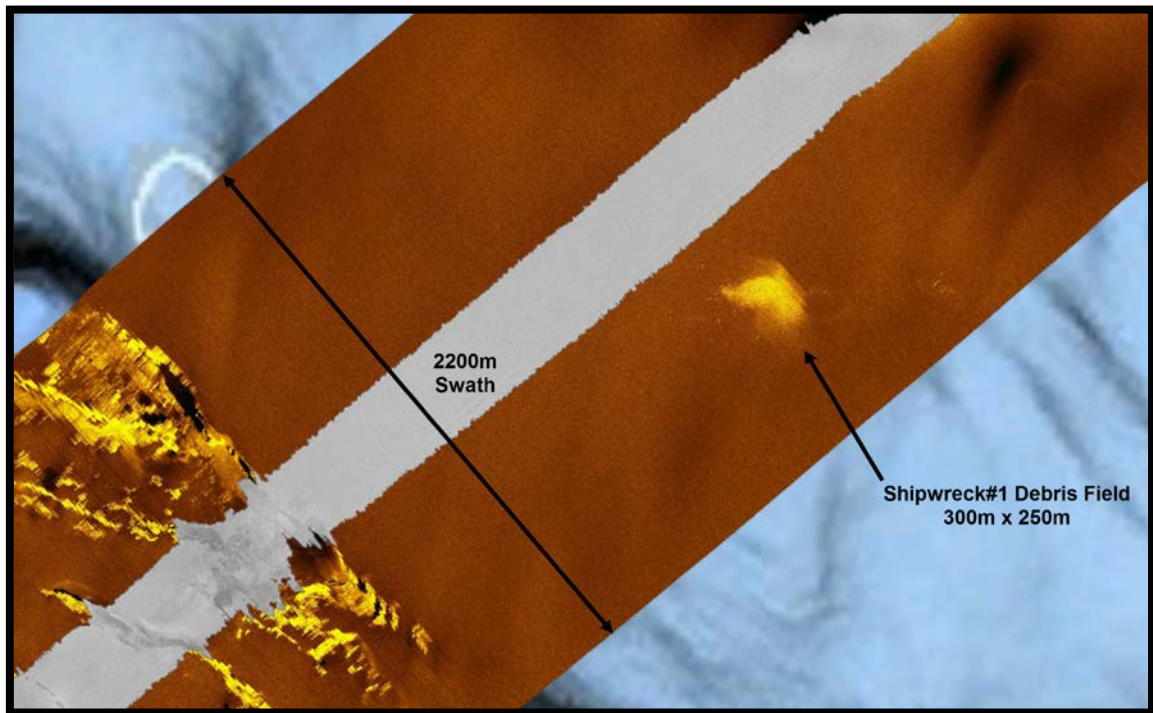
### **Sonar contacts**

Sonar contacts (anomalous features) identified in the sonar data were classified in three ways: level 3 contacts were marked but assessed as unlikely to be related to the aircraft, level 2 contacts were marked but assessed as only possibly being related to the aircraft, and level 1 contacts were of high interest and warranted immediate further investigation. To date, 605 level 3 contacts, 39 level 2 contacts, and two level 1 contacts have been identified. The two level 1 contacts were investigated and found to be the iron remains of a timber shipwreck and a scattered rock field.

In total 74 sonar contacts have been investigated and eliminated (as being related to MH370) by the AUV, ROV, or a deep tow system (using lower range scales/higher frequency sonar/optical imaging).

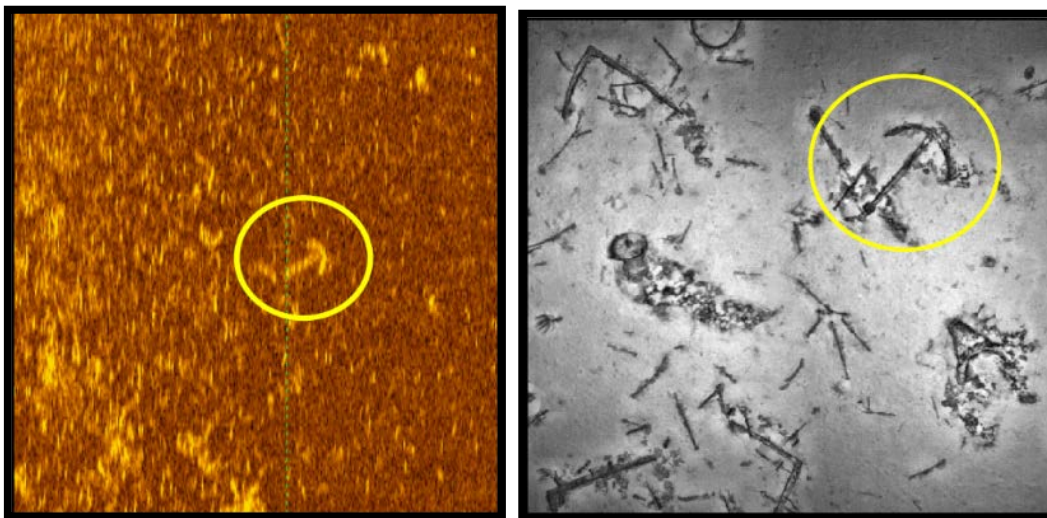


Figure 7. Deep tow data of level 1 sonar contact



Source: Fugro / ATSB

Figure 8. Higher resolution AUV sonar data and optical imagery of shipwreck number 1.



Source: Fugro

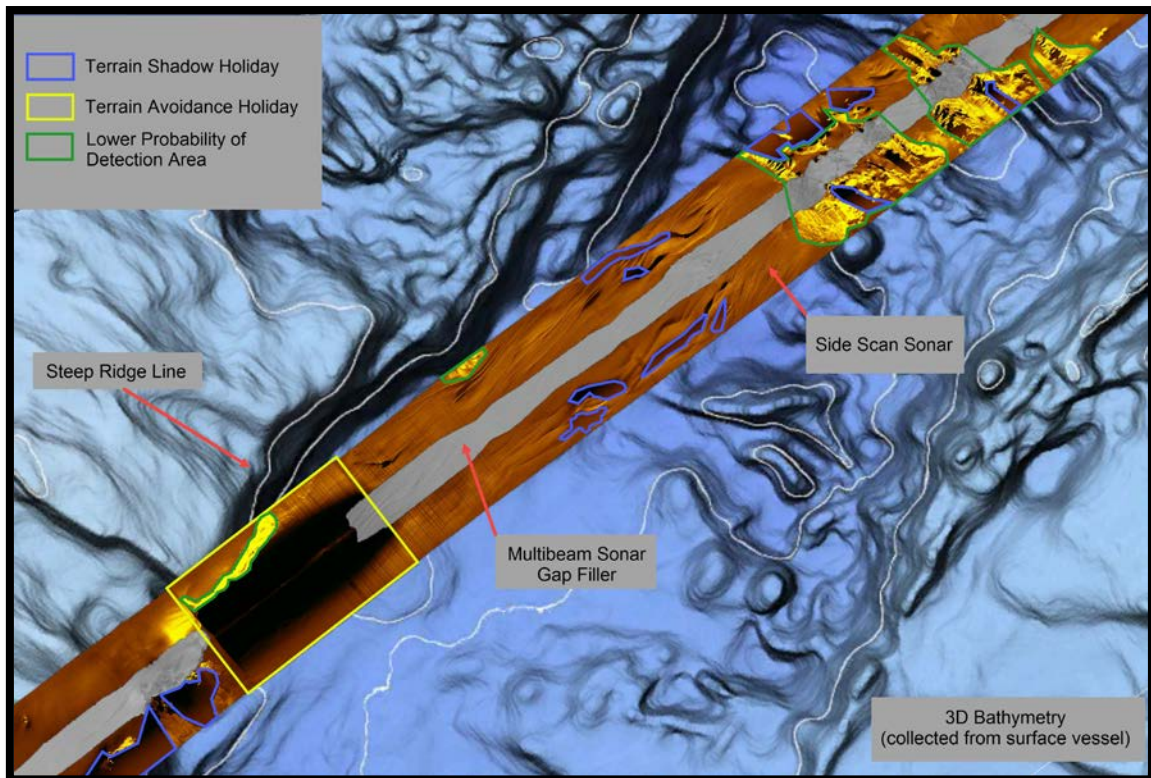
### Sonar coverage

The topography of the seafloor in the search area was such that the deep tow vehicles achieved approximately 97% sonar coverage. The remaining 3% represented areas where the topography or composition of the seafloor or resulted in gaps in the sonar coverage, mostly associated with:

- terrain shadowing, where the terrain masked the area behind it;
- terrain avoidance, where the tow vehicle had to be raised and lowered to negotiate the terrain; and,

- lower probability of detection (LPD), where there was sonar coverage, but the geology comprising the seafloor has the potential to obscure the presence of an aircraft debris field.

**Figure 9. Deep tow sonar data showing an area of complex seafloor topography in the search area and associated sonar coverage classifications.**



Source: Fugro / ATSB

In addition to terrain shadowing and terrain avoidance, there were small areas of the seafloor where failures of the search equipment (mostly multibeam nadir cover) resulted in small gaps in the sonar coverage. Areas which were large enough to contain an aircraft debris field (greater than 200 m x 200 m not including LPD areas) were scheduled for resurvey. Areas closer to the 7<sup>th</sup> arc were given priority for this work.

Areas designated as LPD could be eliminated with varying degrees of confidence (between 50% and 90%) depending on the texture and composition of the seabed in these areas and their ability to obscure any aircraft debris. Approximately 35% of the LPD areas have been searched twice (or more) by various sonar sensors on multiple passes.

**Table 1. Current sonar coverage statistics for the indicative search area (between 36°S and 39.3°S) 27.5 NM to the west and 25 NM to the east of the 7<sup>th</sup> arc, areas greater than 200 m x 200 m.**

Sonar data 'type'	Area km <sup>2</sup>	Percentage of area
Lower Probability of Detection areas	606.7	0.98%
Combined: terrain shadowing, terrain avoidance, equipment failure.	119.29	0.19%

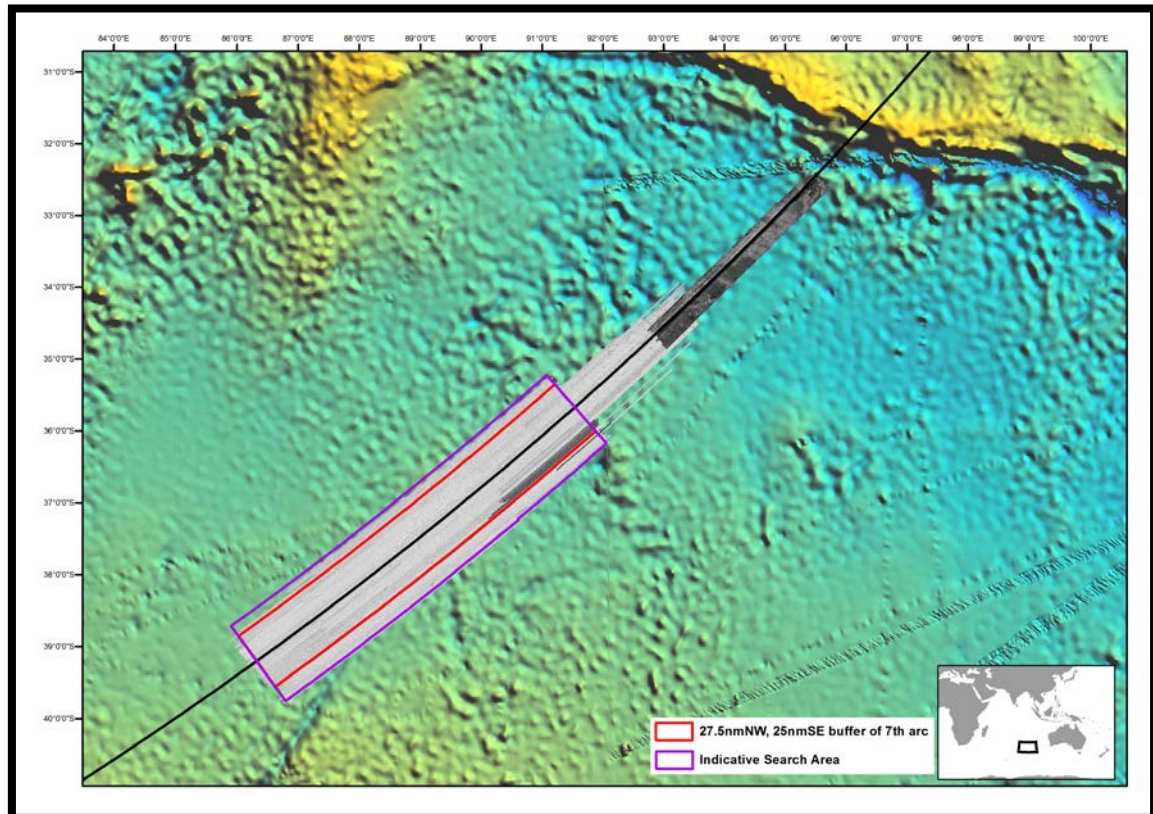
High resolution sonar coverage of the high priority portion of the indicative search area is very high and will be ~99.9% by the time the current AUV campaign is completed. The overall confidence of detection of the MH370 debris field within the current search area is >95%.



## Area searched

Figure 10 shows the area searched to date. Lighter grey areas have been searched using the Fugro deep tow vehicles with conventional side scan sonar for primary coverage, darker grey areas are the portions searched using the ProSAS synthetic aperture sonar deep tow system. The purple box bounds the indicative search area between latitudes 36°S and 39.3°S which has been searched to ~41 NM to the east and ~38 NM to the west of the 7<sup>th</sup> arc. To the north, between latitudes 32.8°S and 36°S along the 7<sup>th</sup> arc the area has been searched to widths which vary from ~12 to 17 NM to the east and ~10 to 21 NM to the west of the 7<sup>th</sup> arc.

**Figure 10. Area searched for MH370**



Source: ATSB

# Satellite data

Throughout the search, data from a communications satellite along with aircraft performance data has been used to attempt to reconstruct the flight path of MH370 from the time of the last radar contact. Information recorded by a satellite ground station at the time of handshakes<sup>2</sup> with MH370 was used to estimate the track of the aircraft. SATCOM information from two unanswered ground to air telephone calls was also available. This information showed that the flight continued for approximately five and a half hours after the last radar data.

The methodologies for the calculation of flight paths were included in the ATSB's reports [MH370 – Definition of Underwater Search Areas report](#) of 26 June 2014 and updated on 18 August 2014, [MH370 – Flight Path Analysis Update](#) of 8 October 2014 and [MH370 – Definition of Underwater Search Area Update](#) of December 2015.

The calculations identified seven 'arcs' which lead to the definition of the search area along the current north-south line of the 7<sup>th</sup> arc (which is regarded as the primary datum for determining the search area). It was then necessary to define which section of the 7<sup>th</sup> arc has the highest likelihood of finding the aircraft and the width of the search area to the east and west of the arc; encompassing aircraft performance limits and end of flight scenarios.

The DST Group provided expert analysis of the available SATCOM data relating to MH370. The analysis used models of the Inmarsat SATCOM data, aircraft dynamics, and meteorological data to determine likely flight paths. The DST Group analysis has been published in the book, [Bayesian Methods in the Search for MH370](#). The methodology was subjected to a set of validation experiments to ensure that the set of predicted flight paths aligned with actual flight data for previous flights of the accident aircraft (registered 9M-MRO) and other flights in the air at the same time as the accident. Further burst frequency offset (BFO) analysis performed by DST Group was contained in the ATSB report of 2 November 2016, [MH370—Search and debris examination update](#).

At the *First Principles Review* meeting, experts discussed their work to refine the analysis and considered the possible analysis techniques, validations and accident result scenarios. Their particular focus was the effect of the sonar search results to date on the probability map for the search area.

## Search results and likely aircraft autopilot mode

The DST Group analysis which used a dynamic model of the aircraft, examined five different lateral aircraft autopilot control modes:

1. Constant magnetic heading (CMH).
2. Constant true heading (CTH).
3. Constant magnetic track (CMT).
4. Constant true track (CTT).
5. Lateral navigation (LNAV).

The initial analysis assumed equal likelihood (uniform probability) across the lateral aircraft modes throughout the southern portion of the accident flight. The results of the analysis suggested that based on the satellite data, the aircraft was more likely to be operating at the time in the CTT or LNAV lateral control modes. These lateral control modes generally resulted in the aircraft's flight path being towards the southern end of the search area. The remaining three lateral control modes generally resulted in the aircraft's flight path ending north of the CTT and LNAV results, up to 33°S in latitude along the 7<sup>th</sup> arc.

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<sup>2</sup> A handshake in satellite communication is a series of signalling messages that establish or maintain a communication channel.

The southern portion of the search area which mainly encompasses the CTT and LNAV lateral control mode results has been thoroughly searched with underwater assets (deep tow, AUV, and ROV). Based on the results of the underwater search, the probability distribution was updated to reflect the new information of the unsuccessful search which then favoured the other control modes.

***Flight crew advice***

During the *First Principles Review* meeting, flight crew with extensive experience on the aircraft type indicated that the aircraft is usually flown in the LNAV or CMH lateral control modes.

This information, combined with the results from the areas already searched to increases the likelihood in the northern section of the probability map in Figure 13.

## Width of the search area

The following factors which affect the width of the search were defined previously, in the ATSB publication [MH370 – Definition of Underwater Search Area Update](#) of December 2015:

- Tolerance in the calculation of the arcs.
- A series of end of flight simulations conducted in 2014.
- A basic turn analysis.
- A review of previous accidents.
- The maximum range of the aircraft if glided after fuel exhaustion.

Analysis of these factors resulted in three areas of decreasing probability at 20 NM, 40 NM, and 100 NM from the 7<sup>th</sup> arc.

The latest ATSB report of 2 November 2016, [MH370—Search and debris examination update](#), provided new information relating to the end of flight. This new information included:

- The analysis of the debris recovered from MH370 indicating that the flaps were likely in a retracted position.
- The analysis of the BFO from the final two SATCOM transmissions which indicated that the aircraft was likely to be on an unstable flight path.
- Results from recent simulations showed high rates of descent broadly consistent with the BFO analysis. These simulations indicated that the aircraft was likely to be within 15 NM of the 7<sup>th</sup> arc.

This information provided significantly more weight to the aircraft being located closer to the arc than the ATSB concluded in 2015—probably within 25 NM, with locations closer to the 7<sup>th</sup> arc a higher likelihood.

This analysis, and the implications for the width of the search area were presented at the *First Principles Review* meeting. All participants were in general agreement that the distance required to be searched from the arc could be reduced to 25 NM from the 7<sup>th</sup> arc with a weighting to the west to account for the arc altitude<sup>3</sup>.

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<sup>3</sup> The reference 7<sup>th</sup> arc (search datum) is at an altitude of 40,000 ft. It is likely that the aircraft was at a lower altitude (and therefore closer to the sub-satellite point) at the time of the final SATCOM transmissions and so the distance to the west of the reference arc which should be searched is slightly more.

# Drift analysis

More than 20 items of debris have been recovered and identified as likely to be, almost certainly or definitely originating from MH370. The first of these was the flaperon, found on La Réunion Island on 29 July 2015. Other items have been located along the east and south coast of Africa, the east coast of Madagascar and the Islands of Mauritius and Rodrigues in the Indian Ocean. A complete list of recovered items was published by the Malaysian investigation team and can be found at [www.mh370.gov.my/index.php/en/](http://www.mh370.gov.my/index.php/en/).

An oceanographer from CSIRO was involved in the initial sea surface search for MH370 coordinated by the Australian Maritime Safety authority (AMSA). CSIRO continued to assist in the search for MH370 by completing work predicting landfall areas for floating debris, and analysing the drift of recovered debris.

In April 2016, the ATSB commissioned CSIRO to perform a detailed study of the drift of the recovered debris. The final report of this study has been released concurrently with this report and should be read in conjunction with this section. The CSIRO report and can be found on the ATSB website: [www.atsb.gov.au/mh370](http://www.atsb.gov.au/mh370)

The aim of the CSIRO drift study was to determine the probability of locations along the 7<sup>th</sup> arc (defined by SATCOM analysis as between 45°S and 22°S) being the origin of the recovered debris.

A forward-tracking numerical simulation was created. Within the simulation, flaperons and other modelled debris were deployed along the 7<sup>th</sup> arc and allowed to drift freely. The simulated paths of the debris were calculated and compared against information from three sets of observations:

1. The extensive aerial and surface search conducted between 18 March and 28 April 2014.
2. The absence of debris from MH370 found anywhere along the coast of Australia.
3. The timing and location of parts from MH370 found on islands in the western Indian Ocean and on the east coast of the African continent.

The following is a summary of the results from the CSIRO drift analysis:

1. From the number and size of items found to date from MH370 there was definitely a surface debris field, so the fact that the sea surface search detected no wreckage argues quite strongly that the site where the aircraft entered the water was not between latitudes 32°S<sup>4</sup> and 25°S along the 7<sup>th</sup> arc. Those latitudes are also contra-indicated by an absence of aircraft parts being found off Africa earlier than December 2015.
2. Latitudes south of 39°S are quite strongly contra-indicated by the arrival times of the flaperon and other debris reaching Africa, and the fact that those items were many while findings anywhere on the Australian coastline were nil.
3. The absence of debris being found on African shores in 2014 suggests that the impact site was likely not north of 25°S.
4. Assuming that the crash was within ~25 NM of the 7<sup>th</sup> arc (ATSB 2016), this leaves only points between 36°S and 32°S that are less than ~25NM from the arc but outside the area that was searched in late 2014 and early 2015.
5. There is a region within the 36-32°S segment of the 7<sup>th</sup> arc, near 35°S that is most consistent with all of the following lines of evidence, taken together including:
  - a) The absence of detections during the 2014 surface search.
  - b) The absence of findings on the WA coastline.

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<sup>4</sup> Latitudes and longitudes specified as integers, or accompanied by the word 'near' in the drift modelling section of the report have an implied uncertainty of 1/2°.



- c) The July 2015 arrival time of the flaperon at La Reunion Island.
- d) The December 2015 and onwards (only) arrival times of other debris in the western Indian Ocean.

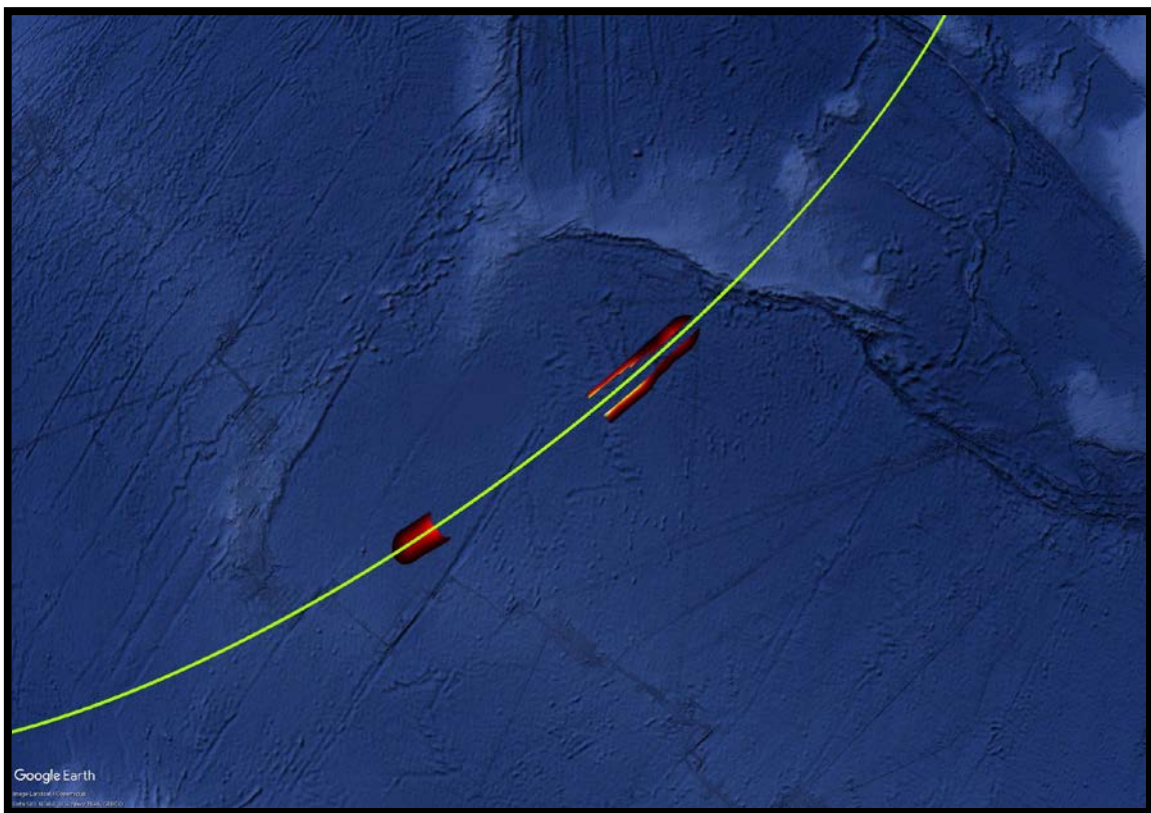
# Residual Probability Map

DST Group have used the Bayesian approach to incorporate multiple sources of analysis into a single probability map, or probability density function (PDF), of the location of the aircraft.

The main PDF is generated from the analysis of the satellite data and the search area width analysis. The residual PDFs show the effects of the other analyses (i.e. search results and drift analysis) on the probabilities.

Figure 11 shows the result of the SATCOM PDF updated with the search results. The areas searched were removed from the PDF. The residual probability is located in areas yet to be searched, with two clear areas of interest: north of the current search area and south of the current search area.

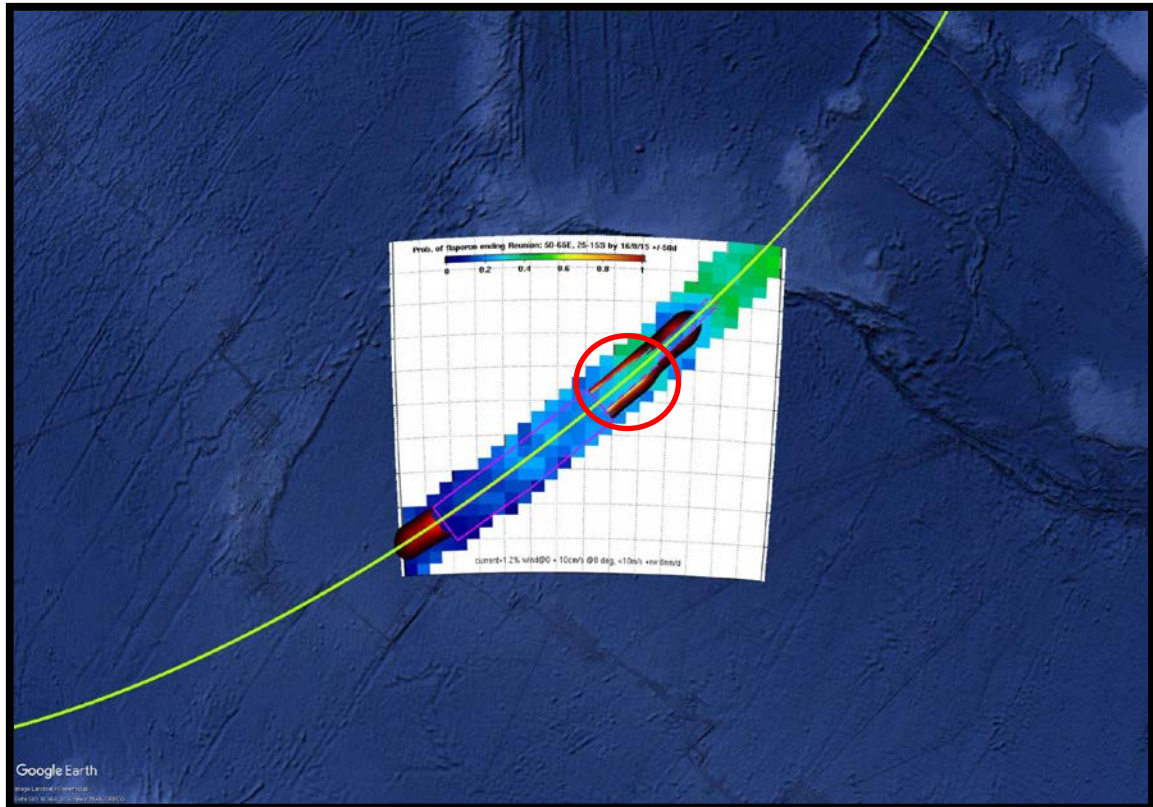
**Figure 11. Updated probability distribution with the results of the underwater search.**



Source: Google Earth / DST Group

Figure 12 shows the SATCOM PDF with the CSIRO drift study of the flaperon arrival at La Reunion Island likelihood overlaid. The alignment of the high likelihood point of origin of the flaperon from the drift analysis (green) and the peak of the northern SATCOM analysis PDF can be clearly seen (red circle).

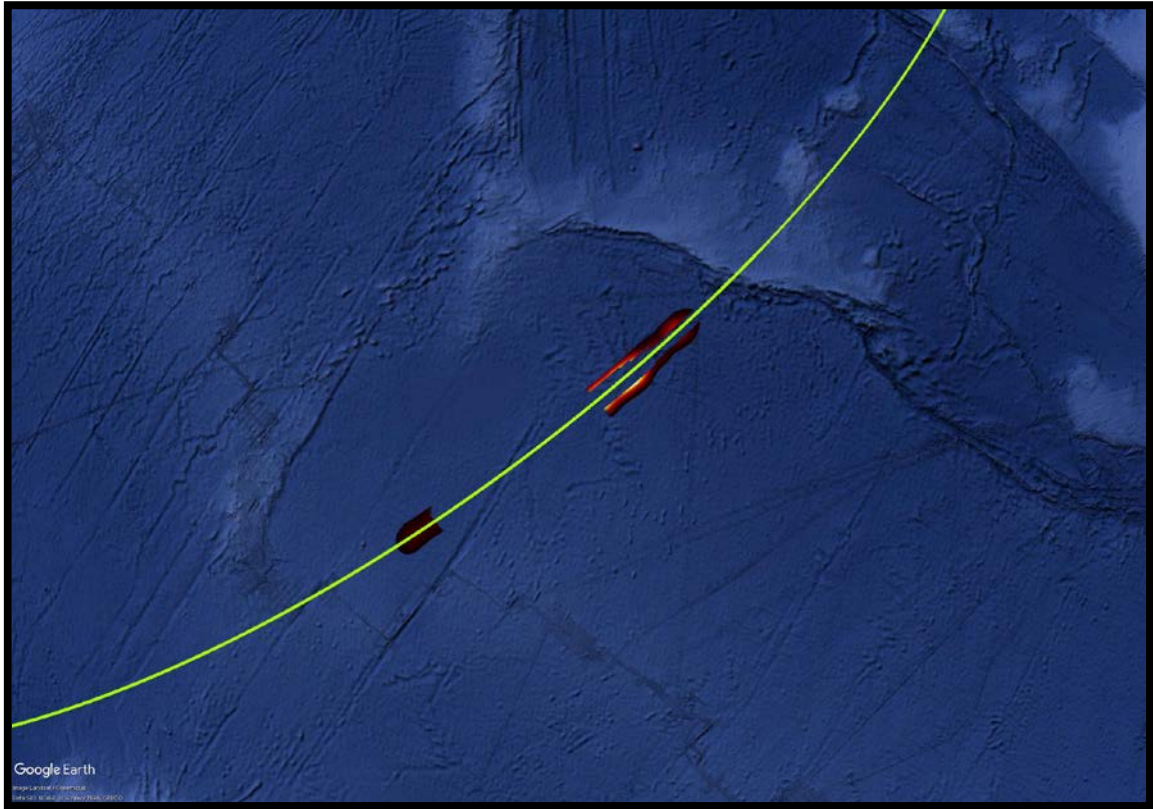
**Figure 12. Updated probability distribution with the results of the underwater search and the drift analysis results overlaid**



Source: Google Earth / DST Group

Figure 13 shows the search probability distribution based on the SATCOM data and CSIRO drift analysis. The section south of the indicative search area (pink box in Figure 12) becomes much less favourable once the drift results are incorporated.

**Figure 13. Updated probability distribution with the results of the underwater search and the drift analysis**



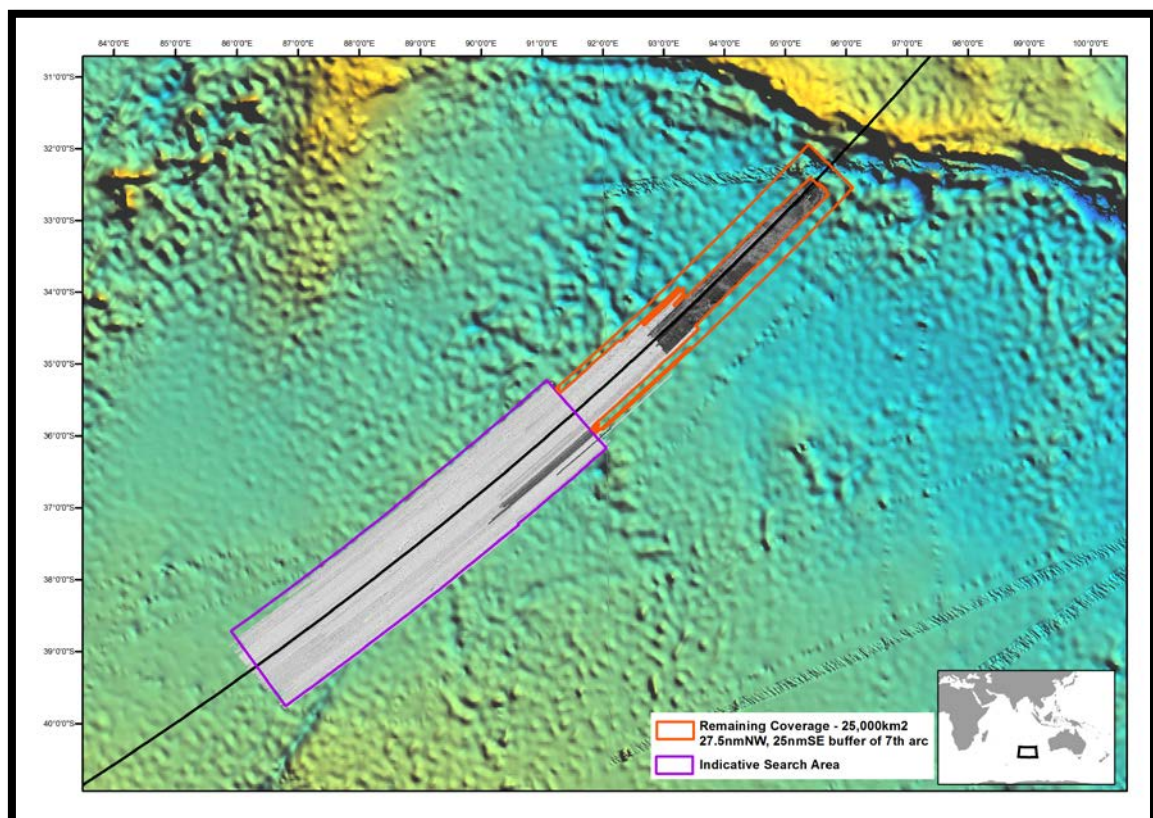
Source: Google Earth / DST Group



# Conclusions

1. There is a very high level of confidence in the search results to date in the current indicative search area. The high resolution sonar coverage is very high and the data has been subjected to a very thorough analysis. The area has been searched to a level of confidence >95% without identifying the aircraft debris field.
2. The analysis of the last two SATCOM transmissions, the likely position of the aircraft's flaps at impact and results from recent end of flight simulations has allowed a revision of the distance required to be searched away from the 7<sup>th</sup> arc. 99% of the DST Group analysis results lie within 25 NM to the east and west of the arc.
3. A residual probability map based on the comprehensive satellite communication data analysis and updated with the latest search results and the CSIRO drift analysis identified a remaining area of high probability between latitudes 32.5°S and 36°S along the 7<sup>th</sup> arc.
4. The participants of the *First Principles Review* were in agreement on the need to search an additional area representing approximately 25,000 km<sup>2</sup> (the orange bordered area in Figure 14). Based on the analysis to date, completion of this area would exhaust all prospective areas for the presence of MH370.

Figure 14. Remaining prospective area to find the wreckage of MH370



Source: ATSB



# Acknowledgements

The ATSB would like to acknowledge the following organisation for their input and continued assistance in the search for MH370:

- Air Accidents Investigation Branch (UK)
- Australian Bureau of Meteorology
- Defence Science and Technology Group, Australia
- Boeing
- Commonwealth Scientific and Industrial Research Organisation
- Curtin University
- Department of Civil Aviation, Malaysia
- Inmarsat
- Malaysian Airlines Berhad
- Malaysian Ministry of Transport
- National Transportation Safety Board (US)
- Thales

Those involved have dedicated many hours outside of normal duties to advance the collective understanding of the event. The main focus has always been in finding the aircraft to assist the Malaysian investigation team and to bring closure to the families of the passengers and crew of MH370.

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## Investigation

**ATSB Transport Safety Report**  
Aviation External Investigation

MH370 – First Principles Review  
AE-2014-054  
20 December 2016